



Beginning

Linux® Programming

3rd Edition

Neil Matthew, Richard Stones

Foreword by Alan Cox



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Third Edition

Neil Matthew
Richard Stones



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About Neil Matthew

Neil Matthew has been interested in and has programmed computers since 1974. A mathematics graduate from the University of Nottingham, Neil is just plain keen on programming languages and likes to explore new ways of solving computing problems. He's written systems to program in BCPL, FP (Functional Programming), Lisp, Prolog, and a structured BASIC. He even wrote a 6502 microprocessor emulator to run BBC microcomputer programs on UNIX systems.

In terms of UNIX experience, Neil has used almost every flavor since the late 1970s, including BSD UNIX, AT&T System V, Sun Solaris, IBM AIX, many others, and of course Linux.

Neil can claim to have been using Linux since August 1993 when he acquired a floppy disk distribution of Soft Landing (SLS) from Canada, with kernel version 0.99.11. He's used Linux-based computers for hacking C, C++, Icon, Prolog, Tcl, and Java at home and at work.

Most of Neil's "home" projects were originally developed using SCO UNIX, but they've all ported to Linux with little or no trouble. He says Linux is much easier because it supports quite a lot of features from other systems, so that both BSD- and System V-targeted programs will generally compile with little or no change.

As the head of software and principal engineer at Camtec Electronics in the 1980s, Neil programmed in C and C++ for real-time embedded systems. Since then he's worked on software development techniques and quality assurance. After a spell as a consultant with Scientific Generics he is currently working as a systems architect with Celesio AG.

Neil is married to Christine and has two children, Alexandra and Adrian. He lives in a converted barn in Northamptonshire, England. His interests include solving puzzles by computer, music, science fiction, squash, mountain biking, and not doing it yourself.

About Rick Stones

Rick started programming at school, more years ago than he cares to remember, on a 6502-powered BBC micro, which with the help of a few spare parts continued to function for the next 15 years. He graduated from Nottingham University with a degree in Electronic Engineering, but decided software was more fun.

Over the years he has worked for a variety of companies, from the very small with just a dozen employees, to the very large, including the IT services giant EDS. Along the way he has worked on a range of projects, from real-time communications to accounting systems, very large help desk systems, and more recently as the technical authority on a large EPoS and retail central systems program.

A bit of a programming linguist, he has programmed in various assemblers, a rather neat proprietary telecommunications language called SL-1, some FORTRAN, Pascal, Perl, SQL, and smidgeons of Python and C++, as well as C. (Under duress he even admits that he was once reasonably proficient in Visual Basic, but tries not to advertise this aberration.)

Rick lives in a village in Leicestershire, England, with his wife Ann, children Jennifer and Andrew, and two cats. Outside work his main interest is classical music, especially early religious music, and he even does his best to find time for some piano practice. He is currently trying to learn to speak German.

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Foreword by Alan Cox

Every computer programmer has his own piles of notes and scribbles. They have their code examples saved from the past heroic dive into the manuals or from Usenet, where sometimes even fools fear to follow. (The other body of opinion is that fools all get free Usenet access and use it nonstop.) It is therefore perhaps strange that so few books follow such a style. In the online world there are a lot of short, to-the-point documents about specific areas of programming and administration. The Linux documentation project released a whole pile of documents covering everything from installing Linux and Windows on the same machine to wiring your coffee machine to Linux. Seriously. Take a look at The Linux Documentation Project on <http://www.tldp.org>.

The book world, on the other hand, seems to consist mostly of either learned tomes, detailed and very complete works that you don't have time to read, or books for complete beginners that you buy for friends as a joke. There are very few books that try to cover the basics of a lot of useful areas. This book is one of them, a compendium of those programmers' notes and scribbles, deciphered (try reading a programmer's handwriting), edited, and brought together coherently as a book.

This updated third edition of Beginning Linux Programming has been reviewed and updated to reflect today's Linux developments, including a chapter on programming with the Qt toolkit, the basis of the KDE GUI.

Chapter 18 is your chance to join the world of kernel programmers. As you will discover, it isn't actually that different from writing modules for large application programs. Put on your pointy hat, grow a beard, drink Jolt Cola, and come join in the fun.

Alan



Introduction

Welcome to *Beginning Linux Programming*, 3rd Edition, an easy-to-use guide to developing programs for the Linux and other UNIX-style operating systems.

In this book we aim to give you an introduction to a wide variety of topics important to you as a developer using Linux. The word *beginning* in the title refers more to the content than to your skill level. We've structured the book to help you learn more about what Linux has to offer, however much experience you have already. Linux programming is a large field and we aim to cover enough about a wide range of topics to give you a good "beginning" in each subject.

Who's This Book For?

If you're a programmer who wishes to get up to speed with the facilities that Linux (or UNIX) offers software developers, to maximize your programming time and your application's use of the Linux system, you've picked up the right book. Clear explanations and a tried and tested step-by-step approach will help you progress rapidly and pick up all the key techniques.

We assume you have some experience in C and/or C++ programming, perhaps in Windows or some other system, but we try to keep the book's examples simple so that you don't need to be an expert C coder to follow this book. Where direct comparisons exist between Linux programming and C/C++ programming, these are indicated in the text.

Watch out if you're totally new to Linux. This isn't a book on installing or configuring Linux. If you want to learn more about administering a Linux system, you may wish to look at some complementary books such as *Running Linux*, 4th Edition, by Matt Welsh, Matthias Kalle Dalheimer, Terry Dawson, and Lar Kaufman (O'Reilly, ISBN 0596002726) or *Linux System Administration: A User's Guide*, by Marcel Gagné (Addison-Wesley, ISBN 0201719347).

As it aims to be a tutorial guide to the various tools and sets of functions/libraries available to you on most Linux systems as well as a handy reference you can return to, this book is unique in its straightforward approach, comprehensive coverage, and extensive examples.

What's Covered in the Book

The book has a number of aims:

- ❑ To teach the use of the standard Linux C libraries and other facilities as specified by the various Linux and UNIX standards.
- ❑ To show how to make the most of the standard Linux development tools.
- ❑ To give a concise introduction to data storage under Linux using both the DBM and MySQL database systems.
- ❑ To show how to build graphical user interfaces for the X Window System. We will use both the GTK (the basis of the GNOME environment) and Qt (the basis of the KDE environment) libraries.
- ❑ Having given you firm grounding, we'll progress to real-world applications that you want to program.

As we cover these topics, we introduce programming theory and then illustrate it with an appropriate example(s) and a clear explanation. In this way you can learn quickly on a first read and look back over things to brush up on all the essential elements if you need to.

While the small examples are designed mainly to illustrate a set of functions or some new theory in action, throughout the book lies a larger sample project: a simple database application for recording audio CD details. As your knowledge expands, you can develop, reimplement and extend the project to your heart's content. That said, however, the CD application doesn't dominate any chapter, so you can skip it if you want to, but we feel that it provides additional useful, in-depth examples of the techniques that we'll discuss. It certainly provides an ideal way to illustrate each of the more advanced topics as they are introduced. Our first discussion of this application occurs at the end of Chapter 2 and shows how a fairly large shell script is organized, how the shell deals with user input, and how it can construct menus and store and search data.

After recapping the basic concepts of compiling programs, linking to libraries, and accessing the online manuals, you will take a sojourn into shells. You then get stuck into C programming, where we cover working with files, getting information from the Linux environment, dealing with terminal input and output, and the `curses` library (which makes interactive input and output more tractable). You're then ready to tackle reimplementing the CD application in C. The application design remains the same, but the code uses the `curses` library for a screen-based user interface.

From there, we cover data management. Meeting the `dbm` database library is sufficient cause for us to reimplement the application, but this time with a design that will re-emerge in some later chapters. In a later chapter we look at how the data could be stored in a relational database using MySQL, and we also reuse this data storage technique later in the chapter, so you can see how the techniques compare. The size of these recent applications means that we then need to deal with such nuts-and-bolts issues as debugging, source code control, software distribution, and makefiles.

You will also look at how different Linux processes can communicate, using a variety of techniques, and then look at how Linux programs can use sockets to support TCP/IP networking to different machines, including the issues of talking to machines that use different processor architectures.

Having got the foundations of Linux programming in place, we cover the creation of graphical programs. We do this over two chapters, looking first at the GTK toolkit, which underlies the GNOME environment, and then at the Qt toolkit, which underlies the KDE environment.

As the book's final “programming” chapter, we give an introduction to writing device drivers—an important step along the path to understanding the Linux kernel itself.

We finish off with a brief look at the standards that keep Linux systems from different vendors similar enough that we can move between them easily and write programs that will work on different distributions of Linux.

As you'd expect, there's a fair bit more in between, but we hope that this gives you a good idea of the material we'll be discussing.

What You Need to Use This Book

In this book, we'll give you a taste of programming for Linux. To help you get the most from the chapters, we would really like you to try out the examples as you read. These also provide a good base for experimentation and will hopefully inspire you to create programs of your own. We hope you will read this book in conjunction with experimenting on your own Linux installation.

Linux is available for many different systems. Its adaptability is such that enterprising souls have persuaded it to run in one form or another on just about anything with a processor in it! Examples include systems based on the Alpha, SPARC, ARM, PowerPC, and 68000 CPUs as well as the Intel x86/Pentium-class processors (and compatibles) found in today's PCs.

To develop this book we primarily used x86-based systems, but very little of what we cover is Intel-specific. Although it is possible to run Linux on a 386 with 2-MB RAM and no hard disk (truly!), to run Linux successfully and follow the examples in this book, we recommend that you pick one of the more popular Linux distributions such as Red Hat, Debian, or SuSE, and check the hardware recommendations they give.

We wrote this book and developed the examples on two Linux systems with different specifications, so we're confident that if you can run Linux, you can make good use of this book. Furthermore, we tested the code on other versions of Linux during the book's technical review.

As for software requirements, we suggest that you use a recent version of a Linux distribution. Although it's possible to put together a Linux from scratch, it's much easier to start with a prepackaged version, and with many of the vendors now providing online updates to keep the versions of components updated, and bugs fixed, it's a good way for most users to run their Linux systems.

Because Linux and the GNU toolset and others are released under the GPL, they have certain properties, one of which is freedom. They will always have the source code available, and no one can take that freedom away. They are, therefore, examples of Open Source software—a weaker term for other software that may also have the source code available subject to certain conditions; see <http://www.open-source.org/> for more details. With GNU/Linux, you will always have the option of support—either doing it yourself with the source code or hiring someone else. There are an ever-increasing number of companies offering commercial support for Linux and associated tools.

Source Code

We have tried to provide example programs and code snippets that best illustrate the concepts being discussed in the text. Please note that, in order to make the new functionality being introduced as clear as possible, we have taken one or two liberties with coding style.

In particular, we do not always check that the return results from every function we call are what we expect. In production code for real applications we would certainly do this check, and you too should adopt a rigorous approach toward error handling. (We discuss some of the ways that errors can be caught and handled in Chapter 3.)

The complete source code from the book is available for download from <http://www.wrox.com>.

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Although all the code you need is listed in the book, we suggest you download a copy of the code to save yourself a lot of typing.

Conventions

To help you get the most from the text and keep track of what's happening, we've used a number of conventions throughout the book:

Boxes like this one hold important, not-to-be-forgotten, mission-critical information that is directly relevant to the surrounding text.

When we introduce them, we highlight *important words* in italics. Characters we want you to **type** are in bold font. We show keyboard strokes like this: Ctrl+A.

We present code in three different ways:

```
$ who
root      tty1          Sep 10 16:12
rick      tty2          Sep 10 16:10
```

When the command line is shown, it's in the above style, whereas output is in this style. The \$ is the prompt (if the superuser is required for the command, the prompt will be a # instead) and the bold text is what you type in and press Enter to execute. Any text following that in the same font but in non-bold is the output of the bolded command. In the example above you type in the command **who**, and you see the output below the command.

Prototypes of UNIX-defined functions and structures are shown in bold as follows:

```
#include <stdio.h>

int printf (const char *format, ...);
```

In our code examples, the code foreground style shows new, important material, such as

```
/* This is what new, important, and pertinent code looks like.
```

while code that looks like this (code background style) is less important:

```
/*This is what code that has been seen before looks like.
```

And often when a program is added to throughout a chapter, code that is added later is in foreground style first and background style later. For example, a new program would look like this:

```
/*Code example
/*That ends here.
```

And if we add to that program later in the chapter, it looks like this instead:

```
/*Code example
/*That ends here.

/*New code added.
```

The last convention we'll mention is that we presage example code with a "Try It Out" heading that aims to split the code up where it's helpful, highlight the component parts, and show the progression of the application. When it's important, we also follow the code with a "How It Works" section to explain any salient points of the code in relation to previous theory. We find these two conventions help break up the more formidable code listings into palatable morsels.

Customer Support

We offer source code for download, errata, and technical support from the Wrox Web site at <http://www.wrox.com>. In addition you can join mailing lists for author and peer discussion at <http://p2p.wrox.com> (see the last section in this introduction for more info on the P2P site).

Source Code and Updates

As you work through the examples in this book, you may choose either to type in all the code manually or to use the source code files that accompany the book. All of the source code used in this book is available for download at <http://www.wrox.com>. Once at the site, simply locate the book's title (either through the Search utility or by using one of the title lists) and double click the Download Code link on the book's detail page and you can obtain all the source code for the book. You can also click the Download Bonus Chapters link to download the Tcl, Perl, programming for X, HTML programming, and CGI chapters that were originally in the second edition.

The files are archived in standard Linux compressed tar format, using the file extension .tgz. You can extract these on Linux using the command 'tar zxvf' followed by the downloaded file's name. If you prefer a graphical tool under Linux, then File Roller can also be used. If you want to extract the files under Windows, the tgz format is supported by several Windows archive programs, such as WinZip. When you extract the files, the code will be extracted into chapter folders as long as you haven't set your compression software to ignore the file structure of the archive.

Errata

We have made every effort to ensure that there are no errors in the text or in the code.

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Getting Started

In this chapter, we discover what Linux is and how it relates to its inspiration, UNIX. We'll take a guided tour of the facilities provided by a Linux development system, and we'll write and run the first program. Along the way, we'll be looking at

- ❑ UNIX, Linux, and GNU
- ❑ Programs and programming languages for Linux
- ❑ How to locate development resources
- ❑ Static and shared libraries
- ❑ The UNIX philosophy

An Introduction to UNIX, Linux, and GNU

In recent years Linux has become a phenomenon. Hardly a day goes by without Linux cropping up in the media in some way. We've lost count of the number of applications that have been made available on Linux and the number of organizations that have adopted it.

Linux owes its success to systems and applications that preceded it: UNIX and GNU software. In this section we will look at how Linux came to be and what its roots are.

What Is UNIX?

The UNIX operating system was originally developed at Bell Laboratories, once part of the telecommunications giant AT&T. Designed in the 1970s for Digital Equipment PDP computers, UNIX has become a very popular multiuser, multitasking operating system for a wide variety of hardware platforms, from PC workstations to multiprocessor servers and supercomputers.

A Brief History of UNIX

Strictly, UNIX is a trademark administered by The Open Group, and it refers to a computer operating system that conforms to a particular specification. This specification, known as The Single UNIX Specification, defines the names of, interfaces to, and behaviors of all mandatory UNIX operating system functions. The specification is largely a superset of an earlier series of specifications, the P1003, or POSIX specifications, developed by the IEEE (Institute of Electrical and Electronic Engineers).

The UNIX source code belongs to SCO. Many UNIX-like systems are available commercially, such as SCO's Unixware, IBM's AIX, HP's HP-UX, and Sun's Solaris. Some have been made available for free, such as FreeBSD and Linux. Only a few systems currently conform to The Open Group specification, which allows them to be marketed with the name UNIX.

In the past, compatibility among different UNIX systems has been a real problem, although POSIX was a great help in this respect. These days, by following a few simple rules it is possible to create applications that will run on all UNIX and UNIX-like systems. More details on Linux and UNIX standards can be found in Chapter 19.

UNIX Philosophy

In the following chapters we hope to convey a flavor of Linux (and therefore UNIX) programming. Although programming in C is in many ways the same whatever the platform, it's true to say that UNIX developers have a special view of program and system development, and this view is equally applicable to Linux.

The UNIX operating system, and hence Linux, encourages a certain programming style. Following are a few characteristics shared by typical UNIX programs and systems:

- ❑ **Simplicity:** Many of the most useful UNIX utilities are very simple and, as a result, small and easy to understand. "Small and Simple" is a good technique to learn. Larger, more complex systems are guaranteed to contain larger, more complex bugs, and debugging is a chore that we'd all like to avoid!
- ❑ **Focus:** It's often better to make a program perform one task well than to throw in every feature along with the kitchen sink. A program with "feature bloat" can be difficult to use and difficult to maintain. Programs with a single purpose are easier to improve as better algorithms or interfaces are developed. In UNIX, small utilities are often combined to perform more demanding tasks when the need arises, rather than trying to anticipate a user's needs in one large program.
- ❑ **Reusable Components:** Make the core of your application available as a library. Well-documented libraries with simple but flexible programming interfaces can help others to develop variations or apply the techniques to new application areas. Examples include the dbm database library, which is a suite of reusable functions rather than a single database management program.
- ❑ **Filters:** Many UNIX applications can be used as filters. That is, they transform their input and produce output. As we'll see, UNIX provides facilities that allow quite complex applications to be developed from other UNIX programs by combining them in novel ways. Of course, this kind of reuse is enabled by the development methods that we've previously mentioned.
- ❑ **Open File Formats:** The more successful and popular UNIX programs use configuration files and data files that are plain ASCII text. If this is an option for your program development, it's a good choice. It enables users to use standard tools to change and search for configuration items

and to develop new tools for performing new functions on the data files. A good example of this is the `ctags` source code cross-reference system, which records symbol location information as regular expressions suitable for use by searching programs.

- **Flexibility:** You can't anticipate exactly how ingeniously users will use your program. Try to be as flexible as possible in your programming. Try to avoid arbitrary limits on field sizes or number of records. If you can, write the program so that it's network-aware and able to run across a network as well as on a local machine. Never assume that you know everything that the user might want to do.

What Is Linux?

As you may already know, Linux is a freely distributed implementation of a UNIX-like kernel, the low-level core of an operating system. Because Linux takes the UNIX system as its inspiration, Linux and UNIX programs are very similar. In fact, almost all programs written for UNIX can be compiled and run on Linux. Also, some commercial applications sold for commercial versions of UNIX can run unchanged in binary form on Linux systems.

Linux was developed by Linus Torvalds at the University of Helsinki, with the help of UNIX programmers from across the Internet. It began as a hobby inspired by Andy Tanenbaum's Minix, a small UNIX-like system, but has grown to become a complete system in its own right. The intention is that the Linux kernel will not incorporate proprietary code but will contain nothing but freely distributable code.

Versions of Linux are now available for a wide variety of computer systems using many different types of CPUs, including PCs based on Intel x86 and compatible processors; workstations and servers using Sun SPARC, IBM PowerPC, and Intel Itanium; and even some handheld PDAs and the Sony Playstation 2. If it's got a processor, someone somewhere is trying to get Linux running on it!

The GNU Project and the Free Software Foundation

Linux owes its existence to the cooperative efforts of a large number of people. The operating system kernel itself forms only a small part of a usable development system. Commercial UNIX systems traditionally come bundled with applications that provide system services and tools. For Linux systems, these additional programs have been written by many different programmers and have been freely contributed.

The Linux community (together with others) supports the concept of free software, that is, software that is free from restrictions, subject to the GNU General Public License. Although there may be a cost involved in obtaining the software, it can thereafter be used in any way desired and is usually distributed in source form.

The Free Software Foundation was set up by Richard Stallman, the author of GNU Emacs, one of the best-known text editors for UNIX and other systems. Stallman is a pioneer of the free software concept and started the GNU Project (the name GNU stands for GNU's Not Unix), an attempt to create an operating system and development environment that would be compatible with UNIX but not suffer the restrictions of the proprietary UNIX name and source code. GNU may turn out to be very different from UNIX at the lowest level but still supports UNIX applications.

The GNU Project has already provided the software community with many applications that closely mimic those found on UNIX systems. All these programs, so-called GNU software, are distributed under

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the terms of the GNU General Public License (GPL), a copy of that may be found at <http://www.gnu.org>. This license embodies the concept of *copyleft* (a takeoff on “copyright”). Copyleft is intended to prevent others from placing restrictions on the use of free software.

A few major examples of software from the GNU Project distributed under the GPL follow:

- ❑ GCC: The GNU Compiler Collection, containing the GNU C compiler
- ❑ G++: A C++ compiler, included as part of GCC
- ❑ GDB: A source code-level debugger
- ❑ GNU make: A version of UNIX make
- ❑ Bison: A parser generator compatible with UNIX yacc
- ❑ bash: A command shell
- ❑ GNU Emacs: A text editor and environment

Many other packages have been developed and released using free software principles and the GPL, including graphical image manipulation tools such as the Gimp, spreadsheets, source code control tools, compilers and interpreters, Internet tools, and two complete object-based environments: GNOME and KDE. We will discuss GNOME and KDE in Chapters 16 and 17.

There is now so much free software available that with the addition of the Linux kernel it could be said that the goal of creating GNU, a free UNIX-like system, has been achieved with Linux. To recognize the contribution made by GNU software, many people now refer to Linux systems in general as GNU/Linux.

You can find out more about the free software concept at <http://www.gnu.org>.

Linux Distributions

As we have already mentioned, Linux is actually just a kernel. You can obtain the sources for the kernel to compile and install it and then obtain and install many other freely distributed software programs to make a complete Linux. These installations are usually referred to as *Linux systems*, although they consist of much more than just the kernel. Most of the utilities come from the GNU Project of the Free Software Foundation.

As you can probably appreciate, creating a Linux system from just source code is a major undertaking. Fortunately, many people have put together *distributions* (often called *flavors*), usually on CD-ROM, that contain not just the kernel but also many other programming tools and utilities. These often include an implementation of the X Window System, a graphical environment common on many UNIX systems. The distributions usually come with a setup program and additional documentation (normally all on the CD[s]) to help you install your own Linux system. Some well-known distributions (particularly on the Intel x86 and Pentium families of processors) are Red Hat Linux, SuSE Linux, and Debian GNU/Linux, but there are many others.

Programming Linux

Many people think that programming Linux means using C. It's true that UNIX was originally written in C and that the majority of UNIX applications are written in C, but C is not the only option available to Linux programmers, or UNIX programmers for that matter. In the course of the book, we'll introduce a couple of the alternatives.

In fact, the first version of UNIX was written in PDP 7 assembler language in 1969. C was conceived by Dennis Ritchie around that time, and in 1973 he and Ken Thompson rewrote essentially the entire UNIX kernel in C, quite a feat in the days when system software was written in assembly language.

A vast range of programming languages are available for Linux systems, and many of them are free and available on CD-ROM collections or from FTP archive sites on the Internet. Here's a partial list of programming languages available to the Linux programmer:

| | | |
|--------|-------------|--------------|
| Ada | C | C++ |
| Eiffel | Forth | Fortran |
| Icon | Java | JavaScript |
| Lisp | Modula 2 | Modula 3 |
| Oberon | Objective C | Pascal |
| Perl | PostScript | Prolog |
| Python | Scheme | Smalltalk |
| SQL | Tcl/Tk | Bourne Shell |

We'll see how we can use a Linux shell (`bash`) to develop small- to medium-sized applications in Chapter 2. For the rest of the book, we'll mainly concentrate on C. We'll direct our attention mostly toward exploring the Linux programming interfaces from the perspective of the C programmer. We will assume knowledge of the C programming language.

Linux Programs

Linux applications are represented by two special types of files: *executables* and *scripts*. Executable files are programs that can be run directly by the computer; they correspond to Windows .exe files. Scripts are collections of instructions for another program, an interpreter, to follow. These correspond to Windows .bat or .cmd files, or interpreted BASIC programs.

Linux doesn't require executables or scripts to have a specific filename or any extension whatsoever. File system attributes, which we discuss in Chapter 2, are used to indicate that a file is a program that may be run. In Linux, we can replace scripts with compiled programs (and vice versa) without affecting other programs or the people who call them. In fact, at the user level, there is essentially no difference between the two.

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When we log in to a Linux system, we interact with a shell program (often bash) that runs programs in the same way that the Windows command prompt does. It finds the programs we ask for by name by searching for a file with the same name in a given set of directories. The directories to search are stored in a shell variable, `PATH`, in much the same way as with Windows. The search path (to which we can add) is configured by your system administrator and will usually contain some standard places where system programs are stored. These include

- ❑ /bin: Binaries, programs used in booting the system
- ❑ /usr/bin: User binaries, standard programs available to users
- ❑ /usr/local/bin: Local binaries, programs specific to an installation

An administrator's login, such as `root`, may use a `PATH` variable that includes directories where system administration programs are kept, such as `/sbin` and `/usr/sbin`.

Optional operating system components and third-party applications may be installed in subdirectories of `/opt`, and installation programs might add to your `PATH` variable by way of user install scripts.

It's not a good idea to delete directories from PATH unless you are sure that you understand what will result if you do.

Note that Linux, like UNIX, uses the colon (:) character to separate entries in the `PATH` variable, rather than the semicolon (;) that MS-DOS and Windows use. (UNIX chose : first, so ask Microsoft why Windows is different, not why UNIX is different!) Here's a sample `PATH` variable:

```
/usr/local/bin:/bin:/usr/bin::/home/neil/bin:/usr/X11R6/bin
```

Here the `PATH` variable contains entries for the standard program locations, the current directory (.), a user's home directory, and the X Window System.

Remember, Linux uses a forward slash (/) to separate directory names in a file name rather than the backslash (\) of Windows. Again, UNIX got there first.

The C Compiler

On POSIX-compliant systems, the C compiler is called `c89`. Historically, the C compiler was simply called `cc`. Over the years, different vendors have sold UNIX-like systems with C compilers with different facilities and options, but often still called `cc`.

When the POSIX standard was prepared, it was impossible to define a standard `cc` command with which all these vendors would be compatible. Instead, the committee decided to create a new standard command for the C compiler, `c89`. When this command is present, it will always take the same options, independent of the machine.

On Linux systems that do try to implement the standards, you might find that any or all of the commands `c89`, `cc`, and `gcc` refer to the system C compiler, usually the GNU C compiler, or `gcc`. On UNIX systems, the C compiler is almost always called `cc`.

In this book, we'll be using gcc because it's provided with Linux distributions and because it supports the ANSI standard syntax for C. If you ever find yourself using a UNIX system without gcc, we recommend that you obtain and install it. You can find it at <http://www.gnu.org>. Wherever we use gcc in the book, simply substitute the relevant command on your system.

Try It Out—Our First Linux C Program

Let's start developing for Linux using C by writing, compiling, and running our first Linux program. It might as well be that most-famous of all starting points, Hello World.

1. Here's the source code for the file `hello.c`:

```
#include <stdio.h>

int main()
{
    printf("Hello World\n");
    exit(0);
}
```

To enter this program, you'll need to use an editor. There are many to choose from on a typical Linux system. Popular with many users is the vi editor. Both of the authors like emacs, so we suggest you take the time to learn some of the features of this powerful editor. To learn more about emacs you can use its online tutorial. To do this, start the editor by running the `emacs` command and then type `Ctrl+H` followed by `t` for the tutorial. emacs also has its entire manual available. When in emacs, type `Ctrl+H` and then `i` for information. Some versions of emacs may have menus that you can use to access the manual and tutorial.

2. Let's compile, link, and run our program.

```
$ gcc -o hello hello.c
$ ./hello
Hello World
$
```

How It Works

We invoked the GNU C compiler (on Linux this will most likely be available as `cc` too) that translated our C source code into an executable file called `hello`. We ran the program and it printed a greeting. This is just about the simplest example there is, but if you can get this far with your system, you should be able to compile and run the remainder of the examples in the book. If this did not work for you, make sure that the C compiler is installed on your system. For example, many Linux distributions have an install option called Software Development that we should select.

Since this is the first program we've run, it's a good time to point something out. The `hello` program will probably be in your home directory. If `PATH` doesn't include a reference to your home directory, the shell won't be able to find `hello`. Furthermore, if one of the directories in `PATH` contains another program called `hello`, that program will be executed instead. This would also happen if such a directory is mentioned in `PATH` before your home directory. To get around this potential problem, we can prefix program names with `./` (e.g., `./hello`). This specifically instructs the shell to execute the program in the current directory with the given name.

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If you forget the `-o name` option that tells the compiler where to place the executable, the compiler will place the program in a file called `a.out` (meaning assembler output). Just remember to look for an `a.out` if you think you've compiled a program and you can't find it! In the early days of UNIX, people wanting to play games on the system often ran them as `a.out` to avoid being caught by system administrators, and some UNIX installations routinely delete all files called `a.out` every evening.

Development System Roadmap

For a Linux developer, it can be important to know a little about where tools and development resources are located. The following sections provide a brief look at some important directories and files.

Applications

Applications are usually kept in directories reserved for them. Applications supplied by the system for general use, including program development, are found in `/usr/bin`. Applications added by system administrators for a specific host computer or local network are often found in `/usr/local/bin` or `/opt`.

Administrators favor `/usr/local`, as it keeps vendor-supplied files and later additions separate from the applications supplied by the system. Keeping `/usr` organized in this way may help when the time comes to upgrade the operating system, since only `/usr/local` need be preserved. We recommend that you compile your applications to run and access required files from the `/usr/local` hierarchy.

Additional features and programming systems may have their own directory structures and program directories. Chief among these is the X Window System, which is commonly installed in the `/usr/X11` directory. Alternative locations include `/usr/X11R6` for Revision 6, also used by the XFree86 variant for Intel processors distributed by the XFree consortium as well as many Linux distributions. Other UNIX-like systems may choose different locations, such as `/usr/openwin` for Sun's Open Windows provided with Solaris.

The GNU compiler system's driver program, `gcc` (which we used in our programming example earlier in the chapter), is typically located in `/usr/bin` or `/usr/local/bin`, but it will run various compiler-support applications from another location. This location is specified when you compile the compiler itself and varies with the host computer type. For Linux systems, this location might be a version-specific subdirectory of `/usr/lib/gcc-lib/`. On one of the author's machines at the time of writing it is `/usr/lib/gcc-lib/i486-suse-linux/3.3/`. The separate passes of the GNU C/C++ compiler, and GNU-specific header files, are stored here.

Header Files

For programming in C and other languages, we need header files to provide definitions of constants and declarations for system and library function calls. For C, these are almost always located in `/usr/include` and subdirectories thereof. You can normally find header files that depend on the particular incarnation of Linux that you are running in `/usr/include/sys` and `/usr/include/linux`.

Other programming systems will also have `include` files that are stored in directories that get searched automatically by the appropriate compiler. Examples include `/usr/include/X11` for the X Window System and `/usr/include/g++` for GNU C++.

We can use include files in subdirectories or nonstandard places by specifying the `-I` flag to the C compiler. For example,

```
$ gcc -I/usr/openwin/include fred.c
```

will direct the compiler to look in the directory `/usr/openwin/include`, as well as the standard places, for header files included in the `fred.c` program. Refer to the manual page for the C compiler (`man gcc`) for more details.

It's often convenient to use the `grep` command to search header files for particular definitions and function prototypes. Suppose we need to know the name of the `#defines` used for returning the exit status from a program. Simply change to the `/usr/include` directory and `grep` for a probable part of the name like this:

```
$ grep EXIT_ *.h
...
stdlib.h:#define      EXIT_FAILURE    1      /* Failing exit status. */
stdlib.h:#define      EXIT_SUCCESS     0      /* Successful exit status. */
...
$
```

Here `grep` searches all the files in the directory with a name ending in `.h` for the string `EXIT_`. In this example, it has found (among others) the definition we need in the file `stdlib.h`.

Library Files

Libraries are collections of precompiled functions that have been written to be reusable. Typically, they consist of sets of related functions to perform a common task. Examples include libraries of screen-handling functions (the `curses` and `ncurses` libraries) and database access routines (the `dbm` library). We'll show you some libraries in later chapters.

Standard system libraries are usually stored in `/lib` and `/usr/lib`. The C compiler (or more exactly, the linker) needs to be told which libraries to search, as by default it searches only the standard C library. This is a remnant of the days when computers were slow and CPU cycles were expensive. It's not enough to put a library in the standard directory and hope that the compiler will find it; libraries need to follow a very specific naming convention and need to be mentioned on the command line.

A library filename always starts with `lib`. Then follows the part indicating what library this is (like `c` for the C library, or `m` for the mathematical library). The last part of the name starts with a dot `.`, and specifies the type of the library:

- `.a` for traditional, static libraries
- `.so` for shared libraries (see the following)

The libraries usually exist in both static and shared formats, as a quick `ls /usr/lib` will show. We can instruct the compiler to search a library either by giving it the full path name or by using the `-l` flag. For example,

```
$ gcc -o fred fred.c /usr/lib/libm.a
```

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tells the compiler to compile file `fred.c`, call the resulting program file `fred`, and search the mathematical library in addition to the standard C library to resolve references to functions. A similar result is achieved with the following command:

```
$ gcc -o fred fred.c -lm
```

The `-lm` (no space between the `l` and the `m`) is shorthand (shorthand is much valued in UNIX circles) for the library called `libm.a` in one of the standard library directories (in this case `/usr/lib`). An additional advantage of the `-lm` notation is that the compiler will automatically choose the shared library when it exists.

Although libraries are usually found in standard places in the same way as header files, we can add to the search directories by using the `-L` (uppercase letter) flag to the compiler. For example,

```
$ gcc -o x11fred -L/usr/openwin/lib x11fred.c -lx11
```

will compile and link a program called `x11fred` using the version of the library `libx11` found in the `/usr/openwin/lib` directory.

Static Libraries

The simplest form of library is just a collection of object files kept together in a ready-to-use form. When a program needs to use a function stored in the library, it includes a header file that declares the function. The compiler and linker take care of combining the program code and the library into a single executable program. We must use the `-l` option to indicate which libraries other than the standard C runtime library are required.

Static libraries, also known as *archives*, conventionally have names that end with `.a`. Examples are `/usr/lib/libc.a` and `/usr/X11/lib/libX11.a` for the standard C library and the X11 library, respectively.

We can create and maintain our own static libraries very easily by using the `ar` (for archive) program and compiling functions separately with `gcc -c`. We should try to keep functions in separate source files as much as possible. If functions need access to common data, we can place them in the same source file and use static variables declared in that file.

Try It Out—Static Libraries

Let's create our own small library containing two functions and then use one of them in an example program. The functions are called `fred` and `bill` and just print greetings.

1. First, we'll create separate source files (imaginatively called `fred.c` and `bill.c`) for each of them. Here's the first:

```
#include <stdio.h>

void fred(int arg)
{
    printf("fred: you passed %d\n", arg);
```

And here's the second:

```
#include <stdio.h>

void bill(char *arg)
{
    printf("bill: you passed %s\n", arg);
}
```

2. We can compile these functions individually to produce object files ready for inclusion into a library. We do this by invoking the C compiler with the `-c` option, which prevents the compiler from trying to create a complete program. Trying to create a complete program would fail because we haven't defined a function called `main`.

```
$ gcc -c bill.c fred.c
$ ls *.o
bill.o  fred.o
```

3. Now let's write a program that calls the function `bill`. First, it's a good idea to create a header file for our library. This will declare the functions in our library and should be included by all applications that wish to use our library. It's a good idea to include the header file in the files `fred.c` and `bill.c` too. This will help the compiler pick up any errors.

```
/*
   This is lib.h. It declares the functions fred and bill for users
*/

void bill(char *);
void fred(int);
```

4. The calling program (`program.c`) can be very simple. It includes the library header file and calls one of the functions from the library.

```
#include "lib.h"

int main()
{
    bill("Hello World");
    exit(0);
}
```

5. We can now compile the program and test it. For now, we'll specify the object files explicitly to the compiler, asking it to compile our file and link it with the previously compiled object module `bill.o`.

```
$ cgcc -c program.c
$ cgcc -o program program.o bill.o
$ ./program
bill: we passed Hello World
$
```

6. Now let's create and use a library. We use the `ar` program to create the archive and add our object files to it. The program is called `ar` because it creates archives, or collections, of individual

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files placed together in one large file. Note that we can also use `ar` to create archives of files of any type. (Like many UNIX utilities, `ar` is a generic tool.)

```
$ ar crv libfoo.a bill.o fred.o
a - bill.o
a - fred.o
```

7. The library is created and the two object files added. To use the library successfully, some systems, notably those derived from Berkeley UNIX, require that a table of contents be created for the library. We do this with the `ranlib` command. In Linux, this step isn't necessary (but it is harmless) when we're using the GNU software development tools.

```
$ ranlib libfoo.a
```

Our library is now ready to use. We can add to the list of files to be used by the compiler to create our program like this:

```
$ gcc -o program program.o libfoo.a
$ ./program
bill: you passed Hello World
$
```

We could also use the `-l` option to access our library, but as it is not in any of the standard places, we have to tell the compiler where to find it by using the `-L` option like this:

```
$ gcc -o program program.o -L. -lfoo
```

The `-L.` option tells the compiler to look in the current directory (`.`) for libraries. The `-lfoo` option tells the compiler to use a library called `libfoo.a` (or a shared library, `libfoo.so`, if one is present).

To see which functions are included in an object file, library, or executable program, we can use the `nm` command. If we take a look at `program` and `lib.a`, we see that the library contains both `fred` and `bill`, but that `program` contains only `bill`. When the program is created, it includes only functions from the library that it actually needs. Including the header file, which contains declarations for all of the functions in the library, doesn't cause the entire library to be included in the final program.

If we're familiar with Windows software development, there are a number of direct analogies here:

| Item | UNIX | Windows |
|----------------|----------------------|--------------------------|
| object module | <code>func.o</code> | <code>FUNC.OBJ</code> |
| static library | <code>lib.a</code> | <code>LIB.LIB</code> |
| program | <code>program</code> | <code>PROGRAM.EXE</code> |

Shared Libraries

One disadvantage of static libraries is that when we run many applications at the same time and they all use functions from the same library, we may end up with many copies of the same functions in memory and indeed many copies in the program files themselves. This can consume a large amount of valuable memory and disk space.

Many UNIX systems and Linux support shared libraries can overcome this disadvantage. A complete discussion of shared libraries and their implementation on different systems is beyond the scope of this book, so we'll restrict ourselves to the visible implementation under Linux.

Shared libraries are stored in the same places as static libraries, but shared libraries have a different filename suffix. On a typical Linux system, the shared version of the standard math library is `/usr/lib/libm.so`.

When a program uses a shared library, it is linked in such a way that it doesn't contain function code itself, but references to shared code that will be made available at run time. When the resulting program is loaded into memory to be executed, the function references are resolved and calls are made to the shared library, which will be loaded into memory if needed.

In this way, the system can arrange for a single copy of a shared library to be used by many applications at once and stored just once on the disk. An additional benefit is that the shared library can be updated independently of the applications that rely on it. Symbolic links from the `/usr/lib/libm.so` file to the actual library revision (`/usr/lib/libm.N` where `N` represents a major version number—6 at the time of writing) are used. When Linux starts an application, it can take into account the version of a library required by the application to prevent major new versions of a library from breaking older applications.

The following example outputs are taken from a SuSE 8.2 distribution. Your output may differ slightly if you are not using this distribution.

For Linux systems, the program (the dynamic loader) that takes care of loading shared libraries and resolving client program function references is called `ld.so` and may be made available as `ld-linux.so.2` or `ld-lsb.so.1`. The additional locations searched for shared libraries are configured in the file `/etc/ld.so.conf`, which needs to be processed by `ldconfig` if changed (for example, if X11 shared libraries are added when the X Window System is installed).

We can see which shared libraries are required by a program by running the utility `ldd`. For example, if we try running it on our example application, we get the following:

```
$ ldd program
    libc.so.6 => /lib/libc.so.6 (0x4002a000)
    /lib/ld-linux.so.2 => /lib/ld-linux.so.2 (0x40000000)
```

In this case, we see that the standard C library (`libc`) is shared (`.so`). Our program requires major Version 6. Other UNIX systems will make similar arrangements for access to shared libraries. Refer to your system documentation for details.

In many ways, shared libraries are similar to dynamic-link libraries used under Windows. The `.so` libraries correspond to `.DLL` files and are required at run time, while the `.sa` libraries are similar to `.LIB` files included in the program executable.

Getting Help

The vast majority of Linux systems are reasonably well documented with respect to the system programming interfaces and standard utilities. This is true because, since the earliest UNIX systems, programmers

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have been encouraged to supply a manual page with their applications. These manual pages, which are sometimes provided in a printed form, are invariably available electronically.

The `man` command provides access to the online manual pages. The pages vary considerably in quality and detail. Some may simply refer the reader to other, more thorough documentation, while others give a complete list of all options and commands that a utility supports. In either case, the manual page is a good place to start.

The GNU software suite and some other free software use an online documentation system called `info`. You can browse full documentation online using a special program, `info`, or via the `info` command of the `emacs` editor. The benefit of the `info` system is that you can navigate the documentation using links and cross-references to jump directly to relevant sections. For the documentation author, the `info` system has the benefit that its files can be automatically generated from the same source as the printed, typeset documentation.

Try It Out—Manual Pages and `info`

Let's look for documentation of the GNU C compiler.

1. First let's look at the manual page.

```
$ man gcc
```

| | | |
|--------|-----|--------|
| GCC(1) | GNU | GCC(1) |
|--------|-----|--------|

NAME
gcc - GNU project C and C++ compiler

SYNOPSIS
gcc [-c|-S|-E] [-std=standard]
[-g] [-pg] [-Olevel]
[-Wwarn...] [-pedantic]
[-Idir...] [-Ldir...]
[-Dmacro[=defn]...] [-Umacro]
[-foption...] [-mmachine-option...]
[-o outfile] infile...

Only the most useful options are listed here; see below for the remainder. `g++` accepts mostly the same options as `gcc`.

DESCRIPTION
When you invoke GCC, it normally does preprocessing, compilation, assembly and linking. The ``overall options'' allow you to stop this process at an intermediate stage. For example, the `-c` option says not to run the linker. Then the output consists of object files output by the assembler.

Other options are passed on to one stage of processing. Some options control the preprocessor and others the compiler itself. Yet other options control the assembler and linker; most of these are not documented here, since you rarely need to use any of them.

...

If we wish, we can read about the options that the compiler supports. The manual page in this case is quite long, but it forms only a small part of the total documentation for GNU C (and C++).

When reading manual pages, we can use the spacebar to read the next page, Enter (or Return if your keyboard has that key instead) to read the next line, and *q* to quit altogether.

2. To get more information on GNU C, we can try `info`.

```
$ info gcc
```

```
File: gcc.info,  Node: Top,  Next: G++ and GCC,  Up: (DIR)
Introduction
*****
```

```
This manual documents how to use the GNU compilers, as well as their
features and incompatibilities, and how to report bugs. It corresponds
to GCC version 3.3. The internals of the GNU compilers, including how
to port them to new targets and some information about how to write
front ends for new languages, are documented in a separate manual.
```

```
*Note Introduction: (gccint)Top.
```

```
* Menu:
```

```
* G++ and GCC::      You can compile C or C++ Applications.
* Standards::       Language standards supported by GCC.
* Invoking GCC::    Command options supported by `gcc'.
* C Implementation:: How GCC implements the ISO C specification.
* C Extensions::   GNU extensions to the C language family.
* C++ Extensions:: GNU extensions to the C++ language.
* Objective-C::    GNU Objective-C runtime features.
* Compatibility::  Binary Compatibility
--zz-Info: (gcc.info.gz)Top, 40 lines -Top- Subfile: gcc.info-1.gz-*** Tags o
Welcome to Info version 4.5. Type ? for help, m for menu item.
```

We're presented with a long menu of options that we can select to move around a complete text version of the documentation. Menu items and a hierarchy of pages allow us to navigate a very large document. On paper, the GNU C documentation runs to many hundreds of pages.

The `info` system also contains its own help page in `info` form pages, of course. If we type `Ctrl+H`, we'll be presented with some help that includes a tutorial on using `info`. The `info` program is available with many Linux distributions and can be installed on other UNIX systems.

Summary

In this introductory chapter, we've looked at Linux programming and the things Linux holds in common with proprietary UNIX systems. We've noted the wide variety of programming systems available to us as UNIX developers. We've also presented a simple program and library to demonstrate the basic C tools, comparing them with their Windows equivalents.

2

Shell Programming

Having just started this book on programming Linux using C, we now take a detour into writing shell programs. Why? Well, Linux isn't like systems where the command-line interface is an afterthought to the graphical interface. UNIX, Linux's inspiration, originally had no graphical interface at all; everything was done from the command line. Consequently, the command line system of UNIX had a lot of development and became a very powerful feature. This has been carried into Linux, and some of the most powerful things that you can do are most easily done from the shell. Because the shell is so important to Linux, we thought we should cover shell programming early.

Throughout this chapter, we'll be learning the syntax, structures, and commands available to you when you're programming the shell, usually making use of interactive (screen-based) examples. These should serve as a useful synopsis of most of the shell's features and their effects. We will also sneak a look at a couple of particularly useful command line utilities often called from the shell: `grep` and `find`. While looking at `grep` we will also cover the fundamentals of regular expressions, which crop up in Linux utilities and also in programming languages such as Perl and PHP. At the end of the chapter, we show you how to program a real-life script, which is reprogrammed and extended in C throughout the book. In this chapter, we'll cover

- ❑ What a shell is
- ❑ Basic considerations
- ❑ The subtleties of syntax: variables, conditions, and program control
- ❑ Lists
- ❑ Functions
- ❑ Commands and command execution
- ❑ Here documents
- ❑ Debugging
- ❑ `grep` and regular expressions
- ❑ `find`

So, whether you're faced with a nightmare of a shell script in your system administration, want to prototype your latest big (but beautifully simple) idea, or just want to speed up some repetitive task, this chapter is for you.

Why Program with a Shell?

In UNIX, which is the parent operating system of Linux and the origin of many of the ideas and of the philosophy of the operating system, a variety of different shell programs are available. The most common on commercial versions of UNIX is probably the Korn shell, but there are many others. So why use a shell to program? Well, the shell leads a double life. Although it has superficial similarities to the Windows command prompt, it's much more powerful, capable of running reasonably complex programs in its own right. You can not only execute commands and call Linux utilities; you can also write them. The shell uses an interpreted language, which generally makes debugging easier because you can execute single lines, and there's no recompile time. However, this can make the shell unsuitable for time-critical or processor-intensive tasks.

One reason to use the shell for programming is that you can program the shell quickly and simply. Also, a shell is always available even on the most basic Linux installation. So for simple prototyping you can find out if your idea works. The shell is also ideal for any small utilities that perform some relatively simple task where efficiency is less important than easy configuration, maintenance, and portability. You can use the shell to organize process control, so that commands run in a predetermined sequence dependent on the successful completion of each stage.

A Bit of Philosophy

Here we come to a bit of UNIX—and of course Linux—philosophy. UNIX is built on and depends on a high level of code reuse. You build a small and simple utility and people use it as one link in a string of others to form a command. One of the pleasures of Linux is the variety of excellent tools available. A simple example is

```
$ ls -al | more
```

This command uses the `ls` and `more` utilities and pipes the output of the file listing to a screen-at-a-time display. Each utility is one more building block. You can often use many small scripts together to create large and complex suites of programs.

For example, if you want to print a reference copy of the bash manual pages, use

```
$ man bash | col -b | lpr
```

Furthermore, because of Linux's automatic file type handling, the users of these utilities usually don't need to know what language the utilities are written in. If the utility needs to run faster, it's quite common to prototype utilities in the shell and reimplement them later in C or C++, Perl, Python, or some other language that executes more swiftly once an idea has proven its worth. Conversely, if the utility works well enough in the shell, you can leave well enough alone.

Whether you ever reimplement the script depends on whether it needs optimizing, whether it needs to be portable, whether it should be easy to change, and whether (as usually happens) it outgrows its original purpose.

There are already loads of examples of shell scripts on your Linux system in case you're curious, including package installers, .xinitrc and startx, and the scripts in /etc/rc.d to configure the system on boot-up.

What Is a Shell?

Before jumping in and discussing how to program using a shell, let's review the shell's function and the different shells available for Linux.

A *shell* is a program that acts as the interface between you and the Linux system, allowing you to enter commands for the operating system to execute. In that respect, it resembles the Windows command prompt, but as we mentioned earlier, Linux shells are much more powerful. For example, input and output can be redirected using < and >, data piped between simultaneously executing programs using |, and output from a subprocess grabbed by using \$ (. . .). On Linux it's quite feasible to have multiple shells installed, with different users able to pick the one they prefer. In Figure 2-1 we show how the shell (two shells actually, both bash and csh) and other programs sit around the Linux kernel.

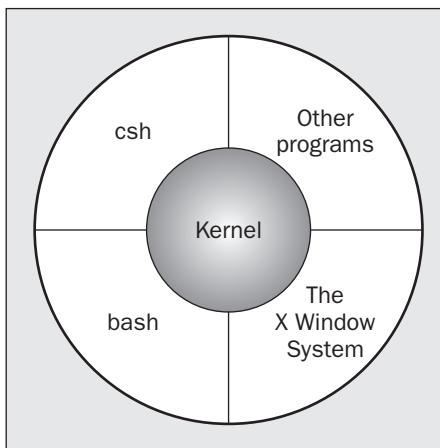


Figure 2-1

Since Linux is so modular, you can slot in one of the many different shells in use, although most of them are derived from the original Bourne shell. On Linux, the standard shell that is always installed as /bin/sh is called bash (the GNU Bourne-Again SHell), from the GNU suite of tools. Because this is an excellent shell that is always installed on Linux systems, is open source, and is portable to almost all UNIX variants, bash is the shell we will be using. In this chapter, we'll use bash version 2 and mostly use the features common to all POSIX-compatible shells. We'll also assume that the shell has been installed as /bin/sh and that it is the default shell for your login. On most Linux distributions, the program /bin/sh, the default shell, is actually a link to the program /bin/bash.

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You can check the version of bash you have with the following command:

```
$ /bin/sh -version  
GNU bash, version 2.05b.0(1)-release (i686-pc-linux-gnu)  
Copyright (C) 2002 Free Software Foundation, Inc.
```

To change to a different shell—if bash isn't the default on your system, for example—just execute the desired shell's program (e.g., /bin/bash) to run the new shell and change the command prompt. If bash isn't installed on your UNIX system, you can download it free from the GNU Web site at <http://www.gnu.org>. The sources are highly portable, and chances are good that it will compile on your version of UNIX straight out of the box.

When you create a Linux user, you can set the shell that she will use. Figure 2-2 shows the default selection available in Red Hat's user manager.

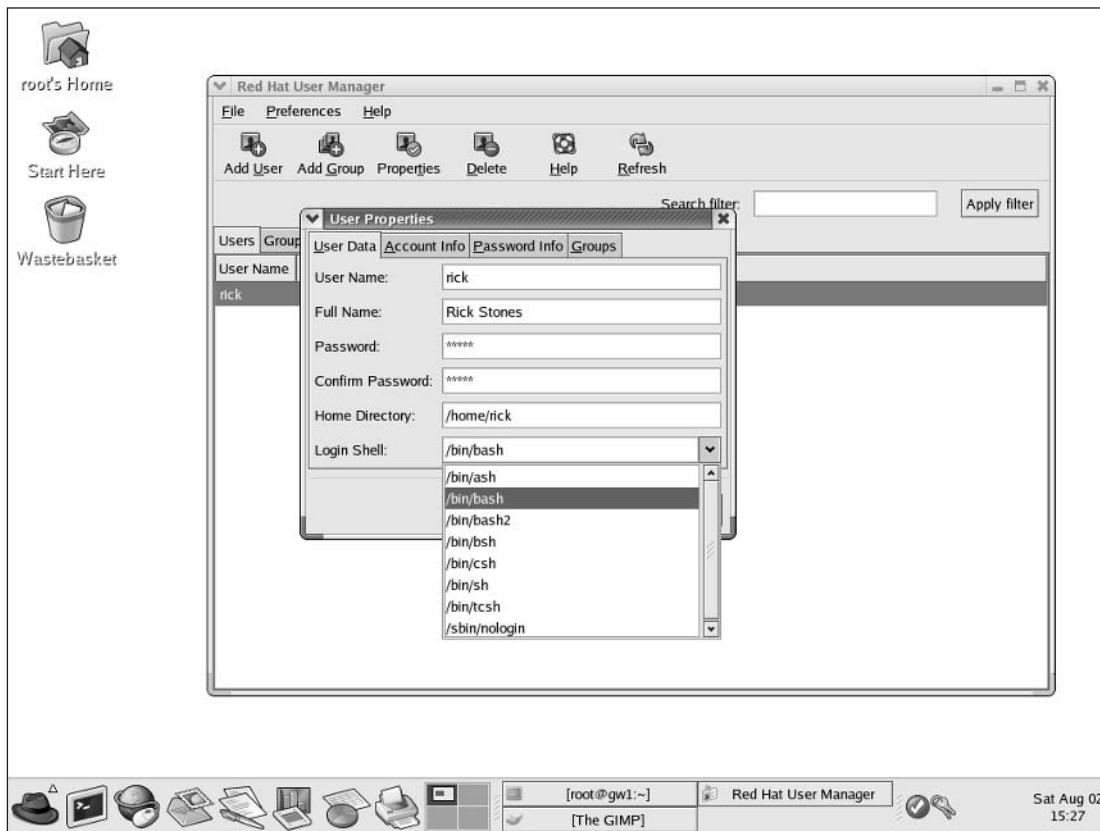


Figure 2-2

Many other shells are available, either free or commercially. Following is a brief summary of some of the more common shells available:

| Shell Name | A Bit of History |
|----------------|--|
| sh (Bourne) | The original shell from early versions of UNIX. |
| csh, tcsh, zsh | The C shell, and its derivatives, originally created by Bill Joy of Berkeley UNIX fame. The C shell is probably the third most popular type of shell after bash and the Korn shell. |
| ksh, pdksh | The Korn shell and its public domain cousin. Written by David Korn, this is the default shell on many commercial UNIX versions. |
| bash | The Linux staple shell from the GNU project. bash, or Bourne Again SHell, has the advantage that the source code is freely available, and even if it's not currently running on your UNIX system, it has probably been ported to it. bash has many similarities to the Korn shell. |

Except for the C shell and a small number of derivatives, all of these are very similar and are closely aligned with the shell specified in the X/Open 4.2 and POSIX 1003.2 specifications. POSIX 1003.2 lays down the minimum specification for a shell, but the extended specification in X/Open provides a more friendly and powerful shell. X/Open is usually the more demanding specification, but it also yields a friendlier system.

Pipes and Redirection

Before we get down to the details of shell programs, we need to say a little about how inputs and outputs of Linux programs (not just shell programs) can be redirected.

Redirecting Output

You may already be familiar with some redirection, such as

```
$ ls -l > lsoutput.txt
```

which saves the output of the `ls` command into a file called `lsoutput.txt`.

However, there is much more to redirection than this simple example reveals. We'll learn more about the standard file descriptors in Chapter 3, but for now all we need to know is that file descriptor 0 is the standard input to a program, file descriptor 1 is the standard output, and file descriptor 2 is the standard error output. You can redirect each of these independently. In fact, you can also redirect other file descriptors, but it's unusual to want to redirect any other than the standard ones: 0, 1, and 2.

In the preceding example, we redirect the standard output into a file by using the `>` operator. By default, if the file already exists, it will be overwritten. If you want to change the default behavior, you can use

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the command set -C, which sets the noclobber option to prevent a file from being overwritten using redirection. We'll show you more options for the set command later in the chapter.

To append to the file, we use the >> operator. For example,

```
$ ps >> lsoutput.txt
```

will append the output of the ps command to the end of the specified file.

To redirect the standard error output, we preface the > operator with the number of the file descriptor we wish to redirect. Since the standard error is on file descriptor 2, we use the 2> operator. This is often useful to discard error information and prevent it from appearing on the screen.

Suppose we want to use the kill command to kill a process from a script. There is always a slight risk that the process will die before the kill command is executed. If this happens, kill will write an error message to the standard error output, which, by default, will appear on the screen. By redirecting both the standard output and the error, you can prevent the kill command from writing any text to the screen.

The following command,

```
$ kill -HUP 1234 >killout.txt 2>killerr.txt
```

will put the output and error information into separate files.

If you prefer to capture both sets of output into a single file, you can use the >& operator to combine the two outputs. So

```
$ kill -1 1234 >killouterr.txt 2>&1
```

will put both the output and error outputs into the same file. Notice the order of the operators. This reads as "redirect standard output to the file killouterr.txt, then direct standard error to the same place as the standard output." If you get the order wrong, the redirect won't work as you expect.

Since you can discover the result of the kill command using the return code (which we discuss in more detail later in this chapter), we don't often want to save either standard output or standard error. We can use the UNIX universal "bit bucket" of /dev/null to efficiently discard the entire output, like this:

```
$ kill -1 1234 >/dev/null 2>&1
```

Redirecting Input

Rather like redirecting output, we can also redirect input. For example,

```
$ more < killout.txt
```

Obviously, this is a rather trivial example under Linux; the Linux more command is quite happy to accept filenames as parameters, unlike the Windows command-line equivalent.

Pipes

We can connect processes using the pipe | operator. In Linux, unlike in MS-DOS, processes connected by pipes can run simultaneously and are automatically rescheduled as data flows between them. As a simple example, we could use the sort command to sort the output from ps.

If we don't use pipes, we must use several steps, like this:

```
$ ps > psout.txt  
$ sort psout.txt > pssort.out
```

A much more elegant solution is to connect the processes with a pipe, like this:

```
$ ps | sort > pssort.out
```

Since we probably want to see the output paginated on the screen, we could connect a third process, more, all on the same command line:

```
$ ps | sort | more
```

There's practically no limit to the permissible number of connected processes. Suppose we want to see all the different process names that are running excluding shells. We could use

```
$ ps -xo comm | sort | uniq | grep -v sh | more
```

This takes the output of ps, sorts it into alphabetical order, extracts processes using uniq, uses grep -v sh to remove the process named sh, and finally displays it paginated on the screen.

As you can see, this is a much more elegant solution than a string of separate commands, each with its own temporary file. There is, however, one thing to be wary of here: If you have a string of commands, the output file is created or written to immediately as the set of commands is created, so never use the same filename twice in a string of commands. If you try to do something like the following:

```
cat mydata.txt | sort | uniq | > mydata.txt
```

you will end up with an empty file, because you will overwrite the mydata.txt file before you read it.

The Shell as a Programming Language

Now that we've seen some basic shell operations, it's time to move on to scripts. There are two ways of writing shell programs. You can type a sequence of commands and allow the shell to execute them interactively, or you can store those commands in a file that you can then invoke as a program.

Interactive Programs

Just typing the shell script on the command line is a quick and easy way of trying out small code fragments and is very useful while you are learning or just testing things out.

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Suppose we have a large number of C files and we wish to examine the files that contain the string POSIX. Rather than search using the grep command for the string in the files and then list the files individually, we could perform the whole operation in an interactive script like this:

```
$ for file in *
> do
> if grep -l POSIX $file
> then
> more $file
> fi
> done
posix
This is a file with POSIX in it - treat it well
$
```

Note how the normal \$ shell prompt changes to a > when you type shell commands. You can type away, letting the shell decide when you're finished, and the script will execute immediately.

In this example, the grep command prints the files it finds containing POSIX and then more prints the contents of the file to the screen. Finally, the shell prompt returns. Note also that we've called the shell variable that deals with each of the files to self-document the script. We could equally well have used i, but file is more meaningful for humans to read.

The shell also performs wildcard expansion (often referred to as "globbing"). You are almost certainly aware of the use of * as a wildcard to match a string of characters. What you may not know is that you can request single-character wildcards using ?, while [set] allows any of a number of single characters to be checked. [^set] negates the set—that is, it includes anything but the set you've specified. Brace expansion using {} (available on some shells, including bash) allows you to group arbitrary strings together in a set that the shell will expand. For example,

```
$ ls my_{finger,toe}s
```

will list the files my_fingers and my_toes. We've used the shell to check every file in the current directory. We will come back to these rules for matching patterns near the end of the chapter when we look in more detail at grep and the power of regular expressions.

Experienced UNIX users would probably perform this simple operation in a much more efficient way, perhaps with a command such as

```
$ more `grep -l POSIX *`
```

or the synonymous construction

```
$ more $(grep -l POSIX *)
```

Also,

```
$ grep -l POSIX * | more
```

will output the name of the file whose contents contained the string POSIX. In this script, we see the shell making use of other commands, such as grep and more, to do the hard work. The shell is simply

allowing us to glue several existing commands together in new and powerful ways. We will see wild-card expansion used many times in the following scripts and will look at the whole area of expansion in more detail when we look at regular expressions in the section on the `grep` command.

Going through this long rigmarole every time we want to execute a sequence of commands is a bore. We need to store the commands in a file, conventionally referred to as a *shell script*, so we can execute them whenever we like.

Creating a Script

First, using any text editor you need to create a file containing the commands, create a file called `first` that looks like this:

```
#!/bin/sh

# first
# This file looks through all the files in the current
# directory for the string POSIX, and then prints the names of
# those files to the standard output.

for file in *
do
    if grep -q POSIX $file
    then
        echo $file
    fi
done

exit 0
```

Comments start with a # and continue to the end of a line. Conventionally, though, # is usually kept in the first column. Having made such a sweeping statement, we next note that the first line, `#!/bin/sh`, is a special form of comment; the `#!` characters tell the system that the argument that follows on the line is the program to be used to execute this file. In this case, `/bin/sh` is the default shell program.

Note the absolute path specified in the comment. It may be wise to keep this shorter than 32 characters, for backwards compatibility, because some older UNIX versions can only use this limited number of characters when using `#!`, although Linux generally does not have this limitation.

Since the script is essentially treated as standard input to the shell (something prepared earlier), it can contain any Linux commands referenced by your `PATH` environment variable.

The `exit` command ensures that the script returns a sensible exit code (more on this later in the chapter). This is rarely checked when programs are run interactively, but if you want to invoke this script from another script and check whether it succeeded, returning an appropriate exit code is very important. Even if you never intend to allow your script to be invoked from another, you should still exit with a reasonable code. Go on and have faith in the usefulness of your script: Assume it may need to be reused as part of another script one day.

A zero denotes success in shell programming. Since the script as it stands can't detect any failures, we always return success. We'll come back to the reasons for using a zero exit code for success later in the chapter, when we look at the `exit` command in more detail.

Notice that we have not used any filename extension, or suffix, on this example; Linux, and UNIX in general, rarely makes use of the filename extension to determine the type of a file. We could have used .sh or added a different extension if we wished, but the shell doesn't care. Most preinstalled scripts will not have any filename extension, and the best way to check if they are scripts or not is to use the `file` command, for example, `file first` or `file /bin/bash`. Use whatever convention is applicable where you work, or suits you.

Making a Script Executable

Now that we have our script file, we can run it in two ways. The simpler way is to invoke the shell with the name of the script file as a parameter, thus:

```
$ /bin/sh first
```

This should work, but it would be much better if we could simply invoke the script by typing its name, giving it the respectability of other Linux commands.

We do this by changing the file mode to make the file executable for all users using the `chmod` command:

```
$ chmod +x first
```

Of course, this isn't the only way to use `chmod` to make a file executable. Use `man chmod` to find out more about octal arguments and other options.

We can then execute it using the command

```
$ first
```

You may get an error saying the command wasn't found. This is almost certainly because the shell environment variable `PATH` isn't set to look in the current directory for commands to execute. To change this, either type `PATH=$PATH:` on the command line or edit your `.bash_profile` file to add this command to the end of the file; then log out and log back in again. Alternatively, type `./first` in the directory containing the script, to give the shell the full relative path to the file.

Specifying the path prepended with `./` does have one other advantage: It ensures that you don't accidentally execute another command on the system with the same name as your script file.

You shouldn't change the `PATH` variable like this for the superuser. It's a security loophole, because the system administrator logged in as root can be tricked into invoking a fake version of a standard command. One of the authors admits to doing this once, just to prove a point to the system administrator about security, of course! It's a slight risk on ordinary accounts to include the current directory in the path, so if you are particularly concerned, just get into the habit of prepending `./` to all commands that are in the local directory.

Once you're confident that your script is executing properly, you can move it to a more appropriate location than the current directory. If the command is just for yourself, you could create a `bin` directory in your home directory and add that to your path. If you want the script to be executable by others, you could use `/usr/local/bin` or another system directory as a convenient location for adding new programs. If you don't have root permissions on your system, you could ask the system administrator to copy your file for you, although you may have to convince them of its worth first. To prevent other users from changing the script, perhaps accidentally, you should remove write access from it. The sequence of commands for the administrator to set ownership and permissions would be something like this:

```
# cp first /usr/local/bin  
# chown root /usr/local/bin/first  
# chgrp root /usr/local/bin/first  
# chmod 755 /usr/local/bin/first
```

Notice that, rather than altering a specific part of the permission flags, we use the absolute form of the `chmod` here because we know exactly what permissions we require.

If you prefer, you can use the rather longer, but perhaps more obvious, form of the `chmod` command, which would be

```
# chmod u=rwx,go=rx /usr/local/bin/first
```

Check the manual page of `chmod` for more details.

In Linux you can delete a file if you have write permission on the directory that contains it. To be safe, you should ensure that only the superuser can write to directories containing files that you want to keep safe. This makes sense because a directory is just another file, and having write permission to a directory file allows users to add and remove names.

Shell Syntax

Now that we've seen an example of a simple shell program, it's time to look in greater depth at the programming power of the shell. The shell is quite an easy programming language to learn, not least because it's easy to test small program fragments interactively before combining them into bigger scripts. We can use the bash shell to write quite large, structured programs. In the next few sections, we'll cover

- ❑ Variables: strings, numbers, environments, and parameters
- ❑ Conditions: shell Booleans
- ❑ Program control: `if`, `elif`, `for`, `while`, `until`, `case`
- ❑ Lists
- ❑ Functions
- ❑ Commands built into the shell
- ❑ Getting the result of a command
- ❑ Here documents

Variables

We don't usually declare variables in the shell before using them. Instead, we create them by simply using them (for example, when we assign an initial value to them). By default, all variables are considered and stored as strings, even when they are assigned numeric values. The shell and some utilities will convert numeric strings to their values in order to operate on them as required. Linux is a case-sensitive system, so the shell considers the variable `foo` to be different from `Foo` and both to be different from `FOO`.

Within the shell we can access the contents of a variable by preceding its name with a `$`. Whenever we extract the contents of a variable, we must give the variable a preceding `$`. When we assign a value to a variable, we just use the name of the variable, which is created dynamically if necessary. An easy way of checking the contents of a variable is to echo it to the terminal, preceding its name with a `$`.

On the command line, we can see this in action when we set and check various values of the variable `salutation`:

```
$ salutation=Hello  
$ echo $salutation  
Hello  
$ salutation="Yes Dear"  
$ echo $salutation  
Yes Dear  
$ salutation=7+5  
$ echo $salutation  
7+5
```

Note how a string must be delimited by quote marks if it contains spaces. Also note that there must be no spaces on either side of the equals sign.

We can assign user input to a variable by using the `read` command. This takes one parameter, the name of the variable to be read into, and then waits for the user to enter some text. The `read` normally completes when the user presses Enter. When reading a variable from the terminal, we don't usually need the quote marks:

```
$ read salutation  
Wie geht's?  
$ echo $salutation  
Wie geht's?
```

Quoting

Before we move on, we need to be clear about one feature of the shell: the use of quotes.

Normally, parameters in scripts are separated by whitespace characters (e.g., a space, a tab, or a newline character). If you want a parameter to contain one or more whitespace characters, you must quote the parameter.

The behavior of variables such as \$foo inside quotes depends on the type of quotes you use. If you enclose a \$ variable expression in double quotes, it's replaced with its value when the line is executed. If you enclose it in single quotes, no substitution takes place. You can also remove the special meaning of the \$ symbol by prefacing it with a \.

Usually, strings are enclosed in double quotes, which protects variables from being separated by white space, but allows \$ expansion to take place.

Try It Out—Variables

This example shows the effect of quotes on the output of a variable:

```
#!/bin/sh

myvar="Hi there"

echo $myvar
echo "$myvar"
echo '$myvar'
echo \$myvar

echo Enter some text
read myvar

echo '$myvar' now equals $myvar
exit 0
```

This gives the output:

```
Hi there
Hi there
$myvar
$myvar
Enter some text
Hello World
$myvar now equals Hello World
```

How It Works

The variable myvar is created and assigned the string Hi there. The contents of the variable are displayed with the echo command, showing how prefacing the variable with a \$ character expands the contents of the variable. We see that using double quotes doesn't affect the substitution of the variable, while single quotes and the backslash do. We also use the read command to get a string from the user.

Environment Variables

When a shell script starts, some variables are initialized from values in the environment. These are normally capitalized to distinguish them from user-defined (shell) variables in scripts, which are conventionally lowercase. The variables created will depend on your personal configuration. Many are listed in the manual pages, but the principal ones are listed in the following table.

| Environment Variable | Description |
|----------------------|---|
| \$HOME | The home directory of the current user. |
| \$PATH | A colon-separated list of directories to search for commands. |
| \$PS1 | A command prompt, frequently \$, but in bash you can use some more complex values; for example, the string [\u@ \h \W] \$ is a popular default that tells you the user, machine name, and current directory, as well as giving a \$ prompt. |
| \$PS2 | A secondary prompt, used when prompting for additional input; usually >. |
| \$IFS | An input field separator; a list of characters that are used to separate words when the shell is reading input, usually space, tab, and newline characters. |
| \$0 | The name of the shell script. |
| \$# | The number of parameters passed. |
| \$\$ | The process ID of the shell script, often used inside a script for generating unique temporary filenames; for example /tmp/tmp-file_\$\$. |

If you want to check out how the program works in a different environment by running the `env <command>`, try looking at the `env` manual pages. Also, we'll show you later in the chapter how to set environment variables in subshells using the `export` command.

Parameter Variables

If your script is invoked with parameters, some additional variables are created. Even if no parameters are passed, the preceding environment variable \$# still exists but has a value of 0.

The parameter variables are listed in the following table.

| Parameter Variable | Description |
|--------------------|--|
| \$1, \$2, ... | The parameters given to the script. |
| \$* | A list of all the parameters, in a single variable, separated by the first character in the environment variable IFS. |
| \$@ | A subtle variation on \$*; it doesn't use the IFS environment variable, so parameters may be run together if IFS is empty. |

It's easy to see the difference between `$@` and `$*` by trying them out:

```
$ IFS=' '
$ set foo bar bam
$ echo "$@"
foo bar bam
$ echo "$*"
foobarbam
$ unset IFS
$ echo "$*"
foo bar bam
```

As you can see, within double quotes, `$@` expands the positional parameters as separate fields, regardless of the `IFS` value. In general, if you want access to the parameters, `$@` is the sensible choice.

In addition to printing the contents of variables using the `echo` command, we can also read them by using the `read` command.

Try It Out—Parameter and Environment Variables

The following script demonstrates some simple variable manipulation. Once you've typed the script and saved it as `try_var`, don't forget to make it executable with `chmod +x try_var`.

```
#!/bin/sh

salutation="Hello"
echo $salutation
echo "The program $0 is now running"
echo "The second parameter was $2"
echo "The first parameter was $1"
echo "The parameter list was $*"
echo "The user's home directory is $HOME"

echo "Please enter a new greeting"
read salutation

echo $salutation
echo "The script is now complete"
exit 0
```

If we run this script, we get the following output:

```
$ ./try_var foo bar baz
Hello
The program ./try_var is now running
The second parameter was bar
The first parameter was foo
The parameter list was foo bar baz
The user's home directory is /home/rick
Please enter a new greeting
Sire
Sire
The script is now complete
$
```

How It Works

This script creates the variable `salutation`, displays its contents, and then shows how various parameter variables and the environment variable `$HOME` already exist and have appropriate values.

We'll return to parameter substitution in more detail later in the chapter.

Conditions

Fundamental to all programming languages is the ability to test conditions and perform different actions based on those decisions. Before we talk about that, though, we'll look at the conditional constructs that we can use in shell scripts and then look at the control structures that use them.

A shell script can test the exit code of any command that can be invoked from the command line, including the scripts that you have written yourself. That's why it's important to always include an `exit` command at the end of any scripts that you write.

The `test`, or `[`, Command

In practice, most scripts make extensive use of the `[` or `test` command, the shell's Boolean check. On most systems, the `[` and `test` commands are synonymous, except that when the `[` command is used, a trailing `]` is also used just for readability. Having a `[` command might seem a little odd, but within the code it does make the syntax of commands look simple, neat, and more like other programming languages.

```
# ls -l /usr/bin/[  
lrwxrwxrwx    1 root      root          4 Oct 13 10:46 /usr/bin/[ -> test
```

These commands call an external program in some older UNIX shells, but they tend to be built in to more modern ones. We'll come back to this when we look at commands in a later section.

Since the `test` command is infrequently used outside shell scripts, many Linux users who have never written shell scripts try to write simple programs and call them `test`. If such a program doesn't work, it's probably conflicting with the shell's `test` command. To find out whether your system has an external command of a given name, try something like `which test`, to check which `test` command is getting executed, or use `./test` to ensure you execute the script in the current directory.

We'll introduce the `test` command using one of the simplest conditions: checking to see if a file exists. The command for this is `test -f <filename>`, so within a script we can write

```
if test -f fred.c  
then  
...  
fi
```

We can also write it like this:

```
if [ -f fred.c ]
then
...
fi
```

The `test` command's exit code (whether the condition is satisfied) determines whether the conditional code is run.

Note that you must put spaces between the [braces and the condition being checked. You can remember this by remembering that [is just the same as writing test, and you would always leave a space after the test command.

If you prefer putting `then` on the same line as `if`, you must add a semicolon to separate the test from the `then`:

```
if [ -f fred.c ]; then
...
fi
```

The condition types that you can use with the `test` command fall into three types: string comparison, arithmetic comparison, and file conditionals. The following three tables describe these condition types.

| String Comparison | Result |
|---------------------------------|---|
| <code>string1 = string2</code> | True if the strings are equal. |
| <code>string1 != string2</code> | True if the strings are not equal. |
| <code>-n string</code> | True if the string is not null. |
| <code>-z string</code> | True if the string is null (an empty string). |

| Arithmetic Comparison | Result |
|--|---|
| <code>expression1 -eq expression2</code> | True if the expressions are equal. |
| <code>expression1 -ne expression2</code> | True if the expressions are not equal. |
| <code>expression1 -gt expression2</code> | True if <code>expression1</code> is greater than <code>expression2</code> . |
| <code>expression1 -ge expression2</code> | True if <code>expression1</code> is greater than or equal to <code>expression2</code> . |
| <code>expression1 -lt expression2</code> | True if <code>expression1</code> is less than <code>expression2</code> . |
| <code>expression1 -le expression2</code> | True if <code>expression1</code> is less than or equal to <code>expression2</code> . |
| <code>! expression</code> | True if the expression is false, and vice versa. |

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| File Conditional | Result |
|----------------------|---|
| <code>-d file</code> | True if the file is a directory. |
| <code>-e file</code> | True if the file exists. Note that, historically, the <code>-e</code> option has not been portable, so <code>-f</code> is usually used. |
| <code>-f file</code> | True if the file is a regular file. |
| <code>-g file</code> | True if set-group-id is set on <code>file</code> . |
| <code>-r file</code> | True if the file is readable. |
| <code>-s file</code> | True if the file has nonzero size. |
| <code>-u file</code> | True if set-user-id is set on <code>file</code> . |
| <code>-w file</code> | True if the file is writable. |
| <code>-x file</code> | True if the file is executable. |

You may be wondering what the set-group-id and set-user-id (also known as set-gid and set-uid) bits are. The set-uid bit gives a program the permissions of its owner, rather than its user, while the set-gid bit gives a program the permissions of its group. The bits are set with `chmod`, using the `s` and `g` options. Remember that set-gid and set-uid flags have no effect when set on shell scripts.

We're getting ahead of ourselves slightly, but following is an example of how we would test the state of the file `/bin/bash`, just so you can see what these look like in use:

```
#!/bin/sh

if [ -f /bin/bash ]
then
    echo "file /bin/bash exists"
fi

if [ -d /bin/bash ]
then
    echo "/bin/bash is a directory"
else
    echo "/bin/bash is NOT a directory"
fi
```

Before the test can be true, all the file conditional tests require that the file also exists. This list contains just the more commonly used options to the `test` command, so for a complete list refer to the manual entry. If you're using bash, where `test` is built in, use the `help test` command to get more details. We'll use some of these options later in the chapter.

Now that we know about conditions, we can look at the control structures that use them.

Control Structures

The shell has a set of control structures, and once again they're very similar to other programming languages.

In the following sections, the statements are the series of commands to perform when, while, or until the condition is fulfilled.

if

The `if` statement is very simple: It tests the result of a command and then conditionally executes a group of statements:

```
if condition
then
    statements
else
    statements
fi
```

Try It Out—Using the if Command

A common use for `if` is to ask a question and then make a decision based on the answer:

```
#!/bin/sh

echo "Is it morning? Please answer yes or no"
read timeofday

if [ $timeofday = "yes" ]; then
    echo "Good morning"
else
    echo "Good afternoon"
fi

exit 0
```

This would give the following output:

```
Is it morning? Please answer yes or no
yes
Good morning
$
```

This script uses the `[` command to test the contents of the variable `timeofday`. The result is evaluated by the `if` command, which then allows different lines of code to be executed.

Notice that we use extra white space to indent the statements inside the `if`. This is just a convenience for the human reader; the shell ignores the additional white space.

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elif

Unfortunately, there are several problems with this very simple script. It will take any answer except `yes` as meaning `no`. We can prevent this by using the `elif` construct, which allows us to add a second condition to be checked when the `else` portion of the `if` is executed.

Try It Out—Doing Further Checks with an elif

We can modify our previous script so that we report an error message if the user types in anything other than `yes` or `no`. We do this by replacing the `else` with `elif` and then adding another condition.

```
#!/bin/sh

echo "Is it morning? Please answer yes or no"
read timeofday

if [ $timeofday = "yes" ]
then
    echo "Good morning"
elif [ $timeofday = "no" ]; then
    echo "Good afternoon"
else
    echo "Sorry, $timeofday not recognized. Enter yes or no"
    exit 1
fi

exit 0
```

How It Works

This is quite similar to the previous example, but now the `elif` command tests the variable again if the first `if` condition is not true. If neither of the tests is successful, an error message is printed and the script exits with the value 1, which the caller can use in a calling program to check if the script was successful.

A Problem with Variables

This fixes the most obvious defect, but a more subtle problem is lurking. Let's try this new script, but just press Enter (or Return on some keyboards) rather than answering the question. We'll get this error message:

```
[ : = : unary operator expected
```

What went wrong? The problem is in the first `if` clause. When the variable `timeofday` was tested, it consisted of a blank string. So the `if` clause looks like

```
if [ = "yes" ]
```

which isn't a valid condition. To avoid this, we must use quotes around the variable:

```
if [ "$timeofday" = "yes" ]
```

An empty variable then gives us the valid test:

```
if [ "" = "yes" ]
```

Our new script is

```
#!/bin/sh

echo "Is it morning? Please answer yes or no"
read timeofday

if [ "$timeofday" = "yes" ]
then
    echo "Good morning"
elif [ "$timeofday" = "no" ]; then
    echo "Good afternoon"
else
    echo "Sorry, $timeofday not recognized. Enter yes or no"
    exit 1
fi

exit 0
```

which is safe against a user just pressing Enter in answer to the question.

If you want the echo command to delete the trailing new line, the most portable choice is to use the printf command (see the “printf” section later in this chapter) rather than the echo command. Some shells use echo -e, but that’s not supported on all systems. bash allows echo -n to suppress the new line, so if you are confident your script needs to work only on bash, you can use that syntax.

```
echo -n "Is it morning? Please answer yes or no: "
```

Note that we need to leave an extra space before the closing quotes so that there is a gap before the user-typed response, which looks neater.

for

We use the for construct to loop through a range of values, which can be any set of strings. They could be simply listed in the program or, more commonly, the result of a shell expansion of filenames.

The syntax is simply

```
for variable in values
do
    statements
done
```

Try It Out—**for** Loop with Fixed Strings

The values are normally strings, so we can write

```
#!/bin/sh

for foo in bar fud 43
do
    echo $foo
done
exit 0
```

We get the following output:

```
bar
fud
43
```

What would happen if you changed the first line from `for foo in bar fud 43` to `for foo in "bar fud 43"`? Remember that adding the quotes tells the shell to consider everything between them as a single string. This is one way of getting spaces to be stored in a variable.

How It Works

This example creates the variable `foo` and assigns it a different value each time around the `for` loop. Since the shell considers all variables to contain strings by default, it's just as valid to use the string `43` as the string `fud`.

Try It Out—**for** Loop with Wildcard Expansion

As we said earlier, it's common to use the `for` loop with a shell expansion for filenames. By this we mean using a wildcard for the string value and letting the shell fill out all the values at run time.

We've already seen this in our original example, `first`. The script used shell expansion, the `*` expanding to the names of all the files in the current directory. Each of these in turn is used as the variable `$i` inside the `for` loop.

Let's quickly look at another wildcard expansion. Imagine that you want to print all the script files starting with the letter `f` in the current directory, and you know that all your scripts end in `.sh`. You could do it like this:

```
#!/bin/sh

for file in $(ls f*.sh); do
    lpr $file
done
exit 0
```

How It Works

This illustrates the use of the `$ (command)` syntax, which we'll review in more detail later (in the section on command execution). Basically, the parameter list for the `for` command is provided by the output of the command enclosed in the `$()` sequence.

The shell expands `f* .sh` to give the names of all the files matching this pattern.

Remember that all expansion of variables in shell scripts is done when the script is executed, never when it's written. So syntax errors in variable declarations are found only at execution time, as we saw earlier when we were quoting empty variables.

while

Since all shell values are considered strings by default, the `for` loop is good for looping through a series of strings, but is a little awkward to use for executing commands a fixed number of times.

Look how tedious a script becomes if we want to loop through twenty values using a `for` loop:

```
#!/bin/sh

for foo in 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
do
    echo "here we go again"
done
exit 0
```

Even with wildcard expansion, you might be in a situation where you just don't know how many times you'll need to loop. In that case, we can use a `while` loop, which has the following syntax:

```
while condition do
    statements
done
```

For example, here is a rather poor password-checking program:

```
#!/bin/sh

echo "Enter password"
read trythis

while [ "$trythis" != "secret" ]; do
    echo "Sorry, try again"
    read trythis
done
exit 0
```

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An example of the output from this script is:

```
Enter password
password
Sorry, try again
secret
$
```

Clearly, this isn't a very secure way of asking for a password, but it does serve to illustrate the `while` statement. The statements between `do` and `done` will be continuously executed until the condition is no longer true. In this case, we're checking that the value of `trythis` isn't equal to `secret`. The loop will continue until `$trythis` equals `secret`. We then continue executing the script at the statement immediately following the `done`.

Try It Out—Here We Go Again, Again

By combining the `while` construct with arithmetic substitution, we can execute a command a fixed number of times. This is less cumbersome than the `for` loop we saw earlier.

```
#!/bin/sh

foo=1

while [ "$foo" -le 20 ]
do
    echo "Here we go again"
    foo=$((foo+1))
done

exit 0
```

Note that the `$(())` construct was a ksh invention that has since been included in the X/Open specification. Older shells will use `expr` instead, which we'll come across later in the chapter. However, this is slower and more resource-intensive; you should use the `$(())` form of the command where available. bash supports the `$(())` form, so we will generally use that.

How It Works

This script uses the `[` command to test the value of `foo` against the value 20 and executes the loop body if it's smaller or equal. Inside the `while` loop, the syntax `(($foo+1))` is used to perform arithmetic evaluation of the expression inside the braces, so `foo` is incremented each time around the loop.

Since `foo` can never be the empty string, we don't need to protect it with double quotes when testing its value. We do this only because it's a good habit to get into.

until

The `until` statement has the following syntax:

```
until condition
do
    statements
done
```

This is very similar to the `while` loop, but with the condition test reversed. In other words, the loop continues until the condition becomes true, not while the condition is true.

The `until` statement fits naturally when we want to keep looping until something happens. As an example, we can set up an alarm that works when another user, whose login name we pass on the command line, logs on:

```
#!/bin/sh

until who | grep "$1" > /dev/null
do
    sleep 60
done

# now ring the bell and announce the expected user.

echo -e \\a
echo "**** $1 has just logged in ****"

exit 0
```

case

The `case` construct is a little more complex than those we have encountered so far. Its syntax is

```
case variable in
    pattern [ | pattern] ...) statements;;
    pattern [ | pattern] ...) statements;;
    ...
esac
```

This may look a little intimidating, but the `case` construct allows us to match the contents of a variable against patterns in quite a sophisticated way and then allows execution of different statements, depending on which pattern was matched.

Notice that each pattern line is terminated with double semicolons (;;). You can put multiple statements between each pattern and the next, so a double semicolon is needed to mark where one statement ends and the next pattern begins.

The ability to match multiple patterns and then execute multiple related statements makes the `case` construct a good way of dealing with user input. The best way to see how `case` works is with an example. We'll develop it over three Try It Out examples, improving the pattern matching each time.

Be careful with the `case` construct if you are using wild cards such as `*` in the pattern. The problem is that the first matching pattern will be taken, even if a later pattern matches more exactly.

Try It Out—Case I: User Input

We can write a new version of our input-testing script and, using the `case` construct, make it a little more selective and forgiving of unexpected input.

```
#!/bin/sh

echo "Is it morning? Please answer yes or no"
read timeofday

case "$timeofday" in
    yes) echo "Good Morning";;
    no ) echo "Good Afternoon";;
    y   ) echo "Good Morning";;
    n   ) echo "Good Afternoon";;
    *   ) echo "Sorry, answer not recognized";;
esac

exit 0
```

How It Works

When the `case` statement is executing, it takes the contents of `timeofday` and compares it to each string in turn. As soon as a string matches the input, the `case` command executes the code following the `)` and finishes.

The `case` command performs normal expansion on the strings that it's using for comparison. You can therefore specify part of a string followed by the `*` wildcard. Using a single `*` will match all possible strings, so we always put one after the other matching strings to make sure the `case` statement ends with some default action if no other strings are matched. This is possible because the `case` statement compares against each string in turn. It doesn't look for a best match, just the first match. The default condition often turns out to be the impossible condition, so using `*` can help in debugging scripts.

Try It Out—Case II: Putting Patterns Together

The preceding `case` construction is clearly more elegant than the multiple `if` statement version, but by putting the patterns together, we can make a much cleaner version:

```
#!/bin/sh

echo "Is it morning? Please answer yes or no"
read timeofday
```

```

case "$timeofday" in
    yes | y | Yes | YES )
        echo "Good Morning";;
    n* | N* )
        echo "Good Afternoon";;
    * )
        echo "Sorry, answer not recognized";;
esac

exit 0

```

How It Works

In this script, we used multiple strings in each entry of the case so that case tests several different strings for each possible statement. This makes the script both shorter and, with practice, easier to read. We also show how the * wildcard can be used, although this may match unintended patterns. For example, if the user enters **never**, this will be matched by n* and Good Afternoon will be displayed, which isn't the intended behavior. Note also that the * wildcard expression doesn't work within quotes.

Try It Out—Case III: Executing Multiple Statements

Finally, to make the script reusable, we need to have a different exit value when the default pattern is used. We also add a set construct to show this in action:

```

#!/bin/sh

echo "Is it morning? Please answer yes or no"
read timeofday

case "$timeofday" in
    yes | y | Yes | YES )
        echo "Good Morning"
        echo "Up bright and early this morning"
        ;;
    [nN]*)
        echo "Good Afternoon"
        ;;
    *)
        echo "Sorry, answer not recognized"
        echo "Please answer yes or no"
        exit 1
        ;;
esac

exit 0

```

How It Works

To show a different way of pattern matching, we change the way in which the no case is matched. We also show how multiple statements can be executed for each pattern in the case statement. Notice that we're careful to put the most explicit matches first and the most general match last. This is important because the case will execute the first match it finds, not the best match. If we put the *) first, it would always be matched, regardless of what was input.

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Note that the ; ; before esac is optional. Unlike C programming, where leaving out a break is poor programming practice, leaving out the final ; ; is no problem if the last case is the default because no other cases will be considered.

To make the case matching more powerful, we could use something like this:

```
[yY] | [Yy] [Ee] [Ss] )
```

This restricts the permitted letters while allowing a variety of answers and gives more control than the * wildcard.

Lists

Sometimes we want to connect commands in a series. For instance, we may want several different conditions to be met before we execute a statement like

```
if [ -f this_file ]; then
    if [ -f that_file ]; then
        if [ -f the_other_file ]; then
            echo "All files present, and correct"
        fi
    fi
fi
```

or you might want at least one of a series of conditions to be true:

```
if [ -f this_file ]; then
    foo="True"
elif [ -f that_file ]; then
    foo="True"
elif [ -f the_other_file ]; then
    foo="True"
else
    foo="False"
fi
if [ "$foo" = "True" ]; then
    echo "One of the files exists"
fi
```

Although these can be implemented using multiple if statements, you can see that the results are awkward. The shell has a special pair of constructs for dealing with lists of commands: the AND list and the OR list. These are often used together, but we'll review their syntax separately.

The AND List

The AND list construct allows us to execute a series of commands, executing the next command only if all the previous commands have succeeded. The syntax is

```
statement1 && statement2 && statement3 && ...
```

Starting at the left, each statement is executed and, if it returns `true`, the next statement to the right is executed. This continues until a statement returns `false`, after which no more statements in the list are executed. The `&&` tests the condition of the preceding command.

Each statement is executed independently, allowing us to mix many different commands in a single list as the following script shows. The AND list as a whole succeeds if all commands are executed successfully, but it fails otherwise.

Try It Out—AND Lists

In the following script, we `touch file_one` (to check whether it exists and create it if it doesn't) and then remove `file_two`. Then the AND list tests for the existence of each of the files and echoes some text in between.

```
#!/bin/sh

touch file_one
rm -f file_two

if [ -f file_one ] && echo "hello" && [ -f file_two ] && echo " there"
then
    echo "in if"
else
    echo "in else"
fi

exit 0
```

Try the script and you'll get the following result:

```
hello
in else
```

How It Works

The `touch` and `rm` commands ensure that the files in the current directory are in a known state. The `&&` list then executes the `[-f file_one]` statement, which succeeds because we just made sure that the file existed. Because the previous statement succeeded, the `echo` command is executed. This also succeeds (`echo` always returns `true`). The third test, `[-f file_two]` is executed. It fails because the file doesn't exist. Because the last command failed, the final `echo` statement isn't executed. The result of the `&&` list is `false` because one of the commands in the list failed, so the `if` statement executes its `else` condition.

The OR List

The OR list construct allows us to execute a series of commands until one succeeds, then not execute any more. The syntax is

```
statement1 || statement2 || statement3 || ...
```

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Starting at the left, each statement is executed. If it returns false, the next statement to the right is executed. This continues until a statement returns true, when no more statements are executed.

The `||` list is very similar to the `&&` list, except that the rules for executing the next statement are that the previous statement must fail.

Try It Out—OR Lists

Copy the previous example and change the shaded lines in the following listing:

```
#!/bin/sh

rm -f file_one

if [ -f file_one ] || echo "hello" || echo " there"
then
    echo "in if"
else
    echo "in else"
fi

exit 0
```

This will give you the output

```
hello
in if
```

How It Works

The first two lines simply set up the files for the rest of the script. The first command, `[-f file_one]`, fails because the file doesn't exist. The `echo` statement is then executed. Surprise, surprise, this returns `true`, and no more commands in the `||` list are executed. The `if` succeeds because one of the commands in the `||` list (the `echo`) was `true`.

The result of both of these constructs is the result of the last statement to be executed.

These list-type constructs execute in a similar way to those in C when multiple conditions are being tested. Only the minimum number of statements is executed to determine the result. Statements that can't affect the result are not executed. This is commonly referred to as *short circuit evaluation*.

Combining these two constructs is a logician's heaven. Try out:

```
[ -f file_one ] && command for true || command for false
```

This will execute the first command if the test succeeds and the second command otherwise. It's always best to experiment with these more unusual lists, and in general you should use braces to force the order of evaluation.

Statement Blocks

If you want to use multiple statements in a place where only one is allowed, such as in an AND or OR list, you can do so by enclosing them in braces {} to make a statement block. For example, in the application presented later in this chapter, you'll see the following code:

```
get_confirm && {
    grep -v "$cdcatnum" $tracks_file > $temp_file
    cat $temp_file > $tracks_file
    echo
    add_record_tracks
}
```

Functions

You can define functions in the shell and, if you write shell scripts of any size, you'll want to use them to structure your code.

As an alternative, you could break a large script into lots of smaller scripts, each of which performs a small task. This has some drawbacks: Executing a second script from within a script is much slower than executing a function. It's more difficult to pass back results, and there can be a very large number of small scripts. You should consider the smallest part of your script that sensibly stands alone and use that as your measure of when to break a large script into a collection of smaller ones.

If you're appalled at the idea of using the shell for large programs, remember that the FSF autoconf program and several Linux package installation programs are shell scripts. You can always guarantee that a basic shell will be on a Linux system. In general, Linux and UNIX systems can't even boot without /bin/sh, never mind allowing users to log in, so you can be certain that your script will have a shell available to interpret it on a huge range of UNIX and Linux systems.

To define a shell function, we simply write its name followed by empty parentheses and enclose the statements in braces:

```
function_name () {
    statements
}
```

Try It Out—A Simple Function

Let's start with a really simple function:

```
#!/bin/sh

foo() {
    echo "Function foo is executing"
}

echo "script starting"
foo
echo "script ended"

exit 0
```

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Running the script will show

```
script starting
Function foo is executing
script ending
```

How It Works

This script starts executing at the top, so nothing is different there. But when it finds the `foo() {` construct, it knows that a function called `foo` is being defined. It stores the fact that `foo` refers to a function and continues executing after the matching `}`. When the single line `foo` is executed, the shell knows to execute the previously defined function. When this function completes, execution resumes at the line after the call to `foo`.

You must always define a function before you can invoke it, a little like the Pascal style of function definition before invocation, except that there are no forward declarations in the shell. This isn't a problem, because all scripts start executing at the top, so simply putting all the functions before the first call of any function will always cause all functions to be defined before they can be invoked.

When a function is invoked, the positional parameters to the script, `$*`, `$@`, `$#`, `$1`, `$2`, and so on are replaced by the parameters to the function. That's how you read the parameters passed to the function. When the function finishes, they are restored to their previous values.

Some older shells may not restore the value of positional parameters after functions execute. It's wise not to rely on this behavior if you want your scripts to be portable.

We can make functions return numeric values using the `return` command. The usual way to make functions return strings is for the function to store the string in a variable, which can then be used after the function finishes. Alternatively, you can `echo` a string and catch the result, like this:

```
foo () { echo JAY; }

...
result=$(foo)
```

Note that you can declare local variables within shell functions by using the `local` keyword. The variable is then only in scope within the function. Otherwise, the function can access the other shell variables that are essentially global in scope. If a local variable has the same name as a global variable, it overlays that variable, but only within the function. For example, we can make the following changes to the preceding script to see this in action:

```
#!/bin/sh

sample_text="global variable"

foo() {

    local sample_text="local variable"
    echo "Function foo is executing"
```

```
    echo $sample_text
}

echo "script starting"
echo $sample_text

foo

echo "script ended"
echo $sample_text

exit 0
```

In the absence of a `return` command specifying a return value, a function returns the exit status of the last command executed.

Try It Out—Returning a Value

In the next script, `my_name`, we show how parameters to a function are passed and how functions can return a `true` or `false` result. You call this script with a parameter of the name you want to use in the question.

1. After the shell header, we define the function `yes_or_no`:

```
#!/bin/sh

yes_or_no() {
    echo "Is your name $* ?"
    while true
    do
        echo -n "Enter yes or no: "
        read x
        case "$x" in
            y | yes ) return 0;;
            n | no )  return 1;;
            * )        echo "Answer yes or no"
        esac
    done
}
```

2. Then the main part of the program begins:

```
echo "Original parameters are $*"

if yes_or_no "$1"
then
    echo "Hi $1, nice name"
else
    echo "Never mind"
fi
exit 0
```

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Typical output from this script might be:

```
$ ./my_name Rick Neil
Original parameters are Rick Neil
Is your name Rick ?
Enter yes or no: yes
Hi Rick, nice name
$
```

How It Works

As the script executes, the function `yes_or_no` is defined but not yet executed. In the `if` statement, the script executes the function `yes_or_no`, passing the rest of the line as parameters to the function after substituting the `$1` with the first parameter to the original script, `Rick`. The function uses these parameters, which are now stored in the positional parameters `$1`, `$2`, and so on, and returns a value to the caller. Depending on the return value, the `if` construct executes the appropriate statement.

As we've seen, the shell has a rich set of control structures and conditional statements. We need to learn some of the commands that are built into the shell; then we'll be ready to tackle a real programming problem with no compiler in sight!

Commands

You can execute two types of commands from inside a shell script. There are "normal" commands that you could also execute from the command prompt (called *external commands*), and there are "built-in" commands (called *internal commands*) that we mentioned earlier. Built-in commands are implemented internally to the shell and can't be invoked as external programs. Most internal commands are, however, also provided as standalone programs—this requirement is part of the POSIX specification. It generally doesn't matter if the command is internal or external, except that internal commands execute more efficiently.

Here we'll cover only the main commands, both internal and external, that we use when we're programming scripts. As a Linux user, you probably know many other commands that are valid at the command prompt. Always remember that you can use any of these in a script in addition to the built-in commands we present here.

break

We use this for escaping from an enclosing `for`, `while`, or `until` loop before the controlling condition has been met. You can give `break` an additional numeric parameter, which is the number of loops to break out of. This can make scripts very hard to read, so we don't suggest you use it. By default, `break` escapes a single level.

```
#!/bin/sh

rm -rf fred*
echo > fred1
echo > fred2
mkdir fred3
echo > fred4
```

```

for file in fred*
do
    if [ -d "$file" ]; then
        break;
    fi
done

echo first directory starting fred was $file

rm -rf fred*
exit 0

```

The : Command

The colon command is a null command. It's occasionally useful to simplify the logic of conditions, being an alias for `true`. Since it's built-in, `:` runs faster than `true`, though its output is also much less readable.

You may see it used as a condition for `while` loops; `while :` implements an infinite loop in place of the more common `while true`.

The `:` construct is also useful in the conditional setting of variables. For example,

```
: ${var:=value}
```

Without the `:`, the shell would try to evaluate `$var` as a command.

In some, mostly older shell scripts, you may see the colon used at the start of a line to introduce a comment, but modern scripts should always use # to start a comment line because this executes more efficiently.

```

#!/bin/sh

rm -f fred
if [ -f fred ]; then
:
else
    echo file fred did not exist
fi

exit 0

```

continue

Rather like the C statement of the same name, this command makes the enclosing `for`, `while`, or `until` loop continue at the next iteration, with the loop variable taking the next value in the list.

```

#!/bin/sh

rm -rf fred*
echo > fred1

```

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```
echo > fred2
mkdir fred3
echo > fred4

for file in fred*
do
    if [ -d "$file" ]; then
        echo "skipping directory $file"
        continue
    fi
    echo file is $file
done

rm -rf fred*
exit 0
```

`continue` can take the enclosing loop number at which to resume as an optional parameter so that you can partially jump out of nested loops. This parameter is rarely used, as it often makes scripts much harder to understand. For example,

```
for x in 1 2 3
do
    echo before $x
    continue 1
    echo after $x
done
```

The output will be

```
before 1
before 2
before 3
```

The . Command

The dot (.) command executes the command in the current shell:

```
. ./shell_script
```

Normally, when a script executes an external command or script, a new environment (a subshell) is created, the command is executed in the new environment, and the environment is then discarded apart from the exit code that is returned to the parent shell. But the external source and the dot command (two more synonyms) run the commands listed in a script in the same shell that called the script.

This means that normally any changes to environment variables that the command makes are lost. The dot command, on the other hand, allows the executed command to change the current environment. This is often useful when you use a script as a wrapper to set up your environment for the later execution of some other command. For example, if you're working on several different projects at the same time, you may find you need to invoke commands with different parameters, perhaps to invoke an older version of the compiler for maintaining an old program.

In shell scripts, the dot command works a little like the `#include` directive in C or C++. Though it doesn't literally include the script, it does execute the command in the current context, so you can use it to incorporate variable and function definitions into a script.

Try It Out—The Dot Command

In the following example, we use the dot command on the command line, but we can just as well use it within a script.

1. Suppose we have two files containing the environment settings for two different development environments. To set the environment for the old, classic commands, `classic_set`, we could use

```
#!/bin/sh

version=classic
PATH=/usr/local/old_bin:/usr/bin:/bin:.
PS1="classic> "
```

2. For the new commands we use `latest_set`:

```
#!/bin/sh

version=latest
PATH=/usr/local/new_bin:/usr/bin:/bin:.
PS1=" latest version> "
```

We can set the environment by using these scripts in conjunction with the dot command, as in the following sample session:

```
$ . ./classic_set
classic> echo $version
classic
classic> . latest_set
latest version> echo $version
latest
latest version>
```

echo

Despite the X/Open exhortation to use the `printf` command in modern shells, we've been following common practice by using the `echo` command to output a string followed by a newline character.

A common problem is how to suppress the newline character. Unfortunately, different versions of UNIX have implemented different solutions. The common method in Linux is to use

```
echo -n "string to output"
```

but you'll often come across

```
echo -e "string to output\c"
```

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The second option, `echo -e`, makes sure that the interpretation of backslashed escape characters, such as `\t` for tab and `\n` for carriage returns, is enabled. It's usually set by default. See the manual pages for details.

If you need a portable way to remove the trailing newline, you can use the external `tr` command to get rid of it, but it will execute somewhat more slowly. If you need portability to UNIX systems, it's generally better to stick to `printf` if you need to lose the newline. If your scripts need to work only on Linux and bash, `echo -n` should be fine.

eval

The `eval` command allows you to evaluate arguments. It's built into the shell and doesn't normally exist as a separate command. It's probably best demonstrated with a short example borrowed from the X/Open specification itself:

```
foo=10
x=foo
y='$' $x
echo $y
```

This gives the output `$foo`. However,

```
foo=10
x=foo
eval y=''$' $x
echo $y
```

gives the output 10. Thus, `eval` is a bit like an extra `$`: It gives you the value of the value of a variable.

The `eval` command is very useful, allowing code to be generated and run on the fly. It does complicate script debugging, but it can let you do things that are otherwise difficult or even impossible.

exec

The `exec` command has two different uses. Its typical use is to replace the current shell with a different program. For example,

```
exec wall "Thanks for all the fish"
```

in a script will replace the current shell with the `wall` command. No lines in the script after the `exec` will be processed, because the shell that was executing the script no longer exists.

The second use of `exec` is to modify the current file descriptors:

```
exec 3< afile
```

This causes file descriptor three to be opened for reading from file `afile`. It's rarely used.

exit n

The `exit` command causes the script to exit with exit code `n`. If you use it at the command prompt of any interactive shell, it will log you out. If you allow your script to exit without specifying an exit status, the status of the last command executed in the script will be used as the return value. It's always good practice to supply an exit code.

In shell script programming, exit code 0 is success and codes 1 through 125 inclusive are error codes that can be used by scripts. The remaining values have reserved meanings:

| Exit Code | Description |
|---------------|------------------------------|
| 126 | The file was not executable. |
| 127 | A command was not found. |
| 128 and above | A signal occurred. |

Using zero as success may seem a little unusual to many C or C++ programmers. The big advantage in scripts is that they allow us to use 125 user-defined error codes without the need for a global error code variable.

Here's a simple example that returns success if a file called `.profile` exists in the current directory:

```
#!/bin/sh

if [ -f .profile ]; then
    exit 0
fi

exit 1
```

If you're a glutton for punishment, or at least for terse scripts, you can rewrite this script using the combined AND and OR list we saw earlier, all on one line:

```
[ -f .profile ] && exit 0 || exit 1
```

export

The `export` command makes the variable named as its parameter available in subshells. By default, variables created in a shell are not available in further (sub)shells invoked from that shell. The `export` command creates an environment variable from its parameter that can be seen by other scripts and programs invoked from the current program. More technically, the exported variables form the environment variables in any child processes derived from the shell. This is best illustrated with an example of two scripts, `export1` and `export2`.

Try It Out—Exporting Variables

1. We list `export2` first:

```
#!/bin/sh

echo "$foo"
echo "$bar"
```

2. Now for `export1`. At the end of this script, we invoke `export2`:

```
#!/bin/sh

foo="The first meta-syntactic variable"
export bar="The second meta-syntactic variable"

export2
```

If we run these, we get

```
$ export1

The second meta-syntactic variable
$
```

The first blank line occurs because the variable `foo` was not available in `export2`, so `$foo` evaluated to nothing; echoing a null variable gives a newline.

Once a variable has been exported from a shell, it's exported to any scripts invoked from that shell and also to any shell they invoke in turn and so on. If the script `export2` called another script, it would also have the value of `bar` available to it.

The commands `set -a` or `set -allexport` will export all variables thereafter.

expr

The `expr` command evaluates its arguments as an expression. It's most commonly used for simple arithmetic in the following form:

```
x=`expr $x + 1`
```

The ```` (back-tick) characters make `x` take the result of executing the command `expr $x + 1`. We could also write it using the syntax `$()` rather than back ticks, like this:

```
x=$((expr $x + 1))
```

We'll mention more about command substitution later in the chapter.

The `expr` command is powerful and can perform many expression evaluations. The principal ones are in the following table:

| Expression Evaluation | Description |
|--------------------------------|---|
| <code>expr1 expr2</code> | <code>expr1</code> if <code>expr1</code> is nonzero, otherwise <code>expr2</code> |
| <code>expr1 & expr2</code> | Zero if either expression is zero, otherwise <code>expr1</code> |
| <code>expr1 = expr2</code> | Equal |
| <code>expr1 > expr2</code> | Greater than |
| <code>expr1 >= expr2</code> | Greater than or equal to |
| <code>expr1 < expr2</code> | Less than |
| <code>expr1 <= expr2</code> | Less than or equal to |
| <code>expr1 != expr2</code> | Not equal |
| <code>expr1 + expr2</code> | Addition |
| <code>expr1 - expr2</code> | Subtraction |
| <code>expr1 * expr2</code> | Multiplication |
| <code>expr1 / expr2</code> | Integer division |
| <code>expr1 % expr2</code> | Integer modulo |

In newer scripts, the use of `expr` is normally replaced with the more efficient `$((. . .))` syntax, which we discuss later in the chapter.

printf

The `printf` command is available only in more recent shells. X/Open suggests that we should use it in preference to `echo` for generating formatted output.

The syntax is

```
printf "format string" parameter1 parameter2 ...
```

The format string is very similar to that used in C or C++, with some restrictions. Principally, floating point isn't supported, because all arithmetic in the shell is performed as integers. The format string consists of any combination of literal characters, escape sequences, and conversion specifiers. All characters in the format string other than `%` and `\` appear literally in the output.

The following escape sequences are supported:

| Escape Sequence | Description |
|-----------------|-------------------------------|
| <code>\\</code> | Backslash character |
| <code>\a</code> | Alert (ring the bell or beep) |

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| Escape Sequence | Description |
|-----------------|---|
| \b | Backspace character |
| \f | Form feed character |
| \n | Newline character |
| \r | Carriage return |
| \t | Tab character |
| \v | Vertical tab character |
| \ooo | The single character with octal value ooo |

The conversion specifier is quite complex, so we'll list only the common usage here. More details can be found in the bash online manual or in the `printf` pages from section 3 of the online manual (`man 3 printf`). The conversion specifier consists of a % character, followed by a conversion character. The principal conversions are as follows:

| Conversion Specifier | Description |
|----------------------|--------------------------|
| d | Output a decimal number. |
| c | Output a character. |
| s | Output a string. |
| % | Output the % character. |

The format string is then used to interpret the remaining parameters and output the result. For example,

```
$ printf "%s\n" hello
hello
$ printf "%s %d\t%s" "Hi There" 15 people
Hi There 15    people
```

Notice how we must use " " to protect the Hi There string and make it a single parameter.

return

The `return` command causes functions to return. We mentioned this when we looked at functions earlier. `return` takes a single numeric parameter that is available to the script calling the function. If no parameter is specified, `return` defaults to the exit code of the last command.

set

The `set` command sets the parameter variables for the shell. It can be a useful way of using fields in commands that output space-separated values.

Suppose we want to use the name of the current month in a shell script. The system provides a `date` command, which contains the month as a string, but we need to separate it from the other fields. We can do this using a combination of the `set` command and the `$(...)` construct to execute the `date` command and return the result (which we'll look at in more detail very soon). The `date` command output has the month string as its second parameter:

```
#!/bin/sh

echo the date is $(date)
set $(date)
echo The month is $2

exit 0
```

This program sets the parameter list to the `date` command's output and then uses the positional parameter `$2` to get at the month.

Notice that we used the `date` command as a simple example to show how to extract positional parameters. Since the `date` command is sensitive to the language local, in reality we would have extracted the name of the month using `date +%B`. The `date` command has many other formatting options; see the manual page for more details.

We can also use the `set` command to control the way the shell executes by passing it parameters. The most commonly used form of the command is `set -x`, which makes a script display a trace of its currently executing command. We discuss `set` and more of its options when we look at debugging, later on in the chapter.

shift

The `shift` command moves all the parameter variables down by one, so that `$2` becomes `$1`, `$3` becomes `$2`, and so on. The previous value of `$1` is discarded, while `$0` remains unchanged. If a numerical parameter is specified in the call to `shift`, the parameters will move that many spaces. The other variables `$*`, `$@`, and `$#` are also modified in line with the new arrangement of parameter variables.

`shift` is often useful for scanning through parameters, and if your script requires 10 or more parameters, you'll need `shift` to access the tenth and beyond.

Just as an example, we can scan through all the positional parameters like this:

```
#!/bin/sh

while [ "$1" != "" ]; do
    echo "$1"
    shift
done

exit 0
```

trap

The `trap` command is used for specifying the actions to take on receipt of signals, which we'll meet in more detail later in the book. A common use is to tidy up a script when it is interrupted. Historically, shells always used numbers for the signals, but new scripts should use names taken from the `#include` file `signal.h`, with the `SIG` prefix omitted. To see the signal numbers and associated names, you can just type `trap -l` at a command prompt.

For those not familiar with signals, they are events sent asynchronously to a program. By default, they normally cause the program to terminate.

The `trap` command is passed the action to take, followed by the signal name (or names) to trap on.

```
trap command signal
```

Remember that the scripts are normally interpreted from top to bottom, so you must specify the `trap` command before the part of the script you wish to protect.

To reset a trap condition to the default, simply specify the command as `-`. To ignore a signal, set the command to the empty string `''`. A `trap` command with no parameters prints out the current list of traps and actions.

The following table lists the more important signals covered by the X/Open standard that can be caught (with the conventional signal number in parentheses). More details can be found under the `signal` manual pages in section 7 of the online manual (`man 7 signal`).

| Signal | Description |
|-----------|---|
| HUP (1) | Hang up; usually sent when a terminal goes off line, or a user logs out |
| INT (2) | Interrupt; usually sent by pressing Ctrl+C |
| QUIT (3) | Quit; usually sent by pressing Ctrl+\ |
| ABRT (6) | Abort; usually sent on some serious execution error |
| ALRM (14) | Alarm; usually used for handling timeouts |
| TERM (15) | Terminate; usually sent by the system when it's shutting down |

Try It Out—Trapping Signals

The following script demonstrates some simple signal handling:

```
#!/bin/sh

trap 'rm -f /tmp/my_tmp_file_$$' INT
echo creating file /tmp/my_tmp_file_$$
date > /tmp/my_tmp_file_$$
```

```
echo "press interrupt (CTRL-C) to interrupt ...."
while [ -f /tmp/my_tmp_file_$$ ]; do
    echo File exists
    sleep 1
done
echo The file no longer exists

trap INT
echo creating file /tmp/my_tmp_file_$$
date > /tmp/my_tmp_file_$$

echo "press interrupt (control-C) to interrupt ...."
while [ -f /tmp/my_tmp_file_$$ ]; do
    echo File exists
    sleep 1
done

echo we never get here
exit 0
```

If we run this script, pressing Ctrl+C (or whatever your interrupt keys are) in each of the loops, we get the following output:

```
creating file /tmp/my_tmp_file_141
press interrupt (CTRL-C) to interrupt ....
File exists
File exists
File exists
File exists
The file no longer exists
creating file /tmp/my_tmp_file_141
press interrupt (CTRL-C) to interrupt ....
File exists
File exists
File exists
File exists
```

How It Works

This script uses the `trap` command to arrange for the command `rm -f /tmp/my_tmp_file_$$` to be executed when an `INT` (interrupt) signal occurs. The script then enters a `while` loop that continues while the file exists. When the user presses `Ctrl+C`, the statement `rm -f /tmp/my_tmp_file_$$` is executed, and then the `while` loop resumes. Since the file has now been deleted, the first `while` loop terminates normally.

The script then uses the `trap` command again, this time to specify that no command be executed when an `INT` signal occurs. It then recreates the file and loops inside the second `while` statement. When the user presses `Ctrl+C` this time, there is no statement configured to execute, so the default behavior occurs, which is to immediately terminate the script. Since the script terminates immediately, the final `echo` and `exit` statements are never executed.

unset

The `unset` command removes variables or functions from the environment. It can't do this to read-only variables defined by the shell itself, such as IFS. It's not often used.

The following script writes `Hello World` once and a newline the second time:

```
#!/bin/sh

foo="Hello World"
echo $foo

unset foo
echo $foo
```

Writing `foo=` would have a very similar effect, but not identical, to `unset` in the preceding program. Writing `foo=` has the effect of setting `foo` to null, but `foo` still exists. Using `unset foo` has the effect of removing the variable `foo` from the environment.

Two More Useful Commands and Regular Expressions

Before we see how we can put this new knowledge of shell programming to use, let's look at a couple of other very useful commands, which, although not part of the shell, are often useful when writing shell programs. Along the way we will also be looking at regular expressions, a pattern-matching feature that crops up all over Linux and its associated programs.

The `find` Command

The first command we will look at is `find`. This command, which we use to search for files, is extremely useful, but newcomers to Linux often find it a little tricky to use, not least because it takes options, tests, and action-type arguments, and the results of one argument can affect the processing of subsequent arguments.

Before we delve into the options, tests, and arguments, let's look at a very simple example for the file `wish` on our local machine. We do this as root to ensure that we have permissions to search the whole machine:

```
# find / -name wish -print
/usr/bin/wish
#
```

As you can probably guess, this says "search starting at `/` for a file named `wish` and then print out the name of the file." Easy, wasn't it?

However, it did take quite a while to run, and the disk on a Windows machine on the network rattled away as well. The Linux machine mounts (using SAMBA) a chunk of the Windows machine's file system. It seems like that might have been searched as well, even though we knew the file we were looking for would be on the Linux machine.

This is where the first of the options comes in. If we specify `-mount`, we can tell `find` not to search mounted directories:

```
# find / -mount -name wish -print
/usr/bin/wish
#
```

We still find the file, but without searching other mounted file systems.

The full syntax for the `find` command is:

```
find [path] [options] [tests] [actions]
```

The `path` part is nice and easy: We can use either an absolute path, such as `/bin`, or a relative path, such as `..`. If we need to, we can also specify multiple paths, for example `find /var /home`.

There are several options; the main ones are as follows:

| Option | Meaning |
|--------------------------------|--|
| <code>-depth</code> | Search the contents of a directory before looking at the directory itself. |
| <code>-follow</code> | Follow symbolic links. |
| <code>-maxdepths N</code> | Search at most <code>N</code> levels of directory when searching. |
| <code>-mount (or -xdev)</code> | Don't search directories on other file systems. |

Now for the tests. There are a large number of tests that can be given to `find`, and each test returns either `true` or `false`. When `find` is working, it considers each file it finds in turn and applies each test, in the order they were defined, on that file. If a test returns `false`, `find` stops considering the file it is currently looking at and moves on; if the test returns `true`, `find` will process the next test or action on the current file. The tests we list in the following table are just the most common; consult the manual pages for the extensive list of possible tests you can apply using `find`.

| Test | Meaning |
|-------------------------------|---|
| <code>-atime N</code> | The file was last accessed <code>N</code> days ago. |
| <code>-mtime N</code> | The file was last modified <code>N</code> days ago. |
| <code>-name pattern</code> | The name of the file, excluding any path, matches the pattern provided. To ensure that the pattern is passed to <code>find</code> , and not evaluated by the shell immediately, the pattern must always be in quotes. |
| <code>-newer otherfile</code> | The file is newer than the file <code>otherfile</code> . |
| <code>-type C</code> | The file is of type <code>C</code> , where <code>C</code> can be of a particular type; the most common are "d" for a directory and "f" for a regular file. For other types consult the manual pages. |
| <code>-user username</code> | The file is owned by the user with the given name. |

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We can also combine tests using operators. Most have two forms: a short form and a longer form:

| Operator, Short Form | Operator, Long Form | Meaning |
|----------------------|---------------------|---------------------------|
| ! | -not | Invert the test. |
| -a | -and | Both tests must be true. |
| -o | -or | Either test must be true. |

We can force the precedence of tests and operators by using parentheses. Since these have a special meaning to the shell, we also have to quote the braces using a backslash. In addition, if we use a pattern for the filename, we must use quotes so that the name is not expanded by the shell but passed directly to the `find` command. So if we wanted to write the test “newer than file `X` or called a name that starts with an underscore” we would write the following test:

```
\(-newer X -o -name "_*"\ \)
```

We will present an example just after the next “How it Works” section.

Try It Out—`find` with Tests

Let’s try searching in the current directory for files modified more recently than the file `while2`:

```
$ find . -newer while2 -print
.
./elif3
./words.txt
./words2.txt
./_trap
$
```

That looks good, except that we also find the current directory, which we didn’t want; we were interested only in regular files. So we add an additional test, `-type f`:

```
$ find . -newer while2 -type f -print
./elif3
./words.txt
./words2.txt
./_trap
$
```

How It Works

How did it work? We specified that `find` should search in the current directory (`.`), for files newer than the file `while2` (`-newer while2`) and that, if that test passed, then to also test that the file was a regular file (`-type f`). Finally, we used the action we already met, `-print`, just to confirm which files we had found.

Now let’s also find files that either start with an underscore or are newer than the file `while2`, but must in either case be regular files. This will show us how to combine tests using parentheses:

```
$ find . \(-name "_*" -or -newer while2 \) -type f -print
./elif3
./words.txt
./words2.txt
./_break
./_if
./_set
./_shift
./_trap
./_unset
./_until
$
```

See, that wasn't so hard, was it? We had to escape the parentheses so that they were not processed by the shell and also quote the * so that it was passed directly into `find` as well.

Now that we can reliably search for files, let's look at the actions we can perform when we find a file matching our specification. Again, this is just a list of the most common actions; the manual page has the full set.

| Action | Meaning |
|---------------|--|
| -exec command | Execute a command. This is one of the most common actions. See the explanation following this table for how parameters may be passed to the command. |
| -ok command | Like <code>-exec</code> , except that it prompts for user confirmation of each file on which it will carry out the command before executing the command. |
| -print | Prints out the name of the file. |
| -ls | Uses the command <code>ls -dils</code> on the current file. |

The `-exec` and `-ok` commands take subsequent parameters on the line as part of their parameters, until terminated with a `\;` sequence. The magic string `{}` is a special type of parameter to an `-exec` or `-ok` command and is replaced with the full path to the current file.

That explanation is perhaps not so easy to understand, but an example should make things clearer.

Let's see a simpler example, using a nice safe command like `ls`:

```
$ find . -newer while2 -type f -exec ls -1 {} \;
-rwxr-xr-x    1 rick      rick          275 Feb  8 17:07 ./elif3
-rwxr-xr-x    1 rick      rick          336 Feb  8 16:52 ./words.txt
-rwxr-xr-x    1 rick      rick        1274 Feb  8 16:52 ./words2.txt
-rwxr-xr-x    1 rick      rick          504 Feb  8 18:43 ./_trap
$
```

As you can see, the `find` command is extremely useful; it just takes a little practice to use it well. However, that practice will pay dividends, so do experiment with the `find` command.

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The grep Command

The second very useful command we are going to look at is `grep`, an unusual name that stands for General Regular Expression Parser. We use `find` to search our system for files, but we use `grep` to search files for strings. Indeed, it's quite common to have `grep` as a command passed after `-exec` when using `find`.

The `grep` command takes options, a pattern to match, and files to search in:

```
grep [options] PATTERN [FILES]
```

If no filenames are given, it searches standard input.

Let's start by looking at the principal options to `grep`. Again we will list only the principal options here; see the manual pages for the full list.

| Option | Meaning |
|-----------------|--|
| <code>-c</code> | Rather than printing matching lines, print a count of the number of lines that match. |
| <code>-E</code> | Turn on extended expressions. |
| <code>-h</code> | Suppress the normal prefixing of each output line with the name of the file it was found in. |
| <code>-i</code> | Ignore case. |
| <code>-l</code> | List the names of the files with matching lines; don't output the actual matched line. |
| <code>-v</code> | Invert the matching pattern to select nonmatching lines rather than matching lines. |

Try It Out—Basic grep Usage

Let's look at `grep` in action with some simple matches:

```
$ grep in words.txt
When shall we three meet again. In thunder, lightning, or in rain?
I come, Graymalkin!
$ grep -c in words.txt words2.txt
words.txt:2
words2.txt:14
$ grep -c -v in words.txt words2.txt
words.txt:9
words2.txt:16
$
```

How It Works

The first example uses no options; it simply searches for the string "in" in the file `words.txt` and prints out any lines that match. The filename isn't printed because we are searching on just a single file.

The second example counts the number of matching lines in two different files. In this case, the file names are printed out.

Finally, we use the `-v` option to invert the search and count lines in the two files that don't match.

Regular Expressions

As we have seen, the basic usage of grep is very easy to master. Now it's time to look at the basics of regular expressions, which allow you to do more sophisticated matching. As was mentioned earlier in the chapter, regular expressions are used in Linux and many other Open Source languages. You can use them in the vi editor and in writing Perl scripts, with the basic principles common wherever they appear.

During the use of regular expressions, certain characters are processed in a special way. The most frequently used are as follows:

| Character | Meaning |
|-----------|---|
| ^ | Anchor to the beginning of a line. |
| \$ | Anchor to the end of a line. |
| . | Any single character. |
| [] | The square braces contain a range of characters, any one of which may be matched, such as a range of characters like a-e or an inverted range by preceding the range with a ^ symbol. |

If you want to use any of these characters as “normal” characters, precede them with a \. So if you wanted to look for a literal “\$” character, you would simply use \\$.

There are also some useful special match patterns that can be used in square braces:

| Match Pattern | Meaning |
|---------------|---|
| [:alnum:] | Alphanumeric characters |
| [:alpha:] | Letters |
| [:ascii:] | ASCII characters |
| [:blank:] | Space or tab |
| [:cntrl:] | ASCII control characters |
| [:digit:] | Digits |
| [:graph:] | Noncontrol, nonspace characters |
| [:lower:] | Lowercase letters |
| [:print:] | Printable characters |
| [:punct:] | Punctuation characters |
| [:space:] | Whitespace characters, including vertical tab |
| [:upper:] | Uppercase letters |
| [:xdigit:] | Hexadecimal digits |

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In addition, if the `-E` for extended matching is also specified, other characters that control the completion of matching may follow the regular expression. With grep it is also necessary to precede these characters with a `\`.

| Option | Meaning |
|--------------------|---|
| <code>?</code> | Match is optional but may be matched at most once. |
| <code>*</code> | Must be matched zero or more times. |
| <code>+</code> | Must be matched one or more times. |
| <code>{n}</code> | Must be matched n times. |
| <code>{n,}</code> | Must be matched n or more times. |
| <code>{n,m}</code> | Must be matched between n or m times inclusive. |

That all looks a little complex, but if we take it in stages, you will see it's not as complex as it perhaps looks at first sight. The easiest way to get the hang of regular expressions is simply to try a few.

Try It Out—Regular Expressions

Let's start by looking for lines that end with the letter *e*. You can probably guess we need to use the special character `$`:

```
$ grep e$ words2.txt
Art thou not, fatal vision, sensible
I see thee yet, in form as palpable
Nature seems dead, and wicked dreams abuse
$
```

As you can see, this finds lines that end in the letter *e*.

Now suppose we want to find words that end with the letter *a*. To do this, we need to use the special match characters in braces. In this case, we will use `[[:blank:]]`, which tests for a space or a tab:

```
$ grep a[[:blank:]] words2.txt
Is this a dagger which I see before me,
A dagger of the mind, a false creation,
Moves like a ghost. Thou sure and firm-set earth,
$
```

Now let's look for three-letter words that start with *Th*. In this case, we need both `[[:space:]]` to delimit the end of the word and `.` to match a single additional character:

```
$ grep Th.[[:space:]] words2.txt
The handle toward my hand? Come, let me clutch thee.
The curtain'd sleep; witchcraft celebrates
Thy very stones prate of my whereabout,
$
```

Finally, let's use the extended grep mode to search for lowercase words that are exactly 10 characters long. We do this by specifying a range of characters to match *a* to *z*, and a repetition of 10 matches:

```
$ grep -E [a-z]\{10\} words2.txt
Proceeding from the heat-oppressed brain?
And such an instrument I was to use.
The curtain'd sleep; witchcraft celebrates
Thy very stones prate of my whereabout,
$
```

We have only really had chance to touch on the more important parts of regular expressions here. As with most things in Linux, there is a lot more documentation out there to help you discover more details, but the best way of learning about regular expressions is to experiment.

Command Execution

When we're writing scripts, we often need to capture the result of a command's execution for use in the shell script; that is, we want to execute a command and put the output of the command into a variable. We can do this by using the `$ (command)` syntax that we introduced in the earlier `set` command example. There is also an older form, ``command``, that is still in common usage.

Note that with the older form of the command execution, the backtick, or backquote (`), is used, not the single quote (') that we used in earlier shell quoting (to protect against variable expansion). Use this form for shell scripts only when you need them to be very portable.

All new scripts should use the `$ (...)` form, which was introduced to avoid some rather complex rules covering the use of the characters `$`, ```, and `\` inside the back-quoted command. If a backtick is used within the ``...`` construct, it must be escaped with a `\` character. These relatively obscure characters often confuse programmers, and sometimes even experienced shell programmers are forced to experiment to get the quoting correct in backticked commands.

The result of the `$ (command)` is simply the output from the command. Note that this isn't the return status of the command but of the string output. For example,

```
#!/bin/sh

echo The current directory is $PWD
echo The current users are $(who)

exit 0
```

Since the current directory is a shell environment variable, the first line doesn't need to use this command execution construct. The result of `who`, however, does need this construct if it is to be available to the script.

If we want to get the result into a variable, we can just assign it in the usual way:

```
whoisthere=$(who)
echo $whoisthere
```

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The ability to put the result of a command into a script variable is very powerful, as it makes it easy to use existing commands in scripts and capture their output. If you ever find yourself trying to convert a set of parameters that are the output of a command on standard output and capture them as arguments for a program, you may well find the command `xargs` can do it for you. Look in the manual pages for further details.

A problem sometimes arises when the command we want to invoke outputs some white space before the text we want, or more output than we require. In such a case, we can use the `set` command as we have already shown.

Arithmetic Expansion

We've already used the `expr` command, which allows simple arithmetic commands to be processed, but this is quite slow to execute because a new shell is invoked to process the `expr` command.

A newer and better alternative is `$((...))` expansion. By enclosing the expression we wish to evaluate in `$((...))`, we can perform simple arithmetic much more efficiently:

```
#!/bin/sh

x=0
while [ "$x" -ne 10 ]; do
    echo $x
    x=$((x+1))
done

exit 0
```

Notice that this is subtly different from the `x=$(...)` command. The double parentheses are used for arithmetic substitution. The single parentheses form that we saw earlier is used for executing commands and grabbing the output.

Parameter Expansion

We've seen the simplest form of parameter assignment and expansion, where we write

```
foo=fred
echo $foo
```

A problem occurs when we want to append extra characters to the end of a variable. Suppose we want to write a short script to process files called `1_tmp` and `2_tmp`. We could try

```
#!/bin/sh

for i in 1 2
do
    my_secret_process ${i}_tmp
done
```

But on each loop, we'll get

```
my_secret_process: too few arguments
```

What went wrong?

The problem is that the shell tried to substitute the value of the variable `$i_tmp`, which doesn't exist. The shell doesn't consider this an error; it just substitutes nothing, so no parameters at all were passed to `my_secret_process`. To protect the expansion of the `$i` part of the variable, we need to enclose the `i` in braces like this:

```
#!/bin/sh

for i in 1 2
do
    my_secret_process ${i}_tmp
done
```

On each loop, the value of `i` is substituted for `${i}` to give the actual file names. We've substituted the value of the parameter into a string.

We can perform many parameter substitutions in the shell. Often, these provide an elegant solution to many parameter-processing problems.

The common ones are in the following table:

| Parameter Expansion | Description |
|----------------------------------|--|
| <code> \${param:-default}</code> | If <code>param</code> is null, set it to the value of <code>default</code> . |
| <code> \${#param}</code> | Gives the length of <code>param</code> . |
| <code> \${param%word}</code> | From the end, removes the smallest part of <code>param</code> that matches <code>word</code> and returns the rest. |
| <code> \${param%%word}</code> | From the end, removes the longest part of <code>param</code> that matches <code>word</code> and returns the rest. |
| <code> \${param#word}</code> | From the beginning, removes the smallest part of <code>param</code> that matches <code>word</code> and returns the rest. |
| <code> \${param##word}</code> | From the beginning, removes the longest part of <code>param</code> that matches <code>word</code> and returns the rest. |

These substitutions are often useful when you're working with strings. The last four, which remove parts of strings, are especially useful for processing filenames and paths, as the following example shows.

Try It Out—Parameter Processing

Each portion of the following script illustrates the parameter-matching operators:

```
#!/bin/sh

unset foo
echo ${foo:-bar}

foo=fud
echo ${foo:-bar}

foo=/usr/bin/X11/startx
echo ${foo##*/}
echo ${foo##*/}

bar=/usr/local/etc/local/networks
echo ${bar%local*}
echo ${bar%%local*}

exit 0
```

This gives the following output:

```
bar
fud
/usr/bin/X11/startx
startx
/usr/local/etc
/usr
```

How It Works

The first statement, `${foo:-bar}`, gives the value `bar`, because `foo` had no value when the statement was executed. The variable `foo` is unchanged as it remains unset.

`${foo:=bar}`, however, would set the variable to `$foo`. This string operator checks that `foo` exists and isn't null. If it isn't null, it returns its value, but otherwise it sets `foo` to `bar` and returns that instead.

`${foo:?bar}` will print `foo: bar` and abort the command if `foo` doesn't exist or is set to null.

Lastly, `${foo:+bar}` returns `bar` if `foo` exists and isn't null.

What a set of choices!

The `{foo#/*/}` statement matches and removes only the left / (remember * matches zero or more characters). The `{foo##*/}` matches and removes as much as possible, so it removes the rightmost / and all the characters before it.

The `{bar%local*}` statement matches characters from the right until the first occurrence of local (followed by any number of characters) is matched, but the `{bar%%local*}` matches as many characters as possible from the right until it finds the leftmost local.

Since both UNIX and Linux are based heavily round the idea of filters, the result of one operation must often be redirected manually. Let's say you want to convert a GIF file into a JPEG file using the `cjpeg` program.

```
$ cjpeg image.gif > image.jpg
```

Sometimes you may want to perform this type of operation on a large number of files. How do you automate the redirection? It's as easy as this:

```
#!/bin/sh

for image in *.gif
do
    cjpeg $image > ${image%gif}jpg
done
```

This script, `giftojpeg`, creates a JPEG file for each GIF file in the current directory.

Here Documents

One special way of passing input to a command from a shell script is to use a *here document*. This document allows a command to execute as though it were reading from a file or the keyboard, whereas in fact it's getting input from the script.

A here document starts with the leader `<<`, followed by a special sequence of characters that will be repeated at the end of the document. `<<` is the shell's label redirector, which in this case forces the command input to be the here document. This special sequence acts as a marker to tell the shell where the here document ends. The marker sequence must not appear in the lines to be passed to the command, so it's best to make them memorable and fairly unusual.

Try It Out—Using Here Documents

The simplest example is simply to feed input to the `cat` command:

```
#!/bin/sh

cat <<! FUNKY!
hello
this is a here
document
!FUNKY!
```

This gives the output:

```
hello
this is a here
document
```

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Here documents might seem a rather curious feature, but they're very powerful because they allow us to invoke an interactive program such as an editor and feed it some predefined input. However, they're more commonly used for outputting large amounts of text from inside a script, as we saw previously, and avoiding having to use echo statements for each line. We've used ! marks on each side of the identifier to ensure that there's no confusion.

If we wish to process several lines in a file in a predetermined way, we could use the ed line editor and feed it commands from a here document in a shell script.

Try It Out—Another Use for a Here Document

1. Let's start with a file called `a_text_file` that contains

```
That is line 1
That is line 2
That is line 3
That is line 4
```

2. We can edit this file using a combination of a here document and the `ed` editor:

```
#!/bin/sh

ed a_text_file <<!FunkyStuff!
3
d
.,\$s/is/was/
w
q
!FunkyStuff!

exit 0
```

If we run this script, the file now contains:

```
That is line 1
That is line 2
That was line 4
```

How It Works

The shell script simply invokes the `ed` editor and passes to it the commands that it needs to move to the third line, delete the line, and then replace it with what was in the current line (because line 3 was deleted, the current line is now what was the last line). These `ed` commands are taken from the lines in the script that form the here document—the lines between the markers `!FunkyStuff!`.

Notice the \ inside the here document to protect the \$ from shell expansion. The \ escapes the \$, so the shell knows not to try to expand \\$s/is/was/ to its value, which of course it doesn't have. Instead, the shell passes the text \\$ as \$, which can then be interpreted by the ed editor.

Debugging Scripts

Debugging shell scripts is usually quite easy, but there are no specific tools to help. In this section we'll quickly summarize the common methods.

When an error occurs, the shell will normally print out the line number of the line containing the error. If the error isn't immediately apparent, we can add some extra `echo` statements to display the contents of variables and test code fragments by simply typing them into the shell interactively.

Since scripts are interpreted, there's no compilation overhead in modifying and retrying a script. The main way to trace more complicated errors is to set various shell options. To do this, you can either use command line options after invoking the shell or use the `set` command. We summarize the options in the following table.

| Command Line Option | <code>set</code> Option | Description |
|-----------------------------------|--|--|
| <code>sh -n <script></code> | <code>set -o noexec set -n</code> | Checks for syntax errors only; doesn't execute commands. |
| <code>sh -v <script></code> | <code>set -o verbose set -v</code> | Echoes commands before running them. |
| <code>sh -x <script></code> | <code>set -o xtrace set -x</code> | Echoes commands after processing on the command line. |
| | <code>set -o nounset set -u</code> | Gives an error message when an undefined variable is used. |

You can set the `set` option flags on, using `-o`, and off, using `+o`, and likewise for the abbreviated versions. You can achieve a simple execution trace by using the `xtrace` option. For an initial check, you can use the command line option, but for finer debugging, you can put the `xtrace` flags (setting an execution trace on and off) inside the script around the problem code. The execution trace causes the shell to print each line in the script, with variables expanded, before executing the line.

Use the following command to turn `xtrace` on:

```
set -o xtrace
```

And use the following command to turn `xtrace` off again:

```
set +o xtrace
```

The level of expansion is denoted (by default) by the number of `+` signs at the start of each line. You can change the `+` to something more meaningful by setting the `PS4` shell variable in your shell configuration file.

In the shell, you can also find out the program state wherever it exits by trapping the `EXIT` signal with a line something like the following placed at the start of the script:

```
trap 'echo Exiting: critical variable = $critical_variable' EXIT
```

Going Graphical—The Dialog Utility

Before we finish discussing shell scripts, there is one more feature, which, although it is not strictly part of the shell, is generally useful only from shell programs, so we will cover it here.

If you know that your script will only ever need to run on the Linux console, there is a rather neat way to brighten up your scripts using a utility command called `dialog`. This command uses text mode graphics and color, but it still looks pleasantly graphically oriented.

The whole idea of `dialog` is beautifully simple—a single program with a variety of parameters and options that allows you to display various types of graphical boxes, ranging from simple Yes/No boxes to input boxes and even menu selections. The utility generally returns when the user has made some sort of input, and the result can be found either from the exit status or if text was entered by retrieving the standard error stream.

Before we move on to more detail, let's look at a very simple use of `dialog` in operation. We can use `dialog` directly from the command line, which is great for prototyping, so let's create a simple message box to display the traditional first program:

```
dialog --msgbox "Hello World" 9 18
```

On the screen appears a graphical information box, complete with OK dialog (see Figure 2-3).



Figure 2-3

Now that we have seen how easy `dialog` is, let's look at the possibilities in more detail.

The principal types of dialogs we can create are in the following table:

| Type | Option Used to Create Type | Meaning |
|-----------------------|----------------------------|---|
| Check boxes | --checklist | Allows you to display a list of items, each of which may be individually selected. |
| Info boxes | --infobox | A simple display in a box that returns immediately, without clearing the screen. |
| Input boxes | --inputbox | Allows the user to type in text. |
| Menu boxes | --menu | Allow the user to pick a single item from a list. |
| Message boxes | --msgbox | Displays a message to the user with an OK button when they wish to continue. |
| Radio selection boxes | --radiolist | Allows the user to select an option from a list. |
| Text boxes | --textbox | Allows you to display a file in a scrolling box. |
| Yes/No boxes | --yesno | Allows you to ask a question, to which the user can select either <i>yes</i> or <i>no</i> . |

There are some additional `dialog` box types available (for example, a gauge and a password-entry box). If you want to know more about the more unusual `dialog` types, details can be found, as ever, in the online manual pages.

To get the output of any type of box that allows textual input, or selections, you have to capture the standard error stream, usually by directing it to a temporary file, which you can then process afterward. To get the result of Yes/No type questions, just look at the exit code, which, like all well-behaved programs, returns 0 for success (i.e., a “yes” section) or 1 for failure.

All `dialog` types have various additional parameters to control, such as the size and shape of the dialog presented. We will list the different parameters required for each type first, and then we will demonstrate some of them on the command line. Finally, we'll write a simple program to combine several dialogs into a single program.

| Dialog Type | Parameters |
|-------------|---|
| --checklist | text height width list-height [tag text status] ... |
| --infobox | text height width |
| --inputbox | text height width [initial string] |
| --menu | text height width menu-height [tag item] ... |
| --msgbox | text height width |
| --radiolist | text height width list-height [tag text status] ... |
| --textbox | filename height width |
| --yesno | text height width |

In addition, all the dialog types take several options. We will not list them all here, except to mention two: `--title`, which allows you to specify a title for the box, and `--clear`, which is used on its own for clearing the screen. As ever, check the manual page for the full list of options.

Try It Out—Using the dialog Utility

Let's leap straight in with a nice complex example. Once you understand this example, all the others will be easy! This example will create a checklist-type box, with a title `Check me` and the instructions `Pick Numbers`. The checklist box will be 15 characters high by 25 characters wide, and each option will occupy 3 characters of height. Last, but not least, we list the options to be displayed, along with a default on/off selection.

```
dialog --title "Check me" --checklist "Pick Numbers" 15 25 3 1 "one" "off" 2 "two"  
"on" 3 "three" "off"
```

Figure 2-4 shows the result onscreen.

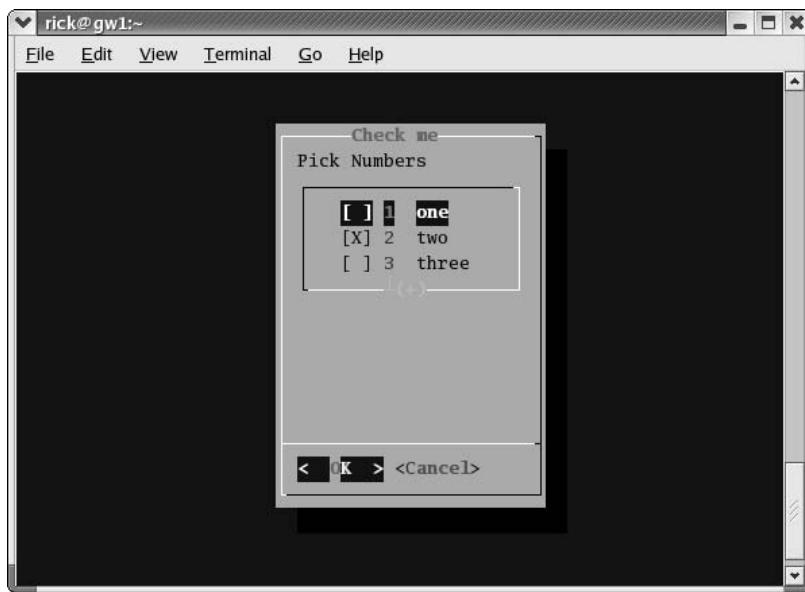


Figure 2-4

How It Works

In this example, the `--checklist` parameter tells us we are to create a checklist-type dialog. We use the `--title` option to set the title to `Check me`, and the next parameter is the prompt message of `Pick Numbers`.

We then move on to set the size of the dialog. It will be 15 lines high by 25 characters wide, and 3 lines will be used for the menu. It's not a perfect sizing, but it does allow you to see how things are laid out.

The options look a little tricky, but all you have to remember is that each menu item has three values:

- Bullet number
- Text
- Status

So the first item has a number of 1, and text display of "one" and is set to "off". We then start on the next menu item, which is 2, "two" and selected. This continues until you run out of menu items.

Easy, wasn't it? Just try some out on the command line and see how easy it is to use.

In order to put this together in a program, we need to be able to access the results of the user input. This is quite easy; we simply redirect the standard error stream for text input, or check the environment variable `$?`, which you will recall is the exit status of the previous command.

Try It Out

Let's look at a simple program called `questions`, which takes note of user responses.

```
#!/bin/sh

# Ask some questions and collect the answer

dialog --title "Questionnaire" --msgbox "Welcome to my simple survey" 9 18
```

We start off by displaying a simple dialog box to tell the user what is happening. You don't need to get the result or obtain any user input, so this is nice and simple.

```
dialog --title "Confirm" --yesno "Are you willing to take part?" 9 18
if [ $? != 0 ]; then
    dialog --infobox "Thank you anyway" 5 20
    sleep 2
    dialog --clear
    exit 0
fi
```

Now we ask the user if he or she wants to proceed, using a simple yes/no dialog box. We use the environment variable `$?` to check if the user selected yes (result code 0) or not. If they didn't want to proceed, we use a simple infobox that requires no user input before exiting.

```
dialog --title "Questionnaire" --inputbox "Please enter your name" 9 30 2>_1.txt
Q_NAME=$(cat _1.txt)
```

We now ask the user his name, using an input box. We redirect the standard error stream, 2, into a temporary file, `_1.txt`, which we can then process into the variable `QNAME`.

```
dialog --menu "$Q_NAME, what music do you like best?" 15 30 4 1 "Classical" 2
"Jazz" 3 "Country" 4 "Other" 2>_1.txt
Q_MUSIC=$(cat _1.txt)
```

Chapter 2

Here we show the menu item with four different options. Again we redirect the standard error stream and load it into a variable.

```
if [ "$Q_MUSIC" == "1" ]; then
    dialog --msgbox "Good choice!" 12 25
fi
```

If the user selects menu option 1, this will be stored in the temporary file `_1.txt`, which we have grabbed in to the variable `Q_MUSIC` so that we can test the result.

```
sleep 5
dialog --clear
exit 0
```

Finally, we clear the last dialog box and exit the program.

Figure 2-5 shows what it looks like onscreen.

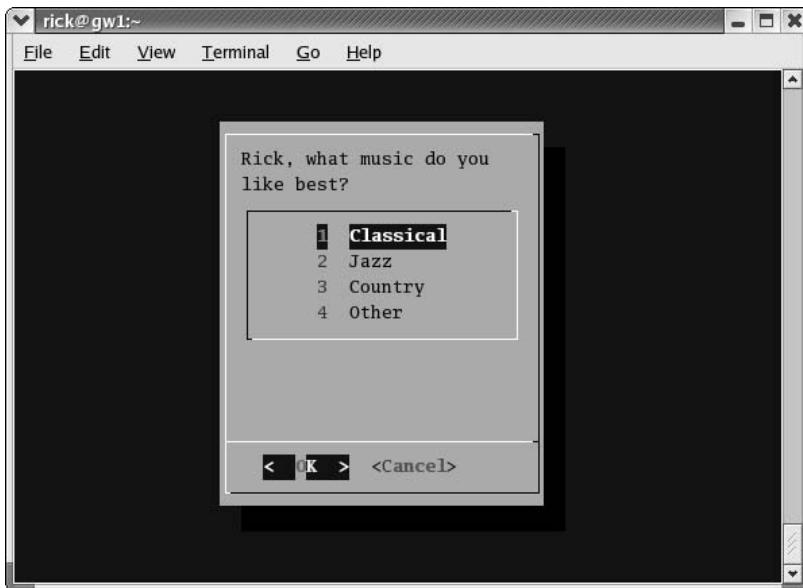


Figure 2-5

Now you have a way, providing you need to use only the Linux console, of writing simple GUI programs from a shell script.

Putting It All Together

Now that we've seen the main features of the shell as a programming language, it's time to write an example program to put some of what we have learned to use.

Throughout this book, we're going to be building a CD database application to show the techniques we've been learning. We start with a shell script, but pretty soon we'll do it again in C, add a database, and so on. Let's start.

Requirements

Suppose we have an extensive CD collection. To make our lives easier, we're going to design and implement a program for managing CDs. An electronic catalogue seems an ideal project to implement as we learn about programming Linux.

We want, at least initially, to store some basic information about each CD, such as the label, type of music, and artist or composer. We would also like to store some simple track information.

We want to be able to search on any of the “per CD” items, but not on any of the track details.

To make the miniapplication complete, we would also like to be able to enter, update, and delete any of the information from within the application.

Design

The three requirements—updating, searching, and displaying the data—suggest that a simple menu will be adequate. All the data we need to store is textual and, assuming our CD collection isn't too big, we have no need for a complex database, so some simple text files will do. Storing information in text files will keep our application simple, and if our requirements change, it's almost always easier to manipulate a text file than any other sort of file. As a last resort, we could even use an editor to manually enter and delete data, rather than write a program to do it.

We need to make an important design decision about our data storage: Will a single file suffice and, if so, what format should it have? Most of the information we expect to store occurs only once per CD (we'll skip lightly over the fact that some CDs contain the work of many composers or artists), except track information. Just about all CDs have more than one track.

Should we fix a limit on the number of tracks we can store per CD? That seems rather an arbitrary and unnecessary restriction, so let's reject that idea right away!

If we allow a flexible number of tracks, we have three options:

- Use a single file, with one line for the “title” type information and then n lines for the track information for that CD.
- Put all the information for each CD on a single line, allowing the line to continue until no more track information needs to be stored.
- Separate the title information from the track information and use a different file for each.

Only the third option allows us to easily fix the format of the files, which we'll need to do if we ever wish to convert our database into a relational form (more on this in Chapter 7), so that's the option we'll choose.

Chapter 2

The next decision is what to put in the files.

Initially, for each CD title, we'll choose to store

- The CD catalog number
- The title
- The type (classical, rock, pop, jazz, etc.)
- The composer or artist

For the tracks, we'll store simply

- Track number
- Track name

In order to join the two files, we must relate the track information to the rest of the CD information. To do this, we'll use the CD catalog number. Since this is unique for each CD, it will appear only once in the titles file and once per track in the tracks file.

Let's look at an example titles file:

| Catalog | Title | Type | Composer |
|---------|----------------|-----------|----------|
| CD123 | Cool sax | Jazz | Bix |
| CD234 | Classic violin | Classical | Bach |
| CD345 | Hits99 | Pop | Various |

Its corresponding tracks file will look like this:

| Catalog | Track No. | Title |
|---------|-----------|-------------------|
| CD123 | 1 | Some jazz |
| CD123 | 2 | More jazz |
| CD345 | 1 | Dizzy |
| CD234 | 1 | Sonata in D minor |

The two files join using the Catalog field. Remember, there are normally multiple rows in the tracks file for a single entry in the titles file.

The last thing we need to decide is how to separate the entries. Fixed-width fields are normal in a relational database, but are not always the most convenient. Another common method is a comma, which we'll use here (i.e., a comma-separated variable, or CSV, file).

In the following Try It Out section, just so you don't get totally lost, we'll be using the following functions:

```
get_return()
get_confirm()
set_menu_choice()
insert_title()
insert_track()
add_record_tracks()
add_records()
find_cd()
update_cd()
count_cds()
remove_records()
list_tracks()
```

Try It Out—A CD Application

1. First in our sample script is, as always, a line ensuring that it's executed as a shell script, followed by some copyright information:

```
#!/bin/sh

# Very simple example shell script for managing a CD collection.
# Copyright (C) 1996-2003 Wrox Press.

# This program is free software; you can redistribute it and/or modify it
# under the terms of the GNU General Public License as published by the
# Free Software Foundation; either version 2 of the License, or (at your
# option) any later version.

# This program is distributed in the hopes that it will be useful, but
# WITHOUT ANY WARRANTY; without even the implied warranty of
# MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU General
# Public License for more details.

# You should have received a copy of the GNU General Public License along
# with this program; if not, write to the Free Software Foundation, Inc.
# 675 Mass Ave, Cambridge, MA 02139, USA.
```

2. The first thing to do is to ensure that some global variables that we'll be using throughout the script are set up. We set the title and track files and a temporary file. We also trap Ctrl+C, so that our temporary file will be removed if the user interrupts the script.

```
menu_choice=""
current_cd=""
title_file="title.cdb"
tracks_file="tracks.cdb"
temp_file=/tmp/cdb.$$
trap 'rm -f $temp_file' EXIT
```

3. Now we define our functions, so that the script, executing from the top line, can find all the function definitions before we attempt to call any of them for the first time. To avoid rewriting the same code in several places, the first two functions are simple utilities.

Chapter 2

```
get_return() {
    echo -e "Press return \c"
    read x
    return 0
}

get_confirm() {
    echo -e "Are you sure? \c"
    while true
    do
        read x
        case "$x" in
            y | yes | Y | Yes | YES )
                return 0;;
            n | no | N | No | NO )
                echo
                echo "Cancelled"
                return 1;;
            *) echo "Please enter yes or no" ;;
        esac
    done
}
```

4. Here we come to the main menu function, `set_menu_choice`. The contents of the menu vary dynamically, with extra options being added if a CD entry has been selected.

Note that `echo -e` may not be portable to some shells.

```
set_menu_choice() {
    clear
    echo "Options :-"
    echo
    echo "    a) Add new CD"
    echo "    f) Find CD"
    echo "    c) Count the CDs and tracks in the catalog"
    if [ "$cdcatnum" != "" ]; then
        echo "    1) List tracks on $cdtitle"
        echo "    r) Remove $cdtitle"
        echo "    u) Update track information for $cdtitle"
    fi
    echo "    q) Quit"
    echo
    echo -e "Please enter choice then press return \c"
    read menu_choice
    return
}
```

5. Here are two more very short functions, `insert_title` and `insert_track`, for adding to the database files. Though some people hate one-liners like these, they help make other functions clearer.

They are followed by the larger add_record_track function that uses them. This function uses pattern matching to ensure that no commas are entered (since we're using commas as a field separator) and also arithmetic operations to increment the current track number as tracks are entered.

```
insert_title() {
    echo $* >> $title_file
    return
}

insert_track() {
    echo $* >> $tracks_file
    return
}

add_record_tracks() {
    echo "Enter track information for this CD"
    echo "When no more tracks enter q"
    cdtrack=1
    cdtitle=""
    while [ "$cdtitle" != "q" ]
    do
        echo -e "Track $cdtrack, track title? \c"
        read tmp
        cdtitle=${tmp%%,*}
        if [ "$tmp" != "$cdtitle" ]; then
            echo "Sorry, no commas allowed"
            continue
        fi
        if [ -n "$cdtitle" ] ; then
            if [ "$cdtitle" != "q" ]; then
                insert_track $cdcatnum,$cdtrack,$cdtitle
            fi
        else
            cdtrack=$((cdtrack+1))
        fi
        cdtrack=$((cdtrack+1))
    done
}
```

6. The add_records function allows entry of the main CD information for a new CD.

```
add_records() {
    # Prompt for the initial information

    echo -e "Enter catalog name \c"
    read tmp
    cdcatnum=${tmp%%,*}

    echo -e "Enter title \c"
    read tmp
    cdtitle=${tmp%%,*}

    echo -e "Enter type \c"
```

Chapter 2

```
read tmp
cdtype=${tmp%%,*}

echo -e "Enter artist/composer \c"
read tmp
cdac=${tmp%%,*}

# Check that they want to enter the information

echo About to add new entry
echo "$cdcatnum $cdtitle $cdtype $cdac"

# If confirmed then append it to the titles file

if get_confirm ; then
    insert_title $cdcatnum,$cdtitle,$cdtype,$cdac
    add_record_tracks
else
    remove_records
fi

return
}
```

7. The `find_cd` function searches for the catalog name text in the CD title file, using the `grep` command. We need to know how many times the string was found, but `grep` returns a value telling us only if it matched zero times or many. To get around this, we store the output in a file, which will have one line per match, then count the lines in the file.

The word count command, `wc`, has white space in its output, separating the number of lines, words, and characters in the file. We use the `$ (wc -l $temp_file)` notation to extract the first parameter from the output in order to set the `linesfound` variable. If we wanted another, later parameter, we would use the `set` command to set the shell's parameter variables to the command output.

We change the IFS (Internal Field Separator) to a comma so we can separate the comma-delimited fields. An alternative command is `cut`.

```
find_cd() {
    if [ "$1" = "n" ] ; then
        asklist=n
    else
        asklist=y
    fi
    cdcatnum=""
    echo -e "Enter a string to search for in the CD titles \c"
    read searchstr
    if [ "$searchstr" = "" ] ; then
        return 0
    fi

    grep "$searchstr" $title_file > $temp_file

    set $(wc -l $temp_file)
    linesfound=$1
```

```

        case "$linesfound" in
        0)    echo "Sorry, nothing found"
              get_return
              return 0
              ;;
        1)    ;;
        2)    echo "Sorry, not unique."
              echo "Found the following"
              cat $temp_file
              get_return
              return 0
        esac

IFS=","
read cdcatnum cdtitle cdtype cdac < $temp_file
IFS=" "

if [ -z "$cdcatnum" ]; then
  echo "Sorry, could not extract catalog field from $temp_file"
  get_return
  return 0
fi

echo
echo Catalog number: $cdcatnum
echo Title: $cdtitle
echo Type: $cdtype
echo Artist/Composer: $cdac
echo
get_return

if [ "$asklist" = "y" ]; then
  echo -e "View tracks for this CD? \c"
  read x
  if [ "$x" = "y" ]; then
    echo
    list_tracks
    echo
  fi
fi
return 1
}

```

- 8.** update_cd allows us to re-enter information for a CD. Notice that we search (using grep) for lines that start (^) with the \$cdcatnum followed by a , and that we need to wrap the expansion of \$cdcatnum in {} so we can search for a , with no whitespace between it and the catalogue number. This function also uses {} to enclose multiple statements to be executed if get_confirm returns true.

```

update_cd() {
  if [ -z "$cdcatnum" ]; then
    echo "You must select a CD first"
    find_cd n
  fi
  if [ -n "$cdcatnum" ]; then

```

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```
echo "Current tracks are :-"
list_tracks
echo
echo "This will re-enter the tracks for $cdtitle"
get_confirm && {
    grep -v "^${cdcatnum},\" $tracks_file > $temp_file
    mv $temp_file $tracks_file
    echo
    add_record_tracks
}
fi
return
}
```

9. count_cds gives us a quick count of the contents of our database.

```
count_cds() {
    set $(wc -l $title_file)
    num_titles=$1
    set $(wc -l $tracks_file)
    num_tracks=$1
    echo found $num_titles CDs, with a total of $num_tracks tracks
    get_return
    return
}
```

10. remove_records strips entries from the database files, using grep -v to remove all matching strings. Notice we must use a temporary file.

If we tried to do this,

```
grep -v "^$cdcatnum" > $title_file
```

the \$title_file would be set to empty by the > output redirection before grep had the chance to execute, so grep would read from an empty file.

```
remove_records() {
    if [ -z "$cdcatnum" ]; then
        echo You must select a CD first
        find_cd n
    fi
    if [ -n "$cdcatnum" ]; then
        echo "You are about to delete $cdtitle"
        get_confirm && {
            grep -v "^${cdcatnum},\" $title_file > $temp_file
            mv $temp_file $title_file
            grep -v "^${cdcatnum},\" $tracks_file > $temp_file
            mv $temp_file $tracks_file
            cdcatnum=""
            echo Entry removed
        }
        get_return
    fi
    return
}
```

- 11.** `list_tracks` again uses `grep` to extract the lines we want, `cut` to access the fields we want, and then `more` to provide a paginated output. If you consider how many lines of C code it would take to reimplement these 20-odd lines of code, you'll appreciate how powerful a tool the shell can be.

```
list_tracks() {
    if [ "$cdcatnum" = "" ]; then
        echo no CD selected yet
        return
    else
        grep "^\${cdcatnum}, " $tracks_file > $temp_file
        num_tracks=$(wc -l $temp_file)
        if [ "$num_tracks" = "0" ]; then
            echo no tracks found for $cdtitle
        else {
            echo
            echo "$cdtitle :-"
            echo
            cut -f 2- -d , $temp_file
            echo
        } | ${PAGER:-more}
    fi
    get_return
    return
}
```

- 12.** Now that all the functions have been defined, we can enter the main routine. The first few lines simply get the files into a known state; then we call the menu function, `set_menu_choice`, and act on the output.

When `quit` is selected, we delete the temporary file, write a message, and exit with a successful completion condition.

```
rm -f $temp_file
if [ ! -f $title_file ]; then
    touch $title_file
fi
if [ ! -f $tracks_file ]; then
    touch $tracks_file
fi

# Now the application proper

clear
echo
echo
echo "Mini CD manager"
sleep 1

quit=n
while [ "$quit" != "y" ];
do
    set_menu_choice
    case "$menu_choice" in
        a) add_records;;
    esac
done
```

```
r) remove_records;;
f) find_cd y;;
u) update_cd;;
c) count_cds;;
l) list_tracks;;
b)
echo
more $title_file
echo
get_return;;
q | Q ) quit=y;;
*) echo "Sorry, choice not recognized";;
esac
done

#Tidy up and leave

rm -f $temp_file
echo "Finished"
exit 0
```

Notes on the Application

The `trap` command at the start of the script is intended to trap the user's pressing of Ctrl+C. This may be either the `EXIT` or the `INT` signal, depending on the terminal setup.

There are other ways of implementing the menu selection, notably the `select` construct in bash and ksh (which, isn't, however, specified in X/Open). This construct is a dedicated menu choice selector. Check it out if your script can afford to be slightly less portable. Multiline information given to users could also make use of here documents.

You might have noticed that there's no validation of the primary key when a new record is started; the new code just ignores the subsequent titles with the same code, but incorporates their tracks into the first title's listing:

```
1 First CD Track 1
2 First CD Track 2
1 Another CD
2 With the same CD key
```

We'll leave this and other improvements to your imagination and creativity, as you can modify the code under the terms of the GPL.

Summary

In this chapter, we've seen that the shell is a powerful programming language in its own right. Its ability to call other programs easily and then process their output makes the shell an ideal tool for tasks involving the processing of text and files.

Next time you need a small utility program, consider whether you can solve your problem by combining some of the many Linux commands with a shell script. You'll be surprised just how many utility programs you can write without a compiler.

3

Working with Files

In this chapter, we'll be looking at Linux files and directories and how to manipulate them. We'll learn how to create files, open them, read, write, and close them. We'll also learn how programs can manipulate directories (to create, scan, and delete them, for example). After the last chapter's diversion into shells, we now start programming in C.

Before proceeding to the way Linux handles file I/O, we'll review the concepts associated with files, directories, and devices. To manipulate files and directories, we need to make system calls (the UNIX and Linux parallel of the Windows API), but there also exists a whole range of library functions, the standard I/O library (`stdio.h`), to make file handling more efficient.

We'll spend the majority of the chapter detailing the various calls to handle files and directories. So this chapter will cover

- Files and devices
- System calls
- Library functions
- Low-level file access
- Managing files
- The standard I/O library
- Formatted input and output
- File and directory maintenance
- Scanning directories
- Errors
- The `/proc` file system
- Advanced topics: `fcntl` and `mmap`

Linux File Structure

“Why,” you may be asking, “are we covering file structure? I know about that already.” Well, as with UNIX, files in the Linux environment are particularly important, as they provide a simple and consistent interface to the operating system services and devices. In Linux, *everything is a file*. Well, almost!

This means that, in general, programs can use disk files, serial ports, printers, and other devices in exactly the same way they would use a file. We’ll cover some exceptions, such as network connections, in Chapter 15, but mainly you need to use only five basic functions: `open`, `close`, `read`, `write`, and `ioctl`.

Directories, too, are special sorts of files. In modern UNIX versions, including Linux, even the superuser may not write to them directly. All users ordinarily use the high-level `opendir`/`readdir` interface to read directories without needing to know the system-specific details of directory implementation. We’ll return to special directory functions later in this chapter.

Really, almost everything is represented as a file under Linux, or can be made available via special files. Even though there are, by necessity, subtle differences from the conventional files we know and love, the general principle still holds. Let’s look at the special cases we’ve mentioned so far.

Directories

As well as its contents, a file has a name and some properties, or “administrative information”; that is, the file’s creation/modification date and its permissions. The properties are stored in the file’s *inode*, a special block of data in the file system that also contains the length of the file and where on the disk it’s stored. The system uses the number of the file’s inode; the directory structure just names the file for our benefit.

A directory is a file that holds the inode numbers and names of other files. Each directory entry is a link to a file’s inode; remove the filename and you remove the link. (You can see the inode number for a file by using `ls -i`.) Using the `ln` command, you can make links to the same file in different directories. If the number of links to a file (the number after the permissions in `ls -l`) reaches zero, the inode and the data it references are no longer in use and are marked as free.

Files are arranged in directories, which may also contain subdirectories. These form the familiar file system hierarchy. A user, say `neil`, usually has his files stored in a “home” directory, perhaps `/home/neil`, with subdirectories for e-mail, business letters, utility programs, and so on. Note that many command shells for UNIX and Linux have an excellent notation for getting straight to your home directory: the tilde `~`. For another user, type `~user`. As you know, home directories for each user are usually subdirectories of a higher-level directory created specifically for this purpose, in this case `/home`.

Note that the standard library functions unfortunately do not understand the tilde notation in file name parameters.

The `/home` directory is itself a subdirectory of the root directory, `/`, which sits at the top of the hierarchy and contains all of the system’s files in subdirectories. The root directory normally includes `/bin` for system programs (‘binaries’), `/etc` for system configuration files, and `/lib` for system libraries. Files that represent physical devices and provide the interface to those devices are conventionally found in a directory called `/dev`. See Figure 3-1 for an example of part of a typical Linux hierarchy. More information on the Linux file system layout is available in the Linux File System Standard, or you can check out `man hier` for a description of the directory hierarchy.

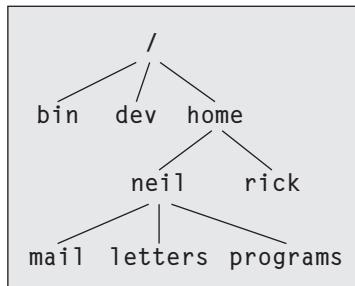


Figure 3-1

Files and Devices

Even hardware devices are very often represented (mapped) by files. For example, as the superuser, you mount a CD-ROM drive as a file:

```
# mount -t iso9660 /dev/hdc /mnt/cdrom
# cd /mnt/cdrom
```

which takes the CD-ROM device (loaded as `/dev/hdc` during boot-up) and mounts its current contents as the file structure beneath `/mnt/cdrom`. You then move around within the CD-ROM's directories just as normal, except, of course, that the contents are read-only.

Three important device files found in both UNIX and Linux are `/dev/console`, `/dev/tty`, and `/dev/null`.

/dev/console

This device represents the system console. Error messages and diagnostics are often sent to this device. Each UNIX system has a designated terminal or screen to receive console messages. At one time, it might have been a dedicated printing terminal. On modern workstations, and on Linux, it's usually the 'active' virtual console, while under X, it will be a special console window on the screen.

/dev/tty

The special file `/dev/tty` is an alias (logical device) for the controlling terminal (keyboard and screen, or window) of a process, if it has one. For instance, processes running from `cron` won't have a controlling terminal, and therefore won't be able to open `/dev/tty`.

Where it can be used, `/dev/tty` allows a program to write directly to the user, without regard to which pseudo-terminal or hardware terminal the user is using. It is useful when the standard output has been redirected. One example is the command `ls -R | more`, where the program `more` has to prompt the user for each new page of output. We'll see more of `/dev/tty` in Chapter 5.

Note that while there's only one `/dev/console` device, there are effectively many different physical devices accessed through `/dev/tty`.

/dev/null

This is the null device. All output written to this device is discarded. An immediate end of file is returned when the device is read, and it can be used as a source of empty files by using the `cp` command. Unwanted output is often redirected to `/dev/null`.

Another way of creating empty files is to use the `touch <filename>` command, which changes the modification time of a file or creates a new file if none exists with the given name. It won't empty it of its contents, though.

```
$ echo do not want to see this >/dev/null  
$ cp /dev/null empty_file
```

Other devices found in `/dev` include hard and floppy disks, communications ports, tape drives, CD-ROMs, sound cards, and some devices representing the system's internal state. There's even a `/dev/zero`, which acts as a source of null bytes to create files of zeros. You need superuser permissions to access some of these devices; normal users can't write programs to directly access low-level devices like hard disks. The names of the device files may vary from system to system. Linux distributions usually have applications that run as superuser to manage the devices that would be otherwise inaccessible, for example, `mount` for user-mountable file systems.

Devices are classified as either *character devices* or *block devices*. The difference refers to the fact that some devices need to be accessed a block at a time. Typically, the only block devices are those that support some type of random access file system, like hard disks.

In this chapter, we concentrate on disk files and directories. We'll cover another device, the user's terminal, in Chapter 5.

System Calls and Device Drivers

We can access and control files and devices using a small number of functions. These functions, known as *system calls*, are provided by UNIX (and Linux) directly, and are the interface to the operating system itself.

At the heart of the operating system, the kernel, are a number of *device drivers*. These are a collection of low-level interfaces for controlling system hardware, which we will cover in detail in Chapter 18. For example, there will be a device driver for a tape drive, which knows how to start the tape, wind it forward and backward, read and write to it, and so on. It will also know that tapes have to be written to in blocks of a certain size. Because tapes are sequential in nature, the driver can't access tape blocks directly, but must wind the tape to the right place.

Similarly, a low-level hard disk device driver will only write whole numbers of disk sectors at a time, but will be able to access any desired disk block directly, because the disk is a random access device.

To provide a similar interface, device drivers encapsulate all of the hardware-dependent features. Idiosyncratic features of the hardware are usually available through `ioctl`.

Device files in `/dev` are used in the same way; they can be opened, read, written, and closed. For example, the same `open` call used to access a regular file is used to access a user terminal, a printer, or a tape drive.

The low-level functions used to access the device drivers, the system calls, include:

- ❑ `open`: Open a file or device
- ❑ `read`: Read from an open file or device
- ❑ `write`: Write to a file or device
- ❑ `close`: Close the file or device
- ❑ `ioctl`: Pass control information to a device driver

The `ioctl` system call is used to provide some necessary hardware-specific control (as opposed to regular input and output), so its use varies from device to device. For example, a call to `ioctl` can be used to rewind a tape drive or set the flow control characteristics of a serial port. For this reason, `ioctl` isn't necessarily portable from machine to machine. In addition, each driver defines its own set of `ioctl` commands.

These and other system calls are usually documented in section 2 of the manual pages. Prototypes providing the parameter lists and function return types for system calls, and associated `#defines` of constants, are provided in include files. The particular ones required for each system call will be included with the descriptions of individual calls.

Library Functions

The problem with using low-level system calls directly for input and output is that they can be very inefficient. Why? Well:

- ❑ There's a performance penalty in making a system call. System calls are therefore expensive compared to function calls because Linux has to switch from running your program code to executing its own kernel code and back again. It's a good idea to keep the number of system calls used in a program to a minimum and get each call to do as much work as possible, for example, by reading and writing large amounts of data rather than a single character at a time.
- ❑ The hardware has limitations that can impose restrictions on the size of data blocks that can be read or written by the low-level system call at any one time. For example, tape drives often have a block size, say 10k, to which they can write. So, if you attempt to write an amount that is not an exact multiple of 10k, the drive will still advance the tape to the next 10k block, leaving gaps on the tape.

To provide a higher-level interface to devices and disk files, a Linux distribution, like UNIX, provides a number of standard libraries. These are collections of functions that you can include in your own programs to handle these problems. A good example is the standard I/O library that provides buffered output. You can effectively write data blocks of varying sizes, and the library functions arrange for the low-level system calls to be provided with full blocks as the data is made available. This dramatically reduces the system call overhead.

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Library functions are usually documented in section 3 of the manual pages and often have a standard include file associated with them, such as `stdio.h` for the standard I/O library.

To summarize the discussion of the last few sections, Figure 3-2 illustrates the Linux system, showing where the various file functions exist relative to the user, the device drivers, the kernel, and the hardware.

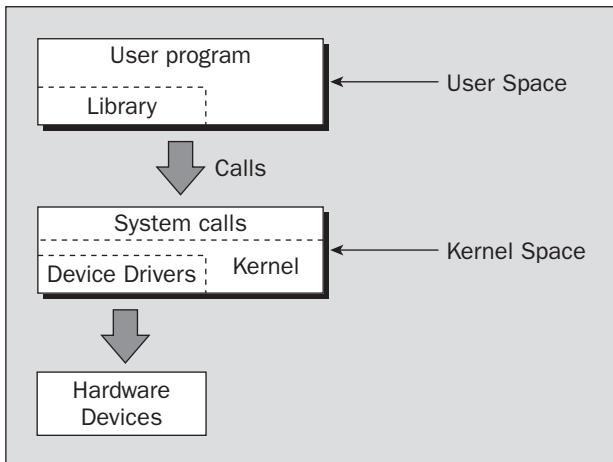


Figure 3-2

Low-Level File Access

Each running program, called a *process*, has a number of file descriptors associated with it. These are small integers that you can use to access open files or devices. How many of these are available will vary depending on how the system has been configured. When a program starts, it usually has three of these descriptors already opened. These are:

- ❑ 0: Standard input
- ❑ 1: Standard output
- ❑ 2: Standard error

You can associate other file descriptors with files and devices by using the `open` system call, which we'll discuss shortly. The file descriptors that are automatically opened, however, already allow us to create some simple programs using `write`.

`write`

The `write` system call arranges for the first `nbytes` bytes from `buf` to be written to the file associated with the file descriptor `fd`. It returns the number of bytes actually written. This may be less than `nbytes` if there has been an error in the file descriptor or if the underlying device driver is sensitive to block size. If the function returns 0, it means no data was written; if it returns -1, there has been an error in the `write` call, and the error will be specified in the `errno` global variable.

Here's the syntax:

```
#include <unistd.h>

size_t write(int fildes, const void *buf, size_t nbytes);
```

With this knowledge, let's write our first program, `simple_write.c`:

```
#include <unistd.h>
#include <stdlib.h>

int main()
{
    if ((write(1, "Here is some data\n", 18)) != 18)
        write(2, "A write error has occurred on file descriptor 1\n", 46);

    exit(0);
}
```

This program simply prints a message to the standard output. When a program exits, all open file descriptors are automatically closed, so we don't need to close them explicitly. This won't be the case, however, when we're dealing with buffered output.

```
$ simple_write
Here is some data
$
```

A point worth noting again is that `write` might report that it wrote fewer bytes than you asked it to. This is not necessarily an error. In your programs, you will need to check `errno` to detect errors and call `write` to write any remaining data.

All the examples in this chapter assume that you have the current directory in your PATH and that, consequently, you're not running them while you're a superuser. If you do not have the current directory in your PATH (an essential superuser precaution), you can run the program specifying the directory explicitly like this:

```
$ ./simple_write
```

read

The `read` system call reads up to `nbytes` bytes of data from the file associated with the file descriptor `fildes` and places them in the data area `buf`. It returns the number of data bytes actually read, which may be less than the number requested. If a `read` call returns 0, it had nothing to read; it reached the end of the file. Again, an error on the call will cause it to return -1.

```
#include <unistd.h>

size_t read(int fildes, void *buf, size_t nbytes);
```

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This program, `simple_read.c`, copies the first 128 bytes of the standard input to the standard output. It copies all of the input if there are fewer than 128 bytes.

```
#include <unistd.h>
#include <stdlib.h>

int main()
{
    char buffer[128];
    int nread;

    nread = read(0, buffer, 128);
    if (nread == -1)
        write(2, "A read error has occurred\n", 26);

    if ((write(1,buffer,nread)) != nread)
        write(2, "A write error has occurred\n", 27);

    exit(0);
}
```

If we run the program, we should see the following:

```
$ echo hello there | simple_read
hello there
$ simple_read < draft1.txt
Files
In this chapter we will be looking at files and directories and how to manipulate
them. We will learn how to create files, o$
```

In the first execution, we create some input for the program using `echo`, which is piped to our program. In the second execution, we redirect input from a file. In this case, we see the first part of the file `draft1.txt` appearing on the standard output.

Note how the next shell prompt appears at the end of the last line of output because, in this example, the 128 bytes don't form a whole number of lines.

open

To create a new file descriptor, we need to use the `open` system call.

```
#include <fcntl.h>
#include <sys/types.h>
#include <sys/stat.h>

int open(const char *path, int oflags);
int open(const char *path, int oflags, mode_t mode);
```

Strictly speaking, we don't need to include `sys/types.h` and `sys/stat.h` to use `open` on POSIX systems, but they may be necessary on some UNIX systems.

In simple terms, `open` establishes an access path to a file or device. If successful, it returns a file descriptor that can be used in `read`, `write`, and other system calls. The file descriptor is unique and isn't shared by any other processes that may be running. If two programs have a file open at the same time, they maintain distinct file descriptors. If they both write to the file, they will continue to write where they left off. Their data isn't interleaved, but one will overwrite the other. Each keeps its own idea of how far into the file (the offset) it has read or written. We can prevent unwanted clashes of this sort by using file locking, which we'll look at in Chapter 7.

The name of the file or device to be opened is passed as a parameter, `path`; the `oflags` parameter is used to specify actions to be taken on opening the file.

The `oflags` are specified as a combination of a mandatory file access mode and other optional modes. The `open` call must specify one of the following file access modes:

| Mode | Description |
|-----------------------|------------------------------|
| <code>O_RDONLY</code> | Open for read-only |
| <code>O_WRONLY</code> | Open for write-only |
| <code>O_RDWR</code> | Open for reading and writing |

The call may also include a combination (using a bitwise OR) of the following optional modes in the `oflags` parameter:

- `O_APPEND`: Place written data at the end of the file.
- `O_TRUNC`: Set the length of the file to zero, discarding existing contents.
- `O_CREAT`: Creates the file, if necessary, with permissions given in `mode`.
- `O_EXCL`: Used with `O_CREAT`, ensures that the caller creates the file. The `open` is atomic; that is, it's performed with just one function call. This protects against two programs creating the file at the same time. If the file already exists, `open` will fail.

Other possible values for `oflags` are documented in the `open` manual page, which can be found in section 2 of the manual pages (use `man 2 open`).

`open` returns the new file descriptor (always a nonnegative integer) if successful, or -1 if it fails, at which time `open` also sets the global variable `errno` to indicate the reason for the failure. We'll look at `errno` more closely in a later section. The new file descriptor is always the lowest-numbered unused descriptor, a feature that can be quite useful in some circumstances. For example, if a program closes its standard output and then calls `open` again, the file descriptor 1 will be reused and the standard output will have been effectively redirected to a different file or device.

There is also a `creat` call standardized by POSIX, but it is not often used. `creat` doesn't only create the file, as one might expect, but also opens it—it's equivalent to calling `open` with `oflags` equal to `O_CREAT | O_WRONLY | O_TRUNC`.

Initial Permissions

When we create a file using the `O_CREAT` flag with `open`, we must use the three-parameter form. `mode`, the third parameter, is made from a bitwise OR of the flags defined in the header file `sys/stat.h`. These are:

- `S_IRUSR`: Read permission, owner
- `S_IWUSR`: Write permission, owner
- `S_IXUSR`: Execute permission, owner
- `S_IRGRP`: Read permission, group
- `S_IWGRP`: Write permission, group
- `S_IXGRP`: Execute permission, group
- `S_IROTH`: Read permission, others
- `S_IWOTH`: Write permission, others
- `S_IXOTH`: Execute permission, others

For example,

```
open ("myfile", O_CREAT, S_IRUSR|S_IXOTH);
```

has the effect of creating a file called `myfile`, with read permission for the owner and execute permission for others, and only those permissions.

```
$ ls -ls myfile
0 -r--x 1 neil      software          0 Sep 22 08:11 myfile*
```

There are a couple of factors that may affect the file permissions. Firstly, the permissions specified are used only if the file is being created. Secondly, the user mask (specified by the shell's `umask` command) affects the created file's permissions. The mode value given in the `open` call is ANDed, with the inverse of the user mask value at run time. For example, if the user mask is set to `001` and the `S_IXOTH` mode flag is specified, the file won't be created with "other" execute permission because the user mask specifies that "other" execute permission isn't to be provided. The flags in the `open` and `creat` calls are, in fact, requests to set permissions. Whether or not the requested permissions are set depends on the run-time value of `umask`.

umask

The `umask` is a system variable that encodes a mask for file permissions to be used when a file is created. You can change the variable by executing the `umask` command to supply a new value. The value is a three-digit octal value. Each digit is the result of ANDing values from 1, 2, or 4; the meanings are shown in the following table. The separate digits refer to "user," "group," and "other" permissions, respectively.

| Digit | Value | Meaning |
|-------|-------|--|
| 1 | 0 | No user permissions are to be disallowed. |
| | 4 | User read permission is disallowed. |
| | 2 | User write permission is disallowed. |
| | 1 | User execute permission is disallowed. |
| 2 | 0 | No group permissions are to be disallowed. |
| | 4 | Group read permission is disallowed. |
| | 2 | Group write permission is disallowed. |
| | 1 | Group execute permission is disallowed. |
| 3 | 0 | No other permissions are to be disallowed. |
| | 4 | Other read permission is disallowed. |
| | 2 | Other write permission is disallowed. |
| | 1 | Other execute permission is disallowed. |

For example, to block “group” write and execute, and “other” write, the umask would be

| Digit | Value |
|-------|-------|
| 1 | 0 |
| 2 | 2 |
| | 1 |
| 3 | 2 |

Values for each digit are ANDed together; so digit 2 will have 2 & 1, giving 3. The resulting umask is 032.

When we create a file via an open or creat call, the mode parameter is compared with the umask. Any bit setting in the mode parameter that is also set in the umask is removed. The end result is that users can set up their environment to say “Don’t create any files with (say) write permission for others, even if the program creating the file requests that permission.” This doesn’t prevent a program or user from subsequently using the chmod command (or chmod system call in a program) to add other write permissions, but it does help protect users by saving them from having to check and set permissions on all new files.

close

We use close to terminate the association between a file descriptor, fildes, and its file. The file descriptor becomes available for reuse. It returns 0 if successful and -1 on error.

```
#include <unistd.h>
int close(int fildes);
```

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Note that it can be important to check the return result from `close`. Some file systems, particularly networked ones, may not report an error writing to a file until the file is closed, as data may not have been confirmed as written when writes are performed.

The number of files that any one running program may have open at once is limited. The limit, defined by the constant `OPEN_MAX` in `limits.h`, varies from system to system, but POSIX requires that it be at least 16. This limit may itself be subject to local system-wide limits.

ioctl

`ioctl` is a bit of a ragbag of things. It provides an interface for controlling the behavior of devices and their descriptors and configuring underlying services. Terminals, file descriptors, sockets, and even tape drives may have `ioctl` calls defined for them and you need to refer to the specific device's `man` page for details. POSIX defines only `ioctl` for streams, which are beyond the scope of this book. Here's the syntax:

```
#include <unistd.h>

int ioctl(int fildes, int cmd, ...);
```

`ioctl` performs the function indicated by `cmd` on the object referenced by the descriptor `fildes`. It may take an optional third argument, depending on the functions supported by a particular device.

Try It Out—A File Copy Program

We now know enough about the `open`, `read`, and `write` system calls to write a low-level program, `copy_system.c`, to copy one file to another, character by character.

We'll do this in a number of ways during this chapter to compare the efficiency of each method. For brevity, we'll assume that the input file exists and the output file does not, and that all reads and writes succeed. Of course, in real-life programs, we would check that these assumptions are valid!

```
#include <unistd.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <stdlib.h>

int main()
{
    char c;
    int in, out;

    in = open("file.in", O_RDONLY);
    out = open("file.out", O_WRONLY|O_CREAT, S_IRUSR|S_IWUSR);
    while(read(in,&c,1) == 1)
        write(out,&c,1);

    exit(0);
}
```

Note that the `#include <unistd.h>` line must come first, as it defines flags regarding POSIX compliance that may affect other include files.

First, we will need to make a test input file, say 1 Mb in size, and name it `file.in`.

Running the program will give something like the following:

```
$ TIMEFORMAT="" time copy_system
4.67user 146.90system 2:32.57elapsed 99%CPU
...
$ ls -ls file.in file.out
1029 -rw-r--r- 1 neil      users     1048576 Sep 17 10:46 file.in
1029 -rw---- 1 neil      users     1048576 Sep 17 10:51 file.out
```

Here we use the `time` facility to measure how long the program takes to run. The `TIMEFORMAT` variable is used on Linux to override the default POSIX output format of `time`, which does not include the CPU usage. We can see that for this fairly old system, the 1-Mb input file, `file.in`, was successfully copied to `file.out`, which was created with read/write permissions for owner only. However, the copy took two-and-a-half minutes and consumed virtually all the CPU time. It was this slow because it had to make over 2 million system calls.

In recent years, Linux has seen great strides in its system call and file system performance. By comparison, a similar test using a 2.4 kernel completed in a little under 5 seconds.

```
$ TIMEFORMAT="" time copy_system
1.07user 3.50system 0:04.77elapsed 95%CPU
...
```

We can improve matters by copying in larger blocks. Take a look at this modified program, `copy_block.c`, which copies the files in 1k blocks, again using system calls:

```
#include <unistd.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <stdlib.h>

int main()
{
    char block[1024];
    int in, out;
    int nread;

    in = open("file.in", O_RDONLY);
    out = open("file.out", O_WRONLY|O_CREAT, S_IRUSR|S_IWUSR);
    while((nread = read(in,block,sizeof(block))) > 0)
        write(out,block,nread);

    exit(0);
}
```

Now try the program, first removing the old output file:

```
$ rm file.out
$ TIMEFORMAT="" time copy_block
0.00user 0.01system 0:00.01elapsed 62%CPU
...
```

Now the program takes a hundredth of a second, as it requires only around 2,000 system calls. Of course, these times are very system-dependent, but they do show that system calls have a measurable overhead, so it's worth optimizing their use.

Other System Calls for Managing Files

There are a number of other system calls that operate on these low-level file descriptors. These allow a program to control how a file is used and to return status information.

lseek

The `lseek` system call sets the read/write pointer of a file descriptor, `fd`; that is, we can use it to set where in the file the next read or write will occur. We can set the pointer to an absolute location in the file or to a position relative to the current position or the end of file.

```
#include <unistd.h>
#include <sys/types.h>

off_t lseek(int fd, off_t offset, int whence);
```

The `offset` parameter is used to specify the position, and the `whence` parameter specifies how the offset is used. `whence` can be one of the following:

- `SEEK_SET`: `offset` is an absolute position
- `SEEK_CUR`: `offset` is relative to the current position
- `SEEK_END`: `offset` is relative to the end of the file

`lseek` returns the `offset` measured in bytes from the beginning of the file that the file pointer is set to, or -1 on failure. The type `off_t`, used for the `offset` in seek operations, is an implementation-dependent type defined in `sys/types.h`.

fstat, stat, and lstat

The `fstat` system call returns status information about the file associated with an open file descriptor. The information is written to a structure, `buf`, the address of which is passed as a parameter.

Here's the syntax:

```
#include <unistd.h>
#include <sys/stat.h>
#include <sys/types.h>
```

```
int fstat(int fildes, struct stat *buf);
int stat(const char *path, struct stat *buf);
int lstat(const char *path, struct stat *buf);
```

Note that the inclusion of sys/types.h is optional, but we recommend it when using system calls, as some of their definitions use aliases for standard types that may change one day.

The related functions `stat` and `lstat` return status information for a named file. They produce the same results, except when the file is a symbolic link. `lstat` returns information about the link itself, while `stat` returns information about the file to which the link refers.

The members of the structure, `stat`, may vary between UNIX-like systems, but will include those in the following table:

| stat Member | Description |
|-----------------------|--|
| <code>st_mode</code> | File permissions and file-type information |
| <code>st_ino</code> | The inode associated with the file |
| <code>st_dev</code> | The device the file resides on |
| <code>st_uid</code> | The user identity of the file owner |
| <code>st_gid</code> | The group identity of the file owner |
| <code>st_atime</code> | The time of last access |
| <code>st_ctime</code> | The time of last change to permissions, owner, group, or content |
| <code>st_mtime</code> | The time of last modification to contents |
| <code>st_nlink</code> | The number of hard links to the file |

The `st_mode` flags returned in the `stat` structure also have a number of associated macros defined in the header file `sys/stat.h`. These macros include names for permission and file-type flags and some masks to help with testing for specific types and permissions.

The permissions flags are the same as for the preceding open system call. File-type flags include

- `S_IFBLK`: Entry is a block special device
- `S_IFDIR`: Entry is a directory
- `S_IFCHR`: Entry is a character special device
- `S_IFIFO`: Entry is a FIFO (named pipe)
- `S_IFREG`: Entry is a regular file
- `S_IFLNK`: Entry is a symbolic link

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Other mode flags include

- ❑ `S_ISUID`: Entry has `setUID` on execution
- ❑ `S_ISGID`: Entry has `setGID` on execution

Masks to interpret the `st_mode` flags include

- ❑ `S_IFMT`: File type
- ❑ `S_IRWXU`: User read/write/execute permissions
- ❑ `S_IRWXG`: Group read/write/execute permissions
- ❑ `S_IRWXO`: Others' read/write/execute permissions

There are some macros defined to help with determining file types. These just compare suitably masked mode flags with a suitable device-type flag. These include

- ❑ `S_ISBLK`: Test for block special file
- ❑ `S_ISCHR`: Test for character special file
- ❑ `S_ISDIR`: Test for directory
- ❑ `S_ISFIFO`: Test for FIFO
- ❑ `S_ISREG`: Test for regular file
- ❑ `S_ISLNK`: Test for symbolic link

For example, to test that a file doesn't represent a directory and has execute permission set for the owner but no other permissions, we can use the following test:

```
struct stat statbuf;
mode_t modes;

stat("filename", &statbuf);
modes = statbuf.st_mode;

if(!S_ISDIR(modes) && (modes & S_IXUSR) == S_IXUSR)
    ...
```

dup and dup2

The `dup` system calls provide a way of duplicating a file descriptor, giving us two or more different descriptors that access the same file. These might be used for reading and writing to different locations in the file. The `dup` system call duplicates a file descriptor, `fd`, returning a new descriptor. The `dup2` system call effectively copies one file descriptor to another by specifying the descriptor to use for the copy.

Here's the syntax:

```
#include <unistd.h>

int dup(int fildes);
int dup2(int fildes, int fildes2);
```

These calls can also be useful when you're using multiple processes communicating via pipes. We discuss the `dup` system in more depth in Chapter 13.

The Standard I/O Library

The standard I/O library and its header file, `stdio.h`, provide a versatile interface to low-level I/O system calls. The library, now part of ANSI standard C, whereas the system calls we met earlier are not, provides many sophisticated functions for formatting output and scanning input. It also takes care of the buffering requirements for devices.

In many ways, you use this library in the same way that you use low-level file descriptors. You need to open a file to establish an access path. This returns a value that is used as a parameter to other I/O library functions. The equivalent of the low-level file descriptor is called a *stream* and is implemented as a pointer to a structure, a `FILE *`.

Don't confuse these file streams with either C++ iostreams or with the STREAMS paradigm of inter-process communication introduced in AT&T UNIX System V Release 3, which is beyond the scope of this book. For more information on STREAMS, check out the X/Open spec (at <http://www.open-group.org>) and the AT&T STREAMS Programming Guide that accompanies System V.

Three file streams are automatically opened when a program is started. They are `stdin`, `stdout`, and `stderr`. These are declared in `stdio.h` and represent the standard input, output, and error output, respectively, which correspond to the low-level file descriptors 0, 1, and 2.

In this next section, we'll look at

- ❑ `fopen`, `fclose`
- ❑ `fread`, `fwrite`
- ❑ `fflush`
- ❑ `fseek`
- ❑ `fgetc`, `getc`, `getchar`
- ❑ `fputc`, `putc`, `putchar`
- ❑ `fgets`, `gets`
- ❑ `printf`, `fprintf`, and `sprintf`
- ❑ `scanf`, `fscanf`, and `sscanf`

fopen

The `fopen` library function is the analog of the low-level `open` system call. You use it mainly for files and terminal input and output. Where you need explicit control over devices, you're better off with the low-level system calls, as they eliminate potentially undesirable side effects from libraries, like input/output buffering.

Here's the syntax:

```
#include <stdio.h>

FILE *fopen(const char *filename, const char *mode);
```

`fopen` opens the file named by the `filename` parameter and associates a stream with it. The `mode` parameter specifies how the file is to be opened. It's one of the following strings:

- ❑ "r" or "rb": Open for reading only
- ❑ "w" or "wb": Open for writing, truncate to zero length
- ❑ "a" or "ab": Open for writing, append to end of file
- ❑ "r+" or "rb+" or "r+b": Open for update (reading and writing)
- ❑ "w+" or "wb+" or "w+b": Open for update, truncate to zero length
- ❑ "a+" or "ab+" or "a+b": Open for update, append to end of file

The `b` indicates that the file is a binary file rather than a text file.

Note that, unlike MS-DOS, UNIX and Linux do not make a distinction between text and binary files. Unix and Linux treat all files exactly the same, effectively as binary files. It's also important to note that the mode parameter must be a string, and not a character. Always use "r," and never `r.'

If successful, `fopen` returns a non-null `FILE *` pointer. If it fails, it returns the value `NULL`, defined in `stdio.h`.

fread

The `fread` library function is used to read data from a file stream. Data is read into a data buffer given by `ptr` from the stream, `stream`. Both `fread` and `fwrite` deal with data records. These are specified by a record size, `size`, and a count, `nitems`, of records to transfer. It returns the number of items (rather than the number of bytes) successfully read into the data buffer. At the end of a file, fewer than `nitems` may be returned, including zero.

Here's the syntax:

```
#include <stdio.h>

size_t fread(void *ptr, size_t size, size_t nitems, FILE *stream);
```

As with all of the standard I/O functions that write to a buffer, it's the programmer's responsibility to allocate the space for the data and check for errors. See `ferror` and `feof` later in this chapter.

fwrite

The `fwrite` library call has a similar interface to `fread`. It takes data records from the specified data buffer and writes them to the output stream. It returns the number of records successfully written.

Here's the syntax:

```
#include <stdio.h>

size_t fwrite (const void *ptr, size_t size, size_t nitems, FILE *stream);
```

Note that `fread` and `fwrite` are not recommended for use with structured data. Part of the problem is that files written with `fwrite` are potentially nonportable between different machines.

fclose

The `fclose` library function closes the specified `stream`, causing any unwritten data to be written. It's important to use `fclose` because the `stdio` library will buffer data. If the program needs to be sure that data has been completely written, it should call `fclose`. Note, however, that `fclose` is called automatically on all file streams that are still open when a program ends normally, but then, of course, you do not get a chance to check for errors reported by `fclose`. The number of available streams is limited, in the same way that file descriptors are limited. The actual limit is `FOPEN_MAX`, which is defined in `stdio.h`, and is always at least eight.

Here's the syntax:

```
#include <stdio.h>

int fclose(FILE *stream);
```

fflush

The `fflush` library function causes all outstanding data on a file stream to be written immediately. You can use this to ensure that, for example, an interactive prompt has been sent to a terminal before any attempt to read a response. It's also useful for ensuring that important data has been committed to disk

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before continuing. You can sometimes use it when you're debugging a program to make sure that the program is writing data and not hanging. Note that an implied flush operation is carried out when `fclose` is called, so you don't need to call `fflush` before `fclose`.

Here's the syntax:

```
#include <stdio.h>

int fflush(FILE *stream);
```

fseek

The `fseek` function is the file stream equivalent of the `lseek` system call. It sets the position in the stream for the next read or write on that stream. The meaning and values of the `offset` and `whence` parameters are the same as those we gave previously for `lseek`. However, where `lseek` returns an `off_t`, `fseek` returns an integer: 0 if it succeeds, -1 if it fails, with `errno` set to indicate the error. So much for standardization!

Here's the syntax:

```
#include <stdio.h>

int fseek(FILE *stream, long int offset, int whence);
```

fgetc, getc, and getchar

The `fgetc` function returns the next byte, as a character, from a file stream. When it reaches the end of the file or there is an error, it returns `EOF`. You must use `ferror` or `feof` to distinguish the two cases.

Here's the syntax:

```
#include <stdio.h>

int fgetc(FILE *stream);
int getc(FILE *stream);
int getchar();
```

The `getc` function is equivalent to `fgetc`, except that it may be implemented as a macro, in which case the `stream` argument must not have side effects (i.e., it can't affect variables that are neither local nor passed to the functions as parameters). Also, you can't then use the address of `getc` as a function pointer.

The `getchar` function is equivalent to `getc(stdin)` and reads the next character from the standard input.

fputc, putc, and putchar

The `fputc` function writes a character to an output file stream. It returns the value it has written, or `EOF` on failure.

```
#include <stdio.h>

int fputc(int c, FILE *stream);
int putc(int c, FILE *stream);
int putchar(int c);
```

As with `fgetc/getc`, the function `putc` is equivalent to `fputc`, but it may be implemented as a macro. The GNU C compiler does this, and you can see the definitions in the `stdio.h` header file.

The `putchar` function is equivalent to `putc(c, stdout)`, writing a single character to the standard output. Note that `putchar` takes and `getchar` returns characters as `ints`, not `char`. This allows the end of file (`EOF`) indicator to take the value `-1` outside the range of character numbers codes.

fgets and gets

The `fgets` function reads a string from an input file stream. It writes characters to the string pointed to by `s` until a newline is encountered, `n-1` characters have been transferred, or the end of file is reached, whichever occurs first. Any newline encountered is transferred to the receiving string and a terminating null byte, `\0`, is added. Only a maximum of `n-1` characters are transferred in any one call because the null byte must be added to finish the string and make up the `n` bytes.

```
#include <stdio.h>

char *fgets(char *s, int n, FILE *stream);
char *gets(char *s);
```

When it successfully completes, `fgets` returns a pointer to the string `s`. If the stream is at the end of a file, it sets the `EOF` indicator for the stream and `fgets` returns a null pointer. If a read error occurs, `fgets` returns a null pointer and sets `errno` to indicate the type of error.

The `gets` function is similar to `fgets`, except that it reads from the standard input and discards any newline encountered. It adds a trailing null byte to the receiving string.

Note that `gets` doesn't limit the number of characters that can be transferred so it could overrun its transfer buffer. Consequently, you should avoid using it and use `fgets` instead. Many security issues on the Internet can be traced back to functions in programs that are made to overflow a buffer of some sort or another. This is one such function, so be careful!

Formatted Input and Output

There are a number of library functions for producing output in a controlled fashion that you may be familiar with if you've programmed in C. These functions include `printf` and friends for printing values to a file stream and `scanf` and others for reading values from a file stream.

printf, fprintf, and sprintf

The `printf` family of functions format and output a variable number of arguments of different types. The way each is represented in the output stream is controlled by the `format` parameter, which is a string that contains ordinary characters to be printed and codes, called *conversion specifiers*, that indicate how and where the remaining arguments are to be printed.

```
#include <stdio.h>

int printf(const char *format, ...);
int sprintf(char *s, const char *format, ...);
int fprintf(FILE *stream, const char *format, ...);
```

The `printf` function produces its output on the standard output. The `fprintf` function produces its output on a specified stream. The `sprintf` function writes its output and a terminating null character into the string `s` passed as a parameter. This string must be large enough to contain all of the output. There are other members of the `printf` family that deal with their arguments in different ways. See the `printf` manual page for more details.

Ordinary characters are passed unchanged into the output. Conversion specifiers cause `printf` to fetch and format additional arguments passed as parameters. They always start with a `%` character. Here's a simple example,

```
printf("Some numbers: %d, %d, and %d\n", 1, 2, 3);
```

which produces, on the standard output:

```
Some numbers: 1, 2, and 3
```

To print a `%` character, we need to use `%%`, so that it doesn't get confused with a conversion specifier.

Here are some of the most commonly used conversion specifiers:

- ❑ `%d, %i`: Print an integer in decimal
- ❑ `%o, %x`: Print an integer in octal, hexadecimal
- ❑ `%c`: Print a character
- ❑ `%s`: Print a string
- ❑ `%f`: Print a floating point (single precision) number
- ❑ `%e`: Print a double precision number, in fixed format
- ❑ `%g`: Print a double in a general format

It's very important that the number and type of the arguments passed to `printf` match the conversion specifiers in the `format` string. An optional size specifier is used to indicate the type of integer arguments. This is either `h`, for example `%hd`, to indicate a `short int`, or `l`, for example `%ld`, to indicate a `long int`. Some compilers can check these `printf` statements, but they aren't infallible. If you are using the GNU compiler `gcc`, then `-Wformat` does this.

Here's another example:

```
char initial = 'A';
char *surname = "Matthew";
double age = 14.5;

printf("Hello Miss %c %s, aged %g\n", initial, surname, age);
```

This produces

```
Hello Miss A Matthew, aged 14.5
```

You can gain greater control over the way items are printed by using field specifiers. These extend the conversion specifiers to include control over the spacing of the output. A common use is to set the number of decimal places for a floating point number or to set the amount of space around a string.

Field specifiers are given as numbers immediately after the % character in a conversion specifier. The following table contains some more examples of conversion specifiers and resulting output. To make things a little clearer, we'll use vertical bars to show the limits of the output.

| Format | Argument | | Output | |
|--------|-------------|------------|---------|--|
| %10s | "Hello" | | Hello | |
| %-10s | "Hello" | Hello | | |
| %10d | 1234 | | 1234 | |
| %-10d | 1234 | 1234 | | |
| %010d | 1234 | 0000001234 | | |
| %10.4f | 12.34 | | 12.3400 | |
| %">*s | 10, "Hello" | | Hello | |

All of these examples have been printed in a field width of 10 characters. Note that a negative field width means that the item is written left-justified within the field. A variable field width is indicated by using an asterisk (*). In this case, the next argument is used for the width. A leading zero indicates the item is written with leading zeros. According to the POSIX specification, `printf` doesn't truncate fields; rather it expands the field to fit. So, for example, if we try to print a string longer than the field, the field grows:

| Format | Argument | | Output | |
|--------|-------------------|-----------------|--------|--|
| %10s | "HelloTherePeeps" | HelloTherePeeps | | |

The `printf` functions return an integer, the number of characters written. This doesn't include the terminating null in the case of `sprintf`. On error, these functions return a negative value and set `errno`.

scanf, fscanf, and sscanf

The `scanf` family of functions works in a way similar to the `printf` group, except that these functions read items from a stream and place values into variables at the addresses they're passed as pointer parameters. They use a format string to control the input conversion in the same way, and many of the conversion specifiers are the same.

```
#include <stdio.h>

int scanf(const char *format, ...);
int fscanf(FILE *stream, const char *format, ...);
int sscanf(const char *s, const char *format, ...);
```

It's very important that the variables used to hold the values scanned in by the `scanf` functions are of the correct type and that they match the format string precisely. If they don't, your memory could be corrupted and your program could crash. There won't be any compiler errors, but if you're lucky, you might get a warning!

The format string for `scanf` and friends contains both ordinary characters and conversion specifiers, as for `printf`. However, the ordinary characters are used to specify characters that must be present in the input.

Here is a simple example:

```
int num;
scanf("Hello %d", &num);
```

This call to `scanf` will succeed only if the next five characters on the standard input match "Hello". Then, if the next characters form a recognizable decimal number, the number will be read and the value assigned to the variable `num`. A space in the format string is used to ignore all whitespace (spaces, tabs, form feeds, and newlines) in the input between conversion specifiers. This means that the call to `scanf` will succeed and place 1234 into the variable `num` given either of the following inputs:

```
Hello      1234
Hello1234
```

Whitespace is also usually ignored in the input when a conversion begins. This means that a format string of `%d` will keep reading the input, skipping over spaces and newlines until a sequence of digits is found. If the expected characters are not present, the conversion fails and `scanf` returns.

This can lead to problems if you are not careful; an infinite loop can occur in your program if you leave a nondigit character in the input while scanning for integers.

Other conversion specifiers are

- ❑ `%d`: Scan a decimal integer
- ❑ `%o, %x`: Scan an octal, hexadecimal integer

- %f, %e, %g: Scan a floating point number
- %c: Scan a character (whitespace not skipped)
- %s: Scan a string
- %[]: Scan a set of characters (see below)
- %%: Scan a % character

Like `printf`, `scanf` conversion specifiers may also have a field width to limit the amount of input consumed. A size specifier (either h for short or l for long) indicates whether the receiving argument is shorter or longer than the default. This means that `%hd` indicates a `short int`, `%ld` a `long int`, and `%lg` a double precision floating point number.

A specifier beginning with an asterisk indicates that the item is to be ignored. This means that the information is not stored and therefore does not need a variable to receive it.

We use the `%c` specifier to read a single character in the input. This doesn't skip initial whitespace characters.

We use the `%s` specifier to scan strings, but we must take care. It skips leading whitespace, but stops at the first whitespace character in the string; so, we're better using it for reading words rather than general strings. Also, without a field-width specifier, there's no limit to the length of string it might read, so the receiving string must be sufficient to hold the longest string in the input stream. It's better to use a field specifier, or a combination of `fgets` and `sscanf`, to read in a line of input and scan it. This will prevent possible buffer overflows that could be exploited by a malicious user.

We use the `%[]` specifier to read a string composed of characters from a set. The format `%[A-Z]` will read a string of capital letters. If the first character in the set is a caret, `^`, the specifier reads a string that consists of characters not in the set. So, to read a string with spaces in it, but stopping at the first comma, we can use `%[^,]`.

Given the input line,

```
Hello, 1234, 5.678, X, string to the end of the line
```

this call to `scanf` will correctly scan four items:

```
char s[256];
int n;
float f;
char c;

scanf("Hello,%d,%g, %c, %[^\n]", &n,&f,&c,s);
```

The `scanf` functions return the number of items successfully read, which will be zero if the first item fails. If the end of the input is reached before the first item is matched, `EOF` is returned. If a read error occurs on the file stream, the stream error flag will be set and the error variable, `errno`, will be set to indicate the type of error. See the "Stream Errors" section later in this chapter for more details.

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In general, `scanf` and friends are not highly regarded; this is for three reasons:

- ❑ Traditionally, the implementations have been buggy.
- ❑ They're inflexible to use.
- ❑ They lead to code where it's very difficult to work out what is being parsed.

Try to use other functions, like `fread` or `fgets`, to read input lines and the string functions to break the input into the items you need.

Other Stream Functions

There are a number of other `stdio` library functions that uses either stream parameters or the standard streams `stdin`, `stdout`, `stderr`:

- ❑ `fgetpos`: Get the current position in a file stream.
- ❑ `fsetpos`: Set the current position in a file stream.
- ❑ `ftell`: Return the current file offset in a stream.
- ❑ `rewind`: Reset the file position in a stream.
- ❑ `freopen`: Reuse a file stream.
- ❑ `setvbuf`: Set the buffering scheme for a stream.
- ❑ `remove`: Equivalent to `unlink` unless the `path` parameter is a directory, in which case it's equivalent to `rmdir`.

These are all library functions documented in section 3 of the manual pages.

You can use the file stream functions to reimplement the file copy program, using library functions instead. Take a look at `copy_stdio.c`.

Try It Out—Another File Copy Program

This program is very similar to earlier versions, but the character-by-character copy is accomplished using calls to the functions referenced in `stdio.h`:

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

int main()
{
    int c;
    FILE *in, *out;

    in = fopen("file.in", "r");
    out = fopen("file.out", "w");
```

```

        while((c = fgetc(in)) != EOF)
            fputc(c,out);

        exit(0);
    }
}

```

Running this program as before, we get

```

$ TIMEFORMAT="" time copy_stdio
0.29user 0.02system 0:00.35elapsed 87%CPU
...

```

This time, the program runs in 0.35 seconds, not as fast as the low-level block version, but a great deal better than the other single-character-at-a-time version. This is because the `stdio` library maintains an internal buffer within the `FILE` structure and the low-level system calls are made only when the buffer fills. Feel free to experiment with testing line-by-line and block `stdio` copying code to see how they perform relative to the three examples we've tested here.

Stream Errors

To indicate an error, many `stdio` library functions return out-of-range values, such as null pointers or the constant `EOF`. In these cases, the error is indicated in the external variable `errno`:

```

#include <errno.h>

extern int errno;

```

Note that many functions may change the value of `errno`. Its value is valid only when a function has failed. You should inspect it immediately after a function has indicated failure. You should always copy it into another variable before using it, because printing functions, such as `fprintf`, might alter `errno` themselves.

You can also interrogate the state of a file stream to determine whether an error has occurred, or the end of file has been reached.

```

#include <stdio.h>

int perror(FILE *stream);
int feof(FILE *stream);
void clearerr(FILE *stream);

```

The `perror` function tests the error indicator for a stream and returns nonzero if it's set, but zero otherwise.

The `feof` function tests the end-of-file indicator within a stream and returns nonzero if it is set, zero otherwise. Use it like this:

```

if(feof(some_stream))
    /* We're at the end */

```

The `clearerr` function clears the end-of-file and error indicators for the stream to which `stream` points. It has no return value and no errors are defined. You can use it to recover from error conditions on streams. One example might be to resume writing to a stream after a “disk full” error has been resolved.

Streams and File Descriptors

Each file stream is associated with a low-level file descriptor. You can mix low-level input and output operations with higher-level stream operations, but this is generally unwise, as the effects of buffering can be difficult to predict.

```
#include <stdio.h>

int fileno(FILE *stream);
FILE *fdopen(int fildes, const char *mode);
```

We can determine which low-level file descriptor is being used for a file stream by calling the `fileno` function. It returns the file descriptor for a given stream, or -1 on failure. This function can be useful if you need low-level access to an open stream, for example, to call `fstat` on it.

We can create a new file stream based on an already-opened file descriptor by calling the `fdopen` function. Essentially, this function provides `stdio` buffers around an already-open file descriptor, which might be an easier way to explain it.

The `fdopen` function operates in the same way as the `fopen` function, but instead of a filename it takes a low-level file descriptor. This can be useful if we have used `open` to create a file, perhaps to get fine control over the permissions, but want to use a stream for writing to it. The `mode` parameter is the same as for the `fopen` function and must be compatible with the file access modes established when the file was originally opened. `fdopen` returns the new file stream or `NULL` on failure.

File and Directory Maintenance

The standard libraries and system calls provide complete control over the creation and maintenance of files and directories.

chmod

You can change the permissions on a file or directory using the `chmod` system call. This forms the basis of the `chmod` shell program.

Here's the syntax:

```
#include <sys/stat.h>

int chmod(const char *path, mode_t mode);
```

The file specified by `path` is changed to have the permissions given by `mode`. The modes are specified as in the `open` system call, a bitwise OR of required permissions. Unless the program has been given appropriate privileges, only the owner of the file or a superuser can change its permissions.

chown

A superuser can change the owner of a file using the chown system call.

```
#include <unistd.h>

int chown(const char *path, uid_t owner, gid_t group);
```

The call uses the numeric values of the user and group IDs (culled from getuid and getgid calls) and a constant that can restrict who can change file ownership. The owner and group of a file are changed if the appropriate privileges are set.

POSIX actually allows systems where non-superusers can change file ownerships. All “proper” POSIX systems won’t allow this, but, strictly speaking, it’s an extension (for FIPS 151-2). The kinds of systems we’ll be dealing with in this book conform to the XSI (X/Open System Interface) specification and do enforce ownership rules.

unlink, link, and symlink

We can remove a file using unlink.

The unlink system call removes the directory entry for a file and decrements the link count for it. It returns 0 if the unlinking was successful, -1 on an error. You must have write and execute permissions in the directory where the file has its directory entry for this call to function.

```
#include <unistd.h>

int unlink(const char *path);
int link(const char *path1, const char *path2);
int symlink(const char *path1, const char *path2);
```

If the count reaches zero and no process has the file open, the file is deleted. In actual fact, the directory entry is always removed, but the file’s space will not be recovered until the last process (if any) closes it. The rm program uses this call. Additional links represent alternative names for a file, normally created by the ln program. We can create new links to a file programmatically by using the link system call.

Creating a file with open and then calling unlink on it is a trick some programmers use to create transient files. These files are available to the program only while they are open; they will effectively be automatically deleted when the program exits and the file is closed.

The link system call creates a new link to an existing file, path1. The new directory entry is specified by path2. We can create symbolic links using the symlink system call in a similar fashion. Note that symbolic links to a file do not prevent the file from being effectively deleted as normal (hard) links do.

mkdir and rmdir

We can create and remove directories using the mkdir and rmdir system calls.

```
#include <sys/stat.h>

int mkdir(const char *path, mode_t mode);
```

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The `mkdir` system call is used for creating directories and is the equivalent of the `mkdir` program. `mkdir` makes a new directory with path as its name. The directory permissions are passed in the parameter `mode` and are given as in the `O_CREAT` option of the `open` system call and, again, subject to `umask`.

```
#include <unistd.h>

int rmdir(const char *path);
```

The `rmdir` system call removes directories, but only if they are empty. The `rmdir` program uses this system call to do its job.

chdir and getcwd

A program can navigate directories in much the same way as a user moves around the file system. As we use the `cd` command in the shell to change directory, so a program can use the `chdir` system call.

```
#include <unistd.h>

int chdir(const char *path);
```

A program can determine its current working directory by calling the `getcwd` function.

```
#include <unistd.h>

char *getcwd(char *buf, size_t size);
```

The `getcwd` function writes the name of the current directory into the given buffer, `buf`. It returns `null` if the directory name would exceed the size of the buffer (an `ERANGE` error), given as the parameter `size`. It returns `buf` on success.

getcwd may also return `NULL` if the directory is removed (`EINVAL`) or permissions changed (`EACCESS`) while the program is running.

Scanning Directories

A common problem on Linux systems is scanning directories, that is, determining the files that reside in a particular directory. In shell programs, it's easy—just let the shell expand a wildcard expression. In the past, different UNIX variants have allowed programmatic access to the low-level file system structure. We can still open a directory as a regular file and directly read the directory entries, but different file system structures and implementations have made this approach nonportable. A standard suite of library functions has now been developed that makes directory scanning much simpler.

The directory functions are declared in a header file `dirent.h`. They use a structure, `DIR`, as a basis for directory manipulation. A pointer to this structure, called a *directory stream* (a `DIR *`), acts in much the same way as a file stream (`FILE *`) does for regular file manipulation. Directory entries themselves are

returned in dirent structures, also declared in dirent.h, as one should never alter the fields in the DIR structure directly.

We'll review these functions:

- ❑ opendir, closedir
- ❑ readdir
- ❑ telldir
- ❑ seekdir

opendir

The opendir function opens a directory and establishes a directory stream. If successful, it returns a pointer to a DIR structure to be used for reading directory entries.

```
#include <sys/types.h>
#include <dirent.h>

DIR *opendir(const char *name);
```

opendir returns a null pointer on failure. Note that a directory stream uses a low-level file descriptor to access the directory itself, so opendir could fail with too many open files.

readdir

The readdir function returns a pointer to a structure detailing the next directory entry in the directory stream dirp. Successive calls to readdir return further directory entries. On error, and at the end of the directory, readdir returns NULL. POSIX-compliant systems leave errno unchanged when returning NULL at end of directory and set it when an error occurs.

```
#include <sys/types.h>
#include <dirent.h>

struct dirent *readdir(DIR *dirp);
```

Note that readdir scanning isn't guaranteed to list all the files (and subdirectories) in a directory if there are other processes creating and deleting files in the directory at the same time.

The dirent structure containing directory entry details includes the following entries:

- ❑ ino_t d_ino: The inode of the file
- ❑ char d_name []: The name of the file

To determine further details of a file in a directory, we need to make a call to stat, which we covered earlier in this chapter.

telldir

The `telldir` function returns a value that records the current position in a directory stream. You can use this in subsequent calls to `seekdir` to reset a directory scan to the current position.

```
#include <sys/types.h>
#include <dirent.h>

long int telldir(DIR *dirp);
```

seekdir

The `seekdir` function sets the directory entry pointer in the directory stream given by `dirp`. The value of `loc`, used to set the position, should have been obtained from a prior call to `telldir`.

```
#include <sys/types.h>
#include <dirent.h>

void seekdir(DIR *dirp, long int loc);
```

closedir

The `closedir` function closes a directory stream and frees up the resources associated with it. It returns 0 on success and 1 if there is an error.

```
#include <sys/types.h>
#include <dirent.h>

int closedir(DIR *dirp);
```

In the next program, `printdir.c`, we put together a lot of the file manipulation functions to create a simple directory listing. Each file in a directory is listed on a line by itself. Each subdirectory has its name followed by a slash and the files listed in it are indented by four spaces.

The program changes directory into the subdirectories so that the files it finds have usable names, that is, they can be passed directly to `opendir`. The program will fail on very deeply nested directory structures because there's a limit on the allowed number of open directory streams.

We could, of course, make it more general by taking a command line argument to specify the start point. Check out the Linux source code of such utilities as `ls` and `find` for ideas on a more general implementation.

Try It Out—A Directory-Scanning Program

1. We start with the appropriate headers and then a function, `printdir`, which prints out the current directory. It will recurse for subdirectories using the `depth` parameter for indentation.

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

```
#include <string.h>
#include <sys/stat.h>
#include <stdlib.h>

void printdir(char *dir, int depth)
{
    DIR *dp;
    struct dirent *entry;
    struct stat statbuf;

    if((dp = opendir(dir)) == NULL) {
        fprintf(stderr,"cannot open directory: %s\n", dir);
        return;
    }
    chdir(dir);
    while((entry = readdir(dp)) != NULL) {
        lstat(entry->d_name,&statbuf);
        if(S_ISDIR(statbuf.st_mode)) {
            /* Found a directory, but ignore . and .. */
            if(strcmp(".",entry->d_name) == 0 ||
               strcmp("..",entry->d_name) == 0)
                continue;
            printf("%*s%s\n",depth,"",entry->d_name);
            /* Recurse at a new indent level */
            printdir(entry->d_name,depth+4);
        }
        else printf("%*s%s\n",depth,"",entry->d_name);
    }
    chdir("..");
    closedir(dp);
}
```

2. Now we move onto the main function:

```
int main()
{
    printf("Directory scan of /home:\n");
    printdir("/home",0);
    printf("done.\n");

    exit(0);
}
```

The program produces output like this (edited for brevity):

```
$ printdir
Directory scan of /home:
neil/
.Xdefaults
.Xmodmap
.Xrresources
.bash_history
.bashrc
.kde/
```

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```
share/
  apps/
    konqueror/
      dirtree/
        public_html.desktop
      toolbar/
      bookmarks.xml
      kong_history
    kdisplay/
      color-schemes/
BLP3/
  Gnu_Public_License
chapter04/
  argopt.c
  args.c
chapter03/
  file.out
  mmap.c
  printdir
done.
```

How It Works

Most of the action is within the `printdir` function, so that's where we'll look. After some initial error checking using `opendir` to see that the directory exists, `printdir` makes a call to `chdir` to the directory specified. While the entries returned by `readdir` aren't null, the program checks to see whether the entry is a directory. If it isn't, it prints the file entry with indentation depth.

If the entry *is* a directory, we meet a little bit of recursion. After the `.` and `..` entries (the current and parent directories) have been ignored, the `printdir` function calls itself and goes through the same process again. How does it get out of these loops? Once the `while` loop has finished, the call `chdir("..")` takes it back up the directory tree and the previous listing can continue. Calling `closedir(dp)` makes sure that the number of open directory streams isn't higher than it needs to be.

For a brief taste of the discussion of the Linux environment in Chapter 4, let's look at one way we can make the program more general. The program is limited because it's specific to the directory `/home/neil`. With the following changes to `main`, we could turn it into a more useful directory browser:

```
int main(int argc, char* argv[])
{
    char *topdir = ".";
    if (argc >= 2)
        topdir=argv[1];

    printf("Directory scan of %s\n",topdir);
    printdir(topdir,0);
    printf("done.\n");

    exit(0);
}
```

We've changed three lines and added five, but now it's a general-purpose utility with an optional parameter of the directory name, which defaults to the current directory. You can run it using the following command:

```
$ printdir2 /usr/local | more
```

The output will be paged so that the user can page through the output. Hence, the user has quite a convenient little general-purpose directory tree browser. With very little effort, you could add space usage statistics, limit depth of display, and so on.

Errors

As we've seen, many of the system calls and functions described in this chapter can fail for a number of reasons. When they do, they indicate the reason for their failure by setting the value of the external variable `errno`. Many different libraries use this variable as a standard way to report problems. It bears repeating that the program must inspect the `errno` variable immediately after the function giving problems because it may be overwritten by the next function called, even if that function itself doesn't fail.

The values and meanings of the errors are listed in the header file `errno.h`. They include

- ❑ EPERM: Operation not permitted
- ❑ ENOENT: No such file or directory
- ❑ EINTR: Interrupted system call
- ❑ EIO: I/O Error
- ❑ EBUSY: Device or resource busy
- ❑ EEXIST: File exists
- ❑ EINVAL: Invalid argument
- ❑ EMFILE: Too many open files
- ❑ ENODEV: No such device
- ❑ EISDIR: Is a directory
- ❑ ENOTDIR: Isn't a directory

There are a couple of useful functions for reporting errors when they occur: `strerror` and `perror`.

strerror

The `strerror` function maps an error number into a string describing the type of error that has occurred. This can be useful for logging error conditions.

Here's the syntax:

```
#include <string.h>

char *strerror(int errnum);
```

perror

The `perror` function also maps the current error, as reported in `errno`, into a string and prints it on the standard error stream. It's preceded by the message given in the string `s` (if not `null`), followed by a colon and a space.

Here's the syntax:

```
#include <stdio.h>

void perror(const char *s);
```

For example,

```
perror("program");
```

might give the following on the standard error output:

```
program: Too many open files
```

The /proc File System

Earlier in the chapter we mentioned that Linux treats most things as files and that there are entries in the file system for hardware devices. These `/dev` files are used to access hardware in a specific way using low-level system calls.

The software drivers that control hardware can often be configured in certain ways, or are capable of reporting information. For example, a hard disk controller may be configured to use a particular DMA mode. A network card might be able to report whether it has negotiated a high-speed, duplex connection.

Utilities for communicating with device drivers have been common in the past. For example, `hdparm` is used to configure some disk parameters and `ifconfig` can report network statistics. In recent years, there has been a trend toward providing a more consistent way of accessing driver information, and, in fact, to extend this to include communication with various elements of the Linux kernel.

Linux provides a special file system, `procfs`, that is usually made available as the directory `/proc`. It contains many special files that allow higher-level access to driver and kernel information. Applications can read and write these files to get information and set parameters as long as they are running with the correct access permissions.

The files that appear in `/proc` will vary from system to system, and more are included with each Linux release as more drivers and facilities support the `procfs` file system. Here, we will look at some of the more common files and briefly consider their use.

A directory listing of `/proc` on the computer being used to write this chapter shows the following entries:

```
1/      1377/  1771/  951/      cpuinfo      modules
10/     1401/  1777/  961/      devices      mounts@
```

```
1007/ 1414/ 1778/ 966/      dma          mtrr
1023/ 1457/ 2/   968/      driver/       net/
1053/ 1460/ 3/   969/      execdomains partitions
1056/ 1463/ 385/ 970/      fb            pci
1059/ 1465/ 388/ 971/      filesystems  scsi/
1061/ 1476/ 4/   974/      fs/           self@
1071/ 1477/ 424/ 975/      ide/          slabinfo
1077/ 1479/ 4775/ 976/     interrupts   splash
1079/ 1480/ 4850/ 977/     iomem         stat
1080/ 1482/ 496/  978/     ioports       swaps
1082/ 1484/ 5/   979/     irq/          sys/
1086/ 1486/ 535/  980/     isapnp        sysv ipc/
1090/ 1491/ 6/   982/     kcore         tty/
1093/ 1494/ 625/  983/     kmsg          uptime
1095/ 1495/ 7/   999/     ksyms        version
1096/ 1496/ 75/   apm      loadavg     video/
1100/ 1502/ 8/   asound/    locks
1101/ 1503/ 884/  buddyinfo lvm/
1104/ 1545/ 905/  bus/      mdstat
1118/ 1546/ 917/  cmdline   meminfo
1119/ 1770/ 932/  config.gz misc
```

In many cases, the files can just be read and will give status information. For example, `/proc/cpuinfo` gives details of the processors available:

```
$ cat /proc/cpuinfo
processor      : 0
vendor_id     : GenuineIntel
cpu family    : 6
model         : 6
model name    : Celeron (Mendocino)
stepping       : 0
cpu MHz       : 451.028
cache size    : 128 KB
fdiv_bug      : no
hlt_bug       : no
f00f_bug      : no
coma_bug      : no
fpu           : yes
fpu_exception : yes
cpuid level   : 2
wp            : yes
flags          : fpu vme de pse tsc msr pae mce cx8 sep mtrr pge mca cmov pat
pse36 mmx fxsr
bogomips      : 897.84
```

Similarly, `/proc/meminfo` and `/proc/version` give information about memory usage and kernel version, respectively.

```
$ cat /proc/meminfo
total:      used:      free:      shared: buffers:  cached:
Mem: 527392768 240873472 286519296          0 8331264 134004736
Swap: 139788288          0 139788288
MemTotal:      515032 kB
```

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```
MemFree:          279804 kB
MemShared:        0 kB
Buffers:          8136 kB
Cached:           130864 kB
SwapCached:       0 kB
Active:           101208 kB
Inactive:         106056 kB
HighTotal:        0 kB
HighFree:         0 kB
LowTotal:         515032 kB
LowFree:          279804 kB
SwapTotal:        136512 kB
SwapFree:         136512 kB
BigFree:          0 kB
$ cat /proc/version
Linux version 2.4.19-4GB (root@Pentium.suse.de) (gcc version 3.2) #1 Wed Nov 27
00:56:40 UTC 2002
```

The information given by these files is generated each time the file is read. So rereading the `meminfo` file at a later time will give up-to-the-second results.

More information from specific kernel functions can be found in subdirectories of `/proc`. For example, you can get network socket usage statistics from `/proc/net/sockstat`:

```
$ cat /proc/net/sockstat
sockets: used 246
TCP: inuse 20 orphan 0 tw 0 alloc 22 mem 11
UDP: inuse 3
RAW: inuse 0
FRAG: inuse 0 memory 0
```

Some of the `/proc` entries can be written to as well as read. For example, the total number of files that all running programs can open at the same time is a Linux kernel parameter. The current value can be read at `/proc/sys/fs/file-max`:

```
$ cat /proc/sys/fs/file-max
52428
```

Here the value is set to 52,428. If we need to increase this value, we can do so by writing to the same file. We may need to do this if we are running a specialist application suite—such as database systems that use many tables—that needs to open many files at once.

Writing `/proc` files requires superuser access. Care needs to be taken when writing `/proc` files; it's possible to cause severe problems by writing inappropriate values.

To increase the system-wide file handle limit to 60,000, we can simply write the new limit to the `file-max` file:

```
# echo 60000 >/proc/sys/fs/file-max
```

Now, when we reread the file, we see the new value:

```
$ cat /proc/sys/fs/file-max  
60000
```

The subdirectories of `/proc` that have numeric names are used to provide access to information about running programs. We will learn more about how programs are executed as processes in Chapter 11.

For now, just notice that each process has a unique identifier: a number between 1 and about 32,000. The `ps` command provides a list of currently running processes. For example, as this chapter is being written:

```
neil@beast:~/BLP3/chapter03> ps  
  PID TTY      TIME CMD  
1104 pts/1    00:00:00 bash  
1503 pts/2    00:00:01 bash  
1771 pts/4    00:00:00 bash  
4991 pts/2    00:00:01 emacs  
4994 pts/2    00:00:00 ps  
neil@beast:~/BLP3/chapter03>
```

Here, we can see several terminal sessions running the bash shell and an edit session running the Emacs text editor. We can get more details about the Emacs session by looking in `/proc`.

The process identifier for Emacs here is given as 4991, so we need to look in `/proc/4991` for details about it:

```
$ ls -l /proc/4991  
total 0  
-r--r--r--  1 neil    users  0 2003-02-09 12:45 cmdline  
lrwxrwxrwx  1 neil    users  0 2003-02-09 12:45 cwd -> /home/neil/BLP3/chapter03  
-r-----r--  1 neil    users  0 2003-02-09 12:45 environ  
lrwxrwxrwx  1 neil    users  0 2003-02-09 12:45 exe -> /usr/bin/emacs  
dr-x-----  2 neil    users  0 2003-02-09 12:45 fd  
-rw-----r-- 1 neil    users  0 2003-02-09 12:45 mapped_base  
-r--r--r--r-- 1 neil    users  0 2003-02-09 12:45 maps  
-rw-----r-- 1 neil    users  0 2003-02-09 12:45 mem  
-r--r--r--r-- 1 neil    users  0 2003-02-09 12:45 mounts  
lrwxrwxrwx  1 neil    users  0 2003-02-09 12:45 root -> /  
-r--r--r--r-- 1 neil    users  0 2003-02-09 12:45 stat  
-r--r--r--r-- 1 neil    users  0 2003-02-09 12:45 statm  
-r--r--r--r-- 1 neil    users  0 2003-02-09 12:45 status
```

Here, we can see various special files that can tell us what is happening with this process.

We can tell that the program `/usr/bin/emacs` is running and that its current working directory is `/home/neil/BLP3/chapter03`. It is possible to read the other files in this directory to see the command line used to start it as well as the shell environment it has. The `cmdline` and `environ` files provide this information as a series of null-terminated strings, so we need to take care when viewing them. We will discuss the Linux environment in depth in Chapter 4.

```
$ od -c /proc/4991/cmdline  
0000000  e  m  a  c  s  \0  d  r  a  f  t  2  .  t  x  t  
0000020  \0  
0000021
```

Here, we can see that Emacs was started with the command line `emacs draft2.txt`.

The `fd` subdirectory provides information about the open file descriptors in use by the process. This information can be useful in determining how many files a program has open at one time. There is one entry per open descriptor; the name matches the number of the descriptor. In this case, we can see that Emacs has open descriptors 0, 1, and 2, as we might expect. These are the standard input, output, and error descriptors. Although it is editing a file at the moment, it is not kept open by this process, and therefore, does not show here.

```
$ ls /proc/4991/fd
0 1 2
```

Advanced Topics: `fcntl` and `mmap`

Here, we'll cover a couple of topics that you might like to skip because they're seldom used. Having said that, we've put them here for your reference because they can provide simple solutions to some tricky problems.

`fcntl`

The `fcntl` system call provides further ways to manipulate low-level file descriptors.

```
#include <fcntl.h>

int fcntl(int fildes, int cmd);
int fcntl(int fildes, int cmd, long arg);
```

You can perform several miscellaneous operations on open file descriptors with the `fcntl` system call, including duplicating them, getting and setting file descriptor flags, getting and setting file status flags, and managing advisory file locking.

The various operations are selected by different values of the command parameter `cmd`, as defined in `fcntl.h`. Depending on the command chosen, the system call will require a third parameter, `arg`:

- `fcntl(fildes, F_DUPFD, newfd)`: This call returns a new file descriptor with a numerical value equal to or greater than the integer `newfd`. The new descriptor is a copy of the descriptor `fildes`. Depending on the number of open files and the value of `newfd`, this can be effectively the same as `dup(fildes)`.
- `fcntl(fildes, F_GETFD)`: This call returns the file descriptor flags as defined in `fcntl.h`. These include `FD_CLOEXEC`, which determines whether the file descriptor is closed after a successful call to one of the `exec` family of system calls.
- `fcntl(fildes, F_SETFD, flags)`: This call is used to set the file descriptor flags, usually just `FD_CLOEXEC`.

- ❑ `fcntl(fildes, F_GETFL)` and `fcntl(fildes, F_SETFL, flags)`: These calls are used, respectively, to get and set the file status flags and access modes. You can extract the file access modes by using the mask `O_ACCMODE` defined in `fcntl.h`. Other flags include those passed in a third argument to open when used with `O_CREAT`. Note that you can't set all flags. In particular, you can't set file permissions using `fcntl`.

You can also implement advisory file locking via `fcntl`. Refer to section 2 of the manual pages for more information, or see Chapter 7, where we discuss file locking.

mmap

UNIX provides a useful facility that allows programs to share memory, and the good news is that it's been included in versions 2.0 and later of the Linux kernel. The `mmap` (for memory map) function sets up a segment of memory that can be read or written by two or more programs. Changes made by one program are seen by the others.

You can use the same facility to manipulate files. You can make the entire contents of a disk file look like an array in memory. If the file consists of records that can be described by C structures, you can update the file using structure array accesses.

This is made possible by the use of virtual memory segments that have special permissions set. Reading from and writing to the segment causes the operating system to read and write the appropriate part of the disk file.

The `mmap` function creates a pointer to a region of memory associated with the contents of the file accessed through an open file descriptor.

```
#include <sys/mman.h>

void *mmap(void *addr, size_t len, int prot, int flags, int fildes, off_t off);
```

You can alter the start of the file data that is accessed by the shared segment by passing the `off` parameter. The open file descriptor is passed as `fildes`. The amount of data that can be accessed (i.e., the length of the memory segment) is set via the `len` parameter.

You can use the `addr` parameter to request a particular memory address. If it's zero, the resulting pointer is allocated automatically. This is the recommended usage, as it is difficult to be portable otherwise; systems vary as to the available address ranges.

The `prot` parameter is used to set access permissions for the memory segment. This is a bitwise OR of the following constant values:

- ❑ `PROT_READ`: The segment can be read
- ❑ `PROT_WRITE`: The segment can be written
- ❑ `PROT_EXEC`: The segment can be executed
- ❑ `PROT_NONE`: The segment can't be accessed

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The `flags` parameter controls how changes made to the segment by the program are reflected elsewhere.

| | |
|-------------|---|
| MAP_PRIVATE | The segment is private, changes are local |
| MAP_SHARED | The segment changes are made in the file |
| MAP_FIXED | The segment must be at the given address, <code>addr</code> |

The `msync` function causes the changes in part or all of the memory segment to be written back to (or read from) the mapped file.

```
#include <sys/mman.h>

int msync(void *addr, size_t len, int flags);
```

The part of the segment to be updated is given by the passed start address, `addr`, and length, `len`. The `flags` parameter controls how the update should be performed.

| | |
|---------------|---------------------------------|
| MS_ASYNC | Perform asynchronous writes |
| MS_SYNC | Perform synchronous writes |
| MS_INVALIDATE | Read data back in from the file |

The `munmap` function releases the memory segment.

```
#include <sys/mman.h>

int munmap(void *addr, size_t len);
```

The following program, `mmap_eg.c`, shows a file of structures being updated using `mmap` and array-style accesses. Linux kernels before 2.0 don't fully support this use of `mmap`. The program does work correctly on Sun Solaris and other systems.

Try It Out—Using `mmap`

1. We start by defining a RECORD structure and then create NRECORDS versions, each recording their number. These are appended to the file `records.dat`.

```
#include <unistd.h>
#include <stdio.h>
#include <sys/mman.h>
#include <fcntl.h>
#include <stdlib.h>

typedef struct {
    int integer;
    char string[24];
} RECORD;
```

```
#define NRECORDS (100)

int main()
{
    RECORD record, *mapped;
    int i, f;
    FILE *fp;

    fp = fopen("records.dat","w+");
    for(i=0; i<NRECORDS; i++) {
        record.integer = i;
        sprintf(record.string,"RECORD-%d",i);
        fwrite(&record,sizeof(record),1,fp);
    }
    fclose(fp);
}
```

- 2.** We now change the integer value of record 43 to 143 and write this to the 43rd record's string:

```
fp = fopen("records.dat","r+");
fseek(fp,43*sizeof(record),SEEK_SET);
fread(&record,sizeof(record),1,fp);

record.integer = 143;
sprintf(record.string,"RECORD-%d",record.integer);

fseek(fp,43*sizeof(record),SEEK_SET);
fwrite(&record,sizeof(record),1,fp);
fclose(fp);
```

- 3.** We now map the records into memory and access the 43rd record in order to change the integer to 243 (and update the record string), again using memory mapping:

```
f = open("records.dat",O_RDWR);
mapped = (RECORD *)mmap(0, NRECORDS*sizeof(record),
                        PROT_READ|PROT_WRITE, MAP_SHARED, f, 0);

mapped[43].integer = 243;
sprintf(mapped[43].string,"RECORD-%d",mapped[43].integer);

msync((void *)mapped, NRECORDS*sizeof(record), MS_ASYNC);
munmap((void *)mapped, NRECORDS*sizeof(record));
close(f);

exit(0);
}
```

In Chapter 13, we'll meet another shared memory facility: System V shared memory.

Summary

In this chapter, we've seen how Linux provides direct access to files and devices. We've seen how library functions build upon these low-level functions to provide flexible solutions to programming problems. As a result, we've been able to write a fairly powerful directory-scanning routine in just a few lines of code.

We've also learned enough about file and directory handling to convert the fledgling CD application that we created at the end of Chapter 2 to a C program using a more structured file-based solution. At this stage, however, we can add no new functionality to the program, so we'll postpone our rewrite until we've learned how to handle the screen and keyboard, which are the subjects of the next two chapters.

4

The Linux Environment

When we write a program for Linux (or UNIX and UNIX-like systems), we have to take into account that the program will run in a *multitasking environment*. This means that there will be multiple programs running at the same time and sharing machine resources such as memory, disk space, and CPU cycles. There may even be several instances of the same program running at the same time. It's important that these programs don't interfere with one another, are aware of their surroundings, and can act appropriately to avoid conflicts such as trying to write the same file at the same time as another program.

In this chapter, we will consider the environment in which programs operate, how they can use that environment to gain information about operating conditions, and how users of the programs can alter their behavior. In particular, we'll be looking at

- Passing arguments to programs
- Environment variables
- Finding out what the time is
- Temporary files
- Getting information about the user and the host computer
- Causing and configuring log messages
- Discovering the limits imposed by the system

Program Arguments

When a Linux or UNIX program written in C runs, it starts at the function `main`. For these programs, `main` is declared as

```
int main(int argc, char *argv[])
```

where `argc` is a count of the program arguments and `argv` is an array of character strings representing the arguments themselves.

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You might also see C programs for Linux simply declaring `main` as

```
main()
```

This will still work, as the return type will default to `int` and formal parameters that are not used in a function need not be declared. `argc` and `argv` are still there, but if you don't declare them, you can't use them.

Whenever the operating system starts a new program, the parameters `argc` and `argv` are set up and passed to `main`. These parameters are usually supplied by another program, very often the shell that has requested that the operating system start the new program. The shell takes the command line that it's given, breaks it up into individual words, and uses these for the `argv` array. Remember that a Linux shell normally performs wild card expansion of filename arguments before `argc` and `argv` are set, whereas the MS-DOS shell expects programs to accept arguments with wild cards and perform their own wild card expansion.

For example, if we give the shell the following command,

```
$ myprog left right 'and center'
```

the program `myprog` will start at `main` with parameters:

```
argc: 4
argv: {"myprog", "left", "right", "and center"}
```

Note that the argument count includes the name of the program itself and the `argv` array contains the program name as its first element, `argv[0]`. Because we used quotes in the shell command, the fourth argument consists of a string containing spaces.

You'll be familiar with all of this if you've programmed in ISO/ANSI C. The arguments to `main` correspond to the positional parameters in shell scripts, `$0`, `$1`, and so on. While ISO/ANSI C states that `main` must return `int`, the X/Open specification contains the explicit declaration given above.

Command line arguments are useful for passing information to programs. For example, we could use them in a database application to pass the name of the database we wish to use, which would allow us to use the same program on more than one database. Many utility programs also use command line arguments to change their behavior or to set options. You would usually set these so-called *flags*, or *switches*, using command line arguments that begin with a dash. For example, the `sort` program takes a switch to reverse the normal sort order:

```
$ sort -r file
```

Command line options are very common and using them consistently will be a real help to those who use your program. In the past, each utility program adopted its own approach to command line options, which led to some confusion. For example, take a look at the way these commands take parameters:

```
$ tar cvfB /tmp/file.tar 1024
$ dd if=/dev/fd0 of=/tmp/file.dd bs=18k
$ ls -lstr
$ ls -l -s -t -r
```

All command line switches should start with a dash and consist of a single letter or number. Options that take no further argument can be grouped together behind one dash. So, the two `ls` examples shown here do follow the guidelines. Each option should be followed by any value it requires as a separate argument. The `dd` example breaks this rule by using multi-character options that do not start with dashes (`if=/dev/fd0`); and the `tar` example separates options and their values completely!

Another little foible of some programs is to make the option `+x` (for example) perform the opposite function to `-x`.

As you can probably tell, remembering the order and meaning of all these program options is difficult enough without having to cope with idiosyncratic formats. Often, the only recourse is to use an `-h` (help) option or a `man` page if the programmer has provided one. As we'll show you a bit later in this chapter, `getopt` provides a neat solution to these problems. For the moment, though, let's just look at dealing with program arguments as they are passed.

Try It Out—Program Arguments

Here's a program, `args.c`, that examines its own arguments:

```
#include <stdio.h>

int main(int argc, char *argv[])
{
    int arg;

    for(arg = 0; arg < argc; arg++) {
        if(argv[arg][0] == '-')
            printf("option: %s\n", argv[arg]+1);
        else
            printf("argument %d: %s\n", arg, argv[arg]);
    }
    exit(0);
}
```

When we run this program, it just prints out its arguments and detects options. The intention is that the program takes a string argument and an optional filename argument introduced by a `-f` option. Other options might also be defined

```
$ ./args -i -lr 'hi there' -f fred.c
argument 0: args
option: i
option: lr
argument 3: hi there
option: f
argument 5: fred.c
```

How It Works

The program simply uses the argument count, `argc`, to set up a loop to examine all of the program arguments. It detects options by looking for an initial dash.

In this example, if we intended the options `-l` and `-r` to be available, we've missed the fact that the `-lr` perhaps ought to be treated the same as `-l -r`.

The X/Open specification defines a standard usage for command line options (the Utility Syntax Guidelines) as well as a standard programming interface for providing command line switches in C programs: the getopt function.

getopt

To help us adhere to these guidelines, Linux gives us the getopt facility, which supports the use of options with and without values and is simple to use.

```
#include <unistd.h>

int getopt(int argc, char *const argv[], const char *optstring);
extern char *optarg;
extern int optind, optarg, opterr;
```

The getopt function takes the `argc` and `argv` parameters as passed to the program's `main` function and an options specifier string that tells getopt what options are defined for the program and whether they have associated values. The `optstring` is simply a list of characters, each representing a single character option. If a character is followed by a colon, it indicates that the option has an associated value that will be taken as the next argument. The `getopts` command in bash performs a very similar function.

For example, the following call would be used to handle our preceding example

```
getopt(argc, argv, "if:lr");
```

It allows for simple options `-i`, `-l`, `-r`, and `-f`, followed by a filename argument. Calling the command with the same parameters but in a different order will alter the behavior. Try it out when we get to the sample code in the next "Try It Out" section in this chapter.

The return result for getopt is the next option character found in the `argv` array (if there is one). We call getopt repeatedly to get each option in turn. It has the following behavior:

- ❑ If the option takes a value, that value is pointed to by the external variable `optarg`.
- ❑ getopt returns `-1` when there are no more options to process. A special argument, `--`, will cause getopt to stop scanning for options.
- ❑ It returns `?` if there is an unrecognized option, which it stores in the external variable `optopt`.
- ❑ If an option requires a value (such as `-f` in our example) and no value is given, getopt returns.

The external variable, `optind`, is set to the index of the next argument to process. getopt uses it to remember how far it's got. Programs would rarely need to set this variable. When all the option arguments have been processed, `optind` indicates where the remaining arguments can be found at the end of the `argv` array.

Some versions of getopt will stop at the first non-option argument, returning `-1` and setting `optind`. Others, such as those provided with Linux, can process options wherever they occur in the program arguments. Note that, in this case, getopt effectively rewrites the `argv` array so that all of the non-option

arguments are presented together, starting at `argv[optind]`. For the GNU version of `getopt`, this behavior is controlled by the `POSIXLY_CORRECT` environment variable. If set, `getopt` will stop at the first non-option argument. Additionally, some `getopt` implementations print error messages for unknown options. Note that the POSIX specification says that, if the `opterr` variable is non-zero, `getopt` will print an error message to `stderr`.

Try It Out—`getopt`

Let's use `getopt` for our example and call the new program `argopt.c`:

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

int main(int argc, char *argv[])
{
    int opt;

    while((opt = getopt(argc, argv, "if:lr")) != -1) {
        switch(opt) {
        case 'i':
        case 'l':
        case 'r':
            printf("option: %c\n", opt);
            break;
        case 'f':
            printf("filename: %s\n", optarg);
            break;
        case ':':
            printf("option needs a value\n");
            break;
        case '?':
            printf("unknown option: %c\n", optopt);
            break;
        }
    }
    for(; optind < argc; optind++)
        printf("argument: %s\n", argv[optind]);
    exit(0);
}
```

Now, when we run the program, we see that all the command line arguments are handled automatically:

```
$ ./argopt -i -lr 'hi there' -f fred.c -q
option: i
option: l
option: r
filename: fred.c
argopt: invalid option--q
unknown option: q
argument: hi there
```

How It Works

The program repeatedly calls `getopt` to process option arguments until none remain, at which point `getopt` returns `-1`. The appropriate action is taken for each option, including dealing with unknown options and missing values. Depending on your version of `getopt`, you might see slightly different output from that shown above—especially error messages—but the meaning will be clear.

Once all options have been processed, the program simply prints out the remaining arguments as before, but starting from `optind`.

`getopt_long`

Many Linux applications also accept arguments that are more meaningful than the single character options we used in the last example. The GNU C library contains a version of `getopt` called `getopt_long` that accepts so-called long arguments that are introduced with a double dash.

We can use `getopt_long` to create a new version of our example program that can be invoked using long equivalents of our options like this:

```
$ ./longopt --initialize -list 'hi there' --file fred.c -q
option: i
option: l
filename: fred.c
./longopt: invalid option - q
unknown option: q
argument: hi there
```

In fact, both the new long options and the original single character options can be mixed. As long as they remain distinguishable, long options also may be abbreviated. Long options that take an argument can be given as a single argument in the form `--option=value`, as follows

```
$ ./longopt --init -l --file=fred.c 'hi there'
option: i
option: l
filename: fred.c
argument: hi there
```

The new program, `longopt.c`, is shown below with changes required from `argopt.c` to support the long options highlighted.

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

#define _GNU_SOURCE
#include <getopt.h>

int main(int argc, char *argv[])
{
    int opt;
```

```

        struct option longopts[] = {
            {"initialize", 0, NULL, 'i'},
            {"file", 1, NULL, 'f'},
            {"list", 0, NULL, 'l'},
            {"restart", 0, NULL, 'r'},
            {0,0,0,0}};
    }

    while((opt = getopt_long(argc, argv, "if:lr", longopts, NULL)) != -1) {
        switch(opt) {
        case 'i':
        case 'l':
        case 'r':
            printf("option: %c\n", opt);
            break;
        case 'f':
            printf("filename: %s\n", optarg);
            break;
        case ':':
            printf("option needs a value\n");
            break;
        case '?':
            printf("unknown option: %c\n", optopt);
            break;
        }
    }
    for(; optind < argc; optind++)
        printf("argument: %s\n", argv[optind]);
    exit(0);
}

```

How It Works

The `getopt_long` function takes two additional parameters over `getopt`. The first of these is an array of structures that describes the long options and tells `getopt_long` how to handle them. The second additional parameter is a pointer to a variable that can be used like a long option version of `optind`; for each long option recognized, its index in the long options array can be written into this variable. In our example, we do not need this information, so we use `NULL` as the second additional parameter.

The long options array consists of a number of structures of type `struct option`, each of which describes the desired behavior of a long option. The array must end with a structure containing all zeros.

The long option structure is defined in `getopt.h` and must be included with the constant `_GNU_SOURCE`, defined to enable the `getopt_long` functionality.

```

struct option {
    const char *name;
    int has_arg;
    int *flag;
    int val;
};

```

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The members of the structure are

| | |
|---------|---|
| name | The name of the long option. Abbreviations will be accepted as long as they cannot be confused with other options. |
| has_arg | Whether this option takes an argument. Set to 0 for options that do not take an argument, 1 for options that must have a value, and 2 for those that have an optional argument. |
| flag | Set to NULL to have getopt_long return the value given in val when this option is found. Otherwise, getopt_long returns 0 and writes the value of val into the variable pointed to by flag. |
| val | The value getopt_long is to return for this option. |

For other options associated with the GNU extensions to getopt and related functions, refer to the getopt manual page.

Environment Variables

We discussed environment variables in Chapter 2. These are variables that can be used to control the behavior of shell scripts and other programs. You can also use them to configure the user's environment. For example, each user has an environment variable, `HOME`, that defines his home directory, the default starting place for his or her session. As we've seen, we can examine environment variables from the shell prompt:

```
$ echo $HOME  
/home/neil
```

You can also use the shell's `set` command to list all of the environment variables.

The UNIX specification defines many standard environment variables used for a variety of purposes, including terminal type, default editors, time zones, and so on. A C program may gain access to environment variables using the `putenv` and `getenv` functions.

```
#include <stdlib.h>  
  
char *getenv(const char *name);  
int putenv(const char *string);
```

The environment consists of strings of the form `name=value`. The `getenv` function searches the environment for a string with the given name and returns the value associated with that name. It will return `null` if the requested variable doesn't exist. If the variable exists but has no value, `getenv` succeeds with a string, the first byte of which is `null`. The string returned by `getenv`, and held in static storage provided by `getenv`, mustn't be overwritten by the application, as it will by any subsequent calls to `getenv`.

The `putenv` function takes a string of the form `name=value` and adds it to the current environment. It will fail and return `-1` if it can't extend the environment due to lack of available memory. When this happens, the error variable `errno` will be set to `ENOMEM`.

Let's write a program to print out the value of any environment variable we choose. We'll also arrange to set the value if we give the program a second argument.

Try It Out—`getenv` and `putenv`

1. The first few lines after the declaration of `main` ensure that the program, `environ.c`, has been called correctly:

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

int main(int argc, char *argv[])
{
    char *var, *value;

    if(argc == 1 || argc > 3) {
        fprintf(stderr,"usage: environ var [value]\n");
        exit(1);
    }
}
```

2. That done, we fetch the value of the variable from the environment, using `getenv`:

```
var = argv[1];
value = getenv(var);
if(value)
    printf("Variable %s has value %s\n", var, value);
else
    printf("Variable %s has no value\n", var);
```

3. Next, we check whether the program was called with a second argument. If it was, we set the variable to the value of that argument by constructing a string of the form `name=value` and then calling `putenv`:

```
if(argc == 3) {
    char *string;
    value = argv[2];
    string = malloc(strlen(var)+strlen(value)+2);
    if(!string) {
        fprintf(stderr,"out of memory\n");
        exit(1);
    }
    strcpy(string,var);
    strcat(string,"=");
    strcat(string,value);
    printf("Calling putenv with: %s\n",string);
    if(putenv(string) != 0) {
        fprintf(stderr,"putenv failed\n");
        free(string);
        exit(1);
    }
}
```

4. Finally, we discover the new value of the variable by calling `getenv` once again:

```
value = getenv(var);
if(value)
    printf("New value of %s is %s\n", var, value);
else
    printf("New value of %s is null??\n", var);
}
exit(0);
}
```

When we run this program, we can see and set environment variables:

```
$ ./environ HOME
Variable HOME has value /home/neil
$ ./environ FRED
Variable FRED has no value
$ ./environ FRED hello
Variable FRED has no value
Calling putenv with: FRED=hello
New value of FRED is hello
$ ./environ FRED
Variable FRED has no value
```

Notice that the environment is local only to the program. Changes that we make within the program are not reflected outside it because variable values are not propagated from the child process (our program) to the parent (the shell).

Use of Environment Variables

Programs often use environment variables to alter the way they work. Users can set the values of these environment variables either in their default environment, via a `.profile` file read by their login shell, using a shell-specific startup (`rc`) file, or by specifying variables on the shell command line. For example:

```
$ ./environ FRED
Variable FRED has no value
$ FRED=hello ./environ FRED
Variable FRED has value hello
```

The shell takes initial variable assignments as temporary changes to environment variables. In the second example above, the program `environ` runs in an environment where the variable `FRED` has a value.

For instance, in a future version of our CD database application, we could change an environment variable, say `CDDB`, to indicate the database to use. Each user could then specify his or her own default value or use a shell command to set it on a run-by-run basis:

```
$ CDDB=mycds; export CDDB
$ cdapp
```

or

```
$ CDDB=mycds cdapp
```

Environment variables are a mixed blessing and you should use them with care. They are more ‘hidden’ to the user than command line options and, as such, this can make debugging harder. In a sense, environment variables are like global variables in that they may alter the behavior of a program, giving unexpected results.

The `environ` Variable

As we’ve seen, the program environment is made up of strings of the form `name=value`. This array of strings is made available to programs directly via the `environ` variable, which is declared as

```
#include <stdlib.h>
```

```
extern char **environ;
```

Try It Out—`environ`

Here’s a program, `showenv.c`, that uses the `environ` variable to print out the environment variables:

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

extern char **environ;

int main()
{
    char **env = environ;

    while(*env) {
        printf("%s\n", *env);
        env++;
    }
    exit(0);
}
```

When we run this program on a Linux system, we get something like the following output, which has been abbreviated a little. The number, order of appearance, and values of these variables depend on the operating system version, the command shell being used, and the user settings in force at the time the program is run.

```
$ ./showenv
HOSTNAME=tilde.provider.com
LOGNAME=neil
MAIL=/var/spool/mail/neil
TERM=console
HOSTTYPE=i386
PATH=/usr/local/bin:/bin:/usr/bin:
HOME=/usr/neil
LS_OPTIONS=-8bit-color=tty -F -T 0
```

```
SHELL=/bin/bash
PS1=\h:\w\$
PS2=>
OSTYPE=Linux
```

How It Works

This program iterates through the `environ` variable, a null-terminated array of strings, to print out the whole environment.

Time and Date

Often it can be useful for a program to be able to determine the time and date. It may wish to log the length of time it is run, or it may need to change the way it behaves at certain times. For example, a game might refuse to run during working hours, or a backup scheduling program might want to wait until the early hours before starting an automatic backup.

UNIX systems all use the same starting point for times and dates: midnight GMT on January 1, 1970. This is the “start of the UNIX epoch” and Linux is no exception. All times in a Linux system are measured as seconds since then. This is similar to the way MS-DOS handles times, except that the MS-DOS epoch started in 1980. Other systems use other epoch start times.

Times are handled using a defined type, a `time_t`. This is an integer type intended to be large enough to contain dates and times in seconds. On Linux systems, it's a `long` integer and is defined, together with functions for manipulating time values, in the header file `time.h`.

Never assume that times are 32 bits. On UNIX and Linux systems using a 32-bit `time_t` type, the time will “rollover” in the year 2038. By that time, we hope that systems have moved to using a `time_t`; that is, larger than 32 bits.

```
#include <time.h>

time_t time(time_t *tloc);
```

You can find the low-level time value by calling the `time` function, which returns the number of seconds since the start of the epoch. It will also write the returned value to a location pointed to by `tloc`, if this isn't a null pointer.

Try It Out—`time`

Here's a simple program, `envtime.c`, to demonstrate the `time` function:

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

int main()
{
```

```

int i;
time_t the_time;

for(i = 1; i <= 10; i++) {
    the_time = time((time_t *)0);
    printf("The time is %ld\n", the_time);
    sleep(2);
}
exit(0);
}

```

When we run this program, it prints the low-level time value every two seconds for 20 seconds.

```

$ ./envtime
The time is 1044695820
The time is 1044695822
The time is 1044695824
The time is 1044695826
The time is 1044695828
The time is 1044695830
The time is 1044695832
The time is 1044695834
The time is 1044695836
The time is 1044695838

```

How It Works

The program calls `time` with a null pointer argument, which returns the time and date as a number of seconds. The program sleeps for two seconds and repeats the call to `time` for a total of ten times.

Using the time and date as a number of seconds since the start of 1970 can be useful for measuring how long something takes to happen. We could consider simply subtracting the values we get from two calls to `time`. However, in its deliberations, the ISO/ANSI C standard committee didn't specify that the `time_t` type be used to measure arbitrary time intervals in seconds, so they invented a function, `difftime`, which will calculate the difference in seconds between two `time_t` values and return it as a `double`:

```

#include <time.h>

double difftime(time_t time1, time_t time2);

```

The `difftime` function calculates the difference between two time values and returns the value `time1 - time2` as a floating-point number. For Linux, the return value from `time` is a number of seconds and can be manipulated, but for the ultimate in portability you should use `difftime`.

To present the time and date in a more meaningful way (to humans), we need to convert the time value into a recognizable time and date. There are standard functions to help with this.

The function `gmtime` breaks down a low-level time value into a structure containing more usual fields:

```

#include <time.h>

struct tm *gmtime(const time_t timeval);

```

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The structure `tm` is defined to contain at least the following members:

| tm Member | Description |
|--------------|-------------------------------------|
| int tm_sec | Seconds, 0-61 |
| int tm_min | Minutes, 0-59 |
| int tm_hour | Hours, 0-23 |
| int tm_mday | Day in the month, 1-31 |
| int tm_mon | Month in the year, 0-11(January= 0) |
| int tm_year | Years since 1900 |
| int tm_wday) | Day in the week, 0-6. (Sunday = 0) |
| int tm_yday | Day in the year, 0-365 |
| int tm_isdst | Daylight savings in effect |

The range for `tm_sec` allows for the occasional leap second or double leap second.

Try It Out—`gmtime`

Here's a program, `gmtime.c`, which prints out the current time and date using the `tm` structure and `gmtime`:

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

int main()
{
    struct tm *tm_ptr;
    time_t the_time;

    (void) time(&the_time);
    tm_ptr = gmtime(&the_time);

    printf("Raw time is %ld\n", the_time);
    printf("gmtime gives:\n");
    printf("date: %02d/%02d/%02d\n",
           tm_ptr->tm_year, tm_ptr->tm_mon+1, tm_ptr->tm_mday);
    printf("time: %02d:%02d:%02d\n",
           tm_ptr->tm_hour, tm_ptr->tm_min, tm_ptr->tm_sec);
    exit(0);
}
```

When we run this program, we get a good approximation of the time and date:

```
$ ./gmtime; date
Raw time is 1044696004
gmtime gives:
```

```
date: 103/02/08
time: 09:20:04
Sat Feb  8 09:20:04 GMT 2003
```

How It Works

The program calls `time` to get the low-level time value and then calls `gmtime` to convert this into a structure with useful time and date values. It prints these out using `printf`. Strictly speaking, we shouldn't print the raw time value in this way because it isn't guaranteed to be a `long` type on all systems. We ran the `date` command immediately after `gmtime` to compare its output.

However, we have a little problem here. If you're running this program in a time zone other than Greenwich Mean Time, or if your local daylight savings time is in effect, you'll notice that the time (and possibly date) is incorrect. This is because `gmtime` returns the time as GMT (now known as Coordinated Universal Time, or UTC). Linux and UNIX do this so that all programs and systems across the world are synchronized. Files created at the same moment in different time zones will appear to have the same creation time. To see the local time, we need to use the function `localtime` instead.

```
#include <time.h>

struct tm *localtime(const time_t *timeval);
```

The `localtime` function is identical to `gmtime`, except that it returns a structure containing values adjusted for local time zone and daylight savings. If you try the `gmtime` program again, but use `localtime` in place of `gmtime`, you should see a correct time and date reported.

To convert a broken-down `tm` structure into a raw `time_t` value, we can use the function `mktme`:

```
#include <time.h>

time_t mktime(struct tm *timeptr);
```

`mktme` will return `-1` if the structure can't be represented as a `time_t` value.

For "friendly," as opposed to machine, time, and date output provided by the `date` program, we can use the functions `asctime` and `ctime`:

```
#include <time.h>

char *asctime(const struct tm *timeptr);
char *ctime(const time_t *timeval);
```

The `asctime` function returns a string that represents the time and date given by the `tm` structure `timeptr`. The string returned has a format similar to

```
Sun Jun  6 12:30:34 1999\n\0
```

It's always a fixed format, 26 characters long. The function `ctime` is equivalent to calling

```
asctime(localtime(timeval))
```

It takes a raw time value and converts it to a more readable local time.

Try It Out—ctime

Let's see `ctime` in action, using the following code:

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

int main()
{
    time_t timeval;

    (void)time(&timeval);
    printf("The date is: %s", ctime(&timeval));
    exit(0);
}
```

Compile and run the surprisingly named `ctime.c` and you should see

```
$ ./ctime
The date is: Sat Feb  8 09:21:17 2003
```

How It Works

The `ctime.c` program calls `time` to get the low-level time value and lets `ctime` do all the hard work, converting it to a readable string, which it then prints.

To gain more control of the exact formatting of time and date strings, Linux and modern UNIX-like systems provide the `strftime` function. This is rather like a `sprintf` for dates and times and works in a similar way:

```
#include <time.h>

size_t strftime(char *s, size_t maxsize, const char *format, struct tm *timeptr);
```

The `strftime` function formats the time and date represented by the `tm` structure pointed to by `timeptr` and places the result in the string `s`. This string is specified as (at least) `maxsize` characters long. The `format` string is used to control the characters written to the string. Like `printf`, it contains ordinary characters that will be transferred to the string and conversion specifiers for formatting time and date elements. The conversion specifiers include

| Conversion Specifier | Description |
|----------------------|--------------------------|
| %a | Abbreviated weekday name |
| %A | Full weekday name |
| %b | Abbreviated month name |
| %B | Full month name |
| %c | Date and time |
| %d | Day of the month, 01-31 |

| Conversion Specifier | Description |
|----------------------|--|
| %H | Hour, 00-23 |
| %I | Hour in 12-hour clock, 01-12 |
| %j | Day of the year, 001-366 |
| %m | Month of the year, 01-12 |
| %M | Minutes, 00-59 |
| %p | a.m. or p.m. |
| %S | Seconds, 00-61 |
| %u | Day in the week, 1-7 (1 = Monday) |
| %U | Week in the year, 01-53 (Sunday is the first day of the week.) |
| %V | Week in the year, 01-53 (Monday is the first day of the week.) |
| %w | Day in the week, 0-6 (0 = Sunday) |
| %x | Date in local format |
| %X | Time in local format |
| %y | Year number less 1900 |
| %Y | Year |
| %Z | Time zone name |
| %% | A % character |

So, the usual date as given by the `date` program corresponds to a `strftime` format string of

```
"%a %b %d %H:%M:%S %Y"
```

To help with reading dates, we can use the `strptime` function, which takes a string representing a date and time and creates a `tm` structure representing the same date and time:

```
#include <time.h>

char *strptime(const char *buf, const char *format, struct tm *timeptr);
```

The `format` string is constructed in exactly the same way as the `format` string for `strftime`. `strptime` acts in a similar way to `sscanf` in that it scans a string, looking for identifiable fields, and writes them into variables. Here it's the members of a `tm` structure that are filled in according to the `format` string. However, the conversion specifiers for `strptime` are a little more relaxed than those for `strftime` because `strptime` will allow both abbreviated and full names for days and months. Either representation will match a `%a` specifier in `strptime`. Also, where `strftime` always uses leading zeros on numbers less than 10, `strptime` regards them as optional.

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`strptime` returns a pointer to the character following the last one consumed in the conversion process. If it encounters characters that can't be converted, the conversion simply stops at that point. The calling program needs to check that enough of the passed string has been consumed to ensure that meaningful values are written to the `tm` structure.

Try It Out—`strftime` and `strptime`

Have a look at the selection of conversion specifiers used in the following program:

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

int main()
{
    struct tm *tm_ptr, timestruct;
    time_t the_time;
    char buf[256];
    char *result;

    (void) time(&the_time);
    tm_ptr = localtime(&the_time);
    strftime(buf, 256, "%A %d %B, %I:%S %p", tm_ptr);

    printf("strftime gives: %s\n", buf);

    strcpy(buf,"Sat 26 July 2003, 17:53 will do fine");

    printf("calling strptime with: %s\n", buf);
    tm_ptr = &timestruct;

    result = strptime(buf,"%a %d %b %Y, %R", tm_ptr);
    printf("strptime consumed up to: %s\n", result);

    printf("strptime gives:\n");
    printf("date: %02d/%02d/%02d\n",
           tm_ptr->tm_year % 100, tm_ptr->tm_mon+1, tm_ptr->tm_mday);
    printf("time: %02d:%02d\n",
           tm_ptr->tm_hour, tm_ptr->tm_min);
    exit(0);
}
```

When we compile and run this program, `strftime.c`, we get

```
$ ./strftime
strftime gives: Sunday 06 June, 11:55 AM
calling strptime with: Sat 26 July 2003, 17:53 will do fine
strptime consumed up to: will do fine
strptime gives:
date: 03/07/26
time: 17:53
```

How It Works

The `strftime` program obtains the current local time by calling `time` and `localtime`. It then converts it to a readable form by calling `strftime` with an appropriate formatting argument. To demonstrate the use of `strftime`, the program sets up a string containing a date and time, then calls `strftime` to extract the raw time and date values, and prints them. The conversion specifier `%R` is a shortcut for `%H:%M` in `strftime`.

It's important to note that `strftime` needs an accurate format string to successfully scan a date. Typically, it won't accurately scan dates read from users unless the format is very much restricted.

It is possible that you will find the compiler issuing a warning when you compile `strftime.c`. This is because the GNU library does not by default declare `strftime`. The fix for this is to explicitly request X/Open standard features by adding the following line before including `time.h`:

```
#define _XOPEN_SOURCE
```

Temporary Files

Often, programs will need to make use of temporary storage in the form of files. These might hold intermediate results of a computation or represent backup copies of files made before critical operations. For example, a database application could use a temporary file when deleting records. The file collects the database entries that need to be retained, and then, at the end of the process, the temporary file becomes the new database and the original is deleted.

This popular use of temporary files has a hidden disadvantage. You must take care to ensure that the applications choose a unique filename to use for the temporary file. If this doesn't happen, because Linux is a multitasking system, another program could choose the same name and the two will interfere with each other.

A unique filename can be generated by the `tmpnam` function:

```
#include <stdio.h>
char *tmpnam(char *s);
```

The `tmpnam` function returns a valid filename that isn't the same as any existing file. If the string `s` isn't `null`, the filename will also be written to it. Further calls to `tmpnam` will overwrite the static storage used for return values, so it's essential to use a string parameter if `tmpnam` is to be called many times. The string is assumed to be at least `L_tmpnam` characters long. `tmpnam` can be called up to `TMP_MAX` times in a single program, and it will generate a different filename each time.

If the temporary file is to be used immediately, you can name it and open it at the same time using the `tmpfile` function. This is important because another program could create a file with the same name as that returned by `tmpnam`. The `tmpfile` function avoids this problem altogether:

```
#include <stdio.h>
FILE *tmpfile(void);
```

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The `tmpfile` function returns a stream pointer that refers to a unique temporary file. The file is opened for reading and writing (via `fopen` with `w+`), and it will be automatically deleted when all references to the file are closed.

`tmpfile` returns a null pointer and sets `errno` on error.

Try It Out—`tmpnam` and `tmpfile`

Let's see these two functions in action:

```
#include <stdio.h>

int main()
{
    char tmpname[L_tmpnam];
    char *filename;
    FILE *tmpfp;

    filename = tmpnam(tmpname);

    printf("Temporary file name is: %s\n", filename);
    tmpfp = tmpfile();
    if(tmpfp)
        printf("Opened a temporary file OK\n");
    else
        perror("tmpfile");
    exit(0);
}
```

When we compile and run this program, `tmpnam.c`, we can see the unique filename generated by `tmpnam`:

```
$ ./tmpnam
Temporary file name is: /tmp/file2S64zc
Opened a temporary file OK
```

How It Works

The program calls `tmpnam` to generate a unique filename for a temporary file. If we wanted to use it, we would have to open it quickly to minimize the risk that another program would open a file with the same name. The `tmpfile` call creates and opens a temporary file at the same time, thus avoiding this risk. In fact, the GNU C compiler may give a warning about the use of `tmpnam` when compiling a program that uses it.

Older versions of UNIX have another way to generate temporary filenames using the functions `mkttemp` and `mkstemp`. These are supported by Linux and are similar to `tmpnam`, except that you can specify a template for the temporary filename, which gives you a little more control over their location and name:

```
#include <stdlib.h>

char *mkttemp(char *template);
int mkstemp(char *template);
```

The `mktemp` function creates a unique filename from the given template. The template argument must be a string with six trailing `x` characters. The `mktemp` function replaces these `x` characters with a unique combination of valid filename characters. It returns a pointer to the generated string or a null pointer if it couldn't generate a unique name.

The `mkstemp` function is similar to `tmpfile` in that it creates and opens a temporary file. The filename is generated in the same way as `mktemp`, but the returned result is an open, low-level file descriptor.

In general, you should use the “create and open” functions `tmpfile` and `mkstemp` rather than `tmpnam` and `mktemp`.

User Information

All Linux programs, with the notable exception of `init`, are started by other programs or users. We'll learn more about how running programs, or processes, interact in Chapter 11. Users most often start programs from a shell that responds to their commands. We've seen that a program can determine a great deal about its environment by examining environment variables and reading the system clock. A program can also find out information about the person using it.

When a user logs into a Linux system, he or she has a username and password. Once these have been validated, the user is presented with a shell. Internally, the user also has a unique user identifier known as a *UID*. Each program that Linux runs is run on behalf of a user and has an associated UID.

You can set up programs to run as if a different user had started them. When a program has its UID permission set, it will run as if started by the owner of the executable file. When the `su` command is executed, the program runs as if it had been started by the superuser. It then validates the user's access, changes the UID to that of the target account, and executes that account's login shell. This also allows a program to be run as if a different user had started it and is often used by system administrators to perform maintenance tasks.

Since the UID is key to the user's identity, let's start with that.

The UID has its own type—`uid_t`—defined in `sys/types.h`. It's normally a small integer. Some are predefined by the system; others are created by the system administrator when new users are made known to the system. Normally, users usually have UID values larger than 100.

```
#include <sys/types.h>
#include <unistd.h>

uid_t getuid(void);
char *getlogin(void);
```

The `getuid` function returns the UID with which the program is associated. This is usually the UID of the user who started the program.

The `getlogin` function returns the login name associated with the current user.

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The system file `/etc/passwd` contains a database dealing with user accounts. It consists of lines, one per user, that contain the username, encrypted password, user identifier (UID), group identifier (GID), full name, home directory, and default shell. Here's an example line:

```
neil:zBqxfqedfpk:500:100:Neil Matthew:/home/neil:/bin/bash
```

If we write a program that determines the UID of the user who started it, we could extend it to look in the password file to find out the user's login name and full name. We don't recommend this because modern UNIX-like systems are moving away from using simple password files to improve system security. Many systems, including Linux, have the option to use *shadow password* files that don't contain any useful encrypted password information at all (this is often held in `/etc/shadow`, a file that ordinary users cannot read). For this reason, a number of functions have been defined to provide a standard and effective programming interface to this user information:

```
#include <sys/types.h>
#include <pwd.h>

struct passwd *getpwuid(uid_t uid);
struct passwd *getpwnam(const char *name);
```

The password database structure, `passwd`, defined in `pwd.h` includes the following members:

| passwd Member | Description |
|-----------------------------|---------------------------|
| <code>char *pw_name</code> | The user's login name |
| <code>uid_t pw_uid</code> | The UID number |
| <code>gid_t pw_gid</code> | The GID number |
| <code>char *pw_dir</code> | The user's home directory |
| <code>char *pw_gecos</code> | The user's full name |
| <code>char *pw_shell</code> | The user's default shell |

Some UNIX systems may use a different name for the field for the user's full name: on some systems, it's `pw_gecos`, as on Linux, and on others, it's `pw_comment`. This means that we can't recommend its use.

The `getpwuid` and `getpwnam` functions both return a pointer to a `passwd` structure corresponding to a user. The user is identified by UID for `getpwuid` and by login name for `getpwnam`. They both return a null pointer and set `errno` on error.

Try It Out—User Information

Here's a program, `user.c`, which extracts some user information from the password database:

```
#include <sys/types.h>
#include <pwd.h>
#include <stdio.h>
#include <unistd.h>
```

```

int main()
{
    uid_t uid;
    gid_t gid;

    struct passwd *pw;
    uid = getuid();
    gid = getgid();

    printf("User is %s\n", getlogin());

    printf("User IDs: uid=%d, gid=%d\n", uid, gid);

    pw = getpwuid(uid);
    printf("UID passwd entry:\n name=%s, uid=%d, gid=%d, home=%s, shell=%s\n",
           pw->pw_name, pw->pw_uid, pw->pw_gid, pw->pw_dir, pw->pw_shell);

    pw = getpwnam("root");
    printf("root passwd entry:\n");
    printf("name=%s, uid=%d, gid=%d, home=%s, shell=%s\n",
           pw->pw_name, pw->pw_uid, pw->pw_gid, pw->pw_dir, pw->pw_shell);
    exit(0);
}

```

It gives the following output, which may differ in minor respects between versions of Linux and UNIX:

```

$ ./user
User is neil
User IDs: uid=500, gid=100
UID passwd entry:
  name=neil, uid=500, gid=100, home=/home/neil, shell=/bin/bash
root passwd entry:
  name=root, uid=0, gid=0, home=/root, shell=/bin/bash

```

How It Works

This program calls `getuid` to obtain the UID of the current user. This UID is used in `getpwuid` to obtain detailed password file information. As an alternative, we show how the username `root` can be given to `getpwnam` to obtain user information.

If you take a look at the Linux source code, you can see another example of using `getuid` in the `id` command.

To scan all the password file information, we can use the `getpwent` function. This fetches successive file entries:

```

#include <pwd.h>
#include <sys/types.h>

void endpwent(void);
struct passwd *getpwent(void);
void setpwent(void);

```

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The `getpwent` function returns each user information entry in turn. When none remain, it returns a null pointer. We can use the `endpwent` function to terminate processing once sufficient entries have been scanned. The `setpwent` function resets the position in the password file to the start so that a new scan can be started with the next call to `getpwent`. These functions operate in a similar way to the directory scanning functions `opendir`, `readdir`, and `closedir` that we discussed in Chapter 3.

User and group identifiers (effective and actual) can be obtained by other, less commonly used functions:

```
#include <sys/types.h>
#include <unistd.h>

uid_t geteuid(void);
gid_t getgid(void);
gid_t getegid(void);
int setuid(uid_t uid);
int setgid(gid_t gid);
```

You should refer to the system manual pages for details on group identifiers and effective user identifiers, although you'll probably find that you won't need to manipulate these at all.

Only the superuser may call `setuid` and `setgid`.

Host Information

Just as it can determine information about the user, a program can also establish some details about the computer on which it's running. The `uname(1)` command provides such information. `uname(2)` also exists as a system call to provide the same information within a C program—check it out using `man 2 uname`.

Host information can be useful in a number of situations. We might wish to customize a program's behavior, depending on the name of the machine it's running on in a network, say, a student's machine or an administrator's. For licensing purposes, we might wish to restrict a program to running on one machine only. All this means that we need a way to establish which machine the program is running on.

If the system has networking components installed, we can obtain its network name very easily with the `gethostname` function:

```
#include <unistd.h>

int gethostname(char *name, size_t namelen);
```

The `gethostname` function writes the machine's network name into the string `name`. This string is assumed to be at least `namelen` characters long. `gethostname` returns 0 if successful and -1 otherwise.

You can obtain more detailed information about the host computer from the `uname` system call:

```
#include <sys/utsname.h>

int uname(struct utsname *name);
```

The `uname` function writes host information into the structure pointed to by the `name` parameter. The `utsname` structure, defined in `sys/utsname.h`, must contain at least these members:

| <code>utsname Member</code> | <code>Description</code> |
|-------------------------------|----------------------------------|
| <code>char sysname []</code> | The operating system name |
| <code>char nodename []</code> | The host name |
| <code>char release []</code> | The release level of the system |
| <code>char version []</code> | The version number of the system |
| <code>char machine []</code> | The hardware type |

`uname` returns a nonnegative integer on success, -1 otherwise, with `errno` set to indicate any error.

Try It Out—Host Information

Here's a program, `hostget.c`, which extracts some host computer information:

```
#include <sys/utsname.h>
#include <unistd.h>
#include <stdio.h>

int main()
{
    char computer[256];
    struct utsname uts;

    if(gethostname(computer, 255) != 0 || uname(&uts) < 0) {
        fprintf(stderr, "Could not get host information\n");
        exit(1);
    }

    printf("Computer host name is %s\n", computer);
    printf("System is %s on %s hardware\n", uts.sysname, uts.machine);
    printf("Nodename is %s\n", uts.nodename);
    printf("Version is %s, %s\n", uts.release, uts.version);
    exit(0);
}
```

It gives the following Linux-specific output. If your machine is networked, you may see an extended host name that includes the network:

```
$ ./hostget
Computer host name is beast
System is Linux on i686 hardware
Nodename is beast
Version is 2.4.19-4GB, #1 Wed Nov 27 00:56:40 UTC 2002
```

How It Works

This program calls `gethostname` to obtain the network name of the host computer. In the preceding examples, it gets the name `tilde`. More detailed information about this Intel Pentium-II-based Linux computer is returned by the call to `uname`. Note that the format of the strings returned by `uname` is implementation-dependent; in the example, the version string contains the date that the kernel was compiled.

For another example of the use of the `uname` function, have a look at the Linux source code for the `uname` command, which uses it.

A unique identifier for each host computer may be available from the `gethostid` function:

```
#include <unistd.h>

long gethostid(void);
```

The `gethostid` function is intended to return a unique value for the host computer. License managers use this to ensure that software programs can run only on machines that hold valid licenses. On Sun workstations, it returns a number that is set in non-volatile memory when the computer is built, and so, is unique to the system hardware.

Other systems, such as Linux, return a value based on the Internet address of the machine, which isn't usually secure enough to be used for licensing.

Logging

Many applications need to record their activities. System programs very often will write messages to the console, or a log file. These messages might indicate errors, warnings, or more general information about the state of the system. For example, the `su` program might record the fact that a user has tried and failed to gain superuser privileges.

Very often, these log messages are recorded in system files in a directory made available for that purpose. This might be `/usr/adm` or `/var/log`. On a typical Linux installation, the file `/var/log/messages` contains all system messages, `/var/log/mail` contains other log messages from the mail system, and `/var/log/debug` may contain debug messages. You can check your system's configuration in the `/etc/syslog.conf` file.

Here are some sample log messages:

```
Feb  8 08:38:37 beast kernel: klogd 1.4.1, log source = /proc/kmsg started.
Feb  8 08:38:37 beast kernel: Inspecting /boot/System.map-2.4.19-4GB
Feb  8 08:38:37 beast kernel: Loaded 20716 symbols from /boot/System.map-
2.4.19-4GB.
Feb  8 08:38:37 beast kernel: Symbols match kernel version 2.4.19.
Feb  8 08:38:37 beast kernel: Loaded 372 symbols from 17 modules.

Feb  8 08:38:37 beast kernel: Linux Tulip driver version 0.9.15-pre11 (May 11,
2002)
```

```
Feb  8 08:38:37 beast kernel: PCI: Found IRQ 5 for device 00:0d.0
Feb  8 08:38:37 beast kernel: eth0: ADMtek Comet rev 17 at 0xe400,
00:04:5A:5F:46:52, IRQ 5.
```

```
...
Feb  8 08:39:20 beast /usr/sbin/cron[932]: (CRON) STARTUP (fork ok)
Feb  8 09:50:35 beast su: (to root) neil on /dev/pts/4
```

Here, we can see the sort of messages that are logged. The first few are reported by the Linux kernel itself as it boots and detects installed hardware. The task scheduler, cron, reports that it's starting up. Finally, the su program reports a superuser account access by user neil.

You may require superuser privilege to view log messages.

Some UNIX systems don't provide a readable messages file in this way, but do provide the administrator with tools to read a database of system events. Refer to your system documentation for details.

Even though the format and storage of system messages may vary, the method of producing the messages is standard. The UNIX specification provides an interface for all programs to produce logging messages using the syslog function:

```
#include <syslog.h>
void syslog(int priority, const char *message, arguments...);
```

The syslog function sends a logging message to the logging facility. Each message has a priority argument that is a bitwise OR of a severity level and a facility value. The severity level controls how the log message is acted upon and the facility value records the originator of the message.

Facility values (from syslog.h) include LOG_USER, used to indicate that the message has come from a user application, (the default), and LOG_LOCAL0, LOG_LOCAL1, up to LOG_LOCAL7, which can be assigned meanings by the local administrator.

The severity levels in descending order of priority are

| Priority Level | Description |
|----------------|--|
| LOG_EMERG | An emergency situation |
| LOG_ALERT | High-priority problem, such as database corruption |
| LOG_CRIT | Critical error, such as hardware failure |
| LOG_ERR | Errors |
| LOG_WARNING | Warning |
| LOG_NOTICE | Special conditions requiring attention |
| LOG_INFO | Informational messages |
| LOG_DEBUG | Debug messages |

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Depending on system configuration, `LOG_EMERG` messages might be broadcast to all users, `LOG_ALERT` messages might be mailed to the administrator, `LOG_DEBUG` messages might be ignored, and the others written to a messages file. We can write a program that uses the logging facility simply by calling `syslog` when we wish to create a log message.

The log message created by `syslog` consists of a message header and a message body. The header is created from the facility indicator and the date and time. The message body is created from the `message` parameter to `syslog`, which acts like a `printf` format string. Further arguments to `syslog` are used according to `printf` style conversion specifiers in the message string. Additionally, the specifier `%m` may be used to insert the error message string associated with the current value of the error variable, `errno`. This can be useful for logging error messages.

Try It Out—`syslog`

In this program, we try to open a nonexistent file:

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

int main()
{
    FILE *f;

    f = fopen("not_here", "r");
    if (!f)
        syslog(LOG_ERR|LOG_USER, "oops - %m\n");
    exit(0);
}
```

When we compile and run this program, `syslog.c`, we see no output, but the file `/var/log/messages` now contains the following line at the end:

```
Feb  8 09:59:14 beast syslog: oops - No such file or directory
```

How It Works

In this program, we try to open a file that doesn't exist. When this fails, we call `syslog` to record the fact in the system logs.

Notice that the log message doesn't indicate which program called the log facility; it just records the fact that `syslog` was called with a message. The `%m` conversion specifier has been replaced by a description of the error, in this case, that the file couldn't be found. This is more useful than just reporting the raw error number.

Other functions used to alter the behavior of logging facilities are also defined in `syslog.h`. These are:

```
#include <syslog.h>

void closelog(void);
void openlog(const char *ident, int logopt, int facility);
int setlogmask(int maskpri);
```

We can alter the way that our log messages are presented by calling the `openlog` function. This allows us to set up a string, `ident`, which will be pre-pended to our log messages. We can use this to indicate which program is creating the message. The `facility` parameter records a default facility value to be used for future calls to `syslog`. The default is `LOG_USER`. The `logopt` parameter configures the behavior of future calls to `syslog`. It's a bitwise OR of zero or more of the following:

| logopt Parameter | Description |
|-------------------------|--|
| <code>LOG_PID</code> | Includes the process identifier, a unique number allocated to each process by the system, in the messages. |
| <code>LOG_CONS</code> | Sends messages to the console if they can't be logged. |
| <code>LOG_ODELAY</code> | Opens the log facility at first call to . |
| <code>LOG_NDELAY</code> | Opens the log facility immediately, rather than at first log. |

The `openlog` function will allocate and open a file descriptor that will be used for writing to the logging facility. You can close this by calling the `closelog` function. Note that you don't need to call `openlog` before calling `syslog` because `syslog` will open the logging facility itself if required.

We can control the priority level of our log messages by setting a log mask using `setlogmask`. All future calls to `syslog` with priority levels not set in the log mask will be rejected, so you could, for example, use this to turn off `LOG_DEBUG` messages without having to alter the body of the program.

We can create the mask for log messages using `LOG_MASK(priority)`, which creates a mask consisting of just one priority level, or `LOG_UPTO(priority)`, which creates a mask consisting of all priorities up to and including the specified priority.

Try It Out—logmask

In this example, we'll see `logmask` in action:

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

int main()
{
    int logmask;

    openlog("logmask", LOG_PID|LOG_CONS, LOG_USER);
    syslog(LOG_INFO,"informative message, pid = %d", getpid());
    syslog(LOG_DEBUG,"debug message, should appear");
    logmask = setlogmask(LOG_UPTO(LOG_NOTICE));
    syslog(LOG_DEBUG,"debug message, should not appear");
    exit(0);
}
```

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This `logmask.c` program produces no output, but on a typical Linux system, toward the end of `/var/log/messages`, we should see the following line:

```
Feb  8 10:00:50 beast logmask[1833]: informative message, pid = 1833
```

The file that is configured to receive debug log entries (depending on logging configuration, this is often the file `/var/log/debug` or sometimes `/var/log/messages`) should contain the following line:

```
Feb  8 10:00:50 beast logmask[1833]: debug message, should appear
```

How It Works

The program initializes the logging facility with its name, `logmask`, and requests that log messages contain the process identifier. The informative message is logged to `/var/log/messages`, and the debug message to `/var/log/debug`. The second debug message doesn't appear because we call `setlogmask` to ignore all messages with a priority below `LOG_NOTICE`. (Note that this may not work on early Linux kernels.)

If your installation does not have debug message logging enabled, or it is configured differently, you may not see the debug messages appear. To enable all debug messages, add the following line to the end of `/etc/syslog.conf` and reboot. (You could also just send a hang-up signal to the `syslogd` process.) However, be sure to check your system documentation for the exact configuration details.

```
*.debug      /var/log/debug
```

`logmask.c` uses the `getpid` function, which is defined along with the closely related `getppid` as follows

```
#include <sys/types.h>
#include <unistd.h>

pid_t getpid(void);
pid_t getppid(void);
```

The functions return the process and parent process identifiers of the calling process. For more information on PIDs, see Chapter 11.

Resources and Limits

Programs running on a Linux system are subject to resource limitations. These might be physical limits imposed by hardware (such as memory), limits imposed by system policies (for example, allowed CPU time), or implementation limits (such as the size of an integer or the maximum number of characters allowed in a filename). The UNIX specification defines some of these limits that can be determined by an application. See Chapter 7 for a further discussion of limits and the consequences of breaking them.

The header file `limits.h` defines many manifest constants that represent the constraints imposed by the operating system. These include

| Limit Constant | What They're For |
|-----------------------|---|
| <code>NAME_MAX</code> | The maximum number of characters in a filename |
| <code>CHAR_BIT</code> | The number of bits in a <code>char</code> value |
| <code>CHAR_MAX</code> | The maximum <code>char</code> value |
| <code>INT_MAX</code> | The maximum <code>int</code> value |

There will be many others that may be of use to an application, so you should refer to your installation's header files.

Note that `NAME_MAX` is file-system specific. For more portable code, you should use the `pathconf` function. Refer to the manual pages on `pathconf` for more information.

The header file `sys/resource.h` provides definitions for resource operations. These include functions for determining and setting limits on a program's allowed size, execution priority, and file resources:

```
#include <sys/resource.h>

int getpriority(int which, id_t who);
int setpriority(int which, id_t who, int priority);
int getrlimit(int resource, struct rlimit *r_limit);
int setrlimit(int resource, const struct rlimit *r_limit);
int getrusage(int who, struct rusage *r_usage);
```

`id_t` is an integral type used for user and group identifiers. The `rusage` structure, defined in `sys/resource.h`, is used to determine how much CPU time has been used by the current program. It must contain at least these members:

| rusage Member | Description |
|--------------------------------------|----------------------|
| <code>struct timeval ru_utime</code> | The user time used |
| <code>struct timeval ru_stime</code> | The system time used |

The `timeval` structure is defined in `sys/time.h` and contains fields `tv_sec` and `tv_usec`, representing seconds and microseconds, respectively.

CPU time consumed by a program is separated into *user time* (the time that the program itself has consumed executing its own instructions) and *system time* (the CPU time consumed by the operating system on the program's behalf; that is, the time spent in system calls performing input and output or other system functions).

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The `getrusage` function writes CPU time information to the `rusage` structure pointed to by the parameter `r_usage`. The `who` parameter can be one of the following constants:

| who Constant | Description |
|------------------------------|--|
| <code>RUSAGE_SELF</code> | Returns usage information about current program only. |
| <code>RUSAGE_CHILDREN</code> | Includes usage information of child processes as well. |

We discuss child processes and task priorities in Chapter 11, but for completeness, we'll cover their implications for system resources here. For now, it's enough to say that each program that's running has a priority associated with it, and that higher priority programs are allocated more of the available CPU time.

Ordinary users are only able to reduce the priorities of their programs, not increase them.

Applications can determine and alter their (and others') priority with the `getpriority` and `setpriority` functions. The process to be examined or changed by the priority functions can be identified either by process identifier, group identifier, or user. The `which` parameter specifies how the `who` parameter is to be treated.

| which Parameter | Description |
|----------------------------|------------------------------|
| <code>PRIOR_PROCESS</code> | who is a process identifier. |
| <code>PRIOR_PGRP</code> | who is a process group. |
| <code>PRIOR_USER</code> | who is a user identifier. |

So, to determine the priority of the current process, we might call

```
priority = getpriority(PRIOR_PROCESS, getpid());
```

The `setpriority` function allows a new priority to be set, if possible.

The default priority is 0. Positive priorities are used for background tasks that run when no other higher priority task is ready to run. Negative priorities cause a program to run more frequently, taking a larger share of the available CPU time. The range of valid priorities is -20 to +20. This is often confusing because the higher the numerical value, the lower the execution precedence.

`getpriority` returns a valid priority if successful or a -1 with `errno` set on error. Because -1 is itself a valid priority, `errno` should be set to zero before calling `getpriority` and checked that it's still zero on return. `setpriority` returns 0 if successful, -1 otherwise.

Limits on system resources can be read and set by `getrlimit` and `setrlimit`. Both of these functions make use of a general purpose structure, `rlimit`, to describe resource limits. It's defined in `sys/resource.h` and has the following members:

| rlimit Member | Description |
|------------------------------|-------------------------|
| <code>rlim_t rlim_cur</code> | The current, soft limit |
| <code>rlim_t rlim_max</code> | The hard limit |

The defined type `rlim_t` is an integral type used to describe resource levels. Typically, the soft limit is an advisory limit that shouldn't be exceeded; doing so may cause library functions to return errors. The hard limit, if exceeded, may cause the system to attempt to terminate the program by sending a signal to it. Examples would be the signal `SIGXCPU` on exceeding the CPU time limit and the signal `SIGSEGV` on exceeding a data size limit. A program may set its own soft limits to any value less than the hard limit. It may reduce its hard limit. Only a program running with superuser privileges may increase a hard limit.

There are a number of system resources that can be limited. These are specified by the `resource` parameter of the `rlimit` functions and are defined in `sys/resource.h` as

| resource Parameter | Description |
|----------------------------|---|
| <code>RLIMIT_CORE</code> | The core dump file size limit, in bytes |
| <code>RLIMIT_CPU</code> | The CPU time limit, in seconds |
| <code>RLIMIT_DATA</code> | The data () segment limit, in bytes |
| <code>RLIMIT_FSIZE</code> | The file size limit, in bytes |
| <code>RLIMIT_NOFILE</code> | The limit on the number of open files |
| <code>RLIMIT_STACK</code> | The limit on stack size, in bytes |
| <code>RLIMIT_AS</code> | The limit on address space (stack and data), in bytes |

The following “Try It Out” shows a program, `limits.c`, that simulates a typical application. It also sets and breaks a resource limit.

Try It Out—Resource Limits

1. Make the includes for all the functions we're going to be using in this program:

```
#include <sys/types.h>
#include <sys/resource.h>
#include <sys/time.h>
#include <unistd.h>
#include <stdio.h>
#include <math.h>
```

2. The void function writes a string to a temporary file 10,000 times and then performs some arithmetic to generate load on the CPU:

```
void work()
{
    FILE *f;
```

```
int i;
double x = 4.5;

f = tmpfile();
for(i = 0; i < 10000; i++) {
    fprintf(f,"Do some output\n");
    if(ferror(f)) {
        fprintf(stderr,"Error writing to temporary file\n");
        exit(1);
    }
}
for(i = 0; i < 1000000; i++)
    x = log(x*x + 3.21);
}
```

3. The main function calls work and then uses the getrusage function to discover how much CPU time it has used. It displays this information on screen:

```
int main()
{
    struct rusage r_usage;
    struct rlimit r_limit;
    int priority;

    work();
    getrusage(RUSAGE_SELF, &r_usage);

    printf("CPU usage: User = %ld.%06ld, System = %ld.%06ld\n",
           r_usage.ru_utime.tv_sec, r_usage.ru_utime.tv_usec,
           r_usage.ru_stime.tv_sec, r_usage.ru_stime.tv_usec);
```

4. Next, it calls getpriority and getrlimit to find out its current priority and file size limits, respectively:

```
priority = getpriority(PRIO_PROCESS, getpid());
printf("Current priority = %d\n", priority);

getrlimit(RLIMIT_FSIZE, &r_limit);
printf("Current FSIZE limit: soft = %ld, hard = %ld\n",
       r_limit.rlim_cur, r_limit.rlim_max);
```

5. Finally, we set a file size limit using setrlimit and call work again, which fails because it attempts to create too large a file:

```
r_limit.rlim_cur = 2048;
r_limit.rlim_max = 4096;
printf("Setting a 2K file size limit\n");
setrlimit(RLIMIT_FSIZE, &r_limit);

work();
exit(0);
}
```

When we run this program, we can see how much CPU resource is being consumed and the default priority at which the program is running. Once a file size limit has been set, the program can't write more than 2,048 bytes to a temporary file.

```
$ cc -o limits limits.c -lm
$ ./limits
CPU usage: User = 0.980000, System = 0.010000
Current priority = 0
Current FSIZE limit: soft = -1, hard = -1
Setting a 2K file size limit
File size limit exceeded
```

We can change the program priority by starting it with the `nice` command. Here, we see the priority changes to `+10` and, as a result, it takes longer to execute the program:

```
$ nice ./limits
CPU usage: User = 1.000000, System = 0.000000
Current priority = 10
Current FSIZE limit: soft = -1, hard = -1
Setting a 2K file size limit
File size limit exceeded
```

How It Works

The `limits` program calls the `work` function to simulate the actions of a typical program. It performs some calculations and produces some output, in this case, about 150K to a temporary file. It calls the resource functions to discover its priority and file size limits. In this case, the file size limits are unset, allowing us to create as large a file as we like (disk space permitting). The program then sets its file size limit to just 2K and again tries to perform some work. This time, the `work` function fails as it can't create such a large temporary file.

Limits may also be placed on a program running under a particular shell with the bash ulimit command.

In this example, the error message 'Error writing to temporary file' may not be printed as we might expect. This is because some systems (such as Linux 2.2 and later) terminate our program when the resource limit is exceeded. It does this by sending a signal, `SIGXFSZ`. We will learn more about signals and how to use them in Chapter 11. Other POSIX-compliant systems may simply cause the function that exceeds the limit to return an error.

Summary

In this chapter, we've looked at the Linux environment and examined the conditions under which programs run. We've covered command line arguments and environment variables, both of which can be used to alter a program's default behavior and provide useful program options.

We've seen how a program can make use of library functions to manipulate date and time values and obtain information about itself and the user and the computer on which it's running.

Linux programs typically have to share precious resources, so we also looked at how those resources can be determined and managed.

5

Terminals

In this chapter, let's consider the improvements we might like to make to our basic application from Chapter 2. Perhaps the most obvious failing is the user interface; it's functional, but not very elegant. Here, we'll look at how to take more control of the user's terminal; that is, both keyboard input and screen output. More than this, though, we'll learn how to "guarantee" that the programs we write can get input from the user, even in the presence of input redirection, and ensure that the output goes to the right place on the screen.

Though the reimplemented CD database application won't see the light of day until the end of Chapter 7, we'll do much of the groundwork for that chapter here. Chapter 6 is on *curses*, which is not some ancient malediction, but rather a library of functions that provide a higher level of code to control the terminal screen display. Along the way, we'll examine a little more of the thinking of the early UNIX meisters by introducing you to some philosophy of Linux and UNIX and the concept of terminal input and output. The low-level access presented here might be just what you're looking for. Most of what we will cover applies equally well to programs running in a console window, such as KDE's Konsole, GNOME's gnome-terminal, or the standard X11 xterm.

Specifically, in this chapter, we'll learn about

- ❑ Reading and writing to the terminal
- ❑ Terminal drivers and the General Terminal Interface
- ❑ `termios`
- ❑ Terminal output and `terminfo`
- ❑ Detecting keystrokes

Reading from and Writing to the Terminal

In Chapter 3, we learned that when a program is invoked from the command prompt, the shell arranges for the standard input and output streams to be connected to our program. We should be able to interact with the user simply by using the `getchar` and `printf` routines to read and write these default streams.

Chapter 5

Let's try to rewrite our menu routines in C, using just those two routines, calling it `menu1.c`.

Try It Out—Menu Routines in C

1. Start with the following lines, which define the array to be used as a menu, and prototype the `getchoice` function:

```
#include <stdio.h>

char *menu[] = {
    "a - add new record",
    "d - delete record",
    "q - quit",
    NULL,
};

int getchoice(char *greet, char *choices[]);
```

2. The main function calls `getchoice` with the sample menu, `menu`:

```
int main()
{
    int choice = 0;

    do
    {
        choice = getchoice("Please select an action", menu);
        printf("You have chosen: %c\n", choice);
    } while(choice != 'q');
    exit(0);
}
```

3. Now for the important code: the function that both prints the menu and reads the user's input:

```
int getchoice(char *greet, char *choices[])
{
    int chosen = 0;
    int selected;
    char **option;

    do {
        printf("Choice: %s\n", greet);
        option = choices;
        while(*option) {
            printf("%s\n", *option);
            option++;
        }
        selected = getchar();
        option = choices;
        while(*option) {
            if(selected == *option[0]) {
                chosen = 1;
            }
        }
    } while(chosen == 0);
}
```

```

        break;
    }
    option++;
}
if(!chosen) {
    printf("Incorrect choice, select again\n");
}
} while(!chosen);
return selected;
}

```

How It Works

`getchoice` prints the program introduction `greet` and the sample menu choices and asks the user to choose the initial character. The program then loops until `getchar` returns a character that matches the first letter of one of the `option` array's entries.

When we compile and run this program, we discover that it doesn't behave as we expected. Here's some terminal dialogue to demonstrate the problem:

```

$ ./menu1
Choice: Please select an action
a - add new record
d - delete record
q - quit
a
You have chosen: a
Choice: Please select an action
a - add new record
d - delete record
q - quit
Incorrect choice, select again
Choice: Please select an action
a - add new record
d - delete record
q - quit
q
You have chosen: q
$
```

Here, the user had to enter A/Enter/Q/Enter to make selections. There seem to be at least two problems: The most serious problem is that we are getting `Incorrect choice` after every correct choice. Plus, we still have to press Enter (or the Return key) before our program reads our input.

Canonical versus Non-Canonical Modes

The two problems are closely related. By default, terminal input is not made available to a program until the user presses Enter. In most cases, this is a benefit because it allows the user to correct typing mistakes using Backspace or Delete. Only when they're happy with what they see on the screen do they press Enter to make the input available to the program.

This behavior is called *canonical*, or *standard*, mode. All the input is processed in terms of lines. Until a line of input is complete (usually when the user presses Enter), the terminal interface manages all the key presses, including Backspace, and no characters may be read by the application.

The opposite of this is *non-canonical* mode, where the application has much greater control over the processing of input characters. We'll come back to these two modes again a little later.

Among other things, the Linux terminal handler likes translating interrupt characters to signals and can automatically perform Backspace and Delete processing for you, so you don't have to reimplement it in each program you write. We'll find out more about signals in Chapter 11.

So, what's happening in our program? Well, Linux is saving the input until the user presses Enter, then passing both the choice character and the subsequent Enter to the program. So, each time you enter a menu choice, the program calls `getchar`, processes the character, then calls `getchar` again, which immediately returns with the Enter character.

The character the program actually sees isn't an ASCII carriage return, CR (decimal 13, hex 0D), but a line feed, LF (decimal 10, hex 0A). This is because, internally, Linux (like UNIX) always uses a line feed to end lines of text; that is, UNIX uses a line feed alone to mean a newline, where other systems, such as MS-DOS, use a carriage return and a line feed together as a pair. If the input or output device also sends or requires a carriage return, the Linux terminal processing takes care of it. This might seem a little strange if you're used to MS-DOS or other environments, but one of the very considerable benefits is that there is no real difference between text and binary files on Linux. Only when you input or output to a terminal or some printers and plotters are carriage returns processed.

We can correct the major deficiency in our menu routine simply by ignoring the additional line feed character with some code such as this:

```
do {  
    selected = getchar();  
} while(selected == '\n');
```

This solves the immediate problem. We'll return to the second problem of needing to press Enter, and a more elegant solution to the line feed handling later.

Handling Redirected Output

It's very common for Linux programs, even interactive ones, to have their input or output redirected, either to files or other programs. Let's see how our program behaves when we redirect its output to a file:

```
$ menu1 > file  
a  
q  
$
```

We could regard this as successful because the output has been redirected to a file rather than the terminal. However, there are cases where we want to prevent this from happening, or where we want to separate prompts that we want the user to see from other output that can be redirected safely.

We can tell whether the standard output has been redirected by finding out if the low-level file descriptor is associated with a terminal. The `isatty` system call does this. We simply pass it a valid file descriptor and it tests to see if that is currently connected to a terminal.

```
#include <unistd.h>

int isatty(int fd);
```

The `isatty` system call returns 1 if the open file descriptor, `fd`, is connected to a terminal and 0 otherwise.

In our program, we are using file streams, but `isatty` operates only on file descriptors. To provide the necessary conversion, we need to combine the `isatty` call with the `fileno` routine that we discussed in Chapter 3.

What are we going to do if `stdout` has been redirected? Just quitting isn't good enough because the user has no way of knowing why the program failed to run. Printing a message on `stdout` won't help either because it must have been redirected away from the terminal. One solution is to write to `stderr`, which isn't redirected by the shell `> file` command.

Try It Out—Checking for Output Redirection

Using the program `menu1.c` we created in the last “Try It Out” section, make a new include, change the `main` function to the following, and call the new file `menu2.c`.

```
#include <unistd.h>
...
int main()
{
    int choice = 0;

    if(!isatty(fileno(stdout))) {
        fprintf(stderr,"You are not a terminal!\n");
        exit(1);
    }
    do {
        choice = getchoice("Please select an action", menu);
        printf("You have chosen: %c\n", choice);
    } while(choice != 'q');
    exit(0);
}
```

Now look at the following sample output:

```
$ menu2
Choice: Please select an action
a - add new record
d - delete record
q - quit
q
You have chosen: q
$ menu2 > file
You are not a terminal!
$
```

How It Works

The new section of code uses the `isatty` function to test whether the standard output is connected to a terminal and halts execution if it isn't. This is the same test the shell uses to decide whether to offer prompts. It's possible, and quite common, to redirect both `stdout` and `stderr` away from the terminal. We can direct the error stream to a different file like this:

```
$ menu2 >file 2>file.error  
$
```

Or combine the two output streams into a single file like this:

```
$ menu2 >file 2>&1  
$
```

(If you're not familiar with output redirection, take another look at Chapter 2, where we explain this syntax in more detail.) In this case, you'll need to send a message to the console.

Talking to the Terminal

If we need to prevent the parts of our program that interact with the user from being redirected, but still allow it to happen to other input or output, we need to separate the interaction from `stdout` and `stderr`. We can do this by reading and writing directly to the terminal. Since Linux is inherently a multiuser system, usually with many terminals either directly connected or connected across a network, how can we discover the correct terminal to use?

Fortunately, Linux and UNIX make things easy for us by providing a special device, `/dev/tty`, which is always the current terminal, or login session. Since Linux treats everything as a file, we can use normal file operations to read and write to `/dev/tty`.

Let's modify our choice program so that we can pass parameters to the `getchoice` routine, to provide better control over the output. We're up to `menu3.c`.

Try It Out—Using `/dev/tty`

Load up `menu2.c` and change the code to the following, so that input and output come from and are directed to `/dev/tty`:

```
#include <stdio.h>  
#include <unistd.h>  
  
char *menu[] = {  
    "a - add new record",  
    "d - delete record",  
    "q - quit",  
    NULL,  
};  
  
int getchoice(char *greet, char *choices[], FILE *in, FILE *out);  
  
int main()
```

```
{  
    int choice = 0;  
    FILE *input;  
    FILE *output;  
  
    if(!isatty(fileno(stdout))) {  
        fprintf(stderr,"You are not a terminal, OK.\n");  
    }  
  
    input = fopen("/dev/tty", "r");  
    output = fopen("/dev/tty", "w");  
    if(!input || !output) {  
        fprintf(stderr,"Unable to open /dev/tty\n");  
        exit(1);  
    }  
    do {  
        choice = getchoice("Please select an action", menu, input, output);  
        printf("You have chosen: %c\n", choice);  
    } while(choice != 'q');  
    exit(0);  
}  
  
int getchoice(char *greet, char *choices[], FILE *in, FILE *out)  
{  
    int chosen = 0;  
    int selected;  
    char **option;  
  
    do {  
        fprintf(out,"Choice: %s\n",greet);  
        option = choices;  
        while(*option) {  
            fprintf(out,"%s\n",*option);  
            option++;  
        }  
        do {  
            selected = fgetc(in);  
        } while(selected == '\n');  
        option = choices;  
        while(*option) {  
            if(selected == *option[0]) {  
                chosen = 1;  
                break;  
            }  
            option++;  
        }  
        if(!chosen) {  
            fprintf(out,"Incorrect choice, select again\n");  
        }  
    } while(!chosen);  
    return selected;  
}
```

Now, when we run the program with the output redirected, we can still see the prompts and the normal program output is separated.

```
$ menu3 > file
You are not a terminal, OK.
Choice: Please select an action
a - add new record
d - delete record
q - quit
d
Choice: Please select an action
a - add new record
d - delete record
q - quit
q
$ cat file
You have chosen: d
You have chosen: q
```

The Terminal Driver and the General Terminal Interface

Sometimes a program needs much finer control over the terminal than can be achieved using simple file operations. Linux provides a set of interfaces that allow us to control the behavior of the terminal driver, giving us much greater control of the processing of terminal input and output.

Overview

As Figure 5-1 shows, we can control the terminal through a set of function calls (the General Terminal Interface, or GTI) separate from those used for reading and writing. This keeps the data (read/write) interface very clean while still allowing detailed control over the terminal behavior. That's not to say that the terminal I/O interface is clean—it's got to deal with a wide variety of different hardware.

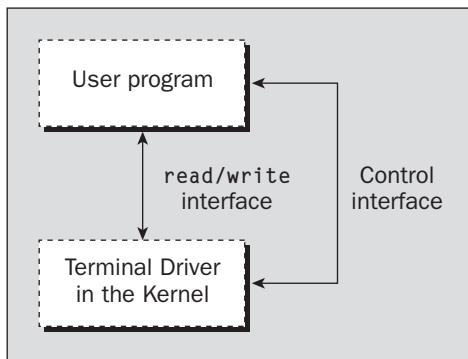


Figure 5-1

In UNIX terminology, the control interface sets a “line discipline” that allows a program considerable flexibility in specifying the behavior of the terminal driver.

The main features that we can control are

- Line editing:** Choose whether to allow *Backspace* for editing.
- Buffering:** Choose whether to read characters immediately, or read them after a configurable delay.
- Echo:** Allows us to control echoing, such as when reading passwords.
- CR/LF:** Determine mapping for input and output: what happens when you print a \n.
- Line speeds:** Rarely used on a PC console, these speeds are very important for modems and terminals on serial lines.

Hardware Model

Before we look at the General Terminal Interface in detail, it's very important that we understand the hardware model that it's intended to drive.

The conceptual arrangement shown in Figure 5-2 (and for some UNIX sites, it will physically be like this) is to have a UNIX machine connected via a serial port to a modem and then via a telephone line and another modem to a remote terminal. In fact, this is just the kind of setup used by some small Internet service providers. It's a distant relative of the client/server paradigm, used when the program ran on a mainframe and users worked at dumb terminals.

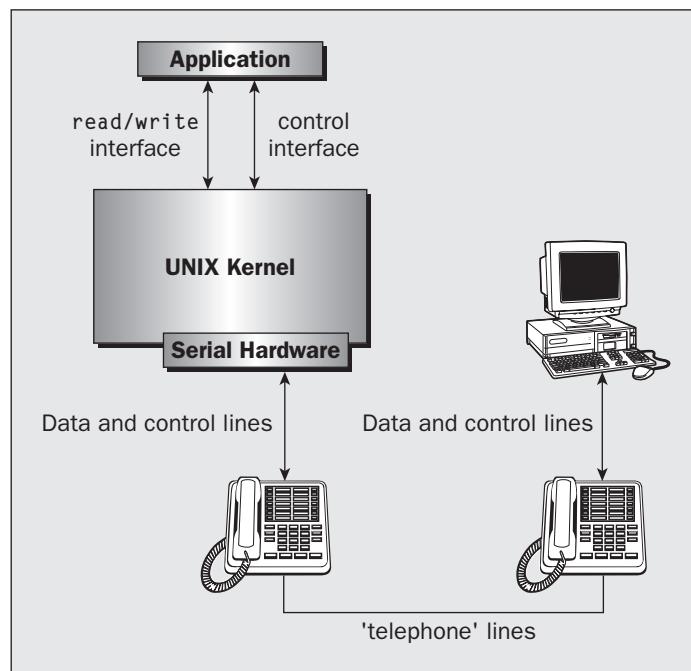


Figure 5-2

If you're working on a PC running Linux, this may seem like an overly complex model. However, as both of the authors have modems, we can, if we choose, use a terminal emulation program like `minicom` to run a remote logon session on each other's machines just like this, using a pair of modems and a telephone line.

The advantage of using such a hardware model is that most real-world situations will form a subset of this, the most complex case. Supporting them will be much easier than if the model had omitted such functionality.

The `termios` Structure

`termios` is the standard interface specified by POSIX and is similar to the System V interface `termio`. The terminal interface is controlled by setting values in a structure of type `termios` and using a small set of function calls. Both are defined in the header file `termios.h`.

Programs that use the function calls defined in `termios.h` will need to be linked with an appropriate function library. This will normally be the `curses` library, so when compiling the examples in this chapter, you'll need to add `-lcurses` to the end of the compiler command line. On some older Linux systems, the `curses` library is provided by a version known as "new curses," or `ncurses`. In these cases, the library name and link argument become `and -lncurses`, respectively.

The values that can be manipulated to affect the terminal are grouped into various modes:

- Input
- Output
- Control
- Local
- Special control characters

A minimum `termios` structure is typically declared as follows (although the X/Open specification allows additional fields to be included).

```
#include <termios.h>
struct termios {
    tcflag_t c_iflag;
    tcflag_t c_oflag;
    tcflag_t c_cflag;
    tcflag_t c_lflag;
    cc_t      c_cc[NCCS];
};
```

The member names correspond with the five parameter types listed in the previous list.

We can initialize a `termios` structure for the terminal by calling the function `tcgetattr`, which has the following prototype:

```
#include <termios.h>

int tcgetattr(int fd, struct termios *termios_p);
```

This call writes the current values of the terminal interface variables into the structure pointed to by `termios_p`. If these values are then altered, we can reconfigure the terminal interface with the `tcsetattr` function as follows

```
#include <termios.h>

int tcsetattr(int fd, int actions, const struct termios *termios_p);
```

The `actions` field for `tcsetattr` controls how any changes are applied. The three possibilities are

- `TCSANOW`: Changes values immediately.
- `TCSADRAIN`: Changes values when current output is complete.
- `TCSAFLUSH`: Changes values when current output is complete, but discards any input currently available and not yet returned in a read call.

Note that it's very important for programs to restore terminal settings to the values they had before the program started. It's always the responsibility of a program to initially save and restore these settings when it finishes.

We'll now look more closely at the modes and related function calls. Some of the detail of the modes is rather specialized and rarely used, so we'll cover only the main features here. If you need to know more, you should consult your local `man` pages or a copy of the POSIX or X/Open specification.

The most important mode to take in on your first read is the local mode. The canonical and non-canonical modes are the solution to the second of our problems in the first application. We can instruct the program to wait for a line of input or pounce on input as soon as it is typed.

Input Modes

The input modes control how input (characters received by the terminal driver at a serial port or keyboard) is processed before being passed on to the program. We control them by setting flags in the `c_iflag` member of the `termios` structure. All the flags are defined as macros and can be combined with a bitwise OR. This is the case for all the terminal modes.

The macros that can be used for `c_iflag` are

- `BRKINT`: Generate an interrupt when a break condition is detected on the line
- `IGNBRK`: Ignore break conditions on the line

- ICRNL: Convert a received carriage return to a newline
- IGNCR: Ignore received carriage returns
- INLCR: Convert received newlines to carriage returns
- IGNPAR: Ignore characters with parity errors
- INPCK: Perform parity checking on received characters
- PARMRK: Mark parity errors
- ISTRIP: Strip (set to seven bits) all incoming characters
- IXOFF: Enable software flow control on input
- IXON: Enable software flow control on output

If neither `BRKINT` nor `IGNBRK` is set, a break condition on the line is read as a NULL (0x00) character.

You won't need to change the input modes very often, as the default values are usually the most suitable, so we won't discuss them further here.

Output Modes

These modes control how output characters are processed; that is, how characters sent from a program are processed before being transmitted to the serial port or screen. As you might expect, many of these are counterparts of the input modes. Several additional flags exist, which are mainly concerned with allowing for slow terminals that require time to process characters such as carriage returns. Almost all of these are either redundant (as terminals get faster) or better handled using the `terminfo` database of terminal capabilities, which we'll use later in this chapter.

We control output modes by setting flags in the `c_oflag` member of the `termios` structure. The macros that we can use in `c_oflag` are

- OPOST: Turn on output processing
- ONLCR: Convert any output newline to a carriage return/line feed pair
- OCRNL: Convert any output carriage return to a newline
- ONOCR: No carriage return output in column 0
- ONLRET: A newline also does a carriage return
- OFILL: Send fill characters to provide delays
- OFDEL: Use DEL as a fill character, rather than NULL
- NLDLY: Newline delay selection
- CRDLY: Carriage return delay selection
- TABDLY: Tab delay selection

- BSDLY: Backspace delay selection
- VTDLY: Vertical tab delay selection
- FFDLY: Form feed delay selection

If OPOST is not set, all the other flags are ignored.

The output modes are also not commonly used, so we won't consider them further here.

Control Modes

These modes control the hardware characteristics of the terminal. We specify control modes by setting flags in the `c_cflag` member of the `termios` structure, which has the following macros:

- CLOCAL: Ignore any modem status lines.
- CREAD: Enable the receipt of characters.
- CS5: Use five bits in sent or received characters.
- CS6: Use six bits in sent or received characters.
- CS7: Use seven bits in sent or received characters.
- CS8: Use eight bits in sent or received characters.
- CSTOPB: Use two stop bits per character, rather than one.
- HUPCL: Hang up modem on close.
- PARENB: Enable parity generation and detection.
- PARODD: Use odd parity rather than even parity.

If HUPCL is set, when the terminal driver detects that the last file descriptor referring to the terminal has been closed, it will set the modem control lines to "hang-up" the line.

The control modes are used mainly when the serial line is connected to a modem, although they may be used when talking to a terminal. Normally, it's easier to change your terminal's configuration than to change the default line behavior by using the control modes of `termios`.

Local Modes

These modes control various characteristics of the terminal. We specify local modes by setting flags in the `c_lflag` member of the `termios` structure, with the following macros:

- ECHO: Enable local echoing of input characters
- ECHOE: Perform a Backspace, Space, Backspace combination on receiving ERASE

- ECHOK: Perform erase line on the KILL character
- ECHONL: Echo newline characters
- ICANON: Enable canonical input processing (see the following)
- IEXTEN: Enable implementation specific functions
- ISIG: Enable signals
- NOFLSH: Disable flush on queue
- TOSTOP: Send background processes a signal on write attempts

The two most important flags here are `ECHO`, which allows you to suppress the echoing of typed characters, and `ICANON`, which switches the terminal between two very distinct modes of processing received characters. If the `ICANON` flag is set, the line is said to be in canonical mode; if not, the line is in non-canonical mode.

Special Control Characters

These are a collection of characters, like `Ctrl-C`, acted upon in special ways when the user types them. The `c_cc` array member of the `termios` structure contains the characters mapped to each of the supported functions. The position of each character (its index into the array) is defined by a macro, but there's no limitation that they must be control characters.

The `c_cc` array is used in two very different ways, depending on whether the terminal is set to canonical mode (i.e., the setting of the `ICANON` flag in the `c_lflag` member of `termios`).

It's important to realize that there is some overlap in the way the array index values are used for the two different modes. Because of this, you should never mix values from these two modes.

For canonical mode, the array indices are

- VEOF: EOF character
- VEOL: EOL character
- VERASE: ERASE character
- VINTR: INTR character
- VKILL: KILL character
- VQUIT: QUIT character
- VSUSP: SUSP character
- VSTART: START character
- VSTOP: STOP character

For non-canonical mode, the array indices are

- VINTR: INTR character
- VMIN: MIN value

- VQUIT: QUIT character
- VSUSP: SUSP character
- VTIME: TIME value
- VSTART: START character
- VSTOP: STOP character

Characters

Since the special characters and non-canonical MIN and TIME values are so important for more advanced input character processing, we explain them in some detail here.

| Character | Description |
|-----------|---|
| INTR | Causes the terminal driver to send a SIGINT signal to processes connected to the terminal. We discuss signals in more detail in Chapter 11. |
| QUIT | Causes the terminal driver to send a SIGQUIT signal to processes connected to the terminal. |
| ERASE | Causes the terminal driver to delete the last character on the line. |
| KILL | Causes the terminal driver to delete the entire line. |
| EOF | Causes the terminal driver to pass all characters on the line to the application reading input. If the line is empty, a <code>read</code> call will return zero characters as though a <code>read</code> had been attempted at the end of a file. |
| EOL | Acts as a line terminator in addition to the more usual newline character. |
| SUSP | Causes the terminal driver to send a SIGSUSP signal to processes connected to the terminal. If your UNIX supports job control, the current application will be suspended. |
| STOP | Acts to “flow off;” that is, prevent further output to the terminal. It’s used to support XON/XOFF flow control and is usually set to the ASCII XOFF character, Ctrl+S. |
| START | Restarts output after a STOP character, often the ASCII XON character. |

The TIME and MIN Values

The values of TIME and MIN are used only in non-canonical mode and act together to control the reading of input. Together, they control what happens when a program attempts to read a file descriptor associated with a terminal.

There are four cases:

- MIN = 0 and TIME = 0: In this case, a `read` will always return immediately. If some characters are available, they will be returned; if none are available, `read` will return zero and no characters will have been read.

- ❑ MIN = 0 and TIME > 0: In this case, the `read` will return when any character is available to be read or when TIME tenths of a second have elapsed. If no character was read because the timer expired, `read` will return zero. Otherwise, it will return the number of characters read.
- ❑ MIN > 0 and TIME = 0: In this case, the `read` will wait until MIN characters can be read and then return that number of characters. Zero is returned on end of file.
- ❑ MIN > 0 and TIME > 0: This is the most complex case. When `read` is called, it waits for a character to be received. When the first character is received, and every subsequent time a character is received, an inter-character timer is started (or restarted if it was already running). The `read` will return when either MIN characters can be read or the inter-character time of TIME tenths of a second expires. This can be useful for telling the difference between a single press of the Escape key and the start of a function key escape sequence. Be aware, though, that network communications or high processor loads neatly erase such fine timing information.

By setting non-canonical mode and using the MIN and TIME values, programs can perform character-by-character processing of input.

Accessing Terminal Modes from the Shell

If you want to see the `termios` settings that are being used while you're using the shell, you can get a list using the command:

```
$ stty -a
```

On our Linux systems, which have some extensions to the standard `termios`, the output is

```
speed 38400 baud; rows 44; columns 109; line = 0;
intr = ^C; quit = ^\; erase = ^?; kill = ^U; eof = ^D; eol = <undef>; eol2 =
<undef>; start = ^Q; stop = ^S;
susp = ^Z; rprnt = ^R; werase = ^W; lnext = ^V; flush = ^O; min = 1; time = 0;
-parenb -parodd cs8 -hupcl -cstopb cread -clocal -crtscscts
-ignbrk -brkint -ignpar -parmrk -inpck -istrip -inlcr -igncr icrnl ixon -ixoff -
iuclc -ixany -imaxbel
opost -olcuc -ocrnrl onlcr -onocr -onlret -ofill -ofdel nl0 cr0 tab0 bs0 vt0 ff0
isig icanon iexten echo echoe echok -echonl -noflsh -xcase -tostop -echopt echoctl
echoke
```

Among other things, we can see that the EOF character is Ctrl+D and that echoing is enabled. When you're experimenting with terminal control, it's very easy to get the terminal left in a nonstandard state, which makes using it very difficult. There are several ways out of this difficulty.

The first method is, if your version of `stty` supports it, to use the command

```
$ stty sane
```

If you have lost the mapping of the carriage return key to the newline character (which terminates the line), you may need to enter `stty sane`, but rather than press Enter, press Ctrl+J (which is the newline character).

The second method is to use the `stty -g` command to write the current `stty` setting in a form ready to reread. On the command line, you can use

```
$ stty -g > save_stty
..
<experiment with settings>
..
$ stty $(cat save_stty)
```

You still may need to use Ctrl+J rather than Enter for the final `stty` command. You can use the same technique in a shell script:

```
save_stty=$(stty -g)
<alter stty settings>
stty $save_stty
```

If you're really stuck, the third method is to go to a different terminal, use the `ps` command to find the shell you have made unusable, and then use `kill HUP <process id>` to force the shell to terminate. Since `stty` parameters are always reset before a logon prompt is issued, you should be able to log in normally.

Setting Terminal Modes from the Command Prompt

We can also use the `stty` command to set the terminal modes directly from the command prompt.

To set a mode in which our shell script could perform single character reads, we need to turn off canonical mode and set `MIN` to 1 and `TIME` to 0. The command is

```
$ stty raw -echo min 1 time 0
```

Now that the terminal is set to read characters immediately, you can try to run our first program, `menu1`, again. You should find it works as originally intended.

We also could improve our attempt to check for a password (Chapter 2) by turning echoing off before we prompt for the password. The command to do this is

```
$ stty raw -echo
```

Remember to use stty echo to turn echoing back on after you try this!

Terminal Speed

The final function served by the `termios` structure is manipulating the line speed. No members are defined for terminal speed; instead, it's set by function calls. Input and output speeds are handled separately.

The four call prototypes are

```
#include <termios.h>

speed_t cfgetispeed(const struct termios *);
speed_t cfgetospeed(const struct termios *);
```

```
int cfsetispeed(struct termios *, speed_t speed);
int cfsetspeed(struct termios *, speed_t speed);
```

Notice that these act on a `termios` structure, not directly on a port. This means that to set a new speed, you must read the current settings with `tcgetattr`, set the speed using one of the above calls, and then write the `termios` structure back using `tcsetattr`. Only after the call to `tcsetattr` will the line speed be changed.

Various values are allowed for `speed` in the function calls above, but the most important are

- B0: Hang up the terminal
- B1200: 1200 baud
- B2400: 2400 baud
- B9600: 9600 baud
- B19200: 19200 baud
- B38400: 38400 baud

There are no speeds greater than 38400 defined by the standard and no standard method of supporting serial ports at speeds greater than this.

Some systems, including Linux, define B57600, B115200, and B230400 for selecting faster speeds. If you're using an earlier version of Linux and these constants are unavailable, you can use the command `setserial` to obtain nonstandard speeds of 57600 and 115200. In this case, these speeds will be used when B38400 is selected. Both of these methods are nonportable, so be careful when you're using them.

Additional Functions

There are a small number of additional functions for the control of terminals. These work directly on file descriptors, without needing to get and set `termios` structures. Their definitions are

```
#include <termios.h>

int tcdrain(int fd);
int tcflow(int fd, int flowtype);
int tcflush(int fd, int in_out_selector);
```

The functions have the following purposes:

- `tcdrain` causes the calling program to wait until all queued output has been sent.
- `tcflow` is used to suspend or restart output.
- `tcflush` can be used to flush input, output, or both.

Now that we've covered the rather large subject of the `termios` structure, let's look at a few practical examples. Possibly the simplest is the disabling of echo to read a password. We do this by turning off the `ECHO` flag.

Try It Out—A Password Program with `termios`

- Our password program, `password.c`, begins with the following definitions:

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

#define PASSWORD_LEN 8

int main()
{
    struct termios initialrsettings, newrsettings;
    char password[PASSWORD_LEN + 1];
```

- Next, add a line to get the current settings from the standard input and copy them into the `termios` structure that we created previously.

```
tcgetattr(fileno(stdin), &initialrsettings);
```

- Make a copy of the original settings to replace them at the end. Turn off the `ECHO` flag on the `newrsettings` and ask the user for their password:

```
newrsettings = initialrsettings;
newrsettings.c_lflag |= ~ECHO;

printf("Enter password: ");
```

- Next, set the terminal attributes to `newrsettings` and read in the password. Lastly, reset the terminal attributes to their original setting and print the password to render all the previous effort useless.

```
if(tcsetattr(fileno(stdin), TCSAFLUSH, &newrsettings) != 0) {
    fprintf(stderr, "Could not set attributes\n");
}
else {
    fgets(password, PASSWORD_LEN, stdin);
    tcsetattr(fileno(stdin), TCSANOW, &initialrsettings);
    fprintf(stdout, "\nYou entered %s\n", password);
}
exit(0);
}
```

How It Works

```
$ ./password
Enter password:
You entered hello
$
```

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In this example, the word `hello` is typed but not echoed at the `Enter password:` prompt. No output is produced until the user presses Enter.

We're careful to change only the flags we need to change, using the construct `x &= ~FLAG` (which clears the bit defined by `FLAG` in the variable `x`). If needed, we could use `x |= FLAG` to set a single bit defined by `FLAG`, although this wasn't necessary in the example above.

When we're setting the attributes, we use `TCSAFLUSH` to discard any typeahead, characters users enter before the program is ready to read them. This is a good way of encouraging users not to start typing their password until echo has been turned off. We also restore the previous setting before our program terminates.

Another common use of the `termios` structure is to put the terminal into a state where we can read each character as it is typed. We do this by turning off canonical mode and using the `MIN` and `TIME` settings.

Try It Out—Reading Each Character

1. Using our new knowledge, we can make changes to our menu program. The following code bears much resemblance to `password.c`, but needs to be inserted into `menu3.c` to make our new program, `menu4.c`. For a start, we must include a new header file at the top of the program:

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

2. Then we need to declare a couple of new variables in the main function:

```
int choice = 0;
FILE *input;
FILE *output;
struct termios initial_settings, new_settings;
```

3. We need to change the terminal's characteristics before we call the `getchoice` function, so that's where we place these lines:

```
fprintf(stderr, "Unable to open /dev/tty\n");
exit(1);
}
tcgetattr(fileno(input), &initial_settings);
new_settings = initial_settings;
new_settings.c_lflag &= ~ICANON;
new_settings.c_lflag &= ~ECHO;
new_settings.c_cc[VMIN] = 1;
new_settings.c_cc[VTIME] = 0;
if(tcsetattr(fileno(input), TCSANOW, &new_settings) != 0) {
    fprintf(stderr, "could not set attributes\n");
}
```

4. We should also return the settings to their original values before exiting

```
do {
    choice = getchoice("Please select an action", menu, input, output);
```

```

        printf("You have chosen: %c\n", choice);
    } while (choice != 'q');
    tcsetattr(fileno(input), TCSANOW, &initial_settings);
    exit(0);
}

```

- 5.** We need to check against carriage returns \r now that we're in non-canonical mode, because the default mapping of CR to LF is no longer being performed.

```

do {
    selected = fgetc(in);
} while (selected == '\n' || selected == '\r');

```

- 6.** Unfortunately, if the user now types Ctrl+C at our program, the program will terminate. We can disable processing of these special characters by clearing the ISIG flag in the local modes. Add the following line to main.

```
new_settings.c_lflag &= ~ISIG;
```

If we put these changes into our menu program, we now get an immediate response and the character we type isn't echoed

```

$ ./menu4
Choice: Please select an action
a - add new record
d - delete record
q - quit
You have chosen: a
Choice: Please select an action
a - add new record
d - delete record
q - quit
You have chosen: q
$ 

```

If we type Ctrl+C, it's passed directly to the program and treated as an incorrect choice.

Terminal Output

Using the `termios` structure, we have control over keyboard input, but it would be good to have the same level of control over the way a program's output is presented on the screen. We used `printf` at the beginning of the chapter to output characters to the screen, but with no way of placing the output at a particular position on the screen.

Terminal Type

Many UNIX systems are used with terminals, although in many cases today, the “terminal” may actually be a PC running a terminal program. Historically, there have been a very large number of hardware terminals from different manufacturers. Although they nearly all use escape sequences (a string of characters

starting with the escape character) to provide control over the position of the cursor and other attributes, such as bold and blinking, they are generally not very well standardized in the way they do this. Some older terminals also have different scrolling capabilities that may or may not erase when backspace is sent, and so on.

There is an ANSI standard set of escape sequences (mostly based on the sequences used in the Digital Equipment Corporation VT series terminals, but not identical). Many software terminal programs provide an emulation of a standard hardware terminal, often VT100, VT220, or ANSI, and sometimes others as well.

This variety of hardware terminals would be a major problem for programmers wishing to write software that controls the screen and runs on many terminal types. For example, an ANSI terminal uses the sequence Escape+[+A to move the cursor up one line. An ADM-3a terminal (very common some years ago) uses the single control character Ctrl+K.

Writing a program that can deal with the many different types of terminals that might be connected to a UNIX system would seem to be an extremely daunting task. The program would need different source code for each type of terminal.

Not surprisingly, there is a solution in a package known as `terminfo`. Instead of each program having to cater for every sort of terminal, the program looks up a database of terminal types to get the correct information. In most modern UNIX systems, including Linux, this has been integrated with another package called `curses`, which we will learn about in the next chapter.

On Linux, we may have to use the implementation of `curses` known as `ncurses`, and include `ncurses.h` to provide prototypes for our `terminfo` functions. The `terminfo` functions themselves are declared in their own header file, `term.h`. Or at least that used to be the case. With newer Linux versions, there's a blurring of the line between `terminfo` and `ncurses` to the point where many programs requiring `terminfo` functions must also include the `ncurses` header file. To confuse matters further, recent Linux distributions also provide a standard `curses` header file and library to be more compatible with UNIX programs. On these distributions we recommend using `curses.h` and `-lcurses`.

Identify Your Terminal Type

The Linux environment contains a variable, `TERM`, which is set to the type of terminal being used. It's usually set automatically by the system at logon time. The system administrator may set a default terminal type for each of the directly connected terminals and may arrange for remote, networked users to be prompted for a terminal type. The value of `TERM` can be negotiated via `telnet` and is passed by `rlogin`.

A user can query the shell to discover the system's idea of the terminal he or she is using.

```
$ echo $TERM
xterm
$
```

In this case, the shell is being run from a program called `xterm`, a terminal emulator for the X Window System, or a program that provides similar functionality such as KDE's Konsole or GNOME's gnome-terminal.

The `terminfo` package contains a database of capabilities and escape sequences for a large number of terminals and provides a uniform programming interface for using them. A single program can then be written that will take advantage of future terminals as the database is extended, rather than each application having to provide support for the many different terminals.

The `terminfo` capabilities are described by attributes. These are stored in a set of compiled `terminfo` files, which are conventionally found in `/usr/lib/terminfo` or `/usr/share/terminfo`. For each terminal (and many printers, which can also be specified in `terminfo`) there's a file that defines its capabilities and how its features can be accessed. To avoid creating a very large directory, the actual files are stored in subdirectories, where the subdirectory name is simply the first letter of the terminal type. Thus, the VT100 definition is found in `...terminfo/v/vt100`.

`terminfo` files are written one per terminal type in a source format that is (just about!) readable, then compiled using the `tic` command into a more compact and efficient format for use by application programs. Curiously, the X/Open specification refers to source and compiled format definitions, but fails to mention the `tic` command for actually getting from source to compiled formats. You can use the `infocmp` program to print a readable version of a compiled `terminfo` entry.

Here's an example `terminfo` file for the VT100 terminal:

```
$ infocmp vt100
vt100|vt100-am|dec vt100 (w/advanced video),
am, mir, msgr, xenl, xon,
cols#80, it#8, lines#24, vt#3,
acsc=``aaffggjjkkllmmmnnooppqqrsssttuuvwxyz{{||}}~~,
bel=G, blink=\E[5m$<2>, bold=\E[1m$<2>,
clear=\E[H\E[J$<50>, cr=\r, csr=\E[%i%p1%d;%p2%dr,
cub=\E[%p1%D, cub1=\b, cud=\E[%p1%dB, cud1=\n,
cuf=\E[%p1%DC, cuf1=\E[C$<2>,
cup=\E[%i%p1%d;%p2%dH$<5>, cuu=\E[%p1%dA,
cuu1=\E[A$<2>, ed=\E[J$<50>, el=\E[K$<3>,
el1=\E[1K$<3>, enacs=\E(B\E)0, home=\E[H, ht=\t,
hts=\EH, ind=\n, ka1=\EOq, ka3=\EOS, kb2=\EOr, kbs=\b,
kc1=\EOp, kc3=\EOn, kcub1=\EOD, kcud1=\EOB,
kcuf1=\EOC, kcuu1=\EOA, kent=\EOM, kf0=\EOy, kf1=\EOP,
kf10=\EOx, kf2=\EOQ, kf3=\EOR, kf4=\EOS, kf5=\EOT,
kf6=\EOu, kf7=\EOv, kf8=\EOl, kf9=\Eow, rc=\E8,
rev=\E[7m$<2>, ri=\EM$<5>, rmacs=^O, rmkx=\E[?1l\E>,
rms0=\E[m$<2>, rmul=\E[m$<2>,
rs2=\E>\E[?31\E[?41\E[?51\E[?7h\E[?8h, sc=\E7,
sgr=\E[0%?%p1%p6%|%t;1%,%?%p2%t;4%,%?%p1%p3%|%t;7%;%?%p4%t;5%;m%?%p9%t^N%e^O%;,
sgr0=\E[m^O$<2>, smacs=^N, smkx=\E[?1h\E=,
smso=\E[1;7m$<2>, smul=\E[4m$<2>, tbc=\E[3g,
```

Each `terminfo` definition consists of three types of entry. Each entry is called a *capname* and defines a terminal capability.

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Boolean capabilities simply indicate whether a terminal supports a particular feature. For example, the Boolean capability `xon` is present if the terminal supports XON/XOFF flow control.

Numeric capabilities define sizes, such as `lines`, the number of lines on the screen, and `cols`, the number of columns on the screen. The actual number is separated from the capability name by a # character. To define a terminal as having 80 columns and 24 lines, we would write `cols#80, lines#24`.

String capabilities are slightly more complex. They are used for two distinct types of capability: defining output strings needed to access terminal features and defining the input strings that will be received when the user presses certain keys, normally function keys or special keys on the numeric keypad. Some string capabilities are quite simple, such as `e1`, which is “erase to end of line.”. On a VT100 terminal, the escape sequence needed to do this is `Esc+[+K`. This is written `e1=\E[K` in `terminfo` source format.

Special keys are defined in a similar way. For example, the F1 function key on a VT100 sends the sequence `Esc+O+P`. This is defined as `kf1=\EOP`.

Things get slightly more complicated where the escape sequence needs some parameters. Most terminals can move the cursor to a specified row and column location. It’s clearly impractical to have a different capability for each possible cursor location, so a generic capability string is used, with parameters defining the values to be inserted when the strings are used. For example, a VT100 terminal uses the sequence `Esc+[+<row>+;+<col>+H` to move the cursor to a specified location. In `terminfo` source format, this is written with the rather intimidating `cup=\E[%i%p1%d;%p2%dH$<5>`.

This means

- \E: Send Escape
- [: Send the [character
- %i: Increment the arguments
- %p1: Put the first argument on the stack
- %d: Output the number on the stack as a decimal number
- ;: Send the ; character
- %p2: Put the second argument on the stack
- %d: Output the number on the stack as a decimal number
- H: Send the H character

This seems more complex than it might be, but allows for the parameters to be in a fixed order, independent of which order the terminal expects them to appear in the final escape sequence. The `%i` to increment the arguments is required because standard cursor addressing is specified as starting from (0,0) at the top left of the screen, but the VT100 addresses this location as (1,1). The final `$<5>` indicates that a delay equivalent to five character output times is required to allow the terminal to process the cursor movement.

We could define many, many capabilities, but, fortunately, most UNIX and Linux systems come with most terminals predefined. If you need to add a new terminal, you'll find the complete capability list in the `terminfo` manual page. A good starting point is usually to locate a terminal that is similar to your new terminal and define the new terminal as a variation on the existing terminal or to work through the capabilities one at a time, updating them where required.

The standard reference outside the man pages is the *Termcap and Terminfo* by John Strang, Linda Mui, and Tim O'Reilly (O'Reilly).

Using `terminfo` Capabilities

Now that we know how to define terminal capabilities, we need to learn how to access them. When we're using `terminfo`, the first thing we need to do is set up the terminal type by calling `setupterm`. This will initialize a `TERMINAL` structure for the current terminal type. We'll then be able to ask for capabilities for the terminal and use its facilities. We do this with the `setupterm` call like this:

```
#include <term.h>

int setupterm(char *term, int fd, int *errret);
```

The `setupterm` library function sets the current terminal type to that specified by the parameter `term`. If `term` is a null pointer, the `TERM` environment variable will be used. An open file descriptor to be used for writing to the terminal must be passed as `fd`. The function outcome is stored in the integer variable pointed to by `errret`, if this isn't a null pointer. The value written will be

- 1: No `terminfo` database
- 0: No matching entry in `terminfo` database
- 1: Success

The `setupterm` function returns the constant `OK` if it succeeds and `ERR` if it fails. If `errret` is set to a null pointer, `setupterm` will print a diagnostic message and exit the program if it fails, as in this example:

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

int main()
{
    setupterm("unlisted", fileno(stdout), (int *)0);
    printf("Done.\n");
    exit(0);
}
```

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The output from running this program on your system may not be exactly that given here, but the meaning should be clear enough. Done . isn't printed, because `setupterm` caused the program to exit when it failed.

```
$ cc -o badterm badterm.c -I/usr/include/ncurses -lncurses
$ badterm
'unlisted': unknown terminal type.
$
```

Notice the compilation line in the example: On this Linux system, the `ncurses` header file is in the directory `/usr/include/ncurses`, so we have to specifically instruct the compiler to look there with the `-I` option. Some Linux systems have arranged for the `ncurses` library to be available in the standard locations. On these systems, we can simply include `curses.h`, and specify `-lcurses` for the library.

For our menu choice function, we would like to be able to clear the screen, move the cursor around the screen, and write at different locations on the screen. Once we've called `setupterm`, we can access the `terminfo` capabilities with three function calls, one for each of the capability types:

```
#include <term.h>

int tigetflag(char *capname);
int tigetnum(char *capname);
char *tigetstr(char *capname);
```

The functions `tigetflag`, `tigetnum`, and `tigetstr` return the value of Boolean, numeric, and string `terminfo` capabilities, respectively. On failure (for example, if the capability isn't present), `tigetflag` returns `-1`, `tigetnum` returns `-2`, and `tigetstr` returns `(char *) -1`.

Let's use the `terminfo` database to find out the size of the terminal by retrieving the `cols` and `lines` capabilities with this program, `sizeterm.c`:

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

int main()
{
    int nrows, ncolumns;

    setupterm(NULL, fileno(stdout), (int *)0);
    nrows = tigetnum("lines");
    ncolumns = tigetnum("cols");
    printf("This terminal has %d columns and %d rows\n", ncolumns, nrows);
    exit(0);
}
$ echo $TERM
vt100
$ sizeterm
This terminal has 80 columns and 24 rows
$
```

If we run the program inside a window on a workstation, we'll get answers that reflect the current window's size:

```
$ echo $TERM
xterm
$ sizeterm
This terminal has 88 columns and 40 rows
$
```

If we use `tigetstr` to retrieve the cursor motion capability (`cup`) of the `xterm` terminal type, we get a parameterized answer: `\E[%p1%d;%p2%dH`.

This capability requires two parameters: a row and column to move the cursor to. Both coordinates are measured starting at zero from the top left corner of the screen.

We can substitute the parameters in a capability with actual values using the `tparm` function. Up to nine parameters can be substituted and a usable escape sequence is returned.

```
#include <term.h>

char *tparm(char *cap, long p1, long p2, ..., long p9);
```

Once we've constructed the terminal escape sequence with `tparm`, we must send it to the terminal. To process this properly, you shouldn't send the string to the terminal with `printf`. Instead, use one of the special functions provided that correctly process any required delays while the terminal completes an operation. These functions are

```
#include <term.h>

int putp(char *const str);
int tputs(char *const str, int affcnt, int (*putfunc)(int));
```

On success, `putp` returns `OK`; on failure, it returns `ERR`. The `putp` function takes the terminal control string and sends it to `stdout`.

So, to move to row 5, column 30 of the screen, we can use a block of code like this:

```
char *cursor;
char *esc_sequence;
cursor = tigetstr("cup");
esc_sequence = tparm(cursor,5,30);
putp(esc_sequence);
```

The `tputs` function is provided for those situations when the terminal isn't accessed via `stdout` and allows you to specify the function to be used for outputting the characters. It returns the result of the user-specified function `putfunc`. The `affcnt` parameter is intended to indicate the number of lines affected by the change. It's normally set to 1. The function used to output the string must have the same parameters and return type as the `putchar` function. Indeed, `putp(string)` is equivalent to the call `tputs(string, 1, putchar)`. We'll see `tputs` used with a user-specified output function in the next example.

Be aware that some older Linux distributions define the final parameter of the `tputs` function as `int (*putfunc)(char)`, which would oblige us to alter the definition of the `char_to_terminal` function in our next “Try It Out” section.

If you consult the manual pages for information on `tparm` and terminal capabilities, you may come across the `tgoto` function. The reason we haven’t used this function, when it apparently offers an easier solution to moving the cursor, is that the X/Open specification (Single UNIX Specification Version 2) does not include them as of the 1997 edition. We therefore recommend that you don’t use any of these functions in new programs.

We’re almost ready to add screen handling to our menu choice function. The only thing left to do is to clear the screen simply by using `clear`. Some terminals don’t support the `clear` capability, which leaves the cursor at the top left corner of the screen. In this case, we can position the cursor at the top left corner and use the “delete to end of display” command, `ed`.

Putting all this information together, we’ll write the final version of our sample menu program, `screen-menu.c`, where we “paint” the options on the screen for the user to pick a valid one.

Try It Out—Total Terminal Control

We can rewrite the `getchoice` function from `menu4.c` to give us total terminal control. In this listing, the main function has been omitted because it isn’t changed. Other differences from `menu4.c` are highlighted.

```
#include <stdio.h>
#include <unistd.h>
#include <termios.h>
#include <term.h>
#include <curses.h>

static FILE *output_stream = (FILE *)0;

char *menu[] = {
    "a - add new record",
    "d - delete record",
    "q - quit",
    NULL,
};

int getchoice(char *greet, char *choices[], FILE *in, FILE *out);
int char_to_terminal(int char_to_write);

int main()
{
    ...
}
```

```
int getchoice(char *greet, char *choices[], FILE *in, FILE *out)
{
    int chosen = 0;
    int selected;
    int screenrow, screencol = 10;

    char **option;
    char *cursor, *clear;

    output_stream = out;

    setupterm(NULL, fileno(out), (int *) 0);
    cursor = tigetstr("cup");
    clear = tigetstr("clear");

    screenrow = 4;
    tputs(clear, 1, (int *) char_to_terminal);
    tputs(tparm(cursor, screenrow, screencol), 1, char_to_terminal);
    fprintf(out, "Choice: %s, %s", greet);
    screenrow += 2;
    option = choices;
    while(*option) {
        tputs(tparm(cursor, screenrow, screencol), 1, char_to_terminal);
        fprintf(out, "%s", *option);
        screenrow++;
        option++;
    }
    fprintf(out, "\n");

    do {
        fflush(out);
        selected = fgetc(in);
        option = choices;
        while(*option) {
            if(selected == *option[0]) {
                chosen = 1;
                break;
            }
            option++;
        }
        if(!chosen) {
            tputs(tparm(cursor, screenrow, screencol), 1, char_to_terminal);
            fprintf(out, "Incorrect choice, select again\n");
        }
    } while(!chosen);
    tputs(clear, 1, char_to_terminal);
    return selected;
}

int char_to_terminal(int char_to_write)
{
    if (output_stream) putc(char_to_write, output_stream);
    return 0;
}
```

How It Works

The rewritten `getchoice` function implements the same menu as in previous examples, but the output routines are modified to make use of the `terminfo` capabilities. If you want to see the `You have chosen:` message for more than a moment before the screen is cleared, ready for the next selection, add a call to `sleep` in the `main` function:

```
do {
    choice = getchoice("Please select an action", menu, input, output);
    printf("\nYou have chosen: %c\n", choice);
    sleep(1);
} while (choice != 'q');
```

The last function in this program, `char_to_terminal`, includes a call to the `putc` function, which we mentioned in Chapter 3.

To round off this chapter, we'll look at a quick example of how to detect keystrokes.

Detecting Keystrokes

People who have programmed MS-DOS often look for the Linux equivalent of the `kbhit` function, which detects whether a key has been pressed without actually reading it. Unfortunately, they fail to find it, since there's no direct equivalent. UNIX programmers don't notice the omission because UNIX is normally programmed in such a way that programs should rarely, if ever, busy-wait on an event. Since this is the normal use for `kbhit`, it's rarely missed on UNIX and Linux.

However, when you're porting programs from MS-DOS, it's often convenient to emulate `kbhit`, which you can do using the non-canonical input mode.

Try It Out—Your Very Own `kbhit`

1. We begin with the standard headings and declare a couple of structures for the terminal settings. `peek_character` is used in the test of whether a key has been pressed. Then we prototype the functions we'll be using later.

```
#include <stdio.h>
#include <termios.h>
#include <term.h>
#include <curses.h>
#include <unistd.h>
static struct termios initial_settings, new_settings;
static int peek_character = -1;
void init_keyboard();
void close_keyboard();
int kbhit();
int readch();
```

- 2.** The main function calls `init_keyboard` to configure the terminal, then loops once a second, calling `kbhit` each time it does. If the key hit is `q`, `close_keyboard` returns the behavior to normal and the program exits.

```
int main()
{
    int ch = 0;

    init_keyboard();
    while(ch != 'q') {
        printf("looping\n");
        sleep(1);
        if(kbhit()) {
            ch = readch();
            printf("you hit %c\n", ch);
        }
    }

    close_keyboard();
    exit(0);
}
```

- 3.** `init_keyboard` and `close_keyboard` configure the terminal at the start and end of the program.

```
void init_keyboard()
{
    tcgetattr(0,&initial_settings);
    new_settings = initial_settings;
    new_settings.c_lflag &= ~ICANON;
    new_settings.c_lflag &= ~ECHO;
    new_settings.c_lflag &= ~ISIG;
    new_settings.c_cc[VMIN] = 1;
    new_settings.c_cc[VTIME] = 0;
    tcsetattr(0, TCSANOW, &new_settings);
}
void close_keyboard()
{
    tcsetattr(0, TCSANOW, &initial_settings);
}
```

- 4.** Now for the function that checks for the keyboard hit:

```
int kbhit()
{
    char ch;
    int nread;

    if(peek_character != -1)
        return 1;
    new_settings.c_cc[VMIN]=0;
    tcsetattr(0, TCSANOW, &new_settings);
    nread = read(0,&ch,1);
    new_settings.c_cc[VMIN]=1;
    tcsetattr(0, TCSANOW, &new_settings);
```

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```
    if(nread == 1) {
        peek_character = ch;
        return 1;
    }
    return 0;
}
```

5. The character pressed is read by the next function, `readch`, which then resets `peek_character` to -1 for the next loop.

```
int readch()
{
    char ch;

    if(peek_character != -1) {
        ch = peek_character;
        peek_character = -1;
        return ch;
    }
    read(0,&ch,1);
    return ch;
}
```

When we run the program, we get

```
$ ./kbhit
looping
looping
looping
you hit h
looping
looping
looping
you hit d
looping
you hit q
$
```

How It Works

The terminal is configured in `init_keyboard` to read one character before returning (`MIN=1, TIME=0`). `kbhit` changes this behavior to check for input and return immediately (`MIN=0, TIME=0`) and then restores the original settings before exiting.

Notice that we have to read the character that has been pressed but that we store it locally, ready for returning when it's required.

Virtual Consoles

Linux provides a feature called virtual consoles. A number of terminal devices are available, all of which share the PC's screen, keyboard, and mouse. Typically, a Linux installation will be configured for 12 of these virtual consoles.

The virtual consoles are made available through the character devices `/dev/ttyn` where `n` is a number, starting at 1.

If you use a text login for your Linux system, you will be presented with a login prompt once Linux is up and running. You then log in using a username and password. The device that you are using at this point is the first virtual console, the terminal device `/dev/tty1`.

Using `who` and `ps`, we can see who is logged in and the shell and programs being executed on this virtual console:

```
$ who
neil      tty1      Mar  8 18:27
$ ps -e
  PID TTY      TIME CMD
 1092 tty1      00:00:00 login
 1414 tty1      00:00:00 bash
 1431 tty1      00:00:00 emacs
```

Here, we can see in this cut-down output that user `neil` is logged in and running Emacs on the PC console device `/dev/tty1`.

Linux will normally start a `getty` process running on the first six virtual consoles so that it is possible to log in six times using the same screen, keyboard, and mouse. We can see these processes with `ps`:

```
$ ps -e
  PID TTY      TIME CMD
 1092 tty1      00:00:00 login
 1093 tty2      00:00:00 mingetty
 1094 tty3      00:00:00 mingetty
 1095 tty4      00:00:00 mingetty
 1096 tty5      00:00:00 mingetty
 1097 tty6      00:00:00 mingetty
```

Here, we can see the SuSE default `getty` program, `mingetty`, running on five further virtual consoles, waiting for a user to log in.

We can switch between virtual consoles using a special key combination: `Ctrl+Alt+F<N>` where `N` is the number of the virtual console we wish to switch to. So, to switch to the second virtual console, we would press `Alt+Ctrl+F2`, and `Ctrl+Alt+F1` to return to the first console. (When switching from text logins rather than graphical logins, the combination `Ctrl+F<N>` also works.)

If Linux starts a graphical login, either by `startx` or via a display manager such as `xdm`, the X Window System will start up using the first free virtual console, normally `/dev/tty7`. When using the X Window System, you can switch out to a text console with `Ctrl+Alt+F<N>` and back with `Ctrl+Alt+F7`.

It is possible to run more than one X session on Linux. If you do this, for example, with

```
$ startx - :1
```

Linux will start the X server on the next free virtual console, in this case, `/dev/tty8`, and it is then possible to switch between them with `Ctrl+Alt+F8` and `Ctrl+Alt+F7`.

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In all other respects, the virtual consoles behave as a terminal, as described in this chapter. If a process has the correct permissions, the virtual consoles may be opened, read from, and written to in the same way as a normal terminal.

Pseudo Terminals

Many UNIX-like systems, including Linux, have a feature called pseudo-terminals. These are devices that behave much like the terminals we have been using in this chapter, except that they have no associated hardware. They can be used to provide a terminal-like interface to other programs.

For example, using pseudo-terminals, it is possible to make two chess programs play each other, despite the fact that the programs themselves were designed to interact with a human player at a terminal. An application acting as an intermediary passes one program's moves to the other and vice versa. It uses pseudo-terminals to fool the programs into behaving normally without a terminal being present.

Pseudo-terminals were at one time implemented in a system-specific manner, if at all. They have now been incorporated into the Single UNIX Specification as UNIX98 Pseudo-Terminals or PTYs.

Summary

In this chapter, we've learned about three different aspects of controlling the terminal. In the first part of the chapter, we learned about detecting redirection and how to talk directly to a terminal even when the standard file descriptors have been redirected. We covered the hardware model for terminals and a little of their history. We then learned about the General Terminal Interface and the `termios` structure that provides detailed control over Linux terminal handling. We also saw how to use the `terminfo` database and related functions to manage screen output in a terminal-independent fashion, and we looked at immediately detecting keystrokes. Finally, we discussed Linux virtual consoles and pseudo-terminals.

6

Managing Text-Based Screens with `curses`

In Chapter 5, we saw how to obtain much finer control over the input of characters and how to provide character output in a terminal-independent way. The problem with using the general terminal interface (GTI, or `termios`) and manipulating escape sequences with `tparm` and its related functions is that it requires a lot of lower-level code. For many programs, a higher-level interface would be more desirable. We would like to be able to simply draw on the screen and use a library of functions to take care of terminal dependencies automatically.

In this chapter, you'll learn about just such a library, the `curses` library. The `curses` standard is important as a halfway house between simple "line-based" programs and the fully graphical (and generally harder to program) X Window System programs, such as GTK/GNOME and Qt/KDE. Linux does have the `svgalib`, but that is not a UNIX standard library, so is not generally available in other UNIX-like operating systems. The `curses` library is used in many full-screen applications as a reasonably easy and terminal-independent way to write full-screen, albeit character-based, programs. It's almost always easier to write such programs with `curses` than to use escape sequences directly. `curses` can also manage the keyboard, providing an easy-to-use, nonblocking character input mode.

You may find that a few of the examples in this chapter don't always display on the plain Linux console exactly as you expect. There are occasions when the combination of the `curses` library and the terminal definition of the console get slightly out of step and the effect is usually some slightly odd layouts when using `curses`. However, you should find that if you use the X Window System, and use an `xterm` window to display the output, things should display as you expect.

In this chapter, we'll cover

- ❑ Using the `curses` library
- ❑ The concepts of `curses`
- ❑ Basic input and output control
- ❑ Multiple windows

- ❑ Keypad
- ❑ Color

We will finish by reimplementing the CD Collection program in C, summarizing what you've learned so far.

Compiling with curses

The `curses` library takes its name from its ability to optimize the movement of the cursor and minimize the updates needed on a screen, and hence, the number of characters that need to be sent to a text-based terminal. Although the number of characters output is much less important than it was in the days of dumb terminals and low-speed modems, the `curses` library survives as a useful addition to the programmer's toolkit.

Since `curses` is a library, to use it we must include a header file, function declarations, and macros from an appropriate system library. There have been several different implementations of `curses`. The original version appeared in BSD UNIX and was then incorporated into the System V flavors of UNIX, before being standardized by X/Open. Linux uses `ncurses` ("new `curses`"), a freeware emulation of System V Release 4.0 `curses` that was developed on Linux. This implementation is highly portable to other UNIX versions, although there are a few nonportable additional features included. There are even versions of `curses` for MS-DOS and Windows. If you find that the `curses` library bundled with your flavor of UNIX doesn't support some features, we suggest you try to obtain a copy of `ncurses` as an alternative; Linux users will almost certainly find they have `ncurses` already installed for them.

The X/Open specification defines two levels of `curses`: base and extended. Extended `curses` contains a somewhat motley crew of additional routines, including a range of functions for handling multicolumn characters and color manipulation routines. Apart from using color later in this chapter, we will be sticking mostly to the base functions.

When you're compiling `curses` programs, you must include the header file `curses.h`, and link against the `curses` library with `-lcurses`. On many Linux systems, the `curses` include and library files are just links to the `ncurses` equivalents.

You can check how your `curses` is setup by executing a `ls -l /usr/include/curses.h` command to look at the header files and a `ls -l /usr/lib/lib*curses*` command to check the library files. If you find that the `curses` files are links to `ncurses` files, then (using `#gcc`), you should be able to compile the files in this chapter using a command such as

```
$ gcc program.c -o program -lcurses
```

If, however, your `curses` setup is not automatically using `ncurses`, you may have to explicitly force the use of `ncurses` by including `ncurses.h`, rather than `curses.h`, and by executing a compile command such as this.

```
$ gcc -I/usr/include/ncurses program.c -o program -lncurses
```

where the `-I` option specifies the directory in which to search for the header file. The `Makefile` in the downloadable code assumes your setup uses `curses` by default, so you will have to change it or compile it by hand if this is not the case on your system.

If you're unsure how `curses` is set up on your system, refer to the manual pages for `ncurses`, or look for other online documentation; a common location is under `/usr/share/doc/`, where you may find a `curses` or `ncurses` directory, often with a version number appended.

Concepts

The `curses` routines work on screens, windows, and subwindows. A *screen* is the device (usually a terminal screen, but it could also be an `xterm` screen) to which we are writing. It occupies all the available display on that device. Of course, if it's a terminal window inside an X window, the screen is simply all the character positions available inside the terminal window. There is always at least one `curses` window, `stdscr`, that is the same size as the physical screen. You can create additional windows that are smaller than the screen. Windows can overlap each other and have many subwindows, but each subwindow must always be contained inside its parent window.

The `curses` library maintains two data structures that act like a map of the terminal screen, `stdscr`, and `curscr`.

`stdscr`, the more important of the two data structures, is updated when `curses` functions produce output. The `stdscr` data structure is the "standard screen." It acts in much the same way as `stdout`, the standard output, does for the `stdio` library. It's the default output window in `curses` programs. The `curscr` structure is similar, but holds what the displayed screen actually looks like at the current moment. Output written to `stdscr` doesn't appear on the screen until the program calls `refresh`, when the `curses` library compares the contents of `stdscr` (what the screen should look like) with the second structure `curscr` (what the screen currently looks like). `curses` then uses the differences between these two structures to update the screen.

Some `curses` programs need to know that `curses` maintains a `stdscr` structure, which is required as a parameter to a few `curses` functions. However, the actual `stdscr` structure is implementation-dependent and should never be accessed directly. `curses` programs should never need to use the `curscr` structure.

Thus, the process for the output of characters in a `curses` program is

1. Use `curses` functions to update a logical screen.
2. Ask `curses` to update the physical screen with `refresh`.

The advantage of a two-level approach, in addition to being much easier to program, is that `curses` screen updates are very efficient and, although this isn't so important on a console screen, it makes a considerable difference if you're running your program over a slow serial or modem link.

A `curses` program will make many calls to logical screen output functions, possibly moving the cursor all over the screen to get to the right position for writing text and drawing lines and boxes. At some stage, the user will need to see all of this output. When this happens, typically during a call to `refresh`,

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curses will calculate the optimum way of making the physical screen correspond to the logical screen. By using appropriate terminal capabilities and by optimizing cursor motions, curses will often be able to update the screen with far fewer characters being output than if all the screen writes had happened immediately.

The layout of the logical screen is a character array, arranged by lines and columns with the screen position (0,0) at the top left-hand corner, as shown in Figure 6-1.

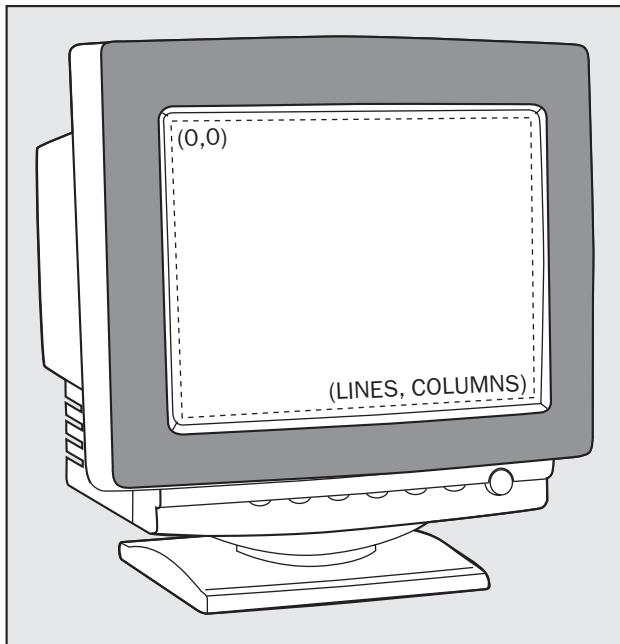


Figure 6-1

All the curses functions use coordinates with the y value (lines) before the x (columns) value. Each position holds not only the character for that screen location, but also its attributes. The attributes that can be displayed depend on the physical terminal's capabilities, but usually at least bold and underline are available. On Linux consoles, we usually also have reverse video and even color, which we will get to later in the chapter.

Since the curses library needs to create and destroy some temporary data structures, all curses programs must initialize the library before use and then allow curses to restore settings after use. This is done with a pair of function calls: `initscr` and `endwin`.

Try It Out—A Simple curses Program

Let's write a very simple curses program, `screen1.c`, to show these and other basic function calls in action. We'll then describe the function prototypes.

1. We add the `curses.h` header file and in the main function we make calls to initialize and reset the `curses` library.

```
#include <unistd.h>
#include <stdlib.h>
#include <curses.h>

int main() {
    initscr();

    ...

    endwin();
    exit(EXIT_SUCCESS);
}
```

2. In between, we add code to move the cursor to the point (5,15) on the logical screen, print "Hello World," and refresh the actual screen. Lastly, we use the call `sleep(2)` to suspend the program for two seconds so that we can see the output before the program ends.

```
move(5, 15);
printw("%s", "Hello World");
refresh();

sleep(2);
```

While the program is running, we see "Hello World" in the top-left quadrant of an otherwise blank screen, as shown in Figure 6-2.

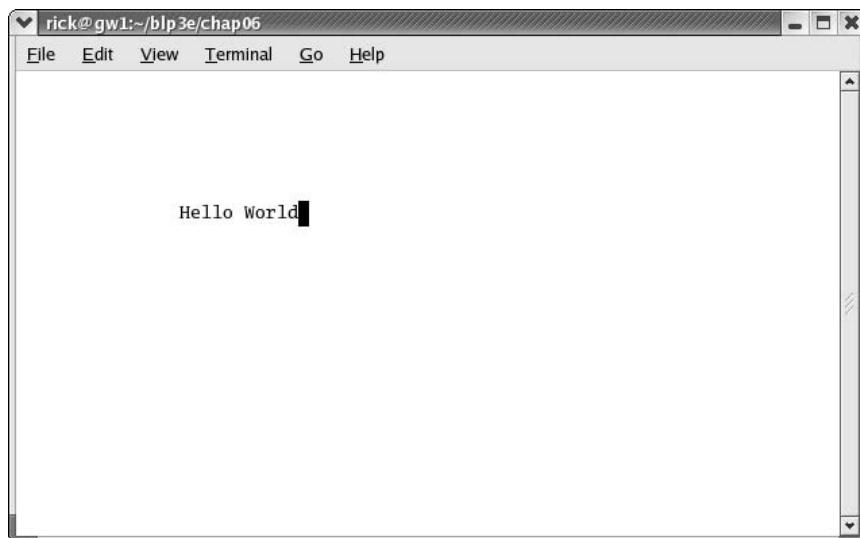


Figure 6-2

Initialization and Termination

As we've already seen, all curses programs must start with `initscr` and end with `endwin`. Here are their header file definitions:

```
#include <curses.h>

WINDOW *initscr(void);
int endwin(void);
```

The `initscr` function should only be called once in each program. The `initscr` function returns a pointer to the `stdscr` structure if it succeeds. If it fails, it simply prints a diagnostic error message and causes the program to exit.

The `endwin` function returns `OK` on success and `ERR` on failure. You can call `endwin` to leave `curses` and then later resume `curses` operation by calling `clearok(stdscr, 1)` and `refresh`. This effectively makes `curses` forget what the physical screen looks like and forces it to perform a complete redisplay.

Output to the Screen

There are several basic functions provided for updating the screen. These are

```
#include <curses.h>

int addch(const chtype char_to_add);
int addchstr(chtype *const string_to_add);
intprintw(char *format, ...);
int refresh(void);
int box(WINDOW *win_ptr, chtype vertical_char, chtype horizontal_char);
int insch(chtype char_to_insert);
int insertln(void);
int delch(void);
int deleteln(void);
int beep(void);
int flash(void);
```

`curses` has its own character type, `chtype`, which may have more bits than a standard `char`. In the standard Linux version of `ncurses`, `chtype` is actually a `typedef` for `unsigned long`.

The `add...` functions add the character or string specified at the current location. The `printw` function formats a string in the same way as `printf` and adds it to the current location. The `refresh` function causes the physical screen to be updated, returning `OK` on success and `ERR` if an error occurred. The `box` function allows you to draw a box around a window.

In standard `curses`, you may only use “normal” characters for the vertical and horizontal line characters. In extended `curses`, though, you can use the two defines `ACS_VLINE` and `ACS_HLINE` for a better-looking box. For this, your terminal needs to support line-drawing characters. Generally, these will work better in an `xterm` window than on the standard console, but support tends to be patchy, so we suggest you avoid them if portability is important.

The `insch` function inserts a character, moving existing characters right, though what will happen at the end of a line isn't specified and will depend on the terminal you're using. `insertln` inserts a blank line, moving existing lines down by one. The two `delete` functions are analogous to the two `insert` functions.

To make a sound, we can call `beep`. A very small number of terminals are unable to make any sound, so some `curses` setups will cause the screen to flash when `beep` is called. If you work in a busy office, where beeps can come from any number of machines, we might find you prefer this. As you might expect, `flash` causes the screen to flash, but if this isn't possible, it tries to make a sound on the terminal.

Reading from the Screen

We can read characters from the screen, although this facility isn't commonly used because normally it's easier to keep track of what was written. If you need it, it's done with the following functions.

```
#include <curses.h>

ctype inch(void);
int instr(char *string);
int innstr(char *string, int number_of_characters);
```

The `inch` function should always be available, but the `instr` and `innstr` functions are not always supported. The `inch` function returns a character and its attribute information from the current screen location of the cursor. Notice that `inch` doesn't return a character, but a `ctype`, while `instr` and `innstr` write to arrays of chars.

Clearing the Screen

There are four principal ways of clearing an area of the screen. These are

```
#include <curses.h>

int erase(void);
int clear(void);
int clrtoobot(void);
int clrtoeol(void);
```

The `erase` function writes blanks to every screen location. The `clear` function, like `erase`, clears the screen, but forces a screen redisplay by also calling `clearok`. `clearok` enforces a clear screen sequence and redisplay when the next `refresh` is called.

The `clear` function usually uses a terminal command that erases the entire screen, rather than simply attempting to erase any currently nonblank screen locations. This makes the `clear` function a reliable way of completely erasing the screen. The combination of `clear` followed by `refresh` can provide a useful redraw command.

`clrtoobot` clears the screen from the cursor position onward to the end of the screen, and `clrtoeol` clears from the cursor position to the end of the line the cursor is on.

Moving the Cursor

A single function is provided for moving the cursor, with an additional command for controlling where curses leaves the cursor after screen updates:

```
#include <curses.h>

int move(int new_y, int new_x);
int leaveok(WINDOW *window_ptr, bool leave_flag);
```

The `move` function simply moves the logical cursor position to the specified location. Remember that the screen coordinates are specified with (0,0) as the top left-hand corner of the screen. In most versions of `curses`, the two `extern` integers `_LINES` and `COLUMNS` contain the physical screen size and can be used to determine the maximum allowed values for `new_y` and `new_x`. Calling `move` won't, in itself, cause the physical cursor to move. It only changes the location on the logical screen at which the next output will appear. If you want the screen cursor to move immediately after calling `move`, follow it with a call to `refresh`.

The `leaveok` function sets a flag that controls where `curses` leaves the physical cursor after a screen update. By default, the flag is `false` and, after a refresh, the hardware cursor will be left in the same position on the screen as the logical cursor. If the flag is set to `true`, the hardware cursor may be left randomly, anywhere on the screen. Generally, the default option is preferred to ensure the cursor is left in a sensible location.

Character Attributes

Each `curses` character can have certain attributes that control how it's displayed on the screen, assuming that the display hardware can support the requested attribute. The defined attributes are `A_BLINK`, `A_BOLD`, `A_DIM`, `A_REVERSE`, `A_STANDOUT`, and `A_UNDERLINE`. You can use these functions to set attributes singly or collectively.

```
#include <curses.h>

int attron(chtype attribute);
int attroff(chtype attribute);
int attrset(chtype attribute);
int standout(void);
int standend(void);
```

The `attrset` function sets the `curses` attributes, `attron` and `attroff` turn on and off specified attributes without disturbing others, while `standout` and `standend` provide a more generic emphasized, or "stand out" mode. This is commonly mapped to reverse video on most terminals.

Try It Out—Moving, Inserting, and Attributes

Now that we know more about managing the screen, we can try out a more complex example, `moveadd.c`. For the purposes of this example, we'll include several calls to `refresh` and `sleep`, to enable you to see what the screen looks like at each stage. Normally, `curses` programs would refresh the screen as little as possible because it's not a very efficient operation. The code is slightly contrived for the purposes of illustration.

Managing Text-Based Screens with curses

1. We include some header files, define some character arrays and a pointer to those arrays, and then initialize the `curses` structures.

```
#include <unistd.h>
#include <stdlib.h>
#include <curses.h>

int main()
{
    const char witch_one[] = " First Witch  ";
    const char witch_two[] = " Second Witch ";
    const char *scan_ptr;

    initscr();
```

2. Now for the three initial sets of text that appear at intervals on the screen—note the on and off flagging of text attributes.

```
move(5, 15);
attron(A_BOLD);
printw("%s", "Macbeth");
attroff(A_BOLD);
refresh();
sleep(1);

move(8, 15);
attron(A_STANDOUT);
printw("%s", "Thunder and Lightning");
attroff(A_STANDOUT);
refresh();
sleep(1);

move(10, 10);
printw("%s", "When shall we three meet again");
move(11, 23);
printw("%s", "In thunder, lightning, or in rain ?");
move(13, 10);
printw("%s", "When the hurlyburly's done,");
move(14,23);
printw("%s", "When the battle's lost and won.");
refresh();
sleep(1);
```

3. The actors are identified and their names are inserted a character at a time.

```
attron(A_DIM);
scan_ptr = witch_one + strlen(witch_one) - 1;
while(scan_ptr != witch_one) {
    move(10,10);
    insch(*scan_ptr);
}
scan_ptr = witch_two + strlen(witch_two) - 1;
while (scan_ptr != witch_two) {
    move(13, 10);
```

```
    insch(*scan_ptr) ;  
}  
attroff(A_DIM) ;  
refresh() ;  
sleep(1) ;
```

- Finally, we move the cursor to the bottom-right of the screen and then tidy up an exit.

```
move(LINES - 1, COLS - 1) ;  
  
refresh() ;  
sleep(1) ;  
  
endwin() ;  
exit(EXIT_SUCCESS) ;  
}
```

When we run this program, the final screen looks like Figure 6-3.

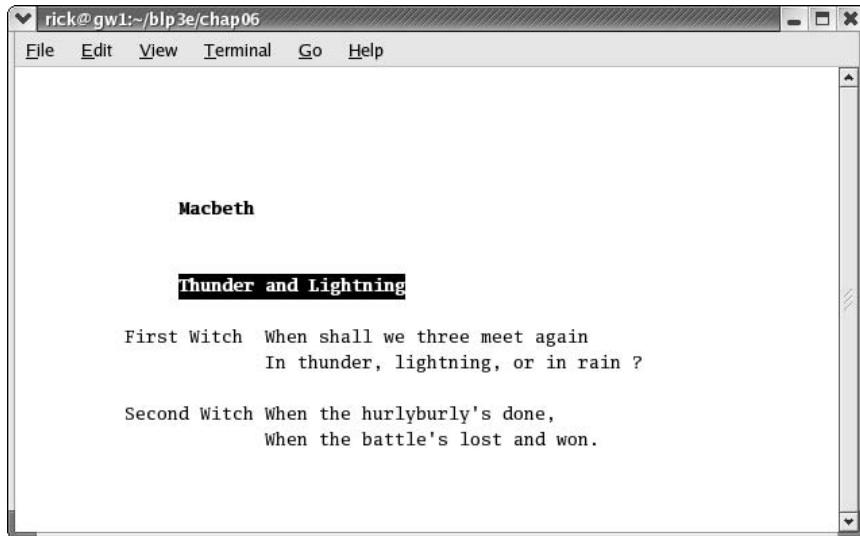


Figure 6-3

The screenshot doesn't convey the full effect very well, nor does it show the cursor, which was parked at the bottom right-hand corner.

You may find that xterm is a more reliable medium for accurately displaying *curses* programs than the raw console.

The Keyboard

As well as providing an easier interface to controlling the screen, *curses* also provides an easier method for controlling the keyboard.

Keyboard Modes

The keyboard reading routines are controlled by modes. The functions that set the modes are:

```
#include <curses.h>

int echo(void);
int noecho(void);
int cbreak(void);
int nocbreak(void);
int raw(void);
int noraw(void);
```

The two `echo` functions simply turn the echoing of typed characters on and off. The remaining four function calls control how characters typed on the terminal are made available to the `curses` program.

To explain `cbreak`, we need to understand the default input mode. When a `curses` program starts by calling `initscr`, the input mode is set to what is termed *cooked mode*. This means that all processing is done on a line-by-line basis; that is, input is only available after the user has pressed Enter (or the Return key on some keyboards). Keyboard special characters are enabled, so typing the appropriate key sequences can generate a signal in the program. Flow control, if the terminal is running from a terminal, is also enabled. By calling `cbreak`, a program may set the input mode to *cbreak mode* where characters are available to the program immediately after they are typed, rather than being buffered up and only made available to the program when Enter is pressed. As in cooked mode, keyboard special characters are enabled, but simple keys, like Backspace, are passed directly to the program to be processed, so if you want the Backspace key to function as expected, you have to program it yourself.

A call to `raw` turns off special character processing, so it becomes impossible to generate signals or flow control by typing special character sequences. Calling `nocbreak` sets the input mode back to cooked mode, but leaves special character processing unchanged; calling `noraw` restores both cooked mode and special character handling.

Keyboard Input

Reading the keyboard is very simple. The principal functions are

```
#include <curses.h>

int getch(void);
int getstr(char *string);
int getnstr(char *string, int number_of_characters);
int scanw(char *format, ...);
```

These act in a very similar way to their non-`curses` equivalents `getchar`, `gets`, and `scanf`. Note that `getstr` provides no way of limiting the string length returned, so you should use it only with great caution. If your version of `curses` supports `getnstr`, which allows you to limit the number of characters read, you should use it in preference to `getstr`. This is very similar to the behavior of `gets` and `fgets` that we saw in Chapter 3.

Here's a short example program, `ipmode.c`, to show how to handle the keyboard.

Try It Out—Keyboard Modes and Input

- First, we set up the program and the initial curses calls.

```
#include <unistd.h>
#include <stdlib.h>
#include <curses.h>
#include <string.h>

#define PW_LEN 25
#define NAME_LEN 256

int main() {
    char name[NAME_LEN];
    char password[PW_LEN];
    char *real_password = "xyzzy";
    int i = 0;

    initscr();

    move(5, 10);
   printw("%s", "Please login:");

    move(7, 10);
   printw("%s", "User name: ");
    getstr(name);

    move(9, 10);
   printw("%s", "Password: ");
    refresh();
```

- When the user enters his password, we need to stop the password being echoed to the screen. Then we check the password against xyzzy.

```
cbreak();
noecho();

memset(password, '\0', sizeof(password));
while (i < PW_LEN) {
    password[i] = getch();
    move(9, 20 + i);
    addch('*');
    refresh();
    if (password[i] == '\n') break;
    if (strcmp(password, real_password) == 0) break;
    i++;
}
```

- Finally, we re-enable the keyboard echo and print out success or failure.

```
echo();
nocbreak();

move(11, 10);
if (strcmp(password, real_password) == 0)printw("%s", "Correct");
```

```
    else printf("%s", "Wrong");
    refresh();

    endwin();
    exit(EXIT_SUCCESS);
}
```

How It Works

Having stopped the echoing of keyboard input and set the input mode to cbreak, we set up a region of memory ready for the password. Each character of the password entered is processed immediately and a * is shown at the next position on the screen. We need to refresh the screen each time. Then we compare the two strings, entered and real passwords, using strcmp.

If you're using a very old version of the curses library, you may need to make an additional refresh call before the getstr call. In ncurses, calling getstr will refresh the screen automatically.

Windows

Until now, we have used the terminal as a full-screen output medium. This is often sufficient for small and simple programs, but the curses library goes a long way beyond that. We can display multiple windows of different sizes concurrently on the physical screen. Many of the functions in this section are only supported by what X/Open terms extended curses. However, since they are supported by ncurses, there should be little problem in them being made available on most platforms. We're now going to move on and use multiple windows. We're also going to see how the commands we have used so far are generalized to the multiple window scenario.

The WINDOW Structure

Although we have mentioned stdscr, the standard screen, we have so far had little need to use it, since almost all of the functions that we've discussed so far assume that they're working on stdscr and it does not need to be passed as a parameter.

The stdscr is just a special case of the WINDOW structure, like stdout is a special case of a file stream. The WINDOW structure is normally declared in curses.h and while it can be instructive to examine it, programs should never access it directly, since the structure can and does change between implementations.

We can create and destroy windows using the newwin and delwin calls:

```
#include <curses.h>

WINDOW *newwin(int num_of_lines, int num_of_cols, int start_y, int start_x);
int delwin(WINDOW *window_to_delete);
```

The newwin function creates a new window, with a screen location of (start_y,start_x) and with the specified number of lines and columns. It returns a pointer to the new window, or null if the creation failed. If you want the new window to have its bottom right-hand corner in the bottom right-hand corner

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of the screen, you can give the number of lines or columns as zero. All windows must fit within the current screen, so newwin will fail if any part of the new window would fall outside the screen area. The new window created by newwin is completely independent of all existing windows. By default, it will be placed on top of any existing windows, hiding (but not changing) their contents.

The delwin function deletes a window previously created by newwin. Since memory has probably been allocated when newwin was called, you should always delete windows when they are no longer required. Take care never to try and delete curses' own windows, stdscr and curscr!

Having created a new window, how do we write to it? The answer is that almost all the functions that you've seen so far have generalized versions that operate on specified windows, and, for convenience, these also include cursor motion.

Generalized Functions

We've already used the addch and printw functions for adding characters to the screen. Along with many other functions, these can be prefixed, either with a w for window, mv for move, or mvw for move and window. If you look in the curses header file for most implementations of curses, you'll find that many of the functions we've used so far are simply macros (#defines) that call these more general functions.

When the w prefix is added, an additional WINDOW pointer must be pre-pended to the argument list. When the mv prefix is added, two additional parameters, a y and an x location, must be pre-pended. These specify the location where the operation will be performed. The y and x are relative to the window rather than the screen, (0,0) being the top left of the window.

When the mvw prefix is added, three additional parameters, a WINDOW pointer and both y and x values must be passed. Confusingly, the WINDOW pointer always comes before the screen coordinates, even though the prefix might suggest the y and x come first.

As an example, here is the full set of prototypes for just the addch and printw sets of functions.

```
#include <curses.h>

int addch(const chtype char);
int waddch(WINDOW *window_pointer, const chtype char)
int mvaddch(int y, int x, const chtype char);
int mvwaddch(WINDOW *window_pointer, int y, int x, const chtype char);
int printw(char *format, ...);
int wprintw(WINDOW *window_pointer, char *format, ...);
int mvprintw(int y, int x, char *format, ...);
int mvwprintw(WINDOW *window_pointer, int y, int x, char *format, ...);
```

Many other functions, such as inch, also have move and window variants available.

Moving and Updating a Window

These commands allow us to move and redraw windows.

```
#include <curses.h>

int mvwin(WINDOW *window_to_move, int new_y, int new_x);
```

```
int wrefresh(WINDOW *window_ptr);
int wclear(WINDOW *window_ptr);
int werase(WINDOW *window_ptr);
int touchwin(WINDOW *window_ptr);
int scrolllok(WINDOW *window_ptr, bool scroll_flag);
int scroll(WINDOW *window_ptr);
```

The `mvwin` function moves a window on the screen. Since all parts of a window must fit within the screen area, `mvwin` will fail if you attempt to move a window so that any part of it falls outside the screen area.

The `wrefresh`, `wclear`, and `werase` functions are simply generalizations of the functions we met earlier; they just take a `WINDOW` pointer so that they can refer to a specific window, rather than `stdscr`.

The `touchwin` function is rather special. It informs the `curses` library that the contents of the window pointed to by its parameter have been changed. This means that `curses` will always redraw that window next time `wrefresh` is called, even if you haven't actually changed the contents of the window. This function is often useful for arranging which window to display when you have several overlapping windows stacked on the screen.

The two scroll functions control scrolling of a window. The `scrolllok` function, when passed a Boolean `true` (usually nonzero) allows a window to scroll. By default, windows can't scroll. The `scroll` function simply scrolls the window up one line. Some `curses` implementations also have a `wsct1` function that also takes a number of lines to scroll, which may be a negative number. We'll return to scrolling a little later in the chapter.

Try It Out—Multiple Windows

Now that we know how to manage more than a single window, let's put these new functions to work in a program, `multiw1.c`. For the sake of brevity, error checking is omitted.

1. As usual, let's get our definitions sorted first:

```
#include <unistd.h>
#include <stdlib.h>
#include <curses.h>

int main()
{
    WINDOW *new_window_ptr;
    WINDOW *popup_window_ptr;
    int x_loop;
    int y_loop;
    char a_letter = 'a';

    initscr();
```

2. Then we fill the base window with characters, refreshing the actual screen once the logical screen has been filled.

```
move(5, 5);
printf("%s", "Testing multiple windows");
refresh();
```

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```
for (y_loop = 0; y_loop < LINES - 1; y_loop++) {
    for (x_loop = 0; x_loop < COLS - 1; x_loop++) {
        mvwaddch(stdscr, y_loop, x_loop, a_letter);
        a_letter++;
        if (a_letter > 'z') a_letter = 'a';
    }
}

/* Update the screen */
refresh();
sleep(2);
```

3. Now we create a new 10 x 20 window and add some text to it before drawing it on the screen.

```
new_window_ptr = newwin(10, 20, 5, 5);
mvwprintw(new_window_ptr, 2, 2, "%s", "Hello World");
mvwprintw(new_window_ptr, 5, 2, "%s",
          "Notice how very long lines wrap inside the window");
wrefresh(new_window_ptr);
sleep(2);
```

4. We now change the contents of the background window and, when we refresh the screen, the window pointed to by `new_window_ptr` is obscured.

```
a_letter = '0';
for (y_loop = 0; y_loop < LINES - 1; y_loop++) {
    for (x_loop = 0; x_loop < COLS - 1; x_loop++) {
        mvwaddch(stdscr, y_loop, x_loop, a_letter);
        a_letter++;
        if (a_letter > '9')
            a_letter = '0';
    }
}

refresh();
sleep(2);
```

5. If we make a call to refresh the new window, nothing will change, because we haven't changed the new window.

```
wrefresh(new_window_ptr);
sleep(2);
```

6. But if we touch the window first and trick curses into thinking that the window has been changed, the next call to `wrefresh` will bring the new window to the front again.

```
touchwin(new_window_ptr);
wrefresh(new_window_ptr);
sleep(2);
```

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7. Next, we add another overlapping window with a box around it.

```
popup_window_ptr = newwin(10, 20, 8, 8);
box(popup_window_ptr, '|', '-');
mvwprintw(popup_window_ptr, 5, 2, "%s", "Pop Up Window!");
wrefresh(popup_window_ptr);
sleep(2);
```

8. Then we fiddle with the new and pop-up windows before clearing and deleting them.

```
touchwin(new_window_ptr);
wrefresh(new_window_ptr);
sleep(2);
wclear(new_window_ptr);
wrefresh(new_window_ptr);
sleep(2);
delwin(new_window_ptr);
touchwin(popup_window_ptr);
wrefresh(popup_window_ptr);
sleep(2);
delwin(popup_window_ptr);
touchwin(stdscr);
refresh();
sleep(2);
endwin();
exit(EXIT_SUCCESS);
}
```

Unfortunately, it's not practical to show you this running in the book, but Figure 6-4 shows a screenshot after the first pop-up window has been drawn.

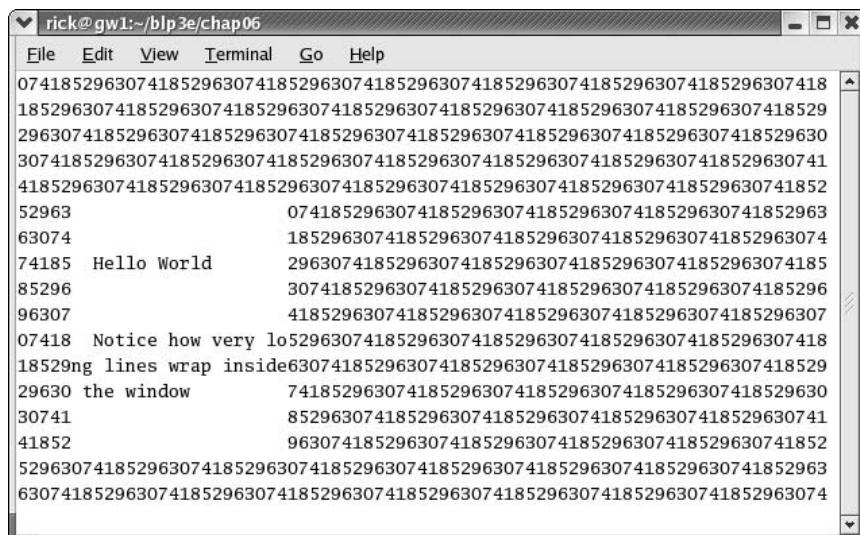


Figure 6-4

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After the background has been changed and a pop-up window has been drawn, we see the display shown in Figure 6-5.

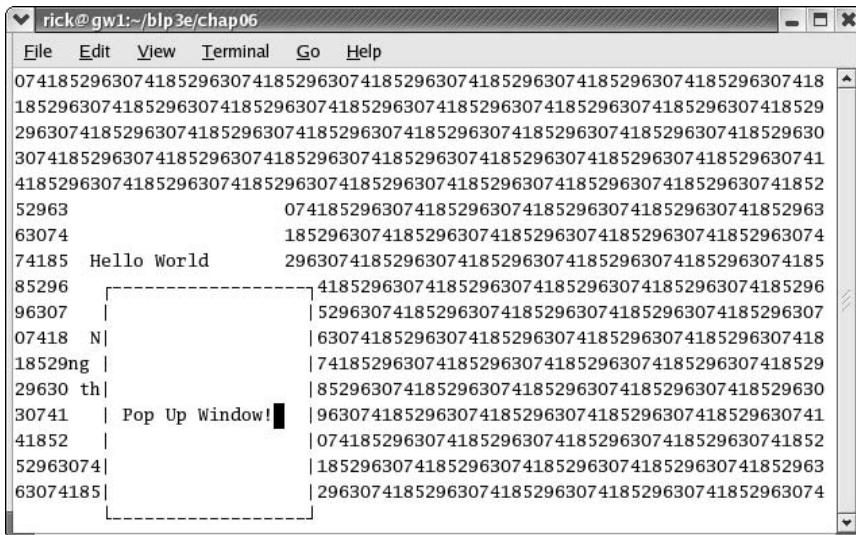


Figure 6-5

As you can see from the example code, you need to be quite careful about refreshing windows to ensure that they appear on the screen in the correct order. If you ask `curses` to refresh a window, it doesn't store any information about the hierarchy of windows. To ensure that `curses` draws the windows in the correct order, you must refresh them in the correct order. One way of doing this is to store all the pointers to your windows in an array or list, which you maintain in the order they should appear on the screen.

Optimizing Screen Refreshes

As we saw in the example in the previous section, refreshing multiple windows can be a little tricky, but not overly onerous. However, a potentially more serious problem arises when the terminal to be updated is on a slow link. Fortunately, this is now a rare problem, but handling it is so easy that we will show you just for the sake of completeness.

The aim is to minimize the number of characters drawn on the screen, since, on slow links, screen draws can be uncomfortably slow. `curses` provides a special way of doing this, with a pair of functions: `wnoutrefresh` and `doupdate`.

```
#include <curses.h>

int wnoutrefreshWINDOW *window_ptr);
int doupdate(void);
```

The `wnoutrefresh` function determines which characters would need sending to the screen, but doesn't actually send them. The `doupdate` function actually sends the changes to the terminal. If you simply call `wnoutrefresh`, followed immediately by `doupdate`, the effect is the same as calling `wrefresh`.

However, if you wish to redraw a stack of windows, you can call `wnoutrefresh` on each window (in the correct order, of course) and then call `doupdate` only after the last `wnoutrefresh`. This allows `curses` to perform its screen update calculations on each window in turn and only then output the updated screen. This almost always allows `curses` to minimize the number of characters that needs to be sent.

Subwindows

Now that we've looked at multiple windows, we can look at a special case of multiple windows, called *subwindows*. We create and destroy subwindows with these calls:

```
#include <curses.h>

WINDOW *subwin(WINDOW *parent, int num_of_lines, int num_of_cols,
               int start_y, int start_x);
int delwin(WINDOW *window_to_delete);
```

The `subwin` function has almost the same parameter list as `newwin` and subwindows are deleted in just the same way as other windows with a `delwin` call. Just like new windows, we can use the range of `mvw` functions to write to subwindows. Indeed, most of the time, subwindows behave in a very similar fashion to new windows, with one very important exception: Subwindows don't themselves store a separate set of screen characters; they share the same character storage space as the parent window specified when the subwindow is created. This means that any changes made in a subwindow are also made in the underlying parent window, so when a subwindow is deleted, the screen doesn't change.

At first sight, subwindows seem like a pointless exercise. Why not just make the changes to the parent window? The main use for subwindows is to provide a clean way of scrolling parts of another window. The need to scroll a small subsection of the screen is surprisingly common when writing a `curses` program. By making this a subwindow and then scrolling the subwindow, we achieve the desired result.

One restriction imposed by using subwindows is that the application should call `touchwin` on the parent window before refreshing the screen.

Try It Out—Subwindows

1. First, the initial code section of `subscr1.c` initializes the base window display with some text.

```
#include <unistd.h>
#include <stdlib.h>
#include <curses.h>

int main()
{
    WINDOW *sub_window_ptr;
    int x_loop;
    int y_loop;
```

```
int counter;
char a_letter = '1';
initscr();

for (x_loop = 0; x_loop < COLS - 1; x_loop++) {
    for (y_loop = 0; y_loop < LINES - 1; y_loop++) {
        mvwaddch(stdscr, y_loop, x_loop, a_letter);
        a_letter++;
        if (a_letter > '9') a_letter = '1';
    }
    if (a_letter > 'Z') a_letter = 'A';
```

- 2.** We now create the new scrolling subwindow and, as advised, we must “touch” the parent window before refreshing the screen.

```
sub_window_ptr = subwin(stdscr, 10, 20, 10, 10);
scrolllok(sub_window_ptr, 1);

touchwin(stdscr);
refresh();
sleep(1);
```

- 3.** Then we erase the contents of the subwindow, print text to it, and refresh it. The scrolling text is achieved by a loop.

```
werase(sub_window_ptr);
mvwprintw(sub_window_ptr, 2, 0, "%s", "This window will now scroll");
wrefresh(sub_window_ptr);
sleep(1);

for (counter = 1; counter < 10; counter++) {
    wprintw(sub_window_ptr, "%s", "This text is both wrapping and \
                                scrolling.");
    wrefresh(sub_window_ptr);
    sleep(1);
}
```

- 4.** Having finished this loop, we delete the subwindow. Then we refresh the base screen.

```
delwin(sub_window_ptr);

touchwin(stdscr);
refresh();
sleep(1);

endwin();
exit(EXIT_SUCCESS);
}
```

Toward the end of the program, we see the output shown in Figure 6-6.

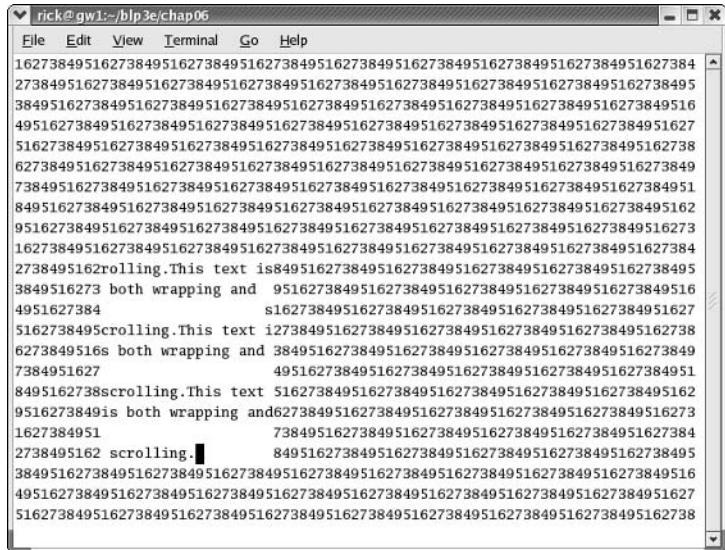


Figure 6-6

How It Works

After arranging for the `sub_window_ptr` to point to the result of the `subwin` call, we make the subwindow scrollable. Even after the subwindow has been deleted and the base window (`stdscr`) is refreshed, the text on the screen remains the same. This is because the subwindow was actually updating the character data for `stdscr`.

The Keypad

You've already seen some of the facilities that `curses` provides for handling the keyboard. Many keyboards have, at the very least, cursor keys and function keys. Many also have a keypad and other keys, such as Insert and Home.

Decoding these keys is a difficult problem on most terminals because they normally send a string of characters, starting with the escape character. Not only does the application have the problem of distinguishing between a single press of the Escape key and a string of characters caused by pressing a function key, but it must also cope with different terminals using different sequences for the same logical key.

Fortunately, `curses` provides an elegant facility for managing function keys. For each terminal, the sequence sent by each of its function keys is stored, normally in a `terminfo` structure, and the include file `curses.h` has a set of defines prefixed by `KEY_` that define the logical keys.

The translation between the sequences and logical keys is disabled when `curses` starts and has to be turned on by the `keypad` function. If the call succeeds, it returns `OK`, otherwise `ERR`.

```
#include <curses.h>

int keypad(WINDOW *window_ptr, bool keypad_on);
```

Once *keypad mode* has been enabled by calling `keypad` with `keypad_on` set to `true`, `curses` takes over the processing of key sequences so that reading the keyboard may now not only return the key that was pressed, but also one of the `KEY_` defines for logical keys.

There are three slight restrictions when using keypad mode:

- ❑ The recognition of escape sequences is timing-dependent and many network protocols will group characters into packets (leading to improper recognition of escape sequences), or separate them (leading to function key sequences being recognized as Escape and individual characters). This behavior is worst over WANs and other busy links. The only workaround is to try to program terminals to send single, unique characters for each function key that you want to use, although this limits the number of control characters.
- ❑ In order for `curses` to separate a press of the Escape key from a keyboard sequence starting with Escape, it must wait for a brief period of time. Sometimes, a very slight delay on processing of the Escape key can be noticed once keypad mode has been enabled.
- ❑ `curses` can't process nonunique escape sequences. If your terminal has two different keys that can send the same sequence, `curses` will simply not process that sequence, since it can't tell which logical key it should return.

In our opinion, having escape sequences for some keys and also putting an Escape key on the keyboard (heavily used for cancels) was a most unfortunate design decision, but one that we must accept and manage as best we can.

Try It Out—Using the Keypad

Here's a short program, `keypad.c`, showing how the keypad mode can be used. When you run this program, try pressing Escape and notice the slight delay while the program waits to see if the Escape is simply the start of an escape sequence or a single key press.

1. Having initialized the program and the `curses` library, we set the keypad mode TRUE.

```
#include <unistd.h>
#include <stdlib.h>
#include <curses.h>

#define LOCAL_ESCAPE_KEY      27

int main()
{
    int key;

    initscr();
    crmode();
    keypad(stdscr, TRUE);
```

2. Next, we must turn echo off to prevent the cursor from being moved when some cursor keys are pressed. The screen is cleared and some text displayed. The program waits for each key stroke and, unless it's Q, or produces an error, the key is printed. If the key strokes match one of the terminal's keypad sequences, that is printed instead.

```
noecho();
clear();
mvprintw(5, 5, "Key pad demonstration. Press 'q' to quit");
move(7, 5);
refresh();
key = getch();

while(key != ERR && key != 'q') {
    move(7, 5);
    clrtoeol();

    if ((key >= 'A' && key <= 'Z') ||
        (key >= 'a' && key <= 'z')) {
       printw("Key was %c", (char)key);
    }
    else {
        switch(key) {
            case LOCAL_ESCAPE_KEY: printf("%s", "Escape key"); break;
            case KEY_END: printf("%s", "END key"); break;
            case KEY_BEG: printf("%s", "BEGINNING key"); break;
            case KEY_RIGHT: printf("%s", "RIGHT key"); break;
            case KEY_LEFT: printf("%s", "LEFT key"); break;
            case KEY_UP: printf("%s", "UP key"); break;
            case KEY_DOWN: printf("%s", "DOWN key"); break;
            default: printf("Unmatched - %d", key); break;
        } /* switch */
    } /* else */

    refresh();
    key = getch();
} /* while */

endwin();
exit(EXIT_SUCCESS);
}
```

Color

Originally, very few “dumb” terminals supported color, so most early versions of curses had no support for it. Now, color is expected and is supported in ncurses and most other modern curses implementations. Unfortunately the “dumb screen” origins of curses has influenced the API, and curses uses color in a very restricted way, reflecting the poor capabilities of early color terminals.

Each character cell on the screen can be written in one of a number of different colors, against one of a number of different colored backgrounds. For example, we can write text in green on a red background.

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Color support in curses is slightly unusual in that the color for a character isn't defined independently of its background. We must define the foreground and background colors of a character as a pair, called, not surprisingly, a *color pair*.

Before you can use color capability in curses, you must check that the current terminal supports color and then initialize the curses color routines. For this, use a pair of routines: `has_colors` and `start_color`.

```
#include <curses.h>

bool has_colors(void);
int start_color(void);
```

The `has_colors` routine returns `true` if color is supported. You should then call `start_color`, which returns `OK` if color has been initialized successfully. Once `start_color` has been called and the colors initialized, the variable `COLOR_PAIRS` is set to the maximum number of color pairs that the terminal can support. A limit of 64 color pairs is common. The variable `COLORS` defines the maximum number of colors available, which is often as few as eight. Internally, numbers from 0 to act as a unique ID for each of the colors available.

Before you can use colors as attributes, you must initialize the color pairs that you wish to use. You do this with the `init_pair` function. Color attributes are accessed with the `COLOR_PAIR` function.

```
#include <curses.h>

int init_pair(short pair_number, short foreground, short background);
int COLOR_PAIR(int pair_number);
int pair_content(short pair_number, short *foreground, short *background);
```

`curses.h` usually defines some basic colors, starting with `COLOR_`. An additional function, `pair_content`, allows previously defined color-pair information to be retrieved.

To define color pair number 1 to be red on green, we would use

```
init_pair(1, COLOR_RED, COLOR_GREEN);
```

We can then access this color pair as an attribute, using `COLOR_PAIR` like this:

```
wattron(window_ptr, COLOR_PAIR(1));
```

This would set future additions to the screen to be red on a green background.

Since a `COLOR_PAIR` is an attribute, we can combine it with other attributes. On a PC, we can often access screen high-intensity colors by combining the `COLOR_PAIR` attribute with the additional attribute `A_BOLD`, by using a bitwise OR of the attributes:

```
wattron(window_ptr, COLOR_PAIR(1) | A_BOLD);
```

Let's check these functions in an example, `color.c`.

Try It Out—Colors

1. First, we check whether the program's display terminal supports color. If it does, we start the color display.

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <curses.h>

int main()
{
    int i;

    initscr();

    if (!has_colors()) {
        endwin();
        fprintf(stderr, "Error - no color support on this terminal\n");
        exit(1);
    }

    if (start_color() != OK) {
        endwin();
        fprintf(stderr, "Error - could not initialize colors\n");
        exit(2);
    }
}
```

2. We can now print out the allowed number of colors and color pairs. We create seven color pairs and display them one at a time.

```
clear();
mvprintw(5, 5, "There are %d COLORS, and %d COLOR_PAIRS available",
          COLORS, COLOR_PAIRS);
refresh();

init_pair(1, COLOR_RED, COLOR_BLACK);
init_pair(2, COLOR_RED, COLOR_GREEN);
init_pair(3, COLOR_GREEN, COLOR_RED);
init_pair(4, COLOR_YELLOW, COLOR_BLUE);
init_pair(5, COLOR_BLACK, COLOR_WHITE);
init_pair(6, COLOR_MAGENTA, COLOR_BLUE);
init_pair(7, COLOR_CYAN, COLOR_WHITE);

for (i = 1; i <= 7; i++) {
    attroff(A_BOLD);
    attrset(COLOR_PAIR(i));
    mvprintw(5 + i, 5, "Color pair %d", i);
    attrset(COLOR_PAIR(i) | A_BOLD);
    mvprintw(5 + i, 25, "Bold color pair %d", i);
    refresh();
    sleep(1);
}
```

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```
    endwin();
    exit(EXIT_SUCCESS);
}
```

This example gives the output shown in Figure 6-7.

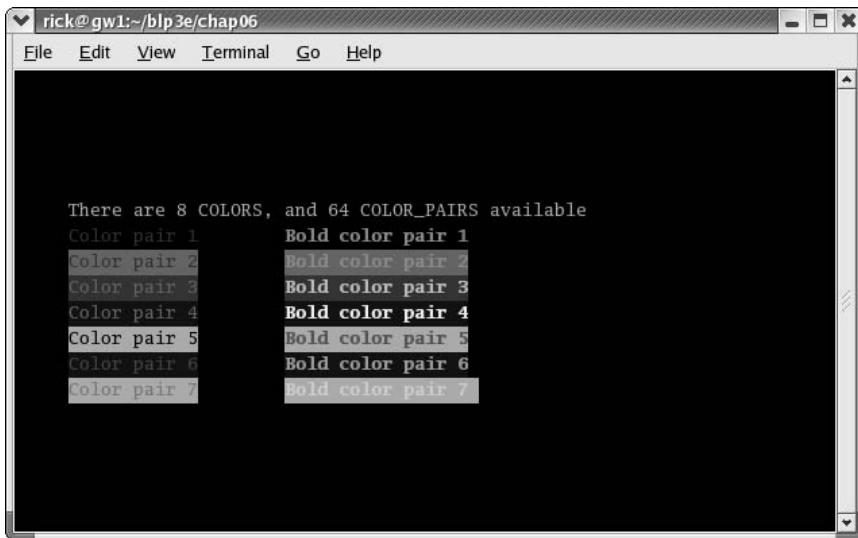


Figure 6-7

Redefining Colors

As a leftover from early dumb terminals that could display very few colors at any one time, but allowed the active color set to be configured, `curses` allows color redefinition with the `init_color` function.

```
#include <curses.h>

int init_color(short color_number, short red, short green, short blue);
```

This allows an existing color (in the range 0 to `COLORS`) to be redefined with new intensity values in the range 0 to 1,000. This is a little like defining color values for GIF format image files.

Pads

When you're writing more advanced `curses` programs, it's sometimes easier to build a logical screen and then output all or part of it to the physical screen later. Occasionally, it's also better to have a logical screen that is actually bigger than the physical screen and to display only part of the logical screen at any one time.

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It's not easy for us to do this with the `curses` functions that we've met so far, since all windows must be no larger than the physical screen. `curses` does provide a special data structure, a *pad*, for manipulating logical screen information that doesn't fit within a normal window.

A pad structure is very similar to a `WINDOW` structure, and all the `curses` routines that write to windows can also be used on pads. However, pads do have their own routines for creation and refreshing.

We create pads in much the same way that we create normal windows:

```
#include <curses.h>

WINDOW *newpad(int number_of_lines, int number_of_columns);
```

Note that the return value is a pointer to a `WINDOW` structure, the same as `newwin`. Pads are deleted with `delwin`, just like windows.

Pads do have different routines for refreshing. Since a pad isn't confined to a particular screen location, we must specify the region of the pad we wish to put on the screen and also the location it should occupy on the screen. We do this with the `prefresh` function:

```
#include <curses.h>

int prefresh(WINDOW *pad_ptr, int pad_row, int pad_column,
             int screen_row_min, int screen_col_min,
             int screen_row_max, int screen_col_max);
```

This causes an area of the pad, starting at `(pad_row, pad_column)` to be written to the screen in the region defined by `(screen_row_min, screen_col_min)` to `(screen_row_max, screen_col_max)`.

An additional routine, `pnoutrefresh`, is also provided. It acts in the same way as `wnoutrefresh`, for more efficient screen updates.

Let's check these out with a quick program, `pad.c`.

Try It Out—Using a Pad

1. At the start of this program, we initialize the pad structure and then create a pad, which returns a pointer to that pad. We add characters to fill the pad structure (which is 50 characters wider and longer than the terminal display).

```
#include <unistd.h>
#include <stdlib.h>
#include <curses.h>

int main()
{
    WINDOW *pad_ptr;
    int x, y;
    int pad_lines;
```

```
int pad_cols;
char disp_char;

initscr();
pad_lines = LINES + 50;
pad_cols = COLS + 50;
pad_ptr = newpad(pad_lines, pad_cols);
disp_char = 'a';

for (x = 0; x < pad_lines; x++) {
    for (y = 0; y < pad_cols; y++) {
        mvwaddch(pad_ptr, x, y, disp_char);
        if (disp_char == 'z') disp_char = 'a';
        else disp_char++;
    }
}
```

- 2.** We can now draw different areas of the pad on the screen at different locations before quitting.

```
refresh(pad_ptr, 5, 7, 2, 2, 9, 9);
sleep(1);
refresh(pad_ptr, LINES + 5, COLS + 7, 5, 5, 21, 19);
sleep(1);
delwin(pad_ptr);
endwin();
exit(EXIT_SUCCESS);
```

Running the program, you should see something like Figure 6-8.

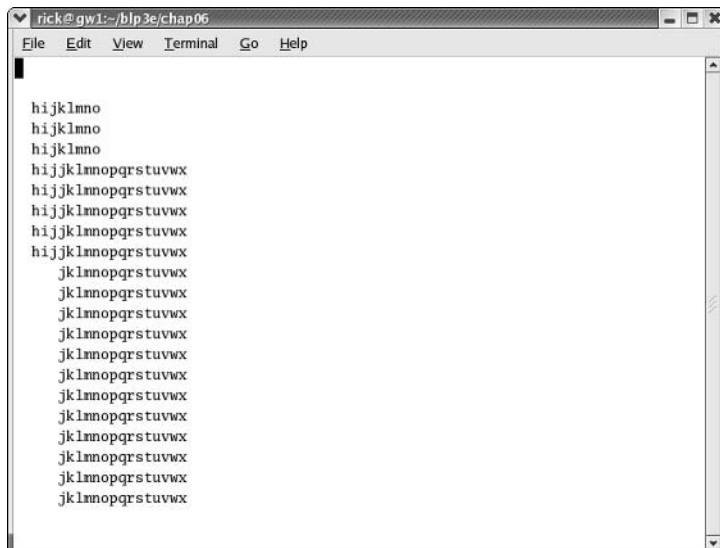


Figure 6-8

The CD Collection Application

Now that you've learned about the facilities that *curses* has to offer, we can develop our sample application. Here's a version written in C using the *curses* library. It offers some advantages in that the information is more clearly displayed on the screen and a scrolling window is used for track listings.

The whole application is eight pages long, so we've split it up into sections and functions within each section. You can get the full source code from the Wrox Web site. As with all the programs in this book, it's under the GNU Public License.

We've written this version of the CD database application using the information presented in earlier chapters. It's derived from the original shell script presented in Chapter 2. It hasn't been redesigned for the C implementation, so you can still see many features of the shell original in this version.

There are some significant limitations with this implementation that we will resolve in later revisions.

Looking at the code, there are several distinct sections that form the "Try It Out" headings. The code conventions used here are slightly different from most of the rest of the book; here, code foreground is used only to show where other application functions are called.

Try It Out—A New CD Collection Application

1. First, we include all those header files and then some global constants.

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <curses.h>

#define MAX_STRING 80          /* Longest allowed response      */
#define MAX_ENTRY 1024         /* Longest allowed database entry */

#define MESSAGE_LINE 6          /* Misc. messages on this line   */
#define ERROR_LINE 22           /* Line to use for errors       */
#define Q_LINE 20                /* Line for questions           */
#define PROMPT_LINE 18           /* Line for prompting on        */
```

2. Next, we need some global variables. The variable *current_cd* is used to store the current CD title with which we are working. It's initialized so that the first character is null to indicate "no CD selected." The \0 is strictly unnecessary, but it ensures the variable is initialized, which is generally a good thing. The variable *current_cat* will be used to record the catalog number of the current CD.

```
static char current_cd[MAX_STRING] = "\0";
static char current_cat[MAX_STRING];
```

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3. Some filenames are now declared. These files are fixed in this version to keep things simple, as is the temporary filename. This could cause a problem if the program is run by two users in the same directory.

A better way to obtain database file names would be either by program arguments or from environment variables. We also need an improved method of generating a unique temporary filename, for which we could use the POSIX `tmpnam` function. We'll address many of these issues in later versions.

```
const char *title_file = "title.cdb";
const char *tracks_file = "tracks.cdb";
const char *temp_file = "cdb.tmp";
```

4. Now, finally, we get on to the function prototypes.

```
void clear_all_screen(void);
void get_return(void);
int get_confirm(void);
int getchoice(char *greet, char *choices[]);
void draw_menu(char *options[], int highlight,
               int start_row, int start_col);
void insert_title(char *cdtitle);
void get_string(char *string);
void add_record(void);
void count_cds(void);
void find_cd(void);
void list_tracks(void);
void remove_tracks(void);
void remove_cd(void);
void update_cd(void);
```

5. Before we look at their implementation, we need some structures (actually, an array of menu options) for the menus. The first character is the one to return when the choice is selected; the remaining text is to be displayed. The extended menu is displayed when a CD is currently selected.

```
char *main_menu[] =
{
    "add new CD",
    "find CD",
    "count CDs and tracks in the catalog",
    "quit",
    0,
};

char *extended_menu[] =
{
    "add new CD",
    "find CD",
    "count CDs and tracks in the catalog",
    "list tracks on current CD",
```

```

    "remove current CD",
    "update track information",
    "quit",
    0,
};

```

That finishes the initialization. Now we move on to the program functions, but first we need to summarize the interrelations of these functions, all 16 of them. They split into functions that

- Draw the menu
- Add CDs to the database
- Retrieve and display CD data

See Figure 6-9 for a visual representation.

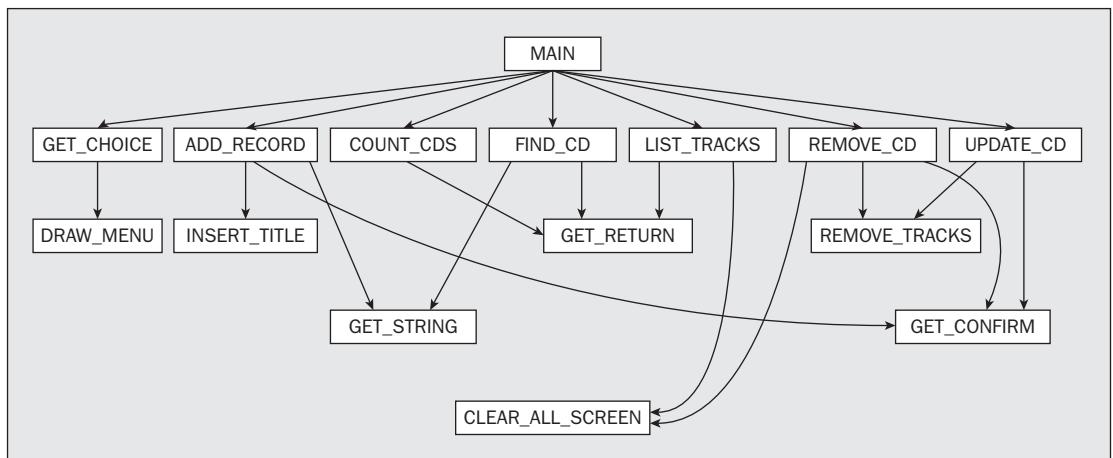


Figure 6-9

Try It Out—Looking at main

main allows us to make selections from the menu until we select quit.

```

int main()
{
    int choice;
    initscr();
    do {
        choice = getchoice("Options:",
                           current_cd[0] ? extended_menu : main_menu);
        switch (choice) {
        case 'q':
            break;
        case 'a':

```

```
        add_record();
        break;
    case 'c':
        count_cds();
        break;
    case 'f':
        find_cd();
        break;
    case 'l':
        list_tracks();
        break;
    case 'r':
        remove_cd();
        break;
    case 'u':
        update_cd();
        break;
    }
} while (choice != 'q');
endwin();
exit(EXIT_SUCCESS);
}
```

Let's now look at the detail of the functions associated with the three program subsections. First, we look at the three functions that relate to the program's user interface.

Try It Out—The Menu

1. The `getchoice` function called by `main` is the principal function in this section. `getchoice` is passed `greet`, an introduction, and `choices`, which points either to the main or the extended menu (depending on whether a CD has been selected). You can see this in the preceding `main` function.

```
int getchoice(char *greet, char *choices[])
{
    static int selected_row = 0;
    int max_row = 0;
    int start_screenrow = MESSAGE_LINE, start_screencol = 10;
    char **option;
    int selected;
    int key = 0;

    option = choices;
    while (*option) {
        max_row++;
        option++;
    }
/* protect against menu getting shorter when CD deleted */
    if (selected_row >= max_row)
        selected_row = 0;
    clear_all_screen();
    mvprintw(start_screenrow - 2, start_screencol, greet);
```

```
keypad(stdscr, TRUE);
cbreak();
noecho();
key = 0;
while (key != 'q' && key != KEY_ENTER && key != '\n') {
    if (key == KEY_UP) {
        if (selected_row == 0)
            selected_row = max_row - 1;
        else
            selected_row--;
    }
    if (key == KEY_DOWN) {
        if (selected_row == (max_row - 1))
            selected_row = 0;
        else
            selected_row++;
    }
    selected = *choices[selected_row];
    draw_menu(choices, selected_row, start_screenrow,
              start_screencol);
    key = getch();
}
keypad(stdscr, FALSE);
nocbreak();
echo();

if (key == 'q')
    selected = 'q';

return (selected);
}
```

2. Note how there are two more local functions called from within `getchoice`: `clear_all_screen` and `draw_menu`. We'll look at `draw_menu` first:

```
void draw_menu(char *options[], int current_highlight,
               int start_row, int start_col)
{
    int current_row = 0;
    char **option_ptr;
    char *txt_ptr;
    option_ptr = options;
    while (*option_ptr) {
        if (current_row == current_highlight) attron(A_STANDOUT);
        txt_ptr = options[current_row];
        txt_ptr++;
        mvprintw(start_row + current_row, start_col, "%s", txt_ptr);
        if (current_row == current_highlight) attron(A_STANDOUT);
        current_row++;
        option_ptr++;
    }

    mvprintw(start_row + current_row + 3, start_col,
            "Move highlight then press Return ");
    refresh();
}
```

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3. `clear_all_screen`, which, surprisingly enough, clears the screen and rewrites the title. If a CD is selected, its information is displayed.

```
void clear_all_screen()
{
    clear();
    mvprintw(2, 20, "%s", "CD Database Application");
    if (current_cd[0]) {
        mvprintw(ERROR_LINE, 0, "Current CD: %s: %s\n",
                 current_cat, current_cd);
    }
    refresh();
}
```

Now we look at the functions that add to or update the CD database. The functions called from `main` are `add_record`, `update_cd`, and `remove_cd`. This function makes several calls to functions that will be defined in the next few sections.

Try It Out—Database File Manipulation

1. First, how do we add a new CD record to the database?

```
void add_record()
{
    char catalog_number[MAX_STRING];
    char cd_title[MAX_STRING];
    char cd_type[MAX_STRING];
    char cd_artist[MAX_STRING];
    char cd_entry[MAX_STRING];

    int screenrow = MESSAGE_LINE;
    int screencol = 10;

    clear_all_screen();
    mvprintw(screenrow, screencol, "Enter new CD details");
    screenrow += 2;

    mvprintw(screenrow, screencol, "Catalog Number: ");
    get_string(catalog_number);
    screenrow++;

    mvprintw(screenrow, screencol, "          CD Title: ");
    get_string(cd_title);
    screenrow++;

    mvprintw(screenrow, screencol, "          CD Type: ");
    get_string(cd_type);
    screenrow++;

    mvprintw(screenrow, screencol, "          Artist: ");
    get_string(cd_artist);
    screenrow++;
}
```

```
mvprintw(PROMPT_LINE-2, 5, "About to add this new entry:");
sprintf(cd_entry, "%s,%s,%s,%s",
       catalog_number, cd_title, cd_type, cd_artist);
mvprintw(PROMPT_LINE, 5, "%s", cd_entry);
refresh();
move(PROMPT_LINE, 0);
if (get_confirm()) {
    insert_title(cd_entry);
    strcpy(current_cd, cd_title);
    strcpy(current_cat, catalog_number);
}
}
```

2. `get_string` prompts for and reads in a string at the current screen position. It also deletes any trailing newline.

```
void get_string(char *string)
{
    int len;

    wgetnstr(stdscr, string, MAX_STRING);
    len = strlen(string);
    if (len > 0 && string[len - 1] == '\n')
        string[len - 1] = '\0';
}
```

3. `get_confirm` prompts and reads user confirmation. It reads the user's input string and checks the first character for Y or y. If it finds any other character, it gives no confirmation.

```
int get_confirm()
{
    int confirmed = 0;
    char first_char;

    mvprintw(Q_LINE, 5, "Are you sure? ");
    clrtoeol();
    refresh();

    cbreak();
    first_char = getch();
    if (first_char == 'Y' || first_char == 'y') {
        confirmed = 1;
    }
    nocbreak();

    if (!confirmed) {
        mvprintw(Q_LINE, 1, "Cancelled");
        clrtoeol();
        refresh();
        sleep(1);
    }
    return confirmed;
}
```

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4. Lastly, we look at `insert_title`. This adds a title to the CD database by appending the title string to the end of the titles file.

```
void insert_title(char *cdtitle)
{
    FILE *fp = fopen(title_file, "a");
    if (!fp) {
        mvprintw(ERROR_LINE, 0, "cannot open CD titles database");
    } else {
        fprintf(fp, "%s\n", cdtitle);
        fclose(fp);
    }
}
```

5. On to the other file manipulation functions called by `main`. We start with `update_cd`. This function uses a scrolling, boxed subwindow and needs some constants, which we define globally, because they will be needed later for the `list_tracks` function. These are

```
#define BOXED_LINES      11
#define BOXED_ROWS       60
#define BOX_LINE_POS      8
#define BOX_ROW_POS       2
```

`update_cd` allows the user to re-enter the tracks for the current CD. Having deleted the previous tracks record, it prompts for new information.

```
void update_cd()
{
    FILE *tracks_fp;
    char track_name[MAX_STRING];
    int len;
    int track = 1;
    int screen_line = 1;
    WINDOW *box_window_ptr;
    WINDOW *sub_window_ptr;

    clear_all_screen();
    mvprintw(PROMPT_LINE, 0, "Re-entering tracks for CD. ");
    if (!get_confirm())
        return;
    move(PROMPT_LINE, 0);
    clrtoeol();

    remove_tracks();

    mvprintw(MESSAGE_LINE, 0, "Enter a blank line to finish");

    tracks_fp = fopen(tracks_file, "a");
```

We'll continue the listing in just a moment; here, we want to take a brief intermission to highlight how we enter the information in a scrolling, boxed window. The trick is to set up a subwindow, draw a box around the edge, and then add a new scrolling subwindow just inside the boxed subwindow.

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```
box_window_ptr = subwin(stdscr, BOXED_LINES + 2, BOXED_ROWS + 2,
                        BOX_LINE_POS - 1, BOX_ROW_POS - 1);
if (!box_window_ptr)
    return;
box(box_window_ptr, ACS_VLINE, ACS_HLINE);

sub_window_ptr = subwin(stdscr, BOXED_LINES, BOXED_ROWS,
                        BOX_LINE_POS, BOX_ROW_POS);
if (!sub_window_ptr)
    return;
scrolllok(sub_window_ptr, TRUE);
werase(sub_window_ptr);
touchwin(stdscr);

do {
    mvwprintw(sub_window_ptr, screen_line++, BOX_ROW_POS + 2,
              "Track %d: ", track);
    clrtoeol();
    refresh();
    wgetnstr(sub_window_ptr, track_name, MAX_STRING);
    len = strlen(track_name);
    if (len > 0 && track_name[len - 1] == '\n')
        track_name[len - 1] = '\0';
    if (*track_name)
        fprintf(tracks_fp, "%s,%d,%s\n", current_cat, track, track_name);
    track++;
    if (screen_line > BOXED_LINES - 1) {
        /* time to start scrolling */
        scroll(sub_window_ptr);
        screen_line--;
    }
} while (*track_name);
delwin(sub_window_ptr);

fclose(tracks_fp);
}
```

6. The last function called from main is remove_cd.

```
void remove_cd()
{
    FILE *titles_fp, *temp_fp;
    char entry[MAX_ENTRY];
    int cat_length;

    if (current_cd[0] == '\0')
        return;

    clear_all_screen();
    mvprintw(PROMPT_LINE, 0, "About to remove CD %s: %s. ",
             current_cat, current_cd);
    if (!get_confirm())
        return;

    cat_length = strlen(current_cat);
```

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```
/* Copy the titles file to a temporary, ignoring this CD */
titles_fp = fopen(title_file, "r");
temp_fp = fopen(temp_file, "w");

while (fgets(entry, MAX_ENTRY, titles_fp)) {
    /* Compare catalog number and copy entry if no match */
    if (strncmp(current_cat, entry, cat_length) != 0)
        fputs(entry, temp_fp);
}
fclose(titles_fp);
fclose(temp_fp);

/* Delete the titles file, and rename the temporary file */
unlink(title_file);
rename(temp_file, title_file);

/* Now do the same for the tracks file */
remove_tracks();

/* Reset current CD to 'None' */
current_cd[0] = '\0';
}
```

7. We now need only to list `remove_tracks`, the function that deletes the tracks from the current CD. It's called by both `update_cd` and `remove_cd`.

```
void remove_tracks()
{
    FILE *tracks_fp, *temp_fp;
    char entry[MAX_ENTRY];
    int cat_length;

    if (current_cd[0] == '\0')
        return;

    cat_length = strlen(current_cat);

    tracks_fp = fopen(tracks_file, "r");
    if (tracks_fp == (FILE *)NULL) return;
    temp_fp = fopen(temp_file, "w");

    while (fgets(entry, MAX_ENTRY, tracks_fp)) {
        /* Compare catalog number and copy entry if no match */
        if (strncmp(current_cat, entry, cat_length) != 0)
            fputs(entry, temp_fp);
    }
    fclose(tracks_fp);
    fclose(temp_fp);

    /* Delete the tracks file, and rename the temporary file */
    unlink(tracks_file);
    rename(temp_file, tracks_file);
}
```

Try It Out—Querying the CD Database

- Essential to all acquisitive hobbies is the knowledge of how many you own of whatever you collect. The next function performs this function admirably; it scans the database, counting titles and tracks.

```
void count_cds()
{
    FILE *titles_fp, *tracks_fp;
    char entry[MAX_ENTRY];
    int titles = 0;
    int tracks = 0;

    titles_fp = fopen(title_file, "r");
    if (titles_fp) {
        while (fgets(entry, MAX_ENTRY, titles_fp))
            titles++;
        fclose(titles_fp);
    }
    tracks_fp = fopen(tracks_file, "r");
    if (tracks_fp) {
        while (fgets(entry, MAX_ENTRY, tracks_fp))
            tracks++;
        fclose(tracks_fp);
    }
    mvprintw(ERROR_LINE, 0,
            "Database contains %d titles, with a total of %d tracks.",
            titles, tracks);
    get_return();
}
```

- You've lost the sleeve notes from your favorite CD, but don't worry! Having carefully typed the details across, you can now find the track listing using `find_cd`. It prompts for a substring to match in the database and sets the global variable `current_cd` to the CD title found.

```
void find_cd()
{
    char match[MAX_STRING], entry[MAX_ENTRY];
    FILE *titles_fp;
    int count = 0;
    char *found, *title, *catalog;

    mvprintw(Q_LINE, 0, "Enter a string to search for in CD titles: ");
    get_string(match);

    titles_fp = fopen(title_file, "r");
    if (titles_fp) {
        while (fgets(entry, MAX_ENTRY, titles_fp)) {

            /* Skip past catalog number */
            catalog = entry;
            if (found == strstr(catalog, ",")) {
                *found = '\0';

```

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```
        title = found + 1;

        /* Zap the next comma in the entry to reduce it to
           title only */
        if (found == strstr(title, ",")) {
            *found = '\0';

            /* Now see if the match substring is present */
            if (found == strstr(title, match)) {
                count++;
                strcpy(current_cd, title);
                strcpy(current_cat, catalog);
            }
        }
    }
    fclose(titles_fp);
}
if (count != 1) {
    if (count == 0) {
        mvprintw(ERROR_LINE, 0, "Sorry, no matching CD found. ");
    }
    if (count > 1) {
        mvprintw(ERROR_LINE, 0,
                 "Sorry, match is ambiguous: %d CDs found. ", count);
    }
    current_cd[0] = '\0';
    get_return();
}
}
```

Though catalog points at a larger array than current_cat and could conceivably overwrite memory, the check in fgets prevents this.

3. Lastly, we need to be able to list the selected CD's tracks on the screen. We make use of the #defines for the subwindows used in update_cd in the last section.

```
void list_tracks()
{
    FILE *tracks_fp;
    char entry[MAX_ENTRY];
    int cat_length;
    int lines_op = 0;
    WINDOW *track_pad_ptr;
    int tracks = 0;
    int key;
    int first_line = 0;

    if (current_cd[0] == '\0') {
        mvprintw(ERROR_LINE, 0, "You must select a CD first. ");
        get_return();
        return;
    }
```

```
clear_all_screen();
cat_length = strlen(current_cat);

/* First count the number of tracks for the current CD */
tracks_fp = fopen(tracks_file, "r");
if (!tracks_fp)
    return;
while (fgets(entry, MAX_ENTRY, tracks_fp)) {
    if (strncmp(current_cat, entry, cat_length) == 0)
        tracks++;
}
fclose(tracks_fp);

/* Make a new pad, ensure that even if there is only a single
   track the PAD is large enough so the later prefresh() is always
   valid. */
track_pad_ptr = newpad(tracks + 1 + BOXED_LINES, BOXED_ROWS + 1);
if (!track_pad_ptr)
    return;

tracks_fp = fopen(tracks_file, "r");
if (!tracks_fp)
    return;

mvprintw(4, 0, "CD Track Listing\n");

/* write the track information into the pad */
while (fgets(entry, MAX_ENTRY, tracks_fp)) {

    /* Compare catalog number and output rest of entry */
    if (strncmp(current_cat, entry, cat_length) == 0) {
        mvwprintw(track_pad_ptr, lines_op++, 0, "%s",
                  entry + cat_length + 1);
    }
}
fclose(tracks_fp);

if (lines_op > BOXED_LINES) {
    mvprintw(MESSAGE_LINE, 0,
             "Cursor keys to scroll, RETURN or q to exit");
} else {
    mvprintw(MESSAGE_LINE, 0, "RETURN or q to exit");
}
wrefresh(stdscr);
keypad(stdscr, TRUE);
cbreak();
noecho();
key = 0;
while (key != 'q' && key != KEY_ENTER && key != '\n') {
    if (key == KEY_UP) {
        if (first_line > 0)
            first_line--;
    }
    if (key == KEY_DOWN) {
```

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```
        if (first_line + BOXED_LINES + 1 < tracks)
            first_line++;
    }

/* now draw the appropriate part of the pad on the screen */
prefresh(track_pad_ptr, first_line, 0,
    BOX_LINE_POS, BOX_ROW_POS,
    BOX_LINE_POS + BOXED_LINES, BOX_ROW_POS + BOXED_ROWS);
key = getch();
}

delwin(track_pad_ptr);
keypad(stdscr, FALSE);
nocbreak();
echo();
}
```

4. The last two functions call `get_return`, which prompts for and reads a carriage return, ignoring other characters:

```
void get_return()
{
    int ch;
    mvprintw(23, 0, "%s", " Press return ");
    refresh();
    while ((ch = getchar()) != '\n' && ch != EOF);
}
```

If you run this program, you should see something like Figure 6-10.



Figure 6-10

Summary

In this chapter, we have explored the `curses` library. `curses` provides a good way for text-based programs to control the screen and read the keyboard. Although `curses` doesn't offer as much control as the general terminal interface (GTI) and direct `terminfo` access, it's considerably easier to use. If you're writing a full-screen, text-based application, you should consider using the `curses` library to manage the screen and keyboard for you.

7

Data Management

In earlier chapters, we touched on the subject of resource limits. In this chapter, we're going to look first at ways of managing your resource allocation, then at ways of dealing with files that are accessed by many users more or less simultaneously, and lastly at one tool provided in Linux systems for overcoming the limitations of flat files as a data storage medium.

We can summarize these topics as three ways of managing data:

- ❑ Dynamic memory management: what to do and what Linux won't let you do
- ❑ File locking: cooperative locking, locking regions of shared files, and avoiding deadlocks
- ❑ The `dbm` database: a basic, non-SQL-based database library featured in most Linux systems

Managing Memory

On all computer systems memory is a scarce resource. No matter how much memory is available, it never seems to be enough. It doesn't seem so long ago that being able to address even a single megabyte of memory was considered more than anyone would ever need, but now numbers like 512MB of RAM are commonplace as minimum requirements.

From the earliest versions of the operating system, UNIX-style operating systems have had a very clean approach to managing memory that Linux, because it implements the X/Open specification, has inherited. Linux applications, except for a few specialized embedded applications, are never permitted to access physical memory directly. It might appear so to the application, but what the application is seeing is a carefully controlled illusion.

Linux provides applications with a clean view of a huge directly addressable memory space. Additionally, it provides protection so that different applications are protected from each other, and it allows applications to apparently access more memory than is physically present in the machine, provided the machine is at least well configured and has sufficient swap space.

Simple Memory Allocation

We allocate memory using the `malloc` call in the standard C library.

```
#include <stdlib.h>

void *malloc(size_t size);
```

Notice that Linux (following the X/Open specification) differs from some UNIX implementations by not requiring a special `malloc.h` include file. Note also that the `size` parameter that specifies the number of bytes to allocate isn't a simple `int`, although it's usually an unsigned integer type.

We can allocate a great deal of memory on most Linux systems. Let's start with a very simple program, but one that would defeat old MS-DOS-based programs, because they cannot access memory outside the base 640k memory map of PCs.

Try It Out—Simple Memory Allocation

Type the following program, `memory1.c`:

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

#define A_MEGABYTE (1024 * 1024)

int main()
{
    char *some_memory;
    int megabyte = A_MEGABYTE;
    int exit_code = EXIT_FAILURE;

    some_memory = (char *)malloc(megabyte);
    if (some_memory != NULL) {
        sprintf(some_memory, "Hello World\n");
        printf("%s", some_memory);
        exit_code = EXIT_SUCCESS;
    }
    exit(exit_code);
}
```

When we run this program, it gives us the following output:

```
$ ./memory1
Hello World
```

How It Works

This program asks the `malloc` library to give it a pointer to a megabyte of memory. We check to ensure that `malloc` was successful and then use some of the memory to show that it exists. When you run the program, you should see `Hello World` printed out, showing that `malloc` did indeed return the megabyte of usable memory. We don't check that all of the megabyte is present; we have to put some trust in the `malloc` code!

Notice that because `malloc` returns a `void *` pointer, we cast the result to the `char *` that we need. The `malloc` function is guaranteed to return memory that is aligned so that it can be cast to a pointer of any type.

The simple reason is that most current Linux systems use 32-bit integers and use 32-bit pointers for pointing to memory, which allows you to specify up to 4 gigabytes. This ability to address directly with a 32-bit pointer, without needing segment registers or other tricks, is termed a *flat 32-bit memory model*. This model is also used in Windows XP and Windows 9x/Me for 32-bit applications. You shouldn't rely on integers being 32-bit, however, as there are also an increasing number of 64-bit versions of Linux in use.

Allocating Lots of Memory

Now that we've seen Linux exceed the limitations of the MS-DOS memory model, let's give it a more difficult problem. The next program will ask to allocate somewhat more memory than is physically present in the machine, so we might expect `malloc` to start failing somewhere a little short of the actual amount of memory present, because the kernel and all the other running processes will be using some memory.

Try It Out—Asking for All Physical Memory

With `memory2.c`, we're going to ask for more than the machine's memory. You may need to adjust the `define PHY_MEM_MEGS` depending on your physical machine:

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

#define A_MEGABYTE (1024 * 1024)
#define PHY_MEM_MEGS      256 /* Adjust this number as required */

int main()
{
    char *some_memory;
    size_t size_to_allocate = A_MEGABYTE;
    int mbytes_obtained = 0;

    while (mbytes_obtained < (PHY_MEM_MEGS * 2)) {
        some_memory = (char *)malloc(size_to_allocate);
        if (some_memory != NULL) {
            mbytes_obtained++;
            sprintf(some_memory, "Hello World");
            printf("%s - now allocated %d Megabytes\n", some_memory,
mbytes_obtained);
        }
        else {
            exit(EXIT_FAILURE);
        }
    }
    exit(EXIT_SUCCESS);
}
```

The output, somewhat abbreviated, is

```
$ ./memory2
Hello World - now allocated 1 Megabytes
Hello World - now allocated 2 Megabytes
...
Hello World - now allocated 511 Megabytes
Hello World - now allocated 512 Megabytes
```

How It Works

The program is very similar to the previous example. It simply loops, asking for more and more memory. The surprise is that it works at all, because we appear to have created a program that uses every single byte of physical memory on the author's machine. Notice that we use the `size_t` type for our call to `malloc`.

The other interesting feature is that, at least on this machine, it ran the program in the blink of an eye. So not only have we apparently used up all the memory, but we've done it very quickly indeed.

Let's investigate further and see just how much memory we can allocate on this machine with `memory3.c`. Since it's now clear that Linux can do some very clever things with requests for memory, we'll allocate memory just 1k at a time and write to each block that we obtain.

Try It Out—Available Memory

This is `memory3.c`. By its very nature, it's extremely system-unfriendly and could affect a multiuser machine quite seriously. If you're at all concerned about the risk, it's better not to run it at all; it won't harm your understanding if you don't.

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

#define ONE_K (1024)

int main()
{
    char *some_memory;
    int size_to_allocate = ONE_K;
    int megs_obtained = 0;
    int ks_obtained = 0;

    while (1) {
        for (ks_obtained = 0; ks_obtained < 1024; ks_obtained++) {
            some_memory = (char *)malloc(size_to_allocate);
            if (some_memory == NULL) exit(EXIT_FAILURE);
            sprintf(some_memory, "Hello World");
        }
        megs_obtained++;
        printf("Now allocated %d Megabytes\n", megs_obtained);
    }
    exit(EXIT_SUCCESS);
}
```

This time, the output, again abbreviated, is

```
$ ./memory3
Now allocated 1 Megabytes
...
Now allocated 377 Megabytes
Now allocated 378 Megabytes
Out of Memory: Killed process 2365
Killed
```

and then the program ends. It also takes quite a few seconds to run, visibly slows down around the same number as the physical memory in the machine, and exercises the hard disk quite noticeably. However, the program has allocated more memory than this author physically has in his machine at the time of writing. Finally the system protects itself from this rather aggressive program and kills it. On some systems it may simply exit quietly when `malloc` fails.

How It Works

The application's allocated memory is managed by the Linux kernel. Each time the program asks for memory or tries to read or write to memory that it has allocated, the Linux kernel takes charge and decides how to handle the request.

Initially, the kernel was simply able to use free physical memory to satisfy the application's request for memory, but once physical memory was full, it started using what's called *swap space*. On Linux, this is a separate disk area allocated when the system was installed. If you're familiar with Windows, the Linux swap space acts a little like the hidden Windows swap file. However, unlike Windows, there are no local heap, global heap, or discardable memory segments to worry about in code—the Linux kernel does all the management for you.

The kernel moves data and program code between physical memory and the swap space so that each time you read or write memory, the data always appears to have been in physical memory, wherever it was actually located before you attempted to access it.

In more technical terms, Linux implements a demand paged virtual memory system. All memory seen by user programs is *virtual*; that is, it doesn't actually exist at the physical address the program uses. Linux divides all memory into pages, commonly 4096 bytes per page. When a program tries to access memory, a virtual to physical translation is made, although how this is implemented and the time it takes depend on the particular hardware you're using. When the access is to memory that isn't physically resident, there is a *page fault* and control is passed to the kernel.

The Linux kernel checks the address being accessed and, if it's a legal address for that program, determines which page of physical memory to make available. It then either allocates it, if it has never been written before, or, if it has been stored on the disk in the swap space, reads the memory page containing the data into physical memory (possibly moving an existing page out to disk). Then, after mapping the virtual memory address to match the physical address, it allows the user program to continue. Linux applications don't need to worry about this activity because the implementation is all hidden in the kernel.

Eventually, when the application exhausts both the physical memory and the swap space, or when the maximum stack size is exceeded, the kernel finally refuses the request for further memory and may preemptively terminate the program.

This “killing the process” behavior is different from early versions of Linux and many other flavors of UNIX, where `malloc` simply fails. It’s termed the “out of memory (OOM) killer,” and although it may seem rather drastic, it is in fact a good compromise between letting processes allocate memory rapidly and efficiently and the Linux kernel protect itself from a total lack of resources, which is a serious issue.

So what does this mean to the application programmer? Basically, it’s all good news. Linux is very good at managing memory and will allow applications to use very large amounts of memory and even very large single blocks of memory. However, you must remember that allocating two blocks of memory won’t result in a single continuously addressable block of memory. What you get is what you ask for: two separate blocks of memory.

So does this apparently limitless supply of memory, followed by pre-emptive killing of the process, mean that there’s no point in checking the return from `malloc`? Definitely not. One of the most common problems in C programs using dynamically allocated memory is to write beyond the end of an allocated block. When this happens, the program may not terminate immediately, but you have probably overwritten some data used internally by the `malloc` library routines.

Usually, the result is that future calls to `malloc` may fail, not because there’s no memory to allocate, but because the memory structures have been corrupted. These problems can be quite difficult to track down and, in programs, the sooner the error is detected, the better the chances of tracking down the cause. In Chapter 10, on debugging and optimizing, we’ll discuss some tools that can help you track down memory problems.

Abusing Memory

Suppose we try to do “bad” things with memory. Let’s allocate some memory and then attempt to write past the end, in `memory4.c`.

Try It Out—Abuse Your Memory

```
#include <stdlib.h>

#define ONE_K (1024)

int main()
{
    char *some_memory;
    char *scan_ptr;

    some_memory = (char *)malloc(ONE_K);
    if (some_memory == NULL) exit(EXIT_FAILURE);

    scan_ptr = some_memory;
    while(1) {
        *scan_ptr = '\0';
        scan_ptr++;
    }
    exit(EXIT_SUCCESS);
}
```

The output is simply

```
$ ./memory4
Segmentation fault (core dumped)
```

How It Works

The Linux memory management system has protected the rest of the system from this abuse of memory. To ensure that one badly behaved program (this one) can't damage any other programs, Linux has terminated it.

Each running program on a Linux system sees its own memory map, which is different from every other program's. Only the operating system knows how physical memory is arranged and not only manages it for user programs, but also protects user programs from each other.

The Null Pointer

Unlike MS-DOS, but more like newer flavors of Windows, modern Linux systems are very protective about writing or reading from the address referred to by a null pointer, although the actual behavior is implementation-specific.

Try It Out—Accessing a Null Pointer

Let's find out what happens when we access a null pointer in `memory5a.c`:

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

int main()
{
    char *some_memory = (char *)0;

    printf("A read from null %s\n", some_memory);
    sprintf(some_memory, "A write to null\n");
    exit(EXIT_SUCCESS);
}
```

The output is

```
$ ./memory5a
A read from null (null)
Segmentation fault (core dumped)
```

How It Works

The first `printf` attempts to print out a string obtained from a null pointer; then the `sprintf` attempts to write to a null pointer. In this case, Linux (in the guise of the GNU "C" library) has been forgiving about the read and has simply given us a "magic" string containing the characters (n u l l) \0. It hasn't been so forgiving about the write and has terminated the program. This can sometimes be helpful in tracking down program bugs.

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If we try this again, but this time don't use the GNU "C" library, we discover that reading from location zero is not permitted. Here is `memory5b.c`:

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

int main()
{
    char z = *(const char *)0;
    printf("I read from location zero\n");

    exit(EXIT_SUCCESS);
}
```

The output is

```
$ ./memory5b
Segmentation fault (core dumped)
```

How It Works

This time we attempt to read directly from location zero. There is no GNU `libc` library between us and the kernel this time, and our program is terminated. You should note that some versions of UNIX do permit reading from location zero, but Linux doesn't.

Freeing Memory

Up to now, we've been simply allocating memory and then hoping that, when the program ends, the memory we've used hasn't been lost. Fortunately, the Linux memory management system is quite capable of reliably ensuring that memory is returned to the system when a program ends. However, most programs don't simply want to allocate some memory, use it for a short period, and then exit. A much more common use is dynamically using memory as required.

Programs that use memory on a dynamic basis should always release unused memory back to the `malloc` memory manager using the `free` call. This allows separate blocks to be remerged and allows the `malloc` library to look after memory, rather than having the application manage it. If a running program (process) uses and then frees memory, that free memory remains allocated to the process. However, if it's not being used, the Linux memory manager will be able to page it out from physical memory to swap space, where it has little impact on the use of resources.

```
#include <stdlib.h>

void free(void *ptr_to_memory);
```

A call to `free` should be made only with a pointer to memory allocated by a call to `malloc`, `calloc`, or `realloc`. We'll meet `calloc` and `realloc` very shortly.

Try It Out—Freeing Memory

This program's called `memory6.c`:

```
#include <stdlib.h>

#define ONE_K (1024)

int main()
{
    char *some_memory;
    int exit_code = EXIT_FAILURE;

    some_memory = (char *)malloc(ONE_K);
    if (some_memory != NULL) {
        free(some_memory);
        exit_code = EXIT_SUCCESS;
    }
    exit(exit_code);
}
```

How It Works

This program simply shows how to call `free` with a pointer to some previously allocated memory.

Remember that once you've called `free` on a block of memory, it no longer belongs to the process. It's not being managed by the `malloc` library. Never try to read or write memory after calling `free` on it.

Other Memory Allocation Functions

Two other memory allocation functions are not used as often as `malloc` and `free`: `calloc` and `realloc`. The prototypes are

```
#include <stdlib.h>

void *calloc(size_t number_of_elements, size_t element_size);
void *realloc(void *existing_memory, size_t new_size);
```

Although `calloc` allocates memory that can be freed with `free`, it has somewhat different parameters: It allocates memory for an array of structures and requires the number of elements and the size of each element as its parameters. The allocated memory is filled with zeros, and if `calloc` is successful, a pointer to the first element is returned. Like `malloc`, subsequent calls are not guaranteed to return contiguous space, so you can't enlarge an array created by `calloc` by simply calling `calloc` again and expecting the second call to return memory appended to that returned by the first call.

The `realloc` function changes the size of a block of memory that has been previously allocated. It's passed a pointer to some memory previously allocated by `malloc`, `calloc`, or `realloc` and resizes it up or down as requested. The `realloc` function may have to move data around to achieve this, so it's important to ensure that once memory has been `reallocated`, you always use the new pointer and never try to access the memory using pointers set up before `realloc` was called.

Another problem to watch out for is that `realloc` returns a null pointer if it has been unable to resize the memory. This means that, in some applications, you should avoid writing code like this:

```
my_ptr = malloc(BLOCK_SIZE);  
....  
my_ptr = realloc(my_ptr, BLOCK_SIZE * 10);
```

If `realloc` fails, it will return a null pointer; `my_ptr` will point to null; and the original memory allocated with `malloc` can no longer be accessed via `my_ptr`. It may, therefore, be to your advantage to request the new memory first with `malloc` and then copy data from the old block to the new block using `memcpy` before freeing the old block. On error, this would allow the application to retain access to the data stored in the original block of memory, perhaps while arranging a clean termination of the program.

File Locking

File locking is a very important part of multiuser, multitasking operating systems. Programs frequently need to share data, usually through files, and it's very important that those programs have some way of establishing control of a file. The file can then be updated in a safe fashion, or a second program can stop itself from trying to read a file that is in a transient state while another program is writing to it.

Linux has several features that you can use for file locking. The simplest method is a technique to create lock files in an atomic way, so that nothing else can happen while the lock is being created. This gives a program a method of creating files that are guaranteed to be unique and could not have been simultaneously created by a different program.

The second method is more advanced; it allows programs to lock parts of a file for exclusive access. There are two different ways of achieving this second form of locking. We'll look at only one in detail, since the second is very similar—it just has a slightly different programming interface.

Creating Lock Files

Many applications just need to be able to create a lock file for a resource. Other programs can then check the file to see whether they are permitted to access the resource.

Usually, these lock files are in a special place with a name that relates to the resource being controlled. For example, when a modem is in use, Linux creates a lock file, often using a directory in the `/usr/spool` or `/var/spool` directory.

Remember that lock files act only as indicators; programs need to cooperate to use them. They are termed *advisory locks* as opposed to mandatory locks, where the system will enforce the lock behavior.

To create a file to use as a lock indicator, we use the `open` system call defined in `fcntl.h` (which we met in an earlier chapter) with the `O_CREAT` and `O_EXCL` flags set. This allows us to check that the file doesn't already exist and then create it in a single, atomic operation.

Try It Out—Creating a Lock File

Let's see this in action with `lock1.c`:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>
#include <errno.h>

int main()
{
    int file_desc;
    int save_errno;

    file_desc = open("/tmp/LCK.test", O_RDWR | O_CREAT | O_EXCL, 0444);
    if (file_desc == -1) {
        save_errno = errno;
        printf("Open failed with error %d\n", save_errno);
    }
    else {
        printf("Open succeeded\n");
    }
    exit(EXIT_SUCCESS);
}
```

The first time we run the program, the output is

```
$ lock1
Open succeeded
```

but the next time we try, we get

```
$ lock1
Open failed with error 17
```

How It Works

The program calls `open` to create a file called `/tmp/LCK.test`, using the `O_CREAT` and `O_EXCL` flags. The first time we run the program, the file doesn't exist, so the `open` call is successful. Subsequent invocations of the program fail because the file already exists. To get the program to succeed again, we'll have to remove the lock file.

On Linux systems at least, error 17 refers to `EEXIST`, an error that is used to indicate that a file already exists. Error numbers are defined in the header file `errno.h` or more commonly by files included by it. In this case, the definition, actually in `/usr/include/asm/errno.h`, reads

```
#define EEXIST          17          /* File exists */
```

This is an appropriate error for an `open(O_CREAT | O_EXCL)` failure.

If a program simply needs a resource exclusively for a short period of its execution, often termed a *critical section*, it should create the lock file before entering the critical section and use `unlink` to delete it afterward, when it exits the critical section.

We can demonstrate how programs can cooperate with this locking mechanism by writing a sample program and running two copies of it at the same time. We're going to use the `getpid` call, which we saw in Chapter 4; it returns the process identifier, a unique number for each currently executing program.

Try It Out—Cooperative Lock Files

1. Here's the source of our test program: `lock2.c`:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>
#include <errno.h>

const char *lock_file = "/tmp/LCK.test2";

int main()
{
    int file_desc;
    int tries = 10;

    while (tries--) {
        file_desc = open(lock_file, O_RDWR | O_CREAT | O_EXCL, 0444);
        if (file_desc == -1) {
            printf("%d - Lock already present\n", getpid());
            sleep(3);
        }
        else {
```

2. The critical section starts here:

```
        printf("%d - I have exclusive access\n", getpid());
        sleep(1);
        (void)close(file_desc);
        (void)unlink(lock_file);
```

3. And it ends here:

```
    }
    sleep(2);
}
exit(EXIT_SUCCESS);
}
```

To run the program, we should first use this command to ensure that the lock file doesn't exist:

```
$ rm -f /tmp/LCK.test2
```

Then we run two copies of the program by using this command:

```
$ ./lock2 & ./lock2
```

This starts a copy of lock2 in the background and a second copy running in the foreground. This is the output that we get:

```
1284 - I have exclusive access
1283 - Lock already present
1283 - I have exclusive access
1284 - Lock already present
1284 - I have exclusive access
1283 - Lock already present
1283 - I have exclusive access
1284 - Lock already present
1284 - I have exclusive access
1283 - Lock already present
1283 - I have exclusive access
1284 - Lock already present
1284 - I have exclusive access
1283 - Lock already present
1283 - I have exclusive access
1284 - Lock already present
1284 - I have exclusive access
1283 - Lock already present
1283 - I have exclusive access
1284 - Lock already present
```

The preceding example shows how the two invocations of the same program are cooperating. If you try this, you'll almost certainly see different process identifiers in the output, but the program behavior will be the same.

How It Works

For the purposes of demonstration, we make the program loop 10 times using the `while` loop. The program then tries to access the critical resource by creating a unique lock file, `/tmp/LCK.test2`. If this fails because the file already exists, the program waits for a short time and tries again. If it succeeds, it can then have access to the resource and, in the part marked "critical section," can carry out whatever processing is required with exclusive access.

Since this is just a demonstration, we wait for only a short period. When the program has finished with the resource, it releases the lock by deleting the lock file. It can then carry out some other processing (just the `sleep` function in this case) before trying to reacquire the lock. The lock file acts as a binary semaphore, giving each program a yes or no answer to the question, "Can I use the resource?" You will learn more about semaphores in Chapter 14.

It's important to realize that this is a cooperative arrangement and that we must write the programs correctly for it to work. A program failing to create the lock file can't simply delete the file and try again. It might then be able to create the lock file, but the other program that created the lock file has no way of knowing that it no longer has exclusive access to the resource.

Locking Regions

Creating lock files is fine for controlling exclusive access to resources such as serial ports, but it isn't so good for access to large shared files. Suppose you have a large file that is written by one program, but updated by many different programs simultaneously. This might occur if a program is logging some data that is obtained continuously over a long period and is being processed by several other programs. The processing programs can't wait for the logging program to finish—it runs continuously—so they need some way of cooperating to provide simultaneous access to the same file.

We can accommodate this situation by locking regions of the file so that a particular section of the file is locked, but other programs may access other parts of the file. This is called *file-segment*, or *file-region*, *locking*. Linux has (at least) two ways to do this: using the `fcntl` system call and using the `lockf` call. We'll look primarily at the `fcntl` interface because that is the most commonly used interface. `lockf` is reasonably similar, and, on Linux, is normally just an alternative interface to `fcntl`. However, the `fcntl` and `lockf` locking mechanisms do not work together: They use different underlying implementations, so you should never mix the two types of call; stick to one or the other.

We met the `fcntl` call in Chapter 3. Its definition is

```
#include <fcntl.h>

int fcntl(int fildes, int command, ...);
```

`fcntl` operates on open file descriptors and, depending on the `command` parameter, can perform different tasks. The three that we're interested in for file locking are

- F_GETLK
- F_SETLK
- F_SETLKW

When we use these, the third argument must be a pointer to a `struct flock`, so the prototype is effectively this:

```
int fcntl(int fildes, int command, struct flock *flock_structure);
```

The `flock` (file lock) structure is implementation-dependent, but it will contain at least the following members:

- short l_type;
- short l_whence;
- off_t l_start;
- off_t l_len;
- pid_t l_pid;

The `l_type` member takes one of several values, also defined in `fcntl.h`. These are in the following table:

| Value | Description |
|---------|---|
| F_RDLCK | A shared (or “read”) lock. Many different processes can have a shared lock on the same (or overlapping) regions of the file. If any process has a shared lock then, no process will be able to get an exclusive lock on that region. In order to obtain a shared lock, the file must have been opened with read or read/write access. |
| F_UNLCK | Unlock; used for clearing locks. |
| F_WRLCK | An exclusive (or “write”) lock. Only a single process may have an exclusive lock on any particular region of a file. Once a process has such a lock, no other process will be able to get any sort of lock on the region. To obtain an exclusive lock, the file must have been opened with write or read/write access. |

The `l_whence` members define a region—a contiguous set of bytes—in a file. The `l_whence` must be one of `SEEK_SET`, `SEEK_CUR`, `SEEK_END` (from `unistd.h`). These correspond to the start, current position, and end of a file, respectively. `l_whence` defines the offset to which `l_start`, the first byte in the region, is relative. Normally, this would be `SEEK_SET`, so `l_start` is counted from the beginning of the file. The `l_len` parameter defines the number of bytes in the region.

The `l_pid` parameter is used for reporting the process holding a lock; see the `F_GETLK` description that follows.

Each byte in a file can have only a single type of lock on it at any one time and may be locked for shared access, locked for exclusive access, or unlocked.

There are quite a few combinations of commands and options to the `fcntl` call, so let’s look at each of them in turn.

The `F_GETLK` Command

The first command is `F_GETLK`. It gets locking information about the file that `fildes` (the first parameter) has open. It doesn’t attempt to lock the file. The calling process passes information about the type of lock it might wish to create, and `fcntl` used with the `F_GETLK` command returns any information that would prevent the lock from occurring.

The values used in the `fllock` structure are in the following table:

| Value | Description |
|-----------------------|---|
| <code>l_type</code> | Either <code>F_RDLCK</code> for a shared (read-only) lock or <code>F_WRLCK</code> for an exclusive (write) lock |
| <code>l_whence</code> | One of <code>SEEK_SET</code> , <code>SEEK_CUR</code> , <code>SEEK_END</code> |
| <code>l_start</code> | The start byte of the file region of interest |
| <code>l_len</code> | The number of bytes in the file region of interest |
| <code>l_pid</code> | The identifier of the process with the lock |

A process may use the `F_GETLK` call to determine the current state of locks on a region of a file. It should set up the `flock` structure to indicate the type of lock it may require and define the region it's interested in. The `fcntl` call returns a value other than -1 if it's successful. If the file already has locks that would prevent a lock request from succeeding, it overwrites the `flock` structure with the relevant information. If the lock will succeed, the `flock` structure is unchanged. If the `F_GETLK` call is unable to obtain the information, it returns -1 to indicate failure.

If the `F_GETLK` call is successful (i.e., it returns a value other than -1), the calling application must check the contents of the `flock` structure to determine whether it was modified. Since the `l_pid` value is set to the locking process (if one was found), this is a convenient field to check to determine if the `flock` structure has been changed.

The `F_SETLK` Command

This command attempts to lock or unlock part of the file referenced by `fildes`. The values used in the `flock` structure (and different from those used by `F_GETLK`) are as follows:

| Value | Description |
|---------------------|--|
| <code>l_type</code> | Either <code>F_RDLCK</code> for a read-only or shared lock or <code>F_WRLCK</code> for an <code>l_type</code> . Either <code>F_RDLCK</code> for a read-only, or shared, lock; <code>F_WRLCK</code> for an exclusive, a write,exclusive or a write lock; and <code>F_UNLCK</code> to unlock a region. |
| <code>l_pid</code> | Unused. |

If the lock is successful, `fcntl` returns a value other than -1; on failure, -1 is returned. The function will always return immediately.

The `F_SETLKW` Command

The `F_SETLKW` command is the same as the `F_SETLK` command above, except that if it can't obtain the lock, the call will wait until it can. Once this call has started waiting, it will return only when the lock can be obtained or a signal occurs. We'll discuss signals in Chapter 11.

All locks held by a program on a file are automatically cleared when the relevant file descriptor is closed. This will also happen automatically when the program finishes.

Use of read and write with Locking

When you're using locking on regions of a file, it's very important to use the lower-level `read` and `write` calls to access the data in the file, rather than the higher-level `fread` and `fwrite`. This is necessary because `fread` and `fwrite` perform buffering of data read or written inside the library, so executing an `fread` call to read the first 100 bytes of a file may (in fact, almost certainly will) read more than 100 bytes and buffer the additional data inside the library. If the program then uses `fread` to read the next 100 bytes, it will actually read data already buffered inside the library and not allow a low-level `read` to pull more data from the file.

To see why this is a problem, consider two programs that wish to update the same file. Suppose the file consists of 200 bytes of data, all zeros. The first program starts first and obtains a write lock on the first 100 bytes of the file. It then uses `fread` to read in those 100 bytes. However, as we saw in an earlier

chapter, `fread` will read ahead by up to `BUFSIZ` bytes at a time, so it actually reads the entire file into memory, but only passes the first 100 bytes back to the program.

The second program then starts. It obtains a write lock on the second 100 bytes of the program. This is successful because the first program locked only the first 100 bytes. The second program writes twos to bytes 100 to 199, closes the file, unlocks it, and exits. The first program then locks the second 100 bytes of the file and calls `fread` to read them in. Because that data was buffered, what the program actually sees is 100 bytes of zeros, not the 100 twos that actually exist in the file. This problem doesn't occur when we're using `read` and `write`.

That description of file locking may seem a complex, but it's actually more difficult to describe than it is to use.

Try It Out—Locking a File with `fcntl`

Let's look at an example of how file locking works: `lock3.c`. To try out locking, we need two programs: one to do the locking and one to test. The first program does the locking.

1. Start with the includes and variable declarations:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>

const char *test_file = "/tmp/test_lock";

int main()
{
    int file_desc;
    int byte_count;
    char *byte_to_write = "A";
    struct flock region_1;
    struct flock region_2;
    int res;
```

2. Open a file descriptor:

```
file_desc = open(test_file, O_RDWR | O_CREAT, 0666);
if (!file_desc) {
    fprintf(stderr, "Unable to open %s for read/write\n", test_file);
    exit(EXIT_FAILURE);
}
```

3. Put some data in the file:

```
for(byte_count = 0; byte_count < 100; byte_count++) {
    (void)write(file_desc, byte_to_write, 1);
}
```

4. Set up region 1 with a shared lock, from bytes 10 to 30:

```
region_1.l_type = F_RDLCK;
region_1.l_whence = SEEK_SET;
```

```
region_1.l_start = 10;
region_1.l_len = 20;
```

5. Set up region 2 with an exclusive lock, from bytes 40 to 50:

```
region_2.l_type = F_WRLCK;
region_2.l_whence = SEEK_SET;
region_2.l_start = 40;
region_2.l_len = 10;
```

6. Now lock the file:

```
printf("Process %d locking file\n", getpid());
res = fcntl(file_desc, F_SETLK, &region_1);
if (res == -1) fprintf(stderr, "Failed to lock region 1\n");
res = fcntl(file_desc, F_SETLK, &region_2);
if (res == -1) fprintf(stderr, "Failed to lock region 2\n");
```

7. Then wait for a while:

```
sleep(60);

printf("Process %d closing file\n", getpid());
close(file_desc);
exit(EXIT_SUCCESS);
}
```

How It Works

The program first creates a file, opens it for both reading and writing, and then fills the file with data. It then sets up two regions: the first from bytes 10 to 30, for a shared (read) lock, and the second from bytes 40 to 50 for an exclusive (write) lock. It then calls `fcntl` to lock the two regions and waits for a minute before closing the file and exiting.

Figure 7-1 shows the situation with locks when the program starts to wait.

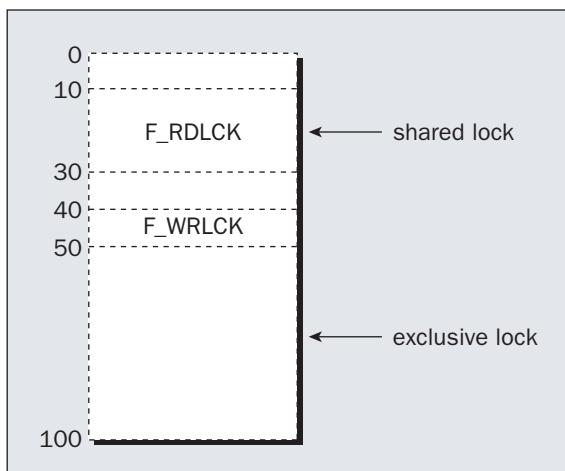


Figure 7-1

On its own, this program isn't very useful. We need a second program to test the locks, `lock4.c`.

Try It Out—Testing Locks on a File

Let's write a program that tests the different sorts of locks that we might need on different regions of a file.

1. As usual, begin with the includes and declarations:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>

const char *test_file = "/tmp/test_lock";
#define SIZE_TO_TRY 5

void show_lock_info(struct flock *to_show);

int main()
{
    int file_desc;
    int res;
    struct flock region_to_test;
    int start_byte;
```

2. Open a file descriptor:

```
file_desc = open(test_file, O_RDWR | O_CREAT, 0666);
if (!file_desc) {
    fprintf(stderr, "Unable to open %s for read/write", test_file);
    exit(EXIT_FAILURE);
}

for (start_byte = 0; start_byte < 99; start_byte += SIZE_TO_TRY) {
```

3. Set up the region we wish to test:

```
region_to_test.l_type = F_WRLCK;
region_to_test.l_whence = SEEK_SET;
region_to_test.l_start = start_byte;
region_to_test.l_len = SIZE_TO_TRY;
region_to_test.l_pid = -1;

printf("Testing F_WRLCK on region from %d to %d\n",
       start_byte, start_byte + SIZE_TO_TRY);
```

4. Now test the lock on the file:

```
res = fcntl(file_desc, F_GETLK, &region_to_test);
if (res == -1) {
    fprintf(stderr, "F_GETLK failed\n");
    exit(EXIT_FAILURE);
}
if (region_to_test.l_pid != -1) {
    printf("Lock would fail. F_GETLK returned:\n");
```

```
        show_lock_info(&region_to_test);
    }
else {
    printf("F_WRLCK - Lock would succeed\n");
}
```

5. Now repeat the test with a shared (read) lock. Set up the region you wish to test again:

```
region_to_test.l_type = F_RDLCK;
region_to_test.l_whence = SEEK_SET;
region_to_test.l_start = start_byte;
region_to_test.l_len = SIZE_TO_TRY;
region_to_test.l_pid = -1;
printf("Testing F_RDLCK on region from %d to %d\n",
       start_byte, start_byte + SIZE_TO_TRY);
```

6. Test the lock on the file again:

```
res = fcntl(file_desc, F_GETLK, &region_to_test);
if (res == -1) {
    fprintf(stderr, "F_GETLK failed\n");
    exit(EXIT_FAILURE);
}
if (region_to_test.l_pid != -1) {
    printf("Lock would fail. F_GETLK returned:\n");
    show_lock_info(&region_to_test);
}
else {
    printf("F_RDLCK - Lock would succeed\n");
}
close(file_desc);
exit(EXIT_SUCCESS);
}

void show_lock_info(struct flock *to_show) {
    printf("\tl_type %d, ", to_show->l_type);
    printf("l_whence %d, ", to_show->l_whence);
    printf("l_start %d, ", (int)to_show->l_start);
    printf("l_len %d, ", (int)to_show->l_len);
    printf("l_pid %d\n", to_show->l_pid);
}
```

To test locking, we first need to run the `lock3` program; then we run the `lock4` program to test the locked file. We do this by executing the `lock3` program in the background, with the following command:

```
$ ./lock3 &
$ process 1534 locking file
```

The command prompt returns because `lock3` is running in the background, and we then immediately run the `lock4` program with the following command:

```
$ ./lock4
```

The output we get, with some omissions for brevity, is

```

Testing F_WRLCK on region from 0 to 5
F_WRLCK - Lock would succeed
Testing F_RDLOCK on region from 0 to 5
F_RDLCK - Lock would succeed
...
Testing F_WRLCK on region from 10 to 15
Lock would fail. F_GETLK returned:
l_type 0, l_whence 0, l_start 10, l_len 20, l_pid 1534
Testing F_RDLOCK on region from 10 to 15
F_RDLCK - Lock would succeed
Testing F_WRLCK on region from 15 to 20
Lock would fail. F_GETLK returned:
l_type 0, l_whence 0, l_start 10, l_len 20, l_pid 1534
Testing F_RDLOCK on region from 15 to 20
F_RDLCK - Lock would succeed
...
Testing F_WRLCK on region from 25 to 30
Lock would fail. F_GETLK returned:
l_type 0, l_whence 0, l_start 10, l_len 20, l_pid 1534
Testing F_RDLOCK on region from 25 to 30
F_RDLCK - Lock would succeed
...
Testing F_WRLCK on region from 40 to 45
Lock would fail. F_GETLK returned:
l_type 1, l_whence 0, l_start 40, l_len 10, l_pid 1534
Testing F_RDLOCK on region from 40 to 45
Lock would fail. F_GETLK returned:
l_type 1, l_whence 0, l_start 40, l_len 10, l_pid 1534
...
Testing F_RDLOCK on region from 95 to 100
F_RDLCK - Lock would succeed

```

How It Works

For each group of five bytes in the file, `lock4` sets up a region structure to test for locks on the file, which it then uses to see if the region can be either write or read locked. The returned information shows the region bytes, offset from byte zero, that would cause the lock request to fail. Since the `l_pid` part of the returned structure contains the process identifier of the program that currently has the file locked, the program sets it to -1 (an invalid value) then checks whether it has been changed when the `fcntl` call returns. If the region isn't currently locked, `l_pid` will be unchanged.

To understand the output, we need to look in the include file `fcntl.h` (normally `/usr/include/fcntl.h`) to find that an `l_type` of 1 is from the definition of `F_WRLCK` as 1, and an `l_type` of 0 is from the definition of `F_RDLCK` as 0. Thus, an `l_type` of 1 tells us that the lock would fail because of an existing write lock and an `l_type` of 0 is caused by an existing read lock. On the regions of the file that `lock3` has not locked, both shared and exclusive locks will succeed.

From bytes 10 to 30, we can see that it would be possible to have a shared lock, because the existing lock from the `lock3` program is a shared, not an exclusive, lock. On the region from bytes 40 to 50, both types of lock will fail because `lock3` has an exclusive (`F_WRLCK`) lock on this region.

Competing Locks

Now that we've seen how to test for existing locks on a file, let's see what happens when two programs compete for locks on the same section of the file. We'll use our `lock3` program for locking the file in the first place and a new program to try to lock it again. To complete the example, we'll also add some calls for unlocking.

Try It Out—Competing Locks

Here's a program, `lock5.c`, that tries to lock regions of a file that are already locked, rather than testing the lock status of different parts of the file.

1. After the `#includes` and declarations, open a file descriptor:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>

const char *test_file = "/tmp/test_lock";

int main()
{
    int file_desc;
    struct flock region_to_lock;
    int res;

    file_desc = open(test_file, O_RDWR | O_CREAT, 0666);
    if (!file_desc) {
        fprintf(stderr, "Unable to open %s for read/write\n", test_file);
        exit(EXIT_FAILURE);
    }
}
```

2. The remainder of the program specifies different regions of the file and tries different locking operations on them:

```
region_to_lock.l_type = F_RDLCK;
region_to_lock.l_whence = SEEK_SET;
region_to_lock.l_start = 10;
region_to_lock.l_len = 5;
printf("Process %d, trying F_RDLCK, region %d to %d\n",
       getpid(),
       (int)region_to_lock.l_start, (int)(region_to_lock.l_start +
region_to_lock.l_len));
res = fcntl(file_desc, F_SETLK, &region_to_lock);
if (res == -1) {
    printf("Process %d - failed to lock region\n", getpid());
} else {
    printf("Process %d - obtained lock region\n", getpid());
}

region_to_lock.l_type = F_UNLCK;
region_to_lock.l_whence = SEEK_SET;
region_to_lock.l_start = 10;
region_to_lock.l_len = 5;
```

```
printf("Process %d, trying F_UNLCK, region %d to %d\n", getpid(),
       (int)region_to_lock.l_start,
(int)(region_to_lock.l_start +
      region_to_lock.l_len));
res = fcntl(file_desc, F_SETLK, &region_to_lock);
if (res == -1) {
    printf("Process %d - failed to unlock region\n", getpid());
} else {
    printf("Process %d - unlocked region\n", getpid());
}

region_to_lock.l_type = F_UNLCK;
region_to_lock.l_whence = SEEK_SET;
region_to_lock.l_start = 0;
region_to_lock.l_len = 50;
printf("Process %d, trying F_UNLCK, region %d to %d\n", getpid(),
       (int)region_to_lock.l_start,
(int)(region_to_lock.l_start +
      region_to_lock.l_len));
res = fcntl(file_desc, F_SETLK, &region_to_lock);
if (res == -1) {
    printf("Process %d - failed to unlock region\n", getpid());
} else {
    printf("Process %d - unlocked region\n", getpid());
}

region_to_lock.l_type = F_WRLCK;
region_to_lock.l_whence = SEEK_SET;
region_to_lock.l_start = 16;
region_to_lock.l_len = 5;
printf("Process %d, trying F_WRLCK, region %d to %d\n", getpid(),
       (int)region_to_lock.l_start,
(int)(region_to_lock.l_start +
      region_to_lock.l_len));
res = fcntl(file_desc, F_SETLK, &region_to_lock);
if (res == -1) {
    printf("Process %d - failed to lock region\n", getpid());
} else {
    printf("Process %d - obtained lock on region\n", getpid());
}

region_to_lock.l_type = F_RDLCK;
region_to_lock.l_whence = SEEK_SET;
region_to_lock.l_start = 40;
region_to_lock.l_len = 10;
printf("Process %d, trying F_RDLCK, region %d to %d\n", getpid(),
       (int)region_to_lock.l_start,
(int)(region_to_lock.l_start +
      region_to_lock.l_len));
res = fcntl(file_desc, F_SETLK, &region_to_lock);
if (res == -1) {
    printf("Process %d - failed to lock region\n", getpid());
} else {
    printf("Process %d - obtained lock on region\n", getpid());
}
```

```
region_to_lock.l_type = F_WRLCK;
region_to_lock.l_whence = SEEK_SET;
region_to_lock.l_start = 16;
region_to_lock.l_len = 5;
printf("Process %d, trying F_WRLCK with wait, region %d to %d\n", getpid(),
       (int)region_to_lock.l_start,
(int)(region_to_lock.l_start +
      region_to_lock.l_len));
res = fcntl(file_desc, F_SETLK, &region_to_lock);
if (res == -1) {
    printf("Process %d - failed to lock region\n", getpid());
} else {
    printf("Process %d - obtained lock on region\n", getpid());
}

printf("Process %d ending\n", getpid());
close(file_desc);
exit(EXIT_SUCCESS);
}
```

If we first run our `lock3` program in the background, then immediately run this new program,

```
$ ./lock3 &
$ process 1845 locking file
$ ./lock5
```

the output we get is

```
Process 227 locking file
Process 228, trying F_RDLCK, region 10 to 15
Process 228 - obtained lock on region
Process 228, trying F_UNLCK, region 10 to 15
Process 228 - unlocked region
Process 228, trying F_UNLCK, region 0 to 50
Process 228 - unlocked region
Process 228, trying F_WRLCK, region 16 to 21
Process 228 - failed to lock on region
Process 228, trying F_RDLCK, region 40 to 50
Process 228 - failed to lock on region
Process 228, trying F_WRLCK with wait, region 16 to 21
Process 227 closing file
Process 228 - obtained lock on region
Process 228 ending
```

How It Works

First, the program attempts to lock a region from bytes 10 to 15 with a shared lock. This region is already locked with a shared lock, but simultaneous shared locks are allowed and the lock is successful.

It then unlocks (its own) shared lock on the region, which is also successful. The program then attempts to unlock the first 50 bytes of the file, even though it doesn't have any locks set. This is also successful because, even though this program had no locks in the first place, the final result of the unlock request is that there are no locks held by this program in the first 50 bytes.

Next, the program attempts to lock the region from bytes 16 to 21 with an exclusive lock. This region is also already locked with a shared lock, so this time the new lock fails, because an exclusive lock could not be created.

After that, the program attempts a shared lock on the region from bytes 40 to 50. This region is already locked with an exclusive lock, so again the lock fails.

Finally, the program again attempts to obtain an exclusive lock on the region from bytes 16 to 21, but this time it uses the `F_SETLCKW` command to wait until it can obtain a lock. There is then a long pause in the output until the `lock3` program, which has already locked the region, closes the file, thus releasing all the locks it had acquired. The `lock5` program resumes execution, successfully locking the region, before it also exits.

Other Lock Commands

There is a second method of locking files: the `lockf` function. This also operates using file descriptors. It has the prototype

```
#include <unistd.h>

int lockf(int fildes, int function, off_t size_to_lock);
```

It can take the following `function` values:

- `F_ULOCK`: Unlock
- `F_LOCK`: Lock exclusively
- `F_TLOCK`: Test and lock exclusively
- `F_TEST`: Test for locks by other processes

The `size_to_lock` parameter is the number of bytes to operate on, from the current offset in the file.

`lockf` has a simpler interface than the `fcntl` interface, principally because it has rather less functionality and flexibility. To use the function, you must seek the start of the region you wish to lock and then call it with the number of bytes to lock.

Like the `fcntl` method of file locking, all locks are only advisory; they won't actually prevent reading from or writing to the file. It's the responsibility of programs to check for locks. The effect of mixing `fcntl` locks and `lockf` locks is undefined, so you must decide which type of locking you wish to use and stick to it.

Deadlocks

No discussion of locking would be complete without a mention of the dangers of deadlocks. Suppose two programs wish to update the same file. They both need to update byte 1 and byte 2 at the same time. Program A chooses to update byte 2, then byte 1. Program B tries to update byte 1 first, then byte 2.

Both programs start at the same time. Program A locks byte 2 and program B locks byte 1. Program A tries for a lock on byte 1. Since this is already locked by program B, program A waits. Program B tries for a lock on byte 2. Since this is locked by program A, Program B too waits.

This situation, when neither program is able to proceed, is called a *deadlock*, or *deadly embrace*. It is a common problem with database applications in which many users are frequently trying to access the same data. Most commercial relational databases detect deadlocks and break them automatically; the Linux kernel doesn't. Some external intervention, perhaps forcibly terminating one of the programs, is required to sort out the resulting mess.

Programmers must be wary of this situation. When you have multiple programs waiting for locks, you need to be very careful to consider if a deadlock could occur. In this example it's quite easy to avoid: Both programs should simply lock the bytes they require in the same order, or use a larger region to lock.

We don't have the space to consider the difficulties of concurrent programs here. If you're interested in reading further, you might like to consider obtaining a copy of Principles of Concurrent and Distributed Programming by M. Ben-Ari (Prentice Hall, ISBN 013711821X).

Databases

We've seen how to use files for storing data, so why should we want to use a database? Quite simply, there are some circumstances where the features of a database provide a better way to solve the problem. Using a database is better than storing files for two reasons:

- ❑ You can store data records that vary in size, which can be a little difficult to implement using flat, unstructured files.
- ❑ Databases store and retrieve data using an index. The big advantage is that this index need not be a simple record number, which would be quite easy to implement in a flat file, but an arbitrary string.

The **dbm** Database

All versions of Linux, and most flavors of UNIX, come with a basic, but very efficient, data storage set of routines called the `dbm` database. The `dbm` database is excellent for storing indexed data that is relatively static. Some database purists would probably argue that `dbm` isn't a database at all, simply an indexed file storage system. The X/Open specification, however, refers to `dbm` as a database, so we'll continue to refer to it as such in this book.

Introduction to dbm

In spite of the rise of free relational databases, such as MySQL and PostgreSQL, the `dbm` database continues to play an important role in Linux. Distributions that use RPM, such as RedHat and SuSE, use `dbm` as the underlying storage for installed package information. The Open Source implementation of LDAP, Open LDAP, can also use `dbm` as a storage mechanism. The advantage of `dbm` is that it is easier to build into a distributed binary because no separate server is installed, and there is little danger of the underlying libraries not being installed.

The `dbm` database lets you store data structures of variable size, using an index, and then retrieve the structure either using the index or simply sequentially scanning the database. The `dbm` database is best used for data that is accessed frequently, but updated rarely, because it tends to be rather slow to create entries but quick to retrieve them.

At this point, we come to a minor problem: Over the years, there have been several variations of the `dbm` database with slightly different APIs and features. There is the original `dbm` set, the “new” `dbm` set, called `ndbm`, and the GNU implementation, `gdbm`. The GNU implementation can also emulate the older `dbm` and `ndbm` interfaces, but natively has a significantly different interface than the other implementations. Different Linux distributions ship with different versions of the `dbm` libraries, although the most common choice is to ship with the `gdbm` library, but installed such that it can emulate the other two interface types.

Here we are going to concentrate on the `ndbm` interface because that is the one standardized by X/OPEN and because it is somewhat simpler to use than the raw `gdbm` implementation.

Getting dbm

If you are interested in other implementations of `dbm`, there is a BSD-licensed version that can be found either at <ftp://ftp.cs.berkeley.edu/ucb/4bsd/> or from <http://www.openbsd.org>. Sleepycat Software (<http://www.sleepycat.com>) has an Open Source product, The Berkeley Database, which also supports the `dbm`/`ndbm` historic interfaces. The GNU version can be found on <http://www.gnu.org>.

Troubleshooting and Reinstalling dbm

This chapter has been written assuming you have an X/OPEN compatible version of `dbm` installed. If you have trouble compiling these examples—either because the `ndbm.h` header file is not present, because the compiler complains that `dbm` is undefined, or the link stage of compiling the program fails—try installing an updated version of the GNU version of the `dbm` libraries.

The easiest way to check what version you have is to look for the `include` files `gdbm.h`, `ndbm.h`, and `dbm.h`. You may find that the latter two are in a subdirectory such as `/usr/include/gdbm`, which is a clue that the underlying implementation is `gdbm`, but the compatible libraries have been already installed for you. If you can’t find an `ndbm.h` file anywhere on your system, you can always install the GNU `gdbm` interface yourself. First, make yourself a temporary directory. Then go to the <http://www.gnu.org> site and search for the latest version of the `gdbm` library. It will probably be in a file called something like `gdbm_?_?_tar.gz`. Download the file to your temporary directory and extract the files using ‘`tar zxvf <filename>`’. Then read the `README` file, which will tell you how to compile and install the library. Generally you first run a `./configure` command that checks how your system is configured, and then you run `make` to compile the programs. Finally, you run `make install` and `make install-compat` to install both the basic files and the additional compatibility files. You may need root permissions to run the `install` step, and it’s often a good idea to use the `-n` option to `make` first (e.g., `make -n install`), to check what it’s going to do.

You should now have an X/OPEN compatible version of `ndbm`, normally in the `/usr/local` part of your system. Your compiler setup may not search these locations by default, in which case you need to add to the `gcc` command the `-I/usr/local/include` option to search for headers and the `-L/usr/local/lib` option to search for libraries:

```
$ gcc -I/usr/local/include program.c -L/usr/local/lib -o program -lgdbm
```

If your system came with the `ndbm.h` file already, but in a subdirectory of `/usr/include`, such as `/usr/include/gdbm`, you may need to add `-I/usr/include/gdbm` to the compile line:

```
$ gcc -I/usr/include/gdbm program.c -o program -lgdbm
```

The `dbm` Routines

Like `curses`, which we discussed in the Chapter 6, the `dbm` facility consists of a header file and a library that must be linked when the program is compiled. The library is called simply `dbm`, so we link it by adding the option `-ldbm` (or occasionally `-lgdbm`) to the compilation line. The header file is `ndbm.h`.

The reason for the `n` prefix is that there have been several predecessors to the `dbm` library, so the `n` simply separates this new `dbm` include file from any older versions that may survive.

Before we can attempt to explain each of these functions, it's important to understand what the `dbm` database is trying to achieve. Once we understand this, we'll be in a much better position to understand how to use the `dbm` functions.

The `dbm` database's basic element is a block of data to store, coupled with a companion block of data that acts as a key for retrieving that data. Each `dbm` database must have a unique key for each block of data to be stored. There's no restriction on either the keys or the data, nor are any errors defined for using data or keys that are too large. The specification allows an implementation to limit the size of the key/data pair to be 1023 bytes, but generally there is no limit, because implementations have been more flexible than they were required to be. The key value acts as an index into the data stored.

To manipulate these blocks as data, the `ndbm.h` include file defines a new type called `datum`. The exact content of this type is implementation-dependent, but it must have at least the following members:

```
void *dptr;
size_t dsize
```

`datum` will be a type defined by `typedef`. Also declared in the `ndbm.h` file is a type definition for `dbm`, which is a structure used for accessing the database, much like a `FILE` is used for accessing files. The internals of the `dbm` type are implementation-dependent and should never be used.

To reference a block of data when we're using the `dbm` library, we must declare a `datum`, set `dptr` to point to the start of the data, and set `dsize` to contain its size. Both the data to store and the index used to access it are always referenced by a `datum` type.

The `dbm` type is best thought of as analogous to a `FILE` type. When we open a `dbm` database, two physical files are created, one with a `.pag` extension and one with a `.dir` extension. A single `dbm` pointer is returned, which is used to access these two files as a pair. The files should never be read or written to directly, as they are intended to be accessed only via the `dbm` routines.

If you are using the `gdbm` library natively, the two files have been merged and only a single new file gets created.

If you're familiar with SQL databases, you'll notice that there are no table or column structures associated with a `dbm` database. These structures are unnecessary because `dbm` neither imposes a fixed size on each item of data to be stored nor requires internal structure to the data. The `dbm` library works on blocks of unstructured binary data.

dbm Access Functions

Now that we've introduced the basis on which the `dbm` library works, we can take a look at the functions in detail. The prototypes for the main `dbm` functions are

```
#include <ndbm.h>

DBM *dbm_open(const char *filename, int file_open_flags, mode_t file_mode);
int dbm_store(DBM *database_descriptor, datum key, datum content, int store_mode);
datum dbm_fetch(DBM *database_descriptor, datum key);
void dbm_close(DBM *database_descriptor);
```

dbm_open

This function is used to open existing databases and can be used to create new databases. The `filename` argument is a base filename, without a `.dir` or `.pag` extension.

The remaining parameters are the same as the second and third parameters to the `open` function, which you met in Chapter 3. We can use the same `#defines`. The second argument controls whether the database can be read from, written to, or both. If you are creating a new database, the flags must be binary ORed with `O_CREAT` to allow the files to be created. The third argument specifies the initial permissions of the files that will be created.

`dbm_open` returns a pointer to a `DBM` type. This is used in all subsequent accesses of the database. On failure, a `(DBM *) 0` is returned.

dbm_store

We use this function for entering data into the database. As we mentioned earlier, all data must be stored with a unique index. To define the data we wish to store and the index used to refer to it, we must set up two `datum` types: one to refer to the index and one for the actual data. The final parameter, `store_mode`, controls what happens if an attempt is made to store some data using a key that already exists. If it's set to `dbm_insert`, the store fails and `dbm_store` returns 1. If it's set to `dbm_replace`, the new data overwrites the existing data and `dbm_store` returns 0. `dbm_store` will return negative numbers on other errors.

dbm_fetch

The `dbm_fetch` routine is used for retrieving data from the database. It takes a `dbm` pointer, as returned from a previous call to `dbm_open`, and a `datum` type, which must be set up to point to a key. A `datum` type is returned. If the data relating to the key used was found in the database, the returned `datum` structure will have `dptr` and `dsiz` values set up to refer to the returned data. If the key was not found, the `dptr` will be set to `null`.

It's important to remember that `dbm_fetch` is returning only a datum containing a pointer to the data. The actual data may still be held in local storage space inside the `dbm` library and should be copied into program variables before any further `dbm` functions are called.

dbm_close

This routine closes a database opened with `dbm_open` and must be passed a `dbm` pointer returned from a previous call to `dbm_open`.

Try It Out—A Simple dbm Database

Now that we've learned the basic functions of the `dbm` database, we know enough to write our first `dbm` program: `dbm1.c`. In this program, we'll use a structure called `test_data`.

1. First of all, here are its `#include` files, `#defines`, the main function, and the declaration of the `test_data` structure:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>
#include <ndbm.h>
#include <string.h>

#define TEST_DB_FILE "/tmp/dbm1_test"
#define ITEMS_USED 3

struct test_data {
    char misc_chars[15];
    int any_integer;
    char more_chars[21];
};

int main()
{
```

2. Within `main`, we set up the `items_to_store` and `items_received` structures, the key string, and datum types:

```
struct test_data items_to_store[ITEMS_USED];
struct test_data item_retrieved;

char key_to_use[20];
int i, result;

datum key_datum;
datum data_datum;

DBM *dbm_ptr;
```

3. Having declared a pointer to a dbm type structure, we now open our test database for reading and writing, creating it if necessary:

```
dbm_ptr = dbm_open(TEST_DB_FILE, O_RDWR | O_CREAT, 0666);
if (!dbm_ptr) {
    fprintf(stderr, "Failed to open database\n");
    exit(EXIT_FAILURE);
}
```

4. Now we add some data to the items_to_store structure:

```
memset(items_to_store, '\0', sizeof(items_to_store));
strcpy(items_to_store[0].misc_chars, "First!");
items_to_store[0].any_integer = 47;
strcpy(items_to_store[0].more_chars, "foo");

strcpy(items_to_store[1].misc_chars, "bar");
items_to_store[1].any_integer = 13;
strcpy(items_to_store[1].more_chars, "unlucky?");

strcpy(items_to_store[2].misc_chars, "Third");
items_to_store[2].any_integer = 3;
strcpy(items_to_store[2].more_chars, "baz");
```

5. For each entry, we need to build a key for future referencing. This is the first letter of each string and the integer. This key is then identified with the key_datum, while the data_datum refers to the items_to_store entry. Then we store the data in the database.

```
for (i = 0; i < ITEMS_USED; i++) {
    sprintf(key_to_use, "%c%c%d",
            items_to_store[i].misc_chars[0],
            items_to_store[i].more_chars[0],
            items_to_store[i].any_integer);

    key_datum.dptr = (void *)key_to_use;
    key_datum.dszie = strlen(key_to_use);
    data_datum.dptr = (void *)&items_to_store[i];
    data_datum.dszie = sizeof(struct test_data);

    result = dbm_store(dbm_ptr, key_datum, data_datum, DBM_REPLACE);
    if (result != 0)
        fprintf(stderr, "dbm_store failed on key %s\n", key_to_use);
        exit(2);
}
}
```

6. Next we see if we can retrieve this new data and, finally, we must close the database:

```
sprintf(key_to_use, "bu%d", 13);
key_datum.dptr = key_to_use;
key_datum.dszie = strlen(key_to_use);
```

```
    data_datum = dbm_fetch(dbm_ptr, key_datum);
    if (data_datum.dptr) {
        printf("Data retrieved\n");
        memcpy(&item_retrieved, data_datum.dptr, data_datum.dszie);
        printf("Retrieved item - %s %d %s\n",
               item_retrieved.misc_chars,
               item_retrieved.any_integer,
               item_retrieved.more_chars);
    }
    else {
        printf("No data found for key %s\n", key_to_use);
    }
    dbm_close(dbm_ptr);
    exit(EXIT_SUCCESS);
}
```

When we compile and run the program, the output is simply

```
$ gcc -o dbm1 -I/usr/include/gdbm dbm1.c -lgdbm
$ ./dbm1
Data retrieved
Retrieved item - bar 13 unlucky?
```

This is the output you'll get if you have `gdbm` installed in compatible mode. If this fails to compile, you may need to install the GNU `gdbm` library compatibility files, as described earlier, and/or specify additional directories when you compile, thus:

```
$ gcc -I/usr/local/include -L/usr/local/lib -o dbm1 dbm1.c -ldbm
```

If this still fails, try replacing the `-ldbm` part of the command with `-lgdbm`, thus:

```
$ gcc -I/usr/local/include -L/usr/local/lib -o dbm1 dbm1.c -lgdbm
```

How It Works

First, we open the database, creating it if necessary. We then fill in three members of `items_to_store` that we are using as test data. For each of these three members we create an index key. To keep it simple, we use the first characters of each of the two strings, plus the integer stored.

We then set up two `datum` structures, one for the key and one for the data to store. Having stored the three items in the database, we construct a new key and set up a `datum` structure to point at it. We then use this key to retrieve data from the database. We check for success by making sure that the `dptr` in the returned `datum` isn't null. Provided it isn't, we can then copy the retrieved data (which may be stored internally within the `dbm` library) into our own structure, being careful to use the size `dbm_fetch` has returned (if we didn't do this and were using variable-sized data, we could attempt to copy nonexistent data). Finally, we print out the retrieved data to show it was retrieved correctly.

Additional dbm Functions

Now that we've seen the principal `dbm` functions, we can cover the few remaining functions that are used with `dbm`:

```
int dbm_delete(DBM *database_descriptor, datum key);
int dbm_error(DBM *database_descriptor);
int dbm_clearerr(DBM *database_descriptor);
datum dbm_firstkey(DBM *database_descriptor);
datum dbm_nextkey(DBM *database_descriptor);
```

dbm_delete

The `dbm_delete` function is used to delete entries from the database. It takes a key `datum` just like `dbm_fetch` but, rather than retrieving the data, it deletes the data. It returns 0 on success.

dbm_error

The `dbm_error` function simply tests whether an error has occurred in the database, returning 0 if there is none.

dbm_clearerr

The `dbm_clearerr` clears any error condition flag that may be set in the database.

dbm_firstkey and dbm_nextkey

These routines are normally used as a pair to scan through all the keys of all the items in a database. The loop structure required is

```
DBM *db_ptr;
datum key;

for(key = dbm_firstkey(db_ptr); key.dptr; key = dbm_nextkey(db_ptr));
```

Try It Out—Retrieving and Deleting

We'll now amend `dbm1.c` with some of these new functions. Have a look at `dbm2.c`.

1. Make a copy of `dbm1.c` and open it for editing. Edit the `#define TEST_DB_FILE` line:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>
#include <nndbm.h>
#include <string.h>

#define TEST_DB_FILE "/tmp/dbm2_test"
#define ITEMS_USED 3
```

2. Then the only change we need to make is in the retrieval section:

```
/* now try to delete some data */
sprintf(key_to_use, "bu%d", 13);
key_datum.dptr = key_to_use;
key_datum.dszie = strlen(key_to_use);
```

```
if (dbm_delete(dbm_ptr, key_datum) == 0) {
    printf("Data with key %s deleted\n", key_to_use);
}
else {
    printf("Nothing deleted for key %s\n", key_to_use);
}
for (key_datum = dbm_firstkey(dbm_ptr),
     key_datum.dptr;
     key_datum = dbm_nextkey(dbm_ptr)) {
    data_datum = dbm_fetch(dbm_ptr, key_datum);
    if (data_datum.dptr) {
        printf("Data retrieved\n");
        memcpy(&item_retrieved, data_datum.dptr, data_datum.dszie);
        printf("Retrieved item - %s %d %s\n",
               item_retrieved.misc_chars,
               item_retrieved.any_integer,
               item_retrieved.more_chars);
    }
    else {
        printf("No data found for key %s\n", key_to_use);
    }
}
```

The output is

```
$ ./dbm2
Data with key bu13 deleted
Data retrieved
Retrieved item - Third 3 baz
Data retrieved
Retrieved item - First! 47 foo
```

How It Works

The first part of this program is identical to the previous example, simply storing some data in the database. We then build a key to match the second item and delete it from the database.

The program then uses `dbm_firstkey` and `dbm_nextkey` to access each key in the database in turn, retrieving the data. Notice that the data isn't retrieved in order: No retrieval order is implied in the key order; it's simply a way of scanning all the entries.

The CD Application

Now that we've learned about the environment and about managing data, it's time to update the application. The `dbm` database seems well suited to storing our CD information, so we'll use that as the basis for our new implementation.

Updating the Design

Since this update will involve a significant rewrite, now would be a good time to look at our design decisions to see if they need revising. Using comma-separated variable files to store the information, although it gave an easy implementation in the shell, has turned out to be very restrictive. A lot of CD titles and tracks turn out to have commas in them. Since we can discard this method of separation entirely using dbm, that's one element of the design that we will change.

The split of the information between title and tracks, using a separate file for each, seems to have been a good decision, so we'll stick to the same logical arrangement.

Both the previous implementations have, to some extent, mixed the data access parts of the application with the user interface parts, not least because it was all implemented in a single file. In this implementation, we'll use a header file to describe the data and the routines to access it and split the user interface and data manipulation into separate files.

Although we could keep the current implementation of the user interface, we'll return to a simple line-based system. This will keep the user interface part of the application small and simple and allow us to concentrate on the other implementation aspects.

Although we can't use SQL with dbm code, we can express our new database in more formal terms using SQL terminology. Don't worry if you're not familiar with SQL; we will explain the definitions. We will see more SQL in Chapter 8. In code, the table can be described as follows:

```
CREATE TABLE cdc_entry (
    catalog CHAR(30) PRIMARY KEY REFERENCES cdt_entry(catalog),
    title    CHAR(70),
    type     CHAR(30),
    artist   CHAR(70)
);

CREATE TABLE cdt_entry (
    catalog CHAR(30) REFERENCES cdc_entry(catalog),
    track_no INTEGER,
    track_txt CHAR(70),
    PRIMARY KEY(catalog, track_no)
);
```

This very succinct description tells us the names and sizes of the fields. For the `cdc_entry` table, it tells us that there's a unique `catalog` column for every entry. For the `cdt_entry` table, it tells us that the track number can't be zero and that the combination of `catalog` and `track_no` columns is unique.

The CD Database Application Using dbm

We're now going to reimplement our application using the dbm database to store the information we need, with the files `cd_data.h`, `app_ui.c`, and `cd_access.c`.

We also rewrite the user interface as a command line program. Later in the book, we'll be reusing the database interface and parts of the user interface as we explore implementing our application using different client/server mechanisms and, finally, as an application that can be accessed across a network

using a Web browser. Converting the interface to a simpler line-driven interface makes it easier for us to focus on the important parts of the application, rather than on the interface.

You'll see the database header file `cd_data.h` and functions from the file `cd_access.c` reused several times in later chapters.

Try It Out—`cd_data.h`

We start here with the header file, to define the structure of our data and the routines that we'll use to access it.

1. This is the data structure definition for the CD database. It defines structures and sizes for the two tables that compose the database. We start by defining some sizes for the fields that we'll use and two structures: one for the catalog entry and one for the track entry.

```
/* The catalog table */
#define CAT_CAT_LEN      30
#define CAT_TITLE_LEN    70
#define CAT_TYPE_LEN     30
#define CAT_ARTIST_LEN   70

typedef struct {
    char catalog[CAT_CAT_LEN + 1];
    char title[CAT_TITLE_LEN + 1];
    char type[CAT_TYPE_LEN + 1];
    char artist[CAT_ARTIST_LEN + 1];
} cdc_entry;

/* The tracks table, one entry per track */
#define TRACK_CAT_LEN    CAT_CAT_LEN
#define TRACK_TTEXT_LEN   70

typedef struct {
    char catalog[TRACK_CAT_LEN + 1];
    int track_no;
    char track_txt[TRACK_TTEXT_LEN + 1];
} cdt_entry;
```

2. Now that we have some data structures, we can define some access routines that we'll need. Functions with `cdc_` are for catalog entries; functions with `cdt_` are for track entries.

Notice that some of the functions return data structures. We can indicate the failure of these functions by forcing the contents of the structure to be empty.

```
/* Initialization and termination functions */
int database_initialize(const int new_database);
void database_close(void);

/* two for simple data retrieval */
cdc_entry get_cdc_entry(const char *cd_catalog_ptr);
cdt_entry get_cdt_entry(const char *cd_catalog_ptr, const int track_no);
```

```

/* two for data addition */
int add_cdc_entry(const cdc_entry entry_to_add);
int add_cdt_entry(const cdt_entry entry_to_add);

/* two for data deletion */
int del_cdc_entry(const char *cd_catalog_ptr);
int del_cdt_entry(const char *cd_catalog_ptr, const int track_no);

/* one search function */
cdc_entry search_cdc_entry(const char *cd_catalog_ptr, int *first_call_ptr);

```

Try It Out—app_ui.c

We now move on to the user interface. This gives us a (relatively) simple program with which to access our database functions. We'll implement the interface in a separate file.

- As usual, we start with some header files:

```

#define _XOPEN_SOURCE

#include <stdlib.h>
#include <unistd.h>
#include <stdio.h>
#include <string.h>

#include "cd_data.h"

#define TMP_STRING_LEN 125 /* this number must be larger than the biggest
                           single string in any database structure */

```

- We make our menu options `typedefs`. This is in preference to using `#defined` constants, as it allows the compiler to check the types of the menu option variables.

```

typedef enum {
    mo_invalid,
    mo_add_cat,
    mo_add_tracks,
    mo_del_cat,
    mo_find_cat,
    mo_list_cat_tracks,
    mo_del_tracks,
    mo_count_entries,
    mo_exit
} menu_options;

```

- Now we write the prototypes for the local functions. Remember that the prototypes for actually accessing the database were included in `cd_data.h`.

```

static int command_mode(int argc, char *argv[]);
static void announce(void);
static menu_options show_menu(const cdc_entry *current_cdc);
static int get_confirm(const char *question);
static int enter_new_cat_entry(cdc_entry *entry_to_update);
static void enter_new_track_entries(const cdc_entry *entry_to_add_to);

```

```
static void del_cat_entry(const cdc_entry *entry_to_delete);
static void del_track_entries(const cdc_entry *entry_to_delete);
static cdc_entry find_cat(void);
static void list_tracks(const cdc_entry *entry_to_use);
static void count_all_entries(void);
static void display_cdc(const cdc_entry *cdc_to_show);
static void display_cdt(const cdt_entry *cdt_to_show);
static void strip_return(char *string_to_strip);
```

4. Finally, we get to main. This starts by ensuring that the `current_cdc_entry`, which we use to keep track of the currently selected CD catalog entry, is initialized. We also parse the command line, announce what program is being run, and initialize the database.

```
void main(int argc, char *argv[])
{
    menu_options current_option;
    cdc_entry current_cdc_entry;
    int command_result;

    memset(&current_cdc_entry, '\0', sizeof(current_cdc_entry));

    if (argc > 1) {
        command_result = command_mode(argc, argv);
        exit(command_result);
    }

    announce();

    if (!database_initialize(0)) {
        fprintf(stderr, "Sorry, unable to initialize database\n");
        fprintf(stderr, "To create a new database use %s -i\n", argv[0]);
        exit(EXIT_FAILURE);
    }
}
```

5. We're now ready to process user input. We sit in a loop, asking for a menu choice and processing it, until the user selects the exit option. Notice that we pass the `current_cdc_entry` structure to the `show_menu` function. We do this to allow the menu choices to change if a catalog entry is currently selected.

```
while(current_option != mo_exit) {
    current_option = show_menu(&current_cdc_entry);

    switch(current_option) {
        case mo_add_cat:
            if (!enter_new_cat_entry(&current_cdc_entry)) {
                if (!add_cdc_entry(current_cdc_entry)) {
                    fprintf(stderr, "Failed to add new entry\n");
                    memset(&current_cdc_entry, '\0',
                           sizeof(current_cdc_entry));
                }
            }
            break;
        case mo_add_tracks:
```

```

        enter_new_track_entries(&current_cdc_entry) ;
        break;
    case mo_del_cat:
        del_cat_entry(&current_cdc_entry) ;
        break;
    case mo_find_cat:
        current_cdc_entry = find_cat() ;
        break;
    case mo_list_cat_tracks:
        list_tracks(&current_cdc_entry) ;
        break;
    case mo_del_tracks:
        del_track_entries(&current_cdc_entry) ;
        break;
    case mo_count_entries:
        count_all_entries() ;
        break;
    case mo_exit:
        break;
    case mo_invalid:
        break;
    default:
        break;
    } /* switch */
} /* while */

```

6. When the main loop exits, we close the database and exit back to the environment. The welcoming sentence is printed by the announce function:

```

database_close();
exit(EXIT_SUCCESS);
} /* main */

static void announce(void)
{
    printf("\n\nWelcome to the demonstration CD catalog database \
           program\n");
}

```

7. Here we implement the show_menu function. This function checks whether a current catalog entry is selected, using the first character of the catalog name. More options are available if a catalog entry is selected.

Note that numbers are now used to select menu items, rather than the initial letters we used in the previous two examples.

```

static menu_options show_menu(const cdc_entry *cdc_selected)
{
    char tmp_str[TMP_STRING_LEN + 1];
    menu_options option_chosen = mo_invalid;

```

```

while (option_chosen == mo_invalid) {
    if (cdc_selected->catalog[0]) {
        printf("\n\nCurrent entry: ");
        printf("%s, %s, %s, %s\n", cdc_selected->catalog,
               cdc_selected->title,
               cdc_selected->type,
               cdc_selected->artist);

        printf("\n");
        printf("1 - add new CD\n");
        printf("2 - search for a CD\n");
        printf("3 - count the CDs and tracks in the database\n");
        printf("4 - re-enter tracks for current CD\n");
        printf("5 - delete this CD, and all its tracks\n");
        printf("6 - list tracks for this CD\n");
        printf("q - quit\n");
        printf("\nOption: ");
        fgets(tmp_str, TMP_STRING_LEN, stdin);

        switch(tmp_str[0]) {
            case '1': option_chosen = mo_add_cat; break;
            case '2': option_chosen = mo_find_cat; break;
            case '3': option_chosen = mo_count_entries; break;
            case '4': option_chosen = mo_add_tracks; break;
            case '5': option_chosen = mo_del_cat; break;
            case '6': option_chosen = mo_list_cat_tracks; break;
            case 'q': option_chosen = mo_exit; break;
        }
    }
    else {
        printf("\n\n");
        printf("1 - add new CD\n");
        printf("2 - search for a CD\n");
        printf("3 - count the CDs and tracks in the database\n");
        printf("q - quit\n");
        printf("\nOption: ");
        fgets(tmp_str, TMP_STRING_LEN, stdin);
        switch(tmp_str[0]) {
            case '1': option_chosen = mo_add_cat; break;
            case '2': option_chosen = mo_find_cat; break;
            case '3': option_chosen = mo_count_entries; break;
            case 'q': option_chosen = mo_exit; break;
        }
    }
} /* while */
return(option_chosen);
}

```

- 8.** There are several places where we wish to ask the user if he is sure about what he requested. Rather than have several places in the code asking the question, we extract the code as a separate function, `get_confirm`:

```

static int get_confirm(const char *question)
{
    char tmp_str[TMP_STRING_LEN + 1];

```

```

    printf("%s", question);
    fgets(tmp_str, TMP_STRING_LEN, stdin);
    if (tmp_str[0] == 'Y' || tmp_str[0] == 'y') {
        return(1);
    }
    return(0);
}

```

9. The function `enter_new_cat_entry` allows the user to enter a new catalog entry. We don't want to store the linefeed that `fgets` returns, so we strip it off.

Notice that we don't use the `gets` function, because we have no way of checking for an overflow of the buffer. Always avoid the `gets` function!

```

static int enter_new_cat_entry(cdc_entry *entry_to_update)
{
    cdc_entry new_entry;
    char tmp_str[TMP_STRING_LEN + 1];

    memset(&new_entry, '\0', sizeof(new_entry));

    printf("Enter catalog entry: ");
    (void)fgets(tmp_str, TMP_STRING_LEN, stdin);
    strip_return(tmp_str);
    strncpy(new_entry.catalog, tmp_str, CAT_CAT_LEN - 1);

    printf("Enter title: ");
    (void)fgets(tmp_str, TMP_STRING_LEN, stdin);
    strip_return(tmp_str);
    strncpy(new_entry.title, tmp_str, CAT_TITLE_LEN - 1);

    printf("Enter type: ");
    (void)fgets(tmp_str, TMP_STRING_LEN, stdin);
    strip_return(tmp_str);
    strncpy(new_entry.type, tmp_str, CAT_TYPE_LEN - 1);

    printf("\nNew catalog entry entry is :-\n");
    display_cdc(&new_entry);
    if (get_confirm("Add this entry ?")) {
        memcpy(entry_to_update, &new_entry, sizeof(new_entry));
        return(1);
    }
    return(0);
}

```

- 10.** We now come to the function for entering the track information: `enter_new_track_entries`. This is slightly more complex than the catalog entry function because we allow an existing track entry to be left alone.

```
static void enter_new_track_entries(const cdc_entry *entry_to_add_to)
{
    cdt_entry new_track, existing_track;
    char tmp_str[TMP_STRING_LEN + 1];
    int track_no = 1;
    if (entry_to_add_to->catalog[0] == '\0') return;

    printf("\nUpdating tracks for %s\n", entry_to_add_to->catalog);
    printf("Press return to leave existing description unchanged,\n");
    printf(" a single d to delete this and remaining tracks,\n");
    printf(" or new track description\n");

    while(1) {
```

- 11.** First, we must check whether a track already exists with the current track number. Depending on what we find, we change the prompt.

```
    memset(&new_track, '\0', sizeof(new_track));
    existing_track = get_cdt_entry(entry_to_add_to->catalog,
                                    track_no);
    if (existing_track.catalog[0]) {
        printf("\tTrack %d: %s\n", track_no,
               existing_track.track_txt);
        printf("\tNew text: ");
    }
    else {
        printf("\tTrack %d description: ", track_no);
    }
    fgets(tmp_str, TMP_STRING_LEN, stdin);
    strip_return(tmp_str);
```

- 12.** If there was no existing entry for this track and the user hasn't added one, we assume that there are no more tracks to be added.

```
    if (strlen(tmp_str) == 0) {
        if (existing_track.catalog[0] == '\0') {
            /* no existing entry, so finished adding */
            break;
        }
        else {
            /* leave existing entry, jump to next track */
            track_no++;
            continue;
        }
    }
```

- 13.** If the user enters a single d character, this deletes the current and any higher-numbered tracks. The `del_cdt_entry` function will return `false` if it can't find a track to delete.

```

if ((strlen(tmp_str) == 1) && tmp_str[0] == 'd') {
    /* delete this and remaining tracks */
    while (del_cdt_entry(entry_to_add_to->catalog, track_no)) {
        track_no++;
    }
    break;
}

```

- 14.** Here we get to the code for adding a new track, or updating an existing one. We construct the `cdt_entry` structure `new_track`, then call the database function `add_cdt_entry` to add it to the database.

```

strncpy(new_track.track_txt, tmp_str, TRACK_TTEXT_LEN - 1);
strcpy(new_track.catalog, entry_to_add_to->catalog);
new_track.track_no = track_no;
if (!add_cdt_entry(new_track)) {
    fprintf(stderr, "Failed to add new track\n");
    break;
}
track_no++;
} /* while */
}

```

- 15.** The function `del_cat_entry` deletes a catalog entry. We never allow tracks for a nonexistent catalog entry to exist.

```

static void del_cat_entry(const cdc_entry *entry_to_delete)
{
    int track_no = 1;
    int delete_ok;

    display_cdc(entry_to_delete);
    if (get_confirm("Delete this entry and all its tracks? ")) {
        do {
            delete_ok = del_cdt_entry(entry_to_delete->catalog,
                                      track_no);
            track_no++;
        } while(delete_ok);

        if (!del_cdc_entry(entry_to_delete->catalog)) {
            fprintf(stderr, "Failed to delete entry\n");
        }
    }
}

```

- 16.** The next function is a utility for deleting all the tracks for a catalog:

```
static void del_track_entries(const cdc_entry *entry_to_delete)
{
    int track_no = 1;
    int delete_ok;

    display_cdc(entry_to_delete);
    if (get_confirm("Delete tracks for this entry? ")) {
        do {
            delete_ok = del_cdt_entry(entry_to_delete->catalog, track_no);
            track_no++;
        } while(delete_ok);
    }
}
```

- 17.** Next, we create a very simple catalog search facility. We allow the user to enter a string, then check for catalog entries that contain the string. Since there could be multiple entries that match, we simply offer the user each match in turn:

```
static cdc_entry find_cat(void)
{
    cdc_entry item_found;
    char tmp_str[TMP_STRING_LEN + 1];
    int first_call = 1;
    int any_entry_found = 0;
    int string_ok;
    int entry_selected = 0;

    do {
        string_ok = 1;
        printf("Enter string to search for in catalog entry: ");
        fgets(tmp_str, TMP_STRING_LEN, stdin);
        strip_return(tmp_str);
        if (strlen(tmp_str) > CAT_CAT_LEN) {
            fprintf(stderr, "Sorry, string too long, maximum %d \
                           characters\n", CAT_CAT_LEN);
            string_ok = 0;
        }
    } while (!string_ok);

    while (!entry_selected) {
        item_found = search_cdc_entry(tmp_str, &first_call);
        if (item_found.catalog[0] != '\0') {
            any_entry_found = 1;
            printf("\n");
            display_cdc(&item_found);
            if (get_confirm("This entry? ")) {
                entry_selected = 1;
            }
        }
        else {
            if (any_entry_found) printf("Sorry, no more matches found\n");
            else printf("Sorry, nothing found\n");
            break;
        }
    }
}
```

```

        }
    }
    return(item_found);
}

```

- 18.** list_tracks is a utility function that prints out all the tracks for a given catalog entry:

```

static void list_tracks(const cdc_entry *entry_to_use)
{
    int track_no = 1;
    cdt_entry entry_found;

    display_cdc(entry_to_use);
    printf("\nTracks\n");
    do {
        entry_found = get_cdt_entry(entry_to_use->catalog,
                                     track_no);
        if (entry_found.catalog[0]) {
            display_cdt(&entry_found);
            track_no++;
        }
    } while(entry_found.catalog[0]);
    (void)get_confirm("Press return");
} /* list_tracks */

```

- 19.** The count_all_entries function counts all the tracks:

```

static void count_all_entries(void)
{
    int cd_entries_found = 0;
    int track_entries_found = 0;
    cdc_entry cdc_found;
    cdt_entry cdt_found;
    int track_no = 1;
    int first_time = 1;
    char *search_string = "";

    do {
        cdc_found = search_cdc_entry(search_string, &first_time);
        if (cdc_found.catalog[0]) {
            cd_entries_found++;
            track_no = 1;
            do {
                cdt_found = get_cdt_entry(cdc_found.catalog, track_no);
                if (cdt_found.catalog[0]) {
                    track_entries_found++;
                    track_no++;
                }
            } while (cdt_found.catalog[0]);
        }
    } while (cdc_found.catalog[0]);

    printf("Found %d CDs, with a total of %d tracks\n",
          cd_entries_found,
          track_entries_found);
    (void)get_confirm("Press return");
}

```

- 20.** Now we have `display_cdc`, a utility for displaying a catalog entry,

```
static void display_cdc(const cdc_entry *cdc_to_show)
{
    printf("Catalog: %s\n", cdc_to_show->catalog);
    printf("\ttitle: %s\n", cdc_to_show->title);
    printf("\ttype: %s\n", cdc_to_show->type);
    printf("\tartist: %s\n", cdc_to_show->artist);
}
```

and `display_cdt`, for displaying a single track entry:

```
static void display_cdt(const cdt_entry *cdt_to_show)
{
    printf("%d: %s\n", cdt_to_show->track_no, cdt_to_show->track_txt);
}
```

- 21.** The utility function `strip_return` removes a trailing linefeed character from a string. Remember that Linux, like UNIX, uses a single linefeed to indicate end of line:

```
static void strip_return(char *string_to_strip)
{
    int len;

    len = strlen(string_to_strip);
    if (string_to_strip[len - 1] == '\n') string_to_strip[len - 1] = '\0';
}
```

- 22.** `command_mode` is a function for parsing the command line arguments. The `getopt` function is a good way of ensuring that our program accepts arguments conforming to the standard Linux conventions.

```
static int command_mode(int argc, char *argv[])
{
    int c;
    int result = EXIT_SUCCESS;
    char *prog_name = argv[0];

    /* these externals used by getopt */
    extern char * optarg;
    extern optind, optarg, opterr, optarg;

    while ((c = getopt(argc, argv, ":i")) != -1) {
        switch(c) {
            case 'i':
                if (!database_initialize(1)) {
                    result = EXIT_FAILURE;
                    fprintf(stderr, "Failed to initialize database\n");
                }
                break;
            case ':':
            case '?':
            default:
```

```

        fprintf(stderr, "Usage: %s [-i]\n", prog_name);
        result = EXIT_FAILURE;
        break;
    } /* switch */
} /* while */
return(result);
}

```

Try It Out—cd_access.c

Now we come to the functions that access the dbm database.

- As usual, we start with some #include files. We then use some #defines for specifying the files that we'll use for storing the data.

```

#define _XOPEN_SOURCE

#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>
#include <string.h>
#include <ndbm.h>

#include "cd_data.h"

#define CDC_FILE_BASE "cdc_data"
#define CDT_FILE_BASE "cdt_data"
#define CDC_FILE_DIR "cdc_data.dir"
#define CDC_FILE_PAG "cdc_data.pag"
#define CDT_FILE_DIR "cdt_data.dir"
#define CDT_FILE_PAG "cdt_data.pag"

```

- We use these two file scope variables to keep track of the current database:

```

static DBM *cdc_dbm_ptr = NULL;
static DBM *cdt_dbm_ptr = NULL;

```

- By default, the database_initialize function opens an existing database, but by passing a nonzero (i.e., true) parameter, new_database, we can force it to create a new (empty) database, effectively removing any existing database. If the database is successfully initialized, the two database pointers are also initialized, indicating that a database is open.

```

int database_initialize(const int new_database)
{
    int open_mode = O_CREAT | O_RDWR;

    /* If any existing database is open then close it */
    if (cdc_dbm_ptr) dbm_close(cdc_dbm_ptr);
    if (cdt_dbm_ptr) dbm_close(cdt_dbm_ptr);

    if (new_database) {
        /* delete the old files */

```

```
        (void) unlink(CDC_FILE_PAG);
        (void) unlink(CDC_FILE_DIR);
        (void) unlink(CDT_FILE_PAG);
        (void) unlink(CDT_FILE_DIR);
    }

/* Open some new files, creating them if required */
cdc_dbm_ptr = dbm_open(CDC_FILE_BASE, open_mode, 0644);
cdt_dbm_ptr = dbm_open(CDT_FILE_BASE, open_mode, 0644);
if (!cdc_dbm_ptr || !cdt_dbm_ptr) {
    fprintf(stderr, "Unable to create database\n");
    cdc_dbm_ptr = cdt_dbm_ptr = NULL;
    return (0);
}
return (1);
}
```

4. `database_close` simply closes the database if it was open and sets the two database pointers to null to indicate that no database is currently open.

```
void database_close(void)
{
    if (cdc_dbm_ptr) dbm_close(cdc_dbm_ptr);
    if (cdt_dbm_ptr) dbm_close(cdt_dbm_ptr);

    cdc_dbm_ptr = cdt_dbm_ptr = NULL;
}
```

5. Next, we have a function that retrieves a single catalog entry, when passed a pointer pointing to a catalog text string. If the entry isn't found, the returned data has an empty catalog field.

```
cdc_entry get_cdc_entry(const char *cd_catalog_ptr)
{
    cdc_entry entry_to_return;
    char entry_to_find[CAT_CAT_LEN + 1];
    datum local_data_datum;
    datum local_key_datum;

    memset(&entry_to_return, '\0', sizeof(entry_to_return));
}
```

6. We start with some sanity checks, to ensure that a database is open and that we were passed reasonable parameters—that is, the search key contains only the valid string and nulls.

```
if (!cdc_dbm_ptr || !cdt_dbm_ptr) return (entry_to_return);
if (!cd_catalog_ptr) return (entry_to_return);
if (strlen(cd_catalog_ptr) >= CAT_CAT_LEN) return (entry_to_return);

memset(&entry_to_find, '\0', sizeof(entry_to_find));
strcpy(entry_to_find, cd_catalog_ptr);
```

7. We set up the datum structure the dbm functions require, then use `dbm_fetch` to retrieve the data. If no data was retrieved, we return the empty `entry_to_return` structure that we initialized earlier.

```

local_key_datum.dptr = (void *) entry_to_find;
local_key_datum.dsize = sizeof(entry_to_find);

memset(&local_data_datum, '\0', sizeof(local_data_datum));
local_data_datum = dbm_fetch(cdc_dbm_ptr, local_key_datum);
if (local_data_datum.dptr) {
    memcpy(&entry_to_return, (char *)local_data_datum.dptr,
           local_data_datum.dsize);
}
return (entry_to_return);
} /* get_cdc_entry */

```

- 8.** We'd better be able to get a single track entry as well, which is what the next function does, in the same fashion as `get_cdc_entry`, but with a pointer pointing to a catalog string and a track number as parameters.

```

cdt_entry get_cdt_entry(const char *cd_catalog_ptr, const int track_no)
{
    cdt_entry entry_to_return;
    char entry_to_find[CAT_CAT_LEN + 10];
    datum local_data_datum;
    datum local_key_datum;

    memset(&entry_to_return, '\0', sizeof(entry_to_return));

    if (!cdc_dbm_ptr || !cdt_dbm_ptr) return (entry_to_return);
    if (!cd_catalog_ptr) return (entry_to_return);
    if (strlen(cd_catalog_ptr) >= CAT_CAT_LEN) return (entry_to_return);
    /* set up the search key, which is a composite key of catalog entry
       and track number */
    memset(&entry_to_find, '\0', sizeof(entry_to_find));
    sprintf(entry_to_find, "%s %d", cd_catalog_ptr, track_no);

    local_key_datum.dptr = (void *) entry_to_find;
    local_key_datum.dsize = sizeof(entry_to_find);

    memset(&local_data_datum, '\0', sizeof(local_data_datum));
    local_data_datum = dbm_fetch(cdt_dbm_ptr, local_key_datum);
    if (local_data_datum.dptr) {
        memcpy(&entry_to_return, (char *) local_data_datum.dptr,
               local_data_datum.dsize);
    }
    return (entry_to_return);
}

```

- 9.** The next function, `add_cdc_entry`, adds a new catalog entry:

```

int add_cdc_entry(const cdc_entry entry_to_add)
{
    char key_to_add[CAT_CAT_LEN + 1];
    datum local_data_datum;
    datum local_key_datum;
    int result;

```

```
/* check database initialized and parameters valid */
if (!cdc_dbm_ptr || !cdt_dbm_ptr) return (0);
if (strlen(entry_to_add.catalog) >= CAT_CAT_LEN) return (0);

/* ensure the search key contains only the valid string and nulls */
memset(&key_to_add, '\0', sizeof(key_to_add));
strcpy(key_to_add, entry_to_add.catalog);

local_key_datum.dptr = (void *) key_to_add;
local_key_datum.dsize = sizeof(key_to_add);
local_data_datum.dptr = (void *) &entry_to_add;
local_data_datum.dsize = sizeof(entry_to_add);

result = dbm_store(cdc_dbm_ptr, local_key_datum, local_data_datum,
DBM_REPLACE);

/* dbm_store() uses 0 for success */
if (result == 0) return (1);
return (0);
}
```

- 10.** add_cdt_entry adds a new track entry. The access key is the catalog string and track number acting as a composite.

```
int add_cdt_entry(const cdt_entry entry_to_add)
{
    char key_to_add[CAT_CAT_LEN + 10];
    datum local_data_datum;
    datum local_key_datum;
    int result;

    if (!cdc_dbm_ptr || !cdt_dbm_ptr) return (0);
    if (strlen(entry_to_add.catalog) >= CAT_CAT_LEN) return (0);

    memset(&key_to_add, '\0', sizeof(key_to_add));
    sprintf(key_to_add, "%s %d", entry_to_add.catalog,
            entry_to_add.track_no);

    local_key_datum.dptr = (void *) key_to_add;
    local_key_datum.dsize = sizeof(key_to_add);
    local_data_datum.dptr = (void *) &entry_to_add;
    local_data_datum.dsize = sizeof(entry_to_add);

    result = dbm_store(cdt_dbm_ptr, local_key_datum, local_data_datum,
DBM_REPLACE);

    /* dbm_store() uses 0 for success and -ve numbers for errors */
    if (result == 0)
        return (1);
    return (0);
}
```

- 11.** If we can add things, we'd better be able to delete them, too. This function deletes catalog entries:

```
int del_cdc_entry(const char *cd_catalog_ptr)
{
    char key_to_del[CAT_CAT_LEN + 1];
    datum local_key_datum;
    int result;

    if (!cdc_dbm_ptr || !cdt_dbm_ptr) return (0);
    if (strlen(cd_catalog_ptr) >= CAT_CAT_LEN) return (0);

    memset(&key_to_del, '\0', sizeof(key_to_del));
    strcpy(key_to_del, cd_catalog_ptr);

    local_key_datum.dptr = (void *) key_to_del;
    local_key_datum.dsize = sizeof(key_to_del);

    result = dbm_delete(cdc_dbm_ptr, local_key_datum);

    /* dbm_delete() uses 0 for success */
    if (result == 0) return (1);
    return (0);
}
```

- 12.** Here's the equivalent function for deleting a track. Remember that the track key is a composite index of both the catalog entry string and the track number.

```
int del_cdt_entry(const char *cd_catalog_ptr, const int track_no)
{
    char key_to_del[CAT_CAT_LEN + 10];
    datum local_key_datum;
    int result;

    if (!cdc_dbm_ptr || !cdt_dbm_ptr) return (0);
    if (strlen(cd_catalog_ptr) >= CAT_CAT_LEN) return (0);

    memset(&key_to_del, '\0', sizeof(key_to_del));
    sprintf(key_to_del, "%s %d", cd_catalog_ptr, track_no);

    local_key_datum.dptr = (void *) key_to_del;
    local_key_datum.dsize = sizeof(key_to_del);

    result = dbm_delete(cdt_dbm_ptr, local_key_datum);

    /* dbm_delete() uses 0 for success */
    if (result == 0) return (1);
    return (0);
}
```

- 13.** Last but not least, we have a simple search function. It's not very sophisticated, but it does demonstrate how we can scan through dbm entries without knowing the keys in advance. Since we don't know in advance how many entries there might be, we implement this function to return a single entry on each call. If nothing is found, the entry will be empty. To scan the

whole database, we start by calling this function with a pointer to an integer, `*first_call_ptr`, which should be 1 the first time the function is called. This function then knows it should start searching at the start of the database. On subsequent calls, the variable is 0 and the function resumes searching after the last entry it found.

When we wish to restart our search, probably with a different catalog entry, we must again call this function with `*first_call_ptr` set to true, which reinitializes the search.

Between calls, the function maintains some internal state information. This hides the complexity of continuing a search from the client and preserves the “secrecy” of how the search function is implemented.

If the search text points to a null character, all entries are considered to match.

```
cdc_entry search_cdc_entry(const char *cd_catalog_ptr, int *first_call_ptr)
{
    static int local_first_call = 1;
    cdc_entry entry_to_return;
    datum local_data_datum;
    static datum local_key_datum; /* notice this must be static */

    memset(&entry_to_return, '\0', sizeof(entry_to_return));
}
```

- 14.** As usual, we start with sanity checks:

```
if (!cdc_dbm_ptr || !cdt_dbm_ptr) return (entry_to_return);
if (!cd_catalog_ptr || !first_call_ptr) return (entry_to_return);
if (strlen(cd_catalog_ptr) >= CAT_CAT_LEN) return (entry_to_return);

/* protect against never passing *first_call_ptr true */
if (local_first_call) {
    local_first_call = 0;
    *first_call_ptr = 1;
}
```

- 15.** If this function has been called with `*first_call_ptr` set to true, we need to start (or restart) searching from the beginning of the database. If `*first_call_ptr` isn't true, we simply move on to the next key in the database:

```
if (*first_call_ptr) {
    *first_call_ptr = 0;
    local_key_datum = dbm_firstkey(cdc_dbm_ptr);
}
else {
    local_key_datum = dbm_nextkey(cdc_dbm_ptr);
}

do {
    if (local_key_datum.dptr != NULL) {
        /* an entry was found */
        local_data_datum = dbm_fetch(cdc_dbm_ptr, local_key_datum);
        if (local_data_datum.dptr) {
            memcpy(&entry_to_return, (char *) local_data_datum.dptr,
                   local_data_datum.dsize);
```

- 16.** Our search facility is a very simple check to see whether the search string occurs in the current catalog entry.

```

        /* check if search string occurs in the entry */
        if (!strstr(entry_to_return.catalog, cd_catalog_ptr))
        {
            memset(&entry_to_return, '\0',
                   sizeof(entry_to_return));
            local_key_datum = dbm_nextkey(cdc_dbm_ptr);
        }
    }
} while (local_key_datum.dptr &&
         local_data_datum.dptr &&
         (entry_to_return.catalog[0] == '\0'));
return (entry_to_return);
} /* search_cdc_entry */

```

We're now in a position to be able to put everything together with this makefile. Don't worry about it too much right now, because we'll be looking at how it works in the next chapter. For the time being, type it and save it as `Makefile`.

```

all:      application

INCLUDE=/usr/include/gdbm
LIBS=gdbm
CFLAGS=

app_ui.o: app_ui.c cd_data.h
        gcc $(CFLAGS) -c app_ui.c

access.o: access.c cd_data.h
        gcc $(CFLAGS) -I$(INCLUDE) -c access.c

application:      app_ui.o access.o
        gcc $(CFLAGS) -o application app_ui.o access.o -l$(LIBS)

clean:
        rm -f application *.o

nodbmfiles:
        rm -f *.dir *.pag

```

Remember that you may need to replace LIBS= and INCLUDE=, depending on your system configuration.

To compile your new CD application, type this at the prompt:

```
$ make
```

If all has gone well, the application executable will be compiled and placed in the current directory.

Summary

In this chapter, we've learned about three aspects of data management. First, we've learned about the Linux memory system and how simple it is to use, even though the internal implementation of demand paged virtual memory is quite involved. We've also found how it protects both the operating system and other programs from attempts at illegal memory access.

We then moved on to look at how file locking allows multiple programs to cooperate in their access to data. We looked first at a simple binary semaphore scheme and then at a more complex situation where we lock different parts of a file for either shared or exclusive access. Next we looked at the `dbm` library and its ability to store and efficiently retrieve arbitrary blocks of data using a very flexible indexing arrangement.

Finally, we redesigned and reimplemented our example CD database application to use the `dbm` library as its data storage technique.

8

MySQL

Now that we've explored some basic data management using flat files and then the simple but very quick dbm, we're ready to move on to a more full-featured data tool: the RDBMS, or Relational Database Management System.

The two best-known open-source RDBMS applications are PostgreSQL and MySQL. PostgreSQL can be used for free in all cases and MySQL is free for many uses, although a license fee is required in some circumstances. Commercial products in the same vein are Oracle, Informix, Sybase, and DB2, which run on multiple platforms. The Windows-only Microsoft SQL Server is another entry into this market. All these packages have their particular strengths; but for reasons of space, and a commitment to Open Source software, this book will focus exclusively on MySQL.

MySQL has origins going back to about 1984, but it has been commercially developed and managed under the auspices of MySQL AB for several years now. Because MySQL is Open Source, its terms of use are often confused with those of other Open Source projects. It's worth pointing out, then, that while many uses can be GPL'ed, many cannot.

If you need an Open Source database; the terms for using MySQL under the GPL are not acceptable, and if you don't wish to purchase a commercial license, then the licensing terms for using PostgreSQL are, at the time of writing, much less restrictive. PostgreSQL is currently also slightly ahead of MySQL in terms of functionality, so we you may wish to consider PostgreSQL as an alternative. You can find details at www.postgresql.org.

In this chapter, we'll be covering the following MySQL topics:

- Installing MySQL and manually or automatically starting the server
- The administrative commands necessary to work with MySQL
- The API for interfacing your C programs with MySQL databases
- Creating a relational database that we can use for our CD database application using C

Installation

Whatever your preferred flavor of Linux, it's likely that it came with a version of MySQL. Slackware, Red Hat, SuSE, and Debian all include it in their current versions. This will provide the easiest way to get up and running with MySQL quickly. If your distribution does not provide a MySQL package, or if you want to get the most current release, you can download either binary or source packages from the MySQL website at www.mysql.com.

Generally, your distribution's MySQL package will include some startup scripts to use with `init.d`. In other cases, you will need to explicitly tell MySQL that you want it to start automatically. With Red Hat Linux 9, for example, look under Server Settings→Services and check that the `mysqld` service is started. (Note that the MySQL service will appear in this list only if the package is installed.)

Precompiled Packages

If for any reason you need to download MySQL rather than using a bundled version, RPMs offer the easiest way to obtain and install the software. The RPM packages are broken down into a number of different packages, four of which are important to this chapter.

- ❑ The *main server package*, with a name like `MySQL-server-<version>. <architecture>. rpm`. This contains the precompiled binaries, documentation in the form of manual pages, and some support files for internationalization. At this writing, the package 4.0.14 is named `MySQL-server-4.0.14.i386.rpm`.
- ❑ The *client package*, with a name like `MySQL-client-<version>. <architecture>. rpm`. This package contains the basic MySQL client that allows you to interact with the server in a command line fashion in real time, issuing queries and such while maintaining an open static connection. Several other peripheral clients for quick stateless access to MySQL are also included. These programs generally serve to simplify some the more mundane administrative tasks associated with maintaining the MySQL server.
- ❑ The *shared component package*, with a name like `MySQL-shared-<version>. <architecture>. rpm`, which contains shared libraries used by some external clients.
- ❑ The *development package*, with a name something like `MySQL-devel-<version>. <architecture>. rpm`. As developers, we are naturally particularly interested in the additional headers and library files included for developing applications that communicate with the MySQL server.

You may also see some "Max" and "Debug" packages available. The Max package contains additional features, such as support for more unusual storage file types. For the purposes of this chapter, and indeed most development or production uses, you will not need the Max packages. The Debug packages have been compiled with additional debugging code and information; hopefully you will not need such low-level debugging! Don't use the Debug versions for production use; the performance is degraded by the additional debug support.

For developing MySQL applications you should install all four of these packages on your system, either using a GUI tool or the `rpm` command directly. In general, simply download the four RPM files to an otherwise empty directory and then execute the following command as the superuser:

```
rpm -i *.rpm
```

You can find more details about the RPM package format in Chapter 9.

During the MySQL installation, the install scripts automatically create an initial database for you. You will also have an `init.d` script (normally in `/etc/rc.d/init.d`) named `mysqld` or `mysql` that is used to start and stop the server. Generally, the easiest way to find the database files on your specific distribution is to locate this script in your `init.d` directory and have a look through it. Standard paths and defines are located near the beginning of the script, and it's very easy to see where files have been located. For example, on our binary installation of Red Hat RPMs the data directory is set to `/var/lib/mysql`.

After installation, you can either start the server manually as root using `/etc/rc.d/init.d/mysql start` (or an equivalent for your distribution) or use symbolic links to the script in `/etc/rc.d/init.d` to ensure that MySQL starts automatically in run levels 3 and 5 and that it is stopped in run levels 0, 1, and 6:

```
# ln -s /etc/rc.d/init.d/mysql /etc/rc.d/rc0.d/K97mysql
# ln -s /etc/rc.d/init.d/mysql /etc/rc.d/rc1.d/K97mysql
# ln -s /etc/rc.d/init.d/mysql /etc/rc.d/rc6.d/K97mysql
# ln -s /etc/rc.d/init.d/mysql /etc/rc.d/rc3.d/S97mysql
# ln -s /etc/rc.d/init.d/mysql /etc/rc.d/rc5.d/S97mysql
```

You may wish to adjust the exact numbers used on your system to keep them unique, although this isn't strictly necessary.

You may be using a system that has the `chkconfig` command, which offers a simpler way to set the run levels in which a service runs. For example, to set the MySQL server to run in run levels 3 and 4, you must first add `mysql` as a `chkconfig`-managed service, like this:

```
chkconfig --add mysql
```

Now we set the service to be "on" in levels 3 and 5,

```
chkconfig --level 35 mysql on
```

and "off" in the other levels:

```
chkconfig --level 01246 mysql off
```

To confirm that your configuration has been changed correctly, we can list the run levels where a service will run as follows:

```
# chkconfig --list mysql
mysql           0:off    1:off    2:off    3:on     4:off    5:on     6:off
```

If you have `chkconfig`, we suggest you use this method rather than directly creating symbolic links, as it is less prone to error. However, the script you use must have been written to support `chkconfig`; for more details, see the online manual for `chkconfig`.

The MySQL installation also creates the user "mysql," which by default is the user name that the MySQL server daemon runs as.

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Once you have started the server, you should be able to check that it is running by looking for the mysqld process as follows:

```
$ ps -el | grep mysqld
```

If you see one or more mysqld processes running, the server has been started. If not, you can get it started by running the mysql script (in init.d) as the mysql user, with the argument start. Red Hat installs a program (*safe_mysqld*) called from the init.d script to perform the change of user for you automatically, so you can run /etc/rc.d/init.d/mysql start directly as root. Otherwise, use the following command:

```
# su - mysql  
$ /etc/rc.d/init.d/mysql start
```

Alternatively, you can use the GUI Services control panel shown in Figure 8-1 (the redhat-config-services command on the command line will also invoke this GUI utility on Red Hat distributions) to start the server.

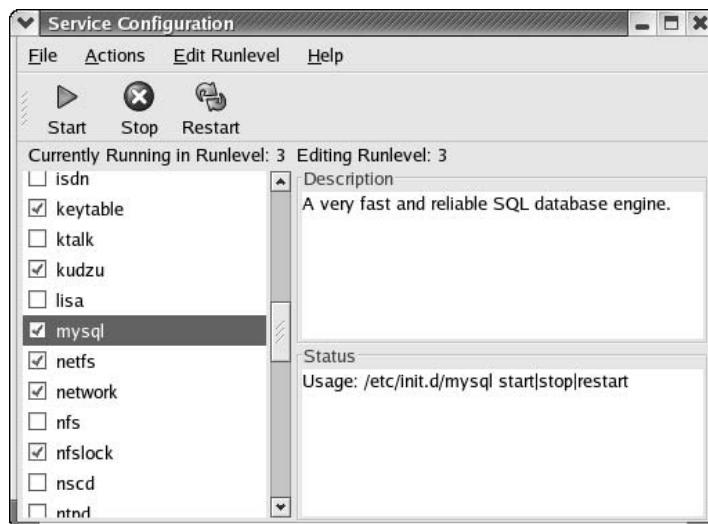


Figure 8-1

Post-Install Configuration

Assuming everything went correctly, MySQL is now installed and started with a common default set of options. Let's test that assumption:

```
$ mysql -u root mysql
```

If you get a "Welcome to the MySQL monitor" message and then a mysql> prompt, we know the server is running. Of course, now anyone can connect to it and have administrator privileges, but we'll address that shortly. Try typing \s to get some additional information on your server. When you've seen enough, type quit to exit the monitor.

You can also check the status of a running server with the `mysqladmin` command:

```
$ mysqladmin -u root version
```

An appropriate response will serve not only to confirm that the server is running but also to give you the version number; at the rate features are being added to MySQL, this could be quite handy.

If the server won't start or you can't connect to the database once it does start, see the next section to troubleshoot your installation.

OK, remember that gaping security hole a few paragraphs back? Let's go plug it up. Once we've tightened down the MySQL root user permissions such as allowing only a local root login to MySQL, we can add only the users and permissions that are absolutely necessary to the function of our application. Don't let yourself be confused by the name of the root user in a MySQL installation. There is no relationship between the MySQL root and the system root, or superuser. The MySQL installation is not protected by your system root password. Any user with an account can log in to it.

Any number of ways will suffice to set a root password, most easily using the command

```
$ mysqladmin -u root password newpassword
```

This will set an initial password of `newpassword`.

This method poses a problem, however, in that the clear text password will be left behind in your shell history and could have been seen by someone using the `ps` command while your command was executing. A better bet will be to use the MySQL monitor again, this time to send some SQL that will change your password.

```
$ mysql -u root
Welcome to the MySQL monitor.  Commands end with ; or \g.
Your MySQL connection id is 4

Type 'help;' or '\h' for help. Type '\c' to clear the buffer.

mysql> SET password=PASSWORD('secretpassword');
Query OK, 0 rows affected (0.15 sec)
```

Pick, of course, a password known only to yourself, not the example "secretpassword" that we used previously to show you where your own password needs to be entered. Now let's have a look at the permissions table to verify that a password has been set:

```
mysql> SELECT user, host, password FROM mysql.user;
+-----+-----+-----+
| user | host   | password          |
+-----+-----+-----+
| root | localhost | 2dxf8e9c23age6ed |
| root | gw1     |                   |
|      | localhost |                   |
|      | gw1     |                   |
+-----+-----+-----+
4 rows in set (0.07 sec)

mysql>
```

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Observe that we have created a password for root only when connecting from the localhost. MySQL can store distinct privileges not only for users, but also for connection classes based on host name. Also notice that we terminate our SQL commands with a semicolon (;). This is not, strictly speaking, part of the actual SQL command; it is used to tell the MySQL client program that we are ready for our SQL statement to be executed.

The next step in securing our installation will be to get rid of those unnecessary users that MySQL installed by default. The following command will remove all nonroot users from the permissions table:

```
mysql> DELETE FROM mysql.user WHERE user != 'root';
Query OK, 2 rows affected (0.11 sec)
```

The next command deletes any login from a host other than localhost:

```
mysql> DELETE FROM mysql.user WHERE host != 'localhost';
Query OK, 1 row affected (0.06 sec)
```

Last, use the following command to check that there are no stray logins:

```
mysql> SELECT user, host, password FROM mysql.user;
+-----+-----+-----+
| user | host      | password          |
+-----+-----+-----+
| root | localhost | 2dx8e9c23age6ed |
+-----+-----+-----+
1 row in set (0.11 sec)

mysql>exit
```

As you can see from the preceding output, we now have a single login that can connect from only localhost.

Now for the moment of truth: Can we still log in using the password we set? Notice that this time we give the -p parameter, which tells MySQL that it must prompt for a password:

```
$ mysql -u root -p
Enter password:
Welcome to the MySQL monitor.  Commands end with ; or \g.
Your MySQL connection id is 7

Type 'help;' or '\h' for help. Type '\c' to clear the buffer.

mysql>
```

We now have a running version of MySQL that is locked down so that only the root user, with a password we have set, may connect to the database server, and that the root user may connect from only the local machine.

Our next step is to add back in the user, or users, we require. As with a Linux system, it's a bad idea to use the root account to log in to MySQL unless it's absolutely necessary, so you should create an everyday user for normal use.

As we hinted earlier, we can create users with different connect permissions from different machines; in particular we have allowed the root user to connect from only the local machine as a security measure. For the purposes of this chapter, we are going to create a new user, `rick`, with fairly wide-ranging permissions. `rick` will be able to connect in three different ways:

- He can connect from the local host.
- He can connect from any machine with IP addresses in the range 192.168.0.0 ⇄ 192.168.0.255.
- He can connect from any machine in the `wiley.com` domain.

The easiest way of doing this in a secure manner is to create three different users with three different connection origins. They could, if we wanted, even have three different passwords, depending on where they connect from.

We create users and assign them privileges by using the `grant` command. Here we create the user with the three different connection origins we listed above. The `IDENTIFIED BY` is slightly odd syntax for setting an initial password. Notice the way quotes are used; it's important to use the single quote characters exactly as shown or we will not create the users exactly as we intended.

Connect to MySQL as the root user and then perform the following sequence:

1. Create a local login for `rick`:

```
mysql> GRANT ALL ON *.* TO rick@localhost IDENTIFIED BY 'secretpassword';
Query OK, 0 rows affected (0.33 sec)
```

2. Then we create a login from anywhere on the class C subnet of 192.168.0. Notice that we must use single quotes to protect the IP range:

```
mysql> GRANT ALL ON *.* TO rick@'192.168.0.0/255.255.255.0' IDENTIFIED BY
'secretpassword';
Query OK, 0 rows affected (0.00 sec)
```

3. Finally, we create a login so that `rick` can log on from any machine in the `wiley.com` domain (again notice the single quotes):

```
mysql> GRANT ALL ON *.* TO rick@'%wiley.com' IDENTIFIED BY 'secretpassword';
Query OK, 0 rows affected (0.00 sec)
```

4. We can now look again at the user table to doublecheck the entries:

```
mysql> SELECT user, host, password FROM mysql.user;
+-----+-----+-----+
| user | host          | password        |
+-----+-----+-----+
| root | localhost     | 2dxf8e8c17ade6ed |
| rick | localhost     | 3742g6348q8378d9 |
| rick | %.wiley.com   | 3742g6348q8378d9 |
| rick | 192.168.0.0/255.255.255.0 | 3742g6348q8378d9 |
+-----+-----+-----+
4 rows in set (0.06 sec)
```

```
mysql>
```

Naturally, you need to adjust the above commands and passwords to suit your local configuration. You will notice we used a `GRANT ALL ON *.*` command, which as you probably surmised gave user `rick` pretty widespread permissions. That's fine for a power user but won't work for creating more restricted users. We discuss the `grant` command in more detail in the "Creating Users, and Giving Them Permissions" section in this chapter, where, among other things, we show you how to create a more restricted user.

Now that we have MySQL up and running (if not, see the next section) and have a nonroot user created ready to do some work with, we'll first discuss troubleshooting after installation and then go back briefly and take a lightning tour through the essentials of MySQL database administration.

Post-Installation Troubleshooting

If the connection failed when you used `mysql`, check that the server process is running using the system `ps` command. If you can't find it in the list, try launching `mysql_safe -log`. This should write a file to MySQL's log directory with some additional information.

It's also possible that the server is running; but simply refusing your connection. The next item to check, in that case, will be the presence of a database, in particular the default MySQL permissions database. By default, the `mysql_install_db` script puts these in <MySQL Install Dir>/var; but if you've installed from someone else's package, these defaults may have changed. Check the MySQL init script, or read through `mysql_install_db` for some clues. Once you find the database directory, verify that it contains at least a default permissions database (called `mysql`) and that the server daemon is using this location as specified in `my.cnf`.

If you're still not connecting, make sure the server is stopped, manually delete the contents of the database directory, and then rerun the `mysql_install_db` script. Restart the server and try connecting again. In the unlikely event you are still not getting anywhere, refer to the MySQL documentation, either with your distribution or on the MySQL Web site (probably more current) to explore some of the more esoteric possibilities.

MySQL Administration

A handful of the utility programs included with the MySQL distribution facilitate administration. The most commonly used of these is the `mysqladmin` program. We'll cover this utility and the others in the following section.

Commands

All of the commands except `mysqlshow` take three standard parameters:

| | | |
|----|------------|--|
| -u | username | By default <code>mysql</code> will attempt to use the same MySQL username as your current Linux user name. Use the <code>-u</code> parameter to specify a different user name. |
| -p | [password] | If <code>-p</code> is given but the password is omitted, the password is prompted for. If the <code>-p</code> parameter is not present, MySQL commands assume no password is needed. |

| | | |
|----|------|--|
| -h | host | Used to connect to a server on a different host (can always be omitted for local servers). |
|----|------|--|

Again, we recommend you avoid putting a password on the command line, as it can be seen by the ps command.

myisamchk

The `myisamchk` utility is designed to check and repair any data tables using the default MYISAM table format natively supported by MySQL. Normally, `myisamchk` should be run as the `mysql` user created at installation from the directory in which the tables reside. In order to check a database, do `su mysql`, change into the directory name corresponding to the name of the database; and run `myisamchk` with one or more of the options suggested by the following table. For example,

```
myisamchk -e -r *.MYI
```

| | |
|----|---------------------------------|
| -c | Check the table for errors. |
| -e | Perform an extended check. |
| -r | Recover (correct) errors found. |

Again, for more information, we can invoke `myisamchk` with no parameters and look through the extensive help message.

mysql

This is the principal, and the only fully interactive, MySQL command line tool. Nearly every administrative or user-level task can be performed here. You can start `mysql` from the command line; then by adding a final parameter, a database name, you can bypass the `use <database>` command from within the monitor. For example, to start the monitor as user `rick` having password `bar` and using database `foo`:

```
$ mysql -u rick -pbar foo
```

It's normally better form and more secure to not pass an argument to `-p` this way; rather, let the program prompt you so that your entry is hidden. Do `mysql -help | less` to page through a list of other command line options for the `mysql` monitor.

If you start MySQL without specifying a database, you can use the `use <databasename>` option from within MySQL to select one, as you can see from the list of commands in the nearby table.

Alternatively, you can run `mysql` in a noninteractive mode by bundling commands into an input file and reading it in from the command line.

```
$ mysql -u rick -pbar foo < sqlcommands.sql
```

Once `mysql` has read and processed your commands, it will return to the command prompt.

While the `mysql` client is connected to the server, a number of specific commands in addition to the standard SQL92 set are supported, as shown in the following table:

| Command | Alternative Shortform | Meaning |
|-------------------|-----------------------|---|
| help or ? | \h or \? | Displays a list of commands. |
| edit | \e | Edit the command. The editor used is determined by the environment variable \$EDITOR. |
| exit or quit | \q | Exit the MySQL client. |
| go | \g | Execute the command. |
| source <filename> | \. | Execute SQL from the given file. |
| status | \s | Display server status information. |
| system <command> | \! | Execute a system command. |
| tee <filename> | \T | Append a copy of all output to the given filename. |
| use <database> | \u | Use the given database. |

SQL92 is the currently used version of the ANSI SQL standard. Its purpose is to create uniformity for how SQL databases work, facilitating interoperability and communication among different database products.

mysqladmin

This utility is the principal tool for quick MySQL database administration. In addition to the usual parameters, the following commands are supported:

| | |
|-------------------------|--|
| create <database_name> | Create a new database. |
| drop <database_name> | Delete a database. |
| password <new_password> | Change a password (as we saw earlier). |
| reload | Reload the grant tables that control permissions. |
| status | Provide the status of the server. |
| shutdown | Shut down the server. |
| variables | Show the variables that control MySQL operation and their current values. |
| version | Provide the version number of the server and how long it has been running. |

Invoke mysqladmin without any parameters to see the full list of options from the command prompt. You'll want to use | less.

mysqlbug

With a little luck, you'll never have the opportunity to use this. As the name implies, this tool creates a bug report for mailing to the maintainers of MySQL. Before sending it off, you may wish to edit the generated file to provide additional information that may be useful to the developers.

This is an extremely useful utility that allows you to dump a partial or an entire database to a single file as a set of SQL commands that can be read back into MySQL or even another SQL RDBMS. It takes as a parameter the standard user and password info as well as database and table names. The additional options in the following table greatly extend its utility:

| | |
|-------------------------------|--|
| <code>--add-drop-table</code> | Add SQL commands to the output file to drop (delete) any tables before the commands to create them. |
| <code>-e</code> | Use extended insert syntax. This is nonstandard SQL, but if you are dumping a large amount of data, then this will help your database dump to reload much more quickly when you try to reload it into MySQL. |
| <code>-t</code> tables. | Dump only the data from tables, not the information to create |
| <code>-d</code> | Dump only the table structure, not the actual data. |

By default, `mysqldump` sends its data to standard output, so you'll want to redirect this to a file.

This utility is handy for migrating data or quick backups, and thanks to the client server implementation of MySQL it can even be used for a nice remote backup implementation:

```
$ mysqldump -u rick -p rick > rick.dump
```

The resulting file, which on our system has only a single table in the `rick` database, looks like this:

```
– MySQL dump 8.22
–
– Host: localhost      Database: rick
–
– Table structure for table 'children'
–
CREATE TABLE children (
    childno int(11) DEFAULT '0' NOT NULL auto_increment,
    fname varchar(30),
    age int(11),
    PRIMARY KEY (childno)
);

–
– Dumping data for table 'children'
–
```

```
INSERT INTO children VALUES (1,'Jenny',17);
INSERT INTO children VALUES (2,'Andrew',13);
INSERT INTO children VALUES (3,'Gavin',4);
INSERT INTO children VALUES (4,'Duncan',2);
INSERT INTO children VALUES (5,'Emma',0);
INSERT INTO children VALUES (6,'Alex',11);
INSERT INTO children VALUES (7,'Adrian',5);
```

mysqlimport

The `mysqlimport` command is the equally useful cousin of `mysqldump`. Using `mysqlimport`, you can read in large quantities of data from an input file. The only command-specific parameters required are a filename and a database. Generally, you'll be reading in a file created by `mysqldump`; but it's possible to manually create a file that can be read by `mysqlimport` as well.

It's also possible to perform SQL commands from a text file by simply running `mysql` with input redirected from a file, as we mentioned earlier.

mysqlshow

This little utility can provide quick information about your MySQL installation and its component databases.

- With no parameters, it lists all available databases.
- With a database as a parameter, it lists the tables in that database.
- With both a database and a table name, it lists the columns in that table.
- With a database, table, and column, it lists the details of the specified column.

Creating Users and Giving Them Permissions

As a MySQL administrator, one of your most common tasks will be user maintenance. Before you try using a wrench on your users (a tempting possibility on the best of days), we mean adding and removing users from MySQL and managing their privileges. Starting with MySQL 3.22, users are managed with the `grant` and `revoke` commands from within the MySQL monitor—a task considerably less daunting than editing the privilege tables directly as was necessary in previous versions.

grant

The MySQL `grant` command closely, though not exactly, follows SQL92. The general format is

```
grant <privilege> on <object> to <user> [identified by user-password] [with grant];
```

There are several privilege values that can be granted, shown in the following table:

| | |
|--------|--------------------------------|
| alter | Alter tables and indexes. |
| create | Create databases and tables. |
| delete | Delete data from the database. |

| | |
|--------|------------------------------|
| drop | Remove databases and tables. |
| index | Manage indexes. |
| insert | Add data to the database. |
| select | Retrieve data. |
| update | Modify data. |
| all | All the above. |

There are also several special administration privileges, but these do not concern us here.

The object on which you grant these privileges is identified as

```
databasename.tablename
```

and in the best Unix tradition, * is the anything-goes operator so that database.* means every object in the database.

If the specified user already exists, privileges are edited to reflect your changes. If no such user exists, the user is created with the specified privileges. You should specify user and host in the same command to get the full flexibility of the MySQL permission scheme.

In SQL syntax, the special character % stands for the wildcard character, much the same as * in a shell environment. You can, of course, issue separate commands for each desired privilege set; but if, for example, you want to grant access to user rick from any host in the domain, you could describe rick as

```
rick@'% .docbox.co.uk'
```

Any use of the wildcard character must be enclosed in quotes to set it off from any literal text.

You can also use IP/Netmask notation (N.N.N.N/M.M.M.M) to set a network address for access control.

Just as we earlier used rick@'192.168.0.0/255.255.255.0' to grant access to rick from any local network computer, we can specify rick@'192.168.0.1' to limit rick's access to a single workstation or specify rick@'192.0.0.0/255.0.0.0' to broaden the scope to include any machine in the 192 class A network.

As one more example,

```
mysql> grant all on foo.* to rick@'%' identified by 'bar';
```

will create a user rick, with full permissions on the database foo, to connect from any machine with an initial password of bar.

If the database foo does not yet exist, then the user rick will now have permissions to create it using the create database SQL command.

The identified by clause is optional; but it's a good idea to set the password each time to ensure there is never a hole in your security.

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Typically, the `with grant` option is used only to create a secondary administrative user; however, it can be used to allow a newly created user to confer the privileges granted to her on other users. Always use `with grant` judiciously.

revoke

Naturally, the administrator that giveth also taketh away, and the administrator can do so with the `revoke` command:

```
revoke a privilege on an object from a user;
```

using much the same format as the `grant` command. For example,

```
revoke insert on foo.* from rick@'%';
```

The `revoke` command, however, does not delete users. If you wish to completely remove a user, don't simply modify their privileges, but use `revoke` to remove their privileges. Then you can completely remove them from the user table with

```
mysql> use mysql
mysql> DELETE FROM user WHERE user = "rick"
mysql> FLUSH PRIVILEGES;
```

In declining to specify a host, we ensure that we get rid of every instance of the MySQL user that we want removed.

Understand that `delete` is not part of the same concept as `grant` and `revoke`. It's SQL syntax that happens to be necessary as a result of the way MySQL handles permissions. Notice that the `use` command is not necessary with `grant` and `revoke`, as MySQL knows in these instances you want manipulate the permissions tables.

```
mysql> use mysql
mysql> DELETE FROM user WHERE user = "rick"
mysql> FLUSH PRIVILEGES;
```

Passwords

If you want to specify passwords for existing users who do not already have them, or you wish to change your own or somebody else's password, you'll need to connect to the MySQL server as the root user, select the `mysql` database, and then

```
mysql> select host, user, password from user;
```

You should get a list like this:

```
+-----+-----+-----+
| host   | user   | password          |
+-----+-----+-----+
| localhost | root    | 67457e226a1a15bd |
| localhost | foo     |                   |
+-----+-----+-----+
2 rows in set (0.00 sec)
```

Say you want to assign the password `bar` to user `foo`; you can do so like this:

```
mysql> UPDATE user SET password = password('bar') WHERE user = 'foo';
```

Display the relevant columns in the `user` table again:

```
mysql> SELECT host, user, password FROM user;
+-----+-----+-----+
| host | user | password |
+-----+-----+-----+
| localhost | root | 65457e236g1a1wbq |
| localhost | foo | 7c9e0a41222752fa |
+-----+-----+-----+
2 rows in set (0.00 sec)
mysql>
```

Sure enough, the user `foo` now has a password.

In MySQL 4.1 the password scheme has been updated. However, you can still set a password using the old algorithm for backward compatibility with the function `OLD_PASSWORD('password to set')`. This implementation is still a little ragged, but it should become more reliable as updated versions are released.

Creating a Database

Let's start with a database called `rick`. You may recall that we've already created a user with the same name.

```
mysql> GRANT ALL ON *.* TO rick@localhost IDENTIFIED BY 'secretpassword';
```

Let's test that privilege set by logging in as `rick` and creating the database:

```
mysql> quit
Bye
$ mysql -u rick -p
Enter password:
...
mysql> CREATE DATABASE rick;
```

Now we'll tell MySQL we want to use our new database:

```
mysql> use rick
```

Now we can populate this database with the tables and information we want. On future logins, we can specify the database on the command line, bypassing the need for the `use` command:

```
$ mysql -u rick -p rick
```

We will then automatically change to use the database `rick`.

Data Types

So now we have a running MySQL server, a secure login for our user, and a database ready to use. What's next? Well, now we need to create some tables with columns to store our data. Before we can do that, however, we need to know about the data types that MySQL supports.

MySQL data types are fairly standard, so we will just run briefly through the main types here. As always, the MySQL manual on the MySQL Web site discusses this in more detail.

Boolean

A Boolean column can be defined using the keyword `BOOL`. As you would expect, it can hold `TRUE` and `FALSE` values. It may also hold the special database “unknown” value `NULL`.

Character

A variety of character types are available and are shown in the following table. The first three are standard and the remaining three specific to MySQL. We suggest you stick to the standard types if practical.

| Definition | Meaning |
|--------------------------|---|
| <code>CHAR</code> | A single character. |
| <code>CHAR (N)</code> | A character string on exactly N characters, which will be padded with space characters if necessary. Limited to 255 characters. |
| <code>VARCHAR (N)</code> | A variable-length array of N characters. Limited to 255 characters. |
| <code>TINYTEXT</code> | Similar to <code>VARCHAR (N)</code> . |
| <code>MEDIUMTEXT</code> | A text string of up to 65,535 characters. |
| <code>LONGTEXT</code> | A text string of up to $2^{32}-1$ characters. |

Number

The number types are broken down into integer and floating point number types, as shown in the following table:

| Definition | Type | Meaning |
|------------------------|----------|---|
| <code>TINYINT</code> | Integer | An 8-bit data type. |
| <code>SMALLINT</code> | Integer | A 16-bit data type. |
| <code>MEDIUMINT</code> | Integer | A 24-bit data type. |
| <code>INT</code> | Integer | A 32-bit data type. This is a standard type, and a good general purpose choice. |
| <code>BIGINT</code> | Integer | A 64-bit signed data type. |
| <code>FLOAT (P)</code> | Floating | A floating point number with at least P digits of precision. |

| Definition | Type | Meaning |
|----------------|----------|---|
| DOUBLE (D, N) | Floating | A signed double-precision floating point number, with D digits and N decimal places. |
| NUMERIC (P, S) | Floating | A real number with a total of P digits, with S of the digits after the decimal place. Unlike DOUBLE, this is an exact number, so it is better for storing currency, but less efficiently processed. |
| DECIMAL (P, S) | Floating | A synonym for NUMERIC. |

In general, we suggest you stick to INT, DOUBLE, and NUMERIC types, as these are closest to the standard SQL types. The other types are nonstandard and may not be available in other database systems if you find you need to move your data at some point in the future.

Temporal

Four temporal data types are available, shown in the following table:

| Definition | Meaning |
|------------|---|
| DATE | Stores dates between January 1, 1000, and December 31, 9999. |
| TIME | Stores times between -838:59:59 and 838:59:59. |
| TIMESTAMP | Stores a timestamp between January 1, 1970, and the year 2037. |
| DATETIME | Stores dates between January 1, 1000, and the last second of December 31, 9999. |

Creating a Table

Now that we have our database server running, know how to assign user permissions, and know how to create a database and some basic database types, we can move on to creating tables.

A database table is simply a sequence of rows, each of which consists of a fixed set of columns. It's rather like a spreadsheet, except that each row must have exactly the same number and type of columns, and each row must, in some way, be different from all other rows in the table.

A database can, within reason, contain pretty much an unlimited number of tables. However, very few databases need more than 100 tables, and for most small systems 10 or 20 tables usually suffice.

The full SQL syntax for creating database objects, known as DDL (data definition language), is too complex to go into fully in one chapter; the full details can be found in the documentation section of the MySQL Web site.

The basic syntax for creating a table is

```
CREATE TABLE <table_name> (
    column_type [NULL | NOT NULL] [AUTO_INCREMENT] [PRIMARY KEY]
```

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```
[, ...]
[, PRIMARY KEY ( column [, ...] ) ]
)
```

You can discard tables using the `DROP TABLE` syntax, which is very simple:

```
DROP TABLE <table_name>
```

For now, there are just a small number of additional keywords we need to know to get up to speed with creating tables, shown in the following table:

| Keyword | Meaning |
|----------------|--|
| AUTO_INCREMENT | This special keyword tells MySQL that, whenever you write a NULL into this column, it should automatically fill in the column data using an automatically allocated incrementing number. This is an immensely useful feature; it allows us to use MySQL to automatically assign unique numbers to rows in our tables. In other databases this functionality is often provided by a serial type, or is managed more explicitly with a sequence. |
| NULL | A special database value that is normally used to mean “not known,” but can also be used to mean “not relevant.” For example, if you are filling in a table with employee details, you might have a column for e-mail address, but perhaps some employees don’t have a company e-mail address. In this case, you would store a NULL against the e-mail address for that employee to show that the information was not relevant to that particular person. The syntax NOT NULL means that this column cannot store a NULL value, and it can be useful to prevent columns from holding NULL values if, for example, the value must always be known, such as an employee’s last name. |
| PRIMARY KEY | Indicates that the data for this column will be unique and different in every row in this table. Each table can have just a single primary key. |

It’s much easier to see table creation in practice than to look at the base syntax, so let’s do that now by creating a table called `children` that will store a unique number for each child, a first name, and an age. We’ll make the child number a primary key:

```
CREATE table children (
    childno INTEGER AUTO_INCREMENT NOT NULL PRIMARY KEY,
    fname VARCHAR(30),
    age INTEGER
);
```

Notice that, unlike most programming languages, the column name (`childno`) comes before the column type (`INTEGER`).

We can also use a syntax that defines the primary key separately from the column; here's a session that shows the alternative syntax:

```
mysql> use rick
Database changed
mysql> CREATE table children (
    -> childno INTEGER AUTO_INCREMENT NOT NULL,
    -> fname varchar(30),
    -> age INTEGER,
    -> PRIMARY KEY(childno)
    -> );
Query OK, 0 rows affected (0.04 sec)
mysql>
```

Notice how we can write the SQL across several lines, and MySQL uses the `->` prompt to show we are on a continuation line. Also notice, as mentioned earlier, we terminate the SQL with a semicolon to indicate we have finished and are ready for the database to process the request.

If you make a mistake, MySQL should allow you to scroll backward through previous commands, edit them, and re-enter them by simply pressing Enter.

Now we have a table to which we can add some data. We do this with the `INSERT` SQL command. Since we defined the `childno` column as an `AUTO_INCREMENT` column, we don't give any data from that column; we simply allow MySQL to allocate a unique number.

We can check whether the data was stored successfully by `SELECTING` the data from the table:

```
mysql> INSERT INTO children(fname, age) VALUES("Jenny", 17);
Query OK, 1 row affected (0.07 sec)

mysql> INSERT INTO children(fname, age) VALUES("Andrew", 13);
Query OK, 1 row affected (0.01 sec)

mysql> SELECT childno, fname, age FROM children;
+-----+-----+-----+
| childno | fname  | age   |
+-----+-----+-----+
|      1  | Jenny  |    17 |
|      2  | Andrew |    13 |
+-----+-----+-----+
2 rows in set (0.06 sec)

mysql>
```

Rather than explicitly list the columns we wanted to select, we could just have used an asterisk (*) for the columns, which will list all columns in the named table. In production code you should always explicitly name the column you wish to select for interactive use, but an asterisk is sometimes convenient during development because it saves typing and the need to remember exact column names.

We don't have space in this chapter to go into full details of SQL, much less database design. For more information see www.mysql.com.

Graphical Tools

Manipulating tables and data on the command line is all well and good, but these days many people prefer graphical tools.

MySQL has had a graphical tool known as MySQLGUI for some time. This tool is still available from the MySQL Web site, but development is now concentrated on an alternative tool, the MySQL Control Center, or MySQLCC. The MySQL Control Center is a very useful all-around tool, and one well worth installing.

We strongly suggest you look at MySQLCC; it's a powerful, stable, and easy-to-use graphical interface for MySQL that is available precompiled for both Linux and Windows (even the source code is available if you want it). It allows you to both administer a MySQL server and execute SQL through a GUI interface.

If a MySQLCC is not available on your Linux distribution, you can download a copy from the MySQL Web site and follow the simple installation instructions. Alternatively, you can manage your copy of MySQL running on your Linux server directly from MySQLCC running on a Windows desktop. They look and run almost identically.

The first time you run MySQLCC, you will be presented with a blank Control Center window, with an empty Console Manager, as shown in Figure 8-2. Hovering the mouse over the first icon on the toolbar reveals that this is the icon for creating a new connection.

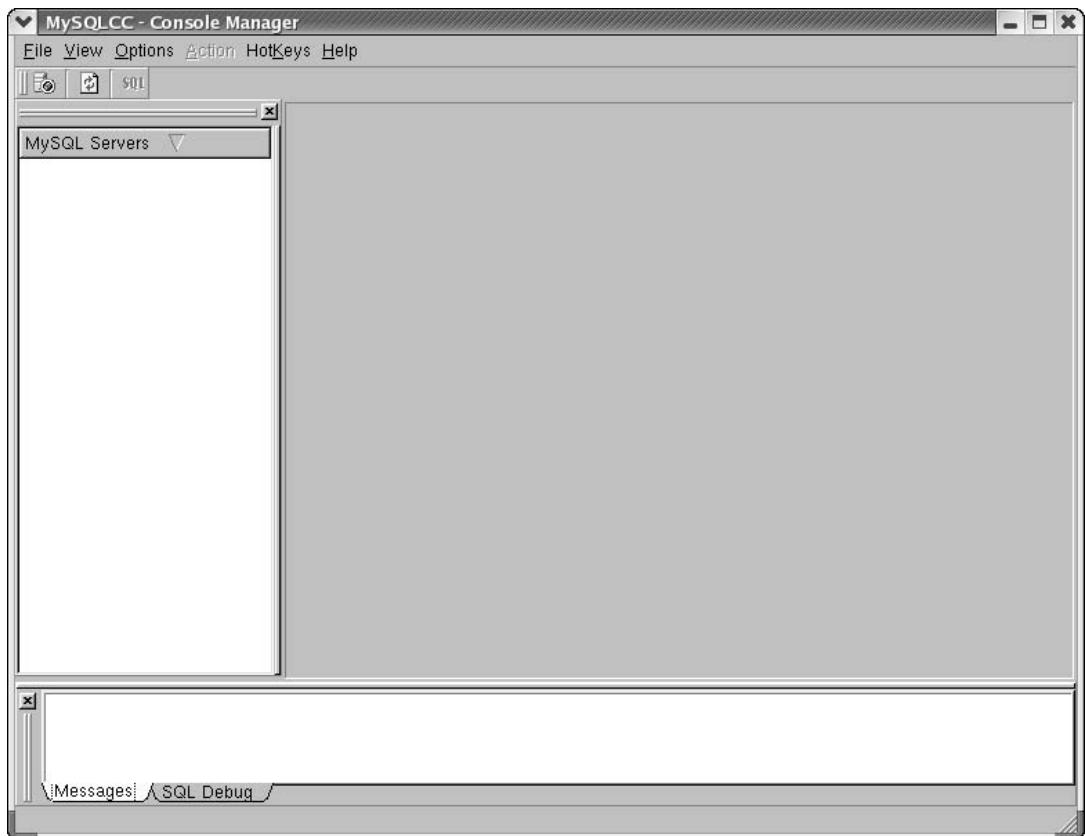


Figure 8-2

When you click this button, you will be asked for some basic details in an additional popup window (see Figure 8-3).

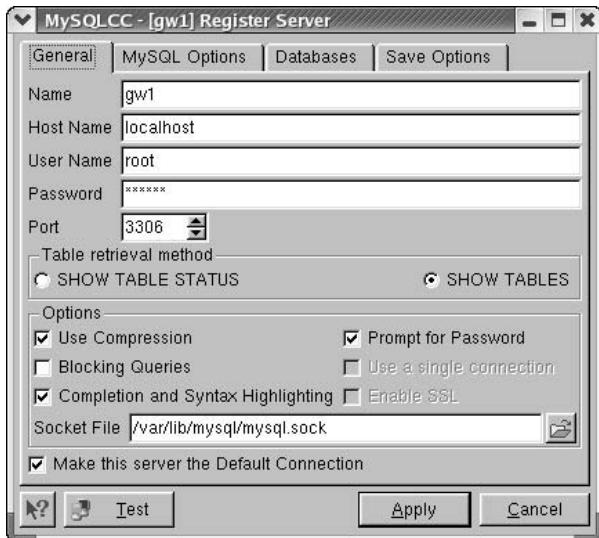


Figure 8-3

If you want to manage your server remotely from a Windows PC, then configuration is almost identical, except that you need to enter a host name or IP address in the Host Name field, as shown in Figure 8-4.

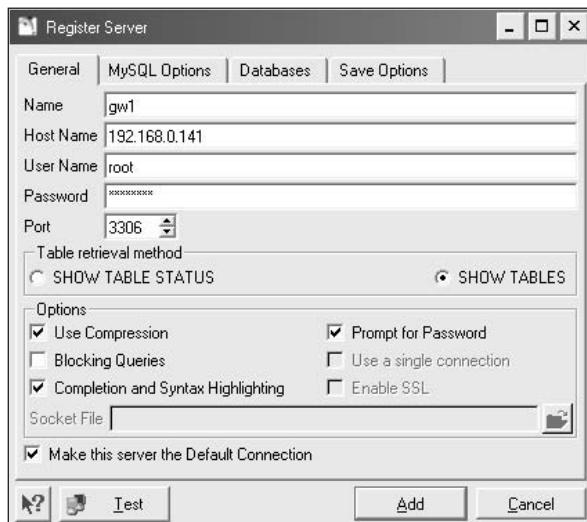


Figure 8-4

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All the information you need to provide is the name to identify the connection (which can be anything you choose), the host name, the user name, and the password. All other values are filled in by default for you. Then click the Test button, which will tell you the connection is okay.

Then click Add to add this connection to the list. The name gw1 (or whatever you chose—gw1 just happens to be the name of the machine the server is running on) should be displayed in the list of MySQL servers, and by clicking it you should be able to drop down more information, as you can see in Figure 8-5.

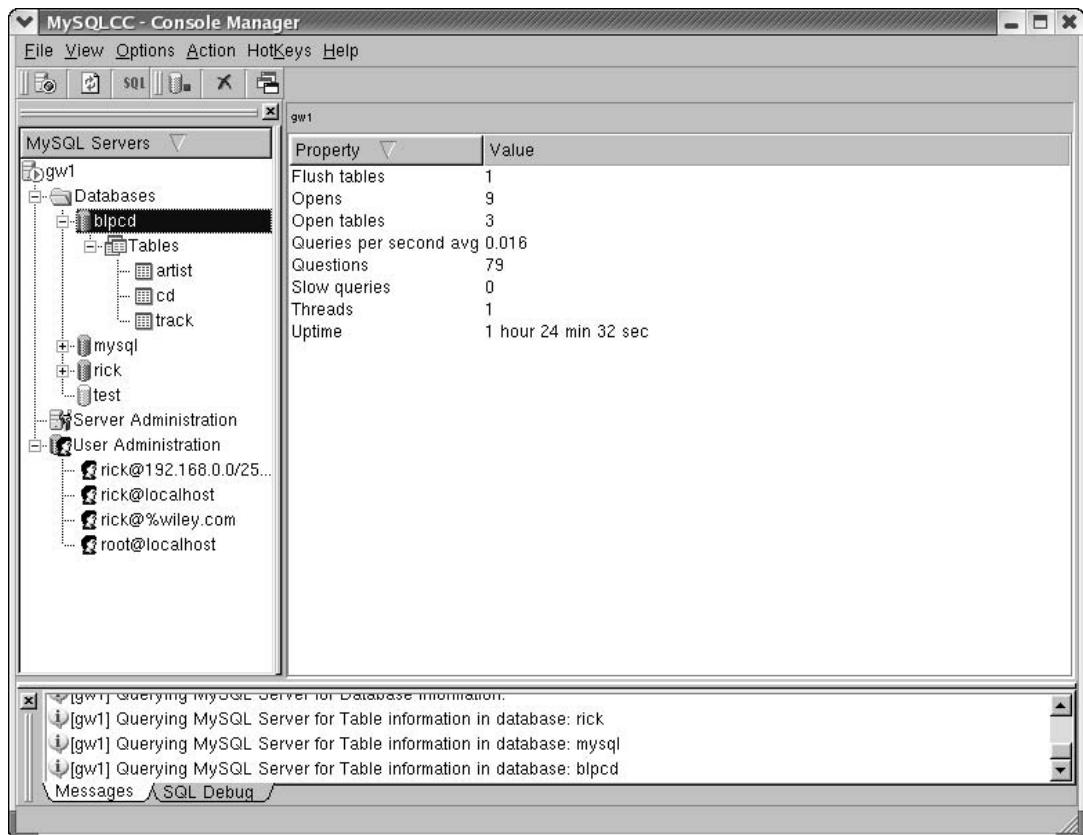


Figure 8-5

If you explore the database section, you can see the tables, and by right-clicking a table, you can edit the table definition or the data in the table, as you can see in Figure 8-6.

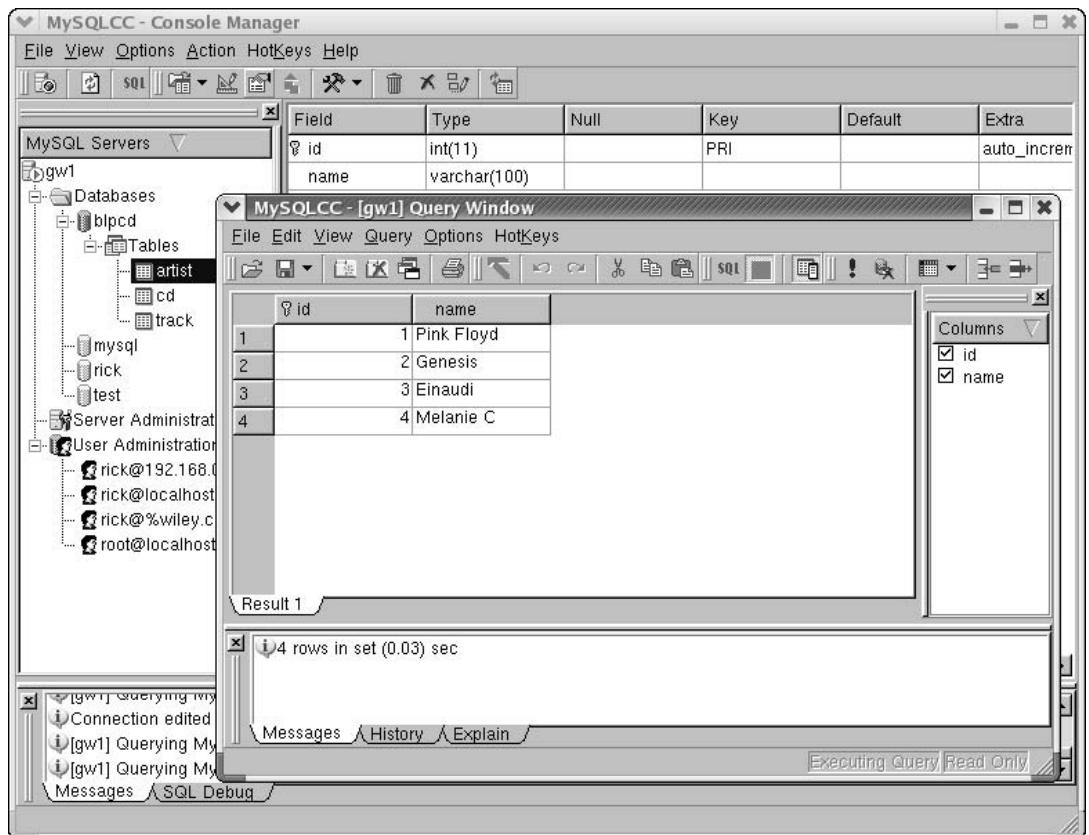


Figure 8-6

You can also edit users and their permissions, execute SQL, look at connections to the database, and do many other things.

Accessing MySQL Data from C

Now that we have the rudiments of MySQL out of the way, let's explore how to access it from our own application, rather than using mysqlcc or the basic mysql client.

MySQL can be accessed from many different languages. We know of

- C
- C++
- Java

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- Perl
- Python
- REXX
- Tcl
- PHP

An ODBC drive is also available for accessing MySQL from Windows-native applications such as Access; and there is even an ODBC driver for Linux, although little reason exists to use it.

In this chapter, we'll limit ourselves to the C interface because that is the primary focus of this book and because the same libraries facilitate connection by a number of other languages.

Connection Routines

The two steps involved in connecting to a MySQL database from C are

- Initializing a connection handle structure
- Physically making the connection

First, we'll use `mysql_init` to initialize our connection handle:

```
MYSQL *mysql_init(MYSQL *);
```

Normally you pass `NULL` to the routine, and a pointer to a newly allocated connection handle structure is returned. If you pass an existing structure, it will be reinitialized. On error, `NULL` is returned.

So far, we've simply allocated and initialized a structure. We still need to offer the parameters for a connection using `mysql_real_connect`:

```
MYSQL *mysql_real_connect(MYSQL *connection,
                           const char *server_host,
                           const char *sql_user_name,
                           const char *sql_password,
                           const char *db_name,
                           unsigned int port_number,
                           const char *unix_socket_name,
                           unsigned int flags);
```

The connection pointer has to identify a structure already initialized using `mysql_init`. The parameters are fairly self-explanatory; however, it should be noted that the `server_host` can take a host name or an IP address. If connecting only to the local machine, we can optimize the connection type by specifying simply `localhost` here.

`sql_user_name` and `sql_password` are exactly what they sound like. If the login name is `NULL`, then the login ID of the current Linux user is assumed. If the password is `NULL`, you will be able to access data only on the server that's accessible without a password. The password is encrypted before being sent across the network.

The `port_number` and `unix_socket_name` should be `0` and `NULL`, respectively, unless you have changed the defaults in your MySQL installation. They will default to appropriate values.

Finally, the `flag` parameter allows you to OR together some bit-pattern defines, allowing you to alter certain features of the protocol being used. None of these are relevant to this introductory chapter; all are fully documented in the manual.

If we are unable to connect, `NULL` is returned. Using `mysql_error` can provide helpful information.

When you are finished with the connection, normally at program termination, call `mysql_close` like this:

```
void mysql_close(MYSQL *connection);
```

This will shut down the connection. If the connection was set up by `mysql_init`, the structure will be freed. The pointer will become invalid and cannot be used again. It is wasteful of resources to leave an unneeded connection open; but there's additional overhead associated with reopening a connection, so use your judgment about when to use these options.

The `mysql_options` routine (which can be called only between `mysql_init` and `mysql_real_connect`) allows us to set some options:

```
int mysql_options(MYSQL *connection, enum option_to_set,
                  const char *argument);
```

Because `mysql_options` is capable of setting only one option at a time, it must be called once for each option you would like to set. You can use it as many times as necessary so long as all uses appear between `mysql_init` and `mysql_real_connect`. Not all of the options are of the `char` type, which must be cast as `const char *`. We have a look at the three most common options in the following table. As always, the extensive online manual lists them all.

| enum Option | Actual Argument Type | Meaning |
|--|-----------------------------------|---|
| <code>MYSQL_OPT_CONNECT_TIMEOUT</code> | <code>const unsigned int *</code> | The number of seconds to wait before timing out a connection. |
| <code>MYSQL_OPT_COMPRESS</code> | <code>None, use NULL</code> | Use compression on the network connection. |
| <code>MYSQL_INIT_COMMAND</code> | <code>const char *</code> | Command to send each time a connection is established. |

A successful call returns zero. Because this is just for setting flags, failure always means that an invalid option has been used.

To set the connection timeout to seven seconds, we use a fragment of code such as this:

```
unsigned int timeout = 7;
...
connection = mysql_init(NULL);
ret = mysql_options(connection, MYSQL_OPT_CONNECT_TIMEOUT, (const char *)&timeout);
```

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```
if (ret) {
    /* Handle error */
    ...
}

connection = mysql_real_connect(connection ...
```

Now that you've learned how to set up and close your connection, let's try a short program just to test things.

Let's start by creating our database and an example table within it. We could do this from the command line, or if you prefer, use mysqlgcc.

```
$ mysql -u rick -psecret
Welcome to the MySQL monitor.  Commands end with ; or \g.
Your MySQL connection id is 12 to server version: 4.0.12

Type 'help;' or '\h' for help. Type '\c' to clear the buffer.

mysql> create database foo;
Query OK, 1 row affected (0.00 sec)

mysql> use foo;
Database changed
mysql> exit
```

We have now created our new database. Rather than type a lot of table creation and population commands directly into the mysql command line, which is somewhat prone to error and not very productive if you ever need to type it again, we will create a file with the commands we need in it.

This file is `create_children.sql`:

```
-
-- Create the table children
-

CREATE TABLE children (
    childno int(11) DEFAULT '0' NOT NULL auto_increment,
    fname varchar(30),
    age int(11),
    PRIMARY KEY (childno)
);

-
-- Populate the table 'children'
-

INSERT INTO children VALUES (1,'Jenny',17);
INSERT INTO children VALUES (2,'Andrew',13);
INSERT INTO children VALUES (3,'Gavin',4);
INSERT INTO children VALUES (4,'Duncan',2);
INSERT INTO children VALUES (5,'Emma',0);
INSERT INTO children VALUES (6,'Alex',11);
INSERT INTO children VALUES (7,'Adrian',5);
```

We can now sign back on to MySQL, selecting the database `foo`, and execute this file:

```
$ mysql -u rick -psecret foo
Welcome to the MySQL monitor.  Commands end with ; or \g.
Your MySQL connection id is 15 to server version: 4.0.12

Type 'help;' or '\h' for help. Type '\c' to clear the buffer.

mysql> \. create_children.sql
Query OK, 0 rows affected (0.01 sec)

Query OK, 1 row affected (0.00 sec)
```

We have removed the many duplicate lines of output as the rows are created in the database. Now that we have a user, a database, and a table with some data stored in it, it's time to see how we can access the data from code.

This is `connect1.c`, which connects to a server on the local machine, as user `rick` with password `bar`, to the database called `foo`.

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

#include "mysql.h"

int main(int argc, char *argv[]) {
    MYSQL *conn_ptr;

    conn_ptr = mysql_init(NULL);
    if (!conn_ptr) {
        fprintf(stderr, "mysql_init failed\n");
        return EXIT_FAILURE;
    }

    conn_ptr = mysql_real_connect(conn_ptr, "localhost", "rick", "bar",
                                  "foo", 0, NULL, 0);

    if (conn_ptr) {
        printf("Connection success\n");
    } else {
        printf("Connection failed\n");
    }

    mysql_close(conn_ptr);

    return EXIT_SUCCESS;
}
```

Let's compile our program and see how we did. You may need to add both the include path and a library path, as well as specifying that the file needs linking with the library module `mysqlclient`. On some systems you may also need `-lz`, to link the compression library. On our system, the required compile line is

```
$ gcc -I/usr/include/mysql connect1.c -L/usr/lib/mysql -lmysqlclient -lz -o
connect1
```

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You may find a simpler line, such as the one that follows, works on newer distributions such as Red Hat Linux 9 and later.

```
$ gcc -I/usr/include/mysql connect1.c -lmysqlclient -o connect1
```

When we run it, we simply get a message saying the connection succeeded:

```
$ ./connect1
Connection success
$
```

In Chapter 9, we show you how to build a makefile to automate this connection.

As you can see, getting a connection to a MySQL database is very easy.

Error Handling

Before we move on to more sophisticated programs, it's useful to have a look at how MySQL handles errors. MySQL uses a number of return codes reported by the connection handle structure. The two must-have routines are

```
unsigned int mysql_errno(MYSQL *connection);
```

and

```
char *mysql_error(MYSQL *connection);
```

We can retrieve the error code, generally any nonzero value, by calling `mysql_errno` and passing the connection structure. Zero is returned if the error code has not been set. Because the code is updated each time a call is made to the library, we can retrieve the error code only for the last command executed, with the exception of these two error routines, which do not cause the error code to be updated.

The return value actually is the error code, and these values are defined in either the `errmsg.h` include file or `mysqld_error.h`. Both of these can be found in the MySQL include directory. The first reports on client-side errors, and the second focuses on server-specific errors.

If you prefer a textual error message, you can call `mysql_error`, which provides a meaningful text message instead. The message text is written to some internal static memory space, so you need to copy it elsewhere if you want to save the error text.

We can add some rudimentary error handling to our code in order to see this all in action. You probably have already noticed, however, that we are likely to experience a problem since `mysql_real_connect` returns a NULL pointer on failure, depriving us of an error code. If we make the connection handle a variable, then we can still get at it should `mysql_real_connect` fail.

Here is `connect2.c`, which illustrates how we use the connection structure when it isn't dynamically allocated, and also how we might write some basic error-handling code. The changes are highlighted:

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

```

#include "mysql.h"

int main(int argc, char *argv[]) {
    MYSQL my_connection;

    mysql_init(&my_connection);
    if (mysql_real_connect(&my_connection, "localhost", "rick",
                           "secret", "foo", 0, NULL, 0)) {
        printf("Connection success\n");
        mysql_close(&my_connection);
    } else {
        fprintf(stderr, "Connection failed\n");
        if (mysql_errno(&my_connection)) {
            fprintf(stderr, "Connection error %d: %s\n", mysql_errno(&my_connection),
                    mysql_error(&my_connection));
        }
    }

    return EXIT_SUCCESS;
}

```

We could have solved our problem quite simply by avoiding overwriting our connection pointer with the return result if `mysql_real_connect` failed. Still, this is a nice example of the other way of using connection structures. We can force an error by choosing an incorrect user or password, and we will still get an error code similar to that offered by the `mysql` tool.

```

$ ./connect2
Connection failed
Connection error 1045: Access denied for user: 'rick@localhost' (Using
password: YES)
$ 

```

Executing SQL Statements

Now that we can connect to our database and correctly handle errors, let's put our program to some real work. The primary API function for executing SQL statements is aptly named:

```

int mysql_query(MYSQL *connection, const char *query)

```

Not too difficult, is it? This routine takes the connection structure pointer and hopefully some valid SQL as a text string (with no terminating semicolon as in the `mysql` tool). A zero is returned if we are successful. A second routine, `mysql_real_query`, can be used if binary data is called for; but in this chapter we'll be using only `mysql_query`.

SQL Statements That Return No Data

For the sake of simplicity, let's start by looking at some SQL statements that do not return any data: `UPDATE`, `DELETE`, and `INSERT`.

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Another important function that we will introduce at this point checks the number of rows affected by our query:

```
my_ulonglong mysql_affected_rows(MYSQL *connection);
```

The first thing you are likely to notice about this function is the very unusual data type returned. An unsigned type is used for reasons of portability. When you are using `printf`, it's recommended that this be cast as unsigned long with a format of `%lu`. This function returns the number of rows affected by the previously issued `UPDATE`, `INSERT`, or `DELETE` query. The return value that MySQL uses may catch you unprepared if you have worked with other SQL databases. MySQL returns the number of rows modified by an update, whereas many other databases would consider a record updated simply because it matches any `WHERE` clause.

In general for the `mysql_` functions, a return of 0 indicates no rows affected and a positive number is the actual result, typically the number of rows affected by the statement.

So let's add some code to `connect2.c` in order to insert a new row into our table; we'll call this new program `insert1.c`. Observe that the wrapping shown is a physical page limitation; you would not normally use a line break in your actual SQL statement.

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

#include "mysql.h"

int main(int argc, char *argv[]) {
    MYSQL my_connection;

    int res;

    mysql_init(&my_connection);
    if (mysql_real_connect(&my_connection, "localhost",
                           "rick", "secret", "foo", 0, NULL, 0)) {
        printf("Connection success\n");

        res = mysql_query(&my_connection, "INSERT INTO children(fname, age)
                                         VALUES ('Ann', 3)");
        if (!res) {
            printf("Inserted %lu rows\n",
                   (unsigned long)mysql_affected_rows(&my_connection));
        } else {
            fprintf(stderr, "Insert error %d: %s\n",
                    mysql_errno(&my_connection),
                    mysql_error(&my_connection));
        }
    }

    mysql_close(&my_connection);
} else {
    fprintf(stderr, "Connection failed\n");
    if (mysql_errno(&my_connection)) {
        fprintf(stderr, "Connection error %d: %s\n",
                mysql_errno(&my_connection), mysql_error(&my_connection));
    }
}
```

```

    }

    return EXIT_SUCCESS;
}
}

```

Not surprisingly, one row is inserted.

Now let's change the code to include an UPDATE, rather than INSERT, and see how affected rows are reported.

```

mysql_errno(&my_connection), mysql_error(&my_connection));
}

res = mysql_query(&my_connection, "UPDATE children SET AGE = 4
                                         WHERE fname = 'Ann'");
if (!res) {
    printf("Updated %lu rows\n",
           (unsigned long)mysql_affected_rows(&my_connection));
} else {
    fprintf(stderr, "Update error %d: %s\n",
            mysql_errno(&my_connection),
            mysql_error(&my_connection));
}

```

We'll call this program update1.c. It attempts to set the age of all children called Ann to 4.

Now suppose our children table has data in it, like this:

| childno | fname | age |
|---------|--------|-----|
| 1 | Jenny | 17 |
| 2 | Andrew | 13 |
| 3 | Gavin | 4 |
| 4 | Duncan | 2 |
| 5 | Emma | 1 |
| 6 | Alex | 11 |
| 7 | Adrian | 5 |
| 8 | Ann | 3 |
| 9 | Ann | 4 |
| 10 | Ann | 3 |
| 11 | Ann | 4 |

Notice that there are four children matching the name Ann. If we execute update1, we might reasonably expect the number of affected rows to be four, the number of rows mandated by our WHERE clause. As you will see, however, the program reports a change of only two rows because those were the only rows that actually required a change to the data. We can opt for more traditional reporting by using the CLIENT_FOUND_ROWS flag to mysql_real_connect.

```

if (mysql_real_connect(&my_connection, "localhost",
                      "rick", "secret", "foo", 0, NULL, CLIENT_FOUND_ROWS)) {

```

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If we reset the data in our database, then run the program with this modification, it reports the number of affected rows as four.

The function `mysql_affected_rows` has one last oddity, which appears when we delete data from the database. If we delete data with a `WHERE` clause, then `mysql_affected_rows` returns the number of rows deleted, as we would expect. However, if there is no `WHERE` clause on a `DELETE` statement, then all rows in the table will be deleted, but number of rows affected is reported by the program as zero. This is because MySQL optimizes the deletion of all rows, rather than performing many single-row deletions. This behavior is not affected by the `CLIENT_FOUND_ROWS` option flag.

Discovering What You Inserted

There is a small but crucial aspect of inserting data. Remember we mentioned the `AUTO_INCREMENT` type of column, where MySQL automatically assigned IDs for you? This feature is extremely useful, particularly when you have several users.

Take a look at that table definition again:

```
CREATE TABLE children (
    childno INTEGER AUTO_INCREMENT NOT NULL PRIMARY KEY,
    fname VARCHAR(30),
    age INTEGER
);
```

As you can see, we have made the `childno` column an `AUTO_INCREMENT` field. That's all very well, but once we have inserted a row, how do we know which number was allocated for the child whose name we just inserted?

We could execute a `SELECT` statement, to retrieve the data, searching on the child's name, but this is very inefficient, and not guaranteed to be unique—suppose we had two children with the same name? Because discovering the value of an `AUTO_INCREMENT` column is such a common problem, MySQL provides a special solution in the form of the `LAST_INSERT_ID()` function.

Whenever MySQL inserts a data value into an `AUTO_INCREMENT` column, it keeps track, on a per-user basis, of the last value it assigned. User programs can recover this value by simply `SELECTing` the rather special function `LAST_INSERT_ID()`, which acts a little like a pseudo column.

Try It Out

```
mysql> INSERT INTO children(fname, age) VALUES('Tom', 13);
Query OK, 1 row affected (0.06 sec)
mysql> SELECT LAST_INSERT_ID();
+-----+
| last_insert_id() |
+-----+
|          4       |
+-----+
1 row in set (0.01 sec)
mysql> INSERT INTO children(fname, age) VALUES('Harry', 17);
Query OK, 1 row affected (0.02 sec)
```

```
mysql> SELECT LAST_INSERT_ID();
+-----+
| last_insert_id() |
+-----+
|      5 |
+-----+
1 row in set (0.00 sec)

mysql>
```

How It Works

Each time we inserted a row, MySQL allocated a new `id` column value and kept track of it so we could retrieve it using `LAST_INSERT_ID()`.

If you want to experiment to see that the number returned is indeed unique to your session, open a different session and insert another row. In the original session re-execute the `SELECT LAST_INSERT_ID()` statement. You will see the number hasn't changed because the number returned is the last number inserted by the current session. However, if you do `SELECT * FROM children`, you should see that the other session has indeed inserted data.

Try It Out

Let's modify our `insert1.c` program to see how this works in C. We will call this modified program `insert2.c`

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

#include "mysql.h"

int main(int argc, char *argv[]) {
    MYSQL my_connection;
    MYSQL_RES *res_ptr;
    MYSQL_ROW sqlrow;
    int res;

    mysql_init(&my_connection);
    if (mysql_real_connect(&my_connection, "localhost",
                           "rick", "bar", "rick", 0, NULL, 0)) {
        printf("Connection success\n");

        res = mysql_query(&my_connection, "INSERT INTO children(fname, age)
VALUES('Robert', 7)");
        if (!res) {
            printf("Inserted %lu rows\n", (unsigned
long)mysql_affected_rows(&my_connection));
        } else {
            fprintf(stderr, "Insert error %d: %s\n",
                    mysql_errno(&my_connection),
                    mysql_error(&my_connection));
        }
    }
}
```

```
res = mysql_query(&my_connection, "SELECT LAST_INSERT_ID()");

if (res) {
    printf("SELECT error: %s\n", mysql_error(&my_connection));
} else {
    res_ptr = mysql_use_result(&my_connection);
    if (res_ptr) {
        while ((sqlrow = mysql_fetch_row(res_ptr))) {
            printf("We inserted childno %s\n", sqlrow[0]);
        }
        mysql_free_result(res_ptr);
    }
}

mysql_close(&my_connection);
} else {
    fprintf(stderr, "Connection failed\n");
    if (mysql_errno(&my_connection)) {
        fprintf(stderr, "Connection error %d: %s\n",
                mysql_errno(&my_connection), mysql_error(&my_connection));
    }
}

return EXIT_SUCCESS;
}
```

The key changes are highlighted. Here is the output:

```
$ gcc -I/usr/include/mysql insert2.c -L/usr/lib/mysql -lmysqlclient -lz -o insert2
$ ./insert2
Connection success
Inserted 1 rows
We inserted childno 6
$ ./insert2
Connection success
Inserted 1 rows
We inserted childno 7
```

How It Works

After we inserted a row, we retrieved the allocated ID using the `LAST_INSERT_ID()` function just like a normal `SELECT` statement. We then used `mysql_use_result()`, which we will explain shortly, to retrieve the data from the `SELECT` statement we executed and print it out. Don't worry too much about the mechanics of retrieving the value just now; all will be explained in the next few pages.

Statements That Return Data

The most common use of SQL, of course, is retrieving rather than inserting or updating data. Data is retrieved with the `SELECT` statement.

MySQL also supports SHOW, DESCRIBE, and EXPLAIN SQL statements for returning results, but we're not going to be considering these here. As usual, the manual contains explanations of these statements.

Retrieving data into our C application will typically involve four steps:

- Issue the query.
- Retrieve the data.
- Process the data.
- Tidy up if necessary.

Just as we did with our `INSERT` and `DELETE` statements, we'll use `mysql_query` to send the SQL. Next we'll retrieve the data using either `mysql_store_result` or `mysql_use_result`, depending on how we want the data retrieved. Next we'll use a sequence of `mysql_fetch_row` calls to process the data. Finally, we'll use `mysql_free_result` to clear the memory we used for our query.

The difference between `mysql_use_result` and `mysql_store_result` basically amounts to whether we want to get our data back a row at a time, or get the whole result set in one go. The latter is more appropriate in circumstances where you anticipate a smaller result set.

Functions for All-At-Once Data Retrieval

We can retrieve all the data from a `SELECT` (or other statement that returns data), in a single call, using `mysql_store_result`:

```
MYSQL_RES *mysql_store_result(MYSQL *connection);
```

Clearly, we want to use this function after a successful call to `mysql_query`. The function will store all the data returned in the client immediately. It returns a pointer to a new structure called a result set structure, or `NULL` if the statement failed.

Upon success, we'll next call `mysql_num_rows` to get the number of records returned, which we hope will be a positive number but may be 0 if no rows were returned.

```
my_ulonglong mysql_num_rows(MYSQL_RES *result);
```

This takes the result structure returned from `mysql_store_result` and returns the number of rows in that result set. Providing `mysql_store_result` succeeded, `mysql_num_rows` will always succeed.

This combination of functions is an easy way to retrieve the data we need. At this point, all data is local to the client and we no longer have to concern ourselves with the possibility of network or database errors. By getting the number of rows returned, we'll facilitate the coding that is to come.

If we happen to be working with a particularly large dataset, it will be better to retrieve smaller, more manageable chunks of information. This will return control to the application more quickly and is an unselfish way to use network resources. We'll explore this idea in more depth later, when we cover `mysql_use_result`.

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Now that we have the data, we can process it using `mysql_fetch_row` and move around in the dataset using `mysql_data_seek`, `mysql_row_seek`, and `mysql_row_tell`. Let's take a look at these functions.

- ❑ `mysql_fetch_row`: This function pulls a single row out of the result structure we got using `mysql_store_result` and puts it in a row structure. `NULL` is returned when the data runs out or if an error occurs. We will come back to processing the data in this row structure in the next section.

```
MYSQL_ROW mysql_fetch_row(MYSQL_RES *result);
```

- ❑ `mysql_data_seek`: This function allows you to jump about in the result set, setting the row that will be returned by the next `mysql_fetch_row` operation. The offset value is a row number, and it must be in the range zero to one less than the number of rows in the result set. Passing zero will cause the first row to be returned on the next call to `mysql_fetch_row`.

```
void mysql_data_seek(MYSQL_RES *result, my_ulonglong offset);
```

- ❑ The function `mysql_row_tell` returns an offset value, indicating the current position in the result set. It is not a row number, and you can't use it with `mysql_data_seek`.

```
MYSQL_ROW_OFFSET mysql_row_tell(MYSQL_RES *result);
```

However, you can use it with

```
MYSQL_ROW_OFFSET mysql_row_seek(MYSQL_RES *result, MYSQL_ROW_OFFSET offset);
```

which moves the current position in the result set and returns the previous position.

This pair of functions is most useful for moving between known points in the result set. Be careful not to confuse the offset value used by `row_tell` and `row_seek` with the `row_number` used by `data_seek`. Your results will be unpredictable.

- ❑ When you've done everything you need to do with your data, you must explicitly use `mysql_free_result`, which allows the MySQL library to clean up after itself.

```
void mysql_free_result(MYSQL_RES *result);
```

When you've finished with a result set you must always call this function to allow the MySQL library to tidy up the objects it has allocated.

Retrieving the Data

Now we can write our first data-retrieval application. We want to select all records where age is greater than 5. We don't know how to process this data yet, so we'll start by simply retrieving it.. The important section, where we retrieve a result set and loop through the retrieved data, is highlighted. This is `select1.c`:

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

#include "mysql.h"
```

```

MYSQL my_connection;
MYSQL_RES *res_ptr;
MYSQL_ROW sqlrow;

int main(int argc, char *argv[]) {
    int res;

    mysql_init(&my_connection);
    if (mysql_real_connect(&my_connection, "localhost", "rick",
                           "secret", "foo", 0, NULL, 0)) {
        printf("Connection success\n");

        res = mysql_query(&my_connection, "SELECT childno, fname,
                                         age FROM children WHERE age > 5");

        if (res) {
            printf("SELECT error: %s\n", mysql_error(&my_connection));
        } else {
            res_ptr = mysql_store_result(&my_connection);
            if (res_ptr) {
                printf("Retrieved %lu rows\n", (unsigned long)mysql_num_rows(res_ptr));
                while ((sqlrow = mysql_fetch_row(res_ptr))) {
                    printf("Fetched data...\n");
                }
                if (mysql_errno(&my_connection)) {
                    fprintf(stderr, "Retrive error: %s\n", mysql_error(&my_connection));
                }
            }
            mysql_free_result(res_ptr);
        }
        mysql_close(&my_connection);
    } else {
        fprintf(stderr, "Connection failed\n");
        if (mysql_errno(&my_connection)) {
            fprintf(stderr, "Connection error %d: %s\n",
                    mysql_errno(&my_connection), mysql_error(&my_connection));
        }
    }
    return EXIT_SUCCESS;
}

```

Retrieving the Data One Row at a Time

To retrieve the data row by row, which is what we really want to do, we'll rely on `mysql_use_result` rather than `mysql_store_result`.

```
MYSQL_RES *mysql_use_result(MYSQL *connection);
```

Like the `mysql_store_result` function, `mysql_use_result` returns `NULL` on error; if successful, it returns a pointer to a result set object. However, it differs in that hasn't retrieved any data into the result set that it initialized.

You must use `mysql_fetch_row` repeatedly until all the data has been retrieved in order to actually get at the data. If you don't get all the data from `mysql_use_result`, subsequent efforts to get at the data may be corrupted.

So what's the impact of calling `mysql_use_result` versus `mysql_store_result`? There are substantial resource management benefits to the former; but it can't be used with `mysql_data_seek`, `mysql_row_seek`, or `mysql_row_tell`, and the utility of `mysql_num_rows` is limited by the fact that it won't actually fire until all the data has been retrieved.

We've also increased our latency, as each row request has to go across the network and the results sent back the same way. Another possibility is that the network connection could fail in mid-operation, leaving us with incomplete data at best and a mess of some degree at worst.

None of this diminishes in any way, however, the benefits alluded to earlier: a better-balanced network load and less storage overhead for possibly very large data sets.

Changing `select1.c` into `select2.c`, which will use the `mysql_use_result` method, is easy, so we just show the changed section here with shaded changed lines:

```
if (res) {
    printf("SELECT error: %s\n", mysql_error(&my_connection));
} else {
    res_ptr = mysql_use_result(&my_connection);
    if (res_ptr) {
        while ((sqlrow = mysql_fetch_row(res_ptr))) {
            printf("Fetched data...\n");
        }
        if (mysql_errno(&my_connection)) {
            printf("Retrive error: %s\n", mysql_error(&my_connection));
        }
    }
    mysql_free_result(res_ptr);
}
```

Observe that we still can't get a row count until our last result is retrieved. However, by checking for errors early and often, we've made the move to `mysql_use_result` much easier to apply. Coding in this way can save a lot of headache on subsequent modifications to the application.

Processing Returned Data

As much as we've accomplished, our data still hasn't done much for us, has it? Time to remedy that. MySQL, like most SQL databases, gives us back two sorts of data:

- ❑ The retrieved information from the table, namely the column data
- ❑ Data about the data, so-called *metadata*, such as column names and types

Let's first focus on getting the data itself into a usable form.

The `mysql_field_count` function provides some basic information about a query result. It takes our connection object and returns the number of fields (columns) in the result set:

```
unsigned int mysql_field_count(MYSQL *connection);
```

In a more generic way, we can use `mysql_field_count` for other things, such as determining why a call to `mysql_store_result` failed. For example, if `mysql_store_result` returns `NULL`, but `mysql_field_count` returns a positive number, we can hint at a retrieval error. However, if `mysql_field_count` returns a 0, there were no columns to retrieve, which would explain the failure to store the result. It's reasonable to expect that you will know how many columns are supposed to be returned by a particular query. This function is most useful, therefore, in generic query-processing components or any situation where queries are constructed on the fly.

In code written for older versions of MySQL, you may see `mysql_num_fields` being used. This could take either a connection structure or a result structure pointer and return the number of columns.

If we lay aside concerns about formatting, then we already know how to print out the data right away. We'll add the simple `display_row` function to our `select2.c` program.

Notice that we have made the connection, result, and row information returned from `mysql_fetch_row` all global to simplify the example. In production code we would not recommend this.

Here is our very simple routine for printing out the data:

```
void display_row() {
    unsigned int field_count;

    field_count = 0;
    while (field_count < mysql_field_count(&my_connection)) {
        printf("%s ", sqlrow[field_count]);
        field_count++;
    }
    printf("\n");
}
```

Append it to `select2.c` and add a declaration and a function call:

```
void display_row();

int main(int argc, char *argv[]) {
    int res;

    mysql_init(&my_connection);
    if (mysql_real_connect(&my_connection, "localhost", "rick",
                           "bar", "rick", 0, NULL, 0)) {
        printf("Connection success\n");

        res = mysql_query(&my_connection, "SELECT childno, fname,
                                         age FROM children WHERE age > 5");
        if (res) {
```

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```
    printf("SELECT error: %s\n", mysql_error(&my_connection));
} else {
    res_ptr = mysql_use_result(&my_connection);
    if (res_ptr) {
        while ((sqlrow = mysql_fetch_row(res_ptr))) {
            printf("Fetched data...\n");
            display_row();
        }
    }
}
```

Now save the finished product as `select3.c`. Finally, compile and run `select3` as follows:

```
$ gcc -I/usr/include/mysql select3.c -L/usr/lib/mysql -lmysqlclient -lz -o select3
$ ./select3
Connection success
Fetched data...
1 Jenny 17
Fetched data...
2 Andrew 13
$
```

So our program is working, even if its output is not aesthetically pleasing. But we've failed to account for possible NULL values in the result. If we wish to print out more neatly formatted (perhaps tabular) data, we'll need both the data and the metadata returned by MySQL. We can simultaneously retrieve both the metadata and the data into a new structure using `mysql_fetch_field`:

```
MYSQL_FIELD *mysql_fetch_field(MYSQL_RES *result);
```

You need to call this function repeatedly until a NULL is returned, which will signal the end of the data. Then we can use the pointer to the field structure data to get information about the column. The structure of `MYSQL_FIELD` is defined in `mysql.h`, as shown in the following table.

| Field in <code>MYSQL_FIELD</code> Structure | Meaning |
|---|---|
| <code>char *name;</code> | The name of the column, as a string. |
| <code>char *table;</code> | The name of the table from which the column came. This tends to be more useful where a query uses multiple tables. Beware that a calculated value in the result, such as MAX, will have an empty string for the table name. |
| <code>char *def;</code> | If you call the <code>mysql_list_fields</code> (which we are not covering here), this will contain the default value of the column. |
| <code>enum enum_field_types type;</code> | Type of the column. See the explanation immediately following this table. |
| <code>unsigned int length;</code> | The width of the column, as specified when the table was defined. |

| Field in MYSQL_FIELD Structure | Meaning |
|--------------------------------|--|
| unsigned int max_length; | If you used mysql_store_result, then this contains the length in bytes of the longest column value retrieved. It is not set if you used mysql_use_result. |
| unsigned int flags; | Flags tell you about the definition of the column, not about the data found. The common flags have obvious meanings and are NOT_NULL_FLAG, PRI_KEY_FLAG, UNSIGNED_FLAG, AUTO_INCREMENT_FLAG, and BINARY_FLAG. The full list can be found in the MySQL documentation. |
| unsigned int decimals; | The number of digits after the decimal place. Valid only for numeric fields. |

Column types are quite extensive. The full list can be found in `mysql_com.h` and in the documentation. The common ones are

```
FIELD_TYPE_DECIMAL
FIELD_TYPE_LONG
FIELD_TYPE_STRING
FIELD_TYPE_VAR_STRING
```

One particularly useful defined macro is `IS_NUM`, which returns `true` if the type of the field is numeric, like this:

```
if (IS_NUM(mysql_field_ptr->type)) printf("Numeric type field\n");
```

Before we update our program, we should mention one extra function:

```
MYSQL_FIELD_OFFSET mysql_field_seek(MYSQL_RES *result,
                                    MYSQL_FIELD_OFFSET offset);
```

We can use this to override the current field number that is internally incremented for each call to `mysql_fetch_field`. If we pass an offset of zero, we'll jump back to the first column.

Now that we have the information, we need to make our `select` program show all the additional data available concerning a given column.

This is `select4.c`; we reproduce the entire program here so that you can get a complete example to look at. Notice that it does not attempt an extensive analysis of the column types; it just demonstrates the principles required.

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

#include "mysql.h"

MYSQL my_connection;
MYSQL_RES *res_ptr;
```

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```
MYSQL_ROW sqlrow;

void display_header();
void display_row();

int main(int argc, char *argv[]) {
    int res;
    int first_row = 1;

    mysql_init(&my_connection);
    if (mysql_real_connect(&my_connection, "localhost", "rick",
                           "bar", "rick", 0, NULL, 0)) {
        printf("Connection success\n");

        res = mysql_query(&my_connection, "SELECT childno, fname,
                                         age FROM children WHERE age > 5");

        if (res) {
            fprintf(stderr, "SELECT error: %s\n", mysql_error(&my_connection));
        } else {
            res_ptr = mysql_use_result(&my_connection);
            if (res_ptr) {
                display_header();
                while ((sqlrow = mysql_fetch_row(res_ptr))) {
                    if (first_row) {
                        display_header();
                        first_row = 0;
                    }
                    display_row();
                }
                if (mysql_errno(&my_connection)) {
                    fprintf(stderr, "Retrive error: %s\n",
                            mysql_error(&my_connection));
                }
            }
            mysql_free_result(res_ptr);
        }
        mysql_close(&my_connection);
    } else {
        fprintf(stderr, "Connection failed\n");
        if (mysql_errno(&my_connection)) {
            fprintf(stderr, "Connection error %d: %s\n",
                    mysql_errno(&my_connection),
                    mysql_error(&my_connection));
        }
    }
}

return EXIT_SUCCESS;
}
```

```

void display_header() {
    MYSQL_FIELD *field_ptr;

    printf("Column details:\n");
    while ((field_ptr = mysql_fetch_field(res_ptr)) != NULL) {
        printf("\t Name: %s\n", field_ptr->name);
        printf("\t Type: ");
        if (IS_NUM(field_ptr->type)) {
            printf("Numeric field\n");
        } else {
            switch(field_ptr->type) {
                case FIELD_TYPE_VAR_STRING:
                    printf("VARCHAR\n");
                    break;
                case FIELD_TYPE_LONG:
                    printf("LONG\n");
                    break;
                default:
                    printf("Type is %d, check in mysql_com.h\n", field_ptr->type);
            } /* switch */
        } /* else */
    }

    printf("\t Max width %ld\n", field_ptr->length);
    if (field_ptr->flags & AUTO_INCREMENT_FLAG)
        printf("\t Auto increments\n");
    printf("\n");
} /* while */
}

void display_row() {
    unsigned int field_count;

    field_count = 0;
    while (field_count < mysql_field_count(&my_connection)) {
        if (sqlrow[field_count]) printf("%s ", sqlrow[field_count]);
        else printf("NULL");
        field_count++;
    }
    printf("\n");
}

```

When we compile and run this program, the output we get is

```

$ ./select4
Connection success
Column details:
    Name: childno
    Type: Numeric field
    Max width 11
    Auto increments

```

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```
Name: fname  
Type: VARCHAR  
Max width 30  
  
Name: age  
Type: Numeric field  
Max width 11  
Column details:  
1 Jenny 17  
2 Andrew 13  
$
```

It's still not very pretty; but it illustrates nicely how we can process both raw data and the metadata that allows us to work more efficiently with our data.

There are other functions that allow you to retrieve arrays of fields and jump between columns. Generally all you need are the routines shown here; the interested reader can find more information in the MySQL manual.

Miscellaneous Functions

There are some additional API functions, shown in the following table, that we recommend you investigate. Generally, what's been discussed so far is enough for a functional program; however, you should find this partial listing useful.

| API Call | Example | What It Does |
|------------------------------------|--|--|
| <code>mysql_get_client_info</code> | <code>char *mysql_get_client_info(void);</code> | Returns version information about the library that the client is using. |
| <code>mysql_get_host_info</code> | <code>char *mysql_get_host_info(MYSQL *connection);</code> | Returns server connection information. |
| <code>mysql_get_server_info</code> | <code>char *mysql_get_server_info(MYSQL *connection);</code> | Returns information about the server that you are currently connected to. |
| <code>mysql_info</code> | <code>char *mysql_info(MYSQL *connection); ..</code> | Returns information about the most recently executed query, but works for only a few query types—generally INSERT and UPDATE statements. Otherwise returns NULL. |
| <code>mysql_select_db</code> | <code>int mysql_select_db(MYSQL *connection, const char *dbname);</code> | Changes the default database to the one given as a parameter, provided that the user has appropriate permissions. On success, zero is returned. |
| <code>mysql_shutdown</code> | <code>int mysql_shutdown(MYSQL *connection);</code> | If you have appropriate permissions, shuts down the database server you are connected to. On success, zero is returned. |

The CD Database Application

We are now going to see how we might create a simple database to store information about your CDs and then write some code to access that data. We are going to keep things very simple, so that it's reasonably easy to understand. In particular, we are going to stick to just three database tables with a very simple relationship among them.

We start by creating a new database to use and then make it the current database:

```
mysql> create database blpcd;
Query OK, 1 row affected (0.00 sec)

mysql> use blpcd
Connection id:      10
Current database:  blpcd

mysql>
```

Now we're ready to design and create the tables you need.

This example will be slightly more sophisticated than before, in that we'll separate three distinct elements of a CD: the artist (or group), the main catalog entry, and the tracks. If you think about a CD collection and what elements it comprises, you realize that each CD is composed of a number of different tracks, but different CDs are related to each other in many ways: by the performer or group, by the company that produced it, by the music style portrayed, and so on.

We could make our database quite complex, attempting to store all these different elements in a flexible way; however, we will restrict ourselves to just the two most important relationships.

First, each CD is composed of a variable number of tracks, so we will store the track data in a table separate from the other CD data. Second, each artist (or band) will often have more than one album, so it would be useful to store the details of the artist once and then separately retrieve all the CDs the artist has made. We will not attempt to break down bands into different artists who may themselves have made solo albums, or deal with compilation CDs—we are trying to keep this simple!

We will keep the relationships quite simple as well—each artist (which might be the name of a band) will have produced one or more CDs and each CD will be composed of one or more tracks. The relationships are illustrated in Figure 8-7.

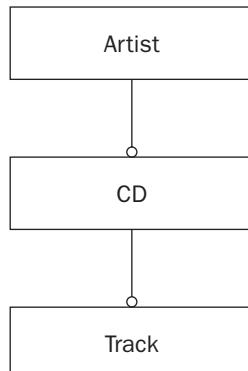


Figure 8-7

Creating the Tables

Now we need to determine the actual structure of the tables. We'll start with the main table—the CD table—which stores most of the information. We will need to store a CD ID, a catalog number, a title, and perhaps some of our own notes. We will also need an ID number from the artist table to tell us which artist made the album.

The artist table is quite simple; we will just store an artist name and a unique artist ID number. The track table is also very simple; we just need a CD ID to tell us which CD the track relates to, a track number, and the title of the track.

The CD table first:

```
CREATE TABLE cd (
    id INTEGER AUTO_INCREMENT NOT NULL PRIMARY KEY,
    title VARCHAR(70) NOT NULL,
    artist_id INTEGER NOT NULL,
    catalogue VARCHAR(30) NOT NULL,
    notes VARCHAR(100)
);
```

This creates a table called `cd` with the following columns:

- An `id` column, containing an integer that autoincrements and is the primary key for the table
- A `title` up to 70 characters long
- `artist_id`, an integer that we will use in our artist table
- A `catalogue` number of up to 30 characters
- Up to 100 characters of `notes`

Notice that only the `notes` column may be `NULL`; all the others must have values.

Now the artist table:

```
CREATE TABLE artist (
    id INTEGER AUTO_INCREMENT NOT NULL PRIMARY KEY,
    name VARCHAR(100) NOT NULL
);
```

Again we have an `id` column and one other column for the artist name.

Finally, the track table:

```
CREATE TABLE track (
    cd_id INTEGER NOT NULL,
    track_id INTEGER NOT NULL,
    title VARCHAR(70),
    PRIMARY KEY(cd_id, track_id)
);
```

Notice that this time we declare the primary key rather differently. The track table is unusual in that the ID for each CD will appear several times, and the ID for any given track, say track one, will also appear several times for different CDs. However, the combination of the two will always be unique, so we declare our primary key to be a combination of the two columns. This is called a composite key, because it comprises more than one column taken in combination.

Store this SQL in a file called `create_table.sql`, save it in the current directory, and then go ahead and create a database and then these tables in it. The sample script provided also drops these tables if they already exist.

```
$ mysql -u rick -p
Enter password:
Welcome to the MySQL monitor. Commands end with ; or \g.
Your MySQL connection id is 50
Type 'help;' or '\h' for help. Type '\c' to clear the buffer.

mysql> use blpcd;
Database changed
mysql> \. create_tables.sql
Query OK, 0 rows affected (0.04 sec)

Query OK, 0 rows affected (0.10 sec)

Query OK, 0 rows affected (0.00 sec)

mysql>
```

Notice that we use the `\.` command to take input from the `create_tables.sql` file as input. If this is the first time you have run the script and you are using the version downloaded from the Web site, you may see some errors about “Unknown table XXX,” as the provided script starts by deleting any pre-existing tables. This means we can use the script, regardless of any existing tables of the same name.

We could just have well have created the tables by executing the SQL inside MySQLCC or by using the edit functionality in MySQLCC. We can go back into MySQLCC and see the database and tables we have created:

Do you notice the two key symbols against the `cd_id` and `track_id` columns in Figure 8-8? This shows us that they are both contributing to the composite primary key. Allowing the track title to be NULL allows for the uncommon but not unseen occurrence of a CD track that has no title.

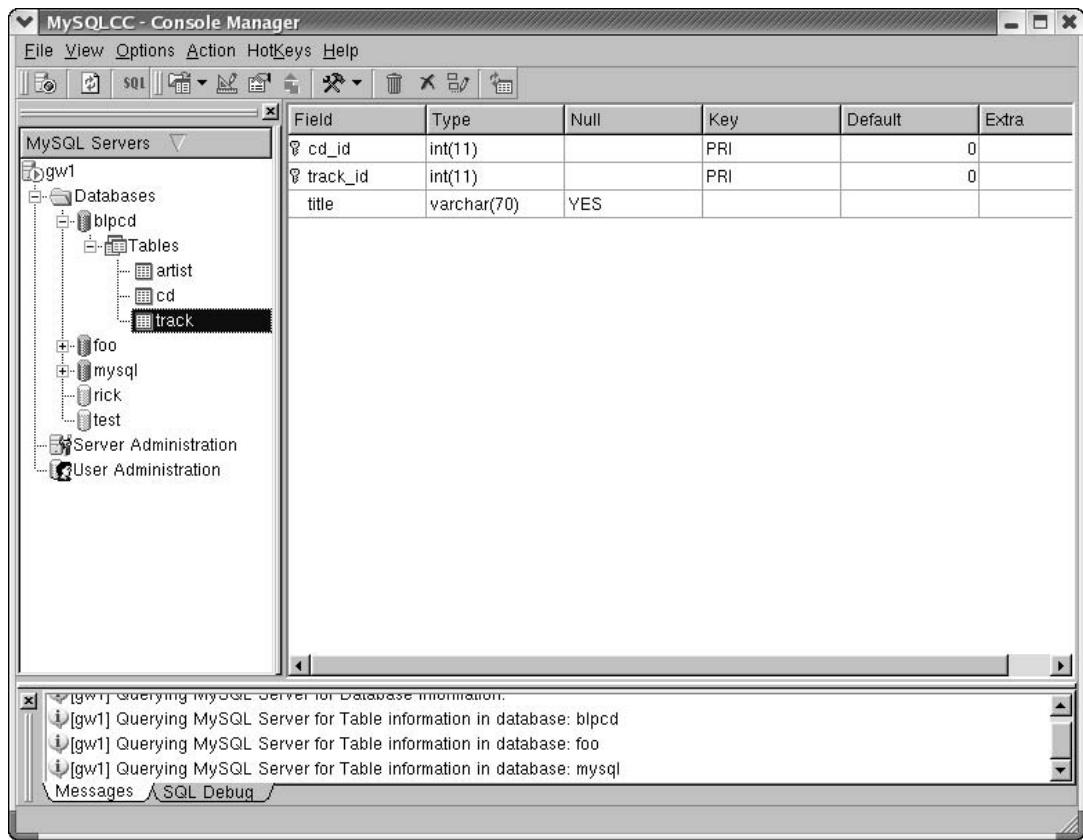


Figure 8-8

Adding Some Data

Now we need to add some data. The best way of checking any database design is to add some sample data and check that it all works.

We will just show a sample of the test import data here, as it's not critical to understanding what is happening because all the imports are basically similar—they just load different tables. There are two important points to note here:

- ❑ The script deletes any existing data to ensure the script starts from a clean position.
- ❑ Insert values into the ID fields rather than allowing the AUTO_INCREMENT to take place. It's safer to do this here because the different inserts need to know which values have been used to ensure that the data relationships are all correct, so it's better to force the values, rather than allow the AUTO_INCREMENT function to automatically allocate values.

This file is called `insert_data.sql` and can be executed using the `\.` command we saw before.

```

--- Delete existing data
delete from track;
delete from cd;
delete from artist;

-- Now the data inserts

--- First the artist (or group) tables
insert into artist(id, name) values(1, 'Pink Floyd');
insert into artist(id, name) values(2, 'Genesis');
insert into artist(id, name) values(3, 'Einaudi');
insert into artist(id, name) values(4, 'Melanie C');

--- Then the cd table
insert into cd(id, title, artist_id, catalogue) values(1, 'Dark Side of the Moon',
1, 'B000024D4P');
insert into cd(id, title, artist_id, catalogue) values(2, 'Wish You Were Here', 1,
'B000024D4S');
insert into cd(id, title, artist_id, catalogue) values(3, 'A Trick of the Tail', 2,
'B000024EXM');
insert into cd(id, title, artist_id, catalogue) values(4, 'Selling England By the
Pound', 2, 'B000024E9M');
insert into cd(id, title, artist_id, catalogue) values(5, 'I Giorni', 3,
'B000071WEV');
insert into cd(id, title, artist_id, catalogue) values(6, 'Northern Star', 4,
'B00004YMST');

--- populate the tracks
insert into track(cd_id, track_id, title) values(1, 1, 'Speak to me');
insert into track(cd_id, track_id, title) values(1, 2, 'Breathe');

```

and the rest of the tracks for this album, and then the next album:

```

insert into track(cd_id, track_id, title) values(2, 1, 'Shine on you crazy
diamond');
insert into track(cd_id, track_id, title) values(2, 2, 'Welcome to the machine');
insert into track(cd_id, track_id, title) values(2, 3, 'Have a cigar');
insert into track(cd_id, track_id, title) values(2, 4, 'Wish you were here');
insert into track(cd_id, track_id, title) values(2, 5, 'Shine on you crazy diamond
pt.2');

```

and so on...

```

insert into track(cd_id, track_id, title) values(4, 1, 'Melodia Africana (part
1)');
insert into track(cd_id, track_id, title) values(4, 2, 'I due fiumi');
insert into track(cd_id, track_id, title) values(4, 3, 'In un\'altra vita');

```

... until the final tracks:

```

insert into track(cd_id, track_id, title) values(6, 11, 'Closer');
insert into track(cd_id, track_id, title) values(6, 12, 'Feel The Sun');

```

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Next save this in `pop_tables.sql` and execute it from the `mysql` prompt using the `\.` command, as before.

Notice that in cd 4 (*I Giorni*) track 3, the track is “In un’altra vita” with an apostrophe. To insert this into the database we must use a backslash (\) to quote the apostrophe.

Try It Out

Now would be a good time to check that your data is looking reasonable. We can use the `mysql` command line client and some SQL to check that the data is looking reasonable. We start by selecting the first two tracks from every album in our database:

```
SELECT artist.name, cd.title AS "CD Title", track.track_id, track.title AS  
"Track" FROM artist, cd, track WHERE artist.id = cd.artist_id AND track.cd_id  
= cd.id AND track.track_id < 3
```

If we try this in MySQLCC, you can see that the data looks fine, as shown in Figure 8-9.

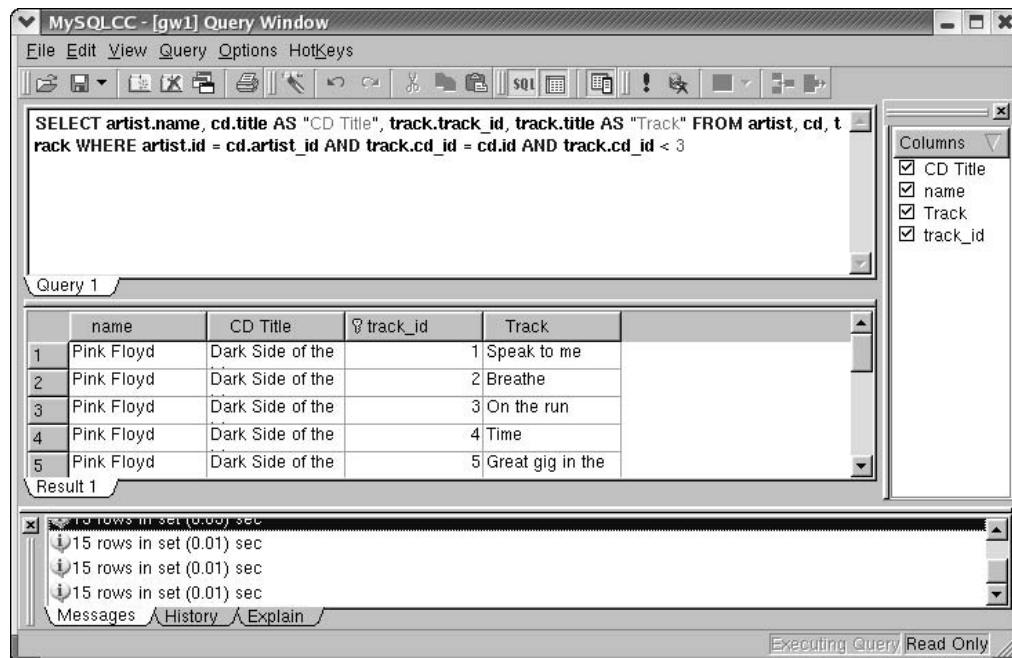


Figure 8-9

How It Works

The SQL looks complex, but it's not so bad if you take it a piece at a time.

Ignoring the `AS` parts of the `SELECT` command for a moment, the first part is simply this:

```
SELECT artist.name, cd.title, track.track_id, track.title
```

This simply tells us which columns we want displayed, using the notation `tablename.column name`.

The AS parts of the SELECT statement, `SELECT artist.name, cd.title AS "CD Title", track.track_id, and track.title AS "Track"`, simply rename the columns in the displayed output. Hence the header column for title from the cd table (`cd.title`) is named “CD Title,” and the `track.track.id` column is titled “Track.” This use of AS gives us more user-friendly output. You would almost never use these names when calling SQL from another language, but AS is a useful clause for working with SQL on the command line.

The next section is also straightforward; it tells the server the name of the tables we are using:

```
FROM artist, cd, track
```

The WHERE clause is the slightly tricky part:

```
WHERE artist.id = cd.artist_id AND track.cd_id = cd.id AND track.track_id < 3
```

The first part tells the server that the ID in the artist’s table is the same number as the `artist_id` in the `cd` column. Remember that we store the artist’s name only once and use an ID to refer to it in the CD table. The next section, `track.cd_id = cd.id`, does the same for the tables `track` and `cd`, telling the server that the track table’s `cd_id` column is the same as the `id` column in the `cd` table. The third section, `track.track_id < 3`, cuts down the amount of data returned so that we get only tracks 1 and 2 from each CD. Last, but not least, we join these three conditions together using AND because we want all three conditions to be true.

Accessing the Application Data from C

We are not going to write a complete application with a GUI in this chapter; rather, we are going to concentrate on writing an interface file to allow us to access our data from C in reasonably simple fashion. A common problem in writing code like this is the unknown number of results that can be returned and how to pass them between the client code and the code that accesses the database. In this application, to keep it simple and focus on the database interface—which is the important part of the code—we are going to use fixed-size structures. In a real application this may not be acceptable. A common solution, which also helps the network traffic, is to always retrieve the data one row at a time, as we saw earlier in the chapter with the functions `mysql_use_result` and `mysql_fetch_row`.

Interface Definition

Start with a header file that defines your structures and functions, named `app_mysql.h`:

First, some structures:

```
/* A simplistic structure to represent the current CD, excluding the track
information */
struct current_cd_st {
    int artist_id;
    int cd_id;
    char artist_name[100];
    char title[100];
    char catalogue[100];
};

/* A simplistic track details structure */
struct current_tracks_st {
    int cd_id;
```

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```
    char track[20][100];
};

#define MAX_CD_RESULT 10
struct cd_search_st {
    int cd_id[MAX_CD_RESULT];
};
```

Now a pair of functions for connecting and disconnecting from the database:

```
/* Database backend functions */
int database_start(char *name, char *password);
void database_end();
```

Now we turn to the functions for manipulating the data. Notice that there are no functions for creating or deleting artists. We are going to implement this behind the scenes, creating artist entries as required and then deleting them when they are no longer in use by any album.

```
/* Functions for adding a CD */
int add_cd(char *artist, char *title, char *catalogue, int *cd_id);
int add_tracks(struct current_tracks_st *tracks);
/* Functions for finding and retrieving a CD */
int find_cds(char *search_str, struct cd_search_st *results);
int get_cd(int cd_id, struct current_cd_st *dest);
int get_cd_tracks(int cd_id, struct current_tracks_st *dest);
/* Function for deleting items */
int delete_cd(int cd_id);
```

We have made our search function fairly general: We pass a string and it searches for that string in the artist, title, or catalogue entries.

Test Application Interface

Before we implement our interface, we're going to write some code to use it. This might seem a little odd, but often it is a good way of understanding how the interface should behave in detail, before we settle down to implement it.

This is `app_test.c`. First some includes and structs:

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

#include "app_mysql.h"

int main() {
    struct current_cd_st cd;
    struct cd_search_st cd_res;
    struct current_tracks_st ct;
    int cd_id;
    int res, i;
```

The first thing our application must always do is initialize a database connection, providing a valid user name and password:

```
database_start("rick", "foobar");
```

Then we test adding a CD:

```
res = add_cd("Mahler", "Symphony No 1", "4596102", &cd_id);
printf("Result of adding a cd was %d, cd_id is %d\n", res, cd_id);

memset(&ct, 0, sizeof(ct));
ct.cd_id = cd_id;
strcpy(ct.track[0], "Langsam Schleppend");
strcpy(ct.track[1], "Kraftig bewegt");
strcpy(ct.track[2], "Feierlich und gemessen");
strcpy(ct.track[3], "Sturmisch bewegt");
add_tracks(&ct);
```

Now search for the CD and retrieve information from the first CD found:

```
res = find_cds("Symphony", &cd_res);
printf("Found %d cds, first has ID %d\n", res, cd_res.cd_id[0]);

res = get_cd(cd_res.cd_id[0], &cd);
printf("get_cd returned %d\n", res);

memset(&ct, 0, sizeof(ct));
res = get_cd_tracks(cd_res.cd_id[0], &ct);
printf("get_cd_tracks returned %d\n", res);
printf("Title: %s\n", cd.title);
i = 0;
while (i < res) {
    printf("\ttrack %d is %s\n", i, ct.track[i]);
    i++;
}
```

Finally, we delete the CD:

```
res = delete_cd(cd_res.cd_id[0]);
printf("Delete_cd returned %d\n", res);
```

Then we disconnect and exit:

```
database_end();

return EXIT_SUCCESS;

}
```

Implementing the Interface

Now comes the harder part: implementing the interface we specified. This is all in the file `app_mysql.c`.

We start with some basic includes, the global connection structure we will need, and a flag, `dbconnected`, that we will use to ensure applications don't try to access data unless they have a connection. We also use an internal function, `get_artist_id`, to improve the structure of our code.

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

#include "mysql.h"
#include "app_mysql.h"

static MYSQL my_connection;
static int dbconnected = 0;

static int get_artist_id(char *artist);
```

Getting a connection to the database is very simple, as we saw earlier in the chapter, and disconnecting again even easier:

```
int database_start(char *name, char *pwd) {

    if (dbconnected) return 1;

    mysql_init(&my_connection);
    if (!mysql_real_connect(&my_connection, "localhost", name, pwd, "blpcd", 0,
                           NULL, 0)) {
        fprintf(stderr, "Database connection failure: %d, %s\n",
                mysql_errno(&my_connection), mysql_error(&my_connection));
        return 0;
    }
    dbconnected = 1;
    return 1;
} /* database start */

void database_end() {
    if (dbconnected) mysql_close(&my_connection);
    dbconnected = 0;
} /* database_end */
```

Now the real work begins, with the function `add_cd`. We'll give you some declarations first as well as a sanity check to ensure that we're connected to the database. We will see this in all the externally accessible functions we write.

Remember we said that we would take care of artist names automatically:

```
int add_cd(char *artist, char *title, char *catalogue, int *cd_id) {

    MYSQL_RES *res_ptr;
    MYSQL_ROW mysqlrow;

    int res;
    char is[100];
    char es[100];
    int artist_id = -1;
    int new_cd_id = -1;

    if (!dbconnected) return 0;
```

The next thing we do is to check if the artist already exists; if not, we create one. This is all taken care of in the function `get_artist_id`, which we will see shortly.

```
artist_id = get_artist_id(artist);
```

Now having got an `artist_id`, we can insert the main CD record. Notice that we use `mysql_escape_string` to protect any special characters in the title of the CD.

```
mysql_escape_string(es, title, strlen(title));
sprintf(is, "INSERT INTO cd(title, artist_id, catalogue) VALUES ('%s', %d, '%s')",
es, artist_id, catalogue);
res = mysql_query(&my_connection, is);
if (res) {
    fprintf(stderr, "Insert error %d: %s\n", mysql_errno(&my_connection),
mysql_error(&my_connection));
    return 0;
}
```

When we come to add the tracks for this CD, we will need to know the ID that was used when the CD record was inserted. We made the field an auto-increment field, so the database has automatically assigned an ID for us, but we need to explicitly retrieve the value. We do this with the special function `LAST_INSERT_ID`, as we saw earlier in the chapter:

```
res = mysql_query(&my_connection, "SELECT LAST_INSERT_ID()");
if (res) {
    printf("SELECT error: %s\n", mysql_error(&my_connection));
    return 0;
} else {
    res_ptr = mysql_use_result(&my_connection);
    if (res_ptr) {
        if ((mysqlrow = mysql_fetch_row(res_ptr))) {
            sscanf(mysqlrow[0], "%d", &new_cd_id);
        }
        mysql_free_result(res_ptr);
    }
}
```

We don't need to worry about other clients inserting CDs at the same time and the IDs becoming messed up; MySQL keeps track of the ID assigned on a per-client connection basis, so even if another application inserted a CD before we retrieved the ID, we would still get the ID corresponding to our row, not the row inserted by the other application.

Last, but not least, we set the ID of the newly added row and return success or failure:

```
*cd_id = new_cd_id;
if (new_cd_id != -1) return 1;
return 0;
}
/* add_cd */
```

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Now let's look at the implementation of `get_artist_id`; the process is very similar to inserting a CD record:

```
/* Find or create an artist_id for the given string */
static int get_artist_id(char *artist) {
    MYSQL_RES *res_ptr;
    MYSQL_ROW mysqlrow;

    int res;
    char qs[100];
    char is[100];
    char es[100];
    int artist_id = -1;

    /* Does it already exist? */
    mysql_escape_string(es, artist, strlen(artist));
    sprintf(qs, "SELECT id FROM artist WHERE name = '%s'", es);

    res = mysql_query(&my_connection, qs);
    if (res) {
        fprintf(stderr, "SELECT error: %s\n", mysql_error(&my_connection));
    } else {
        res_ptr = mysql_store_result(&my_connection);
        if (res_ptr) {
            if (mysql_num_rows(res_ptr) > 0) {
                if (mysqlrow = mysql_fetch_row(res_ptr)) {
                    sscanf(mysqlrow[0], "%d", &artist_id);
                }
            }
            mysql_free_result(res_ptr);
        }
    }
    if (artist_id != -1) return artist_id;

    sprintf(is, "INSERT INTO artist(name) VALUES('%s')", es);
    res = mysql_query(&my_connection, is);
    if (res) {
        fprintf(stderr, "Insert error %d: %s\n", mysql_errno(&my_connection),
                mysql_error(&my_connection));
        return 0;
    }
    res = mysql_query(&my_connection, "SELECT LAST_INSERT_ID()");
    if (res) {
        printf("SELECT error: %s\n", mysql_error(&my_connection));
        return 0;
    } else {
        res_ptr = mysql_use_result(&my_connection);
        if (res_ptr) {
            if ((mysqlrow = mysql_fetch_row(res_ptr))) {
                sscanf(mysqlrow[0], "%d", &artist_id);
            }
            mysql_free_result(res_ptr);
        }
    }
    return artist_id;
} /* get_artist_id */
```

Now we move on to adding the track information for our CD. Again we protect against special characters in the track titles:

```
int add_tracks(struct current_tracks_st *tracks) {

    int res;
    char is[100];
    char es[100];
    int i;

    if (!dbconnected) return 0;

    i = 0;
    while (tracks->track[i][0]) {
        mysql_escape_string(es, tracks->track[i], strlen(tracks->track[i]));
        sprintf(is, "INSERT INTO track(cd_id, track_id, title) VALUES(%d, %d, '%s')",
        tracks->cd_id, i + 1, es);
        res = mysql_query(&my_connection, is);
        if (res) {
            fprintf(stderr, "Insert error %d: %s\n", mysql_errno(&my_connection),
            mysql_error(&my_connection));
            return 0;
        }
        i++;
    }
    return 1;
} /* add_tracks */
```

Now we move on to retrieving information about a CD, given a CD ID value. We will use a database join to retrieve the artist ID at the same time as we retrieve the CD information. This is generally good practice: Databases are good at knowing how to perform complex queries efficiently, so never write application code to do work that you could simply have asked the database to do by passing it SQL. Chances are that you can save yourself effort, by not writing extra code, and have your application execute more efficiently, by allowing the database to do as much of the hard work as possible.

```
int get_cd(int cd_id, struct current_cd_st *dest) {
    MYSQL_RES *res_ptr;
    MYSQL_ROW mysqlrow;

    int res;
    char qs[100];

    if (!dbconnected) return 0;
    memset(dest, 0, sizeof(*dest));
    dest->artist_id = -1;

    sprintf(qs, "SELECT artist.id, cd.id, artist.name, cd.title, cd.catalogue FROM
    artist, cd WHERE artist.id = cd.artist_id and cd.id = %d", cd_id);

    res = mysql_query(&my_connection, qs);
    if (res) {
        fprintf(stderr, "SELECT error: %s\n", mysql_error(&my_connection));
    } else {
```

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```
res_ptr = mysql_store_result(&my_connection);
if (res_ptr) {
    if (mysql_num_rows(res_ptr) > 0) {
        if (mysqlrow = mysql_fetch_row(res_ptr)) {
            sscanf(mysqlrow[0], "%d", &dest->artist_id);
            sscanf(mysqlrow[1], "%d", &dest->cd_id);
            strcpy(dest->artist_name, mysqlrow[2]);
            strcpy(dest->title, mysqlrow[3]);
            strcpy(dest->catalogue, mysqlrow[4]);
        }
    }
    mysql_free_result(res_ptr);
}
if (dest->artist_id != -1) return 1;
return 0;
} /* get_cd */
```

Now we implement the retrieval of track information. Notice that we specify an `ORDER BY` clause in our SQL to ensure that tracks are returned in a sensible order. Again, this allows the database to do the work, which it will do much more efficiently than if we retrieved the rows in any order and then wrote our own code to sort them.

```
int get_cd_tracks(int cd_id, struct current_tracks_st *dest) {
    MYSQL_RES *res_ptr;
    MYSQL_ROW mysqlrow;

    int res;
    char qs[100];
    int i = 0, num_tracks = 0;

    if (!dbconnected) return 0;
    memset(dest, 0, sizeof(*dest));
    dest->cd_id = -1;

    sprintf(qs, "SELECT track_id, title FROM track WHERE track.cd_id = %d ORDER BY
track_id", cd_id);

    res = mysql_query(&my_connection, qs);
    if (res) {
        fprintf(stderr, "SELECT error: %s\n", mysql_error(&my_connection));
    } else {
        res_ptr = mysql_store_result(&my_connection);
        if (res_ptr) {
            if ((num_tracks = mysql_num_rows(res_ptr)) > 0) {
                while (mysqlrow = mysql_fetch_row(res_ptr)) {
                    strcpy(dest->track[i], mysqlrow[1]);
                    i++;
                }
                dest->cd_id = cd_id;
            }
            mysql_free_result(res_ptr);
        }
    }
    return num_tracks;
} /* get_cd_tracks */
```

So far, we have added and retrieved information about CDs; now it's time to search for CDs. We kept our interface simple by limiting the number of results that could be returned, but we still want our function to tell us how many rows there were, even if that's more results than we can retrieve.

```
int find_cds(char *search_str, struct cd_search_st *dest) {
    MYSQL_RES *res_ptr;
    MYSQL_ROW mysqlrow;

    int res;
    char qs[500];
    int i = 0;
    char ss[100];
    int num_rows;

    if (!dbconnected) return 0;
```

Now we clear the result structure and protect against special characters in the query string:

```
memset(dest, -1, sizeof(*dest));
mysql_escape_string(ss, search_str, strlen(search_str));
```

Next we build a query string. Notice the need to use rather a lot of % characters; this is because % is both the character we need to insert in the SQL to match any string and also a special character to sprintf.

```
sprintf(qs, "SELECT DISTINCT artist.id, cd.id FROM artist, cd WHERE artist.id =
cd.artist_id and (artist.name LIKE '%%%s%%' OR cd.title LIKE '%%%s%%' OR
cd.catalogue LIKE '%%%s%%')", ss, ss, ss);
```

Now we can execute the query:

```
res = mysql_query(&my_connection, qs);
if (res) {
    fprintf(stderr, "SELECT error: %s\n", mysql_error(&my_connection));
} else {
    res_ptr = mysql_store_result(&my_connection);
    if (res_ptr) {
        num_rows = mysql_num_rows(res_ptr);
        if (num_rows > 0) {
            while ((mysqlrow = mysql_fetch_row(res_ptr)) && i < MAX_CD_RESULT) {
                sscanf(mysqlrow[1], "%d", &dest->cd_id[i]);
                i++;
            }
        }
        mysql_free_result(res_ptr);
    }
}
return num_rows;
} /* find_cds */
```

Last, but not least, we implement a way of deleting CDs. In line with our policy of managing artist entries silently, we will delete the artist for this CD if no other CDs exist that have the same artist string.

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Curiously, SQL has no way of expressing deletes from multiple tables, so we must delete from each table in turn.

```
int delete_cd(int cd_id) {  
  
    int res;  
    char qs[100];  
    int artist_id, num_rows;  
    MYSQL_RES *res_ptr;  
    MYSQL_ROW mysqlrow;  
  
    if (!dbconnected) return 0;  
  
    artist_id = -1;  
    sprintf(qs, "SELECT artist_id FROM cd WHERE id = '%d'", cd_id);  
    res = mysql_query(&my_connection, qs);  
    if (res) {  
        fprintf(stderr, "SELECT error: %s\n", mysql_error(&my_connection));  
    } else {  
        res_ptr = mysql_store_result(&my_connection);  
        if (res_ptr) {  
            num_rows = mysql_num_rows(res_ptr);  
            if (num_rows == 1) {  
/* Artist not used by any other CDs */  
                mysqlrow = mysql_fetch_row(res_ptr);  
                sscanf(mysqlrow[0], "%d", &artist_id);  
            }  
        }  
    }  
  
    sprintf(qs, "DELETE FROM track WHERE cd_id = '%d'", cd_id);  
    res = mysql_query(&my_connection, qs);  
    if (res) {  
        fprintf(stderr, "Delete error (track) %d: %s\n", mysql_errno(&my_connection),  
mysql_error(&my_connection));  
        return 0;  
    }  
  
    sprintf(qs, "DELETE FROM cd WHERE id = '%d'", cd_id);  
    res = mysql_query(&my_connection, qs);  
    if (res) {  
        fprintf(stderr, "Delete error (cd) %d: %s\n", mysql_errno(&my_connection),  
mysql_error(&my_connection));  
        return 0;  
    }  
  
    if (artist_id != -1) {  
/* artist entry is now unrelated to any CDs, delete it */  
        sprintf(qs, "DELETE FROM artist WHERE id = '%d'", artist_id);  
        res = mysql_query(&my_connection, qs);  
        if (res) {  
    }
```

```
    fprintf(stderr, "Delete error (artist) %d: %s\n",
mysql_errno(&my_connection), mysql_error(&my_connection));
}

return 1;
} /* delete_cd */
```

That completes our code.

For the sake of completeness, we add a makefile to make your life easier. You may need to adjust the include path depending on how MySQL is installed on your system.

```
all: app

app: app_mysql.c app_test.c app_mysql.h
    gcc -g -o app -I/usr/include/mysql app_mysql.c app_test.c -lmysqlclient
```

In later chapters, we will see this interface being used with a real GUI. For now, if you want to watch the database changing as the code executes, we suggest you step through the code in the `gdb` debugger in one window while watching the database data change in another. If you use MySQLCC, remember that you will need to refresh the data displays to see the data change.

Summary

In this chapter, we've looked briefly at MySQL. More experienced users, while likely to be pleased by its speedy performance, may feel disappointed by its limited feature set. MySQL is, on balance, a great database tool with minimal system requirements and an excellent tolerance for high query volumes.

You've learned the basics of installing MySQL and looked at the basic administration of a MySQL database using the client utilities. We examined its C API, one of several languages that can be used with MySQL. You've also learned some SQL in the process.

We hope this chapter has encouraged you to try using an SQL-based database for your data, and also to find out more about these powerful database management tools.

As a reminder, the main resource for MySQL is the MySQL home page at www.mysql.com. For more information on MySQL, check out *MySQL, 2nd Edition*, by Paul DuBois (Sams Publishing).

9

Development Tools

In this chapter, we'll look at some of the tools available for developing programs on Linux systems, some of which are also available for UNIX. In addition to the obvious necessities of compilers and debuggers, Linux provides a set of tools, each of which does a single job, and allows the developer to combine these tools in new and innovative ways. This is part of the UNIX philosophy Linux has inherited. Here, we'll look at a few of the more important tools and see some examples of their being used to solve problems, including

- ❑ The make command and makefiles
- ❑ Source code control using RCS and CVS
- ❑ Writing a manual page
- ❑ Distributing software using patch and tar
- ❑ Development environments

Problems of Multiple Source Files

When they're writing small programs, many people simply rebuild their application after edits by recompiling all the files. However, with larger programs, some problems with this simple approach become apparent. The time for the edit-compile-test cycle will grow. Even the most patient programmer will want to avoid recompiling all the files when only one file has been changed.

A potentially much more difficult problem arises when multiple header files are created and included in different source files. Suppose we have header files `a.h`, `b.h`, and `c.h`, and C source files `main.c`, `2.c`, and `3.c`. (We hope that you choose better names than these for real projects!) We could have the situation following situation.

```
/* main.c */  
#include "a.h"  
...  
/* 2.c */
```

```
#include "a.h"
#include "b.h"
...
/* 3.c */
#include "b.h"
#include "c.h"
...
```

If the programmer changes `c.h`, the files `main.c` and `2.c` don't need to be recompiled, since they don't *depend* on this header file. The file `3.c` does depend on `c.h` and should therefore be recompiled if `c.h` is changed. However, if `b.h` was changed and the programmer forgot to recompile `2.c`, the resulting program might no longer function correctly.

The `make` utility can solve both of these problems by ensuring that all the files affected by changes are recompiled when necessary.

The `make` command is not used only to compile programs. It can be used whenever you produce output files from several input files. Other uses include document processing (such as with troff or TeX).

The `make` Command and Makefiles

Although, as we shall see, the `make` command has a lot of built-in knowledge, it can't know how to build your application all by itself. You must provide a file that tells `make` how your application is constructed. This file is called the *makefile*.

The makefile most often resides in the same directory as the other source files for the project. You can have many different makefiles on your machine at any one time. Indeed, if you have a large project, you may choose to manage it using separate makefiles for different parts of the project.

The combination of the `make` command and a makefile provides a very powerful tool for managing projects. It's often used not only to control the compilation of source code, but also to prepare manual pages and to install the application into a target directory.

The Syntax of Makefiles

A makefile consists of a set of dependencies and rules. A *dependency* has a target (a file to be created) and a set of source files upon which it is dependent. The *rules* describe how to create the target from the dependent files. Typically, the *target* is a single executable file.

The makefile is read by the `make` command, which determines the target file or files that are to be made and then compares the dates and times of the source files to decide which rules need to be invoked to construct the target. Often, other intermediate targets have to be created before the final target can be made. The `make` command uses the makefile to determine the order in which the targets have to be made and the correct sequence of rules to invoke.

Options and Parameters to make

The `make` program itself has several options. The three most commonly used are

- `-k`, which tells `make` to keep going when an error is found, rather than stopping as soon as the first problem is detected. You can use this, for example, to find out in one go which source files fail to compile.
- `-n`, which tells `make` to print out what it would have done without actually doing it.
- `-f <filename>`, which allows you to tell `make` which file to use as its `makefile`. If you don't use this option, `make` looks first for a file called `makefile` in the current directory. If that doesn't exist, it looks for a file called `Makefile`. By convention, many Linux programmers use `Makefile`. This allows the `makefile` to appear first in a directory listing of a directory filled with lowercase-named files.

To tell `make` to build a particular target, which is usually an executable file, you can pass the target name to `make` as a parameter. If you don't, `make` will try to make the first target listed in the `makefile`. Many programmers specify `all` as the first target in their `makefile` and then list the other targets as being dependencies for `all`. This convention makes it clear which target the `makefile` should attempt to build by default when no target is specified. We suggest you stick to this convention.

Dependencies

The dependencies specify how each file in the final application relates to the source files. In our programming example shown earlier in the chapter, we might specify dependencies that say our final application requires (depends on) `main.o`, `2.o`, and `3.o`; and likewise for `main.o` (`main.c` and `a.h`); `2.o` (`2.c`, `a.h`, and `b.h`); and `3.o` (`3.c`, `b.h`, and `c.h`). Thus `main.o` is affected by changes to `main.c` and `a.h`, and it needs to be recreated by recompiling `main.c` if either of these two files changes.

In a `makefile`, we write these rules by writing the name of the target, a colon, spaces or tabs, and then a space- or tab-separated list of files that are used to create the target file. The dependency list for our example is

```
myapp: main.o 2.o 3.o
main.o: main.c a.h
2.o: 2.c a.h b.h
3.o: 3.c b.h c.h
```

This says that `myapp` depends on `main.o`, `2.o`, and `3.o`, `main.o` depends on `main.c` and `a.h`, and so on.

This set of dependencies gives a hierarchy showing how the source files relate to one other. We can see quite easily that, if `b.h` changes, then we need to revise both `2.o` and `3.o`, and since `2.o` and `3.o` will have changed, we also need to rebuild `myapp`.

If we wish to make several files, then we can use the phony target `all`. Suppose our application consisted of both the binary file `myapp` and a manual page, `myapp.1`. We could specify this with the line

```
all: myapp myapp.1
```

Again, if we don't specify an `all` target, `make` simply creates the first target it finds in the `makefile`.

Rules

The second part of the makefile specifies the rules that describe how to create a target. In our example in the previous section, what command should be used after the `make` command has determined that `2.o` needs rebuilding? It may be that simply using `gcc -c 2.c` is sufficient (and, as we'll see later, `make` does indeed know many default rules), but what if we needed to specify an `include` directory, or set the symbolic information option for later debugging? We can do this by specifying explicit rules in the makefile.

At this point, we have to clue you in to a very strange and unfortunate syntax of makefiles: the difference between a space and a tab. All rules must be on lines that start with a tab; a space won't do. Since several spaces and a tab look much the same and because almost everywhere else in Linux programming there's little distinction between spaces and tabs, this can cause problems. Also, a space at the end of a line in the makefile may cause a `make` command to fail. However, it's an accident of history and there are far too many makefiles in existence to contemplate changing it now, so take care! Fortunately, it's usually reasonably obvious when the `make` command isn't working because a tab is missing.

Try It Out—A Simple Makefile

Most rules consist of a simple command that could have been typed on the command line. For our example, we will create our first makefile, `Makefile1`:

```
myapp: main.o 2.o 3.o
    gcc -o myapp main.o 2.o 3.o
main.o: main.c a.h
    gcc -c main.c
2.o: 2.c a.h b.h
    gcc -c 2.c
3.o: 3.c b.h c.h
    gcc -c 3.c
```

We invoke the `make` command with the `-f` option because our makefile doesn't have either of the usual default names of `makefile` or `Makefile`. If we invoke this code in a directory containing no source code, we get this message:

```
$ make -f Makefile1
make: *** No rule to make target 'main.c', needed by 'main.o'. Stop.
$
```

The `make` command has assumed that the first target in the makefile, `myapp`, is the file that we wish to create. It has then looked at the other dependencies and, in particular, has determined that a file called `main.c` is needed. Since we haven't created this file yet and the makefile does not say how it might be created, `make` has reported an error. Let's create the source files and try again. Since we're not interested in the result, these files can be very simple. The header files are actually empty, so we can create them with `touch`.

```
$ touch a.h
$ touch b.h
$ touch c.h
```

`main.c` contains `main`, which calls `function_two` and `function_three`. The other two files define `function_two` and `function_three`. The source files have `#include` lines for the appropriate headers, so they appear to be dependent on the contents of the included headers. It's not much of an application, but here are the listings:

```
/* main.c */
#include <stdlib.h>
#include "a.h"
extern void function_two();
extern void function_three();
int main()
{
    function_two();
    function_three();
    exit (EXIT_SUCCESS);
}
/* 2.c */
#include "a.h"
#include "b.h"
void function_two() {
}
/* 3.c */
#include "b.h"
#include "c.h"
void function_three() {
}
```

Now let's try `make` again:

```
$ make -f Makefile1
gcc -c main.c
gcc -c 2.c
gcc -c 3.c
gcc -o myapp main.o 2.o 3.o
$
```

This is a successful `make`.

How It Works

The `make` command has processed the dependencies section of the `makefile` and determined the files that need to be created and in which order. Even though we listed how to create `myapp` first, `make` has determined the correct order for creating the files. It has then invoked the appropriate commands we gave it in the rules section for creating those files. The `make` command displays the commands as it executes them. We can now test our `makefile` to see whether it handles changes to the file `b.h` correctly.

```
$ touch b.h
$ make -f Makefile1
gcc -c 2.c
gcc -c 3.c
gcc -o myapp main.o 2.o 3.o
$
```

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The `make` command has read our makefile, determined the minimum number of commands required to rebuild `myapp`, and carried them out in the correct order. Let's see what happens if we delete an object file:

```
$ rm 2.o
$ make -f Makefile1
gcc -c 2.c
gcc -o myapp main.o 2.o 3.o
$
```

Again, `make` correctly determines the actions required.

Comments in a Makefile

A comment in a makefile starts with `#` and continues to the end of the line. As in C source files, comments in a makefile can help both the author and others to understand what was intended when the file was written.

Macros in a Makefile

Even if this was all there was to `make` and makefiles, they would be powerful tools for managing multiple source file projects. However, they would also tend to be large and inflexible for projects consisting of a very large number of files. Makefiles therefore allow us to use macros so that we can write them in a more generalized form.

We define a macro in a makefile by writing `MACRONAME=value`, then accessing the value of `MACRONAME` by writing either `$ (MACRONAME)` or `$ {MACRONAME}`. Some versions of `make` may also accept `$MACRONAME`. We can set the value of a macro to blank (which expands to nothing) by leaving the rest of the line after the `=` blank.

Macros are often used in makefiles for options to the compiler. Often, while an application is being developed, it will be compiled with no optimization, but with debugging information included. For a release version the opposite is usually needed: a small binary with no debugging information that runs as fast as possible.

Another problem with `Makefile1` is that it assumes the compiler is called `gcc`. On other UNIX systems, we might be using `cc` or `c89`. If we ever wanted to take our makefile to a different version of UNIX, or even if we obtained a different compiler to use on our existing system, we would have to change several lines of our makefile to make it work. Macros are a good way of collecting all these system-dependent parts, making it easy to change them.

Macros are normally defined inside the makefile itself, but they can be specified by calling `make` with the macro definition, for example, `make CC=c89`. Command line definitions like this override `defines` in the makefile. When used outside makefiles, macro definitions must be passed as a single argument, so either avoid spaces or use quotes like this: `make "CC = c89"`.

Try It Out—A Makefile with Macros

Here's a revised version of our makefile, `Makefile2`, using some macros:

```
all: myapp
# Which compiler
```

```

CC = gcc
# Where are include files kept
INCLUDE =
# Options for development
CFLAGS = -g -Wall -ansi
# Options for release
# CFLAGS = -O -Wall -ansi
myapp: main.o 2.o 3.o
        $(CC) -o myapp main.o 2.o 3.o
main.o: main.c a.h
        $(CC) -I$(INCLUDE) $(CFLAGS) -c main.c
2.o: 2.c a.h b.h
        $(CC) -I$(INCLUDE) $(CFLAGS) -c 2.c
3.o: 3.c b.h c.h
        $(CC) -I$(INCLUDE) $(CFLAGS) -c 3.c

```

If we delete our old installation and create a new one with this new makefile, we get

```

$ rm *.o myapp
$ make -f Makefile2
gcc -I. -g -Wall -ansi -c main.c
gcc -I. -g -Wall -ansi -c 2.c
gcc -I. -g -Wall -ansi -c 3.c
gcc -o myapp main.o 2.o 3.o
$ 

```

How It Works

The `make` program replaces the `$(CC)`, `$(CFLAGS)`, and `$(INCLUDE)` with the appropriate definition, rather like the C compiler does with `#define`. Now if we want to change the compile command, we need to change only a single line of the makefile.

In fact, `make` has several special internal macros that you can use to make makefiles even more succinct. We list the more common ones in the following table; you will see them in use in later examples. Each of these macros is only expanded just before it's used, so the meaning of the macro may vary as the makefile progresses. In fact, these macros would be of very little use if they didn't work this way.

`$?` List of prerequisites changed more recently than the current target

`$@` Name of the current target

`$<` Name of the current prerequisite

`$*` Name of the current prerequisite, without any suffix

There are two other useful special characters you may see in makefile, preceding the command:

- ❑ `-` tells `make` to ignore any errors. For example, if you wanted to make a directory but wished to ignore any errors, perhaps because the directory might already exist, you just precede `mkdir` with a minus sign. We will see `-` in use a bit later in this chapter.
- ❑ `@` tells `make` not to print the command to standard output before executing it. This character is handy if you want to use `echo` to display some instructions.

Multiple Targets

It's often useful to make more than a single target file, or to collect several groups of commands into a single place. We can extend our makefile to do this. Let's add a "clean" option that removes unwanted objects and an "install" option that moves the finished application to a different directory.

Try It Out—Multiple Targets

Here's the next version of the makefile, `Makefile3`.

```
all: myapp
# Which compiler
CC = gcc

# Where to install
INSTDIR = /usr/local/bin
# Where are include files kept
INCLUDE = .

# Options for development
CFLAGS = -g -Wall -ansi
# Options for release
# CFLAGS = -O -Wall -ansi
myapp: main.o 2.o 3.o
    $(CC) -o myapp main.o 2.o 3.o
main.o: main.c a.h
    $(CC) -I$(INCLUDE) $(CFLAGS) -c main.c
2.o: 2.c a.h b.h
    $(CC) -I$(INCLUDE) $(CFLAGS) -c 2.c
3.o: 3.c b.h c.h
    $(CC) -I$(INCLUDE) $(CFLAGS) -c 3.c

clean:
    -rm main.o 2.o 3.o
install: myapp
@if [ -d $(INSTDIR) ]; \
then \
cp myapp $(INSTDIR); \
chmod a+x $(INSTDIR)/myapp; \
chmod og-w $(INSTDIR)/myapp; \
echo "Installed in $(INSTDIR)"; \
else \
echo "Sorry, $(INSTDIR) does not exist"; \
fi
```

There are several things to notice in this makefile. First, the special target `all` still specifies only `myapp` as a target. Thus, when we execute `make` without specifying a target, the default behavior is to build the target `myapp`.

The next important point concerns the two additional targets, `clean` and `install`. The `clean` target uses the `rm` command to remove the objects. The command starts with `-`, which tells `make` to ignore the result of the command, so `make clean` will succeed even if there are no objects and the `rm` command returns an error. The rules for making the target "clean" don't specify `clean` as depending on anything; the rest of the line after `clean:` is blank. Thus the target is always considered out of date, and its rule is always executed if `clean` is specified as a target.

The `install` target is dependent on `myapp`, so `make` knows that it must create `myapp` before carrying out other commands for making `install`. The rules for making `install` consist of some shell script commands. Since `make` invokes a shell for executing rules and uses a new shell for each rule, we must add backslashes so that all the script commands are on one logical line and are all passed together to a single invocation of the shell for execution. This command starts with an `@` sign, which tells `make` not to print the command on standard output before executing the rule.

The `install` target executes several commands one after the other to install the application in its final resting place. It does not check that each command succeeds before executing the next. If it was very important that subsequent commands executed only if the previous one had succeeded, then we could have written the commands joined by `&&`, like this:

```
@if [ -d $(INSTDIR) ] ; \
then \
cp myapp $(INSTDIR) && \
chmod a+x $(INSTDIR)/myapp && \
chmod og-w $(INSTDIR)/myapp && \
echo "Installed in $(INSTDIR)" ; \
else \
echo "Sorry, $(INSTDIR) does not exist" ; false ; \
fi
```

As you may remember from the Chapter 2, this is an “and” command to the shell and has the effect that each subsequent command gets executed only if the previous one succeeded. Here we don’t care too much about whether ensuring previous commands succeeded, so we stick to the simpler form.

You may not have permission as an ordinary user to install new commands in `/usr/local/bin`. You can either change the makefile to use a different install directory, change permissions on this directory, or change user (with the `su` command) to root before invoking `make install`.

```
$ rm *.o myapp
$ make -f Makefile3
gcc -I. -g -Wall -ansi -c main.c
gcc -I. -g -Wall -ansi -c 2.c
gcc -I. -g -Wall -ansi -c 3.c
gcc -o myapp main.o 2.o 3.o
$ make -f Makefile3
make: Nothing to be done for 'all'.
$ rm myapp
$ make -f Makefile3 install
gcc -o myapp main.o 2.o 3.o
Installed in /usr/local/bin
$ make -f Makefile3 clean
rm main.o 2.o 3.o
$
```

How It Works

First we delete `myapp` and all the objects. The `make` command on its own uses the target `all`, which causes `myapp` to be built. Next we run `make` again, but because `myapp` is up to date, `make` does nothing. We then delete the file `myapp` and do a `make install`. This recreates the binary and copies it to the `install` directory. Finally, we run `make clean`, which deletes the objects.

Built-in Rules

So far, we've specified in the makefile exactly how to perform each step of the process. In fact, `make` has a large number of built-in rules that can significantly simplify makefiles, particularly if we have many source files. Let's create `foo.c`, a traditional Hello World program.

```
#include <stdlib.h>
#include <stdio.h>
int main()
{
    printf("Hello World\n");
    exit(EXIT_SUCCESS);
}
```

Without specifying a makefile, we'll try to compile it using `make`.

```
$ make foo
cc      foo.c    -o foo
$
```

As we can see, `make` knows how to invoke the compiler, although, in this case, it chose `cc` rather than `gcc` (on Linux this is okay, as `cc` is usually a link to `gcc`). Sometimes, these built-in rules are referred to as *inference rules*. The default rules use macros, so by specifying some new values for the macros we can change the default behavior.

```
$ rm foo
$ make CC=gcc CFLAGS="-Wall -g" foo
gcc -Wall -g    foo.c    -o foo
$
```

We can ask `make` to print its built-in rules with the `-p` option. There are far too many built-in rules to list them all here, but here's a short extract from the output of `make -p` for the GNU version of `make`, showing part of the rules:

```
OUTPUT_OPTION = -o $@
COMPILE.c = $(CC) $(CFLAGS) $(CPPFLAGS) $(TARGET_ARCH) -c
%.o: %.c
# commands to execute (built-in):
$(COMPILE.c) $(OUTPUT_OPTION) $<
```

We can now simplify our makefile to take account of these built-in rules by taking out the rules for making objects and just specifying the dependencies, so the relevant section of the makefile reads simply

```
main.o: main.c a.h
2.o: 2.c a.h b.h
3.o: 3.c b.h c.h
```

You can find this version in the downloadable code as `Makefile4`.

Suffix and Pattern Rules

The built-in rules that we've seen work by using suffixes (similar to Windows and MS-DOS filename extensions), so that when it's given a file with one ending, `make` knows which rule can be used to create a file with a different ending. The most common rule here is the one used to create a file ending in `.o` from a file ending in `.c`. The rule is to use the compiler to compile but not to link the source file.

Sometimes we need to be able to create new rules. The authors used to work on source files that needed to be compiled by several different compilers: two under MS-DOS and `gcc` under Linux. To keep one of the MS-DOS compilers happy, the source files, which were C++ rather than C, needed to be named with a suffix of `.cpp`. Unfortunately, the version of `make` being used with Linux at the time didn't have a built-in rule for compiling `.cpp` files. (It did have a rule for `.cc`, a more common C++ file extension under UNIX.)

Thus either a rule had to be specified for each individual source file, or we needed to teach `make` a new rule for creating objects from files with the extension `.cpp`. Given that there were rather a large number of source files in this project, specifying a new rule saved a lot of typing and also made adding new source files to the project much easier.

To add a new suffix rule, we first add a line to the makefile telling `make` about the new suffix; we can then write a rule using this new suffix. `make` uses the special syntax

```
.<old_suffix>.<new_suffix>:
```

to define a general rule for creating files with the new suffix from files with the same base name but the old suffix.

Here's a fragment of our makefile with a new general rule for converting `.cpp` files to `.o` files:

```
.SUFFIXES:      .cpp
.cpp.o:
    $(CC) -xc++ $ (CFLAGS) -I$ (INCLUDE) -c $<
```

The special dependency `.cpp .o`: tells `make` that the rules that follow are for translating from a file with a suffix of `.cpp` to a file with a suffix of `.o`. We use special macro names when we write this dependency because we don't yet know the actual names of the files that we'll be translating. To understand this rule, you simply need to remember that `$<` is expanded to the starting filename (with the old suffix). Notice that we tell `make` how to get only from a `.cpp` to a `.o` file; `make` already knows how to get from an object file to a binary executable file.

When we invoke `make`, it uses our new rule to get from `bar.cpp` to `bar.o`, then uses its built-in rules to get from the `.o` to an executable file. The extra `-xc++` flag is to tell `gcc` that this is a C++ source file.

These days `make` knows how to deal with C++ source files with `.cpp` extensions, but the technique is a useful one when transforming from one kind of file to another.

More recent versions of `make` include an alternative syntax for achieving the same effect, and more besides. For example, pattern rules use a wildcard syntax for matching filenames rather than relying on filename extensions alone.

The pattern rule equivalent for the `.cpp` rule example above would be

```
% .cpp: %
    $(CC) -xc++ $(CFLAGS) -I$(INCLUDE) -c $<
```

Managing Libraries with make

When you're working on larger projects, it's often convenient to manage several compilation products using a *library*. Libraries are files, conventionally with the extension `.a` (for *archive*), that contain a collection of object files. The `make` command has a special syntax for dealing with libraries that makes them very easy to manage.

The syntax is `lib(file.o)`, which means the object file `file.o`, as stored in the library `lib.a`. The `make` command has a built-in rule for managing libraries that is usually equivalent to something like this:

```
.c.a:
$(CC) -c $(CFLAGS) $<
$(AR) $(ARFLAGS) $@ $*.o
```

The macros `$(AR)` and `$(ARFLAGS)` normally default to the command `ar` and the options `rv`, respectively. The rather terse syntax tells `make` that to get from a `.c` file to a `.a` library it must apply two rules:

- ❑ The first rule says that it must compile the source file and generate an object.
- ❑ The second rule says to use the `ar` command to revise the library, adding the new object file.

So, if we have a library `fud`, containing the file `bas.o`, in the first rule `$<` is replaced by `bas.c`. In the second rule `$@` is replaced by the library `fud.a` and `$*` is replaced by the name `bas`.

Try It Out—Managing a Library

In practice, the rules for managing libraries are quite simple to use. Let's change our application so that the files `2.o` and `3.o` are kept in a library called `mylib.a`. Our makefile needs very few changes, and `Makefile5` looks like this.

```
all: myapp
# Which compiler
CC = gcc
# Where to install
INSTDIR = /usr/local/bin
# Where are include files kept
INCLUDE = .
# Options for development
CFLAGS = -g -Wall -ansi
# Options for release
# CFLAGS = -O -Wall -ansi
```

```

# Local Libraries
MYLIB = mylib.a
myapp: main.o $(MYLIB)
    $(CC) -o myapp main.o $(MYLIB)
$(MYLIB): $(MYLIB) (2.o) $(MYLIB) (3.o)
main.o: main.c a.h
2.o: 2.c a.h b.h
3.o: 3.c b.h c.h
clean:
    -rm main.o 2.o 3.o $(MYLIB)
install: myapp
@if [ -d $(INSTDIR) ]; \
then \
    cp myapp $(INSTDIR); \
    chmod a+x $(INSTDIR)/myapp; \
    chmod og-w $(INSTDIR)/myapp; \
    echo "Installed in $(INSTDIR)"; \
else \
    echo "Sorry, $(INSTDIR) does not exist"; \
fi

```

Notice how we allow the default rules to do most of the work. Now let's test our new version of the makefile.

```

$ rm -f myapp *.o mylib.a
$ make -f Makefile5
gcc -g -Wall -ansi -c -o main.o main.c
gcc -g -Wall -ansi -c -o 2.o 2.c
ar rv mylib.a 2.o
a - 2.o
gcc -g -Wall -ansi -c -o 3.o 3.c
ar rv mylib.a 3.o
a - 3.o
gcc -o myapp main.o mylib.a
$ touch c.h
$ make -f Makefile5
gcc -g -Wall -ansi -c -o 3.o 3.c
ar rv mylib.a 3.o
r - 3.o
gcc -o myapp main.o mylib.a
$ 

```

How It Works

We first delete all the objects and the library and allow `make` to build `myapp`, which it does by compiling and creating the library before linking `main.o` with the library to create `myapp`. We then test the dependency rule for `3.o`, which tells `make` that, if `c.h` changes, then `3.c` must be recompiled. It does this correctly, compiling `3.c` and updating the library before relinking to create a new `myapp` executable file.

Advanced Topic: Makefiles and Subdirectories

If you're working on a large project, it's sometimes convenient to split some files that compose a library away from the main files and store them in a subdirectory. There are two ways of doing this with `make`.

First, you can have a second makefile in the subdirectory to compile the files, store them in a library, and then copy the library up a level into the main directory. The main makefile in the higher-level directory then has a rule for making the library, which invokes the second makefile like this:

```
mylib.a:  
  (cd mylibdirectory; $(MAKE))
```

This says that you must always try to make `mylib.a`. When `make` invokes the rule for building the library, it changes into the subdirectory `mylibdirectory` and then invokes a new `make` command to manage the library. Since a new shell is invoked for this, the program using the makefile doesn't execute the `cd`. However, the shell invoked to carry out the rule to build the library is in a different directory. The brackets ensure that it's all processed by a single shell.

The second way is to use some additional macros in a single makefile. The extra macros are generated by appending a `D` for directory or an `F` for filename to those macros we've already discussed. We could then override the built-in `.c.o` suffix rule with

```
.c.o:  
  $(CC) $(CFLAGS) -c $(@D)/$() -o $(@D)/$(@F)
```

for compiling files in a subdirectory and leaving the objects in the subdirectory. We then update the library in the current directory with a dependency and rule something like this:

```
mylib.a: mydir/2.o mydir/3.o  
        ar -rv mylib.a $?
```

You need to decide which approach you prefer for your own project. Many projects simply avoid having subdirectories, but this can lead to a source directory with a ridiculous number of files in it. As you can see from the preceding brief overview, you can use `make` with subdirectories with only slightly increased complexity.

GNU make and gcc

If you're using GNU `make` and the GNU `gcc` compiler, there are two interesting extra options:

- ❑ The first is the `-jN` ("jobs") option to `make`. This allows `make` to execute `N` commands at the same time. Where several different parts of the project can be compiled independently, `make` will invoke several rules simultaneously. Depending on your system configuration, this can give a significant improvement in the time to recompile. If you have many source files, it may be worth trying this option. In general, smaller numbers such as `-j 3` are a good starting point. If you share your computer with other users, use this option with care. Other users may not appreciate your starting large numbers of processes every time you compile!

- ❑ The other useful addition is the `-MM` option to `gcc`. This produces a dependency list in a form suitable for `make`. On a project with a significant number of source files, each including different combinations of header files, it can be quite difficult (but very important) to get the dependencies correct. If you make every source file depend on every header file, sometimes you'll compile files unnecessarily. If, on the other hand, you omit some dependencies, the problem is even worse because you're now failing to compile files that need recompiling.

Try It Out—`gcc -MM`

Let's use the `-MM` option to `gcc` to generate a dependency list for our example project:

```
$ gcc -MM main.c 2.c 3.c
main.o: main.c a.h
2.o: 2.c a.h b.h
3.o: 3.c b.h c.h
$
```

How It Works

The `gcc` compiler simply outputs the required dependency lines in a format ready for insertion into a makefile. All we have to do is save the output into a temporary file and then insert it into the makefile for a perfect set of dependency rules. There are no excuses for getting your dependencies wrong if you have a copy of `gcc`!

If you really feel confident about makefiles, you might try using the `makedepend` tool, which performs a function similar to the `-MM` option but actually appends the dependencies at the end of the specified makefile.

Before we leave the topic of makefiles, it's perhaps worth pointing out that you don't have to confine yourself to using makefiles to compile code or create libraries. You can use them to automate any task where there is a sequence of commands that get you from some sort of input file to an output file. A typical "non compiler" use might be for calling `AWK` or `sed` to process some files, or even generating manual pages. You can automate just about any file manipulation, just as long as `make` can work out, from the date and time information on the files, which ones have changed.

Source Code Control

If you move beyond simple projects, particularly if more than one person is working on the project, it becomes important to manage changes to source files properly to avoid conflicting changes and to track changes that have been made.

There are three widely used UNIX systems for managing source files:

- ❑ RCS (Revision Control System)
- ❑ CVS (Concurrent Version System)
- ❑ SCCS (Source Code Control System)

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The RCS utilities, along with their sources, are available from the Free Software Foundation. SCCS was introduced by AT&T in the System V versions of UNIX and is now incorporated in the X/Open standard. CVS, which is more advanced than SCCS or RCS, is fast becoming the tool of choice for collaborative, Internet-based developments.

In this chapter, we'll focus on RCS and CVS and briefly compare the RCS commands with the SCCS commands.

RCS

The RCS system comprises a number of commands for managing source files. It works by tracking a source file as it's changed by maintaining a single file with a list of changes in sufficient detail to recreate any previous version. It also allows you to store comments associated with every change, which can be very useful if you're looking back through the history of changes to a file.

As a project progresses, you can log each major change or bug fix you make to a source file separately and store comments against each change. This can be very useful for reviewing the changes made to a file, checking where bugs were fixed and occasionally, perhaps, where bugs were introduced!

As the RCS saves only the changes between versions, it's also very space efficient. The system also allows us to retrieve previous revisions in case of an accidental deletion.

The `rcs` Command

We'll start with an initial version of the file we wish to manage. In this case, we'll use `important.c`, which starts life as a copy of `foo.c` with the following comment at the beginning:

```
/*
 * This is an important file for managing this project.
 * It implements the canonical "Hello World" program.
 */
```

The first task is to initialize RCS control over the file, using the `rcs` command. The command `rcs -i` initializes the RCS control file.

```
$ rcs -i important.c
RCS file: important.c,v
enter description, terminated with single '.' or end of file:
NOTE: This is NOT the log message!
>> This is an important demonstration file
>> .
done
$
```

We're allowed multiple comment lines. We terminate the prompting with a single `.` on a line by itself, or by typing the end of file character, usually Ctrl+D.

After this command, `rcs` has created a new read-only file with a `.v` extension:

```
$ ls -1
-rw-r--r--    1 neil      users          226 2003-02-15 10:35 important.c
-rw-r--r--    1 neil      users          105 2003-02-15 10:37 important.c,v
$
```

If you prefer to keep your RCS files in a separate directory, simply create a subdirectory called RCS before you use rcs for the first time. All the rcs commands will automatically use the RCS subdirectory for rcs files.

The ci Command

We can now check in our file, using the ci command to store the current version.

```
$ ci important.c
important.c,v  <-  important.c
initial revision: 1.1
done
$
```

If we had forgotten to do rcs -i first, RCS would have asked for a description of the file. One of the advantages of RCS over SCCS is this more relaxed approach to human error. If we now look at the directory, we'll see that important.c has been deleted.

```
$ ls -l
-r--r--r--  1 neil      users          444 2003-02-15 10:39 important.c,v
$
```

The file contents and control information are all stored in the RCS file: important.c,v.

The co Command

If we wish to change the file, we must first "check out" the file. If we just want to read the file, we can use co to recreate the current version of the file and change the permissions to make it read-only. If we wish to edit it, we must lock the file with co -l. The reason for this is that, in a team project, it's important to ensure that only one person at a time is modifying a given file, which is why only one copy of a given version of a file has write permission. When a file is checked out with write permission, the RCS file becomes locked. Let's lock out a copy of the file

```
$ co -l important.c
important.c,v  -->  important.c
revision 1.1 (locked)
done
$
```

and look at the directory:

```
$ ls -l
-rw-r--r--  1 neil      users          226 2003-02-15 10:40 important.c
-r--r--r--  1 neil      users          454 2003-02-15 10:40 important.c,v
$
```

There's now a file for us to edit to put in our new changes. Let's do some edits, store the new version, and use the ci command again to store the changes. The output section of important.c is now

```
printf("Hello World\n");
printf("This is an extra line added later\n");
```

We use `ci` like this:

```
$ ci important.c
important.c,v  <--  important.c
new revision: 1.2; previous revision: 1.1
enter log message, terminated with single '.' or end of file:
>> Added an extra line to be printed out.
>> .
done
$
```

To check in the file and retain the lock so that the user can continue to work on it, you should call `ci` with its `-l` option. The file is automatically checked out again to the same user.

We've now stored the revised version of the file. If we look at the directory, we see that `important.c` has again been removed.

```
$ ls -l
-r--r--r--    1 neil      users          636 2003-02-15 10:42 important.c,v
$
```

The `rlog` Command

It's often useful to look at a summary of changes to a file. We can do this with the `rlog` command.

```
$ rlog important.c
RCS file: important.c,v
RCS file: important.c,v
Working file: important.c
head: 1.2
branch:
locks: strict
access list:
symbolic names:
keyword substitution: kv
total revisions: 2;      selected revisions: 2
description:
This is an important demonstration file
-----
revision 1.2
date: 2003/02/15 10:42:35;  author: neil;  state: Exp;  lines: +1 -0
Added an extra line to be printed out.
-----
revision 1.1
date: 2003/02/15 10:39:45;  author: neil;  state: Exp;
Initial revision
=====
$
```

The first part gives us a description of the file and the options that `rcs` is using. The `rlog` command then lists the revisions of the file, most recent first, along with the text we entered when we checked in the revision. `lines: +1 -0` in revision 1.2 tells us that one line was added and none were deleted.

If we now want the first version of the file back, we can ask `co` for it by specifying the revision we require.

```
$ co -r1.1 important.c
important.c,v  -->  important.c
revision 1.1
done
$
```

`ci` also has a `-r` option, which forces the version number to a specified value. For example,

```
ci -r2 important.c
```

would check in `important.c` as version 2.1. Both RCS and SCCS default to using 1 as the first minor version number.

The `rcsdiff` Command

If we just want to know what was changed between two revisions, we can use the `rcsdiff` command.

```
$ rcsdiff -r1.1 -r1.2 important.c
=====
RCS file: important.c,v
retrieving revision 1.1
retrieving revision 1.2
diff -r1.1 -r1.2
11a12
>     printf("This is an extra line added later\n");
$
```

This tells us that a single line was inserted after the original line 11.

Identifying Revisions

The RCS system can use some special strings (macros) inside the source file to help track the changes. The most common two macros are `$RCSfile$` and `Id`. The macro `$RCSfile$` is expanded to the name of the file and `Id` expands to a string identifying the revision. Consult the manual pages for a full list of the special strings supported. The macros are expanded whenever a file revision is checked out and updated automatically when a revision is checked in.

Let's change our file for a third time and add some of these macros.

```
$ co -l important.c
important.c,v  -->  important.c
revision 1.2 (locked)
done
$
```

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We edit the file and it now looks like this:

```
/*
 This is an important file for managing this project.
 It implements the canonical "Hello World" program.
 Filename: $RCSfile$.
 */
#include <stdlib.h>
#include <stdio.h>
static char *RCSinfo = "$Id$";
int main() {
    printf("Hello World\n");
    printf("This is an extra line added later\n");
    printf("This file is under RCS control. Its ID is\n%s\n", RCSinfo);
    exit(EXIT_SUCCESS);
}
```

Let's check in this revision and see how RCS manages the special strings:

```
$ ci important.c
important.c,v  <-  important.c
new revision: 1.3; previous revision: 1.2
enter log message, terminated with single '.' or end of file:
>> Added $RCSfile$ and $Id$ strings
>> .
done
$
```

If we look in the directory, we find only the RCS file:

```
$ ls -l
-r--r--r--  1 neil      users          912 2003-02-15 10:46 important.c,v
$
```

If we check out (with the `co` command) and examine the current version of the source file, we can see the macros that have been expanded.

```
/*
 This is an important file for managing this project.
 It implements the canonical "Hello World" program.
 Filename: $RCSfile: important.c,v $.
*/
#include <stdlib.h>
#include <stdio.h>
static char *RCSinfo = "$Id: important.c,v 1.3 2003/02/15 10:46:07 neil Exp $";
int main() {
    printf("Hello World\n");
    printf("This is an extra line added later\n");
    printf("This file is under RCS control. Its ID is\n%s\n", RCSinfo);
    exit(EXIT_SUCCESS);
}
```

Try It Out—GNU make with RCS

GNU make already has some built-in rules for managing RCS files. We will now see how make deals with a missing source file.

```
$ rm -f important.c
$ make important
co  important.c,v important.c
important.c,v  -->  important.c
revision 1.3
done
cc   -c important.c -o important.o
cc   important.o   -o important
rm important.o important.c
$
```

How It Works

make has a default rule that to make a file with no extension you can compile a file of the same name but with a .c extension. A second default rule allows make to create `important.c` from `important.c,v` by using RCS. Since no file called `important.c` exists, make has created the .c file by checking out the latest revision with `co`. After compiling, it tidied up by deleting the file `important.c`.

The ident Command

We can use the `ident` command to find the version of a file that contains a `Id` string. Since we stored the string in a variable, it also appears in the resulting executable. You may find that if you include special strings but never access them in the code, some compilers will optimize them away. You can normally get around this problem by adding some dummy accesses to the string, although as compilers get better this is becoming more difficult!

Try It Out—`ident`

```
$ important
Hello World
This is an extra line added later
This file is under RCS control. Its ID is
$Id: important.c,v 1.3 2003/02/15 10:46:07 neil Exp $
$ ident important
important:
$Id: important.c,v 1.3 2003/02/15 10:46:07 neil Exp $
$
```

How It Works

By executing the program, we show the string has been incorporated into the executable. Then we show how the `ident` command can extract `Id` strings from an executable file.

This technique of using RCS and `Id` strings that appear in executables can be a very powerful tool for checking which version of a file a customer is reporting a problem in. You can also use RCS (or SCCS) as part of a project-tracking facility to track problems being reported and how they are fixed. If you're selling software, or even giving it away, it's very important to know what was changed between different releases.

If you'd like more information, the `rcsintro` page in the manual gives a thorough introduction to the RCS system, in addition to the standard RCS pages. There are also manual pages for the individual commands `ci`, `co`, and so on.

SCCS

SCCS offers facilities very similar to RCS. The advantage of SCCS is that it's specified in X/Open, so all branded versions of UNIX should support it. On a more practical level, RCS is very portable and can be freely distributed. So if you have a UNIX-like system, whether it's X/Open conformant or not, you should be able to obtain and install RCS for it. For this reason we don't describe SCCS further here, except to provide a brief command comparison for those moving between the two systems.

Comparing RCS and SCCS

It's difficult to provide a direct comparison of commands between the two systems, so the following table should only be considered as a quick pointer. The commands listed here don't take the same options to perform the same tasks. If you have to use SCCS, you'll need to find the appropriate options, but at least you'll know where to start looking.

| RCS | SCCS |
|----------------------|-----------------------|
| <code>rcs</code> | <code>admin</code> |
| <code>ci</code> | <code>delta</code> |
| <code>co</code> | <code>get</code> |
| <code>rcsdiff</code> | <code>sccsdiff</code> |
| <code>ident</code> | <code>what</code> |

In addition to those listed previously, the SCCS `sccs` command has some crossover with the `rcs` and `co` commands in RCS. For example, `sccs edit` and `sccs create` are equivalent to `co -l`, and `rcs -i`, respectively.

CVS

An alternative to using RCS to manage changes to files is *CVS*, which stands for *Concurrent Versions System*. CVS is becoming more popular, probably because it has one distinct advantage over RCS: It's practical to use CVS over the Internet, not just on a shared local directory like RCS. CVS also allows for parallel development; that is, many programmers can work on the same file at once, whereas RCS allows only one user to work on one particular file at a time. CVS commands resemble RCS commands, because CVS was initially developed as a front end to RCS.

Since it can work across a network in a flexible way, CVS is suitable for use if the only network linking the developers is the Internet. Many Linux and GNU projects are using CVS to help the different developers coordinate their work. In general, the way that you use CVS on a remote set of files is almost identical to how you would use it on a local set.

In this chapter, we will look briefly at the basics of CVS, so that you can get started with local repositories and understand how to get a copy of the latest sources of a project when the CVS server is on the Internet. More information is in the CVS manual, written by Per Cederqvist et. al., copyright Signum Support AB, but distributed under the terms of the GNU General Public License and available on many Web sites, where you will also find FAQ files and various other helpful files.

First we need to create a repository where CVS will store both its control files and the master copies of files that it is managing. A repository has a tree structure, so you can use a single repository to store not just a whole directory structure for a single project, but many projects in the same repository. However, you can use separate repositories for separate unrelated projects as well. In the following sections we'll see how to tell CVS which repository to use.

Using CVS Locally

Let's start by creating a repository. To keep it simple, this will be a local repository, and because we will be using only one, a convenient place to put it is somewhere in `/usr/local`. On most Linux distributions all normal users are members of the group `users`, so we use this as the group of the repository so that all users can access it.

As superuser, create a directory for the repository:

```
# mkdir /usr/local/repository  
# chgrp users /usr/local/repository  
# chmod g+w /usr/local/repository
```

As a normal user again, initialize it as a CVS repository. You will need to have obtained write access to `/usr/local/repository` to do this.

```
$ cvs -d /usr/local/repository init
```

The `-d` option tells CVS where we want the repository to be created.

Now that the repository has been created, we can store our initial versions of the project in CVS. However, at this point we can save ourselves some typing. All `cvs` commands have two ways of looking for the CVS directory. First, they look for a `-d <path>` on the command line (as we used with the `init` command); if the `-d` option is not present, it looks for an environment variable `CVSROOT`. Rather than use the `-d` option all the time, we will set up this environment variable. This is the command to use if you use bash as your shell:

```
$ export CVSROOT=/usr/local/repository
```

First we change to the directory where the project is; then we tell CVS to import all the files in the directory. As far as CVS concerned, a project is any collection of related files and directories. Typically this will include all the files necessary to create an application. The term *import* means to bring files under CVS control and copy them into the CVS repository.

```
$ cd cvs-sp  
$ ls -l  
-rw-r--r--    1 neil      users           68 2003-02-15 11:07 Makefile  
-rw-r--r--    1 neil      users          109 2003-02-15 11:04 hello.c  
$ cvs import -m"Initial version of Simple Project" wrox/chap9-cvs wrox start
```

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This bit of magic tells CVS to import all the files in the current directory and gives it a log message.

The `wrox/chap9-cvs` option tells CVS where, relative to the root of the CVS tree, to store the new project. Remember that CVS can store multiple projects in the same repository if you wish. The option `wrox` is a vendor tag used to identify the supplier of the initial version of files being imported, and `start` is a release tag. Release tags can be used to identify, as a group, sets of related files, such as those that make up a particular release of an application. CVS responds with

```
N wrox/chap9-cvs/hello.c
N wrox/chap9-cvs/Makefile
No conflicts created by this import
```

telling us that it imported two files correctly.

Now is a good time to check that we can retrieve our files from CVS. Let's just create a `junk` directory and check our files back out again to make sure all is well.

```
$ mkdir junk
$ cd junk
$ cvs checkout wrox/chap9-cvs
```

We give CVS the same path as when we checked the files in. CVS creates a directory `wrox/chap9-cvs` in the current directory and puts the files there for us.

Now we are ready to make some changes to our project. Let's edit `hello.c` and make a minor change. Let's just add a line:

```
printf("Have a nice day\n");
```

Then recompile and run the program to check all is well.

We can ask CVS what has been changed in the project. We don't have to tell CVS which file we are interested in; it can work on a whole directory at a time:

```
$ cvs diff
```

CVS responds with

```
cvs diff: Diffing .
Index: hello.c
=====
RCS file: /usr/local/repository/wrox/chap9-cvs/hello.c,v
retrieving revision 1.1.1.1
diff -r1.1.1.1 hello.c
6a7
>     printf("Have a nice day\n");
```

We are happy with our change, so let's commit it to CVS.

When you commit a change with CVS, it will start an editor to allow you to enter a log message. You may want to set the environment variable `CVSEDITOR` to force a particular editor before you run the `commit` command.

```
$ cvs commit
```

CVS responds by telling us what it is checking.

```
cvs commit: Examining .
Checking in hello.c;
/usr/local/repository/wrox/chap9-cvs/hello.c,v  <-- hello.c
new revision: 1.2; previous revision: 1.1
done
```

Now we can ask CVS about changes to the project since we first checked it in. We ask for a set of differences since revision 1.1 (the initial version) on project `wrox/chap9-cvs`.

```
$ cvs rdiff -r1.1 wrox/chap9-cvs
```

CVS tells us the details:

```
cvs rdiff: Diffing wrox/chap9-cvs
Index: wrox/chap9-cvs/hello.c
diff -c wrox/chap9-cvs/hello.c:1.1 wrox/chap9-cvs/hello.c:1.2
*** wrox/chap9-cvs/hello.c:1.1   Sat Feb 15 11:08:33 2003
-- wrox/chap9-cvs/hello.c       Sat Feb 15 11:15:07 2003
*****
*** 4,8 ****
-- 4,9 --
    int main()
{
    printf("Hello World\n");
+    printf("Have a nice day\n");
    exit (EXIT_SUCCESS);
}
```

Suppose you have had a copy of code out of CVS for awhile in a local directory and want to refresh files in your local directory that others have changed but that you have not edited. CVS can do this for you using the `update` command. Move to the top part of the path, in this case to the directory containing `wrox`, and execute the following command:

```
$ cvs update -Pd wrox/chap9-cvs
```

CVS will refresh files for you, extracting from the repository files that others have changed but that you have not and putting them in your local directory. Of course, some of the changes might be incompatible with your changes, but that is a problem you will have to work on. CVS is good, but it can't perform magic!

You can see by now that using CVS is very like using RCS. However, there is one very important difference, that we haven't mentioned yet—the ability to operate over a network without using a mounted file system.

Accessing CVS over a Network

We told CVS where the repository was by either using a `-d` option to each command or setting the `CVSROOT` environment variable. If we want to operate over a network, we simply use a more advanced syntax for this parameter. For example, at the time of writing, the GNOME (GNU Network Object Model Environment, a popular open source graphical desktop system) development sources are all accessible on the Internet using CVS. You need only specify where the appropriate CVS repository is by pre-pending some network information to the front of the path specifier.

For example, at the time of writing you can point CVS at the GNOME source CVS repository by setting `CVSROOT` to `:pserver:anonymous@anoncvs.gnome.org:/cvs/gnome`. This tells CVS that the repository is using password authentication (`pserver`), and is on the server `anoncvs.gnome.org`.

Before we can access the sources, we need to do a login, like this.

```
$ cvs login
```

Press Enter when prompted for the password.

We are now ready to use `cvs` commands, much as though we were working on a local repository, with one minor exception—we add the `-z3` option to all `cvs` commands to force compression, saving network bandwidth.

If we want to fetch the ORBit sources, for example, the command is

```
$ cvs -z3 checkout ORBit
```

If we want to set our own repository to be accessible over the network, then we need to start a CVS server on our machine. This can be done by starting it via `inetd`. We simply add a line to `/etc/inetd.conf` and restart `inetd`. The line we need is

```
2401 stream tcp nowait root /usr/bin/cvs cvs -b /usr/bin --allow-root =  
/usr/local/repository pserver
```

This instructs `inetd` to automatically start a CVS session to clients connecting on port 2401, the standard CVS server port. For more information on starting network services via `inetd`, see the manual pages for `inetd` and `inetd.conf`.

In this brief section, we have barely had room to scratch the surface of the facilities of CVS. If you want to use CVS seriously, we strongly urge you to set up a local repository to experiment on, get the extensive CVS documentation, and have fun! Remember, this is open source, so if you ever get seriously stuck about what the code is doing, or (unlikely, but possible!) think you have found a bug, you can always get the source code and have a look for yourself. The CVS home page is at <http://www.cvshome.org/>.

gCVS

Probably the best user interface for CVS on Linux is gCVS, available from <http://wincvs.org>. It is based on the GNOME libraries and requires the programming language Tcl to be installed. Tcl is commonly available with Linux distributions.

gCVS allows a repository to be created and managed, including remote access to network-based repositories.

Figure 9-1 shows the history of our simple application being displayed by gCVS.

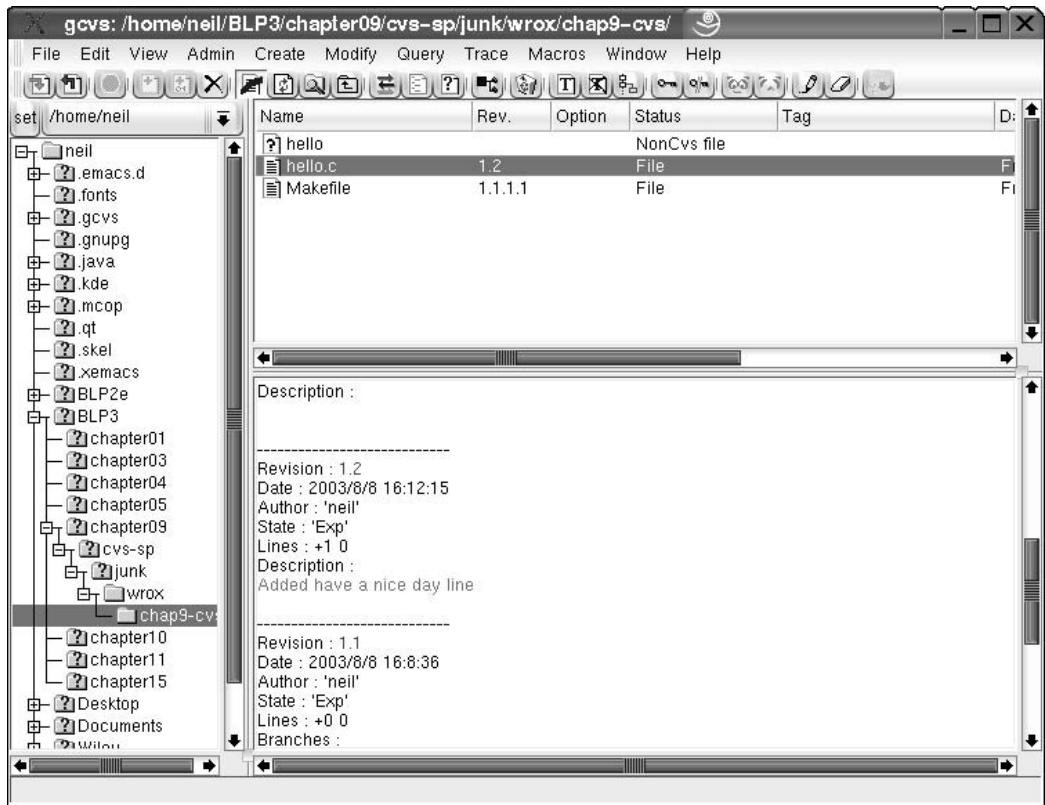


Figure 9-1

BitKeeper

BitKeeper is a source code management tool from BitMover Inc. This is a commercial product that is being used by the Linux kernel developers to manage the many thousands of lines of code that make up the core of Linux. BitMover offer a “free use” license for BitKeeper for anyone working on free software projects. More details are available from <http://www.bitkeeper.com>.

Writing a Manual Page

If you’re writing a new command as part of a task, you should create a manual page to go with it. As you’ve probably noticed, the layout of most manual pages follows a closely set pattern, which is of this form:

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- ❑ Header
- ❑ Name
- ❑ Synopsis
- ❑ Description
- ❑ Options
- ❑ Files
- ❑ See also
- ❑ Bugs

You can leave out sections that aren't relevant. An "Author" section also often appears toward the bottom of Linux manual pages.

UNIX manual pages are formatted with a utility called `nroff`, or on most Linux systems the GNU project's equivalent, `groff`. Both of these are developments of an earlier `roff`, or run-off, command. The input to `nroff` or `groff` is plain text, except that at first glance the syntax looks impenetrably difficult. Don't panic! As with UNIX programming, where the easiest way of writing a new program is to start with an existing program and adapt it, so it is with manual pages.

It's beyond the scope of this book to explain in detail the many options, commands, and macros that the `groff` (or `nroff`) command can use. Rather, we present a simple template that you can borrow and adapt for your own pages.

Here's the source of a simple manual page for our application.

```
.TH MYAPP 1
.SH NAME
Myapp \- A simple demonstration application that does very little.
.SH SYNOPSIS
.B myapp
[\"-option ...]
.SH DESCRIPTION
.PP
\fImyapp\fP is a complete application that does nothing useful.
.PP
It was written for demonstration purposes.
.SH OPTIONS
.PP
It doesn't have any, but let's pretend, to make this template complete:
.TP
.BI \"-option
If there was an option, it would not be -option.
.SH RESOURCES
.PP
myapp uses almost no resources.
.SH DIAGNOSTICS
The program shouldn't output anything, so if you find it doing so there's
probably something wrong. The return value is zero.
```

```
.SH SEE ALSO
The only other program we know with this this little functionality is the
ubiquitous hello world application.
.SH COPYRIGHT
myapp is Copyright (c) 2003 Wrox Press.
This program is free software; you can redistribute it and/or modify
it under the terms of the GNU General Public License as published by
the Free Software Foundation; either version 2 of the License, or
(at your option) any later version.
This program is distributed in the hope that it will be useful,
but WITHOUT ANY WARRANTY; without even the implied warranty of
MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
GNU General Public License for more details.
You should have received a copy of the GNU General Public License
along with this program; if not, write to the Free Software
Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA 02111-1307 USA.
.SH BUGS
There probably are some, but we don't know what they are yet.
.SH AUTHORS
Neil Matthew and Rick Stones
```

As you can see, macros are introduced with a period (.) at the start of the line and tend to be abbreviated. The 1 at the end of the top line is the section of the manual in which the command appears. Since commands appear in section 1, that is where we place our new application.

You should be able to generate your own manual pages by modifying this one and inspecting the source for others. You might also take a look at the Linux Man Page mini-HowTo, written by Jens Schweikhardt as part of the Linux Documentation Project archives at <http://www.tldp.org/>.

Now that we have the source to the manual page, we can process it with `groff`. The `groff` command commonly produces ASCII text (-Tascii) or PostScript (-Tps) output. We tell `groff` it's a manual page using the -man option, which causes special manual page macro definitions to be loaded.

```
$ groff -Tascii -man myapp.1
```

This gives the output

```
MYAPP(1)                                         MYAPP(1)
NAME
  Myapp - A simple demonstration application that does very
  little.

SYNOPSIS
  myapp [-option ...]

DESCRIPTION
  myapp is a complete application that does nothing useful.

  It was written for demonstration purposes.

OPTIONS
  It doesn't have any, but let's pretend, to make this tem-
  plate complete:
```

-option

If there was an option, it would not be -option.

RESOURCES

myapp uses almost no resources.

DIAGNOSTICS

The program shouldn't output anything, so if you find it doing so there's probably something wrong. The return value is zero.

SEE ALSO

The only other program we know with this this little functionality is the ubiquitous Hello World application.

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1

MYAPP(1)

MYAPP(1)

You should have received a copy of the GNU General Public License along with this program; if not, write to the Free Software Foundation, Inc., 59 Temple Place - Suite 330 Boston, MA 02111-1307, USA

BUGS

There probably are some, but we don't know what they are yet, nor do we particularly care ;-)

AUTHORS

Neil Matthew and Rick Stones

Now that we've tested our manual page, we need to install the source for it. The `man` command that shows manual pages uses the `MANPATH` environment variable to search for manual pages. We can either put our new page in a directory for local manual pages or store it directly in the system `/usr/man/man1` directory.

The first time someone asks for this manual page, the `man` command will automatically format and display it. Some versions of `man` can automatically generate and store preformatted (and possibly compressed) ASCII text versions of manual pages to speed up subsequent requests for the same page.

Distributing Software

The main problem with program distribution is ensuring that all the files are included and are of exactly the right version. Fortunately, the Internet programming community has evolved a very robust set of methods that go a long way toward removing the problems. These methods include

- Packaging all component files into a single package file using standard tools available on all Unix machines
- Controlled version numbering of packages
- A file-naming convention that includes the version number in the package file so that users can easily see which version they are dealing with
- Use of subdirectories in the package to ensure that, when files are extracted from the package file, they are placed in a separate directory so there's no confusion about what's included in the package and what isn't

The evolution of these methods has meant that programs can be easily and reliably distributed. The ease with which a program can be installed is another matter, because that depends on the program and the system on which it's being installed, but at least you can be sure that you have the right component files.

The patch Program

When programs have been distributed, it's almost inevitable that users will discover bugs or that the author will want to issue enhancements and updates. When authors distribute programs as binaries, they often simply ship new binaries. Sometimes (all too often), vendors simply release a new version of the program, often with an obscure revision reference and little information about what has changed.

On the other hand, distributing your software as source code is an excellent idea because it allows people to see how you have implemented things and how you have used features. It also allows people to check exactly what programs are doing and to reuse parts of the source code (providing they comply with the licensing agreement).

However, with the source of the Linux kernel weighing in at tens of megabytes of compressed source code, shipping an updated set of kernel sources would involve considerable resources, when, in fact, probably only a small percentage of the source has changed between each release.

Fortunately, there is a utility program for solving this problem: `patch`. It was written by Larry Wall, who also wrote the Perl programming language. The `patch` command allows you to distribute just the differences between the two versions so that anyone with version 1 of a file and a difference file for version 1 to version 2 can use the `patch` command to generate version 2 for themselves.

If we start with version 1 of a file,

```
This is file one
line 2
line 3
there is no line 4, this is line 5
line 6
```

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and then produce version 2,

```
This is file two
line 2
line 3
line 4
line 5
line 6
a new line 8
```

we can create a difference listing with the `diff` command:

```
$ diff file1.c file2.c > diffs
```

The `diffs` file contains

```
1c1
< This is file one
-
> This is file two
4c4,5
< there is no line 4, this is line 5
-
> line 4
> line 5
5a7
> a new line 8
```

This is actually a set of editor commands for changing one file into another. Suppose we have `file1.c` and the `diffs` file. We can update our file using `patch` as follows:

```
$ patch file1.c diffs
Hmm... Looks like a normal diff to me...
Patching file file1.c using Plan A...
Hunk #1 succeeded at 1.
Hunk #2 succeeded at 4.
Hunk #3 succeeded at 7.
done
$
```

The `patch` command has now changed `file1.c` to be the same as `file2.c`.

`patch` has an extra trick: the ability to unpatch. Suppose we decide we don't like the changes and want our original `file1.c` back. No problem; just use `patch` again, using the `-R` (reverse patch) option.

```
$ patch -R file1.c diffs
Hmm... Looks like a normal diff to me...
Patching file file1.c using Plan A...
Hunk #1 succeeded at 1.
Hunk #2 succeeded at 4.
Hunk #3 succeeded at 6.
done
$
```

`file1.c` is returned to its original state.

The `patch` command has several other options, but is generally very good at deciding from its input what you're trying to do and then simply "doing the right thing." If `patch` ever fails, it creates a file with the `.rej` extension containing the parts that couldn't be patched.

When you're dealing with software patches, it's a good idea to use the `diff -c` option, which produces a "context diff." This provides a number of lines before and after each change so that `patch` can verify that the context matches before applying the patch. The patch is also easier to read.

If you find and fix a bug in a program, it's easier, more precise, and more polite to send the author a patch rather than just a description of the fix.

Other Distribution Utilities

Linux programs and sources are commonly distributed in a file whose name contains the version number, with an extension of `.tar.gz` or `.tgz`. These are gzipped TAR (tape archive) files, also known as "tarballs." If you're using normal `tar`, you must process these files in two steps. Let's create a `gzip` file of our application.

```
$ tar cvf myapp-1.0.tar main.c 2.c 3.c *.h myapp.1 Makefile5
main.c
2.c
3.c
a.h
b.h
c.h
myapp.1
Makefile5
$
```

We now have a TAR file.

```
$ ls -l *.tar
-rw-r--r--    1 neil      users        10240 2003-02-15 11:31 myapp-1.0.tar
$
```

We can make this smaller using the compression program `gzip`.

```
$ gzip myapp-1.0.tar
$ ls -l *.gz
-rw-r--r--    1 neil      users        1668 2003-02-15 11:31 myapp-1.0.tar.gz
$
```

As you can see, the result is a very impressive reduction in size. This `.tar.gz` may then be renamed to a simple `.tgz` extension.

```
$ mv myapp-1.0.tar.gz myapp_v1.tgz
```

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This practice of renaming files to end with a dot and three characters seems to be a concession to Windows software, which, unlike Linux and UNIX, is heavily dependent on the correct extension being present. To get our file back, we decompress and extract them from the `tar` file again.

```
$ mv myapp_v1.tgz myapp-1.0.tar.gz
$ gzip -d myapp-1.0.tar.gz
$ tar xvf myapp-1.0.tar
main.c
2.c
3.c
a.h
b.h
c.h
myapp.1
Makefile5
$
```

With GNU's version of `tar`, things are even easier—we can create the compressed archive in a single step.

```
$ tar zcvf myapp_v1.tgz main.c 2.c 3.c *.h myapp.1 Makefile5
main.c
2.c
3.c
a.h
b.h
c.h
myapp.1
Makefile5
$
```

We can also decompress it just as easily:

```
$ tar zxvf myapp_v1.tgz
main.c
2.c
3.c
a.h
b.h
c.h
myapp.1
Makefile5
$
```

If you want to know the contents of the archive without actually extracting them, you should call the `tar` program with the slightly different option `tar ztvf`.

We've been using `tar` for the examples above without describing the options any more than absolutely necessary. We'll now take a quick look at the command and a few of its more popular options. As you can see from our examples, the basic syntax is

```
tar [options] [list of files]
```

The first item in the list is the target, and although we've been dealing with files, it could just as well be a device. The other items in the list are added to a new or existing archive, depending on the options. The list can also include directories, in which case all subdirectories are included in the file by default. If you're extracting files, there's no need to specify names because full paths are preserved by `tar`.

In this section, we've used combinations of six different options:

- `c`: Creates a new archive.
- `f`: Specifies that the target is a file rather than a device.
- `t`: Lists the contents of an archive without actually extracting them.
- `v` (verbose): `tar` displays messages as it goes.
- `x`: Extracts file from an archive.
- `z`: Filters the archive through `gzip` from within GNU `tar`.

There are many more options to `tar` that allow finer control over the operation of the command and the archives it creates. Refer to the `tar` manual pages for more information.

RPM Packages

The RPM Package Manager, or RPM (don't you just love recursive abbreviations?), started life as the packaging format for Red Hat Linux (and was originally known as the Red Hat Package Manager). Since then, RPM has grown to be the accepted package format for many other Linux distributions, including SuSE Linux. RPM has also been adopted as the official package file format by the Linux Standards Base, or LSB, at www.linuxbase.org.

The main advantages of RPM include

- It is used everywhere. Just about every Linux distribution can at least install RPM packages or uses RPM as its native packaging format. RPM has been ported to a number of other operating systems as well.
- It allows you to install packages with a single command. You can also install packages automatically, as RPM was designed for unattended usage. You can remove a package or upgrade a package with a single command as well.
- You have only a single file to deal with. An RPM package is stored in a single file, making it much easier to transport a package from one system to another.
- RPM automatically handles dependency checks. The RPM system includes a database of all the packages you have installed, along with what each package provides to your system and information about each package's requirements.
- RPM packages are designed to be built from pristine sources, allowing you to reproduce a build. RPM supports Linux tools such as `patch` for applying changes to program source code during the build process.

Working with RPM Package Files

Each RPM package is stored in a file with a `.rpm` extension. Package files usually follow a naming convention with the following structure:

```
name-version-release.architecture.rpm
```

With this structure, the *name* holds a generic name for the package, such as `mysql` for the MySQL database, or `make` for the make build tool. The *version* holds the version number of the software, such as `version 3.23.54a` of MySQL. The *release* holds a number that specifies which release of the RPM of that version of the software is contained in the file. This is important because RPM packages are built by a set of instructions (covered in the “Creating an RPM Spec File” section a bit later in this chapter). The release number allows you to track changes to the build instructions.

The *architecture* holds a specifier for the program architecture, such as `i386` for an Intel-based system. For compiled programs this is very important, because an executable created for a SPARC processor will likely not run on an Intel processor, for example. The architecture can be generic, such as `sparc` for a SPARC processor, or specific, such as `sparcv9` for a v9 SPARC or `athlon` for an AMD Athlon chip. Unless you override it, the RPM system will prevent you from installing packages built for a different architecture.

The architecture can also hold special values of `noarch` for packages that are not specific to a particular architecture, such as documentation files, Java programs, or Perl modules, and `src` for a source RPM. Source RPMs contain the files and build instructions to build a binary RPM package. Most RPM packages you will find for downloading are prebuilt for a particular architecture, which adds to the convenience. You can find thousands of Linux programs prebuilt and ready to install as RPM packages. This saves you the hassle of compiling.

In addition, some packages are so dependent on particular versions that it is far easier to download the prebuilt package than it is to test all the components by hand. For example, 802.11b wireless networking packages come prebuilt for specific kernel patch levels for specific distributions of Linux, such as `kernel-wlan-ng-modules-rh9.18-0.2.0-7-athlon.rpm`, which contains kernel modules for Red Hat 9.0 with a 2.4.20-18 kernel on an AMD Athlon processor system.

Installing RPM Packages

To install an RPM package, run the `rpm` command. The format is simple:

```
rpm -Uvh name-version-release.architecture.rpm
```

For example,

```
$ rpm -Uvh mysql-server-3.32.54a-11.i386.rpm
```

This command installs (or upgrades if needed) the package `mysql-server`, for an Intel `x86` architecture system.

The `rpm` command provides for most user interactions with the RPM system. You can query if a package is installed with a command such as the following:

```
$ rpm -qa mysql-server  
mysql-server-3.32.54a-11
```

Building RPM Packages

To build an RPM package, run the `rpmbuild` command. The process is relatively straightforward. We need to

- ❑ Gather the software you want to package.
- ❑ Create the spec file that describes how to build the package.
- ❑ Build the package with the `rpmbuild` command.

As RPM creation can be very complex, we will stick to a simple example in this chapter, one that should be enough to distribute a reasonable application as source or binary. We will leave to the interested reader the more esoteric options and support for packages derived via patches. Check out the manual page for the `rpm` program, or the RPM HOWTO (usually found in `/usr/doc`) for more information. Also, check out the *Red Hat RPM Guide* by Eric Foster-Johnson (Red Hat Press/Wiley).

The following sections follow the three steps above for our trivial application, `myapp`.

Gathering the Software

The first step in building an RPM package is gathering the software you want to package. In most cases, you will have the application source code, a build file such as a makefile, and perhaps an online manual page.

The easiest way to gather this software together is to bundle these files into a *tarball*. Name the tarball with the application name and version number, such as `myapp-1.0.tar.gz`.

We can modify our earlier makefile to add a new target to bundle the files into a tarball. The makefile follows.

```
all: myapp
# Which compiler
CC = gcc

# Where are include files kept
INCLUDE = .

# Options for development
CFLAGS = -g -Wall -ansi
# Options for release
# CFLAGS = -O -Wall -ansi
# Local Libraries
MYLIB = mylib.a
myapp: main.o $(MYLIB)
        $(CC) -o myapp main.o $(MYLIB)

$(MYLIB): $(MYLIB) (2.o) $(MYLIB) (3.o)
main.o: main.c a.h
2.o: 2.c a.h b.h
3.o: 3.c b.h c.h
clean:
        -rm main.o 2.o 3.o $(MYLIB)
```

```
dist: myapp-1.0.tar.gz  
  
myapp-1.0.tar.gz: myapp myapp.l  
    -rm -rf myapp-1.0  
    mkdir myapp-1.0  
    cp *.c *.h *.l Makefile myapp-1.0  
    tar zcvf $@ myapp-1.0
```

The `myapp-1.0.tar.gz` target in the makefile builds a tarball of the sources for our trivial example application. We added a `dist` target that calls the same commands for simplicity. Run the following command to make the bundle:

```
$ make dist
```

We then need to copy the file `myapp-1.0.tar.gz` to the RPM SOURCES directory, typically `/usr/src/redhat/SOURCES` on a Red Hat Linux system. For example,

```
$ cp myapp-1.0.tar.gz /usr/src/redhat/SOURCES
```

The RPM system expects the sources to be located in the `SOURCES` directory as a tarball. (There are other options; this is the simplest.) `SOURCES` is just one of the directories expected by the RPM system.

The RPM system expects the five directories in this table:

| RPM Directory | Usage |
|---------------|---|
| BUILD | The <code>rpmbuild</code> command builds software in this directory. |
| RPMS | The <code>rpmbuild</code> command stores the binary RPMs it creates in this directory. |
| SOURCES | You should put the sources for the application in this directory. |
| SPECS | You should place the spec file for each RPM you plan to make in this directory, although this is not necessary. |
| SRPMS | The <code>rpmbuild</code> command places source RPMs in this directory. |

The `RPMS` directory usually has a number of architecture-specific subdirectories, such as the following (on an Intel `x86` architecture system):

```
$ ls RPMS  
athlon  
i386  
i486  
i586  
i686  
noarch
```

By default, Red Hat Linux systems expect RPMs to be built in the `/usr/src/redhat` directory.

This directory is specific to Red Hat Linux. Other Linux distributions will use other directories, such as /usr/src/packages.

Once we have gathered the sources for your RPM package, the next step is to create a spec file, the file that describes to the rpmbuild command exactly how to build our package.

Creating an RPM Spec File

Creating a spec file can be daunting, given that the RPM system supports thousands of options. Luckily, the RPM system provides reasonable defaults for most options. You can follow the simple example in this section, which should suffice for most packages you will build. In addition, you can copy commands from other spec files.

Good sources for spec file examples are other RPM packages. Look at source RPMs, which are stored in files ending in .src.rpm. Install these RPMs and look through the spec files. You should find more complicated examples than you will ever need. Interesting spec files include those for anonftp, telnet, vnc, and sendmail.

In addition, the designers of the RPM system wisely decided not to try to replace common build tools such as make or configure. The RPM system contains many shorthand features to take advantage of makefiles and configure scripts.

In this example, we will create a spec file for the simple myapp application. Name your spec file myapp.spec. Start the spec file with a set of definitions of the name, version number, and other information about your package. For example,

```
Vendor: Wrox Press
Distribution: Any
Name: myapp
Version: 1.0
Release: 1
Packager: neil@provider.com
License: Copyright 2003 by Wrox Press
Group: Applications/Media
```

This section of an RPM spec file is often called a *preamble*. In our preamble, the most important settings are the Name, Version, and Release. This example sets the name to myapp, the version number to 1.0, and the release of the RPM package at 1, our first attempt at making an RPM package.

The Group setting is used to help graphical installation programs sort the thousands of Linux applications by type. The Distribution is important if you build a package just for one Linux distribution, such as Red Hat or SuSE Linux.

Adding comments to your spec file is a good idea. Like shell scripts and makefiles, the rpmbuild command treats any line starting with a # character as a comment. For example,

```
# This line is a comment.
```

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To help users decide whether to install your package, provide a `Summary` and a `%description` (note the inconsistency in the RPM syntax, with a percent sign before description). For example, we can describe our package as follows:

```
Summary:          Trivial application
%description
MyApp Trivial Application
A trivial application used to demonstrate development tools.
This version pretends it requires MySQL at or above 3.23.
Authors: Neil Matthew and Richard Stones
```

The `%description` section can take up multiple lines (and normally should).

The spec file can contain dependency information, both what your package provides and what your package depends on. (You can also define what the source package depends on, such as special header files necessary for compiling.)

The `Provides` setting defines what capabilities your system provides. For example,

```
Provides:      goodness
```

This example states that our package provides the imaginary capability called `goodness`. The RPM system will also automatically add a `Provides` entry for the name of the package, `myapp` in our case. The `Provides` settings are useful for multiple packages that may provide the same thing. For example, the Apache Web server package provides the capability `webserver`. Other packages, such as `Thy`, may also provide the same capability. (To help deal with conflicting packages, RPM allows you to specify `Conflicts` and `Obsoletes` information as well.)

The most important dependency information, though, is the `Requires` settings. You can state all the packages your package requires for operation. For example, a Web server requires networking and security packages. In our example, we define a requirement for the MySQL database, at version 3.23 or higher. The syntax for this follows:

```
Requires:      mysql >= 3.23
```

If you only want to require the MySQL database, at any version, you can use a setting like the following:

```
Requires:      mysql
```

RPM will prevent users from installing packages if the required packages are not also installed. (Users can override this behavior, though.)

The RPM system will automatically add dependencies such as `/bin/sh` for shell scripts, the Perl interpreter for Perl scripts, and any shared libraries (`.so` files) your application calls. Each release of the RPM system adds more smarts to the automatic dependency checks.

After you have defined the requirements, you need to define the sources that make up your application. For most applications, you can simply copy the following setting:

```
source:      %{name}-%{version}.tar.gz
```

The `%{name}` syntax refers to an RPM macro, in this case, the name of the package. Since we previously set the name to `myapp`, the `rpmbuild` command will expand `%{name}` to `myapp`, and similarly expand `%{version}` to 1.0, making for a file named `myapp-1.0.tar.gz`. The `rpmbuild` command will look for this file in the `SOURCES` directory described previously.

Our example sets up a `Buildroot`, which defines a staging area to test the installation. You can copy the following for your packages:

```
Buildroot:      %{_tmppath}/%{name}-%{version}-root
```

Once a `Buildroot` is set up, install your applications to the `Buildroot` directory. You can use the handy variable `$RPM_BUILD_ROOT`, which is defined for all the shell scripts in the spec file.

After defining all these settings about the package, the next step is to define how to build the package. There are four main sections for building: `%prep`, `%build`, `%install`, and `%clean`.

As the name implies, the `%prep` section is for preparing to build. In most cases, you can run the `%setup` macro, shown here with a `-q` parameter to set it to quiet mode:

```
%prep  
%setup -q
```

The `%build` section builds your application. In most cases, you can use a simple `make` command. For example,

```
%build  
make
```

This is one way that the RPM system takes advantage of the work you've already done in creating your makefile.

The `%install` section installs your application, any manual pages, and any support files. You can often use the RPM macro `%makeinstall`, which calls the `install` target of the makefile. In our case, though, we can manually install the files to show more RPM macros:

```
%install  
mkdir -p $RPM_BUILD_ROOT%{_bindir}  
mkdir -p $RPM_BUILD_ROOT%{_mandir}  
install -m755 myapp $RPM_BUILD_ROOT%{_bindir}/myapp  
install -m755 myapp.1 $RPM_BUILD_ROOT%{_mandir}/myapp.1
```

This example creates the directories for the files, if needed, and then installs the `myapp` executable and `myapp.1` manual page. The `$RPM_BUILD_ROOT` environment variable holds the `Buildroot` location set previously. The `%{_bindir}` and `%{_mandir}` macros expand to the current binary directory and manual page directory, respectively.

If you use a `configure` script to create the makefile, all the various directories get set properly into your makefile. In most cases, you will not need to set up all the installation commands manually in the spec file as shown in the previous example.

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The `%clean` target cleans up the files created by the `rpmbuild` command. For example,

```
%clean  
rm -rf $RPM_BUILD_ROOT
```

After specifying how to build the package, you need to define all the files that will be installed. RPM is very rigid on this; it has to be rigid so that it can properly track every file from every package. The `%files` section names the files to include in the package. In our case, we have only two files to distribute in the binary package: the `myapp` executable and `myapp.1` manual page. For example,

```
%files  
%{_bindir}/myapp  
%{_mandir}/myapp.1
```

The RPM system can run scripts before and after your package is installed. For example, if your package is a daemon process, you probably need to modify the system initialization scripts to start your daemon. Do that with a `%post` script. A simple example that merely sends an e-mail message follows:

```
%post  
mail root -s "myapp installed - please register" </dev/null
```

Look for examples in server RPM spec files.

The complete spec file for our trivial application follows:

```
#  
# spec file for package myapp (Version 1.0)  
#  
Vendor: Wrox Press  
Distribution: Any  
Name: myapp  
Version: 1.0  
Release: 1  
Packager: neil@provider.com  
License: Copyright 2003 by Wrox Press  
Group: Applications/Media  
  
Provides: goodness  
Requires: mysql >= 3.23  
  
Buildroot: %{_tmppath}/%{name}-%{version}-root  
source: %{name}-%{version}.tar.gz  
  
Summary: Trivial application  
%description  
MyApp Trivial Application  
A trivial application used to demonstrate development tools.  
This version pretends it requires MySQL at or above 3.23.  
Authors: Neil Matthew and Richard Stones
```

```
%prep
%setup -q

%build
make

%install
mkdir -p $RPM_BUILD_ROOT%{_bindir}
mkdir -p $RPM_BUILD_ROOT%{_mandir}
install -m755 myapp $RPM_BUILD_ROOT%{_bindir}/myapp
install -m755 myapp.1 $RPM_BUILD_ROOT%{_mandir}/myapp.1

%clean
rm -rf $RPM_BUILD_ROOT

%post
mail root -s "myapp installed - please register" </dev/null

%files
%{_bindir}/myapp
%{_mandir}/myapp.1
```

We are now ready to build the RPM package.

Building an RPM Package with rpmbuild

Build packages with the `rpmbuild` command, which uses the following syntax:

```
rpmbuild -bBuildStage spec_file
```

The `-b` option tells `rpmbuild` to build an RPM. The extra *BuildStage* option is a special code that tells the `rpmbuild` command how far to go when building. We list the options in the following table.

| Option | Usage |
|------------------|---|
| <code>-ba</code> | Build all, both a binary and source RPM. |
| <code>-bb</code> | Build a binary RPM. |
| <code>-bc</code> | Build (compile) the program but do not make the full RPM. |
| <code>-bp</code> | Prepare for building a binary RPM. |
| <code>-bi</code> | Create a binary RPM and install it. |
| <code>-bl</code> | Check the listing of files for the RPM. |
| <code>-bs</code> | Build a source RPM only. |

Older versions of the RPM system used the `rpm` command to build packages in place of the `rpmbuild` command. With the more recent RPM releases, though, the `rpm` command will no longer build RPM packages. You must use the `rpmbuild` command.

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To build both a binary and a source RPM, use the `-ba` option. The source RPM allows you to recreate the binary RPM.

The following shows the output from building our package:

```
$ rpmbuild -ba myapp.spec
Executing(%prep): /bin/sh -e /var/tmp/rpm-tmp.71108
+ umask 022
+ cd /usr/src/redhat/BUILD
+ LANG=C
+ export LANG
+ cd /usr/src/redhat/BUILD
+ rm -rf myapp-1.0
+ /usr/bin/gzip -dc /usr/src/redhat/SOURCES/myapp-1.0.tar.gz
+ tar -xf -
+ STATUS=0
+ '[' 0 -ne 0 ']'
+ cd myapp-1.0
++ /usr/bin/id -u
+ '[' 0 = 0 ']'
+ /bin/chown -Rhf root .
++ /usr/bin/id -u
+ '[' 0 = 0 ']'
+ /bin/chgrp -Rhf root .
+ /bin/chmod -Rf a+rX,g-w,o-w .
+ exit 0
Executing(%build): /bin/sh -e /var/tmp/rpm-tmp.43788
+ umask 022
+ cd /usr/src/redhat/BUILD
+ cd myapp-1.0
+ LANG=C
+ export LANG
+ make
gcc -g -Wall -ansi -c -o main.o main.c
gcc -g -Wall -ansi -c -o 2.o 2.c
ar rv mylib.a 2.o
a - 2.o
gcc -g -Wall -ansi -c -o 3.o 3.c
ar rv mylib.a 3.o
a - 3.o
gcc -o myapp main.o mylib.a
+ exit 0
Executing(%install): /bin/sh -e /var/tmp/rpm-tmp.90688
+ umask 022
+ cd /usr/src/redhat/BUILD
+ cd myapp-1.0
+ LANG=C
+ export LANG
+ mkdir -p /var/tmp/myapp-1.0-root/usr/bin
+ mkdir -p /var/tmp/myapp-1.0-root/usr/share/man
+ install -m755 myapp /var/tmp/myapp-1.0-root/usr/bin/myapp
```

```
+ install -m755 myapp.1 /var/tmp/myapp-1.0-root/usr/share/man/myapp.1
+ /usr/lib/rpm/find-debuginfo.sh /usr/src/redhat/BUILD/myapp-1.0
extracting debug info from /var/tmp/myapp-1.0-root/usr/bin/myapp
1 block
+ /usr/lib/rpm/redhat/brpm-compress
+ /usr/lib/rpm/redhat/brpm-strip /usr/bin/strip
+ /usr/lib/rpm/redhat/brpm-strip-static-archive /usr/bin/strip
+ /usr/lib/rpm/redhat/brpm-strip-comment-note /usr/bin/strip /usr/bin/objdump
Processing files: myapp-1.0-1
Provides: goodness
Requires(interp): /bin/sh
Requires(rpmlib): rpmlib(CompressedFileNames) <= 3.0.4-1
rpmlib(PayloadFilesHavePrefix) <= 4.0-1
Requires(post): /bin/sh
Requires: libc.so.6 libc.so.6(GLIBC_2.0) mysql >= 3.23
Processing files: myapp-debuginfo-1.0-1
Requires(rpmlib): rpmlib(CompressedFileNames) <= 3.0.4-1
rpmlib(PayloadFilesHavePrefix) <= 4.0-1
Checking for unpackage file(s): /usr/lib/rpm/check-files /var/tmp/myapp-1.0-root
Wrote: /usr/src/redhat/SRPMS/myapp-1.0-1.src.rpm
Wrote: /usr/src/redhat/RPMS/i386/myapp-1.0-1.i386.rpm
Wrote: /usr/src/redhat/RPMS/i386/myapp-debuginfo-1.0-1.i386.rpm
Executing(%clean): /bin/sh -e /var/tmp/rpm-tmp.17422
+ umask 022
+ cd /usr/src/redhat/BUILD
+ cd myapp-1.0
+ rm -rf /var/tmp/myapp-1.0-root
+ exit 0
```

When the build is complete, you should see two packages: the binary RPM in the RPMS directory, under an architecture subdirectory such as RPMS/i386, and a source RPM in SRPMS.

The binary RPM filename will appear something like the following:

myapp-1.0-1.i386.rpm

The architecture on your system may be different.

The source RPM filename will appear as follows:

myapp-1.0-1.src.rpm

You need to install packages as the superuser. You do not have to build packages as root, so long as you have write access to the RPM directories, typically /usr/src/redhat. Normally, you should not create RPM packages as root, since a spec file could have commands that may damage your system.

Other Package Formats

Although RPM is fast becoming the most popular way of distributing applications in a way that allows the user to control their installation, and deinstallation, there are competing packages out there. Some software is still distributed as gzipped tar files (`.tgz`). Typically the installation steps consist of unpacking the archive into a temporary directory and running a script to perform the actual installation.

The Debian Linux distributions (and some others) support another package format, similar in functionality to RPM, called `dpkg`. The `dpkg` utility on Debian unpacks and installs package files that usually have a `.deb` extension. If you need to distribute an application using `.deb` file packages, it is possible to convert an RPM package to `dpkg` format using a utility called `Alien`. More details on `Alien` can be found at <http://kitenet.net/programs/alien/>.

Development Environments

Almost all of the tools we have looked at so far in this chapter are essentially command line tools. Developers that have experience with Windows will no doubt have some experience with integrated development environments, or IDEs for short. IDEs are graphical environments that typically bring together some or all of the tools needed to create, debug, and run an application. Usually, they provide at least an editor, a file browser, and a method of running the application and capturing the output. More complete environments add support for generating source code files from templates for certain types of application, integration with a source code control system, and automatic documentation.

In this chapter, we will mention a few of the IDEs available for Linux today. These environments are under active development, with the most advanced of them beginning to rival the quality of commercial offerings.

xwpe

Way back in 1993 Fred Kruse developed a character-based file manager and text editor. It was small, easy to use, and colorful. Its style mimicked the MS-DOS tools of the day. Many programmers appreciated its speed and low demand on precious computer resources.

Called “Window Editor,” and invoked as `we`, the editor is able to edit multiple files at once, search for text, automatically indent source code, and print it. Later developments added support for executing and debugging programs from within the editor. This version became the Window Programming Environment (`wpe`). Both `we` and `wpe` run on Linux, either using a character mode console or inside a color xterm under the X Window System. Versions that run under X11 are also available as `xwe` and `xwpe` respectively. These versions retain all the function key–driven user interface of the originals.

Figure 9-2 shows `xwpe` stepping through the execution of a simple program. As you can see, the editor uses color to highlight the syntax of the C source code and the current state of execution.

Today, XWPE is being developed by Identical Software. You can find more details and download a version for Linux at <http://www.identicalsoftware.com/xwpe/>.

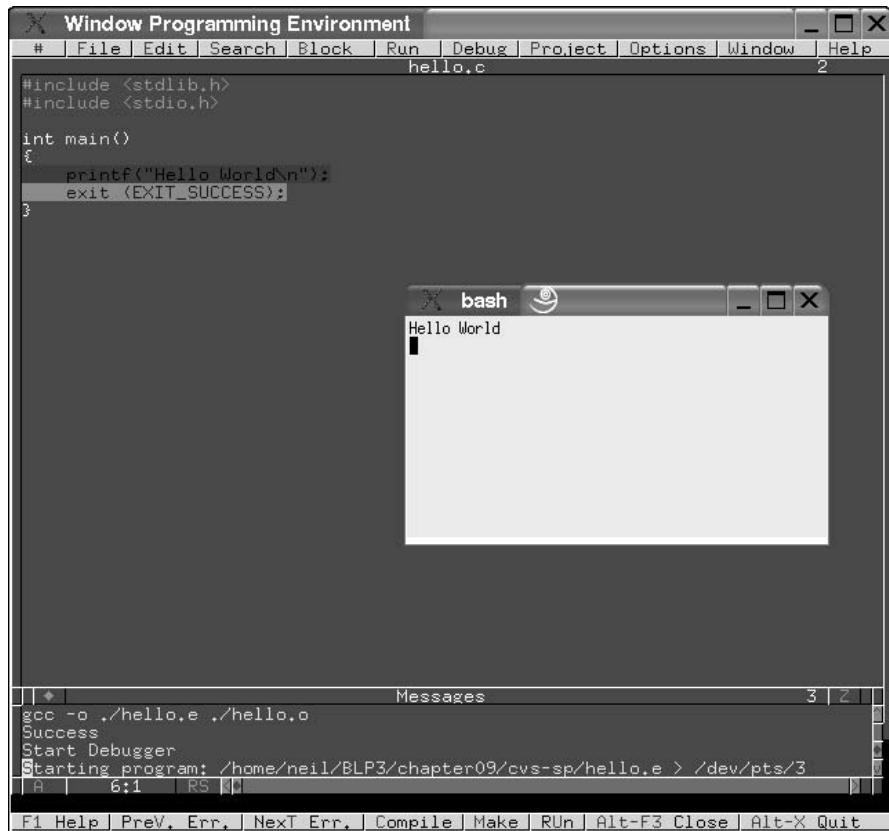


Figure 9-2

C-Forge

C-Forge is a commercial graphical IDE for C and C++ programs from Codeforge. There are a number of versions available for Linux, including a freeware one, which has limited but still useful functionality.

C-Forge will generate a suitable makefile for projects and supports revision control using CVS so that projects developed with it can be readily and easily maintained. Figure 9-3 shows a C-Forge project under construction. You can download the free version of C-Forge from <http://www.codeforge.com/>.

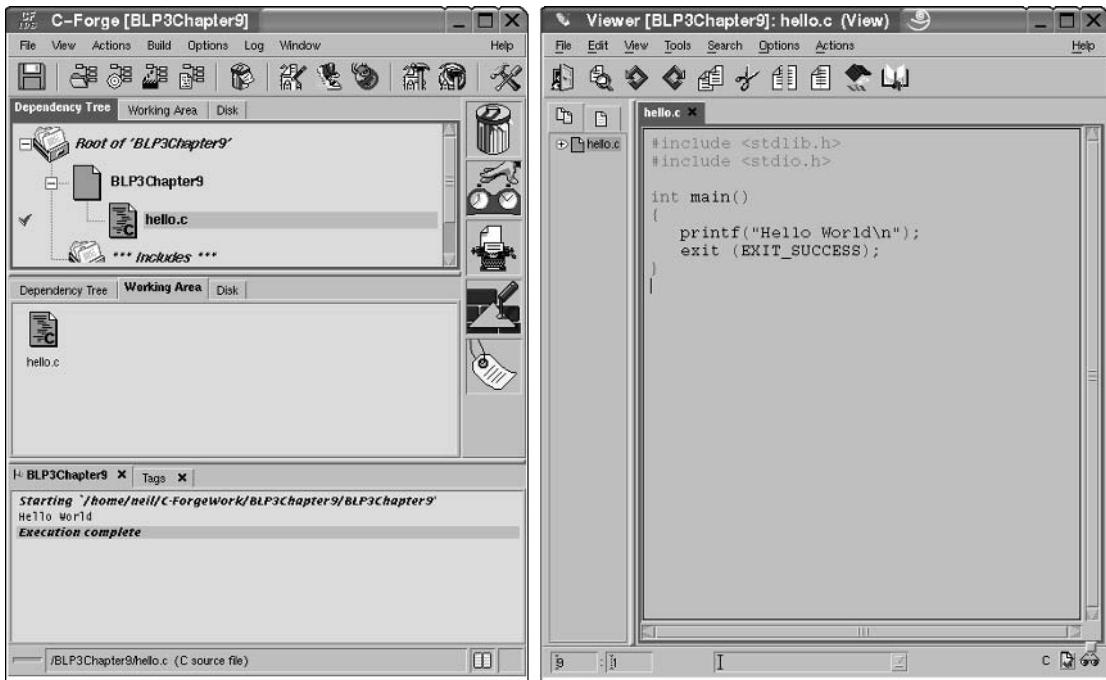


Figure 9-3

KDevelop

KDevelop is an IDE for C and C++ programs. It includes particular support for the creation of applications to run under the K Desktop Environment (KDE), one of the two main graphical user interfaces on Linux today. It can also be used for other project types, including simple C programs.

KDevelop is free software released under the terms of the GNU General Public License (GPL) and is available with many Linux distributions. The latest version can be downloaded from <http://www.kdevelop.org>. Projects created with KDevelop by default follow the standard for GNU projects. For example, they will use the `autoconf` utility to generate makefiles that are tailored to the environment for which they are being built. This means that the project is ready to be distributed as source code that stands a good chance of being able to be compiled on other systems.

KDevelop projects also contain templates for documentation, the GPL license text, and generic installation instructions. The number of files that are generated when making a new KDevelop project can be daunting, but should be familiar to anyone who has downloaded and compiled a typical GPL application.

There is support with KDevelop for CVS source code control, and applications can be both edited and debugged without leaving the environment. Figures 9-4 and 9-5 show the default KDevelop C application (yet another Hello World! program) being edited and executed.

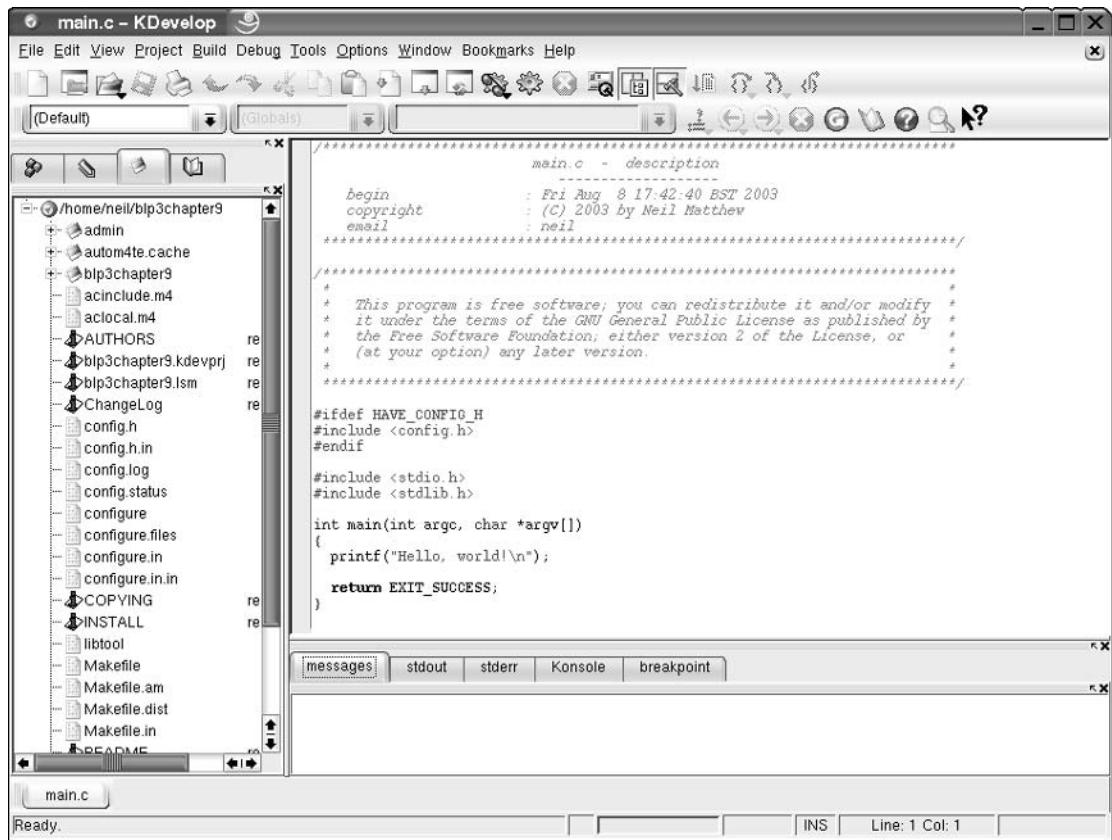


Figure 9-4

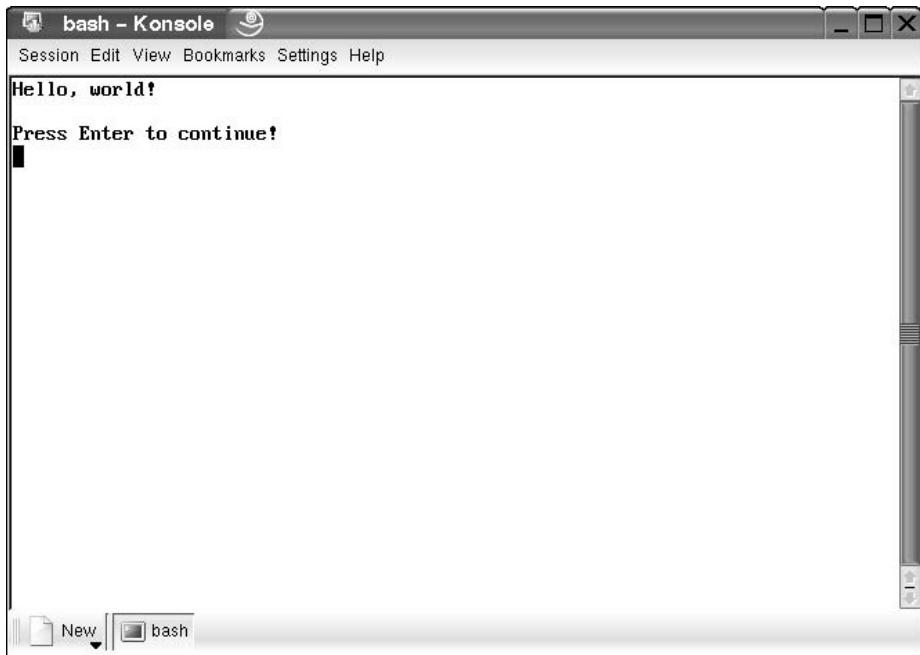


Figure 9-5

Other Environments

There are many other editors and IDEs either available for Linux or under development. The following table's list of links is not intended to be complete, but some of the developments may prove to be interesting.

| Environment | Type | Product URL |
|-------------|---|---|
| gbuilder | An IDE for GNOME | http://gbuilder.sourceforge.net/ |
| Anjuta | An IDE for GNOME | http://anjuta.sourceforge.net/ |
| Klint | An IDE for KDE | http://klint.sourceforge.net/ |
| QtEZ | An IDE for KDE | http://projects.uid0.sk/qtez/index.php |
| RHIDE | A text mode IDE | http://www.rhide.com/ |
| CRISP | A commercial programmer's editor | http://www.crisp.com/ |
| SlickEdit | A commercial multi-language code editor | http://www.slickedit.com/ |

| Environment | Type | Product URL |
|-------------|-------------------------------------|---|
| Kylix | A commercial IDE for C++ and Delphi | http://www.borland.com/kylix |
| Eclipse | Java-based tool platform and IDE | http://www.eclipse.org |

Summary

In this chapter, we've seen just a few of the Linux tools that make development and distribution of programs manageable. First, and perhaps most important, we used `make` and `makefiles` to manage multiple source files. We then looked at source code control with RCS and CVS, which lets us track changes as we develop our code. We then covered program distribution with `patch`, `tar` with `gzip`, and RPM packages. Finally, we took a look at some of the tools that make the edit-run-debug cycle of development a little easier, the IDEs.

10

Debugging

Every significant piece of software will contain defects, typically two to five per 100 lines of code. These mistakes lead to programs and libraries that don't perform as required, often causing a program to behave differently than it's supposed to. Bug tracking, identification, and removal can consume a large amount of a programmer's time during software development.

In this chapter, we'll look at software defects and consider some tools and techniques for tracking down specific instances of erroneous behavior. This isn't the same as testing (the task of verifying the program's operation in all possible conditions), although testing and debugging are, of course, related, and many bugs are discovered during the testing process.

Topics we'll cover include

- Types of errors
- General debugging techniques
- Debugging with GDB and other tools
- Assertions
- Memory use debugging

Types of Errors

A bug usually arises from one of a small number of causes, each of which suggests a method of detection and removal:

- Specification Errors:** If a program is incorrectly specified, it will inevitably fail to perform as required. Even the best programmer in the world can sometimes write the wrong program. Before you start programming (or designing), make sure that you know and understand clearly what your program needs to do. You can detect and remove many (if not all) specification errors by reviewing the requirements and agreeing that they are correct with those who will use the program.

- ❑ **Design Errors:** Programs of any size need to be designed before they're created. It's not usually enough to sit down at a computer keyboard, type source code directly, and expect the program to work the first time. Take time to think about how you will construct the program, what data structures you'll need, and how they will be used. Try to work out the details in advance, because it can save many rewrites later on.
- ❑ **Coding Errors:** Of course, everyone makes typing errors. Creating the source code from your design is an imperfect process. This is where many bugs will creep in. When you're faced with a bug in a program, don't overlook the possibility of simply rereading the source code or asking someone else to. It's surprising just how many bugs you can detect and remove by talking through the implementation with someone else.

Languages with compilers, such as C, have an advantage here in that syntax errors can be caught at compile time, whereas interpreted languages such as the Linux shell might detect syntax errors only when you try to run the program. If the problem is with error-handling code, it might not be easy to spot in testing.

Try executing the core of the program on paper, a process sometimes called *dry running*. For the most important routines, write down the values of inputs and calculate the outputs step by step. You don't always have to use a computer to debug, and sometimes it can be the computer causing the problems. Even the people who write libraries, compilers, and operating systems make mistakes! On the other hand, don't be too quick to blame the tools; it is more likely that there's a bug in a new program than in the compiler.

General Debugging Techniques

There are several distinct approaches to debugging and testing a typical Linux program. We generally run the program and see what happens. If it doesn't work, we need to decide what to do about it. We can change the program and try again (code inspection, trial and error), we can try to gain more information about what's happening inside the program (instrumentation), or we can inspect the program operation directly (controlled execution). The five stages of debugging are

- ❑ **Testing:** Finding out what defects or bugs exist
- ❑ **Stabilization:** Making the bugs reproducible
- ❑ **Localization:** Identifying the line(s) of code responsible
- ❑ **Correction:** Fixing the code
- ❑ **Verification:** Making sure the fix works

A Program with Bugs

Let's look at an example program that contains bugs. During the course of this chapter, we'll try to debug it. The program was written during the development of a larger software system. Its purpose is to test a single function, `sort`, which is intended to implement a bubble sort algorithm on an array of structures of

type `item`. The items are sorted in ascending order of the member, `key`. The program calls `sort` on a sample array to test it. In the real world we would never seek to use this particular sort of algorithm, as it's far too inefficient. We have used it here because it is short, relatively simple to understand, and also easy to get wrong. In fact, the standard C library has a function that performs the desired task already called `qsort`.

Unfortunately, the code is not very readable, there are no comments, and the original programmer isn't available. We'll have to struggle with it on our own, starting from the basic routine `debug1.c`.

```

/* 1 */ typedef struct {
/* 2 */     char *data;
/* 3 */     int key;
/* 4 */ } item;
/* 5 */
/* 6 */ item array[] = {
/* 7 */     {"bill", 3},
/* 8 */     {"neil", 4},
/* 9 */     {"john", 2},
/* 10 */    {"rick", 5},
/* 11 */    {"alex", 1},
/* 12 */ };
/* 13 */
/* 14 */ sort(a,n)
/* 15 */ item *a;
/* 16 */ {
/* 17 */     int i = 0, j = 0;
/* 18 */     int s = 1;
/* 19 */
/* 20 */     for(; i < n && s != 0; i++) {
/* 21 */         s = 0;
/* 22 */         for(j = 0; j < n; j++) {
/* 23 */             if(a[j].key > a[j+1].key) {
/* 24 */                 item t = a[j];
/* 25 */                 a[j] = a[j+1];
/* 26 */                 a[j+1] = t;
/* 27 */                 s++;
/* 28 */             }
/* 29 */         }
/* 30 */         n--;
/* 31 */     }
/* 32 */ }
/* 33 */
/* 34 */ main()
/* 35 */ {
/* 36 */     sort(array,5);
/* 37 */ }
```

Let's try to compile this program:

```
$ cc -o debug1 debug1.c
```

It compiles successfully, with no reported errors or warnings.

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Before we run this program, we'll add some code to print out the result. Otherwise, we won't know whether the program has worked. We will add some additional lines to display the array after it's been sorted. We call the new version `debug2.c`.

```
/* 34 */ main()
/* 35 */
{
/* 36 */     int i;
/* 37 */     sort(array,5);
/* 38 */     for(i = 0; i < 5; i++)
/* 39 */         printf("array[%d] = {%-s, %d}\n",
/* 40 */                 i, array[i].data, array[i].key);
/* 41 */ }
```

This additional code isn't strictly part of the programmer's remit. We've had to put it in just for testing. We'll have to be very careful that we don't introduce further bugs in our test code. Now compile again and, this time, run the program.

```
$ cc -o debug2 debug2.c
$ ./debug2
```

What happens when you do this will depend on your flavor of Linux (or UNIX) and on how it's set up. On one of the authors' systems, we got

```
array[0] = {john, 2}
array[1] = {alex, 1}
array[2] = {(null), -1}
array[3] = {bill, 3}
array[4] = {neil, 4}
```

But on the other author's system (running a different Linux kernel), we got

```
Segmentation fault
```

On your Linux system, you may see either of these outputs or a different result entirely. We expected to see

```
array[0] = {alex, 1}
array[1] = {john, 2}
array[2] = {bill, 3}
array[3] = {neil, 4}
array[4] = {rick, 5}
```

Clearly there's a serious problem with this code. If it runs at all, it's failing to sort the array correctly, and if it's being terminated with a segmentation fault, the operating system is sending a signal to the program saying that it has detected an illegal memory access and is prematurely terminating the program to prevent memory from being corrupted.

The ability of the operating system to detect illegal memory access depends on its hardware configuration and some subtleties of its memory management implementation. On most systems, the memory

allocated to the program by the operating system is larger than the memory actually being used. If the illegal memory access occurs in this region of memory, the hardware may not be able to detect the illegal access. This is why not all versions of Linux and UNIX will generate a segmentation violation.

Some library functions, such as `printf`, will also prevent illegal accesses in some special circumstances, such as using a null pointer.

When you're tracking down array access problems, it's often a good idea to increase the size of array elements, as this increases the size of the error. If we read a single byte beyond the end of an array of bytes, we may get away with it, as the memory allocated to the program will be rounded up to an operating system-specific boundary, possibly as much as 8K.

If we increase the array element size, in this case by changing the `item` member `data` to be an array of 4,096 characters, any access to a nonexistent array element will probably be to a memory location beyond that allocated. Each element of the array is 4K in size, so the memory we use incorrectly will be 0–4K off the end.

If we do this, calling the result `debug3.c`, we get a segmentation fault on both the authors' flavors of Linux.

```
/* 2 */     char data[4096];
$ cc -o debug3 debug3.c
$ ./debug3
Segmentation fault (core dumped)
```

It's possible that some flavors of Linux or UNIX still won't produce a segmentation fault. When the ANSI C standard states that the behavior is undefined, it truly does allow the program to do anything. It certainly looks like we have written a nonconforming C program here, and a nonconforming C program may exhibit very strange behavior! As we will see, the fault does turn out to fall into the category of undefined behavior.

Code Inspection

As we mentioned earlier, it's often a good idea to reread your program when it fails to run as expected. For the purposes of this chapter, let's assume that the code has been reviewed and that obvious faults have been dealt with.

Code inspection is also a term for the more formal process of a group of developers tracing through a few hundred lines of code in detail, but the scale really doesn't matter; it's still code inspection and it's still a very useful technique.

There are tools that you can use to help with code reviews, the compiler being an obvious one. It will tell you if you have any syntax errors in your program.

Some compilers also have options to raise warnings on dubious practices, such as failing to initialize variables and using assignments in conditions. For example, the GNU compiler can be run with these options:

```
gcc -Wall -pedantic -ansi
```

They enable many warnings and additional checks for conformance to C standards. We recommend that you get into the habit of using these options, `Wall` especially. It can generate helpful information when tracking down program faults.

We'll mention other tools, `lint` and `Splint`, a little later. Like the compiler, they analyze source code and report on code that might be incorrect.

Instrumentation

Instrumentation is the adding of code to a program for the purpose of collecting more information about the behavior of the program as it runs. It's very common to add `printf` calls, as we have done in our example, to print out the values of variables at different stages in a program's execution. We could usefully add several `printf` calls, but we should be aware that the process entails an additional edit and compile whenever the program is changed, and of course, we will need to remove the code when the bugs are fixed.

There are two instrumentation techniques that can help here. The first uses the C preprocessor to selectively include instrumentation code so that we only need to recompile the program to include or exclude debugging code. We can do this quite simply with constructs such as

```
#ifdef DEBUG
    printf("variable x has value = %d\n", x);
#endif
```

We can compile the program with the compiler flag `-DDEBUG` to define the `DEBUG` symbol and include the extra code or without to exclude it. We can make more sophisticated use of a numeric debug macro, like this:

```
#define BASIC_DEBUG 1
#define EXTRA_DEBUG 2
#define SUPER_DEBUG 4

#if (DEBUG & EXTRA_DEBUG)
    printf...
#endif
```

In this case, we must always define the `DEBUG` macro, but we can set it to represent a set of debug information, or a level of detail. The compiler flag `-DDEBUG=5` would, in this case, enable `BASIC_DEBUG` and `SUPER_DEBUG`, but not `EXTRA_DEBUG`. The flag `-DDEBUG=0` would disable all debug information. Alternatively, including the following lines eliminates the need to specify `DEBUG` on the command line in the case where no debugging is required:

```
#ifndef DEBUG
#define DEBUG 0
#endif
```

Several macros defined by the C preprocessor can help with debug information. These are macros that expand to give information about the current compilation.

| Macro | Description |
|-----------------------|---|
| <code>__LINE__</code> | A decimal constant representing the current line number |
| <code>__FILE__</code> | A string representing the current file name |
| <code>__DATE__</code> | A string of the form "Mmm dd yyyy", the current date |
| <code>__TIME__</code> | A string of the form "hh:mm:ss", the current time |

Note that these symbols are prefixed and suffixed by two underscores. This is common for standard pre-processor symbols, and you should take care to avoid choosing symbols that might clash. The term *current* in the above descriptions refers to the point at which the preprocessing is being performed, that is, the time and date the compiler was run and the file processed.

Try It Out—Debug Information

Here's a program, `cinfo.c`, that prints information about its compilation date and time if debugging is enabled.

```
#include <stdio.h>

int main()
{
#ifndef DEBUG
    printf("Compiled: " __DATE__ " at " __TIME__ "\n");
    printf("This is line %d of file %s\n", __LINE__, __FILE__);
#endif
    printf("hello world\n");
    exit(0);
}
```

When we compile this program with debug enabled (using `-DDEBUG`), we see the compilation information.

```
$ cc -o cinfo -DDEBUG cinfo.c
$ ./cinfo
Compiled: Mar 1 2003 at 18:17:32
This is line 7 of file cinfo.c
hello world
$
```

How It Works

The C preprocessor part of the compiler keeps track of the current line and file when it's compiling. It substitutes the current (compile time) values of these variables whenever it encounters the symbols `_LINE_` and `_FILE_`. The date and time of compilation are made available similarly. Since `_DATE_` and `_TIME_` are strings, we can concatenate them with format strings for `printf` because ANSI C specifies that adjacent strings be treated as one.

Debugging without Recompiling

Before we move on, it's worth mentioning that there's a way of using the `printf` function to help with debugging without using the `#ifdef DEBUG` technique, which requires a program to be recompiled before it can be used.

The method is to add a global variable as a debug flag, allow a `-d` option at the command line, which allows the user to switch debugging on even after the program has been released, and add a debug logging function. Now you can intersperse things like this in the program code:

```
if (debug) {
    sprintf(msg, ...)
    write_debug(msg)
}
```

You should write debug output to `stderr`, or, if this isn't practical because of the nature of the program, use the logging facilities provided by the `syslog` function.

If you add traces like this to solve problems during development, just leave the code in there. Provided you use a small amount of care, this can be quite safe. The benefit comes when the program has been released; if users encounter a problem, they can run it with debugging on and diagnose the errors for you. Instead of reporting that the program gave the message `segmentation fault`, they can also report exactly what the program was doing at the time, not just what the user was doing. The difference can be immense.

There is obviously a downside to this approach; the program is larger than it needs to be. In most cases, this is more an apparent problem than a real one. The program will probably be 20 percent or 30 percent larger, but in most cases this doesn't have any real impact on performance. Poor performance comes from increasing size by orders of magnitude, not by a mere doubling.

Controlled Execution

Let's get back to the example program. We have a bug. We can modify the program by adding additional code to print out the values of variables as the program runs, or we can use a debugger to control the program's execution and view its state as execution proceeds.

There are a number of debuggers available on commercial UNIX systems, depending on the vendor. Common ones are `adb`, `sdb`, and `dbx`. The more sophisticated ones allow us to look at the state of the program in some detail at a source code level. This is true of `sdb`, `dbx`, and also of the GNU debugger, `gdb`, which can be used with Linux. There also exist "front ends" to `gdb`, which make it more user-friendly; `xxgdb`, `tgdb`, and `ddd` are such programs. Some IDEs, such as the ones we saw in Chapter 9,

also provide debugging facilities or a front end to gdb. The Emacs editor also has a facility (`gdb-mode`) that allows you to run `gdb` on your program, set breakpoints, and see which line in the source code is being executed.

To prepare a program for debugging, you need to compile it with one or more special compiler options. These options instruct the compiler to include extra debugging information into the program. This information includes symbols and line numbers—information the debugger can use to show the user where in the source code execution has reached.

The `-g` flag is the usual one used to compile a program for debugging. We must use it for compiling each source file that needs to be debugged and also for the linker, so that special versions of the standard C library can be used to provide debug support in library functions. The compiler program will pass the flag to the linker automatically. Debugging can be used with libraries that aren't compiled for the purpose, but with less flexibility.

Debug information can make the executable many (up to ten) times larger. Even though the executable may be larger (and take up more disk space) the amount of memory the program needs to run is effectively the same. It is usually a good idea to remove debug information before you release your programs, but only after they have been debugged.

You can remove debug information from an executable file without recompiling by running `strip <file>`.

Debugging with gdb

We'll use the GNU debugger, `gdb`, to debug this program. It's a very capable debugger that is freely available and can be used on many UNIX platforms. It's also the default debugger on Linux systems. `gdb` has been ported to many other platforms and can be used to debug embedded real-time systems.

Starting gdb

Let's recompile our example program for debugging and start `gdb`.

```
$ cc -g -o debug3 debug3.c
$ gdb debug3
GNU gdb 5.2.1
Copyright 2002 Free Software Foundation, Inc.
GDB is free software, covered by the GNU General Public License, and you are
welcome to change it and/or distribute copies of it under certain conditions.
Type "show copying" to see the conditions.
There is absolutely no warranty for GDB. Type "show warranty" for details.
This GDB was configured as "i586-suse-linux"...
(gdb)
```

`gdb` has extensive online help and the complete manual is available as a set of files that can be viewed with the `info` program, or from within Emacs.

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```
(gdb) help
List of classes of commands:

aliases - Aliases of other commands
breakpoints - Making program stop at certain points
data - Examining data
files - Specifying and examining files
internals - Maintenance commands
obscure - Obscure features
running - Running the program
stack - Examining the stack
status - Status inquiries
support - Support facilities
tracepoints - Tracing of program execution without stopping the program
user-defined - User-defined commands
```

Type "help" followed by a class name for a list of commands in that class.

Type "help" followed by command name for full documentation.

Command name abbreviations are allowed if unambiguous.

```
(gdb)
```

gdb is itself a text-based application, but it does provide a few short cuts to help with repetitive tasks. Many versions have command-line editing with a history so that you can scroll back and execute the same command again (try using the cursor keys). All versions support an "empty command"; hitting Enter executes the last command again. This is especially useful when stepping through a program line by line with the step or next commands.

Running a Program

You can execute the program with the run command. Any arguments that you give to the run command are passed to the program as its arguments. In this case, we don't need any arguments.

We'll assume here that your system, like both the authors', is now generating a segmentation fault. If it isn't, read on. You'll find out what to do when one of your own programs does generate a segmentation violation. If you're not getting a segmentation violation, but want to work though this example as you read the book, you can pick up the program again at `debug4.c`, when the first of the memory access problems has been fixed.

```
(gdb) run
Starting program: /home/neil/BLP3/chapter10/debug3

Program received signal SIGSEGV, Segmentation fault.
0x080483c0 in sort (a=0x8049580, n=5) at debug3.c:23
23      /* 23 */           if(a[j].key > a[j+1].key) {
(gdb)
```

The program runs incorrectly as before. When the program faults, gdb shows us the reason and the location. We can now investigate the underlying cause of the problem.

Depending on your kernel, C library, and compiler version, you may see the program fault at a slightly different place, for example, on line 25, when array items are exchanged, rather than line 23, when array item keys are compared. If this is the case, you'll see something like

```
Program received signal SIGSEGV, Segmentation fault.
0x8000613 in sort (a=0x8001764, n=5) at debug3.c:25
25      /* 25 */           a[j] = a[j+1];
```

You should still be able to follow the `gdb` sample session that follows.

Stack Trace

The program has been halted in the `sort` function at line 23 of the source file `debug3.c`. If we hadn't compiled the program with additional debug information (`cc -g`), we wouldn't be able to see where the program had failed, nor would we be able to use variable names to examine data.

We can see how we got to this position by using the `backtrace` command.

```
(gdb) backtrace
#0 0x080483c0 in sort (a=0x8049580, n=5) at debug3.c:23
#1 0x0804849b in main () at debug3.c:37
#2 0x400414f2 in __libc_start_main () from /lib/libc.so.6
(gdb)
```

This is a very simple program, and the trace is short because we haven't called many functions from within other functions. You can see that `sort` was called from `main` at line 37 of the same file, `debug3.c`. Usually, the problem is much more complex and we use `backtrace` to discover the route we took to the error position. This can be very useful when debugging functions that are called from many different places.

The `backtrace` command may be abbreviated `bt`, and, for compatibility with other debuggers, the `where` command has the same function.

Examining Variables

The information printed by `gdb` when it stopped the program and in the stack trace shows us the values of function arguments.

The `sort` function was called with a parameter, `a`, that has the value `0x8049580`. This is the address of the array. It will typically be different on different systems, depending on the compiler used and the operating system.

The offending line, 23, is a comparison of one array element with another.

```
/* 23 */
if(a[j].key > a[j+1].key) {
```

We can use the debugger to examine the contents of function parameters, local variables, and global data. The `print` command shows us the contents of variables and other expressions.

```
(gdb) print j
$1 = 4
```

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Here we can see that the local variable `j` has the value 4. Any values reported by `gdb` commands like this are kept for future use in pseudo variables. Here the variable `$1` is assigned the value 4 in case we need it later. Subsequent commands will store their results as `$2`, `$3`, and so on.

The fact that `j` has the value 4 means that the program has attempted to execute the statement

```
if(a[4].key > a[4+1].key)
```

The array that we have passed to `sort`, `array`, has only five elements, which will be indexed 0 through 4. So this statement reads from the nonexistent `array[5]`. The loop variable `j` has taken an incorrect value.

If you are working through this example and your program faulted at line 25, your system detected a read past the end of the array only when it got to exchanging elements, executing

```
/* 25 */ a[j] = a[j+1];
```

which, with `j` set to 4, results in

```
a[4] = a[4+1];
```

We can take a look at the elements of the passed array by using an expression with `print`. With `gdb`, we can use almost any legal C expression to print the value of variables, array elements, and pointers.

```
(gdb) print a[3]
$2 = {data = "alex", '\000' <repeats 4091 times>, key = 1}
(gdb)
```

`gdb` keeps the results of commands in pseudo variables, `$<number>`. The last result is always `$`, and the one before that is `$$`. This allows one result to be used in another command. For example,

```
(gdb) print j
$3 = 4
(gdb) print a[$-1].key
$4 = 1
```

Listing the Program

We can view the source code of the program from within `gdb` by using the `list` command. This prints out a portion of the code around the current position. Subsequent uses of `list` will print out more. You can also give `list` a line number or function name as an argument and it will show the code at that position.

```
(gdb) list
18      /* 18 */     int s = 1;
19      /* 19 */
20      /* 20 */     for(; i < n && s != 0; i++) {
21      /* 21 */             s = 0;
22      /* 22 */             for(j = 0; j < n; j++) {
23      /* 23 */                 if(a[j].key > a[j+1].key) {
24      /* 24 */                     item t = a[j];
```

```

25      /* 25 */
26      /* 26 */
27      /* 27 */
(gdb)                                a[j] = a[j+1];
                                         a[j+1] = t;
                                         s++;

```

We can see that on line 22 that the loop is set to execute while the variable `j` is less than `n`. In this case, `n` is 5, so `j` will have the final value of 4, which is one too far. A value of 4 causes a comparison of `a[4]` with `a[5]` and possibly a swap. One solution to this particular problem is to correct the loop termination condition to be `j < n-1`.

Let's make that change, call the new program `debug4.c`, recompile, and try again.

```

/* 22 */
for(j = 0; j < n-1; j++) {
$ cc -g -o debug4 debug4.c
$ ./debug4
array[0] = {john, 2}
array[1] = {alex, 1}
array[2] = {bill, 3}
array[3] = {neil, 4}
array[4] = {rick, 5}

```

The program still doesn't work, as it has printed an incorrectly sorted list. Let's use `gdb` to step through the program as it runs.

Setting Breakpoints

To find out where the program is failing, we need to be able to see what it's doing as it runs. We can stop the program at any point by setting breakpoints. These cause the program to stop and return control to the debugger. We'll be able to inspect variables and then allow the program to continue.

There are two loops in the `sort` function. The outer loop, with loop variable `i`, is run once for each element in the array. The inner loop swaps the element with those further down the list. This has the effect of bubbling up the smaller elements to the top. After each run of the outer loop, the largest element should have made its way to the bottom. We can confirm this by stopping the program at the outer loop and examining the state of the array.

A number of commands are used for setting breakpoints. These are listed by `gdb` with `help breakpoint`:

```
(gdb) help breakpoint
Making program stop at certain points.
```

List of commands:

```

awatch – Set a watchpoint for an expression
break – Set breakpoint at specified line or function
catch – Set catchpoints to catch events
clear – Clear breakpoint at specified line or function
commands – Set commands to be executed when a breakpoint is hit
condition – Specify breakpoint number N to break only if COND is true
delete – Delete some breakpoints or auto-display expressions

```

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```
disable - Disable some breakpoints
enable - Enable some breakpoints
hbreak - Set a hardware assisted breakpoint
ignore - Set ignore-count of breakpoint number N to COUNT
rbreak - Set a breakpoint for all functions matching REGEXP
rwatch - Set a read watchpoint for an expression
tbreak - Set a temporary breakpoint
tcatch - Set temporary catchpoints to catch events
thbreak - Set a temporary hardware assisted breakpoint
watch - Set a watchpoint for an expression
```

Type "help" followed by command name for full documentation.
Command name abbreviations are allowed if unambiguous.

Let's set a breakpoint at line 20 and run the program:

```
$ gdb debug4
(gdb) break 20
Breakpoint 1 at 0x804835d: file debug4.c, line 20.
(gdb) run
Starting program: /home/neil/BLP3/chapter10/debug4

Breakpoint 1, sort (a=0x8049580, n=5) at debug4.c:20
20      /* 20 */      for(; i < n && s != 0; i++) {
```

We can print out the array value and then allow the program to continue with the `cont` command. This allows the program to run until it hits the next breakpoint, in this case, until it executes line 20 again. We can have many breakpoints active at any time.

```
(gdb) print array[0]
$1 = {data = "bill", '\000' <repeats 4091 times>, key = 3}
```

To print a number of consecutive items, we can use the construction `@<number>` to cause `gdb` to print a number of array elements. To print all five elements of `array`, we can use

```
(gdb) print array[0]@5
$2 = {{data = "bill", '\000' <repeats 4091 times>, key = 3}, {
      data = "neil", '\000' <repeats 4091 times>, key = 4}, {
      data = "john", '\000' <repeats 4091 times>, key = 2}, {
      data = "rick", '\000' <repeats 4091 times>, key = 5}, {
      data = "alex", '\000' <repeats 4091 times>, key = 1}}
```

Note that the output has been tidied up slightly to make it easier to read. Because this is the first time through the loop, the array is unchanged. When we allow the program to continue, we see successive alterations to `array` as execution proceeds:

```
(gdb) cont
Continuing.

Breakpoint 1, sort (a=0x8049580, n=4) at debug4.c:20
20      /* 20 */      for(; i < n && s != 0; i++) {
```

```
(gdb) print array[0]@5
$3 = {{data = "bill", '\000' <repeats 4091 times>, key = 3}, {
       data = "john", '\000' <repeats 4091 times>, key = 2}, {
       data = "neil", '\000' <repeats 4091 times>, key = 4}, {
       data = "alex", '\000' <repeats 4091 times>, key = 1}, {
       data = "rick", '\000' <repeats 4091 times>, key = 5}}
(gdb)
```

We can use the `display` command to set gdb to display the array automatically whenever the program stops at a breakpoint:

```
(gdb) display array[0]@5
1: array[0] @ 5 = {{data = "bill", '\000' <repeats 4091 times>, key = 3}, {
       data = "john", '\000' <repeats 4091 times>, key = 2}, {
       data = "neil", '\000' <repeats 4091 times>, key = 4}, {
       data = "alex", '\000' <repeats 4091 times>, key = 1}, {
       data = "rick", '\000' <repeats 4091 times>, key = 5}}
```

Furthermore, we can change the breakpoint so that, instead of stopping the program, it simply displays the data we have requested and carries on. To do this, we use the `commands` command. This allows us to specify what debugger commands to execute when a breakpoint is hit. Since we have already specified a `display`, we need only set the `breakpoint` command to continue execution.

```
(gdb) commands
Type commands for when breakpoint 1 is hit, one per line.
End with a line saying just "end".
> cont
> end
```

Now when we allow the program to continue, it runs to completion, printing the value of the array each time around the outer loop.

```
(gdb) cont
Continuing.

Breakpoint 1, sort (a=0x8049684, n=3) at debug4.c:20
20      /* 20 */      for(; i < n && s != 0; i++) {
1: array[0] @ 5 = {{data = "john", '\000' <repeats 4091 times>, key = 2}, {
       data = "bill", '\000' <repeats 4091 times>, key = 3}, {
       data = "alex", '\000' <repeats 4091 times>, key = 1}, {
       data = "neil", '\000' <repeats 4091 times>, key = 4}, {
       data = "rick", '\000' <repeats 4091 times>, key = 5}

Breakpoint 1, sort (a=0x8049684, n=2) at debug4.c:20
20      /* 20 */      for(; i < n && s != 0; i++) {
1: array[0] @ 5 = {{data = "john", '\000' <repeats 4091 times>, key = 2}, {
       data = "alex", '\000' <repeats 4091 times>, key = 1}, {
       data = "bill", '\000' <repeats 4091 times>, key = 3}, {
       data = "neil", '\000' <repeats 4091 times>, key = 4}, {
       data = "rick", '\000' <repeats 4091 times>, key = 5}}
array[0] = {john, 2}
array[1] = {alex, 1}
```

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```
array[2] = {bill, 3}
array[3] = {neil, 4}
array[4] = {rick, 5}

Program exited with code 044.
(gdb)
```

`gdb` reports that the program exits with an unusual exit code. This is because the program itself doesn't call `exit` and doesn't return a value from `main`. The exit code is effectively meaningless in this case, and a meaningful one ought to be provided by a call to `exit`.

The program doesn't seem to execute the outer loop as many times as we expected. We can see that the value of the parameter, `n`, used in the loop termination condition is reducing at each breakpoint. This means that the loop won't execute enough times. The culprit is the decrement of `n` on line 30:

```
/* 30 */          n--;
```

This is an attempt to optimize the program by taking advantage of the fact that at the end of each outer loop the largest element of `array` will be at the bottom, and so there is less left to sort. But, as we've seen, this interferes with the outer loop and causes problems. The simplest fix (though there are others) is to delete the offending line. Let's test whether this change will fix the problem by using the debugger to apply a patch.

Patching with the Debugger

We've already seen that we can use the debugger to set breakpoints and examine the value of variables. By using a breakpoint with actions, we can try out a fix, called a *patch*, before changing the source code and recompiling. In this case, we need to break the program on line 30 and increment the variable `n`. Then, when line 30 is executed, the value will be unchanged.

Let's restart the program from the beginning. First, we must delete our breakpoint and display. We can see what breakpoints and displays we have enabled using the `info` command:

```
(gdb) info display
Auto-display expressions now in effect:
Num Enb Expression
1: y array[0] @ 5
(gdb) info break
Num Type            Disp Enb Address      What
1  breakpoint       keep y  0x0804835d in sort at debug4.c:20
                                breakpoint already hit 4 times
                                cont
```

We can either disable these or delete them entirely. If we disable them, we retain the option to re-enable them at a later time if we need to:

```
(gdb) disable break 1
(gdb) disable display 1
(gdb) break 30
Breakpoint 2 at 0x8048462: file debug4.c, line 30.
(gdb) commands 2
```

```
Type commands for when breakpoint 2 is hit, one per line.  
End with a line saying just "end".  
>set variable n = n+1  
>cont  
>end  
(gdb) run  
Starting program: /home/neil/BLP3/chapter10/debug4  
  
Breakpoint 2, sort (a=0x8049580, n=5) at debug4.c:30  
30      /* 30 */          n--;  
  
Breakpoint 2, sort (a=0x8049580, n=5) at debug4.c:30  
30      /* 30 */          n--;  
  
Breakpoint 2, sort (a=0x8049580, n=5) at debug4.c:30  
30      /* 30 */          n--;  
  
Breakpoint 2, sort (a=0x8049580, n=5) at debug4.c:30  
30      /* 30 */          n--;  
  
Breakpoint 2, sort (a=0x8049580, n=5) at debug4.c:30  
30      /* 30 */          n--;  
array[0] = {alex, 1}  
array[1] = {john, 2}  
array[2] = {bill, 3}  
array[3] = {neil, 4}  
array[4] = {rick, 5}  
  
Program exited with code 044.  
(gdb)
```

The program runs to completion and prints the correct result. We can now make the change and move on to test it with more data.

Learning More about gdb

The GNU debugger is an exceptionally powerful tool that can provide a lot of information about the internal state of executing programs. On systems that support a facility called *hardware breakpoints*, you can use gdb to monitor changes to variables in real time. Hardware breakpoints are a feature of some CPUs; these processors are able to stop automatically if certain conditions arise, typically a memory access in a given region. Alternatively, gdb can *watch* expressions. This means that, with a performance penalty, gdb can stop a program when an expression takes a particular value, regardless of where in the program the calculation took place.

Breakpoints can be set with counts and conditions so that they trigger only after a fixed number of times or when a condition is met.

gdb is also able to attach itself to programs that are already running. This can be very useful when you're debugging client/server systems, as you can debug a misbehaving server process as it runs without having to stop and restart it. You can compile programs with, for example, `gcc -O -g` to get the benefit of optimization and debug information. The downside is that optimization may reorder code

a bit, so, as you single-step through code, you may find yourself jumping around to achieve the same effect as intended by the original source code.

You can also use `gdb` to debug programs that have crashed. Linux and UNIX will often produce a core dump in a file called `core` when a program fails. This is an image of the program's memory and will contain the values of global variables at the time of the failure. You can use `gdb` to work out where the program was when it crashed. Check out the `gdb` manual page for more details.

`gdb` is available under the terms of the GNU Public License and most UNIX systems can support it. We strongly recommend that you get to know it.

More Debugging Tools

Apart from out-and-out debuggers such as `gdb`, Linux systems typically provide a number of other tools that you can use to aid the debugging process. Some of these provide static information about a program; others provide a dynamic analysis.

Static analysis provides information from the program source code only. Programs such as `ctags`, `cxref`, and `cflow` work with the source files and provide useful information about function calling and location.

Dynamic analysis provides information about how a program behaves during execution. Programs such as `prof` and `gprof` provide information about which functions have been executed and for how long.

Let's take a look at some of these tools and their output. Not all of these tools will be available on all systems, although many of them have freely available versions.

Lint: Removing the Fluff from Your Programs

Original UNIX systems provided a utility called `lint`. It was essentially the front end of a C compiler with added tests designed to apply some common sense and produce warnings. It would detect cases where variables were used before being set and where function arguments were not used, among other things.

More modern C compilers can, at a cost to compile-time performance, produce similar warnings. `lint` itself has been overtaken by the standardization of C. Because the tool was based on an early C compiler, it doesn't cope at all well with ANSI syntax. There are some commercial versions of `lint` available for UNIX and at least one on the Internet for Linux, called `splint`. This used to be known as LClint, part of a project at MIT to produce tools for formal specifications. A `lint`-like tool, `splint` can provide useful code review comments. `splint` can be found at <http://www.splint.org>.

Here's an edited sample output from `splint` running on an early version of the example program that we debugged earlier:

```
neil@beast:~/BLP3/chapter10> splint -strict debug0.c
Splint 3.0.1.6 --- 27 Mar 2002

debug0.c:14:22: Old style function declaration
```

```

Function definition is in old style syntax. Standard prototype syntax is
preferred. (Use -oldstyle to inhibit warning)
debug0.c: (in function sort)
debug0.c:20:31: Variable s used before definition
    An rvalue is used that may not be initialized to a value on some execution
    path. (Use -usedef to inhibit warning)
debug0.c:20:23: Left operand of & is not unsigned value (boolean):
    i < n & s != 0
    An operand to a bitwise operator is not an unsigned values. This may have
    unexpected results depending on the signed representations. (Use
    -bitwisesigned to inhibit warning)
debug0.c:20:23: Test expression for for not boolean, type unsigned int:
    i < n & s != 0
    Test expression type is not boolean or int. (Use -predboolint to inhibit
    warning)
debug0.c:20:23: Operands of & are non-integer (boolean) (in post loop test):
    i < n & s != 0
    A primitive operation does not type check strictly. (Use -strictops to
    inhibit warning)
debug0.c:32:14: Path with no return in function declared to return int
    There is a path through a function declared to return a value on which there
    is no return statement. This means the execution may fall through without
    returning a meaningful result to the caller. (Use -noret to inhibit warning)
debug0.c:34:13: Function main declared without parameter list
    A function declaration does not have a parameter list. (Use -noparams to
    inhibit warning)
debug0.c: (in function main)
debug0.c:36:17: Return value (type int) ignored: sort(array, 5)
    Result returned by function call is not used. If this is intended, can cast
    result to (void) to eliminate message. (Use -retvalint to inhibit warning)
debug0.c:37:14: Path with no return in function declared to return int
debug0.c:14:13: Function exported but not used outside debug0: sort
debug0.c:15:17: Definition of sort

Finished checking --- 22 code warnings
$
```

The utility complains about old-style (non-ANSI) function declarations and inconsistencies between function return types and the values they do (or do not) return. These don't affect the operation of the program, but ought to be addressed.

It has also detected two real bugs in the following code fragment:

```

/* 18 */     int s;
/* 19 */
/* 20 */     for(; i < n & s != 0; i++) {
/* 21 */         s = 0;
```

The `splint` tool has determined that the variable `s` is used on line 20, but hasn't been initialized and that the operator `&` has been used in place of the more usual `&&`. In this case, the operator precedence alters the meaning of the test and is a problem for the program.

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Both of these errors were fixed in a code review before debugging started. Although this example is a little contrived for the purposes of demonstration, these are errors that regularly crop up in real world programs.

Function Call Tools

Three utilities—ctags, cxref, and cflow—form part of the X/Open specification and therefore must be present on UNIX-branded systems with software development capabilities.

These utilities and others mentioned in this chapter may not be present in your Linux distribution. If not, you might like to search for implementations on the Internet. A good place to start (for Linux distributions that support the RPM package format) is <http://rufus.w3.org/linux/RPM>.

ctags

The ctags program creates an index of functions. For each function, you get a list of the places it's used, like the index of a book.

```
ctags [-a] [-f filename] sourcefile sourcefile ...
ctags -x sourcefile sourcefile ...
```

By default, ctags creates a file, called `tags`, in the current directory, which contains, for each function declared in any of the input source files, lines of the form

```
announce      app_ui.c      ^static void announce(void) /
```

Each line in the file consists of a function name, the file it's declared in, and a regular expression that can be used to find the function definition within the file. Some editors such as Emacs can use files of this kind to help navigate through source code.

Alternatively, by using the `-x` option to ctags (if available in your version), you can produce lines of a similar form on the standard output:

```
find_cat      403 app_ui.c      static cdc_entry find_cat(
```

You can redirect the output to a different file by using the option `-f filename` and append it to an existing file by specifying the `-a` option.

cxref

The cxref program analyzes C source code and produces a cross-reference. It shows where each symbol (variable, `#define`, and function) is mentioned in the program. It produces a sorted list with each symbol's definition location marked with an asterisk, as shown here:

| SYMBOL | FILE | FUNCTION | LINE |
|---------|--------|----------|-----------------------------|
| BASENID | prog.c | — | *12 *96 124 126 146 156 166 |
| BINSIZE | prog.c | — | *30 197 198 199 206 |

| | | | | | |
|----------|----------------------|------|-----|-----|----|
| BUFSIZE | prog.c | - | *44 | 45 | 90 |
| BUFSIZ | /usr/include/stdio.h | - | *4 | | |
| EOF | /usr/include/stdio.h | - | *27 | | |
| argc | prog.c | - | 36 | | |
| | prog.c | main | *37 | 61 | 81 |
| argv | prog.c | - | 36 | | |
| | prog.c | main | *38 | 61 | |
| calldata | prog.c | - | *5 | | |
| | prog.c | main | 64 | 188 | |
| calls | prog.c | - | *19 | | |
| | prog.c | main | 54 | | |

On the author's machine, the preceding output was generated in the source directory of an application, with the command

```
$ cxref *.c *.h
```

but the exact syntax varies from version to version. Consult the documentation for your system or the man pages for more information on whether cxref is available and how to use it.

cflow

The cflow program prints a *function call tree*, a diagram that shows which functions call others, and which functions are called by them, and so on. It can be useful to find out the structure of a program to understand how it operates and to see what impact changes to a function will have. Some versions of cflow can operate on object files as well as source code. Refer to the manual page for details of operation.

Here's some sample output taken from a version of cflow (cflow-2.0) that is available on the Internet and maintained by Marty Leisner:

```

1      file_ungetc {prcc.c 997}
2      main {prcc.c 70}
3          getopt {}
4          show_all_lists {prcc.c 1070}
5              display_list {prcc.c 1056}
6                  printf {}
7                  exit {}
8          exit {}
9          usage {prcc.c 59}
10             fprintf {}
11             exit {}
```

This sample tells us that main calls (among others) show_all_lists and that show_all_lists in turn calls display_list, which itself calls printf.

One option to this version of cflow is -i, which produces an inverted flow graph. For each function, cflow lists the other functions that make a call to it. It sounds complicated, but it really isn't. Here's a sample.

```

19      display_list {prcc.c 1056}
20          show_all_lists {prcc.c 1070}
21      exit {}
22      main {prcc.c 70}
```

```
23             show_all_lists {prcc.c 1070}
24             usage {prcc.c 59}
...
74     printf {}
75         display_list {prcc.c 1056}
76         maketag {prcc.c 487}
77     show_all_lists {prcc.c 1070}
78         main {prcc.c 70}
...
99     usage {prcc.c 59}
100    main {prcc.c 70}
```

This shows us that the functions that call `exit`, for example, are `main`, `show_all_lists`, and `usage`.

Execution Profiling with `prof/gprof`

A technique that is often useful when you're trying to track down performance problems with a program is *execution profiling*. Normally supported by special compiler options and ancillary programs, a profile of a program shows where it's spending its time.

The `prof` program (and its GNU equivalent, `gprof`) prints a report from an execution trace file that is produced when a profiled program is run. A profiled executable is created by specifying the `-p` flag (for `prof`) or `-pg` flag (for `gprof`) to the compiler:

```
$ cc -pg -o program program.c
```

The program is linked with a special version of the C library and is changed to include monitoring code. This may vary with specific systems, but is commonly achieved by arranging for the program to be interrupted frequently and the execution location to be recorded. The monitor data is written to a file in the current directory, `mon.out` (`gmon.out` for `gprof`).

```
$ ./program
$ ls -ls
2 -rw-r--r-- 1 neil      users          1294 Feb  4 11:48 gmon.out
```

The `prof/gprof` program reads this monitoring data and produces a report. Refer to the manual pages for detail on program options. Here is some (abbreviated) `gprof` output as an example:

| cumulative | self | self | total | | | | |
|------------|---------|---------|--------|---------|---------|--|-----------------|
| time | seconds | seconds | calls | ms/call | ms/call | | name |
| 18.5 | 0.10 | 0.10 | 8664 | 0.01 | 0.03 | | _doscan [4] |
| 18.5 | 0.20 | 0.10 | | | | | mcount (60) |
| 14.8 | 0.28 | 0.08 | 43320 | 0.00 | 0.00 | | _number [5] |
| 9.3 | 0.33 | 0.05 | 8664 | 0.01 | 0.01 | | _format_arg [6] |
| 7.4 | 0.37 | 0.04 | 112632 | 0.00 | 0.00 | | _ungetc [8] |
| 7.4 | 0.41 | 0.04 | 8757 | 0.00 | 0.00 | | _memccpy [9] |
| 7.4 | 0.45 | 0.04 | 1 | 40.00 | 390.02 | | _main [2] |
| 3.7 | 0.47 | 0.02 | 53 | 0.38 | 0.38 | | _read [12] |
| 3.7 | 0.49 | 0.02 | | | | | w4str [10] |
| 1.9 | 0.50 | 0.01 | 26034 | 0.00 | 0.00 | | _strlen [16] |
| 1.9 | 0.51 | 0.01 | 8664 | 0.00 | 0.00 | | strcmp [17] |

Assertions

While it's common to introduce debug code such as `printf` calls, possibly by conditional compilation, during the development of a program, it's sometimes impractical to leave these messages in a delivered system. However, it's often the case that problems occur during the program operation that are related to incorrect assumptions rather than coding errors. These are events that "can't happen." For example, a function may be written with the understanding that its input parameters will be within a certain range. If it's passed incorrect data, it might invalidate the whole system.

For these cases, where the internal logic of the system needs to be confirmed, X/Open provides the `assert` macro that can be used to test that an assumption is correct and halt the program if not.

```
#include <assert.h>
void assert(int expression)
```

The `assert` macro evaluates the expression and, if it's nonzero, writes some diagnostic information to the standard error and calls `abort` to end the program.

The header file `assert.h` defines the macro depending on the definition of `NDEBUG`. If `NDEBUG` is defined when the header file is processed, `assert` is defined to be essentially nothing. This means that you can turn off assertions at compile time by compiling with `-DNDEBUG` or by including the line

```
#define NDEBUG
```

in each source file before including `assert.h`.

This method of use is one problem with `assert`. If you use `assert` during testing, but turn it off for production code, your production code could have less safety checking than when you are testing it. Leaving assertions enabled in production code is not normally an option—would you like your code to present a customer with the unfriendly error `assert failed` and a stopped program? You may consider it better to write your own error trapping routine that still checks the assertion but doesn't need to be completely disabled in production code.

You must also be careful that there are no side effects in the `assert` expression. For example, if you use a function call with a side effect, the effect won't happen in the production code if assertions are removed.

Try It Out—`assert`

Here's a program, `assert.c`, that defines a function that must take a positive value. It protects against the possibility of a bad argument by using an assertion.

After including the `assert.h` header file and a "square root" function that checks that the parameter is positive, we can then write the `main` function:

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

double my_sqrt(double x)
{
```

```
    assert(x >= 0.0);
    return sqrt(x);
}

int main()
{
    printf("sqrt +2 = %g\n", my_sqrt(2.0));
    printf("sqrt -2 = %g\n", my_sqrt(-2.0));
    exit(0);
}
```

Now when we run the program, we see an assertion violation when we pass an illegal value. The exact format of the assertion failure message will vary from system to system.

```
$ cc -o assert assert.c -lm
$ ./assert
sqrt +2 = 1.41421
assert: assert.c:7: my_sqrt: Assertion `x >= 0.0' failed.
Aborted
$
```

How It Works

When we try to call the function `my_sqrt` with a negative number, the assertion fails. The `assert` macro provides the file and line number where the assertion violation occurred, as well as the condition that failed. The program terminates with an abort trap. This is the result of `assert` calling `abort`.

If we recompile the program with `-DNDEBUG`, the assertion is compiled out and we get a mathematical error when we call the `sqrt` function from `my_sqrt`.

```
$ cc -o assert -DNDEBUG assert.c -lm
$ ./assert
sqrt +2 = 1.41421
Floating point exception
$
```

Some more recent mathematics library versions will return a NaN (Not a Number) value indicating an invalid result.

```
sqrt -2 = nan
```

Memory Debugging

One area that is a rich source of bugs that are difficult to track down is dynamic memory allocation. If you write a program that uses `malloc` and `free` to allocate memory, it's important that you keep good track of the blocks you allocate and make sure that you don't use a block that you've freed up.

Typically, memory blocks are allocated by `malloc` and assigned to pointer variables. If the pointer variable is changed and there are no other pointers pointing to the memory block, it will become inaccessible. This is a memory leak and it causes your program to grow in size. If you leak a lot of memory, your system will eventually slow down and run out of memory.

If you write beyond the end of an allocated block (or before the beginning of a block), you'll very likely corrupt the data structures used by the `malloc` library to keep track of allocations. In this case, at some future time, a call to `malloc`, or even `free`, will cause a segmentation violation and your program will crash. Tracking down the precise point at which the fault occurred can be very difficult, as it may have happened a long time before the event that caused the crash.

Unsurprisingly, there are tools, commercial and free, that can help with these two problem types. There are, for example, many different versions of `malloc` and `free`, some of which contain additional code to check on allocations and deallocations to try to cater for the cases where a block is freed twice and some other types of misuse.

ElectricFence

The ElectricFence library was developed by Bruce Perens and is available as an optional component in some Linux distributions such as RedHat and can be readily found on the Internet. It attempts to use the virtual memory facilities of Linux to protect the memory used by `malloc` and `free` to halt the program at the point of memory corruption.

Try It Out—ElectricFence

Here's a program, `efence.c`, that allocates a memory block with `malloc` and then writes beyond the end of the block. Let's see what happens.

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

int main()
{
    char *ptr = (char *) malloc(1024);
    ptr[0] = 0;

    /* Now write beyond the block */
    ptr[1024] = 0;
    exit(0);
}
```

When we compile and run the program, we see no untoward behavior. However, it's likely that the `malloc` memory area has sustained some corruption and we would eventually run into trouble.

```
$ cc -o efence efence.c
$ ./efence
$
```

However, if we take exactly the same program and link with the ElectricFence library, `libefence.a`, we get an immediate response.

```
$ cc -o efence efence.c -lefence
$ ./efence
```

```
Electric Fence 2.2.0 Copyright (C) 1987-1999 Bruce Perens <bruce@perens.com>
Segmentation fault
$
```

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Running under the debugger pinpoints the problem:

```
$ cc -g -o efence efence.c -lefence
$ gdb efence
(gdb) run
Starting program: /home/neil/BLP3/chapter10/efence
[New Thread 1024 (LWP 1869)]

Electric Fence 2.2.0 Copyright (C) 1987-1999 Bruce Perens <bruce@perens.com>

Program received signal SIGSEGV, Segmentation fault.
[Switching to Thread 1024 (LWP 1869)]
0x080484ad in main () at efence.c:10
10          ptr[1024] = 0;
(gdb)
```

How It Works

ElectricFence replaces `malloc` and associated functions with versions that use virtual memory features of the computer's processor to protect against illegal memory access. When such an access occurs, a segmentation violation signal is raised and the program halts.

valgrind

`valgrind` is a tool that is capable of detecting many of the problems that we have discussed. In particular, it can detect array access errors and memory leaks. It may not be included with your Linux distributions but can be found at <http://developer.kde.org/~sewardj>.

Programs do not even need to be recompiled to use `valgrind`, and you can even debug the memory accesses of a running program. It is well worth a look; it has been used on major developments, including KDE version 3.

Try It Out—`valgrind`

Here's a program, `checker.c`, that allocates some memory, reads a location beyond the limit of that memory, writes beyond the end of it, and then makes it inaccessible.

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

int main()
{
    char *ptr = (char *) malloc(1024);
    char ch;

    /* Uninitialized read */
    ch = ptr[1024];

    /* Write beyond the block */
    ptr[1024] = 0;
```

```
/* Orphan the block */
ptr = 0;
exit(0);
}
```

To use valgrind, we simply have to run the valgrind command passing options that we would like to check, followed by the program to run with its arguments (if any).

When we run our program with valgrind, we see many problems diagnosed:

```
$ valgrind --leak-check=yes -v ./checker
==3436== valgrind-1.0.4, a memory error detector for x86 GNU/Linux.
==3436== Copyright (C) 2000-2002, and GNU GPL'd, by Julian Seward.
==3436== Estimated CPU clock rate is 452 MHz
==3436== For more details, rerun with: -v
==3436==
==3436== Invalid read of size 1
==3436==    at 0x8048397: main (checker.c:10)
==3436==    by 0x402574F2: __libc_start_main (in /lib/libc.so.6)
==3436==    by 0x80482D1: exit@@GLIBC_2.0 (in /home/neil/BLP3/chapter10/checker)
==3436==    Address 0x42AD1424 is 0 bytes after a block of size 1024 alloc'd
==3436==    at 0x4003CA75: malloc (vg_clientfuncs.c:100)
==3436==    by 0x8048389: main (checker.c:6)
==3436==    by 0x402574F2: __libc_start_main (in /lib/libc.so.6)
==3436==    by 0x80482D1: exit@@GLIBC_2.0 (in /home/neil/BLP3/chapter10/checker)
==3436==
==3436== Invalid write of size 1
==3436==    at 0x80483A4: main (checker.c:13)
==3436==    by 0x402574F2: __libc_start_main (in /lib/libc.so.6)
==3436==    by 0x80482D1: exit@@GLIBC_2.0 (in /home/neil/BLP3/chapter10/checker)
==3436==    Address 0x42AD1424 is 0 bytes after a block of size 1024 alloc'd
==3436==    at 0x4003CA75: malloc (vg_clientfuncs.c:100)
==3436==    by 0x8048389: main (checker.c:6)
==3436==    by 0x402574F2: __libc_start_main (in /lib/libc.so.6)
==3436==    by 0x80482D1: exit@@GLIBC_2.0 (in /home/neil/BLP3/chapter10/checker)
==3436==
==3436== ERROR SUMMARY: 2 errors from 2 contexts (suppressed: 0 from 0)
==3436== malloc/free: in use at exit: 1024 bytes in 1 blocks.
==3436== malloc/free: 1 allocs, 0 frees, 1024 bytes allocated.
==3436== For counts of detected errors, rerun with: -v
==3436== searching for pointers to 1 not-freed blocks.
==3436== checked 3468724 bytes.
==3436==
==3436== definitely lost: 1024 bytes in 1 blocks.
==3436== possibly lost: 0 bytes in 0 blocks.
==3436== still reachable: 0 bytes in 0 blocks.
==3436==
==3436== 1024 bytes in 1 blocks are definitely lost in loss record 1 of 1
==3436==    at 0x4003CA75: malloc (vg_clientfuncs.c:100)
==3436==    by 0x8048389: main (checker.c:6)
==3436==    by 0x402574F2: __libc_start_main (in /lib/libc.so.6)
==3436==    by 0x80482D1: exit@@GLIBC_2.0 (in /home/neil/BLP3/chapter10/checker)
```

```
==3436==  
==3436== LEAK SUMMARY:  
==3436==   definitely lost: 1024 bytes in 1 blocks.  
==3436==   possibly lost: 0 bytes in 0 blocks.  
==3436==   still reachable: 0 bytes in 0 blocks.  
==3436== Reachable blocks (those to which a pointer was found) are not shown.  
==3436== To see them, rerun with: --show-reachable=yes  
==3436== $
```

Here we can see that the bad reads and writes have been caught and the memory blocks concerned are given along with the place they were allocated. We can use the debugger to break the program at the point of the error.

There are many options to valgrind, including the suppression of certain types of error and memory-leak detection. To detect our example leak, we must use one of the options that are passed to valgrind. To check for memory leaks when the program ends, we need to specify `--leak-check=yes`. You can get a list of options with `valgrind --help`.

How It Works

Our program is executed under the control of valgrind, which intercepts various actions our program takes and performs many checks—including memory accesses. If the access concerns an allocated memory block and is illegal, valgrind prints a message. At the end of the program, a garbage collection routine is run that determines if any memory blocks have been allocated but not freed. These orphaned blocks are reported.

Summary

In this chapter, we've looked at some debugging tools and techniques. Linux provides some powerful aids to help with removing defects from programs. We eliminated some bugs from a program using `gdb` and looked at some static analysis tools such as `cflow` and `splint`. Finally, we looked at problems that arise when we use dynamically allocated memory and some utilities that can help diagnose them, such as `ElectricFence` and `valgrind`.

The utility programs discussed in this chapter have mostly been made available on FTP servers on the Internet. The authors concerned may, in some cases, retain copyright. Many of the utilities were taken from the Linux archive <http://www.ibiblio.org/pub/Linux> and we expect that new versions will be found there as they are released.

11

Processes and Signals

Processes and signals form a fundamental part of the Linux operating environment. They control almost all activities performed by Linux and all other UNIX-like computer systems. An understanding of how Linux and UNIX manage processes will hold any systems programmer, applications programmer, or system administrator in good stead.

In this chapter, we'll look at how processes are handled in the Linux environment and how to find out exactly what the computer is doing at any given time. We'll also see how to start and stop other processes from within our own programs, how to make processes send and receive messages, and how to avoid zombies. In particular, we'll learn about

- ❑ Process structure, type, and scheduling
- ❑ Starting new processes in different ways
- ❑ Parent, child, and zombie processes
- ❑ What signals are and how to use them

What Is a Process?

The Single UNIX Specification, Version 2 (UNIX98) and its predecessor Version 1 (UNIX95), defines a process as “an address space with one or more threads executing within that address space, and the required system resources for those threads.” We will look at threads in Chapter 12. For now, we will regard a process as just a program that is running.

A multitasking operating system such as Linux lets many programs run at once. Each instance of a running program constitutes a process. This is especially evident with a windowing system such as the X Window System (often simply called X). Like Windows, X provides a graphical user interface that allows many applications to be run at once. Each application can display one or more windows.

As a multiuser system, Linux allows many users to access the system at the same time. Each user can run many programs, or even many instances of the same program, at the same time. The system itself runs other programs to manage system resources and control user access.

As we saw in Chapter 4, a program—or process—that is running consists of program code, data, variables (occupying system memory), open files (file descriptors), and an environment. Typically, a Linux system will share code and system libraries among processes so that there’s only one copy of the code in memory at any one time.

Process Structure

Let’s have a look at how a couple of processes might be arranged within the operating system. If two users, `neil` and `rick`, both run the `grep` program at the same time to look for different strings in different files, the processes being used might look like Figure 11-1.

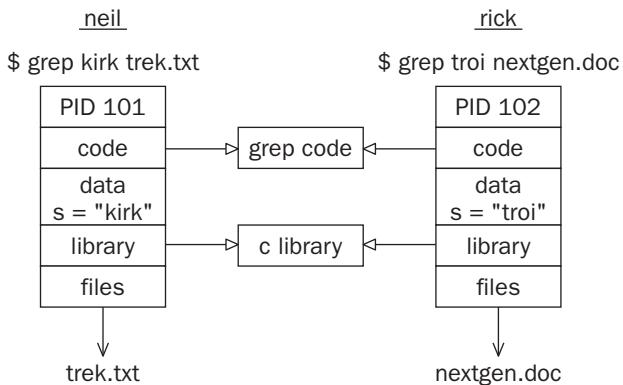


Figure 11-1

If we run the `ps` command, described as follows, the output will look something like this:

```
$ ps -af
UID      PID  PPID   C   STIME   TTY      TIME     CMD
rick     101    96   0 18:24  tty2  00:00:00  grep pid_t /usr/include/sys/*.h
neil     102    92   0 18:24  tty4  00:00:00  grep XOPEN /usr/include/features.h
```

Each process is allocated a unique number, called a *process identifier* or *PID*. This is usually a positive integer between 2 and 32,768. When a process is started, the next unused number in sequence is chosen and the numbers restart at 2 so that they wrap around. The number 1 is typically reserved for the special `init` process, which manages other processes. We will come back to `init` shortly. Here we see that the two processes started by `neil` and `rick` have been allocated the identifiers 101 and 102.

The program code that will be executed by the `grep` command is stored in a disk file. Normally, a Linux process can’t write to the memory area used to hold the program code, so the code is loaded into memory as read-only. We saw in Figure 11-1 that, although this area can’t be written to, it can safely be shared.

The system libraries can also be shared. Thus, there need be only one copy of `printf`, for example, in memory, even if many running programs call it. This is a more sophisticated, but similar, scheme to the way dynamic link libraries (DLLs) work in Windows.

As we can see in the preceding diagram, an additional benefit is that the disk file containing the executable program `grep` is smaller because it doesn't contain shared library code. This might not seem much for a single program, but extracting the common routines for (say) the standard C library saves a significant amount of space over a whole operating system.

Of course, not everything that a program needs to run can be shared. For example, the variables that it uses are distinct for each process. In this example, we see that the search string passed to the `grep` command appears as a variable, `s`, in the data space of each process. These are separate and usually can't be read by other processes. The files that are being used in the two `grep` commands are also different; the processes have their own set of file descriptors used for file access.

Additionally, a process has its own stack space, used for local variables in functions and for controlling function calls and returns. It also has its own environment space, containing environment variables that may be established solely for this process to use, as we saw when we looked at `putenv` and `getenv` in Chapter 4. A process must also maintain its own program counter, a record of where it has got to in its execution, which is the execution thread. In the next chapter we will see that when we use threads, processes can have more than one thread of execution.

On many Linux systems, and some UNIX systems, there is a special set of "files" in a directory called `/proc`. These are special in that rather than being true files they allow you to "look inside" processes while they are running as if they were files in directories. We took a brief look at the `/proc` file system back in Chapter 3.

Finally, because Linux, like UNIX, has a virtual memory system that pages code and data out to an area of the hard disk, many more processes can be managed than would fit into the physical memory.

The Process Table

The Linux *process table* is like a data structure describing all of the processes that are currently loaded with, for example, their PID, status, and command string, the sort of information output by `ps`. The operating system manages processes using their PIDs, and they are used as an index into the process table. The table is of limited size, so the number of processes a system will support is limited. Early UNIX systems were limited to 256 processes. More modern implementations have relaxed this restriction considerably and may be limited only by the memory available to construct a process table entry.

Viewing Processes

The `ps` command shows the processes we're running, the process another user is running, or all the processes on the system. Here is some sample output:

```
$ ps -af
UID      PID  PPID  C STIME TTY          TIME CMD
root      433   425  0 18:12  tty1        00:00:00  [bash]
rick      445   426  0 18:12  tty2        00:00:00  -bash
rick      456   427  0 18:12  tty3        00:00:00  [bash]
```

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```
root      467  433  0 18:12  tty1      00:00:00 sh /usr/X11R6/bin/startx
root      474  467  0 18:12  tty1      00:00:00 xinit /etc/X11/xinit/xinitrc --
root      478  474  0 18:12  tty1      00:00:00 /usr/bin/gnome-session
root      487    1  0 18:12  tty1      00:00:00 gnome-smproxy --sm-client-id def
root      493    1  0 18:12  tty1      00:00:01 [enlightenment]
root      506    1  0 18:12  tty1      00:00:03 panel --sm-client-id default8
root      508    1  0 18:12  tty1      00:00:00 xscreensaver -no-splash -timeout
root      510    1  0 18:12  tty1      00:00:01 gmc --sm-client-id default10
root      512    1  0 18:12  tty1      00:00:01 gnome-help-browser --sm-client-i
root      649  445  0 18:24  tty2      00:00:00 su
root      653  649  0 18:24  tty2      00:00:00 bash
neil     655  428  0 18:24  tty4      00:00:00 -bash
root     713    1  2 18:27  tty1      00:00:00 gnome-terminal
root     715  713  0 18:28  tty1      00:00:00 gnome-pty-helper
root     717  716 13 18:28  pts/0      00:00:01 emacs
root     718  653  0 18:28  tty2      00:00:00 ps -af
```

This shows information about many processes, including the processes involved with the Emacs editor under X on a Linux system. For example, the TTY column shows which terminal the process was started from, TIME gives the CPU time used so far, and the CMD column shows the command used to start the process. Let's take a closer look at some of these.

```
neil      655  428  0 18:24  tty4      00:00:00 -bash
```

The initial login was performed on virtual console number 4. This is just the console on this machine. The shell program that is running is the Linux default, bash.

```
root      467  433  0 18:12  tty1      00:00:00 sh /usr/X11R6/bin/startx
```

The X Window System was started by the command `startx`. This is a shell script that starts the X server and runs some initial X programs.

```
root      717  716 13 18:28  pts/0      00:00:01 emacs
```

This process represents a window in X running Emacs. It was started by the window manager in response to a request for a new window. A new pseudo terminal, `pts/0`, has been assigned for the shell to read from and write to.

```
root      512    1  0 18:12  tty1      00:00:01 gnome-help-browser --sm-client-i
```

This is the GNOME help browser started by the window manager.

By default, the `ps` program shows only processes that maintain a connection with a terminal, a console, a serial line, or a pseudo terminal. Other processes run without needing to communicate with a user on a terminal. These are typically system processes that Linux uses to manage shared resources. We can use `ps` to see all such processes using the `-a` option and to get "full" information with `-f`.

The exact syntax for the `ps` command and the format of the output may vary slightly from system to system. Refer to the manual for more details on the options and output format of `ps`.

System Processes

Here are some of the other processes running on this Linux system. The output has been abbreviated for clarity.

```
$ ps -ax
  PID TTY      STAT   TIME  COMMAND
     1 ?        S      0:05  init
     2 ?        SW     0:00  [keventd]
     3 ?        SW     0:00  [kapmd]
     4 ?        SWN    0:00  [ksoftirqd_CPU0]
     5 ?        SW     0:00  [kswapd]
     6 ?        SW     0:00  [bdfflush]
     7 ?        SW     0:00  [kupdated]
     8 ?        SW     0:00  [kinoded]
    10 ?        SW     0:00  [mdrecoveryd]
    75 ?        SW<   0:00  [lvm-mpd]
   503 ?        S     0:00  /sbin/syslogd -a /var/lib/dhcp/dev/log
   506 ?        S     0:00  /sbin/klogd -c 1 -2
   542 ?        SW     0:00  [khubd]
   614 ?        S     0:00  /sbin/portmap
   653 ?        S     0:00  /usr/sbin/sshd
   730 ?        S     0:00  /sbin/dhcpcd -H -D -N -Y -t 999999 -h beast eth0
   744 ?        S     0:00  /usr/sbin/cupsd
  1004 ?        S     0:00  /usr/lib/postfix/master
  1021 ?        S     0:00  pickup -l -t fifo -u
  1022 ?        S     0:00  qmgr -l -t fifo -u
  1037 ?        S     0:00  /usr/sbin/atd
  1055 ?        S     0:00  /usr/sbin/cron
  1071 ?        S     0:00  /usr/sbin/nscd
  1084 ?        S     0:00  /usr/sbin/nscd
 1094 tty1      S     0:00  /sbin/mingetty --noclear tty1
 1095 tty2      S     0:00  /sbin/mingetty tty2
 1096 tty3      S     0:00  /sbin/mingetty tty3
 1097 tty4      S     0:00  /sbin/mingetty tty4
 1098 tty5      S     0:00  /sbin/mingetty tty5
 1099 tty6      S     0:00  /sbin/mingetty tty6
 1102 ?        S     0:00  /usr/X11R6/bin/xdm
 1106 ?        S     0:02  /usr/X11R6/bin/X :0 vt07 -auth /var/lib/xdm/authdir/a
 1108 ?        S     0:00  :-0
 1124 ?        S     0:00  /usr/X11R6/bin/xconsole -notify -nostdin -verbose -ex
 1155 ?        S     0:00  -192.168.0.25:0
 1168 ?        S     0:00  /bin/sh /usr/X11R6/bin/kde
 1259 pts/2      S     0:00  /bin/bash
 1262 pts/1      S     0:00  /bin/bash
 1273 pts/2      S     0:00  su -
 1274 pts/2      S     0:00  -bash
 1313 pts/1      S     0:00  emacs
 1321 ?        S     0:02  kdeinit: khelpcenter
 1329 ?        S     0:02  kdeinit: konqueror --silent
 1357 pts/2      R     0:00  ps -ax
```

Here we can see one very important process indeed.

```
1  ?  S      0:05 init
```

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In general, each process is started by another process known as its *parent process*. A process so started is known as a *child process*. When Linux starts, it runs a single program, the prime ancestor and process number 1, init. This is, if you like, the operating system process manager and the grandparent of all processes. Other system processes we'll meet soon are started by init or by other processes started by init.

One such example is the login procedure. init starts the getty program once for each serial terminal or dial in modem that we can use to log in. These are shown in the ps output like this:

```
1095  tty2      S      0:00 /sbin/mingetty tty2
```

The getty processes wait for activity at the terminal, prompt the user with the familiar login prompt, and then pass control to the login program, which sets up the user environment and finally starts a shell. When the user shell exits, init starts another getty process.

You can see that the ability to start new processes and to wait for them to finish is fundamental to the system. We'll see later in this chapter how to perform the same tasks from within our own programs with the system calls fork, exec, and wait.

Process Scheduling

One further ps output example is the entry for the ps command itself:

```
1357 pts/2      R      0:00 ps -ax
```

This indicates that process 1357 is in a run state (R) and is executing the command ps -ax. Thus the process is described in its own output! The status indicator shows only that the program is ready to run, not necessarily that it's actually running. On a single processor computer, only one process can run at a time, while others wait their turn. These turns, known as time slices, are quite short and give the impression that programs are running at the same time. The R just shows that the program is not waiting for other processes to finish or waiting for input or output to complete. That is why you may see two such processes listed in ps output. (Another commonly seen process marked as running is the X display server.)

The Linux kernel uses a process scheduler to decide which process will receive the next time slice. It does this using the process priority (we discussed priorities back in Chapter 4). Processes with a high priority get to run more often, while others, such as low-priority background tasks, run less frequently. With Linux, processes can't overrun their allocated time slice. They are pre-emptively multitasked so that they are suspended and resumed without their cooperation. Older systems, such as Windows 3.x, generally require processes to yield explicitly so that others may resume.

In a multitasking system such as Linux where several programs are likely to be competing for the same resource, programs that perform short bursts of work and pause for input are considered better behaved than those that hog the processor by continually calculating some value or continually querying the system to see if new input is available. Well behaved programs are termed *nice* programs, and in a sense this "niceness" can be measured. The operating system determines the priority of a process based on a "nice" value, which defaults to 0, and on the behavior of the program. Programs that run for long periods without pausing generally get lower priorities. Programs that pause while, for example, waiting for input get rewarded. This helps keep a program that interacts with the user responsive; while it is waiting for some input from the user, the system increases its priority, so that when it's ready to resume, it

has a high priority. We can set the process nice value using `nice` and adjust it using `renice`. The `nice` command increases the nice value of a process by 10, giving it a lower priority. We can view the nice values of active processes using the `-l` or `-f` (for long output) option to `ps`. The value we are interested in is shown in the `NI` (nice) column.

```
$ ps -l
  F S   UID   PID  PPID   C PRI  NI ADDR SZ WCHAN  TTY          TIME CMD
000 S  500  1259  1254   0 75    0 -    710 wait4 pts/2    00:00:00 bash
000 S  500  1262  1251   0 75    0 -    714 wait4 pts/1    00:00:00 bash
000 S  500  1313  1262   0 75    0 -  2762 schedu pts/1    00:00:00 emacs
000 S  500  1362  1262   2 80    0 -   789 schedu pts/1    00:00:00 oclock
000 R  500  1363  1262   0 81    0 -   782 -      pts/1    00:00:00 ps
```

Here we can see that the `oclock` program is running (as process 1362) with a default nice value. If it had been started with the command

```
$ nice oclock &
```

it would have been allocated a nice value of +10. If we adjust this value with the command

```
$ renice 10 1362
1362: old priority 0, new priority 10
```

the clock program will run less often. We can see the modified nice value with `ps` again:

```
F S   UID   PID  PPID   C PRI  NI ADDR SZ WCHAN  TTY          TIME CMD
000 S  500  1259  1254   0 75    0 -    710 wait4 pts/2    00:00:00 bash
000 S  500  1262  1251   0 75    0 -    714 wait4 pts/1    00:00:00 bash
000 S  500  1313  1262   0 75    0 -  2762 schedu pts/1    00:00:00 emacs
000 S  500  1362  1262   0 90   10 -   789 schedu pts/1    00:00:00 oclock
000 R  500  1365  1262   0 81    0 -   782 -      pts/1    00:00:00 ps
```

The status column now also contains `N` to indicate that the nice value has changed from the default. The `PPID` field of `ps` output indicates the parent process ID, the PID of either the process that caused this process to start or, if that process is no longer running, `init` (PID 1).

The Linux scheduler decides which process it will allow to run on the basis of priority. Exact implementations vary, of course, but higher priority processes run more often. In some cases, low priority processes don't run at all if higher priority processes are ready to run.

Starting New Processes

We can cause a program to run from inside another program and thereby create a new process by using the `system` library function.

```
#include <stdlib.h>

int system (const char *string);
```

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The `system` function runs the command passed to it as a string and waits for it to complete. The command is executed as if the command

```
$ sh -c string
```

has been given to a shell. `system` returns 127 if a shell can't be started to run the command and -1 if another error occurs. Otherwise, `system` returns the exit code of the command.

Try It Out—`system`

We can use `system` to write a program to run `ps` for us. While this is not tremendously useful in and of itself, we'll see how to develop this technique in later examples. We also don't check that the `system` call actually worked for the sake of simplicity in the example.

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

int main()
{
    printf("Running ps with system\n");
    system("ps -ax");
    printf("Done.\n");
    exit(0);
}
```

When we compile and run this program, `system1.c`, we get the following:

```
$ ./system1
Running ps with system
  PID TTY      STAT      TIME COMMAND
    1 ?        S          0:05  init
    2 ?        SW         0:00  [keventd]
...
 1262 pts/1    S          0:00  /bin/bash
 1273 pts/2    S          0:00  su -
 1274 pts/2    S          0:00  -bash
 1463 pts/1    S          0:00  oclock -transparent -geometry 135x135-10+40
 1465 pts/1    S          0:01  emacs Makefile
 1480 pts/1    S          0:00  ./system1
 1481 pts/1    R          0:00  ps -ax
Done.
```

Because the `system` function uses a shell to start the desired program, we could put it in the background by changing the function call in `system1.c` to the following:

```
system("ps -ax &");
```

When we compile and run this version of the program, we get

```
$ ./system2
Running ps with system
  PID TTY      STAT      TIME COMMAND
```

```

1 ?      S      0:05 init
2 ?      SW     0:00 [keventd]
...
Done .
$ 1246 ?      S      0:00 kdeinit: klipper -icon klipper -miniicon klipper
1274 pts/2    S      0:00 -bash
1463 pts/1    S      0:00 oclock -transparent -geometry 135x135-10+40
1465 pts/1    S      0:01 emacs Makefile
1484 pts/1    R      0:00 ps -ax

```

How It Works

In the first example, the program calls `system` with the string “`ps -ax`”, which executes the `ps` program. Our program returns from the call to `system` when the `ps` command has finished. The `system` function can be quite useful but is also limited. Because our program has to wait until the process started by the call to `system` finishes, we can’t get on with other tasks.

In the second example, the call to `system` returns as soon as the shell command finishes. Because it’s a request to run a program in the background, the shell returns as soon as the `ps` program is started, just as would happen if we had typed

```
$ ps -ax &
```

at a shell prompt. The `system1` program then prints `Done .` and exits before the `ps` command has had a chance to finish all of its output. The `ps` output continues to produce output after `system1` exits. This kind of process behavior can be quite confusing for users. To make good use of processes, we need finer control over their actions. Let’s look at a lower-level interface to process creation, `exec`.

In general, using `system` is a far from ideal way to start other processes, because it invokes the desired program using a shell. This is both inefficient, because a shell is started before the program is started, and also quite dependent on the installation for the shell and environment that are used. In the next section, we see a much better way of invoking programs, which should almost always be used in preference to the `system` call.

Replacing a Process Image

There is a whole family of related functions grouped under the `exec` heading. They differ in the way that they start processes and present program arguments. An `exec` function replaces the current process with a new process specified by the `path` or `file` argument.

```
#include <unistd.h>

char **environ;

int execl(const char *path, const char *arg0, ..., (char *)0);
int execvp(const char *file, const char *arg0, ..., (char *)0);
int execle(const char *path, const char *arg0, ..., (char *)0, char *const
envp[]);
int execv(const char *path, char *const argv[]);
int execvp(const char *file, char *const argv[]);
int execve(const char *path, char *const argv[], char *const envp[]);
```

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These functions belong to two types. `exec`, `execp`, and `execle` take a variable number of arguments ending with a null pointer. `execv` and `execvp` have as their second argument an array of strings. In both cases, the new program starts with the given arguments appearing in the `argv` array passed to `main`. These functions are usually implemented using `execve`, though there is no requirement for it to be done this way.

The functions with names suffixed with a `p` differ in that they will search the `PATH` environment variable to find the new program executable file. If the executable isn't on the path, an absolute file name, including directories, will need to be passed to the function as a parameter.

The global variable `environ` is available to pass a value for the new program environment. Alternatively, an additional argument to the functions `execle` and `execve` is available for passing an array of strings to be used as the new program environment.

If we wish to use an `exec` function to start the `ps` program, we can choose from among the six `exec` family functions, as shown in the calls in the code fragment that follows:

```
#include <unistd.h>

/* Example of an argument list */
/* Note that we need a program name for argv[0] */
char *const ps_argv[] =
    {"ps", "-ax", 0};

/* Example environment, not terribly useful */
char *const ps_envp[] =
    {"PATH=/bin:/usr/bin", "TERM=console", 0};

/* Possible calls to exec functions */
execl("/bin/ps", "ps", "-ax", 0);           /* assumes ps is in /bin */
execlp("ps", "ps", "-ax", 0);               /* assumes /bin is in PATH */
execle("/bin/ps", "ps", "-ax", 0, ps_envp); /* passes own environment */

execv("/bin/ps", ps_argv);
execvp("ps", ps_argv);
execve("/bin/ps", ps_argv, ps_envp);
```

Try It Out—`execlp`

Let's modify our example to use an `execlp` call.

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

int main()
{
    printf("Running ps with execlp\n");
    execlp("ps", "ps", "-ax", 0);
    printf("Done.\n");
    exit(0);
}
```

When we run this program, `pexec.c`, we get the usual `ps` output, but no `Done.` message at all. Note also that there is no reference to a process called `pexec` in the output.

```
$ ./pexec
Running ps with execvp
  PID TTY      STAT   TIME COMMAND
    1 ?        S      0:05 init
    2 ?        SW     0:00 [keventd]
...
 1262 pts/1    S      0:00 /bin/bash
 1273 pts/2    S      0:00 su -
 1274 pts/2    S      0:00 -bash
 1463 pts/1    S      0:00 oclock -transparent -geometry 135x135-10+40
 1465 pts/1    S      0:01 emacs Makefile
 1514 pts/1    R      0:00 ps -ax
```

How It Works

The program prints its first message and then calls `execvp`, which searches the directories given by the `PATH` environment variable for a program called `ps`. It then executes this program in place of our `pexec` program, starting it as if we had given the shell command

```
$ ps -ax
```

When `ps` finishes, we get a new shell prompt. We don't return to `pexec`, so the second message doesn't get printed. The PID of the new process is the same as the original, as are the parent PID and nice value. In effect, all that has happened is that the running program has started to execute new code from a new executable file specified in the call to `exec`.

There is a limit on the combined size of the argument list and environment for a process started by `exec` functions. This is given by `ARG_MAX` and on Linux systems is 128 kilobytes. Other systems may set a more reduced limit that can lead to problems. The `POSIX` specification indicates that `ARG_MAX` should be at least 4,096 bytes.

The `exec` functions generally don't return unless an error occurs, in which case the error variable `errno` is set and the `exec` function returns `-1`.

The new process started by `exec` inherits many features from the original. In particular, open file descriptors remain open in the new process unless their "close on exec flag" has been set (refer to the `fcntl` system call in Chapter 3 for more details). Any open directory streams in the original process are closed.

Duplicating a Process Image

To use processes to perform more than one function at a time, we can either use threads, covered in Chapter 12, or create an entirely separate process from within a program, as `init` does, rather than replace the current thread of execution, as in the `exec` case.

We can create a new process by calling `fork`. This system call duplicates the current process, creating a new entry in the process table with many of the same attributes as the current process. The new process

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is almost identical to the original, executing the same code but with its own data space, environment, and file descriptors. Combined with the `exec` functions, `fork` is all we need to create new processes.

```
#include <sys/types.h>
#include <unistd.h>

pid_t fork(void);
```

As you can see in Figure 11-2, the call to `fork` in the parent returns the PID of the new child process. The new process continues to execute just like the original, with the exception that in the child process the call to `fork` returns 0. This allows both the parent and child to determine which is which.

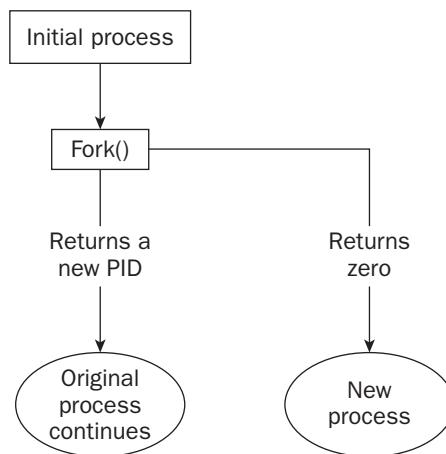


Figure 11-2

If `fork` fails, it returns -1. This is commonly due to a limit on the number of child processes that a parent may have (`CHILD_MAX`), in which case `errno` will be set to `EAGAIN`. If there is not enough space for an entry in the process table, or not enough virtual memory, the `errno` variable will be set to `ENOMEM`.

A typical code fragment using `fork` is

```
pid_t new_pid;

new_pid = fork();

switch(new_pid) {
case -1 :      /* Error */
    break;
case 0 :       /* We are child */
    break;
default :      /* We are parent */
    break;
}
```

Try It Out—fork

Let's look at a simple example, `fork1.c`.

```
#include <sys/types.h>
#include <unistd.h>
#include <stdio.h>

int main()
{
    pid_t pid;
    char *message;
    int n;

    printf("fork program starting\n");
    pid = fork();
    switch(pid)
    {
    case -1:
        perror("fork failed");
        exit(1);
    case 0:
        message = "This is the child";
        n = 5;
        break;
    default:
        message = "This is the parent";
        n = 3;
        break;
    }

    for(; n > 0; n--) {
        puts(message);
        sleep(1);
    }
    exit(0);
}
```

This program runs as two processes. A child is created (born?) and prints a message five times. The original process (the parent) prints a message only three times. The parent process finishes before the child has printed all of its messages, so the next shell prompt appears mixed in with the output.

```
$ ./fork1
fork program starting
This is the parent
This is the child
This is the parent
This is the child
This is the parent
This is the child
$ This is the child
This is the child
```

How It Works

When `fork` is called, this program divides into two separate processes. The parent process is identified by a nonzero return from `fork` and is used to set a number of messages to print, each separated by one second.

Waiting for a Process

When we start a child process with `fork`, it takes on a life of its own and runs independently. Sometimes, we would like to find out when a child process has finished. For example, in the previous program, the parent finishes ahead of the child and we get some messy output as the child continues to run. We can arrange for the parent process to wait until the child finishes before continuing by calling `wait`.

```
#include <sys/types.h>
#include <sys/wait.h>

pid_t wait(int *stat_loc);
```

The `wait` system call causes a parent process to pause until one of its child processes is stopped. The call returns the PID of the child process. This will normally be a child process that has terminated. The status information allows the parent process to determine the exit status of the child process, that is, the value returned from `main` or passed to `exit`. If `stat_loc` is not a null pointer, the status information will be written to the location to which it points.

We can interpret the status information using macros defined in `sys/wait.h`. These include

| Macro | Definition |
|------------------------------------|---|
| <code>WIFEXITED(stat_val)</code> | Nonzero if the child is terminated normally. |
| <code>WEXITSTATUS(stat_val)</code> | If <code>WIFEXITED</code> is nonzero, this returns child exit code. |
| <code>WIFSIGNALED(stat_val)</code> | Nonzero if the child is terminated on an uncaught signal. |
| <code>WTERMSIG(stat_val)</code> | If <code>WIFSIGNALED</code> is nonzero, this returns a signal number. |
| <code>WIFSTOPPED(stat_val)</code> | Nonzero if the child has stopped. |
| <code>WSTOPSIG(stat_val)</code> | If <code>WIFSTOPPED</code> is nonzero, this returns a signal number. |

Try It Out—`wait`

Let's modify our program slightly so we can wait for and examine the child process exit status. Call the new program `wait.c`.

```
#include <sys/types.h>
#include <sys/wait.h>
#include <unistd.h>
#include <stdio.h>

int main()
{
```

```

pid_t pid;
char *message;
int n;
int exit_code;

printf("fork program starting\n");
pid = fork();
switch(pid)
{
    case -1:
        perror("fork failed");
        exit(1);
    case 0:
        message = "This is the child";
        n = 5;
        exit_code = 37;
        break;
    default:
        message = "This is the parent";
        n = 3;
        exit_code = 0;
        break;
}

for(; n > 0; n--) {
    puts(message);
    sleep(1);
}

```

This section of the program waits for the child process to finish.

```

if (pid != 0) {
    int stat_val;
    pid_t child_pid;

    child_pid = wait(&stat_val);

    printf("Child has finished: PID = %d\n", child_pid);
    if(WIFEXITED(stat_val))
        printf("Child exited with code %d\n", WEXITSTATUS(stat_val));
    else
        printf("Child terminated abnormally\n");
}
exit(exit_code);
}

```

When we run this program, we see the parent wait for the child.

```

$ ./wait
fork program starting
This is the child
This is the parent

```

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```
This is the parent
This is the child
This is the parent
This is the child
This is the child
This is the child
Child has finished: PID = 1582
Child exited with code 37
$
```

How It Works

The parent process, which got a nonzero return from the `fork` call, uses the `wait` system call to suspend its own execution until status information becomes available for a child process. This happens when the child calls `exit`; we gave it an exit code of 37. The parent then continues, determines that the child terminated normally by testing the return value of the `wait` call, and extracts the exit code from the status information.

Zombie Processes

Using `fork` to create processes can be very useful, but you must keep track of child processes. When a child process terminates, an association with its parent survives until the parent in turn either terminates normally or calls `wait`. The child process entry in the process table is therefore not freed up immediately. Although no longer active, the child process is still in the system because its exit code needs to be stored in case the parent subsequently calls `wait`. It becomes what is known as defunct, or a *zombie process*.

We can see a zombie process being created if we change the number of messages in the `fork` example program. If the child prints fewer messages than the parent, it will finish first and will exist as a zombie until the parent has finished.

Try It Out—Zombies

`fork2.c` is the same as `fork1.c`, except that the number of messages printed by the child and parent processes is reversed. Here are the relevant lines of code:

```
switch(pid)
{
    case -1:
        perror("fork failed");
        exit(1);
    case 0:
        message = "This is the child";
        n = 3;
        break;
    default:
        message = "This is the parent";
        n = 5;
        break;
}
```

How It Works

If we run the preceding program with `./fork2` & and then call the `ps` program after the child has finished but before the parent has finished, we'll see a line such as this. (Some systems may say `<zombie>` rather than `<defunct>`.)

```
$ ps -al
```

| F | S | UID | PID | PPID | C | PRI | NI | ADDR | SZ | WCHAN | TTY | TIME | CMD |
|-----|---|-----|------|------|---|-----|----|------|------|--------|-------|----------|-----------------|
| 004 | S | 0 | 1273 | 1259 | 0 | 75 | 0 | - | 589 | wait4 | pts/2 | 00:00:00 | su |
| 000 | S | 0 | 1274 | 1273 | 0 | 75 | 0 | - | 731 | schedu | pts/2 | 00:00:00 | bash |
| 000 | S | 500 | 1463 | 1262 | 0 | 75 | 0 | - | 788 | schedu | pts/1 | 00:00:00 | oclock |
| 000 | S | 500 | 1465 | 1262 | 0 | 75 | 0 | - | 2569 | schedu | pts/1 | 00:00:01 | emacs |
| 000 | S | 500 | 1603 | 1262 | 0 | 75 | 0 | - | 313 | schedu | pts/1 | 00:00:00 | fork2 |
| 003 | Z | 500 | 1604 | 1603 | 0 | 75 | 0 | - | 0 | do_exi | pts/1 | 00:00:00 | fork2 <defunct> |
| 000 | R | 500 | 1605 | 1262 | 0 | 81 | 0 | - | 781 | - | pts/1 | 00:00:00 | ps |

If the parent then terminates abnormally, the child process automatically gets the process with PID 1 (`init`) as parent. The child process is now a zombie that is no longer running but has been inherited by `init` because of the abnormal termination of the parent process. The zombie will remain in the process table until collected by the `init` process. The bigger the table, the slower this procedure. You need to avoid zombie processes, as they consume resources until `init` cleans them up.

There's another system call that you can use to wait for child processes. It's called `waitpid`, and you can use it to wait for a specific process to terminate.

```
#include <sys/types.h>
#include <sys/wait.h>

pid_t waitpid(pid_t pid, int *stat_loc, int options);
```

The `pid` argument specifies the PID of a particular child process to wait for. If it's `-1`, `waitpid` will return information for any child process. Like `wait`, it will write status information to the location pointed to by `stat_loc`, if that is not a null pointer. The `options` argument allows us to modify the behavior of `waitpid`. The most useful option is `WNOHANG`, which prevents the call to `waitpid` from suspending execution of the caller. You can use it to find out whether any child processes have terminated and, if not, to continue. Other options are the same as for `wait`.

So, if we wanted to have a parent process regularly check whether a specific child process has terminated, we could use the call

```
waitpid(child_pid, (int *) 0, WNOHANG);
```

This will return zero if the child has not terminated or stopped, or `child_pid` if it has. `waitpid` will return `-1` on error and set `errno`. This can happen if there are no child processes (`errno` set to `ECHILD`), if the call is interrupted by a signal (`EINTR`), or if the option argument is invalid (`EINVAL`).

Input and Output Redirection

We can use our knowledge of processes to alter the behavior of programs by exploiting the fact that open file descriptors are preserved across calls to `fork` and `exec`. The next example involves a *filter program*—a program that reads from its standard input and writes to its standard output, performing some useful transformation as it does so.

Try It Out—Redirection

Here's a very simple filter program, `upper.c`, that reads input and converts it to uppercase.

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

int main()
{
    int ch;
    while((ch = getchar()) != EOF) {
        putchar(toupper(ch));
    }
    exit(0);
}
```

When we run the program, it does what we expect:

```
$ ./upper
hello THERE
HELLO THERE
^D
$
```

We can, of course, use it to convert a file to uppercase by using the shell redirection

```
$ cat file.txt
this is the file, file.txt, it is all lower case.
$ ./upper < file.txt
THIS IS THE FILE, FILE.TXT, IT IS ALL LOWER CASE.
```

What if we want to use this filter from within another program? This program, `useupper.c`, accepts a file name as an argument and will respond with an error if called incorrectly.

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

int main(int argc, char *argv[])
{
    char *filename;

    if (argc != 2) {
        fprintf(stderr, "usage: useupper file\n");
        exit(1);
    }

    filename = argv[1];
```

We reopen the standard input, again checking for any errors as we do so, and then use `exec1` to call `upper`.

```
if(!freopen(filename, "r", stdin)) {
    fprintf(stderr, "could not redirect stdin from file %s\n", filename);
    exit(2);
}

exec1("./upper", "upper", 0);
```

Don't forget that `exec1` replaces the current process; if there is no error, the remaining lines are not executed.

```
perror("could not exec ./upper");
exit(3);
}
```

How It Works

When we run this program, we can give it a file to convert to uppercase. The job is done by the program `upper`, which doesn't handle file-name arguments. Note that we don't require the source code for `upper`; we can run any executable program in this way:

```
$ ./useupper file.txt
THIS IS THE FILE, FILE.TXT, IT IS ALL LOWER CASE.
```

The `useupper` program uses `freopen` to close the standard input and associate the file stream `stdin` with the file given as a program argument. It then calls `exec1` to replace the running process code with that of the `upper` program. Because open file descriptors are preserved across the call to `exec1`, the `upper` program runs exactly as it would have under the shell command:

```
$ upper < file.txt
```

Threads

Linux processes can cooperate, can send each other messages, and can interrupt one another. They can even arrange to share segments of memory between themselves, but they are essentially separate entities within the operating system. They do not readily share variables.

There is a class of process known as a *thread* that is available in many UNIX and Linux systems. While threads can be difficult to program, they can be of great value in some applications, such as multi-threaded database servers. Programming threads on Linux (and UNIX generally) is not as common as using multiple processes, because Linux processes are quite lightweight, and programming multiple cooperation processes is much easier than programming threads. Threads are covered in Chapter 12.

Signals

A *signal* is an event generated by the UNIX and Linux systems in response to some condition, upon receipt of which a process may in turn take some action. We use the term "raise" to indicate the generation of a signal, and the term "catch" to indicate the receipt of a signal. Signals are raised by some error conditions, such as memory segment violations, floating-point processor errors, or illegal instructions.

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They are generated by the shell and terminal handlers to cause interrupts and can also be explicitly sent from one process to another as a way of passing information or modifying behavior. In all these cases, the programming interface is the same. Signals can be raised, caught and acted upon, or (for some at least) ignored.

Signal names are defined by including the header file `signal.h`. They all begin with “SIG” and include those listed in the following table.

| Signal Name | Description |
|-------------|-----------------------------------|
| SIGABORT | *Process abort |
| SIGALRM | Alarm clock |
| SIGFPE | *Floating-point exception |
| SIGHUP | Hangup |
| SIGILL | *Illegal instruction |
| SIGINT | Terminal interrupt |
| SIGKILL | Kill (can't be caught or ignored) |
| SIGPIPE | Write on a pipe with no reader |
| SIGQUIT | Terminal quit |
| SIGSEGV | *Invalid memory segment access |
| SIGTERM | Termination |
| SIGUSR1 | User-defined signal 1 |
| SIGUSR2 | User-defined signal 2 |

*Implementation-dependent actions may also be taken.

If a process receives one of these signals without first arranging to catch it, the process will be terminated immediately. Usually, a core dump file is created. This file, called `core` and placed in the current directory, is an image of the process that can be useful in debugging.

Additional signals include those in the following table.

| Signal Name | Description |
|-------------|---|
| SIGCHLD | Child process has stopped or exited. |
| SIGCONT | Continue executing, if stopped. |
| SIGSTOP | Stop executing. (Can't be caught or ignored.) |
| SIGTSTP | Terminal stop signal. |
| SIGTTIN | Background process trying to read. |
| SIGTTOU | Background process trying to write. |

SIGCHLD can be useful for managing child processes. It's ignored by default. The remaining signals cause the process receiving them to stop, except for SIGCONT, which causes the process to resume. They are used by shell programs for job control and are rarely used by user programs.

We'll look at the first group of signals in a little more detail later. For now, it's enough to know that if the shell and terminal driver are configured normally, typing the interrupt character (often Ctrl+C) at the keyboard will result in the SIGINT signal being sent to the foreground process, that is, the program currently running. This will cause the program to terminate unless it has arranged to catch the signal.

If we want to send a signal to a process other than the current foreground task, we use the `kill` command. This takes an optional signal number or name, and the PID (usually found using the `ps` command) to send the signal to. For example, to send a "hangup" signal to a shell running on a different terminal with PID 512, we would use the command

```
kill -HUP 512
```

A useful variant of the `kill` command is `killall`, which allows us to send a signal to all processes running a specified command. Not all versions of UNIX support it, though Linux generally does. This is useful when you do not know the PID, or when you want to send a signal to several different processes executing the same command. A common use is to tell the `inetd` program to reread its configuration options. To do this we can use the command

```
killall -HUP inetd
```

Programs can handle signals using the signal library function.

```
#include <signal.h>  
  
void (*signal(int sig, void (*func)(int)))(int);
```

This rather complex declaration says that `signal` is a function that takes two parameters, `sig` and `func`. The signal to be caught or ignored is given as argument `sig`. The function to be called when the specified signal is received is given as `func`. This function must be one that takes a single `int` argument (the signal received) and is of type `void`. The `signal` function itself returns a function of the same type, which is the previous value of the function set up to handle this signal, or one of these two special values:

| | |
|----------------------|---------------------------|
| <code>SIG_IGN</code> | Ignore the signal. |
| <code>SIG_DFL</code> | Restore default behavior. |

An example should make things clear. Let's write a program, `ctrlc.c`, that reacts to typing Ctrl+C by printing an appropriate message rather than terminating. Pressing Ctrl+C a second time will end the program.

Try It Out—Signal Handling

The function `ouch` reacts to the signal that is passed in the parameter `sig`. This function will be called when a signal occurs. It prints a message and then resets the signal handling for SIGINT (by default, generated by typing Ctrl+C) back to the default behavior.

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

void ouch(int sig)
{
    printf("OUCH! - I got signal %d\n", sig);
    (void) signal(SIGINT, SIG_DFL);
}
```

The main function has to intercept the `SIGINT` signal generated when we type `Ctrl+C`. For the rest of the time, it just sits in an infinite loop, printing a message once a second.

```
int main()
{
    (void) signal(SIGINT, ouch);

    while(1) {
        printf("Hello World!\n");
        sleep(1);
    }
}
```

Typing `Ctrl+C` for the first time causes the program to react and then continue. When we type `Ctrl+C` again, the program ends because the behavior of `SIGINT` has returned to the default behavior of causing the program to exit.

```
$ ./ctrlc1
Hello World!
Hello World!
Hello World!
Hello World!
Hello World!
^C
OUCH! - I got signal 2
Hello World!
Hello World!
Hello World!
Hello World!
Hello World!
^C
$
```

As you can see from this example, the signal handling function takes a single integer parameter, the signal number that caused the function to be called. This can be useful if the same function is used to handle more than one signal. Here we print out the value of `SIGINT`, which on this system happens to have the value 2. You shouldn't rely on traditional numeric values for signals; always use signal names in new programs.

It is not safe to call all functions, such as `printf`, from within a signal handler. A useful technique is to use a signal handler to set a flag and then check that flag from the main program and print a message if required. Toward the end of the chapter, you will find a list of calls that can safely be made inside signal handlers.

How It Works

The program arranges for the function `ouch` to be called when we give the `SIGINT` signal by typing `Ctrl+C`. After the interrupt function `ouch` has completed, the program carries on, but the signal action is restored to the default. (Different versions of UNIX, particularly those derived from Berkley UNIX, have historically had subtly different signal behaviors. If you want the default action to a signal restored after it has occurred, it's always best to code it that way specifically.) When it receives a second `SIGINT` signal, the program takes the default action, which is to terminate the program.

If we wished to retain the signal handler and continue to react to `Ctrl+C`, we would need to re-establish it by calling `signal` again. This leads to a short time when the signal is not handled, from the start of the interrupt function to just before the signal handler is re-established. It's possible for a second signal to be received in this time and terminate the program against our wishes.

We don't recommend that you use the `signal` interface. We include it here because you will find it in many older programs. We'll see `sigaction`, a more cleanly defined and reliable interface later, which you should use in all new programs.

The `signal` function returns the previous value of the signal handler for the specified signal if there is one, or `SIG_ERR` otherwise, in which case, `errno` will be set to a positive value. `errno` will be set to `EINVAL` if an invalid signal is specified or an attempt is made to handle a signal that may not be caught or ignored, such as `SIGKILL`.

Sending Signals

A process may send a signal to another process, including itself, by calling `kill`. The call will fail if the program doesn't have permission to send the signal, often because the target process is owned by another user. This is the program equivalent of the shell command of the same name.

```
#include <sys/types.h>
#include <signal.h>

int kill(pid_t pid, int sig);
```

The `kill` function sends the specified signal, `sig`, to the process whose identifier is given by `pid`. It returns 0 on success. To send a signal, the sending process must have permission to do so. Normally, this means that both processes must have the same user ID (that is, you can send a signal only to one of your own processes, although the superuser may send signals to any process).

`kill` will fail, return -1, and set `errno` if the signal given is not a valid one (`errno` set to `EINVAL`), if it doesn't have permission (`EPERM`), or if the specified process doesn't exist (`ESRCH`).

Signals provide us with a useful alarm clock facility. The `alarm` function call can be used by a process to schedule a `SIGALRM` signal at some time in the future.

```
#include <unistd.h>

unsigned int alarm(unsigned int seconds);
```

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The alarm call schedules the delivery of a `SIGALRM` signal in `seconds` seconds. In fact, the alarm will be delivered shortly after that, due to processing delays and scheduling uncertainties. A value of 0 will cancel any outstanding alarm request. Calling `alarm` before the signal is received will cause the alarm to be rescheduled. Each process can have only one outstanding alarm. `alarm` returns the number of seconds left before any outstanding alarm call would be sent, or -1 if the call fails.

To see how `alarm` works, we can simulate its effect by using `fork`, `sleep`, and `signal`. A program could start a new process for the sole purpose of sending a signal at some time later.

Try It Out—An Alarm Clock

In `alarm.c`, the first function, `ding`, simulates an alarm clock.

```
#include <sys/types.h>
#include <signal.h>
#include <stdio.h>
#include <unistd.h>

static int alarm_fired = 0;

void ding(int sig)
{
    alarm_fired = 1;
}
```

In `main`, we tell the child process to wait for five seconds before sending a `SIGALRM` signal to its parent.

```
int main()
{
pid_t pid;

printf("alarm application starting\n");

pid = fork();
switch(pid) {
case -1:
    /* Failure */
    perror("fork failed");
    exit(1);
case 0:
    /* child */
    sleep(5);
    kill(getppid(), SIGALRM);
    exit(0);
}
```

The parent process arranges to catch `SIGALRM` with a call to `signal` and then waits for the inevitable.

```
/* if we get here we are the parent process */
printf("waiting for alarm to go off\n");
(void) signal(SIGALRM, ding);
```

```

    pause();
    if (alarm_fired) printf("Ding!\n");

    printf("done\n");
    exit(0);
}

```

When we run this program, it pauses for five seconds while it waits for the simulated alarm clock.

```

$ ./alarm
alarm application starting
waiting for alarm to go off
<5 second pause>
Ding!
done
$

```

This program introduces a new function, `pause`, which simply causes the program to suspend execution until a signal occurs. When it receives a signal, any established handler is run and execution continues as normal. It's declared as

```

#include <unistd.h>

int pause(void);

```

and returns `-1` (if the next received signal doesn't cause the program to terminate) with `errno` set to `EINTR` when interrupted by a signal. It is more common to use `sigsuspend` when waiting for signals, which we will discuss a bit later in the chapter.

How It Works

The alarm clock simulation program starts a new process via `fork`. This child process sleeps for five seconds and then sends a `SIGALRM` to its parent. The parent arranges to catch `SIGALRM` and then pauses until a signal is received. We do not call `printf` in the signal handler directly; rather, we set a flag and then check the flag afterward.

Using signals and suspending execution is an important part of Linux programming. It means that a program need not necessarily run all the time. Rather than run in a loop continually checking whether an event has occurred, it can wait for an event to happen. This is especially important in a multiuser environment where processes share a single processor and this kind of busy wait has a large impact on system performance. A particular problem with signals is that you never know quite "What will happen if a signal occurs in the middle of a system call?" (The answer is a rather unsatisfactory "it depends.") In general, you need to worry only about "slow" system calls, such as reading from a terminal, where the system call will return with an error if a signal occurs while it is waiting. If you start using signals in your program, you need to be aware that some system calls could fail if a signal receives an error condition that you may not have considered before signal handling was added.

You must program your signals carefully, as there are a number of "race conditions" that can occur in programs that use them. For example, if you intend to call `pause` to wait for a signal and that signal occurs before the call to `pause`, your program may wait indefinitely for an event that won't occur. These race conditions, critical timing problems, catch many a novice programmer. Always check signal code very carefully.

A Robust Signals Interface

We've covered raising and catching signals using `signal` and friends in some depth, because they are very common in older UNIX programs. However, the X/Open and UNIX specifications recommend a newer programming interface for signals that is more robust: `sigaction`.

```
#include <signal.h>

int sigaction(int sig, const struct sigaction *act, struct sigaction *oact);
```

The `sigaction` structure, used to define the actions to be taken on receipt of the signal specified by `sig`, is defined in `signal.h` and has at least the following members:

```
void (*) (int) sa_handler      /* function, SIG_DFL or SIG_IGN
sigset_t sa_mask            /* signals to block in sa_handler
int sa_flags                 /* signal action modifiers
```

The `sigaction` function sets the action associated with the signal `sig`. If `oact` is not null, `sigaction` writes the previous signal action to the location it refers to. If `act` is null, this is all `sigaction` does. If `act` isn't null, the action for the specified signal is set.

As with `signal`, `sigaction` returns 0 if successful and -1 if not. The error variable `errno` will be set to `EINVAL` if the specified signal is invalid or if an attempt is made to catch or ignore a signal that can't be caught or ignored.

Within the `sigaction` structure pointed to by the argument `act`, `sa_handler` is a pointer to a function called when signal `sig` is received. This is much like the function `func` we saw earlier passed to `signal`. We can use the special values `SIG_IGN` and `SIG_DFL` in the `sa_handler` field to indicate that the signal is to be ignored or the action is to be restored to its default, respectively.

The `sa_mask` field specifies a set of signals to be added to the process's signal mask before the `sa_handler` function is called. These are the set of signals that are blocked and won't be delivered to the process. This prevents the case we saw earlier where a signal is received before its handler has run to completion. Using the `sa_mask` field can eliminate this race condition.

However, signals caught with handlers set by `sigaction` are by default not reset, and the `sa_flags` field must be set to contain the value `SA_RESETHAND` if we wish to obtain the behavior we saw earlier with `signal`. Before we look in any more detail at `sigaction`, let's rewrite the program `ctrlc.c`, using `sigaction` instead of `signal`.

Try It Out—`sigaction`

Make the changes that follow so that `SIGINT` is intercepted by `sigaction`. We will call the new program `ctrlc2.c`.

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

void ouch(int sig)
{
```

```

        printf("OUCH! - I got signal %d\n", sig);
    }

int main()
{
    struct sigaction act;

    act.sa_handler = ouch;
    sigemptyset(&act.sa_mask);
    act.sa_flags = 0;

    sigaction(SIGINT, &act, 0);

    while(1) {
        printf("Hello World!\n");
        sleep(1);
    }
}

```

When we run this version of the program, we always get a message when we type Ctrl+C because SIGINT is handled repeatedly by `sigaction`. To terminate the program, we have to type Ctrl-\, which generates the SIGQUIT signal by default.

```

$ ./ctrlc2
Hello World!
Hello World!
Hello World!
^C
OUCH! - I got signal 2
Hello World!
Hello World!
^C
OUCH! - I got signal 2
Hello World!
Hello World!
^\
Quit
$
```

How It Works

The program calls `sigaction` instead of `signal` to set the signal handler for Ctrl+C (SIGINT) to the function `ouch`. It first has to set up a `sigaction` structure that contains the handler, a signal mask, and flags. In this case, we don't need any flags, and an empty signal mask is created with the new function, `sigemptyset`.

After running this program, you will find a file called `core` has been created. You can safely delete it.

Signal Sets

The header file `signal.h` defines the type `sigset_t` and functions used to manipulate sets of signals. These sets are used in `sigaction` and other functions to modify process behavior on receipt of signals.

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```
#include <signal.h>

int sigaddset(sigset_t *set, int signo);
int sigemptyset(sigset_t *set);
int sigfillset(sigset_t *set);
int sigdelset(sigset_t *set, int signo);
```

These functions perform the operations suggested by their names. `sigemptyset` initializes a signal set to be empty. `sigfillset` initializes a signal set to contain all defined signals. `sigaddset` and `sigdelset` add and delete a specified signal (`signo`) from a signal set. They all return 0 if successful and -1 with `errno` set on error. The only error defined is `EINVAL` if the specified signal is invalid.

The function `sigismember` determines whether the given signal is a member of a signal set. It returns 1 if the signal is a member of the set, 0 if it isn't, and -1 with `errno` set to `EINVAL` if the signal is invalid.

```
#include <signal.h>

int sigismember(sigset_t *set, int signo);
```

The process signal mask is set or examined by calling the function `sigprocmask`. This signal mask is the set of signals that are currently blocked and will therefore not be received by the current process.

```
#include <signal.h>

int sigprocmask(int how, const sigset_t *set, sigset_t *oset);
```

`sigprocmask` can change the process signal mask in a number of ways according to the `how` argument. New values for the signal mask are passed in the argument `set` if it isn't null, and the previous signal mask will be written to the signal set `oset`.

The `how` argument can be one of the following:

| | |
|-------------|---|
| SIG_BLOCK | The signals in <code>set</code> are added to the signal mask. |
| SIG_SETMASK | The signal mask is set from <code>set</code> . |
| SIG_UNBLOCK | The signals in <code>set</code> are removed from the signal mask. |

If the `set` argument is a null pointer, the value of `how` is not used and the only purpose of the call is to fetch the value of the current signal mask into `oset`.

If it completes successfully, `sigprocmask` returns 0, or it returns -1 if the `how` parameter is invalid, in which case `errno` will be set to `EINVAL`.

If a signal is blocked by a process, it won't be delivered, but will remain pending. A program can determine which of its blocked signals are pending by calling the function `sigpending`.

```
#include <signal.h>

int sigpending(sigset_t *set);
```

This writes a set of signals that are blocked from delivery and are pending into the signal set pointed to by set. It returns 0 if successful, otherwise, -1 with `errno` set to indicate the error. This function can be useful when a program needs to handle signals and to control when the handling function is called.

A process can suspend execution until the delivery of one of a set of signals by calling `sigsuspend`. This is a more general form of the pause function we met earlier.

```
#include <signal.h>

int sigsuspend(const sigset_t *sigmask);
```

The `sigsuspend` function replaces the process signal mask with the signal set given by `sigmask` and then suspends execution. It will resume after the execution of a signal handling function. If the received signal terminates the program, `sigsuspend` will never return. If a received signal doesn't terminate the program, `sigsuspend` returns -1 with `errno` set to `EINTR`.

sigaction Flags

The `sa_flags` field of the `sigaction` structure used in `sigaction` may contain the following values to modify signal behavior:

| | |
|---------------------------|---|
| <code>SA_NOCLDSTOP</code> | Don't generate <code>SIGCHLD</code> when child processes stop. |
| <code>SA_RESETHAND</code> | Reset signal action to <code>SIG_DFL</code> on receipt. |
| <code>SA_RESTART</code> | Restart interruptible functions rather than error with <code>EINTR</code> . |
| <code>SA_NODEFER</code> | Don't add the signal to the signal mask when caught. |

The `SA_RESETHAND` flag can be used to automatically clear a signal function when a signal is caught, as we saw before.

Many system calls that a program uses are interruptible; that is, when they receive a signal they will return with an error and `errno` will be set to `EINTR` to indicate that the function returned due to a signal. This behavior requires extra care by an application using signals. If `SA_RESTART` is set in the `sa_flags` field in a call to `sigaction`, a function that might otherwise be interrupted by a signal will instead be restarted once the signal handling function has been executed.

Ordinarily, when a signal handling function is being executed, the signal received is added to the process signal mask for the duration of the handling function. This prevents a subsequent occurrence of the same signal, causing the signal handling function to run again. If the function is not re-entrant, having it called by another occurrence of a signal before it finishes handling the first may cause problems. If, however, the `SA_NODEFER` flag is set, the signal mask is not altered when it receives this signal.

A signal-handling function could be interrupted in the middle and called again by something else. When you come back to the first call, it's vital that it still operates correctly. It's not just recursive (calling itself), but re-entrant (can be entered and executed again without problems). Interrupt service routines in the kernel that deal with more than one device at a time need to be re-entrant, as a higher priority interrupt might "get in" during the execution of the same code.

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Functions that are safe to call inside a signal handler, those guaranteed by the X/Open specification either to be re-entrant or not to raise signals themselves, are listed as follows.

All functions not listed in the following table should be considered unsafe with respect to signals.

| | | | |
|-------------|-------------|-------------|-------------|
| access | alarm | cfgetispeed | cfgetospeed |
| cfsetispeed | cfsetospeed | chdir | chmod |
| chown | close | creat | dup2 |
| dup | execle | execve | _exit |
| fcntl | fork | fstat | getegid |
| geteuid | getgid | getgroups | getpgrp |
| getpid | getppid | getuid | kill |
| link | lseek | mkdir | mkfifo |
| open | pathconf | pause | pipe |
| read | rename | rmdir | setgid |
| setpgid | setsid | setuid | sigaction |
| sigaddset | sigdelset | sigemptyset | sigfillset |
| sigismember | signal | sigpending | sigprocmask |
| sigsuspend | sleep | stat | sysconf |
| tcdrain | tcflow | tcflush | tcgetattr |
| tcgetpgrp | tcsendbreak | tcsetattr | tcsetpgrp |
| time | times | umask | uname |
| unlink | utime | wait | waitpid |
| write | | | |

Common Signal Reference

In this section, we list the signals that Linux and UNIX programs typically need with their default behaviors.

The default action for the signals in the following table is abnormal termination of the process with all the consequences of `_exit` (which is like `exit` but performs no cleanup before returning to the kernel). However, the status is made available to `wait`, and `waitpid` indicates abnormal termination by the specified signal.

| Signal Name | Description |
|----------------------|--|
| SIGALRM | Generated by the timer set by the <code>alarm</code> function. |
| SIGHUP | Sent to the controlling process by a disconnecting terminal, or by the controlling process on termination to each foreground process. |
| SIGINT | Typically raised from the terminal by typing Ctrl+C or the configured interrupt character. |
| SIGKILL | Typically used from the shell to forcibly terminate an errant process, as this signal can't be caught or ignored. |
| SIGPIPE | Generated by an attempt to write to a pipe with no associated reader. |
| SIGTERM | Sent as a request for a process to finish. Used by UNIX when shutting down to request that system services stop. This is the default signal sent from the <code>kill</code> command. |
| SIGUSR1 , SIGUSR2 | May be used by processes to communicate with each other, possibly to cause them to report status information. |

By default, the signals in the next table also cause abnormal termination. Additionally, implementation-dependent actions, such as creation of a core file, may occur.

| Signal Name | Description |
|-------------|---|
| SIGFPE | Generated by a floating-point arithmetic exception. |
| SIGILL | An illegal instruction has been executed by the processor. Usually caused by a corrupt program or invalid shared memory module. |
| SIGQUIT | Typically raised from the terminal by typing Ctrl+\ or the configured quit character. |
| SIGSEGV | A segmentation violation, usually caused by reading or writing at an illegal location in memory either by exceeding array bounds or dereferencing an invalid pointer. Overwriting a local array variable and corrupting the stack can cause a SIGSEGV to be raised when a function returns to an illegal address. |

A process is suspended by default on receipt of one of the signals in the following table.

| Signal Name | Description |
|----------------------|--|
| SIGSTOP | Stop executing (can't be caught or ignored). |
| SIGTSTP | Terminal stop signal, often raised by typing Ctrl+Z. |
| SIGTTIN , SIGTTOU | Used by the shell to indicate that background jobs have stopped because they need to read from the terminal or produce output. |

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SIGCONT restarts a stopped process and is ignored if received by a process that is not stopped. The SIGCHLD signal is ignored by default.

| Signal Name | Description |
|-------------|---|
| SIGCONT | Continue executing, if stopped. |
| SIGCHLD | Raised when a child process stops or exits. |

Summary

In this chapter, we have seen how processes are a fundamental part of the Linux operating system. We have learned how they can be started, terminated, and viewed and how we can use them to solve programming problems. We've also taken a look at signals, events that can be used to control the actions of running programs. We have seen that all Linux processes, down to and including `init`, use the same set of system calls available to any programmer.

12

POSIX Threads

In Chapter 11, we saw how processes are handled in Linux (and indeed in UNIX). These multi-processing features have long been a feature of UNIX-like operating systems. Sometimes the overhead cost of creating a new process with `fork` is considered too great. In this case, it would be very useful to make a single program do two things at once, or at least to appear to do so. Alternatively, you might want two or more things to happen at the same time in a closely coupled way. That's where threads come in.

In this chapter, we are going to look at

- Creating new threads within a process
- Synchronizing data access between threads in a single process
- Modifying the attributes of a thread
- Controlling one thread from another in the same process

What Is a Thread?

Multiple strands of execution in a single program are called *threads*. A more precise definition is that a thread is a sequence of control within a process. All the programs we have seen so far have executed as a single process, although, like many other operating systems, Linux is quite capable of running multiple processes simultaneously. Indeed, all processes have at least one thread of execution. All the processes that we have seen so far in this book have had just one thread of execution.

It's important to be clear about the difference between the `fork` system call and the creation of new threads. When a process executes a `fork` call, a new copy of the process is created with its own variables and its own PID. This new process is scheduled independently, and (in general) executes almost independently of the process that created it. When we create a new thread in a process, the new thread of execution gets its own stack (and hence local variables) but shares global variables, file descriptors, signal handlers, and its current directory state with the process that created it.

The concept of threads has been around for some time, but until the IEEE POSIX committee published some standards, they had not been widely available in UNIX-like operating systems, and the implementations that did exist tended to vary between different vendors. With the advent of the POSIX 1003.1c specification, all that changed; threads are not only better standardized, but are also available on most Linux distributions.

Linux first acquired thread support around 1996, with a library often referred to as “LinuxThreads.” This was very close to the POSIX standard (indeed, for many purposes the differences are not noticeable) and it was a significant step forward that enabled Linux programmers to use threads for the first time. However, there were slight discrepancies between the Linux implementation and the POSIX standard, most notably with regard to signal handling. These limitations were imposed not so much by the library implementation, but more by the limitations of the underlying support from the Linux kernel.

Various projects looked at how the thread support on Linux might be improved, not just to clear up the slight discrepancies between the POSIX standard and the Linux implementation, but also to improve performance and remove any unnecessary restrictions. Much work centered on how user-level threads should map to kernel-level threads. The two principal projects were New Generation POSIX Threads (NGPT) and Native POSIX Thread Library (NPTL). Both projects had to make changes to the Linux kernel to support the new libraries, and both offered significant performance improvements over the older Linux threads.

In 2002, the NGPT team announced that they did not wish to split the community and would cease adding new features to NGPT, but would continue to work on thread support in Linux, effectively throwing their weight behind the NPTL effort. Thus, it seems clear that NPTL will become the new standard for threads on Linux, and the first mainstream release of NPTL occurred with Red Hat Linux 9. Some interesting background information on NPTL can be found in a paper titled “The Native POSIX Thread Library for Linux” by Ulrich Drepper and Ingo Molnar, which, at the time of this book’s writing, can be found at http://www.redhat.com/partners/pdf/POSIX_Linux_Threading.pdf.

Most of the code in this chapter should work with any of the thread libraries, since it is based on the POSIX standard that is common across all the thread libraries. However, you will see some slight differences if you are not using NPTL, particularly if you use ps to look at the examples while they are running. With the older LinuxThreads library, you will generally see multiple processes, usually one more than you have threads executing; with NPTL, you should see just a single program, even though it has many threads internally.

Advantages and Drawbacks of Threads

Creating a new thread has some distinct advantages over creating a new process in certain circumstances. The overhead cost of creating a new thread is significantly less than that of creating a new process (though Linux is particularly efficient at creating new processes compared with some other operating systems).

Following are some examples of the uses of threads:

- ❑ Sometimes it is very useful to make a program appear to do two things at once. The classic example is to perform a real-time word count on a document while still editing the text. One thread can manage the user’s input and perform editing. The other, which can see the same document content, can continuously update a word count variable. The first thread (or even a third one) can use this shared variable to keep the user informed. Another example is a multithreaded database server where an apparent single process serves multiple clients, improving the overall data throughput by servicing some requests while blocking others, waiting for disk activity.

For a database server, this apparent multitasking is quite hard to do efficiently in different processes, because the requirements for locking and data consistency cause the different processes to be very tightly coupled. This can be done much more easily with multiple threads than with multiple processes.

- ❑ The performance of an application that mixes input, calculation and output may be improved by running these as three separate threads. While the input or output thread is waiting for a connection, one of the other threads can continue. Thus, while any application can ultimately do only one thing at a time, threads enable an application to do something useful while it waits for such things as connections. A server application processing multiple network connects may also be a natural fit for a multithreaded program.
- ❑ In general, switching between threads requires the operating system to do much less work than switching between processes. Thus, multiple threads are much less demanding on resources than multiple processes, and it is more practical to run programs that logically require many threads of execution on single processor systems. That said, the design difficulties of writing a multithreaded program are significant and should not be taken lightly.

Threads also have drawbacks:

- ❑ Writing multithreaded programs requires very careful design. The potential for introducing subtle timing faults, or faults caused by the unintentional sharing of variables in a multithreaded program is considerable. Alan Cox (the Linux guru who wrote the forward to this book) has commented that threads are also known as “how to shoot yourself in both feet at once.”
- ❑ Debugging a multithreaded program is much harder than debugging a single-threaded one, because the interactions between the threads are very hard to control.
- ❑ A program that splits a large calculation into two and runs the two parts as different threads will not necessarily run more quickly on a single processor machine, as there are only so many CPU cycles to be had, though if nothing else is trying to execute and you have multiple processors or a hyperthreaded CPU, a multiple thread approach may offer benefits.

A First Threads Program

There is a whole set of library calls associated with threads, most of whose names start with `pthread_`. To use these library calls, we must define the macro `_REENTRANT`, include the file `pthread.h`, and link with the threads library using `-lpthread`.

When the original UNIX and POSIX library routines were designed, it was assumed that there would be only a single thread of execution in any process. An obvious example is `errno`, the variable used for retrieving error information after a call fails. In a multithreaded program there would, by default, be only one `errno` variable shared between all the threads. The variable could easily be updated by a call in one thread before a different thread has been able to retrieve a previous error code. Similar problems exist with functions, such as `fputs`, that normally use a single global area for buffering output.

We need routines known as *re-entrant* routines. Re-entrant code can be called more than once, whether by different threads or by nested invocations in some way, and still function correctly. Thus, the re-entrant section of code usually must use local variables only in such a way that each and every call to the code gets its own unique copy of the data.

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In multithreaded programs, we tell the compiler that we need this feature by defining the `_REENTRANT` macro before any `#include` lines in our program. This does three things for us, and does them so elegantly that usually we don't even need to know what was done:

- ❑ Some functions get prototypes for a re-entrant safe equivalent. These are normally the same function name, but with `_r` appended so that, for example, `gethostbyname` is changed to `gethostbyname_r`.
- ❑ Some `stdio.h` functions that are normally implemented as macros become proper re-entrant safe functions.
- ❑ The variable `errno`, from `errno.h`, is changed to call a function, which can determine the real `errno` value in a multithread safe way.

Including the file `pthread.h` provides us with other definitions and prototypes that we will need in our code, much like `stdio.h` for standard input and output routines. Finally, we need to ensure that we include the appropriate thread header file and link with the appropriate threads library that implements the `pthread` functions. We will look in more detail at compiling our program in the “Try It Out” section immediately following this section.

`pthread_create` creates a new thread, much as `fork` creates a new process.

```
#include <pthread.h>

int pthread_create(pthread_t *thread, pthread_attr_t *attr, void
  *(*start_routine) (void *), void *arg);
```

This may look imposing, but it is actually quite easy to use. The first argument is a pointer to `pthread_t`. When a thread is created, an identifier is written to the variable to which this pointer points. This identifier enables us to refer to the thread. The next argument sets the thread attributes. You do not usually need any special attributes, and you can simply pass `NULL` as this argument. Later in the chapter we will see how to use these attributes. The final two arguments tell the thread the function that it is to start executing and the arguments that are to be passed to this function.

```
void *(*start_routine) (void *)
```

The preceding line simply says that we must pass the address of a function taking a pointer to `void` as a parameter and the function will return a pointer to `void`. Thus, we can pass any type of single argument and return a pointer to any type. Using `fork` causes execution to continue in the same location with a different return code, whereas using a new thread explicitly provides a pointer to a function where the new thread should start executing.

The return value is `0` for success or an error number if anything goes wrong. The manual pages have details of error conditions for this and other functions used in this chapter.

`pthread_create`, like most `pthread_` functions, is among the few UNIX functions that do not follow the convention of using `-1` for errors. Unless you are very sure, it's always safest to double check the manual before checking the error code.

When a thread terminates, it calls the `pthread_exit` function, much as a process calls `exit` when it terminates. This function terminates the calling thread, returning a pointer to an object. Never use it to return a pointer to a local variable, because the variable will cease to exist when the thread does so, causing a serious bug. `pthread_exit` is declared as follows:

```
#include <pthread.h>

void pthread_exit(void *retval);
```

`pthread_join` is the thread equivalent of `wait` that processes use to collect child processes. This function is declared as follows:

```
#include <pthread.h>

int pthread_join(pthread_t th, void **thread_return);
```

The first parameter is the thread for which to wait, the identifier that `pthread_create` filled in for us. The second argument is a pointer to a pointer that itself points to the return value from the thread. Like `pthread_create`, this function returns zero for success and an error code on failure.

Try It Out—A Simple Threaded Program

This program creates a single extra thread, shows that it is sharing variables with the original thread, and gets the new thread to return a result to the original thread. Multithreaded programs don't get much simpler than this! Here is `thread1.c`:

```
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <pthread.h>

void *thread_function(void *arg);

char message[] = "Hello World";

int main() {
    int res;
    pthread_t a_thread;
    void *thread_result;

    res = pthread_create(&a_thread, NULL, thread_function, (void *)message);
    if (res != 0) {
        perror("Thread creation failed");
        exit(EXIT_FAILURE);
    }
    printf("Waiting for thread to finish...\n");
    res = pthread_join(a_thread, &thread_result);
    if (res != 0) {
        perror("Thread join failed");
        exit(EXIT_FAILURE);
    }
    printf("Thread joined, it returned %s\n", (char *)thread_result);
}
```

```
    printf("Message is now %s\n", message);
    exit(EXIT_SUCCESS);
}

void *thread_function(void *arg) {
    printf("thread_function is running. Argument was %s\n", (char *)arg);
    sleep(3);
    strcpy(message, "Bye!");
    pthread_exit("Thank you for the CPU time");
}
```

1. To compile this, first we need to ensure that `_REENTRANT` is defined. On a few systems, we may also need to define `_POSIX_C_SOURCE`, but normally this will not be necessary.
2. Now we must ensure that the appropriate thread library is linked. Depending on your system, NPTL may or may not be the default, or on older systems, may not even be available or usable, depending on the kernel version. Fortunately, most of the code in this chapter is independent of the exact thread library used. On the authors' systems, checking the standard `/usr/include/pthread.h` file shows that it is entitled Linuxthreads, with a copyright date of 1996, so it is quite clearly the older library. To get the new NPTL we had to install an additional RPM that provided additional include files under `/usr/include/nptl` and additional libraries under `/usr/lib/nptl`.
3. Having identified and installed the appropriate files, we can now compile and link our program like this:

```
$ cc -D _REENTRANT -I/usr/include/nptl thread1.c -o thread1 -L/usr/lib/nptl -lpthread
```

If you have both sets of include files and libraries installed, you may want to consider renaming the older ones to be certain you are using the correct set. If NPTL is the default on your system, you almost certainly don't need the `-I` and `-L` options. The code in this chapter tries to stick closely to the standard, and hopefully you will be able to run it on any Linux system with good support for threads.

4. When you run this program, you should see

```
$ ./thread1
Waiting for thread to finish...
thread_function is running. Argument was Hello World
Thread joined, it returned Thank you for the CPU time
Message is now Bye!
```

It's worth spending a little time on understanding this program, as we will be using it as the basis for most of the examples in this chapter.

How It Works

We declare a prototype for the function that the thread will call when we create it.

```
void *thread_function(void *arg);
```

As required by `pthread_create`, it takes a pointer to `void` as its only argument and returns a pointer to `void`. We will come to the definition (and the implementation) of this function in a moment.

In `main`, we declare some variables and then call `pthread_create` to start running our new thread.

```
pthread_t a_thread;
void *thread_result;

res = pthread_create(&a_thread, NULL, thread_function, (void *)message);
```

We pass the address of a `pthread_t` object that we can use to refer to the thread afterward. We don't wish to modify the default thread attributes, so we pass `NULL` as the second parameter. The final two parameters are the function to call and a parameter to pass to it.

If the call succeeds, two threads will now be running. The original thread (`main`) continues and executes the code after `pthread_create`, and a new thread starts executing in our imaginatively named `thread_function`.

The original thread checks that the new thread has started and then calls `pthread_join`.

```
res = pthread_join(a_thread, &thread_result);
```

Here we pass the identifier of the thread that we are waiting to join and a pointer to a result. This function will wait until the other thread terminates before it returns. It then prints the return value from the thread and the contents of a variable, and exits.

The new thread starts executing and `thread_function` prints out its arguments, sleeps for a short period, updates global variables, and then exits, returning a string to the main thread. The new thread writes to the same array, `message`, to which the original thread has access. This would not be so if we had called `fork` rather than `pthread_create`.

Simultaneous Execution

Next we are going to write a program that checks that the execution of two threads occurs simultaneously (still, of course, on a single processor system, because the CPU is being cleverly switched between the threads). Since we haven't yet met any of the thread synchronization functions we need to do this efficiently, it will be a very inefficient program that does what is known as a *polling* between the two threads. Again, we will make use of the fact that everything except local function variables are shared between the different threads in a process.

Try It Out—Simultaneous Execution of Two Threads

The program we'll create in this section, `thread2.c`, is created by slightly modifying `thread1.c`. We add an extra file scope variable to test which thread is running:

```
int run_now = 1;
```

We will set `run_now` to 1 when the main function is executing and to 2 when our new thread is executing.

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In the `main` function, after the creation of the new thread, we add the following code:

```
int print_count1 = 0;

while(print_count1++ < 20) {
    if (run_now == 1) {
        printf("1");
        run_now = 2;
    }
    else {
        sleep(1);
    }
}
```

If `run_now` is 1, we print "1" and set it to 2. Otherwise, we sleep briefly and check the value again. We are waiting for the value to change to 1 by checking over and over again. This is called a *busy wait*, although we have slowed it down by sleeping for a second between checks. We'll see a better way to do this later in the chapter.

In `thread_function`, where our new thread is executing, we do much the same but with the values reversed.

```
int print_count2 = 0;

while(print_count2++ < 20) {
    if (run_now == 2) {
        printf("2");
        run_now = 1;
    }
    else {
        sleep(1);
    }
}
```

We have also removed the parameter passing and return value passing because we are no longer interested in them.

When we run the program, we see the following output. (You may find that it takes a few seconds for the program to produce output.)

```
$ cc -D_REENTRANT thread3.c -o thread2 -lpthread
$ ./thread2
12121212121212121212
Waiting for thread to finish...
Thread joined
```

How It Works

Each thread tells the other one to run by setting the `run_now` variable and then waits till the other thread has changed its value before running again. This shows that execution passes between the two threads automatically and again illustrates the point that both threads are sharing the `run_now` variable.

Synchronization

In the previous section, we saw that both threads execute together, but our method of switching between them was clumsy and very inefficient. Fortunately, there is a set functions specifically designed to give us better ways to control the execution of threads and access to critical sections of code.

We will look at two basic methods here: *semaphores*, which act as gatekeepers around a piece of code, and *mutexes*, which act as a mutual exclusion (hence the name mutex) device to protect sections of code. Both of these methods are similar; indeed, one can be implemented in terms of the other. However, there are some cases where the semantics of the problem suggest that one is more expressive than the other. For example, controlling access to some shared memory, which only one thread can access at a time, would most naturally involve a mutex. However, controlling access to a set of identical objects as a whole, such as giving one telephone line out of a set of five available lines to a thread, suits a counting semaphore better. Which one you choose depends on personal preference and the most appropriate mechanism for your program.

Synchronization with Semaphores

There are two sets of interface functions for semaphores: One is taken from POSIX Realtime Extensions and used for threads, and the other is known as System V semaphores, which are commonly used for process synchronization. (We will discuss the second type in a later chapter.) The two are not guaranteed to be interchangeable and, although very similar, use different function calls.

In this section we are going to look at the simplest type of semaphore, a binary semaphore that takes only values 0 or 1. There is also a more general semaphore, a counting semaphore that takes a wider range of values. Normally, semaphores are used to protect a piece of code so that only one thread of execution can run it at any one time. For this job a binary semaphore is needed. Occasionally, we want to permit a limited number of threads to execute a given piece of code; for this we would use a counting semaphore. As counting semaphores are much less common, we won't consider them further here except to say that they are just a logical extension of a binary semaphore and that the actual function calls needed are identical.

The semaphore functions do not start with `pthread_`, as most thread-specific functions do, but with `sem_`. There are four basic semaphore functions used in threads. They are all quite simple.

A semaphore is created with the `sem_init` function, which is declared as follows:

```
#include <semaphore.h>

int sem_init(sem_t *sem, int pshared, unsigned int value);
```

This function initializes a semaphore object pointed to by `sem`, sets its sharing option (which we will discuss more in a moment), and gives it an initial integer value. The `pshared` parameter controls the type of semaphore. If the value of `pshared` is 0, then the semaphore is local to the current process. Otherwise, the semaphore may be shared between processes. Here we are interested only in semaphores that are not shared between processes. At the time of writing, Linux doesn't support this sharing, and passing a nonzero value for `pshared` will cause the call to fail.

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The next pair of functions controls the value of the semaphore and is declared as follows:

```
#include <semaphore.h>

int sem_wait(sem_t * sem);

int sem_post(sem_t * sem);
```

These both take a pointer to the semaphore object initialized by a call to `sem_init`.

The `sem_post` function atomically increases the value of the semaphore by 1. *Atomically* here means that if two threads simultaneously try to increase the value of a single semaphore by 1, they do not interfere with each other, as might happen if two programs read, increment, and write a value to a file at the same time. The semaphore will always be correctly increased in value by 2, since two threads tried to change it.

The `sem_wait` function atomically decreases the value of the semaphore by one, but always waits until the semaphore has a nonzero count first. Thus, if you call `sem_wait` on a semaphore with a value of 2, the thread will continue executing but the semaphore will be decreased to 1. If `sem_wait` is called on a semaphore with a value of 0, the function will wait until some other thread has incremented the value so that it is no longer 0. If two threads are both waiting in `sem_wait` for the same semaphore to become nonzero and it is incremented once by a third process, only one of the two waiting processes will get to decrement the semaphore and continue; the other will remain waiting.

This atomic “test and set” ability in a single function is what makes semaphores so valuable. There is another semaphore function, `sem_trywait`, that is the nonblocking partner of `sem_wait`. We don’t discuss it further here, but you can find more details in the manual pages.

The last semaphore function is `sem_destroy`. This function tidies up the semaphore when we have finished with it. It is declared as follows:

```
#include <semaphore.h>

int sem_destroy(sem_t * sem);
```

Again, this function takes a pointer to a semaphore and tidies up any resources that it may have. If you attempt to destroy a semaphore for which some thread is waiting, you will get an error.

Like most Linux functions, these functions all return 0 on success.

Try It Out—A Thread Semaphore

This code, `thread3.c`, is also based on `thread1.c`. Since a lot has changed, we will present it in full.

```
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <string.h>
#include <pthread.h>
#include <semaphore.h>

void *thread_function(void *arg);
sem_t bin_sem;
```

```

#define WORK_SIZE 1024
char work_area[WORK_SIZE];

int main() {
    int res;
    pthread_t a_thread;
    void *thread_result;

    res = sem_init(&bin_sem, 0, 0);
    if (res != 0) {
        perror("Semaphore initialization failed");
        exit(EXIT_FAILURE);
    }
    res = pthread_create(&a_thread, NULL, thread_function, NULL);
    if (res != 0) {
        perror("Thread creation failed");
        exit(EXIT_FAILURE);
    }
    printf("Input some text. Enter 'end' to finish\n");
    while(strncmp("end", work_area, 3) != 0) {
        fgets(work_area, WORK_SIZE, stdin);
        sem_post(&bin_sem);
    }
    printf("\nWaiting for thread to finish...\n");
    res = pthread_join(a_thread, &thread_result);
    if (res != 0) {
        perror("Thread join failed");
        exit(EXIT_FAILURE);
    }
    printf("Thread joined\n");
    sem_destroy(&bin_sem);
    exit(EXIT_SUCCESS);
}

void *thread_function(void *arg) {
    sem_wait(&bin_sem);
    while(strncmp("end", work_area, 3) != 0) {
        printf("You input %d characters\n", strlen(work_area) -1);
        sem_wait(&bin_sem);
    }
    pthread_exit(NULL);
}

```

The first important change is the inclusion of `semaphore.h` to give us access to the semaphore functions. Then we declare a semaphore and some variables and initialize the semaphore *before* we create our new thread.

```

sem_t bin_sem;

#define WORK_SIZE 1024
char work_area[WORK_SIZE];

int main() {
    int res;
    pthread_t a_thread;

```

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```
void *thread_result;
res = sem_init(&bin_sem, 0, 0);
if (res != 0) {
    perror("Semaphore initialization failed");
    exit(EXIT_FAILURE);
}
```

Note that we set the initial value of the semaphore to 0.

In the function `main`, after we have started the new thread, we read some text from the keyboard, load our work area, and then increment the semaphore with `sem_post`.

```
printf("Input some text. Enter 'end' to finish\n");
while(strncmp("end", work_area, 3) != 0) {
    fgets(work_area, WORK_SIZE, stdin);
    sem_post(&bin_sem);
}
```

In the new thread, we wait for the semaphore and then count the characters from the input.

```
sem_wait(&bin_sem);
while(strncmp("end", work_area, 3) != 0) {
    printf("You input %d characters\n", strlen(work_area) -1);
    sem_wait(&bin_sem);
}
```

While the semaphore is set, we are waiting for keyboard input. When we have some input, we release the semaphore, allowing the second thread to count the characters before the first thread reads the keyboard again.

Again both threads share the same `work_area` array. Again, we have omitted some error checking, such as the returns from `sem_wait` to make the code samples more succinct and easier to follow. However, in production code you should always check for error returns unless there is a very good reason to omit this check.

Let's give our program a run:

```
$ cc -D_REENTRANT -I/usr/include/nptl thread3.c -o thread3 -L/usr/lib/nptl -
lpthread
$ ./thread3
Input some text. Enter 'end' to finish
The Wasp Factory
You input 16 characters
Iain Banks
You input 10 characters
end

Waiting for thread to finish...
Thread joined
```

In threaded programs, timing faults are always hard to find, but the program seems resilient to both quick input of text and more leisurely pauses.

How It Works

When we initialize the semaphore, we set its value to 0. Thus, when the thread's function starts, the call to `sem_wait` blocks and waits for the semaphore to become nonzero.

In the main thread, we wait until we have some text and then increment the semaphore with `sem_post`, which immediately allows the other thread to return from its `sem_wait` and start executing. Once it has counted the characters, it again calls `sem_wait` and is blocked until the main thread again calls `sem_post` to increment the semaphore.

It is easy to overlook subtle design errors that result in subtle errors. Let's modify the program slightly to `thread4a.c` to pretend that text input from the keyboard is sometimes replaced with automatically available text. We modify the reading loop in the `main` to this:

```
printf("Input some text. Enter 'end' to finish\n");
while(strncmp("end", work_area, 3) != 0) {
    if (strncmp(work_area, "FAST", 4) == 0) {
        sem_post(&bin_sem);
        strcpy(work_area, "Weeeee...");
```

```
} else {
    fgets(work_area, WORK_SIZE, stdin);
}
sem_post(&bin_sem);
}
```

Now if we enter **FAST**, the program calls `sem_post` to allow the character counter to run, but immediately updates `work_area` with something different.

```
$ cc -D_REENTRANT thread4a.c -o thread4a -lpthread
$ ./thread4a
Input some text. Enter 'end' to finish
Exception
You input 9 characters
FAST
You input 7 characters
You input 7 characters
You input 7 characters
end

Waiting for thread to finish...
Thread joined
```

The problem is that our program was relying on text input from the program taking so long that there was time for the other thread to count the words before the main thread was ever ready to give it more words to count. When we tried to give it two different sets of words to count in quick succession (**FAST** from the keyboard and then **Weeeee...** automatically), there was no time for the second thread to execute. However, the semaphore had been incremented more than once, so the counter thread just kept counting the words and decreasing the semaphore until it became zero again.

This shows just how careful you need to be with timing considerations in multithreaded programs. It's possible to fix the program by using an extra semaphore to make the main thread wait until the counter thread has had the chance to finish its counting.

Synchronization with Mutexes

The other way of synchronizing access in multithreaded programs is with *mutexes*, which act by allowing the programmer to “lock” an object so that only one thread can access it. To control access to a critical section of code you lock a mutex before entering the code section and then unlock it when you have finished.

The basic functions required to use mutexes are very similar to those needed for semaphores. They are declared as follows:

```
#include <pthread.h>

int pthread_mutex_init(pthread_mutex_t *mutex, const pthread_mutexattr_t
                      *mutexattr);

int pthread_mutex_lock(pthread_mutex_t *mutex);

int pthread_mutex_unlock(pthread_mutex_t *mutex);

int pthread_mutex_destroy(pthread_mutex_t *mutex);
```

As usual, 0 is returned for success, and on failure an error code is returned, but `errno` is not set; you must use the return code.

As with semaphores, they all take a pointer to a previously declared object, in this case a `pthread_mutex_t`. The extra attribute parameter `pthread_mutex_init` allows us to provide attributes for the mutex, which control its behavior. The attribute type by default is “fast.” This has the slight drawback that, if your program tries to call `pthread_mutex_lock` on a mutex that it has already locked, the program will block. Since the thread that holds the lock is the one that is now blocked, the mutex can never be unlocked and the program is deadlocked. It is possible to alter the attributes of the mutex so that it either checks for this and returns an error or acts recursively and allows multiple locks by the same thread if there are the same number of unlocks afterward.

Setting the attribute of a mutex is beyond the scope of this book, so we will pass `NULL` for the attribute pointer and use the default behavior. You can find more about changing the attributes by reading the manual page for `pthread_mutex_init`.

Try It Out—A Thread Mutex

Again, this is a modification of our original `thread1.c` but heavily modified. This time, we will be a little paranoid about access to our critical variables and use a mutex to ensure they are ever accessed by only one thread at any one time. To keep the example code easy to read, we have omitted some error checking on the returns from mutex lock and unlock. In production code, we would check these return values. Here is the new program, `thread4.c`:

```
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <string.h>
#include <pthread.h>
#include <semaphore.h>
```

```
void *thread_function(void *arg);
pthread_mutex_t work_mutex; /* protects both work_area and time_to_exit */

#define WORK_SIZE 1024
char work_area[WORK_SIZE];
int time_to_exit = 0;

int main() {
    int res;
    pthread_t a_thread;
    void *thread_result;
    res = pthread_mutex_init(&work_mutex, NULL);
    if (res != 0) {
        perror("Mutex initialization failed");
        exit(EXIT_FAILURE);
    }
    res = pthread_create(&a_thread, NULL, thread_function, NULL);
    if (res != 0) {
        perror("Thread creation failed");
        exit(EXIT_FAILURE);
    }
    pthread_mutex_lock(&work_mutex);
    printf("Input some text. Enter 'end' to finish\n");
    while(!time_to_exit) {
        fgets(work_area, WORK_SIZE, stdin);
        pthread_mutex_unlock(&work_mutex);
        while(1) {
            pthread_mutex_lock(&work_mutex);
            if (work_area[0] != '\0') {
                pthread_mutex_unlock(&work_mutex);
                sleep(1);
            }
            else {
                break;
            }
        }
    }
    pthread_mutex_unlock(&work_mutex);
    printf("\nWaiting for thread to finish...\n");
    res = pthread_join(a_thread, &thread_result);
    if (res != 0) {
        perror("Thread join failed");
        exit(EXIT_FAILURE);
    }
    printf("Thread joined\n");
    pthread_mutex_destroy(&work_mutex);
    exit(EXIT_SUCCESS);
}

void *thread_function(void *arg) {
    sleep(1);
    pthread_mutex_lock(&work_mutex);
    while(strncmp("end", work_area, 3) != 0) {
        printf("You input %d characters\n", strlen(work_area) - 1);
```

```
work_area[0] = '\0';
pthread_mutex_unlock(&work_mutex);
sleep(1);
pthread_mutex_lock(&work_mutex);
while (work_area[0] == '\0') {
    pthread_mutex_unlock(&work_mutex);
    sleep(1);
    pthread_mutex_lock(&work_mutex);
}
}
time_to_exit = 1;
work_area[0] = '\0';
pthread_mutex_unlock(&work_mutex);
pthread_exit(0);
}

$ cc -D_REENTRANT -I/usr/include/nptl thread4.c -o thread4 -L/usr/lib/nptl -lpthread
$ ./thread4
Input some text. Enter 'end' to finish
Whit
You input 4 characters
The Crow Road
You input 13 characters
end

Waiting for thread to finish...
Thread joined
```

How It Works

We start by declaring a mutex, our work area, and this time, an additional variable: `time_to_exit`.

```
pthread_mutex_t work_mutex; /* protects both work_area and time_to_exit */

#define WORK_SIZE 1024
char work_area[WORK_SIZE];
int time_to_exit = 0;
```

Then we initialize the mutex.

```
res = pthread_mutex_init(&work_mutex, NULL);
if (res != 0) {
    perror("Mutex initialization failed");
    exit(EXIT_FAILURE);
}
```

Next we start the new thread. Here is the code that executes in the thread function:

```
pthread_mutex_lock(&work_mutex);
while(strncmp("end", work_area, 3) != 0) {
    printf("You input %d characters\n", strlen(work_area) -1);
```

```

work_area[0] = '\0';
pthread_mutex_unlock(&work_mutex);
sleep(1);
pthread_mutex_lock(&work_mutex);
while (work_area[0] == '\0') {
    pthread_mutex_unlock(&work_mutex);
    sleep(1);
    pthread_mutex_lock(&work_mutex);
}
}
time_to_exit = 1;
work_area[0] = '\0';
pthread_mutex_unlock(&work_mutex);

```

First, the new thread tries to lock the mutex. If it's already locked, the call will block until it is released. Once we have access, we check to see whether we are being requested to exit. If we are requested to exit, we simply set `time_to_exit`, zap the first character of the work area, and exit.

If we don't want to exit, we count the characters and then zap the first character to a null. We use the first character being null as a way of telling the reader program that we have finished the counting. We then unlock the mutex and wait for the main thread to run. Periodically, we attempt to lock the mutex and, when we succeed, check whether the main thread has given us any more work to do. If it hasn't, we unlock the mutex and wait some more. If it has, we count the characters and go round the loop again.

Here is the main thread.

```

pthread_mutex_lock(&work_mutex);
printf("Input some text. Enter 'end' to finish\n");
while(!time_to_exit) {
    fgets(work_area, WORK_SIZE, stdin);
    pthread_mutex_unlock(&work_mutex);
    while(1) {
        pthread_mutex_lock(&work_mutex);
        if (work_area[0] != '\0') {
            pthread_mutex_unlock(&work_mutex);
            sleep(1);
        }
        else {
            break;
        }
    }
}
pthread_mutex_unlock(&work_mutex);

```

This is quite similar. We lock the work area so that we can read text into it and then unlock it to allow the other thread access to count the words. Periodically, we relock the mutex, check whether the words have been counted (`work_area[0]` set to a null), and release the mutex if we need to wait longer. As we noted earlier, this kind of polling for an answer is generally not good programming practice, and in the real world, we would probably have used a semaphore to avoid this. However, the code served its purpose as an example.

Thread Attributes

When we first looked at threads, we did not discuss the question of thread attributes. We will now do so. There are quite a few attributes of threads that you can control. However, here we are only going to look at those that you are most likely to need. Details of the others can be found in the manual pages.

In all of our previous examples, we had to resynchronize our threads using `pthread_join` before allowing the program to exit. We needed to do this if we wanted to allow one thread to return data to the thread that created it. Sometimes we neither need the second thread to return information to the main thread nor want the main thread to wait for it.

Suppose that we create a second thread to spool a backup copy of a data file that is being edited while the main thread continues to service the user. When the backup has finished, the second thread can just terminate. There is no need for it to rejoin the main thread.

We can create threads that behave like this. They are called *detached threads*, and we create them by modifying the thread attributes or by calling `pthread_detach`. Since we want to demonstrate attributes, we will use the former method here.

The most important function that we need is `pthread_attr_init`, which initializes a thread attribute object.

```
#include <pthread.h>

int pthread_attr_init(pthread_attr_t *attr);
```

Once again, 0 is returned for success and an error code is returned on failure.

There is also a destroy function: `pthread_attr_destroy`. Its purpose is to allow clean destruction of the attribute object. Once the object has been destroyed, it cannot be used again until it has been reinitialized.

When we have a thread attribute object initialized, there are many additional functions that we can call to set different attribute behaviors. We will list the main ones here but look closely at only two:

```
int pthread_attr_setdetachstate(pthread_attr_t *attr, int detachstate);

int pthread_attr_getdetachstate(const pthread_attr_t *attr, int *detachstate);

int pthread_attr_setschedpolicy(pthread_attr_t *attr, int policy);

int pthread_attr_getschedpolicy(const pthread_attr_t *attr, int *policy);

int pthread_attr_setschedparam(pthread_attr_t *attr, const struct sched_param
    *param);

int pthread_attr_getschedparam(const pthread_attr_t *attr, struct sched_param
    *param);

int pthread_attr_setinheritsched(pthread_attr_t *attr, int inherit);
```

```

int pthread_attr_getinheritsched(const pthread_attr_t *attr, int *inherit);

int pthread_attr_setscope(pthread_attr_t *attr, int scope);

int pthread_attr_getscope(const pthread_attr_t *attr, int *scope);

int pthread_attr_setstacksize(pthread_attr_t *attr, int scope);

int pthread_attr_getstacksize(const pthread_attr_t *attr, int *scope);

```

As you can see, there are quite a few attributes you can use, but fortunately you will generally get by without ever having to use most of these.

- ❑ **detachedstate:** This attribute allows us to avoid the need for threads to rejoin. As with most of these _set functions, it takes a pointer to the attribute and a flag to determine the state required. The two possible flag values for `pthread_attr_setdetachstate` are `PTHREAD_CREATE_JOINABLE` and `PTHREAD_CREATE_DETACHED`. By default, the attribute will have value `PTHREAD_CREATE_JOINABLE` so that we can allow the two threads to join. If the state is set to `PTHREAD_CREATE_DETACHED`, you cannot call `pthread_join` to recover the exit state of another thread.
- ❑ **schedpolicy:** This controls how threads are scheduled. The options are `SCHED_OTHER`, `SCHED_RR`, and `SCHED_FIFO`. By default, the attribute is `SCHED_OTHER`. The other two types of scheduling are available only to processes running with superuser permissions, as they both have real-time scheduling but with slightly different behavior. `SCHED_RR` uses a round-robin scheduling scheme, and `SCHED_FIFO` uses a “first in, first out” policy. Discussion of these is beyond the scope of this book.
- ❑ **schedparam:** This is a partner to `schedpolicy` and allows control over the scheduling of threads running with schedule policy `SCHED_OTHER`. We will have a look at an example of this a bit later in the chapter.
- ❑ **inheritsched:** This attribute takes two possible values: `PTHREAD_EXPLICIT_SCHED` and `PTHREAD_INHERIT_SCHED`. By default, the value is `PTHREAD_EXPLICIT_SCHED`, which means scheduling is explicitly set by the attributes. By setting it to `PTHREAD_INHERIT_SCHED`, a new thread will instead use the parameters that its creator thread was using.
- ❑ **scope:** This attribute controls how the scheduling of a thread is calculated. Since Linux currently supports only the value `PTHREAD_SCOPE_SYSTEM`, we will not look at this further here.
- ❑ **stacksize:** This attribute controls the thread creation stack size, set in bytes. This is part of the “optional” section of the specification and is supported only on implementations where `_POSIX_THREAD_ATTR_STACKSIZE` is defined. Linux implements threads with a large amount of stack by default, so the feature is generally redundant on Linux.

Try It Out—Setting the Detached State Attribute

For our detached thread example, `thread5.c`, we create a thread attribute, set it to be detached, and then create a thread using the attribute. Now when the child thread has finished, it calls `pthread_exit` in the normal way. This time, however, the originating thread no longer waits for the thread that it created to rejoin. We use a simple `thread_finished` flag to allow the main thread to detect whether the child has finished and to show that the threads are still sharing variables.

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```
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <pthread.h>

void *thread_function(void *arg);

char message[] = "Hello World";
int thread_finished = 0;

int main() {
    int res;
    pthread_t a_thread;

    pthread_attr_t thread_attr;

    res = pthread_attr_init(&thread_attr);
    if (res != 0) {
        perror("Attribute creation failed");
        exit(EXIT_FAILURE);
    }
    res = pthread_attr_setdetachstate(&thread_attr, PTHREAD_CREATE_DETACHED);
    if (res != 0) {
        perror("Setting detached attribute failed");
        exit(EXIT_FAILURE);
    }
    res = pthread_create(&a_thread, &thread_attr, thread_function, (void *)message);
    if (res != 0) {
        perror("Thread creation failed");
        exit(EXIT_FAILURE);
    }
    (void)pthread_attr_destroy(&thread_attr);
    while(!thread_finished) {
        printf("Waiting for thread to say it's finished...\n");
        sleep(1);
    }
    printf("Other thread finished, bye!\n");
    exit(EXIT_SUCCESS);
}

void *thread_function(void *arg) {
    printf("thread_function is running. Argument was %s\n", (char *)arg);
    sleep(4);
    printf("Second thread setting finished flag, and exiting now\n");
    thread_finished = 1;
    pthread_exit(NULL);
}
```

There are no surprises in the output:

```
$ ./thread5
Waiting for thread to say it's finished...
thread_function is running. Argument was Hello World
Waiting for thread to say it's finished...
```

```

Waiting for thread to say it's finished...
Waiting for thread to say it's finished...
Second thread setting finished flag, and exiting now
Other thread finished, bye!

```

As you can see, setting the detached state allowed the secondary thread to complete independently, without the originating thread needing to wait for it.

How It Works

The two important sections of code are

```

pthread_attr_t thread_attr;

res = pthread_attr_init(&thread_attr);
if (res != 0) {
    perror("Attribute creation failed");
    exit(EXIT_FAILURE);
}

```

which declares a thread attribute and initializes it, and

```

res = pthread_attr_setdetachstate(&thread_attr, PTHREAD_CREATE_DETACHED);
if (res != 0) {
    perror("Setting detached attribute failed");
    exit(EXIT_FAILURE);
}

```

which sets the attribute values to have the detached state.

The other slight differences are creating the thread, passing the address of the attributes,

```

res = pthread_create(&a_thread, &thread_attr, thread_function, (void
*)message);

```

and, for completeness, destroying the attributes when we have used them:

```

pthread_attr_destroy(&thread_attr);

```

Thread Attributes—Scheduling

Let's take a look at a second thread attribute we might wish to change: scheduling. Changing the scheduling attribute is very similar to setting the detached state, but there are two more functions that we can use to find the available priority levels, `sched_get_priority_max` and `sched_get_priority_min`.

Try It Out—Scheduling

Since this `thread6.c` is very similar to the previous example, we'll just look at the differences.

1. First, we need some additional variables:

```

int max_priority;
int min_priority;
struct sched_param scheduling_value;

```

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2. After we have set the detached attribute, we set the scheduling policy.

```
res = pthread_attr_setschedpolicy(&thread_attr, SCHED_OTHER);
if (res != 0) {
    perror("Setting scheduling policy failed");
    exit(EXIT_FAILURE);
}
```

3. Next we find the range of priorities that are allowed:

```
max_priority = sched_get_priority_max(SCHED_OTHER);
min_priority = sched_get_priority_min(SCHED_OTHER);
```

4. and set one:

```
scheduling_value.sched_priority = min_priority;
res = pthread_attr_setschedparam(&thread_attr, &scheduling_value);
if (res != 0) {
    perror("Setting scheduling priority failed");
    exit(EXIT_FAILURE);
}
```

How It Works

This is very similar to setting a detached state attribute, except that we set the scheduling policy instead.

Cancelling a Thread

Sometimes, we want one thread to be able to ask another thread to terminate, rather like sending it a signal. There is a way to do this with threads, and, in parallel with signal handling, threads get a way of modifying how they behave when they are asked to terminate.

Let's look first at the function to request a thread to terminate:

```
#include <pthread.h>

int pthread_cancel(pthread_t thread);
```

This is pretty straightforward: Given a thread identifier, we can request that it be canceled. On the receiving end of the cancel request, things are slightly more complicated, but not much. A thread can set its cancel state using `pthread_setcancelstate`.

```
#include <pthread.h>

int pthread_setcancelstate(int state, int *oldstate);
```

The first parameter is either `PTHREAD_CANCEL_ENABLE`, which allows it to receive cancel requests, or `PTHREAD_CANCEL_DISABLE`, which causes them to be ignored. The `oldstate` pointer allows the previous state to be retrieved. If you are not interested, you can simply pass `NULL`. If cancel requests are accepted, there is a second level of control the thread can take, the cancel type, which is set with `pthread_setcanceltype`.

```
#include <pthread.h>

int pthread_setcanceltype(int type, int *oldtype);
```

The type can take one of two values, `PTHREAD_CANCEL_ASYNCHRONOUS`, which causes cancellation requests to be acted upon immediately, and `PTHREAD_CANCEL_DEFERRED`, which makes cancellation requests wait until the thread executes one of these functions: `pthread_join`, `pthread_cond_wait`, `pthread_cond_timedwait`, `pthread_testcancel`, `sem_wait`, or `sigwait`.

We have not seen all of these calls in this chapter, as not all are generally needed. As ever, more details can be found in the manual pages.

According to the POSIX standard, other system calls that may block, such as `read`, `wait`, and so on, should also be cancellation points. At the time of this writing, Linux does not yet support all of these being cancellation points. However, some experimentation suggests that some blocked calls such as `sleep` do allow cancellation to take place. To be on the safe side, you may wish to add some `pthread_testcancel` calls in code that you expect to be canceled.

Again, the `oldtype` allows the previous state to be retrieved, or a `NULL` can be passed if you are not interested in knowing the previous state. By default, threads start with the cancellation state `PTHREAD_CANCEL_ENABLE` and the cancellation type `PTHREAD_CANCEL_DEFERRED`.

Try It Out—Canceling a Thread

Our program `thread7.c` is derived, yet again, from `thread1.c`. This time, the main thread sends a cancel request to the thread that it has created.

```
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <pthread.h>

void *thread_function(void *arg);

int main() {
    int res;
    pthread_t a_thread;
    void *thread_result;

    res = pthread_create(&a_thread, NULL, thread_function, NULL);
    if (res != 0) {
        perror("Thread creation failed");
        exit(EXIT_FAILURE);
    }

    sleep(3);
    printf("Canceling thread...\n");
    res = pthread_cancel(a_thread);
    if (res != 0) {
```

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```
    perror("Thread cancelation failed");
    exit(EXIT_FAILURE);
}
printf("Waiting for thread to finish...\n");
res = pthread_join(a_thread, &thread_result);
if (res != 0) {
    perror("Thread join failed");
    exit(EXIT_FAILURE);
}
exit(EXIT_SUCCESS);
}

void *thread_function(void *arg) {
    int i, res;
    res = pthread_setcancelstate(PTHREAD_CANCEL_ENABLE, NULL);
    if (res != 0) {
        perror("Thread pthread_setcancelstate failed");
        exit(EXIT_FAILURE);
    }
    res = pthread_setcanceltype(PTHREAD_CANCEL_DEFERRED, NULL);
    if (res != 0) {
        perror("Thread pthread_setcanceltype failed");
        exit(EXIT_FAILURE);
    }
    printf("thread_function is running\n");
    for(i = 0; i < 10; i++) {
        printf("Thread is still running (%d)...\\n", i);
        sleep(1);
    }
    pthread_exit(0);
}
```

When we run this, we get the following output, showing that the thread is canceled:

```
$ ./thread7
thread_function is running
Thread is still running (0)...
Thread is still running (1)...
Thread is still running (2)...
Canceling thread...
Waiting for thread to finish...
$
```

How It Works

After the new thread has been created in the usual way, the main thread sleeps (to allow the new thread some time to get started) and then issues a cancel request.

```
sleep(3);
printf("Cancelling thread...\\n");
res = pthread_cancel(a_thread);
if (res != 0) {
    perror("Thread cancelation failed");
    exit(EXIT_FAILURE);
}
```

In the created thread, we first set the cancel state to allow canceling.

```
res = pthread_setcancelstate(PTHREAD_CANCEL_ENABLE, NULL);
if (res != 0) {
    perror("Thread pthread_setcancelstate failed");
    exit(EXIT_FAILURE);
}
```

Then we set the cancel type to be deferred.

```
res = pthread_setcanceltype(PTHREAD_CANCEL_DEFERRED, NULL);
if (res != 0) {
    perror("Thread pthread_setcanceltype failed");
    exit(EXIT_FAILURE);
}
```

Finally, the thread waits around to be canceled.

```
for(i = 0; i < 10; i++) {
    printf("Thread is still running (%d)... \n", i);
    sleep(1);
}
```

Threads in Abundance

Up until now, we have always had the normal thread of execution of a program create just one other thread. However, we don't want you to think that you can create only one extra thread.

Try It Out—Many Threads

For our final example in this chapter, `thread8.c`, we show how to create several threads in the same program and then collect them again in an order different from that in which they were started.

```
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <pthread.h>

#define NUM_THREADS 6

void *thread_function(void *arg);

int main() {
    int res;
    pthread_t a_thread[NUM_THREADS];
    void *thread_result;
    int lots_of_threads;

    for(lots_of_threads = 0; lots_of_threads < NUM_THREADS; lots_of_threads++) {
        res = pthread_create(&(a_thread[lots_of_threads]), NULL, thread_function,
        (void *)&lots_of_threads);
```

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```
if (res != 0) {
    perror("Thread creation failed");
    exit(EXIT_FAILURE);
}
sleep(1);
}
printf("Waiting for threads to finish...\n");
for(lots_of_threads = NUM_THREADS - 1; lots_of_threads >= 0; lots_of_threads--) {
    res = pthread_join(a_thread[lots_of_threads], &thread_result);
    if (res == 0) {
        printf("Picked up a thread\n");
    }
    else {
        perror("pthread_join failed");
    }
}
printf("All done\n");
exit(EXIT_SUCCESS);
}

void *thread_function(void *arg) {
    int my_number = *(int *)arg;
    int rand_num;

    printf("thread_function is running. Argument was %d\n", my_number);
    rand_num=1+(int)(9.0*rand()/(RAND_MAX+1.0));
    sleep(rand_num);
    printf("Bye from %d\n", my_number);
    pthread_exit(NULL);
}
```

When we run this program, we get

```
$ ./thread8
thread_function is running. Argument was 0
thread_function is running. Argument was 1
thread_function is running. Argument was 2
thread_function is running. Argument was 3
thread_function is running. Argument was 4
Bye from 1
thread_function is running. Argument was 5
Waiting for threads to finish...
Bye from 5
Picked up a thread
Bye from 0
Bye from 2
Bye from 3
Bye from 4
Picked up a thread
All done
```

As you can see, we created many threads and allowed them to finish out of sequence. There is a subtle bug in this program that makes itself evident if you remove the call to `sleep` from the loop that starts the threads. We have included it to show you just how careful you need to be when writing programs that use threads. Can you spot it? We'll explain in the following "How It Works" section.

How It Works

This time we create an array of thread IDs:

```
pthread_t a_thread[NUM_THREADS];
```

and loop around creating several threads:

```
for(lots_of_threads = 0; lots_of_threads < NUM_THREADS; lots_of_threads++) {
    res = pthread_create(&(a_thread[lots_of_threads]), NULL,
                         thread_function, (void *)&lots_of_threads);
    if (res != 0) {
        perror("Thread creation failed");
        exit(EXIT_FAILURE);
    }
    sleep(1);
}
```

The threads themselves then wait for a random time before exiting:

```
void *thread_function(void *arg) {
    int my_number = *(int *)arg;
    int rand_num;

    printf("thread_function is running. Argument was %d\n", my_number);
    rand_num=1+(int)(9.0*rand()/(RAND_MAX+1.0));
    sleep(rand_num);
    printf("Bye from %d\n", my_number);
    pthread_exit(NULL);
}
```

While in the main (original) thread, we wait to pick them up, but not in the order in which we created them.

```
for(lots_of_threads = NUM_THREADS - 1; lots_of_threads >= 0; lots_of_threads--) {
    res = pthread_join(a_thread[lots_of_threads], &thread_result);
    if (res == 0) {
        printf("Picked up a thread\n");
    }
    else {
        perror("pthread_join failed");
    }
}
```

If you try to run the program with no `sleep`, you might see some strange effects, including some threads being started with the same argument. Did you spot why this could happen? The threads are being started using a local variable for the argument to the thread function. This variable is updated in the loop. The offending lines are

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```
for(lots_of_threads = 0; lots_of_threads < NUM_THREADS; lots_of_threads++) {  
    res = pthread_create(&(a_thread[lots_of_threads]), NULL,  
                        thread_function, (void *)&lots_of_threads);
```

If the main thread runs fast enough, it might alter the argument (`lots_of_threads`) for some of the threads. Behavior like this arises when not enough care is taken with shared variables and multiple execution paths. We did warn you that programming threads required careful attention to design! To correct the problem, we need to pass the value directly like this:

```
res = pthread_create(&(a_thread[lots_of_threads]), NULL, thread_function, (void  
*)lots_of_threads);
```

and of course change `thread_function`:

```
void *thread_function(void *arg) {  
    int my_number = (int)arg;
```

Summary

In this chapter, we have seen how to create several threads of execution inside a process, where each thread shares file scope variables. We then looked at the two ways that threads can control access to critical code and data, using both semaphores and mutexes. After that, we moved to controlling the attributes of threads and, in particular, how we could separate them from the main thread so that it no longer had to wait for threads that it had created to complete. After a quick look at how one thread can request another to finish and at how the receiving thread can manage such requests, we presented an example of a program with many simultaneous threads executing.

We haven't had the space to cover every last function call and nuance associated with threads, but you should now have sufficient understanding to start writing your own programs with threads and to investigate the more esoteric aspects of threads by reading the manual pages.

13

Inter-Process Communication: Pipes

In Chapter 11, we saw a very simple way of sending messages between two processes using signals. We created notification events that could be used to provoke a response, but the information transferred was limited to a signal number.

In this chapter, we'll be looking at pipes, which allow more useful data to be exchanged between processes. By the end of the chapter, we'll be using our newfound knowledge to reimplement the running CD database program as a very simple client/server application.

We'll cover the following topics in this chapter:

- The definition of a pipe
- Process pipes
- Pipe calls
- Parent and child processes
- Named pipes: FIFOs
- Client/server considerations

What Is a Pipe?

We use the term *pipe* when we connect a data flow from one process to another. Generally we attach, or pipe, the output of one process to the input of another.

Most Linux users will already be familiar with the idea of linking shell commands together, so that the output of one process is fed straight to the input of another. For shell commands, this is entered as

```
cmd1 | cmd2
```

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The shell arranges the standard input and output of the two commands, so that

- ❑ The standard input to cmd1 comes from the terminal keyboard.
- ❑ The standard output from cmd1 is fed to cmd2 as its standard input.
- ❑ The standard output from cmd2 is connected to the terminal screen.

What the shell has done, in effect, is reconnect the standard input and output streams so that data flows from the keyboard input through the two commands and is then output to the screen. See Figure 13-1 for a visual representation of this process.

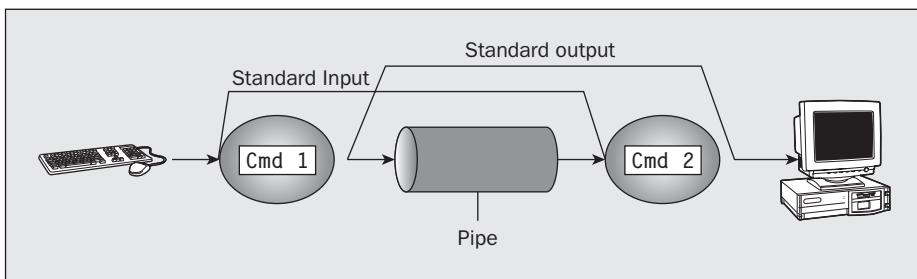


Figure 13-1

In this chapter, we'll see how to achieve this effect in a program and how we can use pipes to connect multiple processes to allow us to implement a simple client/server system.

Process Pipes

Perhaps the simplest way of passing data between two programs is with the `popen` and `pclose` functions. These have the following prototypes:

```
#include <stdio.h>

FILE *popen(const char *command, const char *open_mode);
int pclose(FILE *stream_to_close);
```

popen

The `popen` function allows a program to invoke another program as a new process and either pass data to it or receive data from it. The command string is the name of the program to run, together with any parameters. `open_mode` must be either "r" or "w".

If the `open_mode` is "r", output from the invoked program is made available to the invoking program and can be read from the file stream `FILE *` returned by `popen`, using the usual `stdio` library functions for reading (for example, `fread`). However, if `open_mode` is "w", the program can send data to the invoked command with calls to `fwrite`. The invoked program can then read the data on its standard input. Normally, the program being invoked won't be aware that it's reading data from another process; it simply reads its standard input stream and acts on it.

A to `popen` must specify either “r” or “w”; no other option is supported in a standard implementation of `popen`. This means that we can’t invoke another program and both read and write to it. On failure, `popen` returns a null pointer. If you want bidirectional communication using pipes, then the normal solution is to use two pipes, one for data flow in each direction.

pclose

When the process started with `popen` has finished, we can close the file stream associated with it using `pclose`. The `pclose` call will return only when the process started with `popen` finishes. If it’s still running when `pclose` is called, the `pclose` call will wait for the process to finish.

The `pclose` call normally returns the exit code of the process whose file stream it is closing. If the invoking process has executed a `wait` statement before calling `pclose`, the exit status will be lost and `pclose` will return -1, with `errno` set to `ECHILD`.

Try It Out—Reading Output from an External Program

Let’s try a simple `popen` and `pclose` example, `popen1.c`. We’ll use `popen` in a program to access information from `uname`. The `uname -a` command prints system information, including the machine type, the OS name, version and release, and the machine’s network name.

Having initialized the program, we open the pipe to `uname`, making it readable and setting `read_fp` to point to the output. At the end, the pipe pointed to by `read_fp` is closed.

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main()
{
    FILE *read_fp;
    char buffer[BUFSIZ + 1];
    int chars_read;
    memset(buffer, '\0', sizeof(buffer));
    read_fp = popen("uname -a", "r");
    if (read_fp != NULL) {
        chars_read = fread(buffer, sizeof(char), BUFSIZ, read_fp);
        if (chars_read > 0) {
            printf("Output was:-\n%s\n", buffer);
        }
        pclose(read_fp);
        exit(EXIT_SUCCESS);
    }
    exit(EXIT_FAILURE);
}
```

When we run this program on one of the authors’ machines, we get

```
$ ./popen1
Output was:-
Linux gw1 2.4.20-8 #1 Thu Mar 13 17:54:28 EST 2003 i686 i686 i386 GNU/Linux
```

How It Works

The program uses the `popen` call to invoke the `uname` command with the `-a` parameter. It then uses the returned file stream to read data up to `BUFSIZ` characters (as this is a `#define` from `stdio.h`) and then prints it out so it appears on the screen. Since we've captured the output of `uname` inside a program, it's available for processing.

Sending Output to `popen`

Now that we've seen an example of capturing output from an external program, let's look at sending output to an external program. Here's a program, `popen2.c`, that pipes data to another. Here, we'll use `od` (octal dump).

Try It Out—Sending Output to an External Program

Have a look at the following code; you can even type it if you like.

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

int main()
{
    FILE *write_fp;
    char buffer[BUFSIZ + 1];

    sprintf(buffer, "Once upon a time, there was...\n");
    write_fp = popen("od -c", "w");
    if (write_fp != NULL) {
        fwrite(buffer, sizeof(char), strlen(buffer), write_fp);
        pclose(write_fp);
        exit(EXIT_SUCCESS);
    }
    exit(EXIT_FAILURE);
}
```

When we run this program, we get the following output:

```
$ ./popen2
0000000  O   n   c   e       u   p   o   n       a       t   i   m   e
0000020 ,     t   h   e   r   e           w   a   s   .   .   \n
0000037
```

How It Works

The program uses `popen` with the parameter `"w"` to start the `od -c` command, so that it can send data to that command. It then sends a string which the `od -c` command receives and processes; the `od -c` command then prints the result of the processing on its standard output.

From the command line, we can get the same output with the command

```
$ echo "Once upon a time, there was..." | od -c
```

Passing More Data

The mechanism that we've used so far simply sent or received all the data in a single `fread` or `fwrite`. Sometimes we may want to send the data in smaller pieces, or perhaps we may not know the size of the output. To avoid having to declare a very large buffer, we can just use multiple `fread` or `fwrite` calls and process the data in parts.

Here's a program, `popen3.c`, that reads all of the data from a pipe.

Try It Out—Reading Larger Amounts of Data from a Pipe

In this program, we read data from an invoked `ps -alx` process. There's no way to know in advance how much output there will be, so we must allow for multiple reads of the pipe.

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main()
{
    FILE *read_fp;
    char buffer[BUFSIZ + 1];
    int chars_read;

    memset(buffer, '\0', sizeof(buffer));
    read_fp = popen("ps -ax", "r");
    if (read_fp != NULL) {
        chars_read = fread(buffer, sizeof(char), BUFSIZ, read_fp);
        while (chars_read > 0) {
            buffer[chars_read - 1] = '\0';
            printf("Reading:-\n %s\n", buffer);
            chars_read = fread(buffer, sizeof(char), BUFSIZ, read_fp);
        }
        pclose(read_fp);
        exit(EXIT_SUCCESS);
    }
    exit(EXIT_FAILURE);
}
```

The output we get, edited for brevity, is

```
$ ./popen3
Reading:-
 PID TTY STAT   TIME COMMAND
  1 ? S      0:04 init
  2 ? SW     0:00 [kflushd]
  3 ? SW     0:00 [kpiod]
  4 ? SW     0:00 [kswapd]
  5 ? SW<   0:00 [mdrecoveryd]
...
 240 tty2 S      0:02 emacs draft1.txt
Reading:-
 368 tty1 S      0:00 ./popen3
 369 tty1 R      0:00 ps -ax
...
```

How It Works

The program uses `popen` with an “`r`” parameter in a similar fashion to `popen1.c`. This time, it continues reading from the file stream until there is no more data available. Notice that, although the `ps` command takes some time to execute, Linux arranges the process scheduling so that both programs run when they can. If the reader process, `popen3`, has no input data, it’s suspended until some becomes available. If the writer process, `ps`, produces more output than can be buffered, it’s suspended until the reader has consumed some of the data.

In this example, you may not see `Reading : -` output a second time. This will be the case if `BUFSIZ` is greater than the length of the `ps` command output. Some (mostly more recent) Linux systems set `BUFSIZ` as high as 8,192 or even higher.

How `popen` Is Implemented

The `popen` call runs the program you requested by first invoking the shell, `sh`, passing it the command string as an argument. This has two effects, one good and the other not so good.

In Linux (as in all UNIX-like systems), all parameter expansion is done by the shell, so invoking the shell to parse the command string before the program is invoked allows any shell expansion, such as determining what files `'* .c'` actually refers to, to be done before the program starts. This is often quite useful, and it allows complex shell commands to be started with `popen`. Other process creation functions, such as `exec1`, can be much more complex to invoke, because the calling process has to perform its own shell expansion.

The unfortunate effect of using the shell is that for every call to `popen`, a shell is invoked along with the requested program. Each call to `popen` then results in two extra processes being started, which makes the `popen` function a little expensive in terms of system resources and invocation of the target command slower than it might otherwise have been.

Here’s a program, `popen4.c`, that we can use to demonstrate the behavior of `popen`. We can count the lines in all the `popen` example source files by catting the files and then piping the output to `wc -l`, which counts the number of lines. On the command line, the equivalent command is

```
$ cat popen*.c | wc -l
```

Actually, `wc -l popen.c` is easier to type and much more efficient, but the example serves to illustrate the principle.*

Try It Out—`popen` Starts a Shell

This program uses exactly the preceding command, but through `popen` so that it can read the result:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main()
{
    FILE *read_fp;
    char buffer[BUFSIZ + 1];
    int chars_read;
```

```

    memset(buffer, '\0', sizeof(buffer));
    read_fp = popen("cat popen*.c | wc -l", "r");
    if (read_fp != NULL) {
        chars_read = fread(buffer, sizeof(char), BUFSIZ, read_fp);
        while (chars_read > 0) {
            buffer[chars_read - 1] = '\0';
            printf("Reading:-\n %s\n", buffer);
            chars_read = fread(buffer, sizeof(char), BUFSIZ, read_fp);
        }
        pclose(read_fp);
        exit(EXIT_SUCCESS);
    }
    exit(EXIT_FAILURE);
}

```

When we run this program, the output is

```

$ ./popen4
Reading:-  

93

```

How It Works

The program shows that the shell is being invoked to expand `popen*.c` to the list of all files starting `popen` and ending in `.c` and also to process the pipe (`|`) symbol and feed the output from `cat` into `wc`. We invoke the shell, the `cat` program, and `wc` and cause an output redirection, all in a single `popen` call. The program that invokes the command sees only the final output.

The Pipe Call

We've seen the high-level `popen` function, but we'll now move on to look at the lower-level `pipe` function. This function provides a means of passing data between two programs, without the overhead of invoking a shell to interpret the requested command. It also gives us more control over the reading and writing of data.

The `pipe` function has the following prototype:

```

#include <unistd.h>

int pipe(int file_descriptor[2]);

```

`pipe` is passed (a pointer to) an array of two integer file descriptors. It fills the array with two new file descriptors and returns a zero. On failure, it returns `-1` and sets `errno` to indicate the reason for failure. Errors defined in the Linux manual page (section 2 of the manual) are

- ❑ **EMFILE:** Too many file descriptors are in use by the process.
- ❑ **ENFILE:** The system file table is full.
- ❑ **EFAULT:** The file descriptor is not valid.

Chapter 13

The two file descriptors returned are connected in a special way. Any data written to `file_descriptor[1]` can be read back from `file_descriptor[0]`. The data is processed in a *first in, first out* basis, usually abbreviated to *FIFO*. This means that if you write the bytes 1, 2, 3 to `file_descriptor[1]`, reading from `file_descriptor[0]` will produce 1, 2, 3. This is different from a stack, which operates on a *last in, first out* basis, usually abbreviated to *LIFO*.

It's important to realize that these are file descriptors, not file streams, so we must use the lower-level read and write calls to access the data, rather than fread and fwrite.

Here's a program, `pipe1.c`, that uses `pipe` to create a pipe.

Try It Out—The pipe Function

Type the following code. Note the `file_pipes` pointer, which is passed to the `pipe` function as a parameter.

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main()
{
    int data_processed;
    int file_pipes[2];
    const char some_data[] = "123";
    char buffer[BUFSIZ + 1];

    memset(buffer, '\0', sizeof(buffer));

    if (pipe(file_pipes) == 0) {
        data_processed = write(file_pipes[1], some_data, strlen(some_data));
        printf("Wrote %d bytes\n", data_processed);
        data_processed = read(file_pipes[0], buffer, BUFSIZ);
        printf("Read %d bytes: %s\n", data_processed, buffer);
        exit(EXIT_SUCCESS);
    }
    exit(EXIT_FAILURE);
}
```

When we run this program, the output is

```
$ ./pipe1
Wrote 3 bytes
Read 3 bytes: 123
```

How It Works

The program creates a pipe using the two file descriptors `file_pipes[]`. It then writes data into the pipe using the file descriptor `file_pipes[1]` and reads it back from `file_pipes[0]`. Notice that the pipe has some internal buffering that stores the data in between the calls to write and read.

You should be aware that the effect of trying to write using `file_descriptor[0]`, or read using `file_descriptor[1]`, is undefined, so the behavior could be very strange and may change without warning. On the authors' systems, such calls fail with a `-1` return value, which at least ensures that it's easy to catch this mistake.

At first glance, this example of a pipe doesn't seem to offer us anything that we couldn't have done with a simple file. The real advantage of pipes comes when you wish to pass data between two processes. As we saw in the Chapter 12, when a program creates a new process using the `fork` call, file descriptors that were previously open remain open. By creating a pipe in the original process and then forking to create a new process, we can pass data from one process to the other down the pipe.

Try It Out—Pipes across a fork

1. This is `pipe2.c`. It starts rather like the first example, up until we make the call to `fork`.

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main()
{
    int data_processed;
    int file_pipes[2];
    const char some_data[] = "123";
    char buffer[BUFSIZ + 1];
    pid_t fork_result;

    memset(buffer, '\0', sizeof(buffer));

    if (pipe(file_pipes) == 0) {
        fork_result = fork();
        if (fork_result == -1) {
            fprintf(stderr, "Fork failure");
            exit(EXIT_FAILURE);
        }
    }
}
```

2. We've made sure the `fork` worked, so if `fork_result` equals zero, we're in the child process:

```
if (fork_result == 0) {
    data_processed = read(file_pipes[0], buffer, BUFSIZ);
    printf("Read %d bytes: %s\n", data_processed, buffer);
    exit(EXIT_SUCCESS);
}
```

3. Otherwise, we must be in the parent process:

```
else {
    data_processed = write(file_pipes[1], some_data,
                           strlen(some_data));
    printf("Wrote %d bytes\n", data_processed);
}
exit(EXIT_SUCCESS);
}
```

When we run this program, the output is, as before,

```
$ ./pipe2
Wrote 3 bytes
Read 3 bytes: 123
```

You may find that in practice the command prompt reappears before the last part of the output, but we have tidied the output here to make it easier to read.

How It Works

First, the program creates a pipe with the `pipe` call. It then uses the `fork` call to create a new process. If the `fork` was successful, the parent writes data into the pipe, while the child reads data from the pipe. Both parent and child exit after a single `write` and `read`. If the parent exits before the child you might see the shell prompt between the two outputs.

Although the program is superficially very similar to the first pipe example, we've taken a big step forward by being able to use separate processes for the reading and writing, as we illustrate in Figure 13-2.

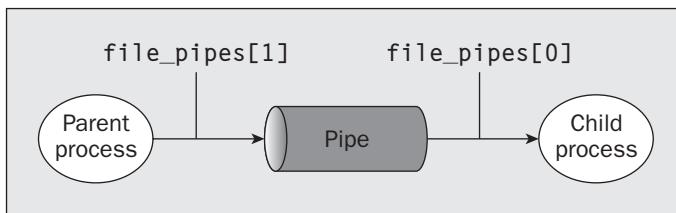


Figure 13-2

Parent and Child Processes

The next logical step in our investigation of the `pipe` call is to allow the child process to be a different program from its parent, rather than just a different process running the same program. We do this using the `exec` call. One difficulty is that the new `execed` process needs to know which file descriptor to access. In our previous example, this wasn't a problem because the child had access to its copy of the `file_pipes` data. After an `exec` call, this will no longer be the case, as the old process has been replaced by the new child process. We can get around this by passing the file descriptor (which is, after all, just a number) as a parameter to the newly `execed` program.

To show how this works, we need two programs. The first is the *data producer*. It creates the pipe and then invokes the child, the *data consumer*.

Try It Out—Pipes and exec

- For the first program, we adapt `pipe2.c` to `pipe3.c`. The lines that we've changed are shown shaded:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main()
{
    int data_processed;
    int file_pipes[2];
    const char some_data[] = "123";
    char buffer[BUFSIZ + 1];
    pid_t fork_result;

    memset(buffer, '\0', sizeof(buffer));

    if (pipe(file_pipes) == 0) {
        fork_result = fork();
        if (fork_result == (pid_t)-1) {
            fprintf(stderr, "Fork failure");
            exit(EXIT_FAILURE);
        }

        if (fork_result == 0) {
            sprintf(buffer, "%d", file_pipes[0]);
            (void)execl("pipe4", "pipe4", buffer, (char *)0);
            exit(EXIT_FAILURE);
        }
        else {
            data_processed = write(file_pipes[1], some_data,
                                   strlen(some_data));
            printf("%d - wrote %d bytes\n", getpid(), data_processed);
        }
    }
    exit(EXIT_SUCCESS);
}
```

- The consumer program, `pipe4.c`, which reads the data, is much simpler:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main(int argc, char *argv[])
{
    int data_processed;
```

```
char buffer[BUFSIZ + 1];
int file_descriptor;

memset(buffer, '\0', sizeof(buffer));
sscanf(argv[1], "%d", &file_descriptor);
data_processed = read(file_descriptor, buffer, BUFSIZ);

printf("%d - read %d bytes: %s\n", getpid(), data_processed, buffer);
exit(EXIT_SUCCESS);
}
```

Remembering that `pipe3` invokes the `pipe4` program for us, we get the following output when we run `pipe3`:

```
$ ./pipe3
980 - wrote 3 bytes
981 - read 3 bytes: 123
```

How It Works

The `pipe3` program starts like the previous example, using the `pipe` call to create a pipe and then using the `fork` call to create a new process. It then uses `sprintf` to store the “read” file descriptor number of the pipe in a buffer that will form an argument of `pipe4`.

A call to `exec1` is used to invoke the `pipe4` program. The arguments to `exec1` are

- ❑ The program to invoke
- ❑ `argv[0]`, which takes the program name
- ❑ `argv[1]`, which contains the file descriptor number we want the program to read from
- ❑ `(char *) 0`, which terminates the parameters

The `pipe4` program extracts the file descriptor number from the argument string and then reads from that file descriptor to obtain the data.

Reading Closed Pipes

Before we move on, we need to look a little more carefully at the file descriptors that are open. Up to this point we have allowed the reading process simply to read some data and then exit, assuming that Linux will clean up the files as part of the process termination.

Most programs that read data from the standard input do so differently than the examples we’ve seen so far. They don’t usually know how much data they have to read, so they will normally loop—reading data, processing it, and then reading more data until there’s no more data to read.

A `read` call will normally block; that is, it will cause the process to wait until data becomes available. If the other end of the pipe has been closed, then no process has the pipe open for writing, and the `read` blocks. Since this isn’t very helpful, a `read` on a pipe that isn’t open for writing returns zero rather than blocking. This allows the reading process to detect the pipe equivalent of end of file and act appropriately.

Notice that this isn't the same as reading an invalid file descriptor, which `read` considers an error and indicates by returning `-1`.

If we use a pipe across a `fork` call, there are two different file descriptors that we can use to write to the pipe: one in the parent and one in the child. We must close the `write` file descriptors of the pipe in both parent and child processes before the pipe is considered closed and a `read` call on the pipe will fail. We'll see an example of this later when we return to this subject in more detail to look at the `O_NONBLOCK` flag and FIFOs.

Pipes Used as Standard Input and Output

Now that we know how to make a `read` on an empty pipe fail, we can look at a much cleaner method of connecting two processes with a pipe. We arrange for one of the pipe file descriptors to have a known value, usually the standard input, `0`, or the standard output, `1`. This is slightly more complex to set up in the parent, but it allows the child program to be much simpler.

The one big advantage is that we can invoke standard programs, ones that don't expect a file descriptor as a parameter. In order to do this, we need to use the `dup` function, which we met in Chapter 3. There are two closely related versions of `dup` that have the following prototypes:

```
#include <unistd.h>

int dup(int file_descriptor);
int dup2(int file_descriptor_one, int file_descriptor_two);
```

The purpose of the `dup` call is to open a new file descriptor, a little like the `open` call. The difference is that the new file descriptor created by `dup` refers to the same file (or pipe) as an existing file descriptor. In the case of `dup`, the new file descriptor is always the lowest number available, while in the case of `dup2` it's the same as, or the first available descriptor greater than, the parameter `file_descriptor_two`.

We can get the same effect as `dup` and `dup2` by using the more general `fcntl` call, with a command `F_DUPFD`. Having said that, the `dup` call is easier to use because it's tailored specifically to the needs of creating duplicate file descriptors. It's also very commonly used, so you'll find it more frequently in existing programs than `fcntl` and `F_DUPFD`.

So how does `dup` help us in passing data between processes? The trick is knowing that the standard input file descriptor is always `0` and that `dup` always returns a new file descriptor using the lowest available number. By first closing file descriptor `0` and then calling `dup`, the new file descriptor will have the number `0`. Since the new descriptor is a duplicate of an existing one, standard input will have been changed to access the file or pipe whose file descriptor we passed to `dup`. We will have created two file descriptors that refer to the same file or pipe, and one of them will be the standard input.

File Descriptor Manipulation by `close` and `dup`

The easiest way to understand what happens when we close file descriptor `0`, and then call `dup`, is to look at how the state of the first four file descriptors changes during the sequence. This is shown in the following table:

| File Descriptor Number | Initially | After close of File Descriptor 0 | After dup |
|------------------------|----------------------|----------------------------------|----------------------|
| 0 | Standard input | {closed} | Pipe file descriptor |
| 1 | Standard output | Standard output | Standard output |
| 2 | Standard error | Standard error | Standard error |
| 3 | Pipe file descriptor | _ipe file descriptor | Pipe file descriptor |

Try It Out—Pipes and dup

Let's return to our previous example, but this time we'll arrange for the child program to have its `stdin` file descriptor replaced with the `read` end of the pipe we create. We'll also do some tidying up of file descriptors so the child program can correctly detect the end of the data in the pipe. As usual, we'll omit some error checking for the sake of brevity.

Modify `pipe3.c` to `pipe5.c` using the following code:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main()
{
    int data_processed;
    int file_pipes[2];
    const char some_data[] = "123";
    (pid_t) fork_result;

    if (pipe(file_pipes) == 0) {
        fork_result = fork();
        if (fork_result == (pid_t)-1) {
            fprintf(stderr, "Fork failure");
            exit(EXIT_FAILURE);
        }

        if (fork_result == (pid_t)0) {
            close(0);
            dup(file_pipes[0]);
            close(file_pipes[0]);
            close(file_pipes[1]);

            execlp("od", "od", "-c", (char *)0);
            exit(EXIT_FAILURE);
        }
    }
}
```

```

        else {
            close(file_pipes[0]);
            data_processed = write(file_pipes[1], some_data,
                                   strlen(some_data));
            close(file_pipes[1]);
            printf("%d - wrote %d bytes\n", (int)getpid(), data_processed);
        }
    exit(EXIT_SUCCESS);
}

```

The output from this program is

```

$ ./pipe5
1239 - wrote 3 bytes
0000000 1 2 3
0000003

```

How It Works

As before, the program creates a pipe and then forks, creating a child process. At this point, both the parent and child have file descriptors that access the pipe, one each for reading and writing, so there are four open file descriptors in total.

Let's look at the child process first. The child closes its standard input with `close(0)` and then calls `dup(file_pipes[0])`. This duplicates the file descriptor associated with the `read` end of the pipe as file descriptor 0, the standard input. The child then closes the original file descriptor for reading from the pipe, `file_pipes[0]`. Since the child will never write to the pipe, it also closes the `write` file descriptor associated with the pipe, `file_pipes[1]`. It now has a single file descriptor associated with the pipe: file descriptor 0, its standard input.

The child can then use `exec` to invoke any program that reads standard input. In this case, we use the `od` command. The `od` command will wait for data to be available to it as if it were waiting for input from a user terminal. In fact, without some special code to explicitly detect the difference, it won't know that the input is from a pipe rather than a terminal.

The parent starts by closing the `read` end of the pipe `file_pipes[0]`, since it will never read the pipe. It then writes data to the pipe. When all the data has been written, the parent closes the `write` end of the pipe and exits. Since there are now no file descriptors open that could write to the pipe, the `od` program will be able to read the three bytes written to the pipe, but subsequent reads will then return 0 bytes, indicating an end of file. When the read returns 0, the `od` program exits. This is analogous to running the `od` command on a terminal, then pressing `Ctrl+D` to send end of file to the `od` command.

Figure 13-3 shows the sequence after the call to the `pipe`, Figure 13-4 shows the sequence after the call to the `fork`, and Figure 13-5 represents the program when it's ready to transfer data.

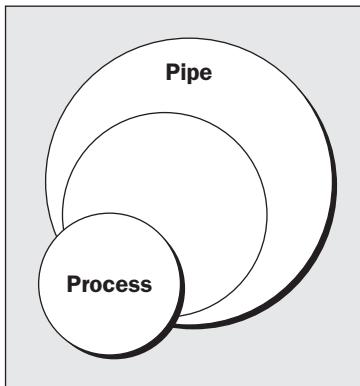


Figure 13-3

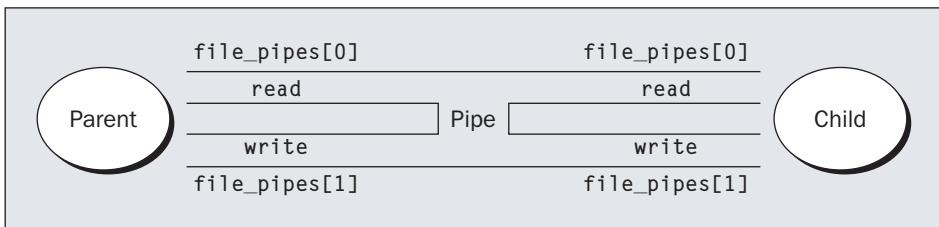


Figure 13-4

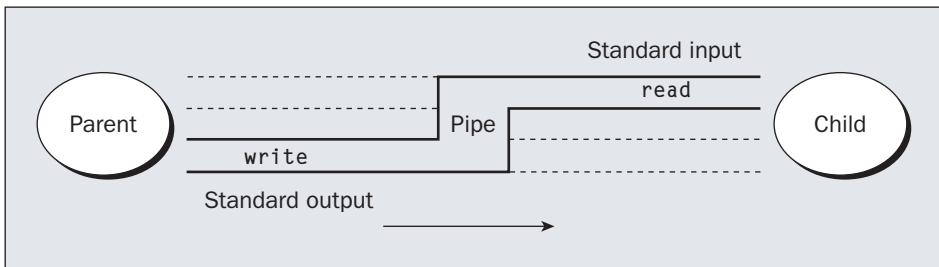


Figure 13-5

Named Pipes: FIFOs

So far, we have only been able to pass data between related programs, that is, programs that have been started from a common ancestor process. Often this isn't very convenient, as we would like unrelated processes to be able to exchange data.

We do this with *FIFOs*, often referred to as *named pipes*. A named pipe is a special type of file (remember that everything in Linux is a file!) that exists as a name in the file system but behaves like the unnamed pipes that we've met already.

We can create named pipes from the command line and from within a program. Historically, the command line program for creating them was `mknod`:

```
$ mknod filename p
```

However, the `mknod` command is not in the X/Open command list, so it may not be available on all UNIX-like systems. The preferred command line method is to use

```
$ mkfifo filename
```

Some older versions of UNIX only had the mknod command. X/Open Issue 4 Version 2 has the mknod function call, but not the command line program. Linux, friendly as ever, supplies both mknod and mkfifo.

From inside a program, we can use two different calls:

```
#include <sys/types.h>
#include <sys/stat.h>

int mkfifo(const char *filename, mode_t mode);
int mknod(const char *filename, mode_t mode | S_IFIFO, (dev_t) 0);
```

Like the `mknod` command, you can use the `mknod` function for making many special types of files. Using a `dev_t` value of 0 and ORing the file access mode with `S_IFIFO` is the only portable use of this function that creates a named pipe. We'll use the simpler `mkfifo` function in our examples.

Try It Out—Creating a Named Pipe

For `fifo1.c`, just type the following code:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <sys/types.h>
#include <sys/stat.h>

int main()
{
    int res = mkfifo("/tmp/my_fifo", 0777);
    if (res == 0) printf("FIFO created\n");
    exit(EXIT_SUCCESS);
}
```

We can look for the pipe with

```
$ ls -lF /tmp/my_fifo
prwxr-xr-x 1 rick      users          0 July 10 14:55 /tmp/my_fifo|
```

Notice that the first character of output is a `p`, indicating a pipe. The `|` symbol at the end is added by the `ls` command's `-F` option and also indicates a pipe.

How It Works

The program uses the `mkfifo` function to create a special file. Although we ask for a mode of `0777`, this is altered by the user mask (`umask`) setting (in this case `022`), just as in normal file creation, so the resulting file has mode `755`. If your `umask` is set differently, for example to `0002`, you will see different permissions on the created file.

We can remove the FIFO just like a conventional file by using the `rm` command, or from within a program by using the `unlink` system call.

Accessing a FIFO

One very useful feature of named pipes is that, because they appear in the file system, we can use them in commands where we would normally use a filename. Before we do more programming using the FIFO file we've created, we can investigate the behavior of our FIFO file using normal file commands.

Try It Out—Accessing a FIFO File

1. First, let's try reading the (empty) FIFO:

```
$ cat < /tmp/my_fifo
```

2. Now try writing to the FIFO. You will have to use a different terminal because the first command will now be hanging, waiting for some data to appear in the FIFO.

```
$ echo "sdsdfasdf" > /tmp/my_fifo
```

You will see the output appear from the `cat` command. If you don't send any data down the FIFO, the `cat` command will hang until you interrupt it, conventionally with `Ctrl+C`.

3. We can do both at once by putting the first command in the background:

```
$ cat < /tmp/my_fifo &
[1] 1316
$ echo "sdsdfasdf" > /tmp/my_fifo
sdsdfasdf

[1]+  Done                      cat </tmp/my_fifo
$
```

How It Works

Since there was no data in the FIFO, the `cat` and `echo` programs block, waiting for some data to arrive and some other process to read the data, respectively.

Looking at the third stage, the `cat` process is initially blocked in the background. When `echo` makes some data available, the `cat` command reads the data and prints it to the standard output. Notice that the `cat` program then exits without waiting for more data. It doesn't block because the pipe will have been closed when the second command putting data in the FIFO completed, so calls to read in the `cat` program will return 0 bytes, indicating the end of file.

Now that we've seen how the FIFO behaves when we access it using command line programs, let's look in more detail at the program interface, which allows us more control over how reads and writes behave when we're accessing a FIFO.

Unlike a pipe created with the `pipe` call, a FIFO exists as a named file, not as an open file descriptor, and it must be opened before it can be read from or written to. You open and close a FIFO using the same `open` and `close` functions that we saw used earlier for files, with some additional functionality. The `open` call is passed the path name of the FIFO, rather than that of a regular file.

Opening a FIFO with `open`

The main restriction on opening FIFOs is that a program may not open a FIFO for reading and writing with the mode `O_RDWR`. If a program does this, the result is undefined. This is quite a sensible restriction since, normally, we use a FIFO only for passing data in a single direction, so we have no need for an `O_RDWR` mode. A process would read its own output back from a pipe if it were opened read/write.

If we do wish to pass data in both directions between programs, it's much better to use either a pair of FIFOs or pipes, one for each direction, or (unusually) explicitly change the direction of the data flow by closing and reopening the FIFO. We'll return to bidirectional data exchange using FIFOs later in the chapter.

The other difference between opening a FIFO and a regular file is the use of the `open_flag` (the second parameter to `open`) with the option `O_NONBLOCK`. Using this `open` mode not only changes how the `open` call is processed, but also changes how `read` and `write` requests are processed on the returned file descriptor.

There are four legal combinations of `O_RDONLY`, `O_WRONLY`, and the `O_NONBLOCK` flag. We'll consider each in turn.

```
open(const char *path, O_RDONLY);
```

In this case, the `open` call will block; it will not return until a process opens the same FIFO for writing. This is like the first preceding `cat` example.

```
open(const char *path, O_RDONLY | O_NONBLOCK);
```

The `open` call will now succeed and return immediately, even if the FIFO has not been opened for writing by any process.

```
open(const char *path, O_WRONLY);
```

In this case, the `open` call will block until a process opens the same FIFO for reading.

```
open(const char *path, O_WRONLY | O_NONBLOCK);
```

This will always return immediately, but if no process has the FIFO open for reading, `open` will return an error, `-1`, and the FIFO won't be opened. If a process does have the FIFO open for reading, the file descriptor returned can be used for writing to the FIFO.

Notice the asymmetry between the use of `O_NONBLOCK` with `O_RDONLY` and `O_WRONLY`, in that a nonblocking open for writing fails if no process has the pipe open for reading, but a nonblocking read doesn't fail. The behavior of the `close` call isn't affected by the `O_NONBLOCK` flag.

Try It Out—Opening FIFO Files

Let's look at how we can use the behavior of `open` with the `O_NONBLOCK` flag to synchronize two processes. Rather than use a number of example programs, we'll write a single test program, `fifo2.c`, that allows us to investigate the behavior of FIFOs by passing in different parameters.

1. Let's start with the header files, a `#define`, and the check that the correct number of command line arguments has been supplied:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <fcntl.h>
#include <sys/types.h>
#include <sys/stat.h>

#define FIFO_NAME "/tmp/my_fifo"

int main(int argc, char *argv[])
{
    int res;
    int open_mode = 0;

    if (argc < 2) {
        fprintf(stderr, "Usage: %s <some combination of\
                     O_RDONLY O_WRONLY O_NONBLOCK>\n", *argv);
        exit(EXIT_FAILURE);
    }
}
```

2. Assuming that the program passed the test, we now set the value of `open_mode` from those arguments:

```
argv++;
if (strncmp(*argv, "O_RDONLY", 8) == 0) open_mode |= O_RDONLY;
if (strncmp(*argv, "O_WRONLY", 8) == 0) open_mode |= O_WRONLY;
if (strncmp(*argv, "O_NONBLOCK", 10) == 0) open_mode |= O_NONBLOCK;
argv++;
if (*argv) {
    if (strncmp(*argv, "O_RDONLY", 8) == 0) open_mode |= O_RDONLY;
    if (strncmp(*argv, "O_WRONLY", 8) == 0) open_mode |= O_WRONLY;
    if (strncmp(*argv, "O_NONBLOCK", 10) == 0) open_mode |= O_NONBLOCK;
}
```

3. We now check whether the FIFO exists, and we create it if necessary. Then the FIFO is opened and output given to that effect while the program catches forty winks. Last of all, the FIFO is closed.

```

if (access(FIFO_NAME, F_OK) == -1) {
    res = mkfifo(FIFO_NAME, 0777);
    if (res != 0) {
        fprintf(stderr, "Could not create fifo %s\n", FIFO_NAME);
        exit(EXIT_FAILURE);
    }
}

printf("Process %d opening FIFO\n", getpid());
res = open(FIFO_NAME, open_mode);
printf("Process %d result %d\n", getpid(), res);
sleep(5);
if (res != -1) (void)close(res);
printf("Process %d finished\n", getpid());
exit(EXIT_SUCCESS);
}

```

How It Works

This program allows us to specify on the command line the combinations of `O_RDONLY`, `O_WRONLY`, and `O_NONBLOCK` that we wish to use. It does this by comparing known strings with command line parameters and setting (with `|=`) the appropriate flag if the string matches. The program uses the `access` function to check whether the FIFO file already exists and will create it if required.

We never destroy the FIFO, because we have no way of telling if another program already has the FIFO in use.

`O_RDONLY` and `O_WRONLY` with No `O_NONBLOCK`

We now have our test program, so let's try out a couple of combinations; notice that we put the file program in the background:

```

$ ./fifo2 O_RDONLY &
[1] 152
Process 152 opening FIFO
$ ./fifo2 O_WRONLY
Process 153 opening FIFO
Process 152 result 3
Process 153 result 3
Process 152 finished
Process 153 finished

```

This is probably the most common use of named pipes. It allows the reader process to start and wait in the open call and then allows both programs to continue when the second program opens the FIFO. Notice that both the reader and writer processes have synchronized at the open call.

When a Linux process is blocked, it doesn't consume CPU resources, so this method of process synchronization is very CPU-efficient.

O_RDONLY with O_NONBLOCK and O_WRONLY

This time, the reader process executes the open call and continues immediately, even though no writer process is present. The writer also immediately continues past the open call, since the FIFO is already open for reading.

```
$ ./fifo2 O_RDONLY O_NONBLOCK &
[1] 160
Process 160 opening FIFO
$ ./fifo2 O_WRONLY
Process 161 opening FIFO
Process 160 result 3
Process 161 result 3
Process 160 finished
Process 161 finished
[1]+ Done fifo2 O_RDONLY O_NONBLOCK
```

These two examples are probably the most common combinations of open modes. Feel free to use the example program to experiment with some other combinations.

Reading and Writing FIFOs

Using the O_NONBLOCK mode affects how `read` and `write` calls behave on FIFOs.

A `read` on an empty blocking FIFO (i.e., one not opened with O_NONBLOCK) will wait until some data can be read. Conversely, a `read` on a nonblocking FIFO with no data will return 0 bytes.

A `write` on a full blocking FIFO will wait until the data can be written. A `write` on a FIFO that can't accept all of the bytes being written will either:

- ❑ Fail, if the request is for PIPE_BUF bytes or less and the data can't be written.
- ❑ Write part of the data, if the request is for more than PIPE_BUF bytes, returning the number of bytes actually written, which could be 0.

The size of a FIFO is an important consideration. There is a system-imposed limit on how much data can be "in" a FIFO at any one time. This is the `#define PIPE_BUF`, usually found in `limits.h`. On Linux and many other UNIX-like systems, this is commonly 4,096 bytes, but it could be as low as 512 bytes on some systems. The system guarantees that writes of PIPE_BUF or fewer bytes on a FIFO that has been opened O_WRONLY (i.e., blocking) will either write all or none of the bytes.

Although this limit is not very important in the simple case of a single FIFO writer and a single FIFO reader, it's quite common to use a single FIFO to allow many different programs to send requests to a single FIFO reader. If several different programs try to write to the FIFO at the same time, it's usually vital that the blocks of data from different programs don't get interleaved—that is, each `write` must be "atomic." How do you do this?

Well, if you ensure that all your `write` requests are to a blocking FIFO and are less than PIPE_BUF bytes in size, the system will ensure that data never gets interleaved. In general, it's a good idea to restrict the data transferred via a FIFO to blocks of PIPE_BUF bytes, unless you're using only a single-writer and a single-reader process.

Try It Out—Inter-Process Communication with FIFOs

To show how unrelated processes can communicate using named pipes, we need two separate programs, `fifo3.c` and `fifo4.c`.

1. The first program is our producer program. It creates the pipe if required, then writes data to it as quickly as possible.

Note that, for illustration purposes, we don't mind what the data is, so we don't bother to initialize a buffer. In both listings, shaded lines show the changes from `fifo2.c`, with all the command line argument code removed.

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <fcntl.h>

#include <limits.h>
#include <sys/types.h>
#include <sys/stat.h>

#define FIFO_NAME "/tmp/my_fifo"
#define BUFFER_SIZE PIPE_BUF
#define TEN_MEG (1024 * 1024 * 10)

int main()
{
    int pipe_fd;
    int res;
    int open_mode = O_WRONLY;
    int bytes_sent = 0;
    char buffer[BUFFER_SIZE + 1];

    if (access(FIFO_NAME, F_OK) == -1) {
        res = mkmkfifo(FIFO_NAME, 0777);
        if (res != 0) {
            fprintf(stderr, "Could not create fifo %s\n", FIFO_NAME);
            exit(EXIT_FAILURE);
        }
    }

    printf("Process %d opening FIFO O_WRONLY\n", getpid());
    pipe_fd = open(FIFO_NAME, open_mode);
    printf("Process %d result %d\n", getpid(), pipe_fd);

    if (pipe_fd != -1) {
        while (bytes_sent < TEN_MEG) {
            res = write(pipe_fd, buffer, BUFFER_SIZE);
            if (res == -1) {
                fprintf(stderr, "Write error on pipe\n");
                exit(EXIT_FAILURE);
            }
            bytes_sent += res;
        }
    }
}
```

```
        }
        (void)close(pipe_fd);
    }
    else {
        exit(EXIT_FAILURE);
    }

    printf("Process %d finished\n", getpid());
    exit(EXIT_SUCCESS);
}
```

- 2.** Our second program, the consumer, is much simpler. It reads and discards data from the FIFO.

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <fcntl.h>

#include <limits.h>
#include <sys/types.h>
#include <sys/stat.h>

#define FIFO_NAME "/tmp/my_fifo"
#define BUFFER_SIZE PIPE_BUF

int main()
{
    int pipe_fd;
    int res;

    int open_mode = O_RDONLY;
    char buffer[BUFFER_SIZE + 1];
    int bytes_read = 0;

    memset(buffer, '\0', sizeof(buffer));

    printf("Process %d opening FIFO O_RDONLY\n", getpid());
    pipe_fd = open(FIFO_NAME, open_mode);
    printf("Process %d result %d\n", getpid(), pipe_fd);

    if (pipe_fd != -1) {
        do {
            res = read(pipe_fd, buffer, BUFFER_SIZE);
            bytes_read += res;
        } while (res > 0);
        (void)close(pipe_fd);
    }
    else {
        exit(EXIT_FAILURE);
    }

    printf("Process %d finished, %d bytes read\n", getpid(), bytes_read);
    exit(EXIT_SUCCESS);
}
```

When we run these programs at the same time, using the `time` command to time the reader, the output we get (with some tidying for clarity) is

```
$ ./fifo3 &
[1] 375
Process 375 opening FIFO O_WRONLY
$ time ./fifo4
Process 377 opening FIFO O_RDONLY
Process 375 result 3
Process 377 result 3
Process 375 finished
Process 377 finished, 10485760 bytes read

real    0m0.053s
user    0m0.020s
sys     0m0.040s

[1]+  Done                      fifo3
```

How It Works

Both programs use the FIFO in blocking mode. We start `fifo3` (the writer/producer) first, which blocks, waiting for a reader to open the FIFO. When `fifo4` (the consumer) is started, the writer is then unblocked and starts writing data to the pipe. At the same time, the reader starts reading data from the pipe.

Linux arranges the scheduling of the two processes so that they both run when they can and are blocked when they can't. Thus, the writer is blocked when the pipe is full, and the reader is blocked when the pipe is empty.

The output from the `time` command shows us that it took the reader well under one-tenth of a second to run, reading 10 megabytes of data in the process. This shows us that pipes, at least as implemented in the author's version of Linux, can be an efficient way of transferring data between programs.

Advanced Topic: Client/Server Using FIFOs

For our final look at FIFOs, let's consider how we might build a very simple client/server application using named pipes. We want to have a single server process that accepts requests, processes them, and returns the resulting data to the requesting party: the client.

We want to allow multiple client processes to send data to the server. In the interests of simplicity, we'll assume that the data to be processed can be broken into blocks, each smaller than `PIPE_BUF` bytes. Of course, we could implement this system in many ways, but we'll consider only one method as an illustration of how named pipes can be used.

Since the server will process only one block of information at a time, it seems logical to have a single FIFO that is read by the server and written to by each of the clients. By opening the FIFO in blocking mode, the server and the clients will be automatically blocked as required.

Returning the processed data to the clients is slightly more difficult. We need to arrange a second pipe, one per client, for the returned data. By passing the process identifier (PID) of the client in the original data sent to the server, both parties can use this to generate the unique name for the return pipe.

Try It Out—An Example Client/Server Application

1. First, we need a header file, `client.h`, that defines the data common to both client and server programs. It also includes the required system headers, for convenience.

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <fcntl.h>
#include <limits.h>
#include <sys/types.h>
#include <sys/stat.h>

#define SERVER_FIFO_NAME "/tmp/serv_fifo"
#define CLIENT_FIFO_NAME "/tmp/cli_%d_fifo"

#define BUFFER_SIZE 20

struct data_to_pass_st {
    pid_t client_pid;
    char some_data[BUFFER_SIZE - 1];
};
```

2. Now for the server program, `server.c`. In this section, we create and then open the server pipe. It's set to be read-only, with blocking. After sleeping (for demonstration purposes), the server reads in any data from the client, which has the `data_to_pass_st` structure.

```
#include "client.h"
#include <ctype.h>

int main()
{
    int server_fifo_fd, client_fifo_fd;
    struct data_to_pass_st my_data;
    int read_res;
    char client_fifo[256];
    char *tmp_char_ptr;

    mkfifo(SERVER_FIFO_NAME, 0777);
    server_fifo_fd = open(SERVER_FIFO_NAME, O_RDONLY);
    if (server_fifo_fd == -1) {
        fprintf(stderr, "Server fifo failure\n");
        exit(EXIT_FAILURE);
    }

    sleep(10); /* lets clients queue for demo purposes */

    do {
        read_res = read(server_fifo_fd, &my_data, sizeof(my_data));
        if (read_res > 0) {
```

- 3.** In this next stage, we perform some processing on the data just read from the client: We convert all the characters in `some_data` to uppercase and combine the `CLIENT_FIFO_NAME` with the received `client_pid`.

```

tmp_char_ptr = my_data.some_data;
while (*tmp_char_ptr) {
    *tmp_char_ptr = toupper(*tmp_char_ptr);
    tmp_char_ptr++;
}
sprintf(client_fifo, CLIENT_FIFO_NAME, my_data.client_pid);

```

- 4.** Then we send the processed data back, opening the client pipe in write-only, blocking mode. Finally, we shut down the server FIFO by closing the file and then unlinking the FIFO.

```

client_fifo_fd = open(client_fifo, O_WRONLY);
if (client_fifo_fd != -1) {
    write(client_fifo_fd, &my_data, sizeof(my_data));
    close(client_fifo_fd);
}
}
} while (read_res > 0);
close(server_fifo_fd);
unlink(SERVER_FIFO_NAME);
exit(EXIT_SUCCESS);
}

```

- 5.** Here's the client, `client.c`. The first part of this program opens the server FIFO, if it already exists, as a file. It then gets its own process ID, which forms some of the data that will be sent to the server. The client FIFO is created, ready for the next section.

```

#include "client.h"
#include <ctype.h>

int main()
{
    int server_fifo_fd, client_fifo_fd;
    struct data_to_pass_st my_data;
    int times_to_send;
    char client_fifo[256];

    server_fifo_fd = open(SERVER_FIFO_NAME, O_WRONLY);
    if (server_fifo_fd == -1) {
        fprintf(stderr, "Sorry, no server\n");
        exit(EXIT_FAILURE);
    }

    my_data.client_pid = getpid();
    sprintf(client_fifo, CLIENT_FIFO_NAME, my_data.client_pid);
    if (mkfifo(client_fifo, 0777) == -1) {
        fprintf(stderr, "Sorry, can't make %s\n", client_fifo);
        exit(EXIT_FAILURE);
    }
}

```

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6. For each of the five loops, the client data is sent to the server. Then the client FIFO is opened (read-only, blocking mode) and the data read back. Finally, the server FIFO is closed and the client FIFO removed from memory.

```
for (times_to_send = 0; times_to_send < 5; times_to_send++) {
    sprintf(my_data.some_data, "Hello from %d", my_data.client_pid);
    printf("%d sent %s, ", my_data.client_pid, my_data.some_data);
    write(server_fifo_fd, &my_data, sizeof(my_data));
    client_fifo_fd = open(client_fifo, O_RDONLY);
    if (client_fifo_fd != -1) {
        if (read(client_fifo_fd, &my_data, sizeof(my_data)) > 0) {
            printf("received: %s\n", my_data.some_data);
        }
        close(client_fifo_fd);
    }
}
close(server_fifo_fd);
unlink(client_fifo);
exit(EXIT_SUCCESS);
}
```

To test this application, we need to run a single copy of the server and several clients. To get them all started at close to the same time, we use the following shell commands:

```
$ server &
$ for i in 1 2 3 4 5
do
client &
done
$
```

This starts one server process and five client processes. The output from the clients, edited for brevity, looks like this:

```
531 sent Hello from 531, received: HELLO FROM 531
532 sent Hello from 532, received: HELLO FROM 532
529 sent Hello from 529, received: HELLO FROM 529
530 sent Hello from 530, received: HELLO FROM 530
531 sent Hello from 531, received: HELLO FROM 531
532 sent Hello from 532, received: HELLO FROM 532
```

As you can see, different client requests are being interleaved and each client is getting the suitably processed data returned to it. Note that the interleaving is random and the order in which client requests are received will vary between machines and possibly between runs on the same machine.

How It Works

Now we'll (hopefully!) explain the sequence of client and server operations as they interact, something that we haven't covered so far.

The server creates its FIFO in read-only mode and blocks. This it does until the first client connects by opening the same FIFO for writing. At that point, the server process is unblocked and the `sleep` is executed, so the `writes` from the clients queue up. (In a real application, the `sleep` would be removed; we're only using it to demonstrate the correct operation of our program with multiple simultaneous clients.)

In the meantime, after the client has opened the server FIFO, it creates its own uniquely named FIFO for reading data back from the server. Only then does the client write data to the server (blocking if the pipe is full or the server's still sleeping) and then blocks on a read of its own FIFO, waiting for the reply.

On receiving the data from the client, the server processes it, opens the client pipe for writing, and writes the data back, which unblocks the client. When the client is unblocked, it can read from its pipe the data written to it by the server.

The whole process repeats until the last client closes the server pipe, causing the server's read to fail (returning 0) because no process has the server pipe open for writing. If this were a real server process that needed to wait for further clients, we would need to modify it to either

- Open a file descriptor to its own server pipe, so `read` always blocks rather than returning 0.
- Close and reopen the server pipe when `read` returns 0 bytes, so the server process blocks in the `open` waiting for a client, just as it did when it first started.

Both of these techniques are illustrated in the rewrite of the CD database application to use named pipes.

The CD Database Application

Now that we've seen how we can use named pipes to implement a simple client/server system, we can revisit our CD database application and convert it accordingly. We'll also incorporate some signal handling to allow us to perform some tidy-up actions when the process is interrupted. We will use the earlier `dbm` version with just a command line interface to see the code as straightforwardly as possible.

Before we get to look in detail at this new version, let's compile the application. If you have the source code from the Web site, use the makefile to compile it to `server` and `client` programs.

Typing `server -i` allows the program to initialize a new CD database.

Needless to say, the client won't run unless the server is up and running. Here's the makefile to show how the programs fit together.

```
all:      server client

CC=cc
CFLAGS= -pedantic -Wall

# For debugging un-comment the next line
# DFLAGS=-DDEBUG_TRACE=1 -g

# Where, and which version, of dbm are we using.
# This assumes gdbm is pre-installed in a standard place, but we are
# going to use the gdbm compatibility routines, that make it emulate ndbm.
# We do this because ndbm is the 'most standard' of the dbm versions.
# Depending on your distribution, these may need changing.
DBM_INC_PATH=/usr/include/gdbm
DBM_LIB_PATH=/usr/lib
DBM_LIB_FILE=gdbm
```

```
.c.o:
$(CC) $(CFLAGS) -I$(DBM_INC_PATH) $(DFLAGS) -c $<

app_ui.o: app_ui.c cd_data.h
cd_dbm.o: cd_dbm.c cd_data.h
client_f.o: clientif.c cd_data.h cliserv.h
pipe_imp.o: pipe_imp.c cd_data.h cliserv.h
server.o: server.c cd_data.h cliserv.h

client: app_ui.o clientif.o pipe_imp.o
$(CC) -o client $(DFLAGS) app_ui.o clientif.o pipe_imp.o

server: server.o cd_dbm.o pipe_imp.o
$(CC) -o server -L$(DBM_LIB_PATH) $(DFLAGS) server.o cd_dbm.o pipe_imp.o -l$(DBM_LIB_FILE)

clean:
rm -f server client_app *.o *~
```

Aims

Our aim is to split the part of the application that deals with the database away from the user interface part of the application. We also wish to run a single-server process, but allow many simultaneous clients. We also wish to minimize changes to the existing code. Wherever possible, we'll leave existing code unchanged.

To keep things simple, we also want to be able to create (and delete) pipes within the application, so there's no need for a system administrator to create named pipes before we can use them.

It's also important to ensure that we never "busy wait," wasting CPU time, for an event. As we've seen, Linux allows us to block, waiting for events without using significant resources. We should use the blocking nature of pipes to ensure that we use the CPU efficiently. After all, the server could, in theory, wait for many hours for a request to arrive.

Implementation

In the earlier, single-process version of the application that we saw in Chapter 7, we used a set of data access routines for manipulating the data. These were

```
int database_initialize(const int new_database);
void database_close(void);
cdc_entry get_cdc_entry(const char *cd_catalog_ptr);
cdt_entry get_cdt_entry(const char *cd_catalog_ptr, const int track_no);
int add_cdc_entry(const cdc_entry entry_to_add);
int add_cdt_entry(const cdt_entry entry_to_add);
int del_cdc_entry(const char *cd_catalog_ptr);
int del_cdt_entry(const char *cd_catalog_ptr, const int track_no);
cdc_entry search_cdc_entry(const char *cd_catalog_ptr,
                           int *first_call_ptr);
```

These functions provide a convenient place to make a clean separation between client and server.

Inter-Process Communication: Pipes

In the single-process implementation, we can view the application as having two parts, even though it was compiled as a single program, as shown in Figure 13-6.

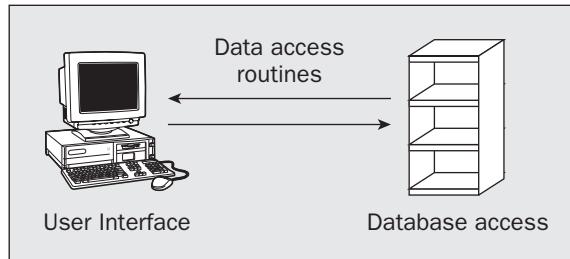


Figure 13-6

In the client-server implementation, we want to logically insert some named pipes and supporting code between the two major parts of the application. Figure 13-7 shows the structure we need.

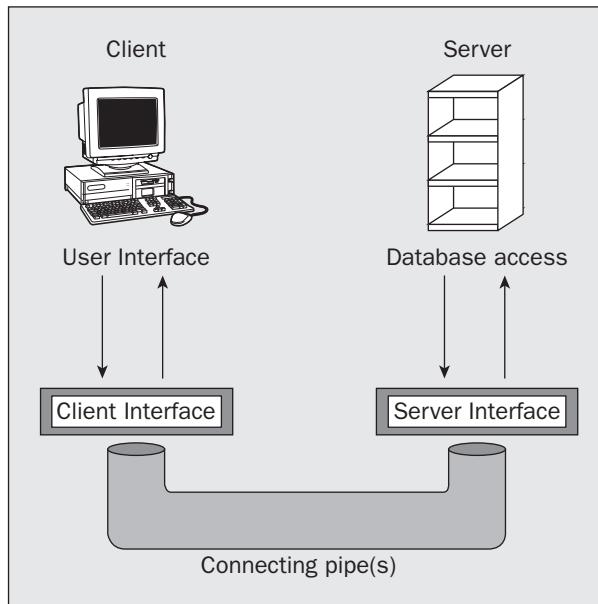


Figure 13-7

In our implementation, we choose to put both the client and server interface routines in the same file, `pipe_imp.c`. This keeps all the code that depends on the use of named pipes for the client/server implementation in a single file. The formatting and packaging of the data being passed is kept separate from the routines that implement the named pipes. We end up with more source files, but a better logical division between them. The calling structure in the application is illustrated in Figure 13-8.

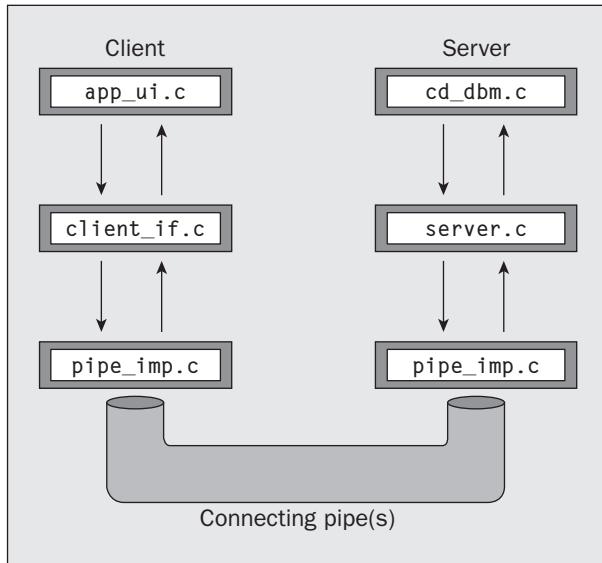


Figure 13-8

The files `app_ui.c`, `client_if.c`, and `pipe_imp.c` are compiled and linked together to give a client program. The files `cd_dbm.c`, `server.c`, and `pipe_imp.c` are compiled and linked together to give a server program. A header file, `cliserv.h`, acts as a common definitions header file to tie the two together.

The files `app_ui.c` and `cd_dbm.c` have only very minor changes, principally to allow for the split into two programs. Since the application is now quite large and a significant proportion of the code is unchanged from that previously seen, we show here only the files `cliserv.h`, `client_if.c`, and `pipe_imp.c`.

First we'll look at `cliserv.h`. This file defines the client/server interface. It's required by both client and server implementations.

Some parts of this file are dependent on the specific client/server implementation, in this case named pipes. We'll be changing to a different client/server model at the end of the Chapter 14.

Try It Out—The Header File, `cliserv.h`

1. Following are the required `#include` headers:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>
#include <limits.h>
#include <sys/types.h>
#include <sys/stat.h>
```

- 2.** We then define the named pipes. We use one pipe for the server and one pipe for each client. Since there may be multiple clients, the client incorporates a process ID into the name to ensure that its pipe is unique:

```
#define SERVER_PIPE "/tmp/server_pipe"
#define CLIENT_PIPE "/tmp/client_%d_pipe"

#define ERR_TEXT_LEN 80
```

- 3.** We implement the commands as enumerated types, rather than `#defines`.

This is a good way of allowing the compiler to do more type checking and also helps in debugging the application, as many debuggers are able to show the name of enumerated constants, but not the name defined by a `#define` directive.

The first `typedef` gives the type of request being sent to the server; the second gives the server response to the client.

```
typedef enum {
    s_create_new_database = 0,
    s_get_cdc_entry,
    s_get_cdt_entry,
    s_add_cdc_entry,
    s_add_cdt_entry,
    s_del_cdc_entry,
    s_del_cdt_entry,
    s_find_cdc_entry
} client_request_e;

typedef enum {
    r_success = 0,
    r_failure,
    r_find_no_more
} server_response_e;
```

- 4.** Next we declare a structure that will form the message passed in both directions between the two processes.

Since we don't actually need to return both a `cdc_entry` and `cdt_entry` in the same response, we could have combined them in a union. However, for simplicity we keep them separate. This also makes the code easier to maintain.

```
typedef struct {
    pid_t client_pid;
    client_request_e request;
    server_response_e response;
    cdc_entry cdc_entry_data;
    cdt_entry cdt_entry_data;
    char error_text[ERR_TEXT_LEN + 1];
} message_db_t;
```

5. Finally, we get to the pipe interface functions that perform data transfer, implemented in `pipe_imp.c`. These divide into server- and client-side functions, in the first and second blocks, respectively:

```
int server_starting(void);
void server_ending(void);
int read_request_from_client(message_db_t *rec_ptr);
int start_resp_to_client(const message_db_t mess_to_send);
int send_resp_to_client(const message_db_t mess_to_send);
void end_resp_to_client(void);

int client_starting(void);
void client_ending(void);
int send_mess_to_server(message_db_t mess_to_send);
int start_resp_from_server(void);
int read_resp_from_server(message_db_t *rec_ptr);
void end_resp_from_server(void);
```

We split the rest of the discussion into the client interface functions and details of the server- and client-side functions found in `pipe_imp.c`, and we'll look at the source code as necessary.

Client Interface Functions

Now we look at `client_if.c`. This provides “fake” versions of the database access routines. These encode the request in a `message_db_t` structure and then use the routines in `pipe_imp.c` to transfer the request to the server. This allows us to make minimal changes to the original `app_ui.c`.

Try It Out—The Client’s Interpreter

1. This file implements the nine database functions prototyped in `cd_data.h`. It does so by passing requests to the server and then returning the server response from the function, acting as an intermediary. The file starts with `#include` files and constants:

```
#define _POSIX_SOURCE

#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>
#include <limits.h>
#include <sys/types.h>
#include <sys/stat.h>

#include "cd_data.h"
#include "cliserv.h"
```

2. The static variable `mypid` reduces the number of calls to `getpid` that would otherwise be required. We use a local function, `read_one_response`, to eliminate duplicated code:

```
static pid_t mypid;

static int read_one_response(message_db_t *rec_ptr);
```

3. The `database_initialize` and `close` routines are still called, but are now used, respectively, for initializing the client side of the pipes interface and for removing redundant named pipes when the client exits.

```
int database_initialize(const int new_database)
{
    if (!client_starting()) return(0);
    mypid = getpid();
    return(1);

} /* database_initialize */

void database_close(void) {
    client_ending();
}
```

4. The `get_cdc_entry` routine is called to get a catalog entry from the database, given a CD catalog title. Here we encode the request in a `message_db_t` structure and pass it to the server. We then read the response back into a different `message_db_t` structure. If an entry is found, it's included inside the `message_db_t` structure as a `cdc_entry` structure, so we pass back the appropriate part of the structure:

```
cdc_entry get_cdc_entry(const char *cd_catalog_ptr)
{
    cdc_entry ret_val;
    message_db_t mess_send;
    message_db_t mess_ret;

    ret_val.catalog[0] = '\0';
    mess_send.client_pid = mypid;
    mess_send.request = s_get_cdc_entry;
    strcpy(mess_send.cdc_entry_data.catalog, cd_catalog_ptr);

    if (send_mess_to_server(mess_send)) {
        if (read_one_response(&mess_ret)) {
            if (mess_ret.response == r_success) {
                ret_val = mess_ret.cdc_entry_data;
            } else {
                fprintf(stderr, "%s", mess_ret.error_text);
            }
        } else {
            fprintf(stderr, "Server failed to respond\n");
        }
    } else {
        fprintf(stderr, "Server not accepting requests\n");
    }
    return(ret_val);
}
```

5. Here's the source for the function `read_one_response` that we use to avoid duplicating code:

```
static int read_one_response(message_db_t *rec_ptr) {

    int return_code = 0;
    if (!rec_ptr) return(0);
```

```
    if (start_resp_from_server()) {
        if (read_resp_from_server(rec_ptr)) {
            return_code = 1;
        }
        end_resp_from_server();
    }
    return(return_code);
}
```

6. The other `get_xxx`, `del_xxx` and `add_xxx` routines are implemented in a similar way to the `get_cdc_entry` function and are reproduced here for completeness. First, the function for retrieving CD tracks:

```
cdt_entry get_cdt_entry(const char *cd_catalog_ptr, const int track_no)
{
    cdt_entry ret_val;
    message_db_t mess_send;
    message_db_t mess_ret;

    ret_val.catalog[0] = '\0';
    mess_send.client_pid = mypid;
    mess_send.request = s_get_cdt_entry;
    strcpy(mess_send.cdt_entry_data.catalog, cd_catalog_ptr);
    mess_send.cdt_entry_data.track_no = track_no;

    if (send_mess_to_server(mess_send)) {
        if (read_one_response(&mess_ret)) {
            if (mess_ret.response == r_success) {
                ret_val = mess_ret.cdt_entry_data;
            } else {
                fprintf(stderr, "%s", mess_ret.error_text);
            }
        } else {
            fprintf(stderr, "Server failed to respond\n");
        }
    } else {
        fprintf(stderr, "Server not accepting requests\n");
    }
    return(ret_val);
}
```

7. Next, two functions for adding data, first to the catalog and then to the tracks database:

```
int add_cdc_entry(const cdc_entry entry_to_add)
{
    message_db_t mess_send;
    message_db_t mess_ret;

    mess_send.client_pid = mypid;
    mess_send.request = s_add_cdc_entry;
    mess_send.cdc_entry_data = entry_to_add;

    if (send_mess_to_server(mess_send)) {
        if (read_one_response(&mess_ret)) {
```

```

        if (mess_ret.response == r_success) {
            return(1);
        } else {
            fprintf(stderr, "%s", mess_ret.error_text);
        }
    } else {
        fprintf(stderr, "Server failed to respond\n");
    }
} else {
    fprintf(stderr, "Server not accepting requests\n");
}
return(0);
}

int add_cdt_entry(const cdt_entry entry_to_add)
{
    message_db_t mess_send;
    message_db_t mess_ret;

    mess_send.client_pid = mypid;
    mess_send.request = s_add_cdt_entry;
    mess_send.cdt_entry_data = entry_to_add;

    if (send_mess_to_server(mess_send)) {
        if (read_one_response(&mess_ret)) {
            if (mess_ret.response == r_success) {
                return(1);
            } else {
                fprintf(stderr, "%s", mess_ret.error_text);
            }
        } else {
            fprintf(stderr, "Server failed to respond\n");
        }
    } else {
        fprintf(stderr, "Server not accepting requests\n");
    }
    return(0);
}

```

8. Last two functions for data deletion:

```

int del_cdc_entry(const char *cd_catalog_ptr)
{
    message_db_t mess_send;
    message_db_t mess_ret;

    mess_send.client_pid = mypid;
    mess_send.request = s_del_cdc_entry;
    strcpy(mess_send.cdc_entry_data.catalog, cd_catalog_ptr);

    if (send_mess_to_server(mess_send)) {
        if (read_one_response(&mess_ret)) {
            if (mess_ret.response == r_success) {
                return(1);
            } else {

```

```
        fprintf(stderr, "%s", mess_ret.error_text);
    }
} else {
    fprintf(stderr, "Server failed to respond\n");
}
} else {
    fprintf(stderr, "Server not accepting requests\n");
}
return(0);
}

int del_cdt_entry(const char *cd_catalog_ptr, const int track_no)
{
    message_db_t mess_send;
    message_db_t mess_ret;

    mess_send.client_pid = mypid;
    mess_send.request = s_del_cdt_entry;
    strcpy(mess_send.cdt_entry_data.catalog, cd_catalog_ptr);
    mess_send.cdt_entry_data.track_no = track_no;

    if (send_mess_to_server(mess_send)) {
        if (read_one_response(&mess_ret)) {
            if (mess_ret.response == r_success) {
                return(1);
            } else {
                fprintf(stderr, "%s", mess_ret.error_text);
            }
        } else {
            fprintf(stderr, "Server failed to respond\n");
        }
    } else {
        fprintf(stderr, "Server not accepting requests\n");
    }
    return(0);
}
```

Searching the Database

The function for the search on the CD key is more complex. The user of this function expects to call it once to start a search. We catered to this expectation in Chapter 7 by setting `*first_call_ptr` to true on this first call and the function then to return the first match. On subsequent calls to the search function, `*first_call_ptr` is false and further matches are returned, one per call.

Now that we've split the application across two processes, we can no longer allow the search to proceed one entry at a time in the server, because a different client may request a different search from the server while our search is in progress. We can't make the server side store the context (how far the search has gotten) for each client search separately, since the client side can simply stop searching part of the way through a search, when a user finds the CD they are looking for or if the client "falls over."

We can either change the way the search is performed or, as we have chosen here, hide the complexity in the interface routine. What we've done is to arrange for the server to return all the possible matches to a search and then store them in a temporary file until the client requests them.

Try It Out—Searching

1. This function looks more complicated than it is because it calls three pipe functions that we'll be looking at in the next section: `send_mess_to_server`, `start_resp_from_server`, and `read_resp_from_server`.

```
cdc_entry search_cdc_entry(const char *cd_catalog_ptr, int *first_call_ptr)
{
    message_db_t mess_send;
    message_db_t mess_ret;

    static FILE *work_file = (FILE *)0;
    static int entries_matching = 0;
    cdc_entry ret_val;

    ret_val.catalog[0] = '\0';

    if (!work_file && (*first_call_ptr == 0)) return(ret_val);
```

2. Here's the first call to search, that is, with `*first_call_ptr` set to `true`. It's set to `false` immediately, in case we forget. A `work_file` is created and the client message structure initialized.

```
if (*first_call_ptr) {
    *first_call_ptr = 0;
    if (work_file) fclose(work_file);
    work_file = tmpfile();
    if (!work_file) return(ret_val);

    mess_send.client_pid = mypid;
    mess_send.request = s_find_cdc_entry;
    strcpy(mess_send.cdc_entry_data.catalog, cd_catalog_ptr);
```

3. Next, there's this three-deep condition test, which makes calls to functions in `pipe_imp.c`. If the message is successfully sent to the server, the client waits for the server's response. While reads from the server are successful, the search matches are returned to the client's `work_file` and the `entries_matching` counter is incremented.

```
if (send_mess_to_server(mess_send)) {
    if (start_resp_from_server()) {
        while (read_resp_from_server(&mess_ret)) {
            if (mess_ret.response == r_success) {
                fwrite(&mess_ret.cdc_entry_data, sizeof(cdc_entry), 1, work_file);
                entries_matching++;
            } else {
                break;
            }
        } /* while */
    } else {
        fprintf(stderr, "Server not responding\n");
    }
} else {
    fprintf(stderr, "Server not accepting requests\n");
}
```

4. The next test checks whether the search had any luck. Then the `fseek` call sets the `work_file` to the next place for data to be written.

```
if (entries_matching == 0) {  
    fclose(work_file);  
    work_file = (FILE *)0;  
    return(ret_val);  
}  
(void)fseek(work_file, 0L, SEEK_SET);
```

5. If this is not the first call to the search function with this particular search term, the code checks whether there are any matches left. Finally, the next matching entry is read to the `ret_val` structure. The previous checks guarantee that a matching entry exists.

```
} else {  
    /* not *first_call_ptr */  
    if (entries_matching == 0) {  
        fclose(work_file);  
        work_file = (FILE *)0;  
        return(ret_val);  
    }  
}  
  
fread(&ret_val, sizeof(cdc_entry), 1, work_file);  
entries_matching--;  
  
return(ret_val);  
}
```

The Server Interface

Just as the client side has an interface to the `app_ui.c` program, so the server side needs a program to control the (renamed) `cd_access.c`, now `cd_dbm.c`. The server's `main` function is listed here.

Try It Out—server.c

1. We start by declaring some global variables, a prototype for the `process_command` function, and a signal-catcher function to ensure a clean exit.

```
#include <unistd.h>  
#include <stdlib.h>  
#include <stdio.h>  
#include <fcntl.h>  
#include <limits.h>  
#include <signal.h>  
#include <string.h>  
#include <errno.h>  
#include <sys/types.h>  
#include <sys/stat.h>
```

```
#include "cd_data.h"
#include "cliserv.h"
int save_errno;
static int server_running = 1;

static void process_command(const message_db_t mess_command);

void catch_signals()
{
    server_running = 0;
}
```

- 2.** Now we come to the `main` function. After checking that the signal-catching routines are all right, the program checks to see whether you passed `-i` on the command line. If you did, it will create a new database. If the call to the `database_initialize` routine in `cd_dbm.c` fails, an error message is shown. If all is well and the server is running, any requests from the client are fed to the `process_command` function, which we'll show you in a moment.

```
int main(int argc, char *argv[]) {
    struct sigaction new_action, old_action;
    message_db_t mess_command;
    int database_init_type = 0;

    new_action.sa_handler = catch_signals;
    sigemptyset(&new_action.sa_mask);
    new_action.sa_flags = 0;
    if ((sigaction(SIGINT, &new_action, &old_action) != 0) ||
        (sigaction(SIGHUP, &new_action, &old_action) != 0) ||
        (sigaction(SIGTERM, &new_action, &old_action) != 0)) {
        fprintf(stderr, "Server startup error, signal catching failed\n");
        exit(EXIT_FAILURE);
    }

    if (argc > 1) {
        argv++;
        if (strncmp("-i", *argv, 2) == 0) database_init_type = 1;
    }
    if (!database_initialize(database_init_type)) {
        fprintf(stderr, "Server error:-\n"
                    "could not initialize database\n");
        exit(EXIT_FAILURE);
    }

    if (!server_starting()) exit(EXIT_FAILURE);

    while(server_running) {
        if (read_request_from_client(&mess_command)) {
            process_command(mess_command);
        } else {
            if(server_running) fprintf(stderr, "Server ended - can not \
                                         read pipe\n");
        }
    }
}
```

```
        server_running = 0;
    }
} /* while */
server_ending();
exit(EXIT_SUCCESS);
}
```

3. Any client messages are fed to the `process_command` function, where they are fed into a case statement that makes the appropriate calls to `cd_dbm.c`.

```
static void process_command(const message_db_t comm)
{
    message_db_t resp;
    int first_time = 1;

    resp = comm; /* copy command back, then change resp as required */

    if (!start_resp_to_client(resp)) {
        fprintf(stderr, "Server Warning:-\
                    start_resp_to_client %d failed\n", resp.client_pid);
        return;
    }

    resp.response = r_success;
    memset(resp.error_text, '\0', sizeof(resp.error_text));
    save_errno = 0;

    switch(resp.request) {
        case s_create_new_database:
            if (!database_initialize(1)) resp.response = r_failure;
            break;
        case s_get_cdc_entry:
            resp.cdc_entry_data =
                get_cdc_entry(comm.cdc_entry_data.catalog);
            break;
        case s_get_cdt_entry:
            resp.cdt_entry_data =
                get_cdt_entry(comm.cdt_entry_data.catalog,
                            comm.cdt_entry_data.track_no);
            break;
        case s_add_cdc_entry:
            if (!add_cdc_entry(comm.cdc_entry_data)) resp.response =
                r_failure;
            break;
        case s_add_cdt_entry:
            if (!add_cdt_entry(comm.cdt_entry_data)) resp.response =
                r_failure;
            break;
        case s_del_cdc_entry:
```

```

        if (!del_cdc_entry(comm.cdc_entry_data.catalog)) resp.response
            = r_failure;
        break;
    case s_del_cdt_entry:
        if (!del_cdt_entry(comm.cdt_entry_data.catalog,
                           comm.cdt_entry_data.track_no)) resp.response = r_failure;
        break;
    case s_find_cdc_entry:
        do {
            resp.cdc_entry_data =
                search_cdc_entry(comm.cdc_entry_data.catalog,
                                  &first_time);
            if (resp.cdc_entry_data.catalog[0] != 0) {
                resp.response = r_success;
                if (!send_resp_to_client(resp)) {
                    fprintf(stderr, "Server Warning:-\
                               failed to respond to %d\n", resp.client_pid);
                    break;
                }
            } else {
                resp.response = r_find_no_more;
            }
        } while (resp.response == r_success);
        break;
    default:
        resp.response = r_failure;
        break;
    } /* switch */

    sprintf(resp.error_text, "Command failed:\n\t%s\n",
            strerror(save_errno));

    if (!send_resp_to_client(resp)) {
        fprintf(stderr, "Server Warning:-\
                   failed to respond to %d\n", resp.client_pid);
    }

    end_resp_to_client();
    return;
}

```

Before we look at the actual pipe implementation, let's discuss the sequence of events that needs to occur to pass data between the client and server processes. Figure 13-9 shows both client and server processes starting and how both parties loop while processing commands and responses.

In this implementation, the situation is slightly more difficult, since, for a search request, the client passes a single command to the server and then expects to receive one or more responses from the server. This leads to some additional complexity, mainly in the client.

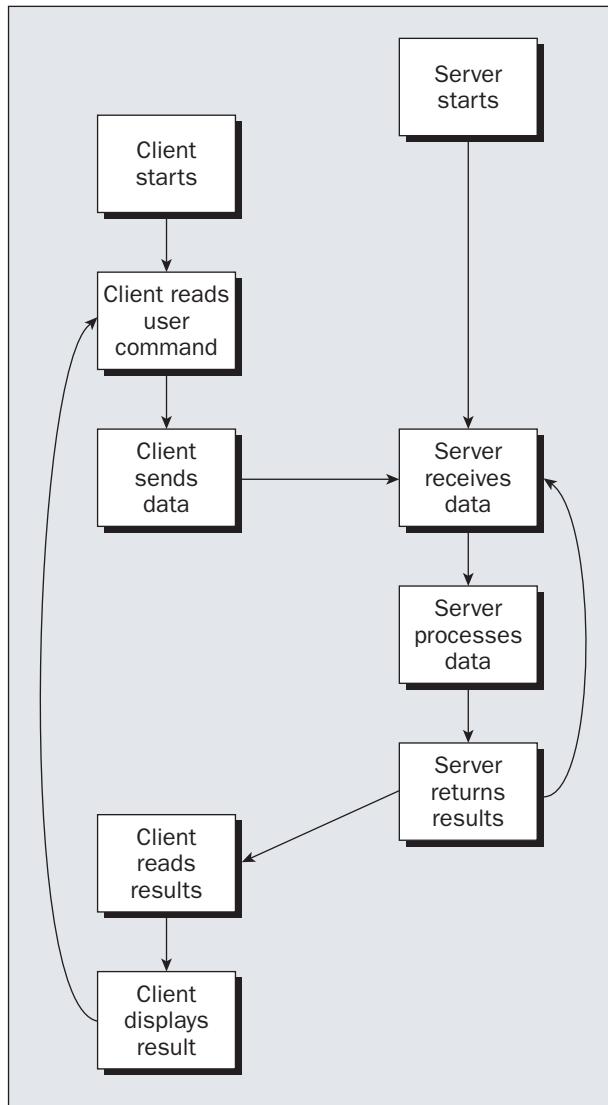


Figure 13-9

The Pipe

Here's the pipes implementation file, `pipe_imp.c`, which has both the client- and server-side functions.

As we saw in Chapter 10, the symbol `DEBUG_TRACE` can be defined to show the sequence of calls as the client and server processes pass messages between each other.

Try It Out—Pipes Implementation Header

- First the #includes:

```
#include "cd_data.h"
#include "cliserv.h"
```

- We also define some values that we need in different functions within the file:

```
static int server_fd = -1;
static pid_t mypid = 0;
static char client_pipe_name[PATH_MAX + 1] = {'\0'};
static int client_fd = -1;
static int client_write_fd = -1;
```

Server-Side Functions

Next, we need to look at the server-side functions. The following Try It Out section shows the functions that open and close the named pipe and read messages from the clients. The second Try It Out shows the code that opens, sends, and closes the client pipes based on the process ID the client includes in its message.

Try It Out—Server Functions

- The `server_starting` routine creates the named pipe from which the server will read commands. It then opens that pipe for reading. This open will block until a client opens the pipe for writing. We use a blocking mode so that the server can perform blocking reads on the pipe while waiting for commands to be sent to it.

```
int server_starting(void)
{
    #if DEBUG_TRACE
        printf("%d :- server_starting()\n", getpid());
    #endif

    unlink(SERVER_PIPE);
    if (mkfifo(SERVER_PIPE, 0777) == -1) {
        fprintf(stderr, "Server startup error, no FIFO created\n");
        return(0);
    }

    if ((server_fd = open(SERVER_PIPE, O_RDONLY)) == -1) {
        if (errno == EINTR) return(0);
        fprintf(stderr, "Server startup error, no FIFO opened\n");
        return(0);
    }
    return(1);
}
```

Chapter 13

2. When the server ends, it removes the named pipe so that clients can detect that no server is running.

```
void server_ending(void)
{
    #if DEBUG_TRACE
        printf("%d :- server_ending()\n", getpid());
    #endif

    (void)close(server_fd);
    (void)unlink(SERVER_PIPE);
}
```

3. The `read_request_from_client` function shown in the following example will block reading in the server pipe until a client writes a message into it:

```
int read_request_from_client(message_db_t *rec_ptr)
{
    int return_code = 0;
    int read_bytes;

    #if DEBUG_TRACE
        printf("%d :- read_request_from_client()\n", getpid());
    #endif

    if (server_fd != -1) {
        read_bytes = read(server_fd, rec_ptr, sizeof(*rec_ptr));
        ...
    }
    return(return_code);
}
```

4. In the special case where no clients have the pipe open for writing, the `read` will return 0; that is, it detects an EOF. Then the server closes the pipe and opens it again, so that it blocks until a client also opens the pipe. This is just the same as when the server first starts; we have reinitialized the server. Insert this code into the preceding function:

```
if (read_bytes == 0) {
    (void)close(server_fd);
    if ((server_fd = open(SERVER_PIPE, O_RDONLY)) == -1) {
        if (errno != EINTR) {
            fprintf(stderr, "Server error, FIFO open failed\n");
        }
        return(0);
    }
    read_bytes = read(server_fd, rec_ptr, sizeof(*rec_ptr));
}
if (read_bytes == sizeof(*rec_ptr)) return_code = 1;
```

The server is a single process that may be serving many clients simultaneously. Since each client uses a different pipe to receive its responses, the server needs to write to a different pipe to send responses to

different clients. Since file descriptors are a limited resource, the server opens a client pipe for writing only when it has data to send.

We split the opening, writing, and closing of the client pipe into three separate functions. We need to do this when we're returning multiple results to a search, so we can open the pipe once, write many responses, and close it again.

Try It Out—Plumbing the Pipes

- First we open the client pipe:

```
int start_resp_to_client(const message_db_t mess_to_send)
{
    #if DEBUG_TRACE
        printf("%d :- start_resp_to_client()\n", getpid());
    #endif

    (void)sprintf(client_pipe_name, CLIENT_PIPE, mess_to_send.client_pid);
    if ((client_fd = open(client_pipe_name, O_WRONLY)) == -1) return(0);
    return(1);
}
```

- The messages are all sent using calls to this function. We'll look at the corresponding client-side functions that field the message in just a bit.

```
int send_resp_to_client(const message_db_t mess_to_send)
{
    int write_bytes;

    #if DEBUG_TRACE
        printf("%d :- send_resp_to_client()\n", getpid());
    #endif

    if (client_fd == -1) return(0);
    write_bytes = write(client_fd, &mess_to_send, sizeof(mess_to_send));
    if (write_bytes != sizeof(mess_to_send)) return(0);
    return(1);
}
```

- Finally, we close the client pipe:

```
void end_resp_to_client(void)
{
    #if DEBUG_TRACE
        printf("%d :- end_resp_to_client()\n", getpid());
    #endif

    if (client_fd != -1) {
        (void)close(client_fd);
        client_fd = -1;
    }
}
```

Client-Side Functions

Complementing the server are the client functions in `pipe_imp.c`. They are very similar to the server-side functions, except for the worryingly named `send_mess_to_server` function.

Try It Out—Client Functions

- After checking that a server is accessible, the `client_starting` function initializes the client-side pipe:

```
int client_starting(void)
{
    #if DEBUG_TRACE
        printf("%d :- client_starting\n", getpid());
    #endif

    mypid = getpid();
    if ((server_fd = open(SERVER_PIPE, O_WRONLY)) == -1) {
        fprintf(stderr, "Server not running\n");
        return(0);
    }

    (void)sprintf(client_pipe_name, CLIENT_PIPE, mypid);
    (void)unlink(client_pipe_name);
    if (mkfifo(client_pipe_name, 0777) == -1) {
        fprintf(stderr, "Unable to create client pipe %s\n",
                client_pipe_name);
        return(0);
    }
    return(1);
}
```

- The `client_ending` function closes file descriptors and deletes the now-redundant named pipe:

```
void client_ending(void)
{
    #if DEBUG_TRACE
        printf("%d :- client_ending()\n", getpid());
    #endif

    if (client_write_fd != -1) (void)close(client_write_fd);
    if (client_fd != -1) (void)close(client_fd);
    if (server_fd != -1) (void)close(server_fd);
    (void)unlink(client_pipe_name);
}
```

- The `send_mess_to_server` function passes the request through the server pipe:

```
int send_mess_to_server(message_db_t mess_to_send)
{
    int write_bytes;

    #if DEBUG_TRACE
```

```

        printf("%d :- send_mess_to_server()\n", getpid());
#endif

        if (server_fd == -1) return(0);
        mess_to_send.client_pid = mypid;
        write_bytes = write(server_fd, &mess_to_send, sizeof(mess_to_send));
        if (write_bytes != sizeof(mess_to_send)) return(0);
        return(1);
    }
}

```

As with the server-side functions we saw earlier, the client gets results back from the server using three functions, to cater to multiple search results.

Try It Out—Getting Server Results

1. This client function starts to listen for the server response. It opens a client pipe as read-only and then reopens this pipe's file as write-only. We'll see why a bit later in the section.

```

int start_resp_from_server(void)
{
    #if DEBUG_TRACE
        printf("%d :- start_resp_from_server()\n", getpid());
   #endif

    if (client_pipe_name[0] == '\0') return(0);
    if (client_fd != -1) return(1);

    client_fd = open(client_pipe_name, O_RDONLY);
    if (client_fd != -1) {
        client_write_fd = open(client_pipe_name, O_WRONLY);
        if (client_write_fd != -1) return(1);
        (void)close(client_fd);
        client_fd = -1;
    }
    return(0);
}

```

2. Here's the main read from the server that gets the matching database entries:

```

int read_resp_from_server(message_db_t *rec_ptr)
{
    int read_bytes;
    int return_code = 0;

    #if DEBUG_TRACE
        printf("%d :- read_resp_from_server()\n", getpid());
   #endif

    if (!rec_ptr) return(0);
    if (client_fd == -1) return(0);

    read_bytes = read(client_fd, rec_ptr, sizeof(*rec_ptr));
    if (read_bytes == sizeof(*rec_ptr)) return_code = 1;
    return(return_code);
}

```

3. And finally, here's the client function that marks the end of the server response:

```
void end_resp_from_server(void)
{
    #if DEBUG_TRACE
        printf("%d :- end_resp_from_server()\n", getpid());
    #endif

    /* This function is empty in the pipe implementation */
}
```

How It Works

The second, additional open of the client pipe for writing in `start_resp_from_server`

```
client_write_fd = open(client_pipe_name, O_WRONLY);
```

is used to prevent a race condition when the server needs to respond to several requests from the client in quick succession.

To explain this a little more, consider the following sequence of events:

1. The client writes a request to the server.
2. The server reads the request, opens the client pipe and sends the response back, but is suspended before it gets as far as closing the client pipe.
3. The client opens its pipe for reading, reads the first response and closes its pipe.
4. The client then sends a new command and opens the client pipe for reading.
5. The server then resumes running, closing its end of the client pipe.

Unfortunately, at this point the client is trying to read the pipe, looking for a response to its next request, but the `read` will return with 0 bytes because no process has the client pipe open for writing.

By allowing the client to open its pipe for both reading and writing, thus removing the need for repeatedly reopening the pipe, we avoid this race condition. Note that the client never writes to the pipe, so there's no danger of reading erroneous data.

Application Summary

We've now separated our CD database application into a client and a server, enabling us to develop the user interface and the underlying database technology independently. We can see that a well-defined database interface allows each major element of the application to make the best use of computer resources. If we took things a little further, we could change the pipes implementation to a networked one and use a dedicated database server machine. We'll learn more about networking in Chapter 15.

Summary

In this chapter, we've looked at passing data between processes using pipes. First, we looked at unnamed pipes, created with the `popen` or the `pipe` call, and discussed how, using a pipe and the `dup` call, we can pass data from one program to the standard input of another. We then looked at named pipes and saw how we can pass data between unrelated programs. Finally, we implemented a simple client/server example, using FIFOs to give us not only process synchronization, but also bidirectional data flow.

14

Semaphores, Shared Memory, and Message Queues

In this chapter, we are going to discuss a set of inter-process communication facilities that were introduced in the AT&T System V.2 release of UNIX. Since all these facilities appeared in the same release and have a similar programmatic interface, they are often referred to as the IPC (Inter-Process Communication) facilities, or more commonly System V IPC. As we've already seen, they are by no means the only way of communicating between processes, but the expression System V IPC is usually used to refer to these specific facilities.

We will cover the following topics in this chapter:

- ❑ Semaphores, for managing access to resources
- ❑ Shared memory, for highly efficient data sharing between programs
- ❑ Messaging, for an easy way of passing data between programs

Semaphores

When we write programs that use threads operating in multiuser systems, multiprocessing systems, or a combination of the two, we often discover that we have *critical sections* of code, where we need to ensure that a single process (or a single thread of execution) has exclusive access to a resource.

Semaphores have a complex programming interface. Fortunately, we can easily provide ourselves with a much-simplified interface that is sufficient for most semaphore-programming problems.

In our first example application in Chapter 7—using `dbm` to access a database—the data could be corrupted if multiple programs tried to update the database at exactly the same time. There's no trouble with two different programs asking different users to enter data for the database; the only potential problem is in the parts of the code that update the database. These sections of code,

which actually perform data updates and need to execute exclusively, are called critical sections. Frequently they are just a few lines of code from much larger programs.

To prevent problems caused by more than one program simultaneously accessing a shared resource, we need a way of generating and using a token that grants access to only one thread of execution in a critical section at a time. We saw briefly in Chapter 12 some thread-specific ways we could use a mutex or semaphores to control access to critical sections in a threaded program. In this chapter, we return to the topic of semaphores, but look more generally at how they are used between different processes.

The semaphore functions used with threads that we saw in Chapter 12 are *not* the more general ones we will discuss in this chapter, so be careful not to confuse the two types.

It's surprisingly difficult to write general-purpose code that ensures that one program has exclusive access to a particular resource, although there's a solution known as Dekker's Algorithm. Unfortunately, this algorithm relies on a "busy wait," or "spin lock," where a process runs continuously, waiting for a memory location to be changed. In a multitasking environment such as Linux, this is an undesirable waste of CPU resources. The situation is much easier if hardware support, generally in the form of specific CPU instructions, is available to support exclusive access. An example of hardware support would be an instruction to access and increment a register in an atomic way, such that no other instruction (not even an interrupt) could occur between the read/increment/write operations.

One possible solution that we've already seen is to create files using the `O_EXCL` flag with the `open` function, which provides atomic file creation. This allows a single process to succeed in obtaining a token: the newly created file. This method is fine for simple problems, but rather messy and very inefficient for more complex examples.

An important step forward in this area of concurrent programming occurred when Dijkstra introduced the concept of the semaphore. As discussed in Chapter 12, a semaphore is a special variable that takes only whole positive numbers and upon which only two operations are allowed: wait and signal. Since "wait" and "signal" already have special meanings in Linux and UNIX programming, we'll use the original notation:

- ❑ `P(semaphore variable)` for wait
- ❑ `V(semaphore variable)` for signal

These letters come from the Dutch words for wait (*passeren*: to pass, as in a checkpoint before the critical section) and signal (*vrijgeven*: to give or release, as in giving up control of the critical section). You may also come across the terms "up" and "down" used in relation to semaphores, taken from the use of signaling flags.

Semaphore Definition

The simplest semaphore is a variable that can take only the values 0 and 1, a *binary semaphore*. This is the most common form. Semaphores that can take many positive values are called *general semaphores*. For the remainder of this chapter, we'll concentrate on binary semaphores.

Semaphores, Shared Memory, and Message Queues

The definitions of `P` and `V` are surprisingly simple. Suppose we have a semaphore variable `sv`. The two operations are then defined as follows:

| | |
|--------------------|---|
| <code>P(sv)</code> | If <code>sv</code> is greater than zero, decrement <code>sv</code> . If <code>sv</code> is zero, suspend execution of this process. |
| <code>V(sv)</code> | If some other process has been suspended waiting for <code>sv</code> , make it resume execution. If no process is suspended waiting for <code>sv</code> , increment <code>sv</code> . |

Another way of thinking about semaphores is that the semaphore variable, `sv`, is `true` when the critical section is available, is decremented by `P(sv)` so it's `false` when the critical section is busy, and is incremented by `V(sv)` when the critical section is again available. Be aware that simply having a normal variable that you decrement and increment is not good enough, because you can't express in C, C++, or almost any conventional programming language the need to make a single, atomic operation of the test to see whether the variable is `true`, and if so change the variable to make it `false`. This is what makes the semaphore operations special.

A Theoretical Example

We can see how this works with a simple theoretical example. Suppose we have two processes `proc1` and `proc2`, both of which need exclusive access to a database at some point in their execution. We define a single binary semaphore, `sv`, that starts with the value 1 and can be accessed by both processes. Both processes then need to perform the same processing to access the critical section of code; indeed, the two processes could simply be different invocations of the same program.

The two processes share the `sv` semaphore variable. Once one process has executed `P(sv)`, it has obtained the semaphore and can enter the critical section. The second process is prevented from entering the critical section because, when it attempts to execute `P(sv)`, it's made to wait until the first process has left the critical section and executed `V(sv)` to release the semaphore.

The required pseudocode is

```
semaphore sv = 1;

loop forever {
    P(sv);
    critical code section;
    V(sv);
    noncritical code section;
}
```

The code is surprisingly simple because the definition of the `P` and `V` operations is very powerful. Figure 14-1 shows a diagram showing how the `P` and `V` operations act as a gate into critical sections of code.

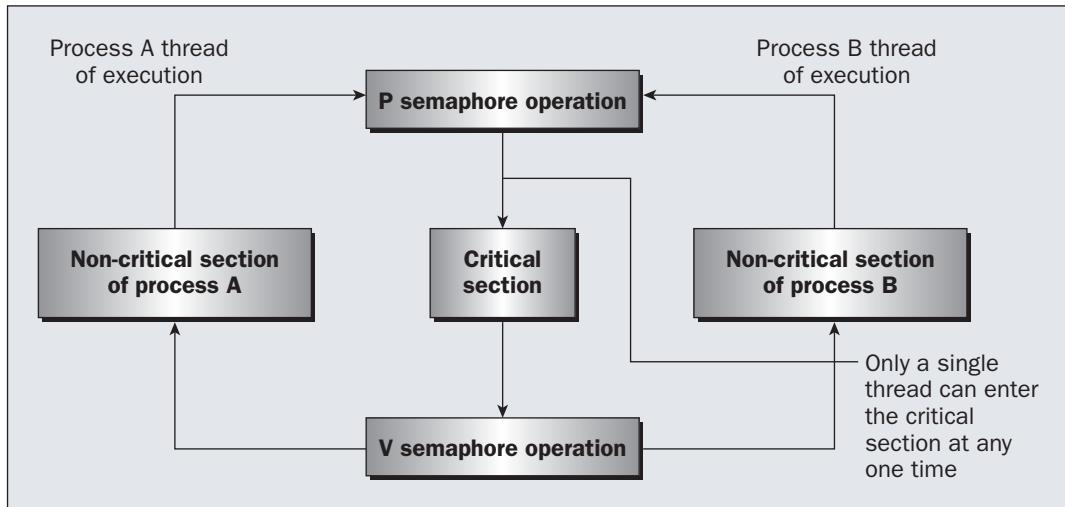


Figure 14-1

Linux Semaphore Facilities

Now that we've seen what semaphores are and how they work in theory, we can look at how the features are implemented in Linux. The interface is rather elaborate and offers far more facilities than are generally required. All the Linux semaphore functions operate on arrays of general semaphores rather than a single binary semaphore. At first sight, this just seems to make things more complicated, but in complex cases where a process needs to lock multiple resources, the ability to operate on an array of semaphores is a big advantage. In this chapter, we will concentrate on using single semaphores, since in most cases that's all you will need to use.

The semaphore function definitions are

```
#include <sys/sem.h>

int semctl(int sem_id, int sem_num, int command, ...);
int semget(key_t key, int num_sems, int sem_flags);
int semop(int sem_id, struct sembuf *sem_ops, size_t num_sem_ops);
```

In practice, the #include files sys/types.h and sys/ipc.h are usually required to be included before sys/sem.h in order get some of the #defines you need for particular operations. There are, however, a few cases where they won't be necessary.

As we work through each function in turn, remember that these functions were designed to work for arrays of semaphore values, which makes their operation significantly more complex than would have been required for a single semaphore.

Notice that key acts very much like a filename in that it represents a resource that programs may use and cooperate in using if they agree on a common name. Similarly, the identifier returned by semget and used by the other shared memory functions is very much like the FILE * file stream returned by fopen in that it's a value used by the process to access the shared file. And, just as with files, different processes will have different semaphore identifiers, though they refer to the same semaphore. This use of a key and identifiers is common to all of the IPC facilities discussed here, although each facility uses independent keys and identifiers.

semget

The semget function creates a new semaphore or obtains the semaphore key of an existing semaphore.

```
int semget(key_t key, int num_sems, int sem_flags);
```

The first parameter, key, is an integral value used to allow unrelated processes to access the same semaphore. All semaphores are accessed indirectly by the program supplying a key, for which the system then generates a semaphore identifier. The semaphore key is used only with semget. All other semaphore functions use the semaphore identifier returned from semget.

There is a special semaphore key value, `IPC_PRIVATE` (usually 0), that is intended to create a semaphore that only the creating process could access. This rarely has any useful purpose, which is fortunate, because on some Linux systems the manual pages list as a bug the fact that `IPC_PRIVATE` may not prevent other processes from accessing the semaphore.

The num_sems parameter is the number of semaphores required. This is almost always 1.

The sem_flags parameter is a set of flags, very much like the flags to the open function. The lower nine bits are the permissions for the semaphore, which behave like file permissions. In addition, these can be bitwise ORed with the value `IPC_CREAT` to create a new semaphore. It's not an error to have the `IPC_CREAT` flag set and give the key of an existing semaphore. The `IPC_CREAT` flag is silently ignored if it is not required. We can use `IPC_CREAT` and `IPC_EXCL` together to ensure that we obtain a new, unique semaphore. It will return an error if the semaphore already exists.

The semget function returns a positive (nonzero) value on success; this is the semaphore identifier used in the other semaphore functions. On error, it returns -1.

semop

The function semop is used for changing the value of the semaphore:

```
int semop(int sem_id, struct sembuf *sem_ops, size_t num_sem_ops);
```

The first parameter, `sem_id`, is the semaphore identifier, as returned from semget. The second parameter, `sem_ops`, is a pointer to an array of structures, each of which will have at least the following members:

```
struct sembuf {
    short sem_num;
    short sem_op;
    short sem_flg;
}
```

The first member, `sem_num`, is the semaphore number, usually 0 unless you’re working with an array of semaphores. The `sem_op` member is the value by which the semaphore should be changed. (You can change a semaphore by amounts other than 1.) In general, only two values are used, `-1`, which is our `P` operation to wait for a semaphore to become available, and `+1`, which is our `V` operation to signal that a semaphore is now available.

The final member, `sem_flg`, is usually set to `SEM_UNDO`. This causes the operating system to track the changes made to the semaphore by the current process and, if the process terminates without releasing the semaphore, allows the operating system to automatically release the semaphore if it was held by this process. It’s good practice to set `sem_flg` to `SEM_UNDO`, unless you specifically require different behavior. If you do decide you need a value other than `SEM_UNDO`, it’s important to be consistent, or you can get very confused as to whether the kernel is attempting to “tidy up” your semaphores when your process exits.

All actions called for by `semop` are taken together to avoid a race condition implied by the use of multiple semaphores. You can find full details of the processing of `semop` in the manual pages.

semctl

The `semctl` function allows direct control of semaphore information:

```
int semctl(int sem_id, int sem_num, int command, ...);
```

The first parameter, `sem_id`, is a semaphore identifier, obtained from `semget`. The `sem_num` parameter is the semaphore number. You use this when you’re working with arrays of semaphores. Usually, this is 0, the first and only semaphore. The `command` parameter is the action to take, and a fourth parameter, if present, is a union `semun`, which according to the X/OPEN specification, must have at least the following members:

```
union semun {
    int val;
    struct semid_ds *buf;
    unsigned short *array;
}
```

Many versions of Linux have a definition of the `semun` union in a header file (usually `sem.h`), though X/Open does say that you have to declare your own. If you do find that you need to declare your own, check the manual pages for `semctl` to see if there is a definition given. If there is, we suggest you use exactly the definition given in your manual, even if it differs from that above.

There are many different possible values of `command` allowed for `semctl`. Only the two that we describe here are commonly used. For full details of the `semctl` function, you should consult the manual page.

The two common values of `command` are

- ❑ `SETVAL`: Used for initializing a semaphore to a known value. The value required is passed as the `val` member of the union `semun`. This is required to set the semaphore up before it’s used for the first time.
- ❑ `IPC_RMID`: Used for deleting a semaphore identifier when it’s no longer required.

The `semctl` function returns different values depending on the `command` parameter. For `SETVAL` and `IPC_RMID` it returns 0 for success and `-1` on error.

Using Semaphores

As you can see from the previous section's descriptions, semaphore operations can be rather complex. This is most unfortunate, since programming multiple processes or threads with critical sections is quite a difficult problem on its own and having a complex programming interface simply adds to the intellectual burden.

Fortunately, we can solve most problems that require semaphores using only a single binary semaphore, the simplest type. In our example, we'll use the full programming interface to create a much simpler P and V type interface for a binary semaphore. We'll then use this much simpler interface to demonstrate how semaphores function.

To experiment with semaphores, we'll use a single program, `sem1.c`, that we can invoke several times. We'll use an optional parameter to specify whether the program is responsible for creating and destroying the semaphore.

We use the output of two different characters to indicate entering and leaving the critical section. The program invoked with a parameter prints an X on entering and exiting its critical section. Other invocations of the program print an O on entering and exiting their critical sections. Since only one process should be able to enter its critical section at any given time, all X and O characters should appear in pairs.

Try It Out—Semaphores

1. After the #includes, the function prototypes, and the global variable, we come to the main function. There the semaphore is created with a call to `semget`, which returns the semaphore ID. If the program is the first to be called (i.e., it's called with a parameter and `argc > 1`), a call is made to `set_semvalue` to initialize the semaphore and `op_char` is set to X.

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

#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>

#include "semun.h"

static int set_semvalue(void);
static void del_semvalue(void);
static int semaphore_p(void);
static int semaphore_v(void);

static int sem_id;

int main(int argc, char *argv[])
{
    int i;
    int pause_time;
    char op_char = 'O';

    srand((unsigned int) getpid());
```

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```
sem_id = semget((key_t)1234, 1, 0666 | IPC_CREAT);

if (argc > 1) {
    if (!set_semvalue()) {
        fprintf(stderr, "Failed to initialize semaphore\n");
        exit(EXIT_FAILURE);
    }
    op_char = 'X';
    sleep(2);
}
```

2. Then we have a loop that enters and leaves the critical section 10 times. There we first make a call to `semaphore_p`, which sets the semaphore to wait as this program is about to enter the critical section.

```
for(i = 0; i < 10; i++) {

    if (!semaphore_p()) exit(EXIT_FAILURE);
    printf("%c", op_char);fflush(stdout);
    pause_time = rand() % 3;
    sleep(pause_time);
    printf("%c", op_char);fflush(stdout);
}
```

3. After the critical section, we call `semaphore_v`, setting the semaphore as available, before going through the `for` loop again after a random wait. After the loop, the call to `del_semvalue` is made to clean up the code.

```
if (!semaphore_v()) exit(EXIT_FAILURE);

pause_time = rand() % 2;
sleep(pause_time);
}

printf("\n%d - finished\n", getpid());

if (argc > 1) {
    sleep(10);
    del_semvalue();
}

exit(EXIT_SUCCESS);
}
```

4. The function `set_semvalue` initializes the semaphore using the `SETVAL` command in a `semctl` call. We need to do this before we can use the semaphore:

```
static int set_semvalue(void)
{
    union semun sem_union;

    sem_union.val = 1;
    if (semctl(sem_id, 0, SETVAL, sem_union) == -1) return(0);
    return(1);
}
```

5. The `del_semvalue` function has almost the same form, except that the call to `semctl` uses the command `IPC_RMID` to remove the semaphore's ID:

```
static void del_semvalue(void)
{
    union semun sem_union;

    if (semctl(sem_id, 0, IPC_RMID, sem_union) == -1)
        fprintf(stderr, "Failed to delete semaphore\n");
}
```

6. `semaphore_p` changes the semaphore by -1 (waiting):

```
static int semaphore_p(void)
{
    struct sembuf sem_b;

    sem_b.sem_num = 0;
    sem_b.sem_op = -1; /* P() */
    sem_b.sem_flg = SEM_UNDO;
    if (semop(sem_id, &sem_b, 1) == -1) {
        fprintf(stderr, "semaphore_p failed\n");
        return(0);
    }
    return(1);
}
```

7. `semaphore_v` is similar except for setting the `sem_op` part of the `sembuf` structure to 1, so that the semaphore becomes available.

```
static int semaphore_v(void)
{
    struct sembuf sem_b;

    sem_b.sem_num = 0;
    sem_b.sem_op = 1; /* V() */
    sem_b.sem_flg = SEM_UNDO;
    if (semop(sem_id, &sem_b, 1) == -1) {
        fprintf(stderr, "semaphore_v failed\n");
        return(0);
    }
    return(1);
}
```

Notice that this simple program allows only a single binary semaphore per program, although we could extend it to pass the semaphore variable if we need more semaphores. Normally, a single binary semaphore is sufficient.

We can test our program by invoking it several times. The first time, we pass a parameter to tell the program that it's responsible for creating and deleting the semaphore. The other invocations have no parameter.

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Here's some sample output, with two invocations of the program:

```
$ ./sem1 1 &
[1] 1082
$ ./sem1
OOXXOOXXOOXXOOXXOOXXOOOOXXOOXXOOXXOOXXXX
1083 - finished
1082 - finished
$
```

As you can see, the os and xs are properly paired, indicating that the critical section is being correctly processed. If this doesn't work on your particular system, you may have to use the command `stty -tostop` before invoking the program to ensure that the background program generating `tty` output does not cause a signal to be generated.

How It Works

The program starts by obtaining a semaphore identity from the (arbitrary) key that we've chosen using the `semget` function. The `IPC_CREAT` flag causes the semaphore to be created if one is required.

If the program has a parameter, it's responsible for initializing the semaphore, which it does with our function `set_semvalue`, a simplified interface to the more general `semctl` function. It also uses the presence of the parameter to determine which character it should print out. The `sleep` simply allows us some time to invoke other copies of the program before this copy gets to execute too many times around its loop. We use `srand` and `rand` to introduce some pseudo-random timing into the program.

The program then loops 10 times, with pseudo-random waits in its critical and noncritical sections. The critical section is guarded by calls to our `semaphore_p` and `semaphore_v` functions, which are simplified interfaces to the more general `semop` function.

Before it deletes the semaphore, the program that was invoked with a parameter then waits to allow other invocations to complete. If the semaphore isn't deleted, it will continue to exist in the system even though no programs are using it. In real programs, it's very important to ensure you don't unintentionally leave semaphores around after execution. It may cause problems next time you run the program, and semaphores are a limited resource that you must conserve.

Shared Memory

Shared memory is the second of the three IPC facilities. It allows two unrelated processes to access the same logical memory. Shared memory is a very efficient way of transferring data between two running processes. Although the X/Open standard doesn't require it, it's probable that most implementations of shared memory arrange for the memory being shared between different processes to be the same physical memory.

Shared memory provides an efficient way of sharing and passing data between multiple processes. Since it provides no synchronization facilities, we usually need to use some other mechanism to synchronize access to the shared memory. Typically, we might use shared memory to provide efficient access to large areas of memory and pass small messages to synchronize access to that memory.

Semaphores, Shared Memory, and Message Queues

Shared memory is a special range of addresses that is created by IPC for one process and appears in the address space of that process. Other processes can then “attach” the same shared memory segment into their own address space. All processes can access the memory locations just as if the memory had been allocated by `malloc`. If one process writes to the shared memory, the changes immediately become visible to any other process that has access to the same shared memory.

By itself, shared memory doesn’t provide any synchronization facilities. There are no automatic facilities to prevent a second process from starting to read the shared memory before the first process has finished writing to it. It’s the responsibility of the programmer to synchronize access. Figure 14-2 shows an illustration of how shared memory works.

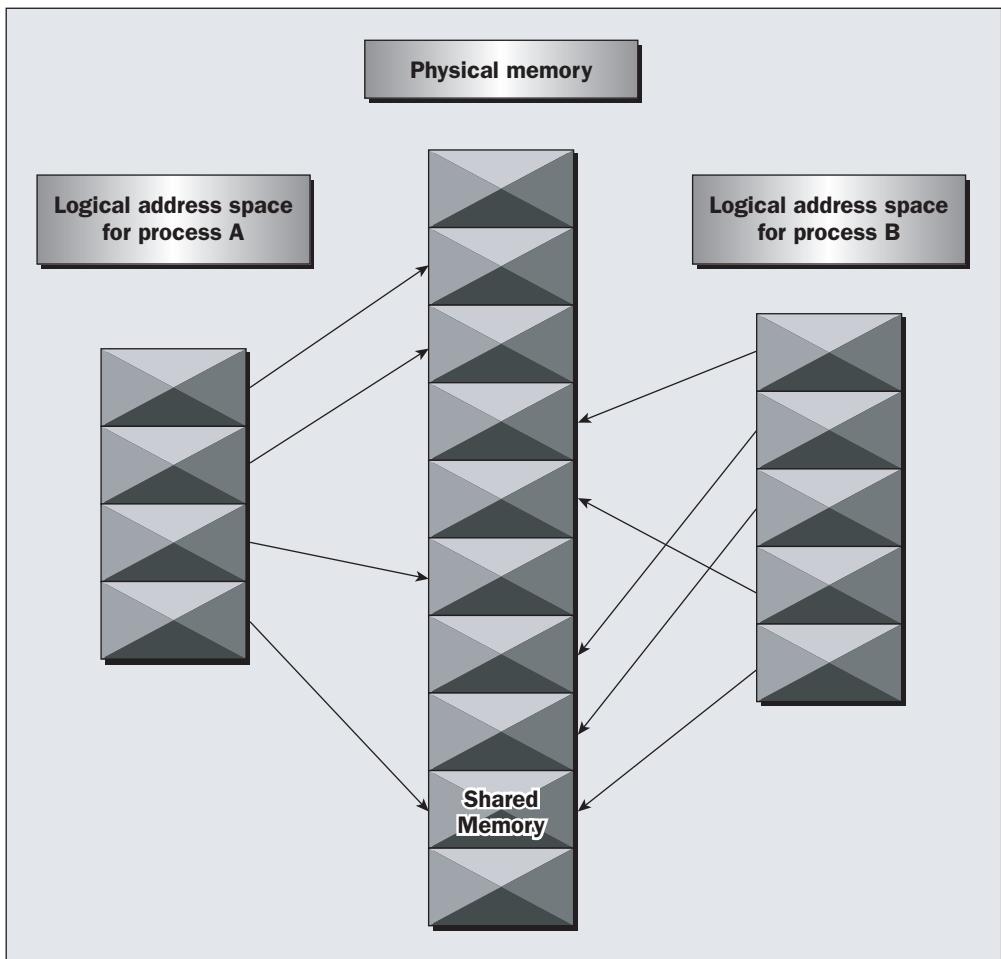


Figure 14-2

The arrows show the mapping of the logical address space of each process to the physical memory available. In practice, the situation is more complex because the available memory actually consists of a mix of physical memory and memory pages that have been swapped out to disk.

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The functions for shared memory resemble those for semaphores:

```
#include <sys/shm.h>

void *shmat(int shm_id, const void *shm_addr, int shmflg);
int shmctl(int shm_id, int cmd, struct shmid_ds *buf);
int shmdt(const void *shm_addr);
int shmget(key_t key, size_t size, int shmflg);
```

As with semaphores, the include files `sys/types.h` and `sys/ipc.h` are normally also required before `shm.h` is included.

shmget

We create shared memory using the `shmget` function:

```
int shmget(key_t key, size_t size, int shmflg);
```

As with semaphores, the program provides `key`, which effectively names the shared memory segment, and the `shmget` function returns a shared memory identifier that is used in subsequent shared memory functions. There's a special key value, `IPC_PRIVATE`, that creates shared memory private to the process. You wouldn't normally use this value, and, as with semaphores, you may find the private shared memory is not actually private on many Linux systems.

The second parameter, `size`, specifies the amount of memory required in bytes.

The third parameter, `shmflg`, consists of nine permission flags that are used in the same way as the mode flags for creating files. A special bit defined by `IPC_CREAT` must be bitwise ORed with the permissions to create a new shared memory segment. It's not an error to have the `IPC_CREAT` flag set and pass the key of an existing shared memory segment. The `IPC_CREAT` flag is silently ignored if it is not required.

The permission flags are very useful with shared memory because they allow a process to create shared memory that can be written by processes owned by the creator of the shared memory but only read by processes that other users have created. We can use this to provide efficient read-only access to data by placing it in shared memory without the risk of its being changed by other users.

If the shared memory is successfully created, `shmget` returns a nonnegative integer, the shared memory identifier. On failure, it returns `-1`.

shmat

When we first create a shared memory segment, it's not accessible by any process. To enable access to the shared memory, we must attach it to the address space of a process. We do this with the `shmat` function:

```
void *shmat(int shm_id, const void *shm_addr, int shmflg);
```

The first parameter, `shm_id`, is the shared memory identifier returned from `shmget`.

The second parameter, `shm_addr`, is the address at which the shared memory is to be attached to the current process. This should almost always be a null pointer, which allows the system to choose the address at which the memory appears.

Semaphores, Shared Memory, and Message Queues

The third parameter, `shmflg`, is a set of bitwise flags. The two possible values are `SHM_RND`, which, in conjunction with `shm_addr`, controls the address at which the shared memory is attached, and `SHM_RDONLY`, which makes the attached memory read-only. It's very rare to need to control the address at which shared memory is attached; you should normally allow the system to choose an address for you, as doing otherwise will make the application highly hardware-dependent.

If the `shmat` call is successful, it returns a pointer to the first byte of shared memory. On failure `-1` is returned.

The shared memory will have read or write access depending on the owner (the creator of the shared memory), the permissions, and the owner of the current process. Permissions on shared memory are similar to the permissions on files.

An exception to this rule arises if `shmflg & SHM_RDONLY` is true. Then the shared memory won't be writable, even if permissions would have allowed write access.

`shmdt`

The `shmdt` function detaches the shared memory from the current process. It takes a pointer to the address returned by `shmat`. On success, it returns `0`, on error `-1`. Note that detaching the shared memory doesn't delete it; it just makes that memory unavailable to the current process.

`shmctl`

The control functions for shared memory are (thankfully) somewhat simpler than the more complex ones for semaphores:

```
int shmctl(int shm_id, int command, struct shmid_ds *buf);
```

The `shmid_ds` structure has at least the following members:

```
struct shmid_ds {  
    uid_t shm_perm.uid;  
    uid_t shm_perm.gid;  
    mode_t shm_perm.mode;  
}
```

The first parameter, `shm_id`, is the identifier returned from `shmget`.

The second parameter, `command`, is the action to take. It can take three values:

| Command | Description |
|-----------------------|--|
| <code>IPC_STAT</code> | Sets the data in the <code>shmid_ds</code> structure to reflect the values associated with the shared memory. |
| <code>IPC_SET</code> | Sets the values associated with the shared memory to those provided in the <code>shmid_ds</code> data structure, if the process has permission to do so. |
| <code>IPC_RMID</code> | Deletes the shared memory segment. |

The third parameter, `buf`, is a pointer to structure containing the modes and permissions for the shared memory.

On success, it returns 0, on failure, -1. X/Open doesn't specify what happens if you attempt to delete a shared memory segment while it's attached. Generally, a shared memory segment that is attached but deleted continues to function until it has been detached from the last process. However, because this behavior isn't specified, it's best not to rely on it.

Try It Out—Shared Memory

Now that we've seen the shared memory functions, we can write some code to use them. We'll write a pair of programs, `shm1.c` and `shm2.c`. The first (the consumer) will create a shared memory segment and then display any data that is written into it. The second (the producer) will attach to an existing shared memory segment and allow us to enter data into that segment.

1. First, we create a common header file to describe the shared memory we wish to pass around. We call this `shm_com.h`.

```
#define TEXT_SZ 2048

struct shared_use_st {
    int written_by_you;
    char some_text[TEXT_SZ];
};
```

This defines a structure to use in both the consumer and producer programs. We use an `int` flag `written_by_you` to tell the consumer when data has been written to the rest of the structure and arbitrarily decide that we need to transfer up to 2k of text.

2. Our first program is for a consumer. After the headers the shared memory segment (the size of our shared memory structure) is created with a call to `shmget`, with the `IPC_CREAT` bit specified:

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>

#include "shm_com.h"

int main()
{
    int running = 1;
    void *shared_memory = (void *)0;
    struct shared_use_st *shared_stuff;
    int shmid;

    srand((unsigned int) getpid());

    shmid = shmget((key_t)1234, sizeof(struct shared_use_st), 0666 | IPC_CREAT);
```

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```
if (shmid == -1) {
    fprintf(stderr, "shmget failed\n");
    exit(EXIT_FAILURE);
}
```

3. We now make the shared memory accessible to the program:

```
shared_memory = shmat(shmid, (void *)0, 0);
if (shared_memory == (void *)-1) {
    fprintf(stderr, "shmat failed\n");
    exit(EXIT_FAILURE);
}

printf("Memory attached at %X\n", (int)shared_memory);
```

4. The next portion of the program assigns the shared_memory segment to shared_stuff, which then prints out any text in written_by_you. The loop continues until end is found in written_by_you. The call to sleep forces the consumer to sit in its critical section, which makes the producer wait.

```
shared_stuff = (struct shared_use_st *)shared_memory;
shared_stuff->written_by_you = 0;
while(running) {
    if (shared_stuff->written_by_you) {
        printf("You wrote: %s", shared_stuff->some_text);
        sleep( rand() % 4 ); /* make the other process wait for us ! */
        shared_stuff->written_by_you = 0;
        if (strncmp(shared_stuff->some_text, "end", 3) == 0) {
            running = 0;
        }
    }
}
```

5. Finally, the shared memory is detached and then deleted:

```
if (shmrdt(shared_memory) == -1) {
    fprintf(stderr, "shmrdt failed\n");
    exit(EXIT_FAILURE);
}

if (shmctl(shmid, IPC_RMID, 0) == -1) {
    fprintf(stderr, "shmctl(IPC_RMID) failed\n");
    exit(EXIT_FAILURE);
}

exit(EXIT_SUCCESS);
}
```

6. Our second program, shm2.c, is the producer; it allows us to enter data for consumers. It's very similar to shm1.c and looks like this:

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

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```
#include <string.h>

#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>

#include "shm_com.h"

int main()
{
    int running = 1;
    void *shared_memory = (void *)0;
    struct shared_use_st *shared_stuff;
    char buffer[BUFSIZ];
    int shmid;

    shmid = shmget((key_t)1234, sizeof(struct shared_use_st), 0666 | IPC_CREAT);

    if (shmid == -1) {
        fprintf(stderr, "shmget failed\n");
        exit(EXIT_FAILURE);
    }
    shared_memory = shmat(shmid, (void *)0, 0);
    if (shared_memory == (void *)-1) {
        fprintf(stderr, "shmat failed\n");
        exit(EXIT_FAILURE);
    }

    printf("Memory attached at %X\n", (int)shared_memory);

    shared_stuff = (struct shared_use_st *)shared_memory;
    while(running) {
        while(shared_stuff->written_by_you == 1) {
            sleep(1);
            printf("waiting for client...\n");
        }
        printf("Enter some text: ");
        fgets(buffer, BUFSIZ, stdin);

        strncpy(shared_stuff->some_text, buffer, TEXT_SZ);
        shared_stuff->written_by_you = 1;

        if (strcmp(buffer, "end", 3) == 0) {
            running = 0;
        }
    }

    if (shmctl(shared_memory) == -1) {
        fprintf(stderr, "shmctl failed\n");
        exit(EXIT_FAILURE);
    }
    exit(EXIT_SUCCESS);
}
```

When we run these programs, we get sample output such as this:

```
$ ./shm1 &
[1] 294
Memory attached at 40017000
$ ./shm2
Memory attached at 40017000
Enter some text: hello
You wrote: hello
waiting for client...
waiting for client...
Enter some text: Linux!
You wrote: Linux!
waiting for client...
waiting for client...
waiting for client...
Enter some text: end
You wrote: end
$
```

How It Works

The first program, `shm1`, creates the shared memory segment and then attaches it to its address space. We impose a structure, `shared_use_st` on the first part of the shared memory. This has a flag, `written_by_you`, that is set when data is available. When this flag is set, the program reads the text, prints it out, and clears the flag to show it has read the data. We use the special string, `end`, to allow a clean exit from the loop. The program then detaches the shared memory segment and deletes it.

The second program, `shm2`, gets and attaches the same shared memory segment, since it uses the same key, 1234. It then prompts the user to enter some text. If the flag `written_by_you` is set, `shm2` knows that the client process hasn't yet read the previous data and waits for it. When the other process clears this flag, `shm2` writes the new data and sets the flag. It also uses the magic string `end` to terminate and detach the shared memory segment.

Notice that we had to provide our own, rather crude synchronization flag, `written_by_you`, which involves a very inefficient busy wait (by continuously looping). In real programs we would have passed a message, either using a pipe or IPC messages (which we'll discuss shortly), generated a signal, or used a semaphore to provide synchronization between the reading and writing parts of the application.

Message Queues

We'll now take a look at the third and final System V IPC facility: *message queues*. In many ways, message queues are like named pipes, but without the complexity associated with opening and closing the pipe. However, using messages doesn't get us away from the problems that we have with named pipes, such as blocking on full pipes.

Message queues provide a reasonably easy and efficient way of passing data between two unrelated processes. They have the advantage over named pipes that the message queue exists independently of both the sending and receiving processes, which removes some of the difficulties that occur in synchronizing the opening and closing of named pipes.

Message queues provide a way of sending a block of data from one process to another. Additionally, each block of data is considered to have a type, and a receiving process may receive blocks of data having different type values independently. The good news is that we can almost totally avoid the synchronization and blocking problems of named pipes by sending messages. Even better, we can “look ahead” for messages that are urgent in some way. The bad news is that, just like pipes, there’s a maximum size limit imposed on each block of data and also a limit on the maximum total size of all blocks on all queues throughout the system.

While stating that these limits are imposed, the X/Open specification offers no way of discovering what the limits are, except that exceeding them is a valid reason for some message queue functions to fail. Linux does have two defines, `MSGMAX` and `MSGMNB`, which define the maximum size in bytes of an individual message and the maximum size of a queue, respectively. These macros may be different or, for that matter, not even present on other systems.

The message queue function definitions are

```
#include <sys/msg.h>

int msgctl(int msqid, int cmd, struct msqid_ds *buf);
int msgget(key_t key, int msgflg);
int msgrcv(int msqid, void *msg_ptr, size_t msg_sz, long int msgtype, int msgflg);
int msgsnd(int msqid, const void *msg_ptr, size_t msg_sz, int msgflg);
```

As with semaphores and shared memory, the include files `sys/types.h` and `sys/ipc.h` are normally also required.

msgget

We create and access a message queue using the `msgget` function:

```
int msgget(key_t key, int msgflg);
```

The program must provide a `key` value that, as with other IPC facilities, names a particular message queue. The special value `IPC_PRIVATE` creates a private queue, which in theory is accessible only by the current process. As with semaphores and messages, on some Linux systems the message queue may not actually be private. Since a private queue has very little purpose, that’s not a significant problem. As before, the second parameter, `msgflg`, consists of nine permission flags. A special bit defined by `IPC_CREAT` must be bitwise ORed with the permissions to create a new message queue. It’s not an error to set the `IPC_CREAT` flag and give the key of an existing message queue. The `IPC_CREAT` flag is silently ignored if the message queue already exists.

The `msgget` function returns a positive number, the queue identifier, on success or `-1` on failure.

msgsnd

The `msgsnd` function allows us to add a message to a message queue:

```
int msgsnd(int msqid, const void *msg_ptr, size_t msg_sz, int msgflg);
```

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The structure of the message is constrained in two ways. First, it must be smaller than the system limit, and second, it must start with a `long int`, which will be used as a message type in the receive function. When you're using messages, it's best to define your message structure something like this:

```
struct my_message {
    long int message_type;
    /* The data you wish to transfer */
}
```

Since the `message_type` is used in message reception, you can't simply ignore it. You must declare your data structure to include it, and it's also wise to initialize it, so that it contains a known value.

The first parameter, `msqid`, is the message queue identifier returned from a `msgget` function.

The second parameter, `msg_ptr`, is a pointer to the message to be sent, which must start with a `long int` type as described previously.

The third parameter, `msg_sz`, is the size of the message pointed to by `msg_ptr`. This size must not include the `long int` message type.

The fourth parameter, `msgflg`, controls what happens if either the current message queue is full or the systemwide limit on queued messages has been reached. If `msgflg` has the `IPC_NOWAIT` flag set, the function will return immediately without sending the message and the return value will be `-1`. If the `msgflg` has the `IPC_NOWAIT` flag clear, the sending process will be suspended, waiting for space to become available in the queue.

On success, the function returns `0`, on failure `-1`. If the call is successful, a copy of the message data has been taken and placed on the message queue.

msgrcv

The `msgrcv` function retrieves messages from a message queue:

```
int msgrcv(int msqid, void *msg_ptr, size_t msg_sz, long int msgtype, int msgflg);
```

The first parameter, `msqid`, is the message queue identifier returned from a `msgget` function.

The second parameter, `msg_ptr`, is a pointer to the message to be received, which must start with a `long int` type as described above in the `msgsnd` function.

The third parameter, `msg_sz`, is the size of the message pointed to by `msg_ptr`, not including the `long int` message type.

The fourth parameter, `msgtype`, is a `long int`, which allows a simple form of reception priority to be implemented. If `msgtype` has the value `0`, the first available message in the queue is retrieved. If it's greater than zero, the first message with the same message type is retrieved. If it's less than zero, the first message that has a type the same as or less than the absolute value of `msgtype` is retrieved.

This sounds more complicated than it actually is in practice. If you simply want to retrieve messages in the order in which they were sent, set `msgtype` to `0`. If you want to retrieve only messages with a specific

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message type, set `msgtype` equal to that value. If you want to receive messages with a type of `n` or smaller, set `msgtype` to `-n`.

The fifth parameter, `msgflg`, controls what happens when no message of the appropriate type is waiting to be received. If the `IPC_NOWAIT` flag in `msgflg` is set, the call will return immediately with a return value of `-1`. If the `IPC_NOWAIT` flag of `msgflg` is clear, the process will be suspended, waiting for an appropriate type of message to arrive.

On success, `msgrecv` returns the number of bytes placed in the receive buffer, the message is copied into the user-allocated buffer pointed to by `msg_ptr`, and the data is deleted from the message queue. It returns `-1` on error.

msgctl

The final message queue function is `msgctl`, which is very similar to that of the control function for shared memory.

```
int msgctl(int msqid, int command, struct msqid_ds *buf);
```

The `msqid_ds` structure has at least the following members:

```
struct msqid_ds {  
    uid_t msg_perm.uid;  
    uid_t msg_perm.gid  
    mode_t msg_perm.mode;  
}
```

The first parameter, `msqid`, is the identifier returned from `msgget`.

The second parameter, `command`, is the action to take. It can take three values:

| Command | Description |
|-----------------------|---|
| <code>IPC_STAT</code> | Sets the data in the <code>msqid_ds</code> structure to reflect the values associated with the message queue. |
| <code>IPC_SET</code> | If the process has permission to do so, this sets the values associated with the message queue to those provided in the <code>msqid_ds</code> data structure. |
| <code>IPC_RMID</code> | Deletes the message queue. |

`0` is returned on success, `-1` on failure. If a message queue is deleted while a process is waiting in a `msgsnd` or `msgrecv` function, the send or receive function will fail.

Try It Out—Message Queues

Now that we've seen the definitions for message queues, we can see how they work in practice. As before, we'll write two programs: `msg1.c` to receive and `msg2.c` to send. We'll allow either program to create the message queue, but use the receiver to delete it after it receives the last message.

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1. Here's the receiver program:

```
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <errno.h>
#include <unistd.h>

#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

struct my_msg_st {
    long int my_msg_type;
    char some_text[BUFSIZ];
};

int main()
{
    int running = 1;
    int msgid;
    struct my_msg_st some_data;
    long int msg_to_receive = 0;
```

2. First, we set up the message queue:

```
msgid = msgget((key_t)1234, 0666 | IPC_CREAT);

if (msgid == -1) {
    fprintf(stderr, "msgget failed with error: %d\n", errno);
    exit(EXIT_FAILURE);
}
```

3. Then the messages are retrieved from the queue until an end message is encountered. Finally, the message queue is deleted:

```
while(running) {
    if (msgrecv(msgid, (void *)&some_data, BUFSIZ,
                msg_to_receive, 0) == -1) {
        fprintf(stderr, "msgrecv failed with error: %d\n", errno);
        exit(EXIT_FAILURE);
    }
    printf("You wrote: %s", some_data.some_text);
    if (strcmp(some_data.some_text, "end", 3) == 0) {
        running = 0;
    }
}

if (msgctl(msgid, IPC_RMID, 0) == -1) {
    fprintf(stderr, "msgctl(IPC_RMID) failed\n");
    exit(EXIT_FAILURE);
}

exit(EXIT_SUCCESS);
}
```

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4. The sender program is very similar to msg1.c. In the main setup, delete the msg_to_receive declaration, and replace it with buffer [BUFSIZ]. Remove the message queue delete, and make the following changes to the running loop. We now have a call to msgsnd to send the entered text to the queue.

```
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <errno.h>
#include <unistd.h>

#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

#define MAX_TEXT 512

struct my_msg_st {
    long int my_msg_type;
    char some_text[MAX_TEXT];
};

int main()
{
    int running = 1;
    struct my_msg_st some_data;
    int msgid;
    char buffer[BUFSIZ];

    msgid = msgget((key_t)1234, 0666 | IPC_CREAT);

    if (msgid == -1) {
        fprintf(stderr, "msgget failed with error: %d\n", errno);
        exit(EXIT_FAILURE);
    }

    while(running) {
        printf("Enter some text: ");
        fgets(buffer, BUFSIZ, stdin);
        some_data.my_msg_type = 1;
        strcpy(some_data.some_text, buffer);

        if (msgsnd(msgid, (void *)&some_data, MAX_TEXT, 0) == -1) {
            fprintf(stderr, "msgsnd failed\n");
            exit(EXIT_FAILURE);
        }
        if (strncmp(buffer, "end", 3) == 0) {
            running = 0;
        }
    }

    exit(EXIT_SUCCESS);
}
```

Unlike in the pipes example, there's no need for the processes to provide their own synchronization method. This is a significant advantage of messages over pipes.

Providing there's room in the message queue, the sender can create the queue, put some data into the queue, and then exit before the receiver even starts. We'll run the sender, `msg2`, first. Here's some sample output:

```
$ ./msg2
Enter some text: hello
Enter some text: How are you today?
Enter some text: end
$ ./msg1
You wrote: hello
You wrote: How are you today?
You wrote: end
$
```

How It Works

The sender program creates a message queue with `msgget`; then it adds messages to the queue with `msgsnd`. The receiver obtains the message queue identifier with `msgget` and then receives messages until the special text `end` is received. It then tidies up by deleting the message queue with `msgctl`.

The CD Database Application

We're now in a position to modify our CD database application to use the IPC facilities that we've seen in this chapter.

We could use many different combinations of the three IPC facilities, but because the information we need to pass is quite small, it's sensible to implement the passing of requests and responses directly using message queues.

If the amounts of data that we needed to pass were large, we could have considered passing the actual data in shared memory and using either semaphores or messages to pass a "token" to inform the other process that data was available in shared memory.

The message queue interface removes the problem that we had in Chapter 11, where we needed both processes to have the pipe open while data was passed. Using message queues allows one process to put messages in the queue, even if that process is currently the only user of the queue.

The only significant decision we need to make is how to return answers to clients. A simple choice would be to have one queue for the server and one queue for each client. If there were a large number of simultaneous clients, this could cause problems by requiring a large number of message queues. By using the message ID field in the message, we can allow all the clients to use a single queue and "address" response messages to particular client processes by using the client process ID in the message. Each client can then retrieve messages addressed only to itself, leaving messages for other clients in the queue.

To convert our CD application to use IPC facilities, we need to replace only the file `pipe_imp.c` from the code accompanying Chapter 13. In the following pages, we'll describe the principal sections of the replacement file, `ipc_imp.c`.

Try It Out—Revising the Server Functions

- First, we include the appropriate headers, declare some message queue keys, and define a structure to hold our message data:

```
#include "cd_data.h"
#include "cliserv.h"

#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

#define SERVER_MQUEUE 1234
#define CLIENT_MQUEUE 4321

struct msg_passed {
    long int msg_key; /* used for client pid */
    message_db_t real_message;
};
```

- Two variables with file scope hold the two queue identifiers returned from the `msgget` function:

```
static int serv_qid = -1;
static int cli_qid = -1;
```

- We make the server responsible for creating both message queues:

```
int server_starting()
{
    #if DEBUG_TRACE
        printf("%d :- server_starting()\n", getpid());
    #endif

    serv_qid = msgget((key_t)SERVER_MQUEUE, 0666 | IPC_CREAT);
    if (serv_qid == -1) return(0);

    cli_qid = msgget((key_t)CLIENT_MQUEUE, 0666 | IPC_CREAT);
    if (cli_qid == -1) return(0);

    return(1);
}
```

- The server is also responsible for tidying up if it ever exits. When the server ends, we set our file-scope variables to illegal values. This will catch any bugs if the server attempts to send messages after it has called `server_ending`.

```
void server_ending()
{
    #if DEBUG_TRACE
        printf("%d :- server_ending()\n", getpid());
    #endif

    (void)msgctl(serv_qid, IPC_RMID, 0);
    (void)msgctl(cli_qid, IPC_RMID, 0);
```

```
    serv_qid = -1;
    cli_qid = -1;
}
```

5. The server read function reads a message of any type (that is, from any client) from the queue, and it returns the data part (ignoring the type) of the message.

```
int read_request_from_client(message_db_t *rec_ptr)
{
    struct msg_passed my_msg;
#ifdef DEBUG_TRACE
    printf("%d :- read_request_from_client()\n", getpid());
#endif

    if (msgrecv(serv_qid, (void *)&my_msg, sizeof(*rec_ptr), 0, 0) == -1) {
        return(0);
    }
    *rec_ptr = my_msg.real_message;
    return(1);
}
```

6. Sending a response uses the client process ID that was stored in the request to address the message:

```
int send_resp_to_client(const message_db_t mess_to_send)
{
    struct msg_passed my_msg;
#ifdef DEBUG_TRACE
    printf("%d :- send_resp_to_client()\n", getpid());
#endif

    my_msg.real_message = mess_to_send;
    my_msg.msg_key = mess_to_send.client_pid;

    if (msgsnd(cli_qid, (void *)&my_msg, sizeof(mess_to_send), 0) == -1) {
        return(0);
    }
    return(1);
}
```

Try It Out—Revising the Client Functions

1. When the client starts, it needs to find the server and client queue identifiers. The client doesn't create the queues. This function will fail if the server isn't running, as the message queues won't exist.

```
int client_starting()
{
#ifdef DEBUG_TRACE
    printf("%d :- client_starting\n", getpid());
#endif

    serv_qid = msgget((key_t)SERVER_MQUEUE, 0666);
    if (serv_qid == -1) return(0);
```

```
    cli_qid = msgget((key_t)CLIENT_MQUEUE, 0666);
    if (cli_qid == -1) return(0);
    return(1);
}
```

2. As with the server, when the client ends, we set our file-scope variables to illegal values. This will catch any bugs where the client attempts to send messages after it has called `client_ending`.

```
void client_ending()
{
    #if DEBUG_TRACE
        printf("%d :- client_ending()\n", getpid());
    #endif

    serv_qid = -1;
    cli_qid = -1;
}
```

3. To send a message to the server, we store the data inside our structure. Notice that we must set the message key. As 0 is an illegal value for the key, leaving the key undefined would mean that it takes an (apparently) random value, so this function could occasionally fail if the value happens to be 0.

```
int send_mess_to_server(message_db_t mess_to_send)
{
    struct msg_packed my_msg;
    #if DEBUG_TRACE
        printf("%d :- send_mess_to_server()\n", getpid());
    #endif

    my_msg.real_message = mess_to_send;
    my_msg.msg_key = mess_to_send.client_pid;

    if (msgsnd(serv_qid, (void *)&my_msg, sizeof(mess_to_send), 0) == -1) {
        perror("Message send failed");
        return(0);
    }
    return(1);
}
```

4. When the client retrieves a message from the server, it uses its process ID to receive only messages addressed to itself, ignoring any messages for other clients.

```
int read_resp_from_server(message_db_t *rec_ptr)
{
    struct msg_packed my_msg;
    #if DEBUG_TRACE
        printf("%d :- read_resp_from_server()\n", getpid());
    #endif

    if (msggrcv(cli_qid, (void *)&my_msg, sizeof(*rec_ptr), getpid(), 0) == -1) {
        return(0);
    }
```

```
    *rec_ptr = my_msg.real_message;
    return(1);
}
```

5. To retain complete compatibility with `pipe_imp.c`, we need to define an extra four functions. In our new program, however, the functions are empty. The operations they implemented when using pipes are simply not needed anymore.

```
int start_resp_to_client(const message_db_t mess_to_send)
{
    return(1);
}

void end_resp_to_client(void)
{
}

int start_resp_from_server(void)
{
    return(1);
}

void end_resp_from_server(void)
{
}
```

The conversion of the application to message queues illustrates the power of IPC message queues. We require fewer functions, and even those we do need are much smaller than they were previously.

IPC Status Commands

Although they're not required for X/Open compliance, most Linux systems provide a set of commands that allow command line access to IPC information, and to tidy up stray IPC facilities. These are the `ipcs` and `ipcrm` commands, which are very useful when you're developing programs.

One of the irritations of the IPC facilities is that a poorly written program, or a program that fails for some reason, can leave its IPC resources (such as data in a message queue) loitering on the system long after the program completes. This can cause a new invocation of the program to fail, because the program expects to start with a clean system, but actually finds some leftover resource. The status (`ipcs`) and remove (`ipcrm`) commands provide a way of checking and tidying up IPC facilities.

Semaphores

To examine the state of semaphores on the system, use the `ipcs -s` command. If any semaphores are present, the output will have this form:

```
$ ./ipcs -s
----- Semaphore Arrays -----
semid      owner      perms      nsems      status
768        rick       666         1
```

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You can use the `ipcrm` command to remove any semaphores accidentally left by programs. To delete the preceding semaphore, the command (on Linux) is

```
$ ./ipcrm -s 768
```

Some older Linux systems used to use a slightly different syntax:

```
$ ./ipcrm sem 768
```

but that style is now deprecated. Check the manual pages for your system to see which format is valid on your particular system.

Shared Memory

Like semaphores, many systems provide command line programs for accessing the details of shared memory. These are `ipcs -m` and `ipcrm -m <id>` (or `ipcrm shm <id>`).

Here's some sample output from `ipcs -m`:

```
$ ipcs -m
----- Shared Memory Segments -----
shmid     owner      perms      bytes      nattch      status
 384       rick       666        4096          2
```

This shows a single shared memory segment of 4 kB attached by two processes.

The `ipcrm -m <id>` command allows shared memory to be removed. This is sometimes useful when a program has failed to tidy up shared memory.

Message Queues

For message queues the commands are `ipcs -q` and `ipcrm -q <id>` (or `ipcrm msg <id>`).

Here's some sample output from `ipcs -q`:

```
$ ipcs -q
----- Message Queues -----
msqid     owner      perms      used-bytes   messages
 384       rick       666        2048          2
```

This shows two messages, with a total size of 2,048 bytes in a message queue.

The `ipcrm -q <id>` command allows a message queue to be removed.

Summary

In this chapter, we've looked at the three inter-process communication facilities that first became widely available in UNIX System V.2 and have been available in Linux from the early versions. These facilities are semaphores, shared memory, and message queues. We've seen the sophisticated functionality that they offer and how, once these functions are understood, they offer a powerful solution to many inter-process communication requirements.

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Sockets

In this chapter, we'll look at yet another method of process communication, but one with a crucial difference from those we've discussed in Chapters 13 and 14. Until now, all the facilities we've discussed have relied on shared resources on a single computer system. The resource varies; it can be file system space, shared physical memory, or message queues, but only processes running on a single machine can use them.

The Berkeley versions of UNIX introduced a new communication tool, the *socket interface*, which is an extension of the concept of a pipe, which we covered in Chapter 13. Socket interfaces are available on Linux. You can use sockets in much the same way as pipes, but they include communication across a network of computers. A process on one machine can use sockets to communicate with a process on another, which allows for client/server systems that are distributed across a network. Sockets may also be used between processes on the same machine.

Also, the sockets interface has been made available for Windows via a publicly available specification called *Windows Sockets*, or *WinSock*. Windows socket services are provided by a *Winsock.dll* system file. Thus, Windows programs can communicate across a network to Linux and UNIX computers and vice versa providing client/server systems. Although the programming interface for WinSock isn't quite the same as UNIX sockets, it still has sockets as its basis.

We can't cover the extensive Linux networking capabilities in a single chapter, so you'll find here a description of the principal programmatic networking interfaces. These should allow you to write your own network programs. Specifically, we'll look at the following:

- ❑ How a socket connection operates
- ❑ Socket attributes, addresses, and communications
- ❑ Network information and the Internet daemon (*inetd*)
- ❑ Clients and servers

What Is a Socket?

A *socket* is a communication mechanism that allows client/server systems to be developed either locally, on a single machine, or across networks. Linux functions such as printing and network utilities such as `rlogin` and `ftp` usually use sockets to communicate.

Sockets are created and used differently from pipes because they make a clear distinction between client and server. The socket mechanism can implement multiple clients attached to a single server.

Socket Connections

You can think of socket connections as telephone calls into a busy building. A call comes into an organization and is answered by a receptionist who puts the call through to the correct department (the server process) and from there to the right person (the server socket). Each incoming call (client) is routed to an appropriate end point and the intervening operators are free to deal with further calls. Before you look at the way socket connections are established in Linux systems, you need to understand how they operate for socket applications that maintain a connection.

First of all, a server application creates a socket, which like a file descriptor is a resource assigned to the server process and that process alone. The server creates it using the system call `socket`, and it can't be shared with other processes.

Next, the server process gives the socket a name. Local sockets are given a filename in the Linux file system, often to be found in `/tmp` or `/usr/tmp`. For network sockets, the filename will be a service identifier (port number/access point) relevant to the particular network to which the clients can connect. This identifier allows Linux to route incoming connections specifying a particular port number to the correct server process. A socket is named using the system call `bind`. The server process then waits for a client to connect to the named socket. The system call, `listen`, creates a queue for incoming connections. The server can accept them using the system call `accept`.

When the server calls `accept`, a new socket is created that is distinct from the named socket. This new socket is used solely for communication with this particular client. The named socket remains for further connections from other clients. If the server is written appropriately, it can take advantage of multiple connections. For a simple server, further clients wait on the `listen` queue until the server is ready again.

The client side of a socket-based system is more straightforward. The client creates an unnamed socket by calling `socket`. It then calls `connect` to establish a connection with the server by using the server's named socket as an address.

Once established, sockets can be used like low-level file descriptors, providing two-way data communications.

Try It Out—A Simple Local Client

Here's an example of a very simple socket client program, `client1.c`. It creates an unnamed socket and connects it to a server socket called `server_socket`. We'll cover the details of the `socket` system call a little later, after we've discussed some addressing issues.

1. Make the necessary includes and set up the variables.

```
#include <sys/types.h>
#include <sys/socket.h>
#include <stdio.h>
#include <sys/un.h>
#include <unistd.h>

int main()
{
    int sockfd;
    int len;
    struct sockaddr_un address;
    int result;
    char ch = 'A';
```

2. Create a socket for the client.

```
sockfd = socket(AF_UNIX, SOCK_STREAM, 0);
```

3. Name the socket as agreed with the server.

```
address.sun_family = AF_UNIX;
strcpy(address.sun_path, "server_socket");
len = sizeof(address);
```

4. Connect our socket to the server's socket.

```
result = connect(sockfd, (struct sockaddr *)&address, len);

if(result == -1) {
    perror("oops: client1");
    exit(1);
}
```

5. You can now read and write via sockfd.

```
write(sockfd, &ch, 1);
read(sockfd, &ch, 1);
printf("char from server = %c\n", ch);
close(sockfd);
exit(0);
}
```

This program fails when you run it because you haven't yet created the server-side named socket. (The exact error message may differ from system to system.)

```
$ ./client1
oops: client1: Connection refused
$
```

Try It Out—A Simple Local Server

Here's a very simple server program, `server1.c`, that accepts connections from our client. It creates the server socket, binds it to a name, creates a listen queue, and accepts connections.

1. Make the necessary `includes` and set up the variables.

```
#include <sys/types.h>
#include <sys/socket.h>
#include <stdio.h>
#include <sys/un.h>
#include <unistd.h>

int main()
{
    int server_sockfd, client_sockfd;
    int server_len, client_len;
    struct sockaddr_un server_address;
    struct sockaddr_un client_address;
```

2. Remove any old sockets and create an unnamed socket for the server.

```
unlink("server_socket");
server_sockfd = socket(AF_UNIX, SOCK_STREAM, 0);
```

3. Name the socket.

```
server_address.sun_family = AF_UNIX;
strcpy(server_address.sun_path, "server_socket");
server_len = sizeof(server_address);
bind(server_sockfd, (struct sockaddr *)&server_address, server_len);
```

4. Create a connection queue and wait for clients.

```
listen(server_sockfd, 5);
while(1) {
    char ch;

    printf("server waiting\n");
```

5. Accept a connection.

```
client_len = sizeof(client_address);
client_sockfd = accept(server_sockfd,
    (struct sockaddr *)&client_address, &client_len);
```

6. Read and write to client on `client_sockfd`.

```
read(client_sockfd, &ch, 1);
ch++;
write(client_sockfd, &ch, 1);
close(client_sockfd);
}
```

The server program in this example can serve only one client at a time. It just reads a character from the client, increments it, and writes it back. In more sophisticated systems, where the server has to perform more work on the client's behalf, this wouldn't be acceptable, as other clients would be unable to connect until the server had finished. You'll see a couple of ways to allow multiple connections later.

When you run the server program, it creates a socket and waits for connections. If you start it in the background so that it runs independently, you can then start clients in the foreground.

```
$ server1 &
[1] 1094
$ server waiting
```

As it waits for connections, the server prints a message. In the preceding example, the server waits for a file system socket and you can see it with the normal `ls` command.

Remember that it's polite to remove a socket when you've finished with it, even if the program terminates abnormally via a signal.

```
$ ls -lF server_socket
srwxr-xr-x    1 neil      users            0 2003-06-21 13:42 server_socket=
```

The device type is "socket," shown by the `s` at the front of the permission and the `=` at the end. The socket has been created just as an ordinary file would be, with permissions modified by the current `umask`. If you use the `ps` command, you can see the server running in the background. It's shown sleeping (`STAT` is `S`) and is therefore not consuming CPU resources.

```
$ ps lx
F   UID   PID   PPID PRI NI   VSZ   RSS WCHAN STAT TTY          TIME COMMAND
0   500  3165  2154  15   0 1344   280 schedu S   pts/1        0:00 ./server1
```

Now, when you run the client program, you are successful in connecting to the server. Since the server socket exists, you can connect to it and communicate with the server.

```
$ ./client1
server waiting
char from server = B
$
```

The output from the server and the client get mixed on our terminal, but you can see that the server has received a character from the client, incremented it, and returned it. The server then continues and waits for the next client. If you run several clients together, they will be served in sequence, although the output you see may be more mixed up.

```
$ ./client1 & ./client1 & ./client1 &
[2] 1106
[3] 1107
[4] 1108
server waiting
char from server = B
server waiting
char from server = B
server waiting
```

```
char from server = B
server waiting
[2] Done client1
[3] - Done client1
[4] + Done client1
$
```

Socket Attributes

To fully understand the system calls used in this example, you need to learn a little about UNIX networking.

Sockets are characterized by three attributes: *domain*, *type*, and *protocol*. They also have an address used as their name. The formats of the addresses vary depending on the domain, also known as the *protocol family*. Each protocol family can use one or more address families to define the address format.

Socket Domains

Domains specify the network medium that the socket communication will use. The most common socket domain is AF_INET, which refers to Internet networking that's used on many Linux local area networks and, of course, the Internet itself. The underlying protocol, *Internet Protocol* (IP), which only has one address family, imposes a particular way of specifying computers on a network. This is called the *IP address*.

Although names almost always refer to networked machines on the Internet, these are translated into lower-level IP addresses. An example IP address is 192.168.1.99. All IP addresses are represented by four numbers, each less than 256, a so-called *dotted quad*. When a client connects across a network via sockets, it needs the IP address of the server computer.

There may be several services available at the server computer. A client can address a particular service on a networked machine by using an IP port. A port is identified within the system by assigning a unique 16-bit integer and externally by the combination of IP address and port number. The sockets are communication end points that must be bound to ports before communication is possible.

Servers wait for connections on particular ports. Well-known services have allocated port numbers that are used by all Linux and UNIX machines. These are usually, but not always, numbers less than 1024. Examples are the printer spooler (515), rlogin (513), ftp (21), and httpd (80). The last of these is the server for the World Wide Web (WWW). Usually, port numbers less than 1024 are reserved for system services and may only be served by processes with superuser privileges. X/Open defines a constant in netdb.h, IPPORT_RESERVED, to stand for the highest reserved port number.

Because there is a standard set of port numbers for standard services, computers can easily connect to each other without having to establish the correct port. Local services may use nonstandard port addresses. The domain in our first example is the UNIX file system domain, AF_UNIX, which can be used by sockets based on a single computer that perhaps isn't networked. When this is so, the underlying protocol is file input/output and the addresses are absolute filenames. The address that you used for the server socket was server_socket, which you saw appear in the current directory when you ran the server application.

Other domains that might be used include AF_ISO for networks based on ISO standard protocols and AF_XNS for the Xerox Network System. We won't cover these here.

Socket Types

A socket domain may have a number of different ways of communicating, each of which might have different characteristics. This isn't an issue with AF_UNIX domain sockets, which provide a reliable two-way communication path. In networked domains, however, you need to be aware of the characteristics of the underlying network.

Internet protocols provide two distinct levels of service: *streams* and *datagrams*.

Stream Sockets

Stream sockets (in some ways similar to standard input/output streams) provide a connection that is a sequenced and reliable two-way byte stream. Thus, data sent is guaranteed not to be lost, duplicated, or reordered without an indication that an error has occurred. Large messages are fragmented, transmitted, and reassembled. This is like a file stream, as it accepts large amounts of data and writes it to the low-level disk in smaller blocks. Stream sockets have predictable behavior.

Stream sockets, specified by the type SOCK_STREAM, are implemented in the AF_INET domain by TCP/IP connections. They are also the usual type in the AF_UNIX domain. We'll concentrate on SOCK_STREAM sockets in this chapter because they are more commonly used in programming network applications.

TCP/IP stands for Transmission Control Protocol/Internet Protocol. IP is the low-level protocol for packets that provides routing through the network from one computer to another. TCP provides sequencing, flow control, and retransmission to ensure that large data transfers arrive with all of the data present and correct or with an appropriate error condition reported.

Datagram Sockets

In contrast, a datagram socket, specified by the type SOCK_DGRAM, doesn't establish and maintain a connection. There is also a limit on the size of a datagram that can be sent. It's transmitted as a single network message that may get lost, duplicated, or arrive out of sequence—ahead of datagrams sent after it.

Datagram sockets are implemented in the AF_INET domain by UDP/IP connections and provide an unsequenced, unreliable service. However, they are relatively inexpensive in terms of resources, since network connections need not be maintained. They're fast because there is no associated connection setup time. UDP stands for User Datagram Protocol.

Datagrams are useful for “single-shot” inquiries to information services, for providing regular status information, or for performing low-priority logging. They have the advantage that the death of a server doesn't necessarily require a client restart. Because datagram-based servers usually retain no connection information, they can be stopped and restarted without unduly disturbing their clients.

For now, we leave the topic of datagrams; see the “Datagrams” section near the end of this chapter for more information on datagrams.

Socket Protocols

Where the underlying transport mechanism allows for more than one protocol to provide the requested socket type, you can select a specific protocol for a socket. In this chapter, we'll concentrate on UNIX network and file system sockets, which don't require you to choose a protocol other than the default.

Creating a Socket

The `socket` system call creates a socket and returns a descriptor that can be used for accessing the socket.

```
#include <sys/types.h>
#include <sys/socket.h>

int socket(int domain, int type, int protocol);
```

The socket created is one end point of a communication channel. The `domain` parameter specifies the address family, the `type` parameter specifies the type of communication to be used with this socket, and `protocol` specifies the protocol to be employed.

Domains include the following:

| | |
|--------------|--|
| AF_UNIX | UNIX internal (file system sockets) |
| AF_INET | ARPA Internet protocols (UNIX network sockets) |
| AF_ISO | ISO standard protocols |
| AF_NS | Xerox Network Systems protocols |
| AF_IPX | Novell IPX protocol |
| AF_APPLETALK | Appletalk DDS |

The most common socket domains are `AF_UNIX`, which is used for local sockets implemented via the UNIX and Linux file systems, and `AF_INET`, which is used for UNIX network sockets. The `AF_INET` sockets may be used by programs communicating across a TCP/IP network including the Internet. The Windows Winsock interface also provides access to this socket domain.

The socket parameter `type` specifies the communication characteristics to be used for the new socket. Possible values include `SOCK_STREAM` and `SOCK_DGRAM`.

`SOCK_STREAM` is a sequenced, reliable, connection-based two-way byte stream. For an `AF_INET` domain socket, this is provided by default by a TCP connection that is established between the two end points of the stream socket when it's connected. Data may be passed in both directions along the socket connection. The TCP protocols include facilities to fragment and reassemble long messages and to retransmit any parts that may be lost in the network.

`SOCK_DGRAM` is a datagram service. You can use this socket to send messages of a fixed (usually small) maximum size, but there's no guarantee that the message will be delivered or that messages won't be reordered in the network. For `AF_INET` sockets, this type of communication is provided by UDP datagrams.

The protocol used for communication is usually determined by the socket type and domain. There is normally no choice. The `protocol` parameter is used where there is a choice. 0 selects the default protocol, which we'll use in all our examples.

The `socket` system call returns a descriptor that is in many ways similar to a low-level file descriptor. When the socket has been connected to another end-point socket, you may use the `read` and `write` system calls with the descriptor to send and receive data on the socket. The `close` system call is used to end a socket connection.

Socket Addresses

Each socket domain requires its own address format. For an `AF_UNIX` socket, the address is described by a structure, `sockaddr_un`, defined in the `sys/un.h` include file.

```
struct sockaddr_un {
    sa_family_t sun_family;    /* AF_UNIX */
    char        sun_path[];    /* pathname */
};
```

So that addresses of different types may be passed to the socket-handling system calls, each address format is described by a similar structure that begins with a field (in this case, `sun_family`) that specifies the address type (the socket domain). In the `AF_UNIX` domain, the address is specified by a filename in the `sun_path` field of the structure.

On current Linux systems, the type `sa_family_t`, defined by X/Open as being declared in `sys/un.h`, is taken to be a `short`. Also, the pathname specified in `sun_path` is limited in size (Linux specifies 108 characters; others may use a manifest constant such as `UNIX_MAX_PATH`). Because address structures may vary in size, many socket calls require or provide as an output a length to be used for copying the particular address structure.

In the `AF_INET` domain, the address is specified using a structure called `sockaddr_in`, defined in `netinet/in.h`, which contains at least these members:

```
struct sockaddr_in {
    short int          sin_family;   /* AF_INET */
    unsigned short int sin_port;     /* Port number */
    struct in_addr     sin_addr;     /* Internet address */
};
```

The IP address structure, `in_addr`, is defined as follows:

```
struct in_addr {
    unsigned long int s_addr;
};
```

The four bytes of an IP address constitute a single 32-bit value. An `AF_INET` socket is fully described by its domain, IP address, and port number. From an application's point of view, all sockets act like file descriptors and are addressed by a unique integer value.

Naming a Socket

To make a socket (as created by a call to `socket`) available for use by other processes, a server program needs to give the socket a name. Thus, `AF_UNIX` sockets are associated with a file system pathname, as you saw in the `server1` example. `AF_INET` sockets are associated with an IP port number.

```
#include <sys/socket.h>

int bind(int socket, const struct sockaddr *address, size_t address_len);
```

The `bind` system call assigns the address specified in the parameter, `address`, to the unnamed socket associated with the file descriptor `socket`. The length of the address structure is passed as `address_len`.

The length and format of the address depend on the address family. A particular address structure pointer will need to be cast to the generic address type (`struct sockaddr *`) in the call to `bind`.

On successful completion, `bind` returns 0. If it fails, it returns -1 and sets `errno` to one of the following.

| | |
|---------------|--|
| EBADF | The file descriptor is invalid. |
| ENOTSOCK | The file descriptor doesn't refer to a socket. |
| EINVAL | The file descriptor refers to an already-named socket. |
| EADDRNOTAVAIL | The address is unavailable. |
| EADDRINUSE | The address has a socket bound to it already. |

There are some more values for `AF_UNIX` sockets:

| | |
|-----------------------|---|
| EACCES | Can't create the file system name due to permissions. |
| ENOTDIR, ENAMETOOLONG | Indicates a poor choice of filename. |

Creating a Socket Queue

To accept incoming connections on a socket, a server program must create a queue to store pending requests. It does this using the `listen` system call.

```
#include <sys/socket.h>

int listen(int socket, int backlog);
```

A Linux system may limit the maximum number of pending connections that may be held in a queue. Subject to this maximum, `listen` sets the queue length to `backlog`. Incoming connections up to this queue length are held pending on the socket; further connections will be refused and the client's connection will fail. This mechanism is provided by `listen` to allow incoming connections to be held pending while a server program is busy dealing with a previous client. A value of 5 for `backlog` is very common.

The `listen` function will return 0 on success or -1 on error. Errors include `EBADF`, `EINVAL`, and `ENOTSOCK`, as for the `bind` system call.

Accepting Connections

Once a server program has created and named a socket, it can wait for connections to be made to the socket by using the accept system call.

```
#include <sys/socket.h>

int accept(int socket, struct sockaddr *address, size_t *address_len);
```

The accept system call returns when a client program attempts to connect to the socket specified by the parameter `socket`. The client is the first pending connection from that socket's queue. The accept function creates a new socket to communicate with the client and returns its descriptor. The new socket will have the same type as the server listen socket.

The socket must have previously been named by a call to `bind` and had a connection queue allocated by `listen`. The address of the calling client will be placed in the `sockaddr` structure pointed to by `address`. A null pointer may be used here if the client address isn't of interest.

The `address_len` parameter specifies the length of the client structure. If the client address is longer than this value, it will be truncated. Before calling `accept`, `address_len` must be set to the expected address length. On return, `address_len` will be set to the actual length of the calling client's address structure.

If there are no connections pending on the socket's queue, `accept` will block (so that the program won't continue) until a client makes a connection. You may change this behavior by using the `O_NONBLOCK` flag on the socket file descriptor, using the `fcntl` function like this:

```
int flags = fcntl(socket, F_GETFL, 0);

fcntl(socket, F_SETFL, O_NONBLOCK|flags);
```

The `accept` function returns a new socket file descriptor when there is a client connection pending or -1 on error. Possible errors are similar to those for `bind` and `listen`, with the addition of `EWOULDBLOCK`, where `O_NONBLOCK` has been specified and there are no pending connections. The error `EINTR` will occur if the process is interrupted while blocked in `accept`.

Requesting Connections

Client programs connect to servers by establishing a connection between an unnamed socket and the server listen socket. They do this by calling `connect`.

```
#include <sys/socket.h>

int connect(int socket, const struct sockaddr *address, size_t address_len);
```

The socket specified by the parameter `socket` is connected to the server socket specified by the parameter `address`, which is of length `address_len`. The socket must be a valid file descriptor obtained by a call to `socket`.

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If it succeeds, `connect` returns `0`, and `-1` is returned on error. Possible errors this time include the following:

| | |
|--------------|--|
| EBADF | An invalid file descriptor was passed in <code>socket</code> . |
| EALREADY | A connection is already in progress for this socket. |
| ETIMEDOUT | A connection timeout has occurred. |
| ECONNREFUSED | The requested connection was refused by the server. |

If the connection can't be set up immediately, `connect` will block for an unspecified timeout period. Once this timeout has expired, the connection will be aborted and `connect` will fail. However, if the call to `connect` is interrupted by a signal that is handled, the `connect` call will fail (with `errno` set to `EINTR`), but the connection attempt won't be aborted but rather will be set up asynchronously.

As with `accept`, the blocking nature of `connect` may be altered by setting the `O_NONBLOCK` flag on the file descriptor. In this case, if the connection can't be made immediately, `connect` will fail with `errno` set to `EINPROGRESS` and the connection will be made asynchronously.

While asynchronous connections can be tricky to handle, you can use a call to `select` on the socket file descriptor to indicate that the socket is ready for writing. We'll cover `select` later in this chapter.

Closing a Socket

You can terminate a socket connection at the server and client by calling `close`, just as you would for low-level file descriptors. You should always close the socket at both ends. For the server, you should do this when `read` returns zero, but the `close` call could block if the socket has untransmitted data, is of a connection-oriented type, and has the `SOCK_LINGER` option set. You'll learn about setting socket options later in this chapter.

Socket Communications

Now that we have covered the basic system calls associated with sockets, we can take a closer look at the example programs. We'll try to convert them to use a network socket rather than a file system socket. The file system socket has the disadvantage that, unless the author uses an absolute pathname, it's created in the server program's current directory. To make it more generally useful, you need to create it in a globally accessible directory (such as `/tmp`) that is agreed between the server and its clients. For network sockets, you need only choose an unused port number.

For our example, we'll choose port number 9734. This is an arbitrary choice that avoids the standard services (we can't use port numbers below 1024 as they are reserved for system use). Other port numbers are often listed, with the services provided on them, in the system file `/etc/services`. When you're writing socket-based applications, always choose a port number not listed in this configuration file.

Be aware that there is a deliberate error in the programs `client2.c` and `server2.c` that we will fix in `client3.c` and `server3.c`. Please do not use the code from `client2.c` and `server2.c` in your own programs.

We'll run our client and server across a local network, but network sockets are not only useful on a local area network; any machine with an Internet connection (even a modem dial-up) can use network sockets to communicate with others. You can even use a network-based program on a stand-alone UNIX computer because a UNIX computer is usually configured to use a loopback network that contains only itself. For illustration purposes, we'll use this loopback network, which can also be useful for debugging network applications as it eliminates any external network problems.

The loopback network consists of a single computer, conventionally called `localhost`, with a standard IP address of 127.0.0.1. This is the local machine. You'll find its address listed in the network hosts file, `/etc/hosts`, with the names and addresses of other hosts on shared networks.

Each network with which a computer communicates has a hardware interface associated with it. A computer may have different network names on each network and certainly will have different IP addresses. For example, Neil's machine `tilde` has three network interfaces and therefore three addresses. These are recorded in `/etc/hosts` as follows:

```
127.0.0.1      localhost          # Loopback
192.168.1.1    tilde.localnet     # Local, private Ethernet
158.152.X.X    tilde.demon.co.uk  # Modem dial-up
```

The first is the simple loopback network, the second is a local area network accessed via an Ethernet adapter, and the third is the modem link to an Internet service provider. You can write a network socket-based program to communicate with servers accessed via any of these interfaces without alteration.

Try It Out—Network Client

Here's a modified client program, `client2.c`, to connect to a network socket via the loopback network. It contains a subtle bug concerned with hardware dependency, but we'll discuss that later in this chapter.

1. Make the necessary includes and set up the variables.

```
#include <sys/types.h>
#include <sys/socket.h>
#include <stdio.h>

#include <netinet/in.h>
#include <arpa/inet.h>
#include <unistd.h>

int main()
{
    int sockfd;
    int len;

    struct sockaddr_in address;
    int result;
    char ch = 'A';
```

2. Create a socket for the client.

```
    sockfd = socket(AF_INET, SOCK_STREAM, 0);
```

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3. Name the socket, as agreed with the server.

```
address.sin_family = AF_INET;
address.sin_addr.s_addr = inet_addr("127.0.0.1");
address.sin_port = 9734;
len = sizeof(address);
```

The rest of this program is the same as `client1.c` from earlier in this chapter. When you run this version, it fails to connect because there isn't a server running on port 9734 on this machine.

```
$ ./client2
oops: client2: Connection refused
$
```

How It Works

The client program used the `sockaddr_in` structure from the include file `netinet/in.h` to specify an `AF_INET` address. It tries to connect to a server on the host with IP address 127.0.0.1. It uses a function, `inet_addr`, to convert the text representation of an IP address into a form suitable for socket addressing. The manual page for `inet` has more information on other address translation functions.

Try It Out—Network Server

You also need to modify the server program to wait for connections on your chosen port number. Here's a modified server: `server2.c`.

1. Make the necessary includes and set up the variables.

```
#include <sys/types.h>
#include <sys/socket.h>
#include <stdio.h>

#include <netinet/in.h>
#include <arpa/inet.h>
#include <unistd.h>

int main()
{
    int server_sockfd, client_sockfd;
    int server_len, client_len;
    struct sockaddr_in server_address;
    struct sockaddr_in client_address;
```

2. Create an unnamed socket for the server.

```
server_sockfd = socket(AF_INET, SOCK_STREAM, 0);
```

3. Name the socket.

```
server_address.sin_family = AF_INET;
server_address.sin_addr.s_addr = inet_addr("127.0.0.1");
server_address.sin_port = 9734;
server_len = sizeof(server_address);
bind(server_sockfd, (struct sockaddr *)&server_address, server_len);
```

From here on, the listing follows `server1.c` exactly.

How It Works

The server program creates an AF_INET domain socket and arranges to accept connections on it. The socket is bound to your chosen port. The address specified determines which computers are allowed to connect. By specifying the loopback address, as in the client program, you are restricting communications to the local machine.

If you want to allow the server to communicate with remote clients, you must specify a set of IP addresses that you are willing to allow. You can use the special value, INADDR_ANY, to specify that you'll accept connections from all of the interfaces your computer may have. If you chose to, you could distinguish between different network interfaces to separate, for example, internal Local Area Network and external Wide Area Network connections. INADDR_ANY is a 32-bit integer value that you could use in the `sin_addr.s_addr` field of the address structure. However, you have a problem to resolve first.

Host and Network Byte Ordering

When I run these versions of the server and client programs on my computer, an Intel processor-based Linux machine, I can see the network connections by using the `netstat` command. This command will also be available on most UNIX systems configured for networking. It shows the client/server connection waiting to close down. The connection closes down after a small timeout. (Again, the exact output may vary among different versions of Linux.)

```
$ server2 &
[4] 1225
$ server waiting
client2
server waiting
char from server = B
$ netstat
Active Internet connections
Proto Recv-Q Send-Q Local Address      Foreign Address      (State)          User
tcp        1      0 localhost:1574    localhost:1174      TIME_WAIT        root
```

Before you try out further examples in this book, be sure to terminate running example server programs, as they will compete to accept connections from clients and you'll see confusing results. You can kill them all with the following command:

```
killall server1 server2 server3 server4 server5
```

You can see the port numbers that have been assigned to the connection between the server and the client. The local address shows the server, and the foreign address is the remote client. (Even though it's on the same machine, it's still connected over a network.) To ensure that all sockets are distinct, these client ports are typically different from the server listen socket and unique to the computer.

However, the local address (the server socket) is given as 1574 (or you may see `mvel-1m` as a service name), but we chose the port 9734. Why are they different? The answer is that port numbers and addresses are communicated over socket interfaces as binary numbers. Different computers use different byte ordering for integers. For example, an Intel processor stores the 32-bit integer as four consecutive bytes in memory in the order 1-2-3-4, where 1 is the most significant byte. Motorola processors would store the integer in the byte order 4-3-2-1. If the memory used for integers were simply copied byte-by-byte, the two different computers would not be able to agree on integer values.

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To enable computers of different types to agree on values for multibyte integers transmitted over a network, you need to define a network ordering. Client and server programs must convert their internal integer representation to the network ordering before transmission. They do this by using functions defined in `netinet/in.h`.

These are

```
#include <netinet/in.h>

unsigned long int htonl(unsigned long int hostlong);
unsigned short int htons(unsigned short int hostshort);
unsigned long int ntohl(unsigned long int netlong);
unsigned short int ntohs(unsigned short int netshort);
```

These functions convert 16-bit and 32-bit integers between native host format and the standard network ordering. Their names are abbreviations for conversions—for example, “host to network, long” (`htonl`) and “host to network, short” (`htons`). For computers where the native ordering is the same as network ordering, these represent null operations.

To ensure correct byte ordering of the 16-bit port number, your server and client need to apply these functions to the port address. The change to `server3.c` is

```
server_address.sin_addr.s_addr = htonl(INADDR_ANY);
server_address.sin_port = htons(9734);
```

You don’t need to convert the function call, `inet_addr("127.0.0.1")`, because `inet_addr` is defined to produce a result in network order. The change to `client3.c` is

```
address.sin_port = htons(9734);
```

The server has also been changed to allow connections from any IP address by using `INADDR_ANY`.

Now, when you run `server3` and `client3`, you see the correct port being used for the local connection.

```
$ netstat
Active Internet connections
Proto Recv-Q Local Address      Foreign Address      (State)      User
tcp        1      0 localhost:9734  localhost:1175      TIME_WAIT    root
```

Remember that if you’re using a computer that has the same native and network byte ordering, you won’t see any difference. It’s still important to always use the conversion functions to allow correct operation with clients and servers on computers with a different architecture.

Network Information

So far, your client and server programs have had addresses and port numbers compiled into them. For a more general server and client program, you can use network information functions to determine addresses and ports to use.

If you have permission to do so, you can add your server to the list of known services in `/etc/services`, which assigns a name to port numbers so that clients can use symbolic services rather than numbers.

Similarly, given a computer's name, you can determine the IP address by calling host database functions that resolve addresses for you. They do this by consulting network configuration files, such as `/etc/hosts`, or network information services, such as NIS (Network Information Services, formerly known as Yellow Pages) and DNS (Domain Name Service).

Host database functions are declared in the interface header file `netdb.h`.

```
#include <netdb.h>

struct hostent *gethostbyaddr(const void *addr, size_t len, int type);
struct hostent *gethostbyname(const char *name);
```

The structure returned by these functions must contain at least these members:

```
struct hostent {
    char *h_name;           /* name of the host */
    char **h_aliases;       /* list of aliases (nicknames) */
    int h_addrtype;         /* address type */
    int h_length;            /* length in bytes of the address */
    char **h_addr_list;     /* list of address (network order) */
};
```

If there is no database entry for the specified host or address, the information functions return a null pointer.

Similarly, information concerning services and associated port numbers is available through some service information functions.

```
#include <netdb.h>

struct servent *getservbyname(const char *name, const char *proto);
struct servent *getservbyport(int port, const char *proto);
```

The `proto` parameter specifies the protocol to be used to connect to the service, either "tcp" for `SOCK_STREAM` TCP connections or "udp" for `SOCK_DGRAM` UDP datagrams.

The structure `servent` contains at least these members:

```
struct servent {
    char *s_name;           /* name of the service */
    char **s_aliases;       /* list of aliases (alternative names) */
    int s_port;              /* The IP port number */
    char *s_proto;           /* The service type, usually "tcp" or "udp" */
};
```

You can gather host database information about a computer by calling `gethostbyname` and printing the results. Note that the address list needs to be cast to the appropriate address type and converted from network ordering to a printable string using the `inet_ntoa` conversion, which has the following definition:

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```
#include <arpa/inet.h>

char *inet_ntoa(struct in_addr in)
```

The function converts an Internet host address to a string in dotted quad format. It returns -1 on error, but POSIX doesn't define any errors. The other new function you use is `gethostname`.

```
#include <unistd.h>

int gethostname(char *name, int namelength);
```

This function writes the name of the current host into the string given by `name`. The hostname will be null-terminated. The argument `namelength` indicates the length of the string `name`, and the returned hostname will be truncated if it's too long to fit. `gethostname` returns 0 on success and -1 on error, but again no errors are defined in POSIX.

Try It Out—Network Information

This program, `getname.c`, gets information about a host computer.

1. As usual, make the appropriate `includes` and declare the variables.

```
#include <netinet/in.h>
#include <arpa/inet.h>
#include <unistd.h>
#include <netdb.h>
#include <stdio.h>

int main(int argc, char *argv[])
{
    char *host, **names, **addrs;
    struct hostent *hostinfo;
```

2. Set the host to the argument supplied with the `getname` call, or by default to the user's machine.

```
if(argc == 1) {
    char myname[256];
    gethostname(myname, 255);
    host = myname;
}
else
    host = argv[1];
```

3. Call `gethostbyname` and report an error if no information is found.

```
hostinfo = gethostbyname(host);
if(!hostinfo) {
    fprintf(stderr, "cannot get info for host: %s\n", host);
    exit(1);
}
```

4. Display the hostname and any aliases that it may have.

```
printf("results for host %s:\n", host);
printf("Name: %s\n", hostinfo -> h_name);
printf("Aliases:");
names = hostinfo -> h_aliases;
while(*names) {
    printf(" %s", *names);
    names++;
}
printf("\n");
```

5. Warn and exit if the host in question isn't an IP host.

```
if(hostinfo -> h_addrtype != AF_INET) {
    fprintf(stderr, "not an IP host!\n");
    exit(1);
}
```

6. Otherwise, display the IP address(es).

```
addrs = hostinfo -> h_addr_list;
while(*addrs) {
    printf(" %s", inet_ntoa(*(struct in_addr *)*addrs));
    addrs++;
}
printf("\n");
exit(0);
}
```

Alternatively, you could use the function `gethostbyaddr` to determine which host has a given IP address. You might use this in a server to find out where the client is calling from.

How It Works

The `getname` program calls `gethostbyname` to extract the host information from the host database. It prints out the hostname, its aliases (other names the computer is known by), and the IP addresses that the host uses on its network interfaces. When I ran the example, specifying `tilde` gave the two interfaces: Ethernet and modem.

```
$ ./getname tilde
results for host tilde:
Name: tilde.localnet
Aliases: tilde
192.168.1.1 158.152.x.x
```

When we use the hostname, `localhost`, the loopback network is given.

```
$ ./getname localhost
results for host localhost:
Name: localhost
Aliases:
127.0.0.1
```

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We can now modify our client to connect to any named host. Instead of connecting to our example server, we'll connect to a standard service so that we can also demonstrate extracting the port number.

Most UNIX and some Linux systems make their system time and date available as a standard service called `daytime`. Clients may connect to this service to discover the server's idea of the current time and date. Here's a client program, `getdate.c`, that does just that.

Try It Out—Connecting to a Standard Service

1. Start with the usual includes and declarations.

```
#include <sys/socket.h>
#include <netinet/in.h>
#include <netdb.h>
#include <stdio.h>
#include <unistd.h>

int main(int argc, char *argv[])
{
    char *host;
    int sockfd;
    int len, result;
    struct sockaddr_in address;
    struct hostent *hostinfo;
    struct servent *servinfo;
    char buffer[128];

    if(argc == 1)
        host = "localhost";
    else
        host = argv[1];
```

2. Find the host address and report an error if none is found.

```
hostinfo = gethostbyname(host);
if(!hostinfo) {
    fprintf(stderr, "no host: %s\n", host);
    exit(1);
}
```

3. Check that the `daytime` service exists on the host.

```
servinfo = getservbyname("daytime", "tcp");
if(!servinfo) {
    fprintf(stderr, "no daytime service\n");
    exit(1);
}
printf("daytime port is %d\n", ntohs(servinfo -> s_port));
```

4. Create a socket.

```
sockfd = socket(AF_INET, SOCK_STREAM, 0);
```

5. Construct the address for use with connect.

```
address.sin_family = AF_INET;
address.sin_port = servinfo -> s_port;
address.sin_addr = *(struct in_addr *)hostinfo -> h_addr_list;
len = sizeof(address);
```

6. Then connect and get the information.

```
result = connect(sockfd, (struct sockaddr *)&address, len);
if(result == -1) {
    perror("oops: getdate");
    exit(1);
}

result = read(sockfd, buffer, sizeof(buffer));
buffer[result] = '\0';
printf("read %d bytes: %s", result, buffer);

close(sockfd);
exit(0);
}
```

You can use `getdate` to get the time of day from any known host.

```
$ ./getdate localhost
daytime port is 13
read 26 bytes: 21 JUN 2003 14:18:18 BST
$
```

If you receive an error message such as

```
oops: getdate: Connection refused
```

or

```
oops: getdate: No such file or directory
```

it may be because the computer you are connecting to has not enabled the daytime service. This is the default behavior in recent Linux systems. In the next section, you will see how to enable this and other services.

How It Works

When you run this program, you can specify a host to connect to. The `daytime` service port number is determined from the network database function `getservbyname`, which returns information about network services in a similar way to host information. The program `getdate` tries to connect to the address given first in the list of alternate addresses for the specified host. If successful, it reads the information returned by the `daytime` service, a character string representing the UNIX time and date.

The Internet Daemon (`inetd`)

UNIX systems providing a number of network services often do so by way of a super-server. This program (the Internet daemon, `inetd`) listens for connections on many port addresses at once. When a client connects to a service, the `inetd` program runs the appropriate server. This cuts down on the need for servers to be running all the time; they can be started by `inetd` as required. Here's an extract from the `inetd` configuration file, `/etc/inetd.conf`, which is used to decide which servers to run:

```
# <service_name> <sock_type> <proto> <flags> <user> <server_path> <args>
#
# Echo, discard, daytime, and chargen are used primarily for testing.
#
daytime    stream    tcp      nowait    root     internal
daytime    dgram     udp      wait     root     internal
#
# These are standard services.
#
ftp        stream    tcp      nowait    root     /usr/sbin/tcpd    /usr/sbin/wu.ftpd
telnet    stream    tcp      nowait    root     /usr/sbin/tcpd    /usr/sbin/in.telnetd
#
# End of inetd.conf.
```

The `daytime` service that our `getdate` program connects to is actually handled by `inetd` itself (marked as `internal`) and is available using both `SOCK_STREAM` (`tcp`) and `SOCK_DGRAM` (`udp`) sockets.

The `ftp` file transfer service is available only via `SOCK_STREAM` sockets and is provided by an external program, in this case `wu.ftpd`, which `inetd` will start when a client connects to the `ftp` port.

If your system is running `inetd`, you can change the services provided by editing `/etc/inetd.conf` (a `#` at the start of a line indicates that the line is a comment) and restarting the `inetd` process. This can be done by sending it a hang-up signal using `kill`. To make this easier, some systems are configured so that `inetd` writes its process ID to a file. Alternatively, `killall` can be used:

```
# killall -HUP inetd
```

Linux systems typically run a replacement to `inetd` called `xinetd` and provide a more user-friendly way of configuring services. To allow our time-of-day client to connect, enable the `daytime` service using the tools provided on your Linux system. On SuSE Linux the services may be configured from the SuSE Control Center as shown in Figure 15-1. Red Hat Linux has a similar configuration interface. Here, the `daytime` service is being enabled for both TCP and UDP queries.

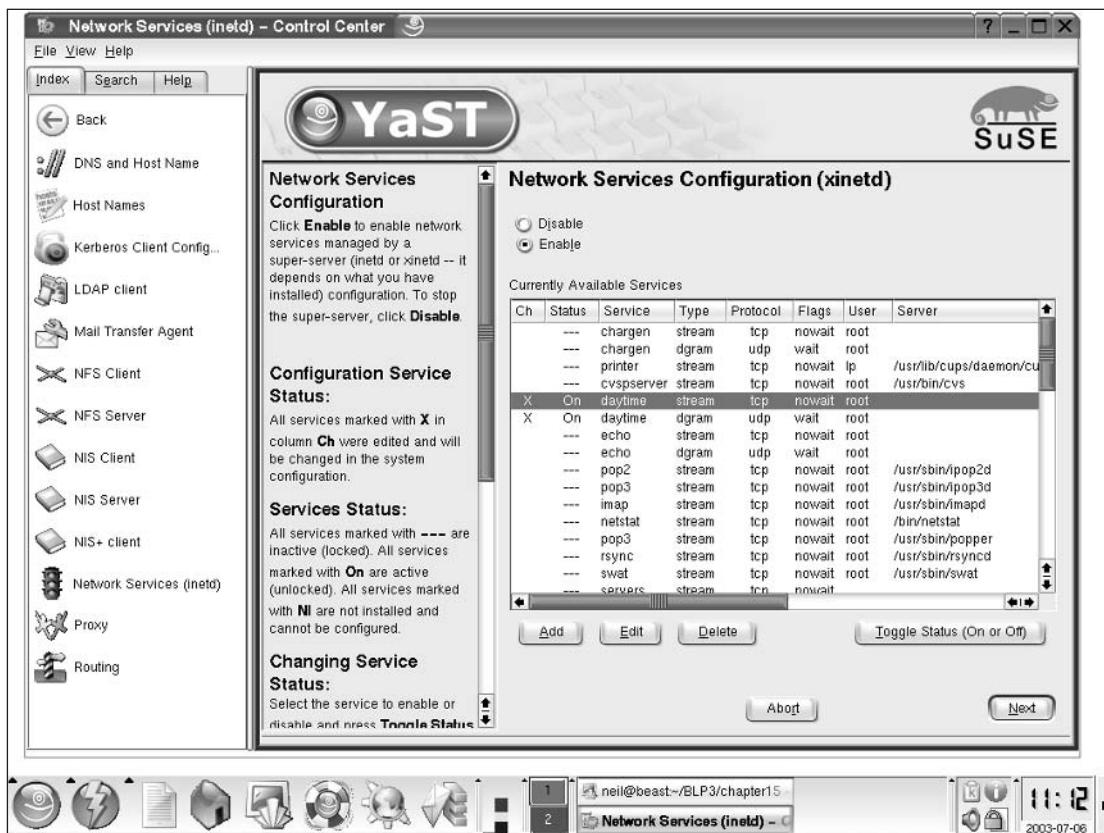


Figure 15-1

Socket Options

There are many options that you can use to control the behavior of socket connections—too many to detail here. The `setsockopt` function is used to manipulate options.

```
#include <sys/socket.h>

int setsockopt(int socket, int level, int option_name,
               const void *option_value, size_t option_len);
```

You can set options at various levels in the protocol hierarchy. To set options at the socket level, you must set `level` to `SOL_SOCKET`. To set options at the underlying protocol level (TCP, UDP, etc.), set `level` to the number of the protocol (from either the header file `netinet/in.h` or as obtained by the function `getprotobynumber`).

The `option_name` parameter selects an option to set; the `option_value` parameter is an arbitrary value of length `option_len` bytes passed unchanged to the underlying protocol handler.

Socket level options defined in `sys/socket.h` include the following:

| | |
|---------------------------|--|
| <code>SO_DEBUG</code> | Turn on debugging information. |
| <code>SO_KEEPALIVE</code> | Keep connections active with periodic transmissions. |
| <code>SO_LINGER</code> | Complete transmission before close. |

`SO_DEBUG` and `SO_KEEPALIVE` take an integer `option_value` used to turn the option on (1) or off (0). `SO_LINGER` requires a `linger` structure defined in `sys/socket.h` to define the state of the option and the linger interval.

`setsockopt` returns 0 if successful, -1 otherwise. The manual pages describe further options and errors.

Multiple Clients

So far in this chapter, you've seen how you can use sockets to implement client/server systems both locally and across networks. Once established, socket connections behave like low-level open file descriptors and in many ways like bi-directional pipes.

You might need to consider the case of multiple, simultaneous clients connecting to a server. You've seen that when a server program accepts a new connection from a client, a new socket is created and the original listen socket remains available for further connections. If the server doesn't immediately accept further connections, they will be held pending in a queue.

The fact that the original socket is still available and that sockets behave as file descriptors gives us a method of serving multiple clients at the same time. If the server calls `fork` to create a second copy of itself, the open socket will be inherited by the new child process. It can then communicate with the connecting client while the main server continues to accept further client connections. This is, in fact, a fairly easy change to make to your server program, which is shown in the following "Try It Out" section.

Since you're creating child processes but not waiting for them to complete, you must arrange for the server to ignore `SIGCHLD` signals to prevent zombie processes.

Try It Out—A Server for Multiple Clients

1. This program, `server4.c`, begins in similar vein to our last server, with the notable addition of an include for the `signal.h` header file. The variables and the procedure of creating and naming a socket are the same.

```
#include <sys/types.h>
#include <sys/socket.h>
#include <stdio.h>
#include <netinet/in.h>
#include <signal.h>
#include <unistd.h>

int main()
{
```

```

int server_sockfd, client_sockfd;
int server_len, client_len;
struct sockaddr_in server_address;
struct sockaddr_in client_address;

server_sockfd = socket(AF_INET, SOCK_STREAM, 0);

server_address.sin_family = AF_INET;
server_address.sin_addr.s_addr = htonl(INADDR_ANY);
server_address.sin_port = htons(9734);
server_len = sizeof(server_address);
bind(server_sockfd, (struct sockaddr *)&server_address, server_len);

```

- 2.** Create a connection queue, ignore child exit details, and wait for clients.

```

listen(server_sockfd, 5);

signal(SIGCHLD, SIG_IGN);

while(1) {
    char ch;

    printf("server waiting\n");

```

- 3.** Accept connection.

```

client_len = sizeof(client_address);
client_sockfd = accept(server_sockfd,
    (struct sockaddr *)&client_address, &client_len);

```

- 4.** Fork to create a process for this client and perform a test to see whether you're the parent or the child.

```

if(fork() == 0) {

```

- 5.** If you're the child, you can now read/write to the client on `client_sockfd`. The five-second delay is just for this demonstration.

```

    read(client_sockfd, &ch, 1);
    sleep(5);
    ch++;
    write(client_sockfd, &ch, 1);
    close(client_sockfd);
    exit(0);
}

```

- 6.** Otherwise, you must be the parent and your work for this client is finished.

```

    else {
        close(client_sockfd);
    }
}
}

```

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We have inserted a five-second delay in the processing of the client's request to simulate server calculation or database access. If we had done this with the previous server, each run of `client3` would have taken five seconds. With the new server, we can handle multiple `client3` programs concurrently, with an overall elapsed time of just over five seconds.

```
$ ./server4&
[7] 1571
$server waiting
./client3 & ./client3 & ./client3 & ps -ax
[8] 1572
[9] 1573
[10] 1574
server waiting
server waiting
server waiting
PID TTY STAT TIME COMMAND
1557 pp0 S    0:00 ./server4
1572 pp0 S    0:00 ./client3
1573 pp0 S    0:00 ./client3
1574 pp0 S    0:00 ./client3
1575 pp0 R    0:00 ps -ax
1576 pp0 S    0:00 ./server4
1577 pp0 S    0:00 ./server4
1578 pp0 S    0:00 ./server4
$ char from server = B
char from server = B
char from server = B
ps -ax
PID TTY STAT TIME COMMAND
1557 pp0 S    0:00 ./server4
1580 pp0 R    0:00 ps -ax
[8]- Done          ./client3
[9]+ Done          ./client3
[10]+ Done          ./client3
$
```

How It Works

The server program now creates a new child process to handle each client, so you see several server waiting messages as the main program continues to wait for new connections. The `ps` output (edited here) shows the main `server4` process, PID 1557, waiting for new clients while the three `client3` processes are being served by three children of the server. After a five-second pause, all of the clients get their results and finish. The child server processes exit to leave just the main server alone again.

The server program uses `fork` to handle multiple clients. In a database application, this may not be the best solution, since the server program may be quite large and there is still the problem of coordinating database accesses from multiple server copies. In fact, what you really need is a way for a single server to handle multiple clients without blocking and waiting on client requests to arrive. The solution to this problem involves handling multiple open file descriptors at once and isn't limited to socket applications. Enter `select`.

select

Quite often when you're writing Linux applications, you may need to examine the state of a number of inputs to determine the next action to take. For example, a communication program such as a terminal emulator needs to read the keyboard and the serial port effectively at the same time. In a single-user system, it might be acceptable to run in a "busy wait" loop, repeatedly scanning the input for data and reading it if it arrives. This behavior is expensive in terms of CPU time.

The `select` system call allows a program to wait for input to arrive (or output to complete) on a number of low-level file descriptors at once. This means that the terminal emulator program can block until there is something to do. Similarly, a server can deal with multiple clients by waiting for a request on many open sockets at the same time.

The `select` function operates on data structures, `fd_set`, that are sets of open file descriptors. A number of macros are defined for manipulating these sets:

```
#include <sys/types.h>
#include <sys/time.h>

void FD_ZERO(fd_set *fdset);
void FD_CLR(int fd, fd_set *fdset);
void FD_SET(int fd, fd_set *fdset);
int FD_ISSET(int fd, fd_set *fdset);
```

As suggested by their names, `FD_ZERO` initializes an `fd_set` to the empty set, `FD_SET` and `FD_CLR` set and clear elements of the set corresponding to the file descriptor passed as `fd`, and `FD_ISSET` returns nonzero if the file descriptor referred to by `fd` is an element of the `fd_set` pointed to by `fdset`. The maximum number of file descriptors in an `fd_set` structure is given by the constant `FD_SETSIZE`.

The `select` function can also use a timeout value to prevent indefinite blocking. The timeout value is given using a `struct timeval`. This structure, defined in `sys/time.h`, has the following members:

```
struct timeval {
    time_t    tv_sec;      /* seconds */
    long      tv_usec;     /* microseconds */
}
```

The `time_t` type is defined in `sys/types.h` as an integral type.

The `select` system call has the following prototype:

```
#include <sys/types.h>
#include <sys/time.h>

int select(int nfds, fd_set *readfds, fd_set *writefds, fd_set *errorfds, struct
           timeval *timeout);
```

A call to `select` is used to test whether any one of a set of file descriptors is ready for reading or writing or has an error condition pending and will optionally block until one is ready.

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The `nfds` argument specifies the number of file descriptors to be tested, and descriptors from 0 to `nfds`-1 are considered. Each of the three descriptor sets may be a null pointer, in which case the associated test isn't carried out.

The `select` function will return if any of the descriptors in the `readfds` set are ready for reading, if any in the `writefd`s set are ready for writing, or if any in `errorfd`s have an error condition. If none of these conditions apply, `select` will return after an interval specified by `timeout`. If the `timeout` parameter is a null pointer and there is no activity on the sockets, the call will block forever.

When `select` returns, the descriptor sets will have been modified to indicate which descriptors are ready for reading or writing or have errors. You should use `FD_ISSET` to test them, to determine the descriptor(s) needing attention. You can modify the `timeout` value to indicate the time remaining until the next timeout, but this behavior isn't specified by X/Open. In the case of a timeout occurring, all descriptor sets will be empty.

The `select` call returns the total number of descriptors in the modified sets. It returns -1 on failure, setting `errno` to describe the error. Possible errors are `EBADF` for invalid descriptors, `EINTR` for return due to interrupt, and `EINVAL` for bad values for `nfds` or `timeout`.

Although Linux modifies the structure pointed to by `timeout` to indicate the time remaining, most versions of UNIX do not. Much existing code that uses the `select` function initializes a `timeval` structure and then continues to use it without ever reinitializing the contents. On Linux, this code may operate incorrectly because Linux is modifying the `timeval` structure every time a timeout occurs. If you're writing or porting code that uses the `select` function, you should watch out for this difference and always reinitialize the `timeout`. Note that both behaviors are correct; they're just different!

Try It Out—`select`

Here is a program, `select.c`, to illustrate the use of `select`. We'll see and discuss a more complete example a little later. This program reads the keyboard (standard input—file descriptor 0) with a timeout of 2.5 seconds. It reads the keyboard only when input is ready. It's quite straightforward to extend it to include other descriptors, such as serial lines or pipes and sockets, depending on the application.

1. Begin as usual with the includes and declarations and then initialize inputs to handle input from the keyboard.

```
#include <sys/types.h>
#include <sys/time.h>
#include <stdio.h>
#include <fcntl.h>
#include <sys/ioctl.h>
#include <unistd.h>

int main()
{
    char buffer[128];
    int result, nread;
```

```

fd_set inputs, testfds;
struct timeval timeout;

FD_ZERO(&inputs);
FD_SET(0, &inputs);

```

- 2.** Wait for input on `stdin` for a maximum of 2.5 seconds.

```

while(1) {
    testfds = inputs;
    timeout.tv_sec = 2;
    timeout.tv_usec = 500000;

    result = select(FD_SETSIZE, &testfds, (fd_set *)NULL, (fd_set *)NULL,
                    &timeout);

```

- 3.** After this time, test `result`. If there has been no input, the program loops again. If there has been an error, the program exits.

```

switch(result) {
case 0:
    printf("timeout\n");
    break;
case -1:
    perror("select");
    exit(1);

```

- 4.** If, during the wait, you have some action on the file descriptor, read the input on `stdin` and echo it whenever an <end of line> character is received, until that input is `Ctrl+D`.

```

default:
    if(FD_ISSET(0,&testfds)) {
        ioctl(0,FIONREAD,&nread);
        if(nread == 0) {
            printf("keyboard done\n");
            exit(0);
        }
        nread = read(0,buffer,nread);
        buffer[nread] = 0;
        printf("read %d from keyboard: %s", nread, buffer);
    }
    break;
}
}

```

When you run this program, it prints `timeout` every two and a half seconds. If you type at the keyboard, it reads the standard input and reports what was typed. With most shells, the input will be sent to the program when the user presses the Enter (or in some cases Return) key or keys in a control sequence, so your program will print the input whenever you press Enter. Note that the Enter key itself is read and processed like any other character (try this by not pressing Enter, but a number of characters followed by `Ctrl+D`).

```
$ ./select
timeout
hello
read 6 from keyboard: hello
fred
read 5 from keyboard: fred
timeout
^D
keyboard done
$
```

How It Works

The program uses the `select` call to examine the state of the standard input. By arranging a timeout value, the program resumes every 2.5 seconds to print a timeout message. This is indicated by `select` returning zero. On end of file, the standard input descriptor is flagged as ready for input, but there are no characters to be read.

Multiple Clients

Our simple server program can benefit by using `select` to handle multiple clients simultaneously, without resorting to child processes. For real applications using this technique, you must take care that you do not make other clients wait too long while you deal with the first to connect.

The server can use `select` on both the listen socket and the clients' connection sockets at the same time. Once activity has been indicated, you can use `FD_ISSET` to cycle through all the possible file descriptors to discover which one the activity is on.

If the listen socket is ready for input, this will mean that a client is attempting to connect and you can call `accept` without risk of blocking. If a client descriptor is indicated ready, this means that there's a client request pending that you can read and deal with. A read of zero bytes will indicate that a client process has ended and you can close the socket and remove it from your descriptor set.

Try It Out—An Improved Multiple Client/Server

1. For our final example, `server5.c`, we include the `sys/time.h` and `sys/ioctl.h` headers instead of `signal.h` in our last program and declare some extra variables to deal with `select`.

```
#include <sys/types.h>
#include <sys/socket.h>
#include <stdio.h>
#include <netinet/in.h>
#include <sys/time.h>
#include <sys/ioctl.h>
#include <unistd.h>

int main()
{
```

```

int server_sockfd, client_sockfd;
int server_len, client_len;
struct sockaddr_in server_address;
struct sockaddr_in client_address;
int result;
fd_set readfds, testfds;

```

- 2.** Create and name a socket for the server.

```

server_sockfd = socket(AF_INET, SOCK_STREAM, 0);

server_address.sin_family = AF_INET;
server_address.sin_addr.s_addr = htonl(INADDR_ANY);
server_address.sin_port = htons(9734);
server_len = sizeof(server_address);

bind(server_sockfd, (struct sockaddr *)&server_address, server_len);

```

- 3.** Create a connection queue and initialize `readfds` to handle input from `server_sockfd`.

```

listen(server_sockfd, 5);

FD_ZERO(&readfds);
FD_SET(server_sockfd, &readfds);

```

- 4.** Now wait for clients and requests. Since you have passed a null pointer as the `timeout` parameter, no timeout will occur. The program will exit and report an error if `select` returns a value less than 1.

```

while(1) {
    char ch;
    int fd;
    int nread;

    testfds = readfds;

    printf("server waiting\n");
    result = select(FD_SETSIZE, &testfds, (fd_set *)0,
                    (fd_set *)0, (struct timeval *) 0);

    if(result < 1) {
        perror("server5");
        exit(1);
    }
}

```

- 5.** Once you know you've got activity, you can find which descriptor it's on by checking each in turn using `FD_ISSET`.

```

for(fd = 0; fd < FD_SETSIZE; fd++) {
    if(FD_ISSET(fd,&testfds)) {

```

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6. If the activity is on `server_sockfd`, it must be a request for a new connection, and you add the associated `client_sockfd` to the descriptor set.

```
if(fd == server_sockfd) {
    client_len = sizeof(client_address);
    client_sockfd = accept(server_sockfd,
                           (struct sockaddr *)&client_address, &client_len);
    FD_SET(client_sockfd, &readfds);
    printf("adding client on fd %d\n", client_sockfd);
}
```

7. If it isn't the server, it must be client activity. If `close` is received, the client has gone away, and you remove it from the descriptor set. Otherwise, you "serve" the client as in the previous examples.

```
else {
    ioctl(fd, FIONREAD, &nread);

    if(nread == 0) {
        close(fd);
        FD_CLR(fd, &readfds);
        printf("removing client on fd %d\n", fd);
    }

    else {
        read(fd, &ch, 1);
        sleep(5);
        printf("serving client on fd %d\n", fd);
        ch++;
        write(fd, &ch, 1);
    }
}
}
```

In a real-world program, it would be advisable to include a variable holding the largest `fd` number connected (not necessarily the most recent `fd` number connected). This would prevent looping through potentially thousands of `fds` that aren't even connected and couldn't possibly be ready for reading. We've omitted it here simply for brevity's sake and to make the code simpler.

When you run this version of the server, it deals with multiple clients sequentially in a single process.

```
$ ./server5 &
[7] 1670
$ server waiting
./client3 & ./client3 & ./client3 & ps -ax
[8] 1671
[9] 1672
[10] 1673
adding client on fd 4
```

```

server waiting
adding client on fd 5
server waiting
adding client on fd 6
server waiting
PID TTY STAT TIME COMMAND
1670 pp0 S 0:00 ./server5
1671 pp0 S 0:00 ./client3
1672 pp0 S 0:00 ./client3
1673 pp0 S 0:00 ./client3
1674 pp0 R 0:00 ps -ax
$ serving client on fd 4
server waiting
char from server = B
serving client on fd 5
char from server = B
serving client on fd 6
server waiting
removing client on fd 4
removing client on fd 5
server waiting
char from server = B
removing client on fd 6
server waiting

[8] Done ./client3
[9]- Done ./client3
[10]+ Done ./client3
$
```

To complete the analogy at the start of the chapter, the following table shows the parallels between socket connections and a telephone exchange.

| Telephone | Network Sockets |
|--|--|
| Call company on 555-0828 | Connect to IP address 127.0.0.1. |
| Call answered by reception | Connection established to remote host. |
| Ask for finance department | Route using specified port (9734). |
| Call answered by finance administration | Server returns from select. |
| Call put through to free account manager | Server calls accept, creating new socket on extension 456. |

Datagrams

In this chapter, we have concentrated on programming applications that maintain connections to their clients. We have used connection-oriented TCP socket connections for this. There are cases where the overhead of establishing and maintaining a socket connection is unnecessary.

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The `daytime` service we used in `getdate.c` earlier provides a good example. We create a socket, make a connection, read a single response, and close the connection. That's a lot of operations just to get the date.

The `daytime` service is also available by UDP using datagrams. To use it, you send a single datagram to the service and get a single datagram containing the date and time in response. It's simple.

Services provided by UDP are typically used where a client needs to make a short query of a server and expects a single short response. If the cost in terms of processing time is low enough, the server is able to provide this service by dealing with requests from clients one at a time, allowing the operating system to hold incoming requests in a queue. This simplifies the coding of the server.

Since UDP is not a guaranteed service, however, you may find that your datagram or your response goes missing. So if the data is important to you, you would need to code your UDP clients carefully to check for errors and retry if necessary. In practice, on a local area network, UDP datagrams are very reliable.

To access a service provided by UDP, you need to use the `socket` and `close` system calls as before, but rather than using `read` and `write` on the socket, you use two datagram-specific system calls, `sendto` and `recvfrom`.

Here's a modified version of `getdate.c` that gets the date via a UDP datagram service. Changes from the earlier version are highlighted.

```
/* Start with the usual includes and declarations. */

#include <sys/socket.h>
#include <netinet/in.h>
#include <netdb.h>
#include <stdio.h>
#include <unistd.h>

int main(int argc, char *argv[])
{
    char *host;
    int sockfd;
    int len, result;
    struct sockaddr_in address;
    struct hostent *hostinfo;
    struct servent *servinfo;
    char buffer[128];

    if(argc == 1)
        host = "localhost";
    else
        host = argv[1];

    /* Find the host address and report an error if none is found. */

    hostinfo = gethostbyname(host);
    if(!hostinfo) {
        fprintf(stderr, "no host: %s\n", host);
        exit(1);
    }

    /* Check that the daytime service exists on the host. */

    /* Start with the usual includes and declarations. */
```

```

servinfo = getservbyname("daytime", "udp");
if(!servinfo) {
    fprintf(stderr,"no daytime service\n");
    exit(1);
}
printf("daytime port is %d\n", ntohs(servinfo -> s_port));

/* Create a UDP socket. */

sockfd = socket(AF_INET, SOCK_DGRAM, 0);

/* Construct the address for use with sendto/recvfrom... */

address.sin_family = AF_INET;
address.sin_port = servinfo -> s_port;
address.sin_addr = *(struct in_addr *)hostinfo -> h_addr_list;
len = sizeof(address);

result = sendto(sockfd, buffer, 1, 0, (struct sockaddr *)&address, len);
result = recvfrom(sockfd, buffer, sizeof(buffer), 0,
                  (struct sockaddr *)&address, &len);
buffer[result] = '\0';
printf("read %d bytes: %s", result, buffer);

close(sockfd);
exit(0);
}

```

As you can see, the changes required are very small. You find the daytime service with `getservbyname` as before, but you specify the datagram service by requesting the UDP protocol. You create a datagram socket using `socket` with a `SOCK_DGRAM` parameter. You set up the destination address as before, but now you have to send a datagram rather than just read from the socket.

Because you are not making an explicit connection to services provided by UDP, you have to have some way of letting the server know that you want to receive a response. In this case, you send a datagram (here you send a single byte from the buffer you are going to receive the response into) to the service, and it responds with the date and time.

The `sendto` system call sends a datagram from a buffer on a socket using a socket address and address length. Its prototype is essentially

```
int sendto(int sockfd, void *buffer, size_t len, int flags,
          struct sockaddr *to, socklen_t tolen);
```

In normal use, the `flags` parameter can be kept zero.

The `recvfrom` system call waits on a socket for a datagram from a specified address and receives it into a buffer. Its prototype is essentially

```
int recvfrom(int sockfd, void *buffer, size_t len, int flags,
            struct sockaddr *from, socklen_t *fromlen);
```

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Again, in normal use, the `flags` parameter can be kept zero.

To keep the example short, we have omitted error handling. Both `sendto` and `recvfrom` will return `-1` if an error occurs and will set `errno` appropriately. Possible errors include the following:

| | |
|-------|--|
| EBADF | An invalid file descriptor was passed. |
| EINTR | A signal occurred. |

Unless the socket is set nonblocking using `fcntl` (as you saw for accepting TCP connections earlier), the `recvfrom` call will block indefinitely. The socket can, however, be used with `select` and a timeout to determine whether any data has arrived in the same way that you have seen with the connection-based servers earlier. Alternatively, an alarm clock signal can be used to interrupt a receive operation (see Chapter 11).

Summary

In this chapter, we've covered another method of inter-process communication: sockets. These allow you to develop true distributed client/server applications to run across networks. We briefly covered some of the host database information functions and how Linux handles standard system services with the Internet daemon. We developed a number of client/server example programs that demonstrate networking and handling multiple clients.

Finally, you learned about the `select` system call that allows a program to be advised of input and output activity on several open file descriptors and sockets at once.

16

Programming GNOME Using GTK+

So far in this book, we've covered the major topics in Linux programming that deal with complex, under-the-hood stuff. Now it's time to breathe some life into our applications and look at how to add a Graphical User Interface (GUI) to them. In this chapter and Chapter 17, we're going to look at the second of the two most popular GUI libraries for Linux: KDE/Qt.

All GUI libraries in Linux sit on top of the underlying windowing system called the *X Window System* (or more commonly *X11* or just *X*), so before we delve into GNOME/GTK+ details we'll provide an overview of how *X* operates and help you understand how the various layers of the windowing system fit together to create what we call the *desktop*.

In this chapter, we'll cover

- The X Window System
- An introduction to GNOME/GTK+
- GTK+ Widgets
- GNOME Widgets and Menus
- Dialogs
- CD Database GUI using GNOME/GTK+

Introducing X

If you've ever used a desktop windowing system on Linux, then you've most likely used *XFree86*, which is the Open Source, freely distributable clone of the X Window System that almost all Linux distributions are shipped with. The Linux desktop does not begin and end with *X*, however. In truth, the desktop in Linux is a rather nebulous thing, with no single project or group releasing a definitive version. A modern installation contains a myriad of libraries, utilities, and applications that collectively are called "the desktop."

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X has a long and illustrious history, having been originally developed at MIT in the early 1980s. X was developed to provide a unified windowing system for the high-end scientific workstations of the day, which were hugely expensive, number-crunching beasts.

As the 1990s came and hardware prices dropped, X was ported by enthusiasts to run on inexpensive home PCs, a project that became known as XFree86 (PC processors made by Intel and other companies are known as x86 processors), and it is the descendants of XFree86 that are distributed today with Linux.

The X Window System is separated into hardware-level and application-level components known as the X Server and the X Client. These components communicate using the aptly named X Protocol. In the following sections, we'll look at each of these in turn.

X Server

The X server runs on the user's local machine and is the part that performs the low-level operation of drawing the graphics on screen. Since the X server talks directly to the graphics card, we must use an X server specific to our graphics card, and it must be configured with appropriate resolution, refresh rate, color depth, and so on. The configuration file is named `XFree86Config` which in the past usually had to be manually edited to get X working properly. Thankfully, modern Linux distributions autodetect the correct settings, saving users time and a great deal of head scratching!

The X server listens for user input via the mouse and keyboard and relays keyboard presses and mouse clicks to the X client. These messages are called *events*; they form a key element of GUI programming. We'll be looking at events and their logical GTK+ extension, *signals*, in detail later in this chapter.

X Client

An X client is any program that uses the X Window System as a GUI. Examples are xterm, xcalc, and a more advanced application, like Abiword. An X client typically waits for user events sent by the X server and responds by sending redraw messages back to the server.

The X client need not be on the same machine as the X server.

X Protocol

The X client and X server communicate using the X Protocol, which enables the Client and Server to be separated over a network. For instance, you can run an X client application from a remote computer on the Internet or over an encrypted Virtual Private Network (VPN).

Xlib

Xlib is the library used indirectly by an X client to generate the X Protocol messages. It provides a very low-level API to allow the client to draw very basic elements on the X server and to respond to the simplest of inputs. We must emphasize that Xlib is a very low level—to create something even as simple as a menu using Xlib is an incredibly laborious process that needs hundreds of lines of code.

A GUI programmer cannot sensibly program directly with Xlib. We need an API that makes GUI elements such as menus, buttons, and drop-down lists easy and simple to create. In a nutshell, this is the role of the *toolkit*.

Toolkits

A toolkit is a GUI library that X clients utilize to greatly simplify the creation of windows, menus, buttons, and so on. Using a toolkit, we can create buttons, menus, frames, and the like with single function calls. The generic term for GUI elements such as these is *widgets*, a universal term you'll find in all modern GUI libraries.

There are dozens of toolkits for X to choose from, each with their defining strengths and weaknesses. Which one we choose is an important design decision for our application, and some of the factors we should consider are

- Who are you targeting with your application? Will your users have the toolkit libraries installed?
- Does the toolkit have a port for other popular operating systems?
- What software license does the toolkit use, and is it compatible with your intended use?
- Does the toolkit support your programming language?
- Does the toolkit have a modern look and feel?

Historically, the most popular toolkits were Motif, OpenLook, and Xt, but these have been largely superceded by the technically superior GTK+ and Qt toolkits that form the basis of the GNOME and KDE desktops, respectively.

Window Managers

The final piece in the X puzzle is the window manager, which is responsible for positioning windows onscreen. Window managers often support separate "workspaces" that divide the desktop, increasing the area with which you can interact. The window manager is also responsible for adding decoration around each window, which usually consists of a frame and title bar with maximize, minimize, and close icons.

Other Ways to GUI—Platform-Independent Windowing APIs

It's worth mentioning other ways to create GUIs that are not specific to Linux—there are languages that have native GUI support that function under Linux.

- The Java Language** supports programming GUIs using the Swing and older AWT APIs. The look and feel of Java GUIs isn't to everybody's taste, and on older machines the interface can feel clunky and unresponsive. A great advantage of Java is that once you've compiled your Java code, it runs unchanged on any platform with a Java Virtual Machine, which includes Linux, Windows, MacOS, and mobile devices. See <http://java.sun.com> for more information.
- Tcl/Tk** is a scripting language that is excellent for rapid development of GUIs and works with X, Windows, and MacOS. Great for rapid prototyping or for small utilities where you want the simplicity and maintainability of a script. You can find all the details at <http://tcl.tk>.

With the platform independence that these languages bring there is a price to pay. Sharing information with native applications—for instance, using "drag and drop"—is difficult, and saving configuration usually has to be done in a proprietary rather than the desktop standard way. Sometimes vendors of Java software cheat by shipping with platform-specific extensions to get around these sorts of problems.

Introducing GTK+

Now that you've looked at the X Window System, it's time to look at the GTK+ Toolkit. GTK+ started out life as part of the popular image manipulation program The GIMP, which is how GTK derives its name (The Gimp ToolKit). The GIMP programmers clearly had great foresight in making GTK+ a project in its own right since it has grown and developed into one of the most powerful and popular toolkits around. The homepage of the GTK+ project is <http://www.gtk.org>.

To recap, GTK+ is a library that greatly simplifies the creation of Graphical User Interfaces (GUIs) by providing a set of ready-made components called widgets that we bolt together with easy-to-use function calls to our application logic.

Although GTK+ is a GNU project like The GIMP, it is released under the terms of the more liberal LGPL (Lesser General Public License) that permits software (including closed source proprietary software) to be written using GTK+ without payment of fees, royalties, or other restrictions. The freedom offered by the GTK+ license is in contrast to its competitor Qt (the subject of the next chapter), whose GPL license prohibits commercial software from being developed using Qt.

GTK+ is written entirely in C, and the majority of GTK+ software is also written in C. Fortunately there are a number of language bindings that allow you to use GTK+ in your preferred language, be it C++, Python, PHP, Ruby, Perl, or even Java.

GLib Type System

If you've ever browsed through GTK+ code, you may have wondered why you saw a lot of C data types prefixed with the letter g, such as `gint`, `gchar`, `gshort`, as well as unfamiliar types such as `gint32` and `gpointer`. This is because GTK+ is based on a C portability library called *GLib* that defines these types to aid in cross-platform development.

GLib aids cross platform development by providing a standard set of replacement data types, functions, and macros to handle memory management and common tasks. These types, functions, and macros mean that as GTK+ programmers we can be confident that our code will port reliably to other platforms and architectures.

GLib also defines some convenient constants:

```
#include <glib/gmacros.h>

#define FALSE 0
#define TRUE !FALSE
```

The GLib additional data types are essentially those that are replacements for the standard C types (for consistency and readability) and those that guarantee byte length across all platforms.

- ❑ `gint`, `guint`, `gchar`, `guchar`, `glong`, `gulong`, `gfloat`, `gdouble` are simple replacements for the standard C types for consistency
- ❑ `gpointer` is synonymous with `(void *)`

- ❑ `gboolean` is useful for representing boolean values and is a wrapper for `int`
- ❑ `gint8, guint8, gint16, guint16, gint32, guint32` are signed and unsigned types with a guaranteed byte length

Usefully, using GLib is almost transparent. GLib is used extensively in GTK+, so if you have a working GTK+ setup, you'll find GLib installed. When programming with GTK+ we don't even need to explicitly include the `glib.h` header file, as we'll see later in the chapter.

GTK+ Object System

Anybody who has experimented with GUI programming before will probably understand when we write that GUI libraries strongly lend themselves to the paradigm of object-oriented (OO) programming; so much so that all modern Toolkits are written in an object-oriented fashion, including GTK+.

Despite GTK+ being written purely in C, it supports objects and OO programming through the `GObject` library. This library supports object inheritance and polymorphism using macros.

Let's look at an example of inheritance and polymorphism by looking at the `GtkWindow` object hierarchy taken from the GTK+ API documentation:

```
GObject
  +—GtkObject
    +—GtkWidget
      +—GtkContainer
        +—GtkBin
          +—GtkWindow
```

This list of objects tells you that `GtkWindow` is a child of `GtkBin`, and therefore any function you can call with a `GtkBin` can be called with `GtkWindow`. Similarly, `GtkWindow` inherits from `GtkContainer`, which inherits from `GtkWidget`.

As a matter of convenience, all widget creation functions return a `GtkWidget` type. For example:

```
GtkWidget* gtk_window_new (GtkWindowType type);
```

Suppose we create a `GtkWindow`, and want to pass the returned value to a function that expects a `GtkContainer` such as `gtk_container_add`:

```
void gtk_container_add (GtkContainer *container, GtkWidget *widget);
```

We use the `GTK_CONTAINER` macro to cast between a `GtkWidget` and `GtkContainer`:

```
GtkWidget * window = gtk_window_new(GTK_WINDOW_TOPLEVEL);
gtk_container_add(GTK_CONTAINER(window), awidget);
```

You'll see the meaning of these functions later but observe now using the macro. Macros exist for every conceivable cast.

Don't worry if all this is meaningless; you don't need to understand OO programming in any detail to come to grips with GNOME/GTK+. In fact, it's a painless way to learn the ideas and benefits behind OO programming while still in the comfort zone of C.

Introducing GNOME

GNOME is the name given to a project started in 1997 by programmers working on the GNU Image Manipulation Program (The GIMP) to create a unified desktop for Linux. There was a general consensus that adoption of Linux as a desktop platform was being held back by the lack of a coherent strategy. At that time, the Linux desktop resembled the Wild West, with no overall standards or agreed-upon practices and an “anything goes” programmer mentality. With no overarching group controlling things such as desktop menus, a consistent look and feel, documentation, translation, and so on, the newbie experience on the desktop was at best confusing and at worst unusable.

The GNOME team set out to create a desktop for Linux licensed entirely under the GPL, developing utilities and configuration programs in a uniform and consistent style while promoting standards for inter-application communication, printing, session-management, and best-practices in GUI application programming.

The results of their efforts are clear for all to see—GNOME is the basis of the default Red Hat Linux desktop (see Figure 16-1).

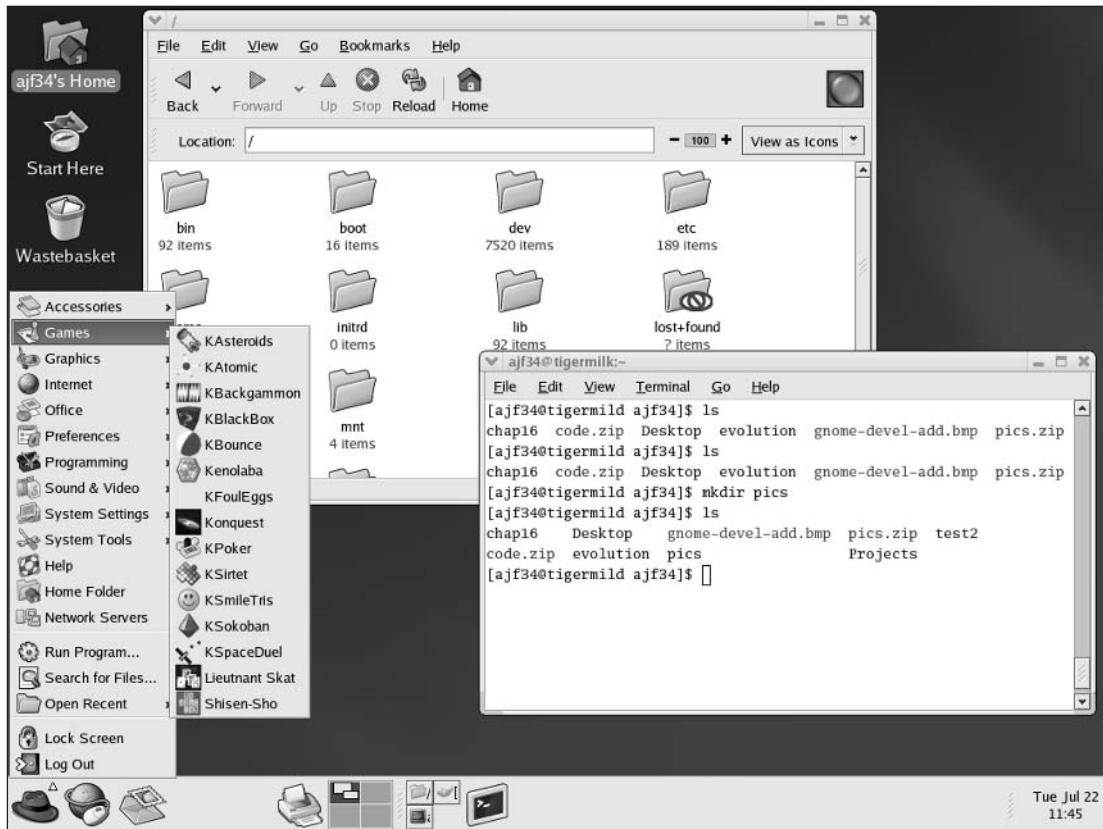


Figure 16-1

The default desktop in Red Hat 8 onward is Red Hat's own GNOME/KDE hybrid desktop that aims to bridge the look-and-feel gap between GNOME and KDE.

GNOME originally stood for the GNU Network Object Model Environment—this reflects one of the early goals, which was to introduce an object framework to Linux like the Microsoft OLE, so that you could embed, for example, a spreadsheet in a word processor document. Now the design goals have moved on, and what we know as GNOME refers to the complete desktop environment, which consists of a panel for launching apps, a suite of programs and utilities, programming libraries, and developer support features.

Before we start programming, we need to make sure we've got all the libraries installed.

Installing the GNOME/GTK+ Development Libraries

The complete GNOME desktop with its standard applications and the GNOME/GTK+ development libraries stretches over more than 60 RPMs; as a result, installing GNOME from scratch either manually or from source code is a daunting prospect. Thankfully, modern Linux distributions have excellent package management utilities that make installing GNOME/GTK+ and the development libraries a breeze.

In Red Hat Linux 8 onward, open the Package Management tool by clicking the Main Menu button (a big red hat in the lower left) and choose System Settings → Add/Remove Applications. When the Package Management tool appears (see Figure 16-2), make sure that the GNOME Software Development checkbox is checked.



Figure 16-2

In this chapter, we will be working with GNOME/GTK+ 2, so make sure your installation contains the version 2.x libraries.

For distributions that use RPMS, you should have at least the following RPMS installed:

```
gtk2-2.2.1-4.rpm  
gtk2-engines-1.1.8-5.rpm  
gtk2-devel-2.2.1-4.rpm  
libgnome-2.2.0.1-8.rpm  
libgnomeui-2.2.0.1-5.rpm  
libgnome-devel-2.2.0.1-8.rpm  
libgnomeui-devel-2.2.0.1-5.rpm
```

In Debian, you can use `apt-get` to install the GNOME/GTK+ packages from various mirrors—follow the links from <http://www.gnome.org> for details.

To check that everything is installed properly, try running `pkg-config` on the command line:

```
$ pkg-config
```

`pkg-config` is a handy utility for finding out how GTK+ and GNOME are configured on your system. Note that `pkg-config` supercedes the `gtk-config` utility that comes with GTK+ 1.x

Also try out the GTK+ demo application that shows off all the widgets in their finery (see Figure 16-3):

```
$ gtk-demo
```

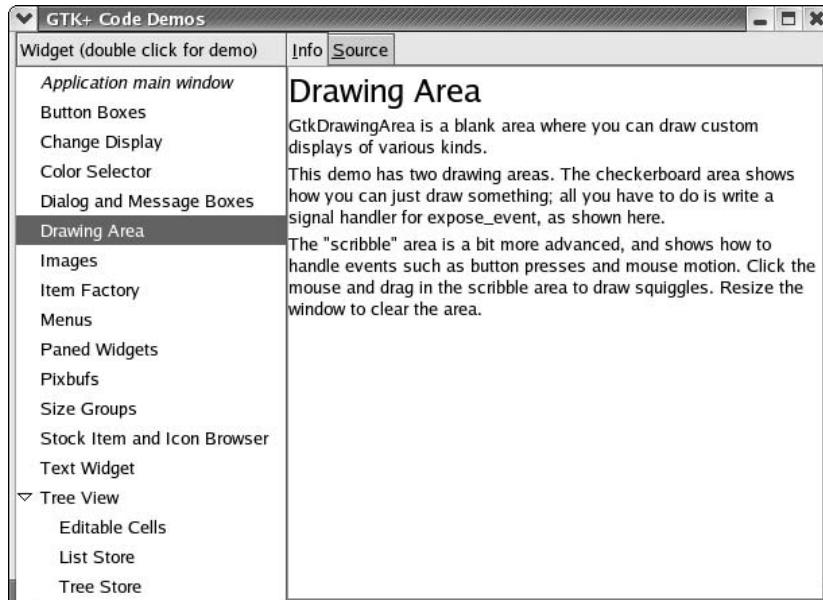


Figure 16-3

Try it Out—A Plain GtkWindow

Let's start programming GTK+ with the simplest of GUI programs: displaying a window. We'll see the GTK+ libraries in action, and see how much functionality we get from surprisingly little code.

- Type this program and call it `gtk1.c`:

```
#include <gtk/gtk.h>

int main (int argc, char *argv[])
{
    GtkWidget *window;

    gtk_init(&argc, &argv);
    window = gtk_window_new(GTK_WINDOW_TOPLEVEL);
    gtk_widget_show(window);
    gtk_main ();

    return 0;
}
```

- To compile `gtk1.c` type:

```
$ gcc gtk1.c -o gtk1 `pkg-config --cflags --libs gtk+-2.0`
```

Take care to type backticks, not apostrophes—remember that backticks are instructions to the shell to execute and append the output of the enclosed command.

When we run this program with the following command, your window should pop up (see Figure 16-4).

```
$ ./gtk1
```



Figure 16-4

Note that we can move, resize, minimize, and maximize the window.

How It Works

We include the necessary GTK+ and related library headers (including GLib) with a single `#include <gtk/gtk.h>` statement. Next, we declare the window to be a pointer to a `GtkWidget`.

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Next, to initialize the GTK+ libraries, we must make a call to `gtk_init` passing in the command line arguments `argc` and `argv`. This gives GTK+ a chance to parse any command line parameters it needs to know about. Note that we must always initialize GTK+ in this way before calling any GTK+ functions.

The core of the example is the call we make to `gtk_window_new`. The prototype is

```
GtkWidget* gtk_window_new (GtkWindowType type);
```

Type can take one of two values depending on the purpose of the window.

- ❑ `GTK_WINDOW_TOPLEVEL`: A standard framed window
- ❑ `GTK_WINDOW_POPUP`: A frameless window suitable for dialog boxes

We'll almost always use `GTK_WINDOW_TOPLEVEL`, as there are far more convenient ways of creating dialogs, as you'll see later.

The call to `gtk_window_new` sets up the window in memory, so we have a chance to populate it with widgets, resize it, change the window title, and so forth, before actually displaying it on screen. To make the window actually appear on screen, we call `gtk_widget_show`

```
gtk_widget_show(window);
```

Conveniently, this takes a `GtkWidget` pointer, so we simply pass in the reference to our window.

The final call we make is to `gtk_main`. This key function starts up the interactivity process by passing control to GTK+ and doesn't return until a call to `gtk_main_quit` is made. As you can see, in `gtk1.c` this never happens, so the application doesn't end even after the window is closed. Try this out by clicking on the close icon and seeing that the command prompt doesn't return. We'll rectify this after we've learned about signals and callbacks in the next section.

Events, Signals, and Callbacks

All GUI libraries have one thing in common: Some mechanism must exist to execute code in response to a user action. A command line program has the luxury of halting execution to wait for input and can then use something like a switch statement to branch execution based on the input. This approach is impractical with a GUI application because the application must continually respond to user input; for example, it needs to continually update areas of the window.

Modern windowing systems have systems of events and event listeners that address this problem. The idea is that each user input, usually from the mouse or keyboard, triggers an event. A keyboard press would trigger a "keyboard event," for example. Code is then written to listen for these events and to execute when such an event is triggered.

As we saw earlier, the X Window System emits these events, but they aren't much help to us as a GTK+ programmer, as they're very low level. When a mouse button is clicked, X emits an event that contains the coordinates of the pointer—what we really need to know is when a user activates a widget.

Accordingly, GTK+ has its own system of events and event listeners, known as signals and callbacks. They're very easy to use because you can use a very useful feature of C, a pointer to a function, to set the signal handler.

First some definitions: A GTK+ *signal* is emitted by a `GtkObject` when something such as user input occurs. A function that is connected to a signal, and therefore called whenever that signal is emitted, is known as a *callback function*.

Note that a GTK+ signal is quite separate from a UNIX signal, discussed in Chapter 11.

As a GTK+ programmer, all you need to worry about is writing and connecting callback functions, since the signal-emitting code is internal to the particular widget.

The callback function prototype is typically like this

```
void a_callback_function ( GtkWidget *widget, gpointer user_data);
```

We are passed two parameters, the first a pointer to the widget that emitted the signal and the second an arbitrary pointer that we pick ourselves when we connect the callback. We can use this pointer for any purpose.

Connecting the callback is just as simple. We simply call `g_signal_connect` and pass in the widget, signal name as a string, callback function pointer, and our arbitrary pointer.

```
gulong g_signal_connect(gpointer *object, const gchar *name, GCallback func,
                      gpointer user_data );
```

One point worthy of noting—there are no restrictions in connecting callbacks. You can have multiple signals to a single callback function, and multiple callback functions connected to a single signal. You can see in detail the signals that each widget emits by reading the GTK+ API documentation.

Prior to GTK+ 2, the function to connect callback functions was `gtk_signal_connect`. This function has been replaced by `g_signal_connect` and should not be used in new code.

We'll try out `g_signal_connect` in our next example.

Try It Out—A Callback Function

In `gtk2.c`, we'll add a button to our window and attach the button's "clicked" signal to our callback function to print a short message.

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

static int count = 0;

void button_clicked ( GtkWidget *button, gpointer data)
```

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```
{  
    printf("%s pressed %d time(s) \n", (char *) data, ++count);  
}  
  
int main (int argc, char *argv[])  
{  
    GtkWidget *window;  
    GtkWidget *button;  
  
    gtk_init(&argc, &argv);  
    window = gtk_window_new(GTK_WINDOW_TOPLEVEL);  
    button = gtk_button_new_with_label("Hello World!");  
    gtk_container_add(GTK_CONTAINER(window), button);  
  
    g_signal_connect(GTK_OBJECT(button), "clicked",  
                    GTK_SIGNAL_FUNC(button_clicked),  
                    "Button 1");  
    gtk_widget_show(button);  
    gtk_widget_show(window);  
  
    gtk_main();  
  
    return 0;  
}
```

When running this program, you'll get a window with a button. Each time you click the button, it prints out a short message (see Figure 16-5).

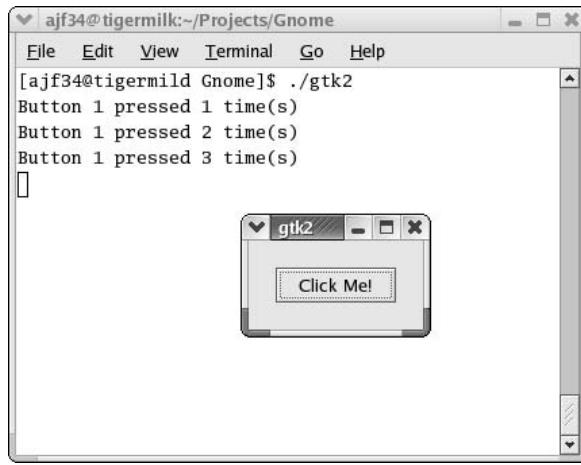


Figure 16-5

How It Works

We've introduced two new features in `gtk2.c`: a `GtkButton` and a callback function. A `GtkButton` is a simple button widget that can contain text, in this case "Hello World," and emits a signal called "clicked" whenever the button is pressed with the mouse.

The callback function `button_clicked` is connected to the “clicked” signal of the button widget using the `g_signal_connect` function:

```
g_signal_connect(GTK_OBJECT (app), "clicked",
                 GTK_SIGNAL_FUNC (button_clicked),
                 "Button 1");
```

Note that the name of the button—“Button 1”—is passed as user data to the callback function.

The rest of the additional code deals with the button widget, which is created in the same way as the window—a call to a `gtk_button_new_with_label` function—and `gtk_widget_show` makes it visible.

To place the button on the window, we call `gtk_container_add`. This simple function places a `GtkWidget` inside a `GtkContainer` and takes the container and widget as arguments.

```
void gtk_container_add (GtkContainer *container, GtkWidget *widget);
```

As we saw before, `GtkWindow` is a child of `GtkContainer`, so we can cast our `window` object to a `GtkContainer` type using the `GTK_CONTAINER` macro:

```
gtk_container_add(GTK_CONTAINER(window), button);
```

`gtk_container_add` is great for placing a single widget inside a container, but more often we’ll need to arrange several widgets in various positions in a window to create a decent interface. GTK+ has special widgets just for this purpose, called *Box* or *Container* widgets.

Packing Box Widgets

The layout of a GUI is of key importance to its usability and one of the hardest things to get right. The real difficulty with arranging widgets is that you can’t rely on all users to have the same screen resolution, or to have the same window size, theme, font, or color scheme. What might be a pleasing interface on one system might be impossible to read on another.

To create a GUI that appears uniform on all systems, you need to avoid placing widgets using absolute coordinates and instead use a more flexible system of layout. GTK+ has box widgets for this purpose.

Box widgets are invisible widgets whose job it is to contain other widgets and control their layout. To control the size of the individual widgets contained inside the box widget, we specify rules instead of coordinates. Since box widgets contain any `GtkWidget`, and a `GtkBox` is itself a `GtkWidget`, we can nest box widgets inside one another to create complex layouts.

There are two main subclasses of `GtkBox`:

- ❑ `GtkHBox` is a single row horizontal packing box widget.
- ❑ `GtkVBox` is a single column vertical packing box widget.

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When the packing boxes are created, you should specify two parameters, homogeneous and spacing:

```
GtkWidget* gtk_hbox_new (gboolean homogeneous, gint spacing);
GtkWidget* gtk_vbox_new (gboolean homogeneous, gint spacing);
```

These parameters control layout for all of the widgets in that particular packing box. `homogeneous` is a boolean that, when set to TRUE, forces contained widgets to occupy equal space, regardless of individual size. `spacing` sets the gap between widgets in pixels.

Once you've created the packing box, add widgets using `gtk_box_pack_start` and `gtk_box_pack_end` functions.

```
void gtk_box_pack_start (GtkBox *box, GtkWidget *child,
                        gboolean expand, gboolean fill,
                        guint padding);

void gtk_box_pack_end (GtkBox *box, GtkWidget *child,
                      gboolean expand, gboolean fill,
                      guint padding);
```

`gtk_box_pack_start` adds widgets to the left side of a `GtkHbox` and to the bottom of a `GtkVBox`; conversely `gtk_box_pack_end` from the right and top. Their parameters control the spacing and format of each widget within the packing box.

| Parameter | Description |
|-------------------------------|--|
| <code>GtkBox *box</code> | The packing box to be filled. |
| <code>GtkWidget *child</code> | The widget to be placed in the packing box. |
| <code>gboolean expand</code> | If TRUE, this widget fills all available space shared between the other widgets with this flag also set to TRUE. |
| <code>gboolean fill</code> | If TRUE, this widget will fill the space allocated to it, rather than use it as padding around the edges. Only valid when <code>expand</code> is TRUE. |
| <code>Guint padding</code> | Padding size in pixels around widget. |

Let's take a look at these packing box widgets now and create a more complex user interface, showing off nested packing boxes.

Try It Out—Widget Container Layout

In this example, we'll lay out some simple `GtkLabel` widgets using `GtkHBox` and `GtkVBox`. Label widgets are simple widgets that are useful for displaying short amounts of text. We call this program `container.c`.

```
#include <gtk/gtk.h>

void closeApp ( GtkWidget *window, gpointer data)
```

```

{
    gtk_main_quit();
}

int main (int argc, char *argv[])
{
    GtkWidget *window;
    GtkWidget *label1, *label2, *label3;
    GtkWidget *hbox;
    GtkWidget *vbox;

    gtk_init(&argc, &argv);
    window = gtk_window_new(GTK_WINDOW_TOPLEVEL);

    gtk_window_set_title(GTK_WINDOW(window), "The Window Title");
    gtk_window_set_position(GTK_WINDOW(window), GTK_WIN_POS_CENTER);
    gtk_window_set_default_size(GTK_WINDOW(window), 300, 200);

    g_signal_connect ( GTK_OBJECT (window), "destroy",
                      GTK_SIGNAL_FUNC ( closeApp ), NULL );

    label1 = gtk_label_new("Label 1");
    label2 = gtk_label_new("Label 2");
    label3 = gtk_label_new("Label 3");

    hbox = gtk_hbox_new ( TRUE, 5 );
    vbox = gtk_vbox_new ( FALSE, 10 );

    gtk_box_pack_start(GTK_BOX(vbox), label1, TRUE, FALSE, 5);
    gtk_box_pack_start(GTK_BOX(vbox), label2, TRUE, FALSE, 5);

    gtk_box_pack_start(GTK_BOX(hbox), vbox, FALSE, FALSE, 5);
    gtk_box_pack_start(GTK_BOX(hbox), label3, FALSE, FALSE, 5);

    gtk_container_add(GTK_CONTAINER(window), hbox);
    gtk_widget_show_all(window);
    gtk_main ();

    return 0;
}

```

When we run this program, we see the layout of label widgets in our window (see Figure 16-6).



Figure 16-6

How It Works

We create two packing box widgets, `hbox` and `vbox`. We fill `vbox` with `label1` and `label2` using `gtk_box_pack_start`, so `label2` appears at the bottom because it is added after `label1`. Next `vbox` itself is added to `hbox` along with `label3`.

`hbox` is finally added to the window and is shown on screen using `gtk_widget_show_all`.

The packing box layout is understood best with a diagram, as shown in Figure 16-7.

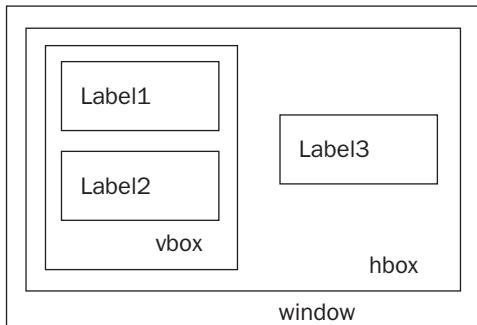


Figure 16-7

Now that we've looked at widgets, signals, callbacks, and container widgets, we've covered the essentials of GTK+. Becoming a knowledgeable GTK+ programmer involves understanding how best to use the available widgets.

GTK+ Widgets

In this section, we'll look at the API of the common GTK+ widgets we use most often in our applications.

GtkWindow

`GtkWindow` is the basic element of all GTK+ applications. We've used it so far to hold our widgets.

```
GtkWidget
  +—GtkContainer
    +—GtkBin
      +—GtkWindow
```

There are dozens of `GtkWindow` API calls, but here are the functions worthy of special attention.

```
GtkWidget* gtk_window_new (GtkWindowType type);
void gtk_window_set_title (GtkWindow *window, const gchar *title);
void gtk_window_set_position (GtkWindow *window, GtkWindowPosition position);
void gtk_window_set_default_size (GtkWindow *window, gint width, gint height);
void gtk_window_resize (GtkWindow *window, gint width, gint height);
```

```
void gtk_window_set_resizable (GtkWindow *window, gboolean resizable);
void gtk_window_present (GtkWindow *window);
void gtk_window_maximize (GtkWindow *window);
void gtk_window_unmaximize (GtkWindow *window);
```

As we've just seen, `gtk_window_new` creates a new, empty window in memory. The window title is unset, and the size and screen position of the window are undefined. We will normally populate the window with widgets and set up a menu and toolbar before making the window visible onscreen with a call to `gtk_widget_show`.

The `gtk_window_set_title` function changes the text of the title bar by informing the window manager of the request.

Note that because it is the window manager, not GTK+, that is responsible for painting the window surround, the font, color, and size of the text are dependent on your choice of window manager.

`gtk_window_set_position` controls the position of the initial placement on screen. The position parameter can take five values.

| Position Parameter | Description |
|---|--|
| <code>GTK_WIN_POS_NONE</code> | The window is placed at the discretion of the window manager. |
| <code>GTK_WIN_POS_CENTER</code> | The window is positioned centrally on screen. |
| <code>GTK_WIN_POS_MOUSE</code> | The window is positioned at the mouse pointer. |
| <code>GTK_WIN_POS_CENTER_ALWAYS</code> | Keep the window centered regardless of size. |
| <code>GTK_WIN_POS_CENTER_ON_PARENT</code> | Sets the window centrally on its parent (useful for dialog boxes). |

`gtk_window_set_default_size` sets the size of the window on screen in GTK+ drawing units. Explicitly setting the size of the window ensures that the contents of the window aren't obscured or hidden. To force a resize of the window once it's onscreen, we can use `gtk_window_resize`. By default, the user is able to resize the window by dragging the frame in the usual way. To prevent this, we can call `gtk_window_set_resizable` set to FALSE.

To ensure that our window is on screen and visible to the user—that is, not minimized or hidden—`gtk_window_present` fits the bill. `gtk_window_present` is useful for dialog boxes to make sure they're not minimized when we need some user input. Alternatively, to force maximizing and minimizing we have `gtk_window_maximize` and `gtk_window_minimize`.

GtkEntry

The `GtkEntry` widget is a single-line text entry widget that is commonly used to enter simple textual information, for example an e-mail address, a username, or a hostname. There are API calls that enable us to set as well as read the entered text, set the maximum number of allowed characters, and set other things to control the positioning and selection of the text.

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```
GtkWidget
+—GtkEntry
```

GtkEntry can be set to display asterisks (or any other user-definable character) in place of the literal typed characters, which can be very useful for entering passwords when we don't want anybody to lean over our shoulder and read the text.

We'll describe the most useful GtkEntry functions:

```
GtkWidget* gtk_entry_new                  (void);
GtkWidget* gtk_entry_new_with_max_length (gint max);
void     gtk_entry_set_max_length        (GtkEntry *entry, gint max);
G_CONST_RETURN gchar* gtk_entry_get_text  (GtkEntry *entry);
void     gtk_entry_set_text              (GtkEntry *entry, const gchar *text);
void     gtk_entry_append_text          (GtkEntry *entry, const gchar *text);
void     gtk_entry_prepend_text         (GtkEntry *entry, const gchar *text);
void    gtk_entry_set_visibility       (GtkEntry *entry, gboolean visible);
void    gtk_entry_set_invisible_char   (GtkEntry *entry, gchar invch);
void    gtk_entry_set_editable        (GtkEntry *entry, gboolean editable);
```

We can create a GtkEntry with either `gtk_entry_new`, or with a fixed maximum length of input text with `gtk_entry_new_with_max_length`. Restricting the input to a certain length saves us the effort of validating the input length and possibly having to inform the user that the text is too long.

To get the contents of the GtkEntry, we call `gtk_entry_get_text`, which returns a `const char` pointer internal to the GtkEntry (`G_CONST_RETURN` is a GLib-defined macro). If we wish to modify the text, or pass it to a function that might modify it, we must copy the string using, for example, `strcpy`.

We can manually set and modify the contents of the GtkEntry using the `_set_text`, `_append_text`, and `_modify_text` functions. Note that these take `const` pointers.

To use GtkEntry as a password entry box that displays asterisks in place of characters, we use `gtk_entry_set_visibility` passing FALSE as the visible parameter. The invisible character can be changed using `gtk_entry_set_invisible_char` to suit our requirements.

Try It Out—Username and Password Entry

Now that we've seen the GtkEntry functions, let's show them in action with a short program. `entry.c` will create a username and password entry window and compare the entered password with a secret password.

1. First we define the secret password, cunningly chosen to be `secret`.

```
#include <gtk/gtk.h>
#include <stdio.h>
#include <string.h>

const char * password = "secret";
```

- 2.** We have two callback functions that are called when the window is destroyed and the Ok button is clicked.

```
void closeApp ( GtkWidget *window, gpointer data)
{
    gtk_main_quit();
}

void button_clicked ( GtkWidget *button, gpointer data)
{
    const char *password_text = gtk_entry_get_text(GTK_ENTRY((GtkWidget *) data));

    if (strcmp(password_text, password) == 0)
        printf("Access granted!\n");
    else
        printf("Access denied!\n");
}
```

- 3.** In main, the interface is created and laid out, and the callbacks connected. We use hbox and vbox container widgets to lay out the label and entry widgets.

```
int main (int argc, char *argv[])
{
    GtkWidget *window;
    GtkWidget *username_label, *password_label;
    GtkWidget *username_entry, *password_entry;
    GtkWidget *ok_button;
    GtkWidget *hbox1, *hbox2;
    GtkWidget *vbox;

    gtk_init(&argc, &argv);

    window = gtk_window_new(GTK_WINDOW_TOPLEVEL);
    gtk_window_set_title(GTK_WINDOW(window), "GtkEntryBox");
    gtk_window_set_position(GTK_WINDOW(window), GTK_WIN_POS_CENTER);
    gtk_window_set_default_size(GTK_WINDOW(window), 200, 200);

    g_signal_connect ( GTK_OBJECT (window), "destroy",
                      GTK_SIGNAL_FUNC ( closeApp ), NULL );

    username_label = gtk_label_new("Login:");
    password_label = gtk_label_new("Password:");

    username_entry = gtk_entry_new();
    password_entry = gtk_entry_new();
    gtk_entry_set_visibility(GTK_ENTRY (password_entry), FALSE);

    ok_button = gtk_button_new_with_label("Ok");

    g_signal_connect ( GTK_OBJECT (ok_button), "clicked",
                      GTK_SIGNAL_FUNC(button_clicked), password_entry );
```

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```
hbox1 = gtk_hbox_new ( TRUE, 5 );
hbox2 = gtk_hbox_new ( TRUE, 5 );

vbox = gtk_vbox_new ( FALSE, 10 );

gtk_box_pack_start(GTK_BOX(hbox1), username_label, TRUE, FALSE, 5);
gtk_box_pack_start(GTK_BOX(hbox1), username_entry, TRUE, FALSE, 5);

gtk_box_pack_start(GTK_BOX(hbox2), password_label, TRUE, FALSE, 5);
gtk_box_pack_start(GTK_BOX(hbox2), password_entry, TRUE, FALSE, 5);

gtk_box_pack_start(GTK_BOX(vbox), hbox1, FALSE, FALSE, 5);
gtk_box_pack_start(GTK_BOX(vbox), hbox2, FALSE, FALSE, 5);
gtk_box_pack_start(GTK_BOX(vbox), ok_button, FALSE, FALSE, 5);

gtk_container_add(GTK_CONTAINER(window), vbox);

gtk_widget_show_all(window);
gtk_main ();

return 0;
}
```

When we run this program, we get a window that appears as in Figure 16-8.

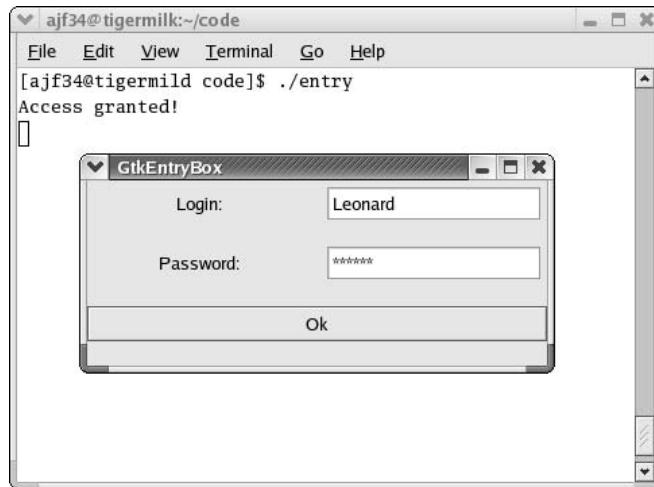


Figure 16-8

How It Works

The program creates two `GtkEntry` widgets, `username_entry` and `password_entry`, and sets `password_entry` with a visibility of `FALSE` to hide our entered password. It then creates a `GtkButton` with which we connect the “clicked” signal to the `button_clicked` callback function.

Once in the callback function, the program retrieves the entered password and compares it to the secret password, printing the appropriate message.

Notice that we have repeated `gtk_box_pack_start` statements to add the widgets to their containers. To reduce this repeated code, we'll define a helper function in later examples.

GtkSpinButton

Sometimes we'll want the user to enter a numeric value such as a maximum speed or length of device, and in these situations, a `GtkSpinButton` is ideal. `GtkSpinButton` restricts a user to entering numeric characters only, and we can set the range for allowed values between a lower and upper bound. The widget also provides up and down arrows so we can "spin" the value using only the mouse for convenience.

```
GtkWidget
+--GtkEntry
+--GtkSpinButton
```

Again, the API is straightforward, and we'll list the most commonly used calls.

```
GtkWidget* gtk_spin_button_new (GtkAdjustment *adjustment, gdouble climb_rate,
                               guint digits);
GtkWidget* gtk_spin_button_new_with_range (gdouble min, gdouble max, gdouble step);
void gtk_spin_button_set_digits (GtkSpinButton *spin_button, guint digits);
void gtk_spin_button_set_increments (GtkSpinButton *spin_button, gdouble step,
                                     gdouble page);
void gtk_spin_button_set_range (GtkSpinButton *spin_button, gdouble min,
                               gdouble max);
gdouble gtk_spin_button_get_value (GtkSpinButton *spin_button);
gint gtk_spin_button_get_value_as_int (GtkSpinButton *spin_button);
void gtk_spin_button_set_value (GtkSpinButton *spin_button, gdouble value);
```

To create a `GtkSpinButton` using `gtk_spin_button_new`, we first need to create a `GtkAdjustment` object. A `GtkAdjustment` widget is an abstract object that contains logic to deal with controlling bounded values. `GtkAdjustment` is also used in other widgets, such as `GtkHScale` and `GtkVScale`.

To create a `GtkAdjustment`, we pass in an initial value, lower and upper bounds, and increment sizes.

```
GtkObject* gtk_adjustment_new (gdouble value, gdouble lower, gdouble upper,
                             gdouble step_increment, gdouble page_increment,
                             gdouble page_size);
```

The values of `step_increment` and `page_increment` set the size of minor and major size increments. In the case of `GtkSpinButton`, the `step_increment` sets how much the value changes when the arrows are clicked. `page_increment` and `page_size` are not important when used with `GtkSpinButton` widgets.

`climb_rate`, the second parameter of `gtk_spin_button_new`, controls how quickly the values "spin" when you press and hold the arrow buttons. Finally, `digits` sets the precision of the widget, so a digit of 3 would set the spin button to display 0.00.

`gtk_spin_button_new_with_range` is a convenience method that creates a `GtkAdjustment` for us. We simply pass in the lower bound, upper bound, and step rate.

Reading the current value is easy with `gtk_spin_button_get_value`, and if we want an integer value, we can use `gtk_spin_button_get_value_as_int`.

Try It Out—GtkSpinButton

We'll now see a GtkSpinButton in action with a short example.

```
#include <gtk/gtk.h>

void closeApp ( GtkWidget *window, gpointer data)
{
    gtk_main_quit();
}

int main ( int argc, char *argv[] )
{
    GtkWidget *window;
    GtkWidget *spinbutton;
    GtkObject *adjustment;

    gtk_init (&argc, &argv);
    window = gtk_window_new(GTK_WINDOW_TOPLEVEL);
    gtk_window_set_default_size ( GTK_WINDOW(window), 300, 200 );
    g_signal_connect ( GTK_OBJECT (window), "destroy",
                      GTK_SIGNAL_FUNC ( closeApp ), NULL );

    adjustment = gtk_adjustment_new(100.0, 50.0, 150.0, 0.5, 0.05, 0.05);
    spinbutton = gtk_spin_button_new(GTK_ADJUSTMENT(adjustment), 0.01, 2);

    gtk_container_add(GTK_CONTAINER(window), spinbutton);
    gtk_widget_show_all(window);
    gtk_main ();

    return 0;
}
```

When we run this program, we get a spin button bounded between 50 and 100 (see Figure 16-9).

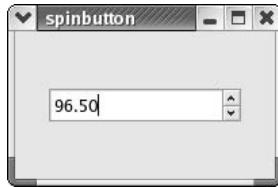


Figure 16-9

GtkButton

We've already seen GtkButton in action, but there are more button widgets descended from GtkButton that have slightly more functionality and deserve a mention.

```
GtkButton
+---GtkToggleButton
+---GtkCheckButton
+---GtkRadioButton
```

As you can see from the widget hierarchy, `GtkToggleButton` is descended directly from `GtkButton`, `GtkCheckButton` from `GtkToggleButton` and similarly with `GtkRadioButton`, each child widget specializing in purpose.

GtkToggleButton

`GtkToggleButton` is identical to a `GtkButton` except in one important regard: `GtkToggleButton` possesses *state*. That is, it can be on or off. When the user clicks a `GtkToggleButton`, it emits the “clicked” signal in the usual manner and changes (or “toggles”) its state.

The API for `GtkToggleButton` is very straightforward:

```
GtkWidget* gtk_toggle_button_new (void);
GtkWidget* gtk_toggle_button_new_with_label (const gchar *label);
gboolean gtk_toggle_button_get_active (GtkToggleButton *toggle_button);
void gtk_toggle_button_set_active (GtkToggleButton *toggle_button,
                                  gboolean is_active);
```

The interesting functions are `gtk_toggle_button_get_active` and `gtk_toggle_button_set_active`, which we call to read and set the state of the toggle button. An activity of TRUE indicates the `GtkToggleButton` is “on.”

GtkCheckButton

`GtkCheckButton` is a `GtkToggleButton` in disguise. Instead of the boring, rectangular blob of `GtkToggleButton`, `GtkCheckButton` appears as an exciting checkbox with text at the side. There are no functional differences.

```
GtkWidget* gtk_check_button_new (void);
GtkWidget* gtk_check_button_new_with_label (const gchar *label);
```

GtkRadioButton

This next button is rather different, as it can be grouped with other buttons of the same type. `GtkRadioButton` is one of those buttons that allows you to select only one option at a time from a group of options. The name comes from old-style radios that have mechanical buttons that pop back out when you press in another button.

```
GtkWidget* gtk_radio_button_new (GSList *group);
GtkWidget* gtk_radio_button_new_from_widget (GtkRadioButton *group);
GtkWidget* gtk_radio_button_new_with_label (GSList *group, const gchar *label);
void gtk_radio_button_set_group (GtkRadioButton *radio_button, GSList *group);
GSList* gtk_radio_button_get_group (GtkRadioButton *radio_button);
```

The `RadioButton` group is represented in a GLib list object, called a `GSList`. To place radio buttons in a group, we can create a `GSList` and pass it to each button using `gtk_radio_button_new` and `gtk_radio_button_get_group`. There’s an easier way, however, in the shape of `gtk_radio_button_new_with_widget`, which grabs the `GSList` out of an existing button for us. We’ll see this in action in the next example, where we try out different `GtkButtons`:

Try It Out—GtkCheckButton, GtkToggleButton, and GtkRadioButton

1. First, we declare the button pointers as global variables:

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

GtkWidget *togglebutton;
GtkWidget *checkbutton;
GtkWidget *radiobutton1, *radiobutton2;

void closeApp ( GtkWidget *window, gpointer data)
{
    gtk_main_quit();
}
```

2. Here we define a helper function that packs a GtkWidget and GtkLabel into a GtkHbox and then adds this GtkHbox into a given container widget. This helps us cut down on repeated code.

```
void add_widget_with_label ( GtkContainer * box, gchar * caption, GtkWidget *
widget)
{
    GtkWidget *label = gtk_label_new (caption);
    GtkWidget *hbox = gtk_hbox_new (TRUE, 4);

    gtk_container_add(GTK_CONTAINER (hbox), label);
    gtk_container_add(GTK_CONTAINER (hbox), widget);

    gtk_container_add(box, hbox);
}
```

3. print_active is another helper function that prints out the current state of the given GtkToggleButton with a describing string. It is called from button_clicked, which is a callback function attached to the clicked signal of the Ok button. Every time this button is clicked, we get a printout of the state of the buttons.

```
void print_active(char * button_name, GtkToggleButton *button)
{
    gboolean active = gtk_toggle_button_get_active(button);

    printf("%s is %s\n", name, active?"active":"not active");
}

void button_clicked(GtkWidget *button, gpointer data)
{
    print_active("Checkbutton", GTK_TOGGLE_BUTTON(checkbutton));
    print_active("Togglebutton", GTK_TOGGLE_BUTTON(togglebutton));
    print_active("Radiobutton1", GTK_TOGGLE_BUTTON(radiobutton1));
    print_active("Radiobutton2", GTK_TOGGLE_BUTTON(radiobutton2));
    printf("\n");
}
```

- 4.** In main, we create the button widgets, stack them up in a GtkVBox adding descriptive labels, and connect the callback signal to the Ok button.

```

gint main (gint argc, gchar *argv[])
{
    GtkWidget *window;
    GtkWidget *button;
    GtkWidget *vbox;

    gtk_init (&argc, &argv);
    window = gtk_window_new(GTK_WINDOW_TOPLEVEL);
    gtk_window_set_default_size(GTK_WINDOW(window), 200, 200);
    g_signal_connect ( GTK_OBJECT (window), "destroy",
                      GTK_SIGNAL_FUNC (closeApp), NULL);

    button = gtk_button_new_with_label("Ok");
    togglebutton = gtk_toggle_button_new_with_label("Toggle");
    checkbutton = gtk_check_button_new();
    radiobutton1 = gtk_radio_button_new(NULL);
    radiobutton2 = gtk_radio_button_new_from_widget(GTK_RADIO_BUTTON(radiobutton1));

    vbox = gtk_vbox_new (TRUE, 4);
    add_widget_with_label (GTK_CONTAINER(vbox), "ToggleButton:", togglebutton);
    add_widget_with_label (GTK_CONTAINER(vbox), "CheckButton:", checkbutton);
    add_widget_with_label (GTK_CONTAINER(vbox), "Radio 1:", radiobutton1);
    add_widget_with_label (GTK_CONTAINER(vbox), "Radio 2:", radiobutton2);
    add_widget_with_label (GTK_CONTAINER(vbox), "Button:", button);

    g_signal_connect (GTK_OBJECT(button), "clicked",
                      GTK_SIGNAL_FUNC(button_clicked), NULL);

    gtk_container_add(GTK_CONTAINER(window), vbox);
    gtk_widget_show_all(window);
    gtk_main ();

    return 0;
}

```

Figure 16-10 shows buttons.c in action, with the four common types of GtkButton.

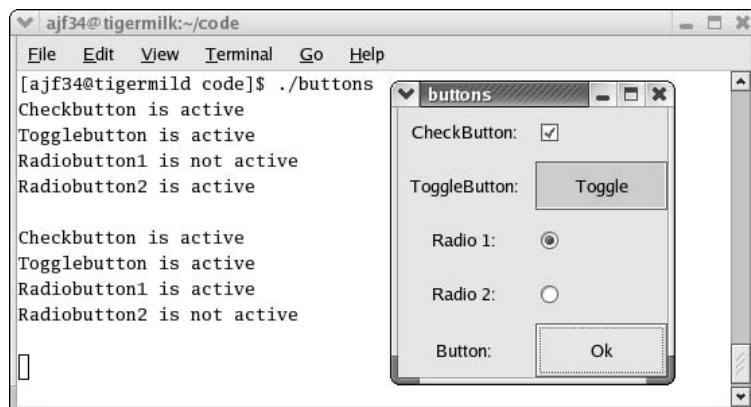


Figure 16-10

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This program is a simple example of using the four types of `GtkButton` and shows how we can read the state of the `GtkToggleButton`, `GtkCheckButton`, and `GtkRadioButton` using the single `gtk_toggle_button_get_active`. This is one of the great benefits of an Object Oriented approach—because we don't need separate `get_active` functions for each type of button, we can cut down the amount of code we need.

GtkTreeView

Up until now, we've looked at some of the simple GTK+ widgets, but not all widgets are single-line input or display devices. There are, of course, no limits to the complexity of a `GtkWidget`, and `GtkTreeView` is a great example of a widget that encapsulates a vast amount of functionality.

```
GtkWidget
 +--GtkContainer
      +--GtkTreeView
```

`GtkTreeView` is part of a family of widgets new to GTK+ 2 that creates list and tree views of data of the sort you find in a spreadsheet or file manager. Using `GtkTreeView`, we can create complex views of data, mix text, and bitmap graphics, and even input data using `GtkEntry` widgets, and so forth.

The quickest way of taking `GtkTreeView` for a test drive is to fire up the `gtk-demo` application that ships with GTK+. The demo application shows off the capability of each GTK+ widget including `GtkTreeView`, which is shown in Figure 16-11.

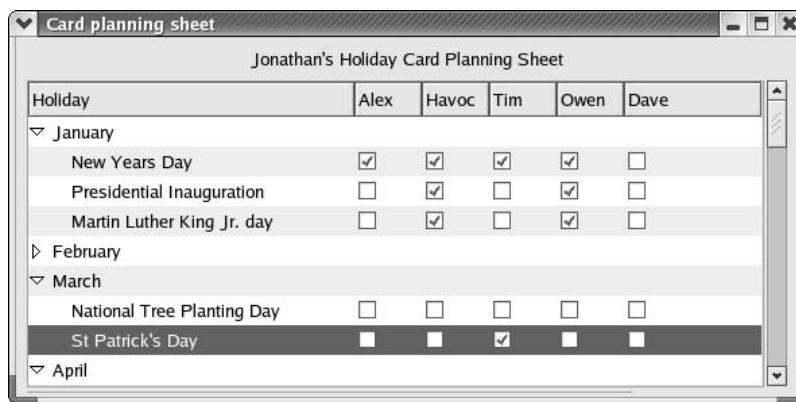


Figure 16-11

The `GtkTreeView` family is made up of four components.

- ❑ `GtkTreeView`: The Tree and List View
- ❑ `GtkTreeViewColumn`: Represents a list or tree column
- ❑ `GtkCellRenderer`: Controls drawing cells
- ❑ `GtkTreeModel`: Represents Tree and List data

The first three make up what is known as the *View*, and the last is the *Model*. The concept of separating the View from the Model (often called a Model/View/Controller, or MVC, Pattern) is not particular to GTK+, but a design increasingly favored in all programming circles.

The key advantage of the MVC design pattern is that data can be rendered simultaneously by different views without unnecessary duplication. For example, text editors can have split panes and edit different parts of the document without two copies of the document in memory.

The MVC pattern is also very popular in Web programming because it makes it easy to create a Web site that renders differently in mobile or WAP browsers than it does in desktop browsers, simply by having separate View components optimized for each browser type.

We'll start by looking at the Model component, of which GTK+ has two. `GtkTreeStore` holds multilevel data such as a directory hierarchy, and `GtkListStore` is for flat data.

To create a `GtkTreeStore` we pass in the number of columns followed by the type of each column:

```
GtkWidget *store = gtk_tree_store_new (3, G_TYPE_STRING, G_TYPE_INT,  
G_TYPE_BOOLEAN);
```

Reading, adding, editing, and removing data from the store are done with the aid of `GtkTreeIter` structures. These iterator structures point to nodes in the tree (or rows in a list) and aid us in locating and manipulating parts of the potentially very large data structure. There are several API calls to get the iterator object at various points in a tree, but we'll look at the simplest, `gtk_tree_store_append`.

Before we can add any data to the tree store, we need an iterator to point to a new row. `gtk_tree_store_append` fills in a `GtkTreeIter` object that represents a new row in the tree, as either a top-level row (if we pass `NULL` to the third argument) or as a child row (we pass the iterator of the parent row).

```
GtkTreeIter iter;  
gtk_tree_store_append (store, &iter, NULL);
```

Once we have an iterator, we can populate the row using `gtk_tree_store_set`:

```
gtk_tree_store_set (store, &iter,  
0, "Def Leppard",  
1, 1987,  
2, TRUE,  
-1);
```

We pass the column number and data in pairs, terminated by `-1`. We'll use an `enum` later to make the column numbers descriptive.

To add a branch to this row (a child row), we just need an iterator for the child row that we get by calling `gtk_tree_store_append` again, passing in the top-level row this time:

```
GtkTreeIter child;  
gtk_tree_store_append (store, &child, &iter);
```

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You can read more about `GtkTreeStore` and `GtkListStore` functions in the API documentation, so let's move on and look at the `GtkTreeView` View component.

Creating a `GtkTreeView` is simplicity itself; we just pass in our `GtkTreeStore` or `GtkListStore` model to the constructor:

```
GtkWidget *view = gtk_tree_view_new_with_model (GTK_TREE_MODEL (store));
```

It's now a case of configuring the widget to display the data exactly as we want it. For each column we must define a `GtkCellRenderer` and set the data source. We can choose to display only certain data columns, for example, or swap the display order of columns.

`GtkCellRenderer` is the object that deals with drawing each cell on screen, and there are three subclasses that deal with text cells, pixmap graphic cells, and togglebutton cells:

- `GtkCellRendererText`
- `GtkCellRendererPixBuf`
- `GtkCellRendererToggle`

We'll use the text renderer in our View: `GtkCellRendererText`:

```
GtkCellRenderer *renderer = gtk_cell_renderer_text_new ();
gtk_tree_view_insert_column_with_attributes (GTK_TREE_VIEW(view),
                                             0,
                                             "This is the column title",
                                             renderer,
                                             "text", 0,
                                             NULL);
```

Here we create the renderer and pass it to the column insert function. This function enables us to set the `GtkCellRendererText` properties in one go, passed as `NULL`-terminated key/value pairs. The parameters are the view to a column, the column number, column title, renderer, and renderer properties. We're setting the "text" attribute here, passing in the column number of the data source. `GtkCellRendererText` defines several other attributes, including underlining, font, size, and so forth.

Let's see how this works in practice in the next example, where we put a `GtkTreeView` through its paces.

Try It Out—`GtkTreeView`

1. We use an enum to label the columns so we can refer to them by name. `N_COLUMNS` conveniently is the total number of columns.

```
#include <gtk/gtk.h>

enum {
    COLUMN_TITLE,
    COLUMN_ARTIST,
    COLUMN_CATALOGUE,
    N_COLUMNS
```

```

};

void closeApp ( GtkWidget *window, gpointer data)
{
    gtk_main_quit();
}

int main (int argc, char *argv[])
{
    GtkWidget *window;
    GtkTreeStore *store;
    GtkWidget *view;
    GtkTreeIter parent_iter, child_iter;
    GtkCellRenderer *renderer;

    gtk_init(&argc, &argv);
    window = gtk_window_new(GTK_WINDOW_TOPLEVEL);
    gtk_window_set_default_size ( GTK_WINDOW(window), 300, 200 );
    g_signal_connect ( GTK_OBJECT (window), "destroy",
                      GTK_SIGNAL_FUNC ( closeApp ), NULL );
}

```

- 2.** Here we create the tree store, passing in the number and type of each column:

```

store = gtk_tree_store_new (N_COLUMNS, G_TYPE_STRING, G_TYPE_STRING,
                           G_TYPE_STRING);

```

- 3.** The next part adds a parent and child row to the tree.

```

gtk_tree_store_append (store, &parent_iter, NULL);

gtk_tree_store_set (store, &parent_iter, COLUMN_TITLE, "Dark Side of the Moon",
                    COLUMN_ARTIST, "Pink Floyd",
                    COLUMN_CATALOGUE, "B000024D4P",
                    -1);

gtk_tree_store_append (store, &child_iter, &parent_iter);

gtk_tree_store_set (store, &child_iter, COLUMN_TITLE, "Speak to Me",
                    -1);

view = gtk_tree_view_new_with_model (GTK_TREE_MODEL (store));

```

- 4.** Finally, we add columns to the view, setting their data source and titles.

```

renderer = gtk_cell_renderer_text_new ();
gtk_tree_view_insert_column_with_attributes (GTK_TREE_VIEW(view),
                                             COLUMN_TITLE,
                                             "Title", renderer,
                                             "text", COLUMN_TITLE,
                                             NULL);
gtk_tree_view_insert_column_with_attributes (GTK_TREE_VIEW(view),
                                             COLUMN_ARTIST,
                                             "Artist", renderer,
                                             "text", COLUMN_ARTIST,
                                             NULL);

```

```
        NULL) ;  
    gtk_tree_view_insert_column_with_attributes (GTK_TREE_VIEW(view),  
                                                COLUMN_CATALOGUE,  
                                                "Catalogue", renderer,  
                                                "text", COLUMN_CATALOGUE,  
                                                NULL) ;  
  
    gtk_container_add(GTK_CONTAINER(window), view);  
  
    gtk_widget_show_all(window);  
    gtk_main ();  
  
    return 0;  
}
```

We'll use a GtkTreeView as the core of our CD application, where we'll modify the contents of the GtkTreeView as we query the CD database.

We've finished our tour of GTK+ widgets, and now we'll turn our attention to the other half of the story: GNOME. We'll see how to add menus to our application using the GNOME libraries and how the GNOME widgets make programming for the GNOME desktop even easier.

GNOME Widgets

GTK+ is designed to be desktop neutral; that is, GTK+ doesn't make any assumptions that it's running in GNOME, or even that it's running on Linux. The reason behind this is that GTK+ can be ported to run on Windows or any other windowing system with relative ease. The upshot of this is that GTK+ lacks the means to tie the program into the desktop, such as a means of saving program configuration, displaying help files, or programming applets (applets are small utilities that run on the edge panels).

The GNOME libraries include GNOME widgets that extend GTK+ and replace parts of GTK+ with easier-to-use widgets. In this section we'll look at how to program using GNOME widgets.

Before we use the GNOME libraries, we must initialize them at the start of our programs in the same way we did GTK+. We call `gnome_program_init` just as we do `gtk_init` for purely GTK+ programs.

This function takes an `app_id` and `app_version` that we use to describe our program to GNOME, a `module_info` that tells GNOME which library module to initialize, command line parameters, and application properties set as a NULL-terminated list of name/value pairs.

```
GnomeProgram* gnome_program_init (const char *app_id, const char *app_version,  
                                 const GnomeModuleInfo *module_info,  
                                 int argc, char **argv,  
                                 const char *first_property_name,  
                                 ...);
```

The optional property list allows us to set things such as the directory to look for bitmap graphics.

Try It Out—A GNOME Window

Let's look at a GNOME program now, by looking at the GNOME replacement to `GtkWindow`, a `GnomeApp` widget.

Type in this program and call it `gnome1.c`:

```
#include <gnome.h>

int main (int argc, char *argv[])
{
    GtkWidget *app;

    gnome_program_init ("gnome1", "1.0", MODULE, argc, argv, NULL);
    app = gnome_app_new ("gnome1", "The Window Title");
    gtk_widget_show(app);
    gtk_main ();

    return 0;
}
```

To compile, we need to include the GNOME headers, so we pass `libgnomeui` and `libgnome` to `pkg-config`:

```
$ gcc gnome1.c -o gnome1 `pkg-config --cflags --libs libgnome-2.0 libgnomeui-2.0`
```

A `GnomeApp` widget extends `GtkWindow` and makes it easy to add menus, toolbars, and a status bar along the bottom. Since it inherits from `GtkWindow`, we can use any `GtkWindow` function with a `GnomeApp` widget. We'll look at creating menus now, and we'll add a status bar in our final example.

You can use GTK+ to create menus, but GNOME provides helpful structures and macros that make the job much easier. The online GTK+ documentation describes how to create menus in GTK+.

GNOME Menus

Creating a drop-down menu bar in GNOME is pleasantly simple. Each menu in the menu bar is represented by an array of `GNOMEUIInfo` structs with each element in the array corresponding to a single menu item. For example, if we have File, Edit, and View menus, we will have three arrays describing the contents of each menu.

Once we've defined each individual menu, we create the menu bar itself by referencing these arrays in another array of `GNOMEUIInfo` structs.

The `GNOMEUIInfo` struct is a little complicated and needs to be explained.

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```
typedef struct {
    GnomeUIInfoType type;
    gchar const *label;
    gchar const *hint;
    gpointer moreinfo;
    gpointer user_data;
    gpointer unused_data;
    GnomeUIPixmapType pixmap_type;
    gconstpointer pixmap_info;
    guint accelerator_key;
    GdkModifierType ac_mods;
    GtkWidget *widget;
} GnomeUIInfo;
```

The first item in the struct, `type`, defines the type of the menu element that follows. It can be one of 10 `GnomeUIInfoTypes` defined by GNOME:

| GnomeUIInfoType | Description |
|---|--|
| <code>GNOME_APP_UI_ENDOFINFO</code> | Denotes that this is last menu item in the array. |
| <code>GNOME_APP_UI_ITEM</code> | A normal menu item or a radio button if preceded by a <code>GNOME_APP_UI_RADIOITEMS</code> entry. |
| <code>GNOME_APP_UI_TOGGLEITEM</code> | A toggle button or check button menu item. |
| <code>GNOME_APP_UI_RADIOITEMS</code> | A radio button group. |
| <code>GNOME_APP_UI_SUBTREE</code> | Denotes this element is a submenu. Set <code>moreinfo</code> to point to the submenu array. |
| <code>GNOME_APP_UI_SEPARATOR</code> | Inserts a separator line in the menu. |
| <code>GNOME_APP_UI_HELP</code> | Creates a help topic list for use in a Help menu. |
| <code>GNOME_APP_UI_BUILDER_DATA</code> | Specifies builder data for the following entries. |
| <code>GNOME_APP_UI_ITEM_CONFIGURABLE</code> | A configurable menu item. |
| <code>GNOME_APP_UI_SUBTREE_STOCK</code> | Same as <code>GNOME_APP_UI_SUBTREE</code> except that the label text should be looked up in the gnome-libs catalog. |
| <code>GNOME_APP_UI_INCLUDE</code> | Same as <code>GNOME_APP_UI_SUBTREE</code> except that the items are included in the current menu and not as a submenu. |

The second and third members of the struct define the text of the menu item and the pop-up hint. (The hint is shown in the status bar at the bottom of the window).

The purpose of `moreinfo` depends on `type`. For `ITEM` and `TOGGLEITEM`, it points to the callback function to be called when the menu item is activated. For `RADIOITEMS` it points to an array of `GnomeUIInfo` structs that are grouped radio buttons.

`user_data` is an arbitrary pointer passed to the callback function. `pixmap_type` and `pixmap_info` allow us to add a bitmap icon to the menu item, and `accelerator_key` and `ac_mods` help us define a keyboard shortcut.

Finally, `widget` is used to internally hold the menu item widget pointer by the menu creation function.

Try It Out—GNOME Menus

Let's try out menus with this short program. Call it `menu1.c`.

```
#include <gnome.h>

void closeApp ( GtkWidget *window, gpointer data)
{
    gtk_main_quit();
}
```

1. We define a callback function for the menu items called `item_clicked`:

```
void item_clicked(GtkWidget *widget, gpointer user_data)
{
    printf("Item Clicked!\n");
}
```

2. Next are our menu definitions. We have a submenu, top-level menu, and a menu bar array.

```
static GnomeUIInfo submenu[] = {
    {GNOME_APP_UI_ITEM, "SubMenu", "SubMenu Hint",
     GTK_SIGNAL_FUNC(item_clicked), NULL, NULL, 0, NULL, 0, 0, NULL},
    {GNOME_APP_UI_ENDOFINFO, NULL, NULL, NULL, NULL, NULL, 0, NULL, 0, 0, NULL}
};

static GnomeUIInfo menu[] = {
    {GNOME_APP_UI_ITEM, "Menu Item 1", "Menu Hint",
     NULL, NULL, NULL, 0, NULL, 0, 0, NULL},
    {GNOME_APP_UI_SUBTREE, "Menu Item 2", "Menu Hint", submenu,
     NULL, NULL, 0, NULL, 0, 0, NULL},
    {GNOME_APP_UI_ENDOFINFO, NULL, NULL, NULL, NULL, NULL, 0, NULL, 0, 0, NULL}
};

static GnomeUIInfo menubar[] = {
    {GNOME_APP_UI_SUBTREE, "Toplevel Item", NULL, menu, NULL,
     NULL, 0, NULL, 0, 0, NULL},
    {GNOME_APP_UI_ENDOFINFO, NULL, NULL, NULL, NULL, NULL, 0, NULL, 0, 0, NULL}
};
```

3. In `main`, we deal with the usual initialization and then create our `GnomeApp` widget and set the menus:

```
int main (int argc, char *argv[])
{
    GtkWidget *app;
```

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```
gnome_program_init ("gnome1", "0.1", LIBGNOMEUI_MODULE,
                    argc, argv,
                    GNOME_PARAM_NONE) ;
app = gnome_app_new("gnome1", "Menus, menus, menus") ;

gtk_window_set_default_size ( GTK_WINDOW(app), 300, 200) ;
g_signal_connect ( GTK_OBJECT (app), "destroy",
                   GTK_SIGNAL_FUNC ( closeApp), NULL) ;

gnome_app_create_menus ( GNOME_APP(app), menubar) ;

gtk_widget_show(app) ;

gtk_main();
return 0;

}
```

Try running `menu1` and see the menu bar, submenu, and callback GNOME menu in action, as shown in Figure 16-12.

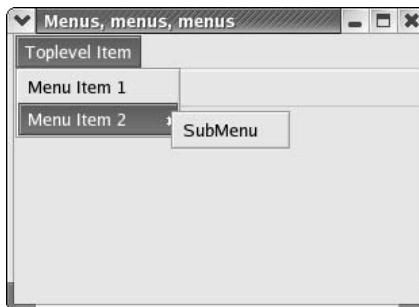


Figure 16-12

The `GnomeUIInfo` struct is hardly programmer-friendly, given that it consists of 11 entries, most of which are normally `NULL` or zero valued. It's quite easy to make a mistake typing them in, and it's difficult to tell one field from another in a long array of items. To improve the situation, GNOME defines macros to take out the hard work of writing the structs by hand. These macros also add icons and keyboard accelerators for us, all for no cost. In fact, there's rarely any reason to use anything but these macros.

There are two sets of macros, the first of which defines individual menu items. They take two parameters, the callback function pointer, and user data.

```
#include <libgnomeui/libgnomeui.h>

#define GNOMEUIINFO_MENU_OPEN_ITEM      (cb, data)
#define GNOMEUIINFO_MENU_SAVE_ITEM     (cb, data)
#define GNOMEUIINFO_MENU_SAVE_AS_ITEM   (cb, data)
#define GNOMEUIINFO_MENU_PRINT_ITEM    (cb, data)
#define GNOMEUIINFO_MENU_PRINT_SETUP_ITEM(cb, data)
#define GNOMEUIINFO_MENU_CLOSE_ITEM     (cb, data)
```

```

#define      GNOMEUIINFO_MENU_EXIT_ITEM      (cb, data)
#define      GNOMEUIINFO_MENU_QUIT_ITEM     (cb, data)
#define      GNOMEUIINFO_MENU_CUT_ITEM      (cb, data)
#define      GNOMEUIINFO_MENU_COPY_ITEM     (cb, data)
#define      GNOMEUIINFO_MENU_PASTE_ITEM    (cb, data)
#define      GNOMEUIINFO_MENU_SELECT_ALL_ITEM(cb, data)
... etc

```

And the second set is for top-level definitions to which we simply pass the array:

```

#define      GNOMEUIINFO_MENU_FILE_TREE      (tree)
#define      GNOMEUIINFO_MENU_EDIT_TREE      (tree)
#define      GNOMEUIINFO_MENU_VIEW_TREE      (tree)
#define      GNOMEUIINFO_MENU_SETTINGS_TREE  (tree)
#define      GNOMEUIINFO_MENU_FILES_TREE    (tree)
#define      GNOMEUIINFO_MENU_WINDOWS_TREE   (tree)
#define      GNOMEUIINFO_MENU_HELP_TREE     (tree)
#define      GNOMEUIINFO_MENU_GAME_TREE     (tree)

```

Try It Out—Menus with GNOME Macros

Let's make use of these menus and see how the macros work. Make the following changes to `menu1.c`, and call this `menu2.c`.

```

#include <gnome.h>

static GnomeUIInfo filemenu[] = {
    GNOMEUIINFO_MENU_NEW_ITEM ("New", "Menu Hint", NULL, NULL ),
    GNOMEUIINFO_MENU_OPEN_ITEM (NULL, NULL),
    GNOMEUIINFO_MENU_SAVE_AS_ITEM (NULL, NULL),
    GNOMEUIINFO_SEPARATOR,
    GNOMEUIINFO_MENU_EXIT_ITEM (NULL, NULL),
    GNOMEUIINFO_END
};

static GnomeUIInfo editmenu[] = {
    GNOMEUIINFO_MENU_FIND_ITEM (NULL, NULL),
    GNOMEUIINFO_END
};

static GnomeUIInfo menubar[] = {
    GNOMEUIINFO_MENU_FILE_TREE (filemenu),
    GNOMEUIINFO_MENU_EDIT_TREE (editmenu),
    GNOMEUIINFO_END
};

int main (int argc, char *argv[])
{
    GtkWidget *app, *toolbar;

    gnome_program_init ("gnome1", "0.1", LIBGNOMEUI_MODULE,
                        argc, argv,
                        GNOME_PARAM_NONE);

```

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```
app = gnome_app_new("gnome1", "Menus, menus, menus");
gtk_window_set_default_size ( GTK_WINDOW(app), 300, 200);
gnome_app_create_menus ( GNOME_APP(app), menubar);

gtk_widget_show(app);

gtk_main();
return 0;
}
```

By using the `libgnomeui` macros in `menu2.c`, we've significantly reduced the code we need to type and made the menu code much more readable. The macros save us time and effort when creating menus and make the wording, keyboard shortcuts, and icons consistent with other GNOME applications. Try to use them in your own applications whenever you can.

Figure 16-13 shows `menu3.c` in action with the now standardized GNOME menu items.

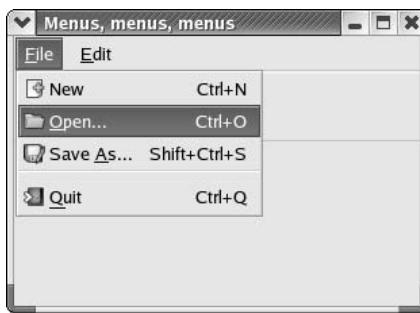


Figure 16-13

Dialogs

An important part of any GUI application is interacting with and informing users of important events. Usually, we'll create a temporary window with Ok and Cancel buttons for this, and if the information is important enough to require an immediate response, such as deleting a file, we'll want to block access to all other windows until the user has made a choice.

What we've described here is a *dialog*, and GTK+ provides special dialog widgets that are descended from `GtkWindow` to make our programming job that much easier.

GtkDialog

As we can see, `GtkDialog` is a child of `GtkWindow` and therefore inherits all its functions and properties.

```
GtkWindow
 +--GtkDialog
```

GtkDialog divides the window into two areas, one for widget content and one for buttons that run along the bottom. We can specify the buttons we want as well as other dialog settings when we create the dialog box.

```
GtkWidget* gtk_dialog_new_with_buttons (const gchar *title,
                                       GtkWindow *parent,
                                       GtkDialogFlags flags,
                                       const gchar *first_button_text,
                                       ...);
```

This function creates a dialog window complete with a title and buttons. The second parameter, parent, should point to the main window of our application so that GTK+ can make sure the dialog stays attached to the window and is minimized when the main window is minimized.

flags determines the combination of properties the dialog can take:

- GTK_DIALOG_MODAL
- GTK_DIALOG_DESTROY_WITH_PARENT
- GTK_DIALOG_NO_SEPARATOR

We can combine the flags using the bitwise OR operator; for example, (GTK_DIALOG_MODAL | GTK_DIALOG_NO_SEPARATOR) is both a modal dialog *and* one with no separator line between the main window area and the button area.

The remaining parameters are a NULL-terminated list of buttons and corresponding response code. We'll see exactly what this response code means when we see `gtk_dialog_run`. Normally we'll pick buttons from the long list of stock buttons that GTK+ defines as we get ready-made icons in the buttons.

Here's how we would create a dialog with Ok and Cancel buttons that return GTK_RESPONSE_ACCEPT and GTK_RESPONSE_REJECT when those respective buttons are clicked:

```
GtkWidget *dialog = gtk_dialog_new_with_buttons ("Important question",
                                                parent_window,
                                                GTK_DIALOG_DESTROY_WITH_PARENT,
                                                GTK_STOCK_OK, GTK_RESPONSE_ACCEPT,
                                                GTK_STOCK_CANCEL, GTK_RESPONSE_REJECT,
                                                NULL);
```

We've chosen to have two buttons here, but there's no limit to the number of buttons you can have in the dialog.

Naturally, we'll need to add content to our dialog, and for this GtkDialog contains a ready-made GtkVBox to populate with widgets. We get a pointer directly from the object:

```
GtkWidget *vbox = GTK_DIALOG(dialog) ->vbox;
```

We use this GtkVbox in the usual way, with `gtk_box_pack_start` or something similar.

Once we've created a dialog box, the next step is to present it to the user and wait for a response. This can be done in one of two ways: in a modal fashion, which blocks all input except to the dialog box, or a nonmodal way, which treats the dialog the same as any other window. Let's look at running a modal dialog first.

Modal Dialog Box

A modal dialog box forces the user to respond before any other action can take place. It's useful in situations where the user is about to do something with serious repercussions or to report errors and warning messages.

You can make a dialog box modal by setting the `GTK_DIALOG_MODAL` flag and calling `gtk_widget_show`, but there's a better way. `gtk_dialog_run` does the hard work for us by stopping further program execution until a button is pressed.

When the user presses a button (or the dialog is destroyed), `gtk_dialog_run` returns with an `int` result that indicates which button the user pressed. GTK+ usefully defines an `enum` to describe the possible values:

```
typedef enum
{
    GTK_RESPONSE_NONE = -1,
    GTK_RESPONSE_REJECT = -2,
    GTK_RESPONSE_ACCEPT = -3,
    GTK_RESPONSE_DELETE_EVENT = -4
    GTK_RESPONSE_OK = -5,
    GTK_RESPONSE_CANCEL = -6,
    GTK_RESPONSE_CLOSE = -7,
    GTK_RESPONSE_YES = -8,
    GTK_RESPONSE_NO = -9,
    GTK_RESPONSE_APPLY = -10,
    GTK_RESPONSE_HELP = -11
} GtkResponseType;
```

Now we can explain the result code passed in `gtk_dialog_new_with_buttons`—the result code is a `GtkResponseType` that `gtk_dialog_run` returns when that button is pressed. We get a result of `GTK_RESPONSE_NONE` if the dialog is destroyed (this happens if the user clicks the close icon, for example).

The `switch` construction is ideal for calling the appropriate logic:

```
GtkWidget *dialog = create_dialog();
int result = gtk_dialog_run(GTK_DIALOG(dialog));

switch (result)
{
    case GTK_RESPONSE_ACCEPT:
        delete_file();
        break;
    case GTK_RESPONSE_REJECT:
        do_nothing();
        break;
    default:
```

```
    dialog_was_cancelled ();
    break;
}
gtk_widget_destroy (dialog);
```

That's all there is to simple modal dialogs in GTK+. As you can see, there's very little code involved or effort expended. All we do at the end is tidy up with a `gtk_widget_destroy`.

Things aren't so straightforward, however, when we want a nonmodal dialog box. We can't use `gtk_dialog_run`—instead we must connect callback functions to the dialog buttons.

Nonmodal Dialogs

We've seen how to use `gtk_dialog_run` to create a modal (blocking) dialog. Nonmodal dialogs work slightly differently, although we create them in the same way. Instead of calling `gtk_dialog_run`, we connect a callback function to the `GtkDialog` "response" signal that is emitted when a button is clicked or the window is destroyed.

Connecting the callback signal is done in the usual way, with the difference being that the callback function has an extra response argument that plays the same role as the return value of `gtk_dialog_run`. This code snippet shows the basic use of a nonmodal dialog:

```
void dialog_button_clicked (GtkWidget *dialog, gint response, gpointer user_data)
{
    switch (result)
    {

        case GTK_RESPONSE_ACCEPT:
            do_stuff();
            break;
        case GTK_RESPONSE_REJECT:
            do_nothing();
            break;
        default:
            dialog_was_cancelled ();
            break;

    }
    gtk_widget_destroy(dialog);
}

int main()
{
    ...
    GtkWidget *dialog = create_dialog();

    g_signal_connect ( GTK_OBJECT (dialog), "response",
                      GTK_SIGNAL_FUNC (dialog_button_clicked), user_data );

    gtk_widget_show(dialog);
    ...
}
```

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With nonmodal dialogs, complications can arise because the user isn't compelled to respond instantly and can minimize and forget about the dialog. We need to consider what to do if the user tries to open the dialog a second time before closing the first instance. What we need to do is check if the dialog pointer is `NULL`, and if not to reshew the existing dialog by calling `gtk_window_present`. You can see this in action in the "CD Database Application" section near the end of this chapter.

GtkMessageDialog

For very simple dialog boxes, even `GtkDialog` is unnecessarily complicated.

```
GtkDialog
+--GtkMessageDialog
```

With `GtkMessageDialog`, we can create a message dialog box in a single line of code.

```
GtkWidget* gtk_message_dialog_new (GtkWindow *parent, GtkDialogFlags flags,
                                  GtkMessageType type,
                                  GtkButtonsType buttons,
                                  const gchar *message_format,
                                  ...);
```

This function creates a dialog complete with icons, a title, and configurable buttons. The parameter `type` sets the stock icon and title of the dialog according to its intended purpose; for instance, the warning type has a warning triangle icon. There are four possible values to cover the simple dialog types we most often come across:

- `GTK_MESSAGE_INFO`
- `GTK_MESSAGE_WARNING`
- `GTK_MESSAGE_QUESTION`
- `GTK_MESSAGE_ERROR`

With a `GtkMessageDialog`, we can pass a `GtkButtonsType` rather than list each button individually, as described in the following table.

| <code>GtkButtonsType</code> | Description |
|------------------------------------|-----------------------|
| <code>GTK_BUTTONS_OK</code> | An Ok button |
| <code>GTK_BUTTONS_CLOSE</code> | A Close button |
| <code>GTK_BUTTONS_CANCEL</code> | A Cancel button |
| <code>GTK_BUTTONS_YES_NO</code> | Yes and No buttons |
| <code>GTK_BUTTONS_OK_CANCEL</code> | Ok and Cancel buttons |
| <code>GTK_BUTTONS_NONE</code> | No buttons |

All that remains is the text of the dialog, which we can make up from a substituted string in the same way we do with `printf`. In this example, we ask the user if she is sure she wants to delete a file:

```
GtkWidget *dialog = gtk_message_dialog_new (main_window,
                                             GTK_DIALOG_DESTROY_WITH_PARENT,
                                             GTK_MESSAGE_QUESTION,
                                             GTK_BUTTONS_YES_NO,
                                             "Are you sure you wish to delete %s?",
                                             filename);
result = gtk_dialog_run (GTK_DIALOG (dialog));
gtk_widget_destroy (dialog);
```

This dialog appears like that in Figure 16-14.

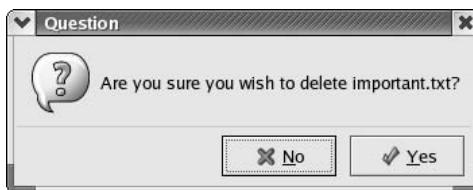


Figure 16-14

`GtkMessageDialog` is the simplest way of communicating information or asking yes/no type questions. We'll make use of them in the following section, when we put our knowledge to use by creating a GUI for our CD application.

CD Database Application

In the previous chapters we've developed a CD database with MySQL and a C interface. We'll now show how easy it is to put a GUI front end using GNOME/GTK+, and how quickly we can develop a rich user interface.

For the sake of brevity and clarity we'll develop a basic, bare-bones interface that implements only a subset of the features—we won't allow adding of track information to CDs or deleting of CDs, for example. We'll try to see all of the widgets we've covered in this chapter in action in our application so that we can see how we use them in a real-life situation.

The key features we'll code are

- ❑ Logging on to the database from the GUI
- ❑ Searching for a CD
- ❑ Displaying CD and track information
- ❑ Adding a CD to the database
- ❑ Creating an About window
- ❑ Confirming when the user wishes to quit

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We'll divide our code into three source files that share a common header file, `cdapp_gnome.h`. The source files will separate the functions that create windows and dialogs—interface generating functions—from callback functions.

Try It Out—`cdapp_gnome.h`

We'll look at `cdapp_gnome.h` and see the functions that we'll be implementing.

1. We include the GNOME headers and the header file for the interface functions we developed in Chapter 8.

```
#include <gnome.h>
#include "app_mysql.h"
```

2. The enum labels the columns of the `GtkTreeView` widget that we'll use to display the CDs and tracks.

```
enum {
    COLUMN_TITLE,
    COLUMN_ARTIST,
    COLUMN_CATALOGUE,
    N_COLUMNS
};
```

3. We have three window-creation functions in `interface.c`:

```
GtkWidget *create_main_window();
GtkWidget *create_login_dialog();
GtkWidget *create_adddc_dialog();
```

4. Callback functions for the menu items, toolbar, dialog buttons, and search button are in `callbacks.c`:

```
/* Callback to quit application */
void quit_app( GtkWidget * window, gpointer data);

/* Callback useful for confirming exit before quitting */
gboolean delete_event_handler ( GtkWidget *window, GdkEvent *event, gpointer data);

/* Callback connected to 'response' signal of addcd dialog */
void addcd_dialog_button_clicked (GtkDialog * dialog, gint response,
                                  gpointer userdata);

/* Callback for menu and toolbar 'Add CD' button */
void on_adddc_activate (GtkWidget *widget, gpointer user_data);

/* Callback for menu 'About' button */
void on_about_activate (GtkWidget *widget, gpointer user_data);

/* Callback for search button */
void on_search_button_clicked (GtkWidget *widget, gpointer userdata);
```

Try It Out—interface.c

Let's take a look first at `interface.c`, where we define the windows and dialogs we use in the application:

1. First, some widget pointers that we refer to in `callbacks.c` and `main.c`:

```
#include "app_gnome.h"

GtkWidget *treeview;
GtkWidget *appbar;
GtkWidget *artist_entry;
GtkWidget *title_entry;
GtkWidget *catalogue_entry;
GtkWidget *username_entry;
GtkWidget *password_entry;
```

2. `app` is the main window pointer that has file scope.

```
static GtkWidget *app;
```

3. We define a helper function that adds a widget with given label text to a container.

```
void add_widget_with_label ( GtkContainer *box, gchar *caption, GtkWidget *widget)
{
    GtkWidget *label = gtk_label_new (caption);
    GtkWidget *hbox = gtk_hbox_new (TRUE, 4);

    gtk_container_add(GTK_CONTAINER (hbox), label);
    gtk_container_add(GTK_CONTAINER (hbox), widget);

    gtk_container_add(box, hbox);
}
```

4. The menubar definitions use GNOMEUIINFO macros for convenience.

```
static GnomeUIInfo filemenu[] =
{
    GNOMEUIINFO_MENU_NEW_ITEM ("_New CD", NULL, on_adddcd_activate, NULL),
    GNOMEUIINFO_SEPARATOR,
    GNOMEUIINFO_MENU_EXIT_ITEM (close_app, NULL),
    GNOMEUIINFO_END
};

static GnomeUIInfo helpmenu[] =
{
    GNOMEUIINFO_MENU_ABOUT_ITEM (on_about_activate, NULL),
    GNOMEUIINFO_END
};

static GnomeUIInfo menubar[] =
{
    GNOMEUIINFO_MENU_FILE_TREE (filemenu),
```

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```
GNOMEUIINFO_MENU_HELP_TREE (helpmenu),  
GNOMEUIINFO_END  
};
```

5. Here we create the main window, add menu and toolbar, set its size, center on screen, and assemble the widgets that make up the interface. Note that the function doesn't show the window onscreen, but returns a pointer to the window instead.

```
GtkWidget * create_main_window()  
{  
    GtkWidget *toolbar;  
    GtkWidget *vbox;  
    GtkWidget *hbox;  
    GtkWidget *label;  
    GtkWidget *entry;  
    GtkWidget *search_button;  
    GtkWidget *scrolledwindow;  
    GtkCellRenderer *renderer;  
  
    app = gnome_app_new ("GnomeCD", "CD Database");  
  
    gtk_window_set_position ( GTK_WINDOW( app ), GTK_WIN_POS_CENTER );  
    gtk_window_set_default_size ( GTK_WINDOW( app ), 540, 480 );  
  
    gnome_app_create_menus ( GNOME_APP (app), menubar );
```

6. We create the toolbar using GTK+ stock icons and connect the callback functions.

```
toolbar = gtk_toolbar_new ();  
gnome_app_add_toolbar (GNOME_APP (app), GTK_TOOLBAR (toolbar), "toolbar",  
                      BONOBO_DOCK_ITEM_BEH_EXCLUSIVE,  
                      BONOBO_DOCK_TOP, 1, 0, 0);  
gtk_container_set_border_width (GTK_CONTAINER (toolbar), 1);  
gtk_toolbar_insert_stock (GTK_TOOLBAR (toolbar),  
                         "gtk-add",  
                         "Add new CD",  
                         NULL, GTK_SIGNAL_FUNC (on_addcd_activate), NULL, -  
1);  
gtk_toolbar_insert_space (GTK_TOOLBAR (toolbar), 1);  
gtk_toolbar_insert_stock (GTK_TOOLBAR (toolbar),  
                         "gtk-quit",  
                         "Quit the Application",  
                         NULL, GTK_SIGNAL_FUNC (on_quit_activate), NULL, -  
1);
```

7. Here we create widgets that we'll use to search for a CD.

```
label = gtk_label_new("Search String:");  
entry = gtk_entry_new ();  
search_button = gtk_button_new_with_label("Search");
```

8. `gtk_scrolled_window` provides scrollbars to allow a widget (in this case a `GtkTreeView`) to expand beyond the window size.

```

scrolledwindow = gtk_scrolled_window_new (NULL, NULL);
gtk_scrolled_window_set_policy (GTK_SCROLLED_WINDOW (scrolledwindow),
                               GTK_POLICY_AUTOMATIC,
                               GTK_POLICY_AUTOMATIC);

```

9. Next, we arrange the interface using container widgets in the usual way.

```

vbox = gtk_vbox_new (FALSE, 0);
hbox = gtk_hbox_new (FALSE, 0);
gtk_box_pack_start (GTK_BOX (vbox), hbox, FALSE, FALSE, 5);
gtk_box_pack_start (GTK_BOX (hbox), label, FALSE, FALSE, 5);
gtk_box_pack_start (GTK_BOX (hbox), entry, TRUE, TRUE, 6);
gtk_box_pack_start (GTK_BOX (hbox), search_button, FALSE, FALSE, 5);
gtk_box_pack_start (GTK_BOX (vbox), scrolledwindow, TRUE, TRUE, 0);

```

10. Then we create the `GtkTreeView` widget, add three columns, and place it in the `GtkScrolledWindow`.

```

treeview = gtk_tree_view_new ();
renderer = gtk_cell_renderer_text_new ();
gtk_tree_view_insert_column_with_attributes (GTK_TREE_VIEW(treeview),
                                             COLUMN_TITLE,
                                             "Title", renderer,
                                             "text", COLUMN_TITLE,
                                             NULL);
gtk_tree_view_insert_column_with_attributes (GTK_TREE_VIEW(treeview),
                                             COLUMN_ARTIST,
                                             "Artist", renderer,
                                             "text", COLUMN_ARTIST,
                                             NULL);
gtk_tree_view_insert_column_with_attributes (GTK_TREE_VIEW(treeview),
                                             COLUMN_CATALOGUE,
                                             "Catalogue", renderer,
                                             "text", COLUMN_CATALOGUE,
                                             NULL);

gtk_tree_view_set_search_column (GTK_TREE_VIEW (treeview),
                                 COLUMN_TITLE);

gtk_container_add (GTK_CONTAINER (scrolledwindow), treeview);

```

11. Finally, we set the contents of the main window, add a `GnomeAppbar`, and connect the necessary callbacks.

```

gnome_app_set_contents (GNOME_APP (app), vbox);

appbar = gnome_appbar_new (FALSE, TRUE, GNOME_PREFERENCES_NEVER);
gnome_app_set_statusbar (GNOME_APP (app), appbar);

gnome_app_install_menu_hints (GNOME_APP (app), menubar);

```

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```
g_signal_connect (GTK_OBJECT (search_button), "clicked",
                  GTK_SIGNAL_FUNC (on_search_button_clicked),
                  entry);

g_signal_connect (GTK_OBJECT (app), "delete_event",
                  GTK_SIGNAL_FUNC ( delete_event_handler ),
                  NULL);

g_signal_connect (GTK_OBJECT (app), "destroy",
                  GTK_SIGNAL_FUNC ( quit_app ), NULL);

return app;
}
```

- 12.** The next function creates a simple dialog box that enables us to add a new CD to the database. It consists of entry boxes for the artist, title, and catalogue fields, as well as Ok and Cancel buttons.

```
GtkWidget *create_addcd_dialog()
{
    artist_entry = gtk_entry_new();
    title_entry = gtk_entry_new();
    catalogue_entry = gtk_entry_new();

    GtkWidget *dialog = gtk_dialog_new_with_buttons ("Add CD",
                                                    app,
                                                    GTK_DIALOG_DESTROY_WITH_PARENT,
                                                    GTK_STOCK_OK,
                                                    GTK_RESPONSE_ACCEPT,
                                                    GTK_STOCK_CANCEL,
                                                    GTK_RESPONSE_REJECT,
                                                    NULL);

    add_widget_with_label ( GTK_CONTAINER (GTK_DIALOG (dialog) ->vbox),
                           "Artist", artist_entry);
    add_widget_with_label ( GTK_CONTAINER (GTK_DIALOG (dialog) ->vbox),
                           "Title", title_entry);
    add_widget_with_label ( GTK_CONTAINER (GTK_DIALOG (dialog) ->vbox),
                           "Catalogue", catalogue_entry);

    g_signal_connect ( GTK_OBJECT (dialog), "response",
                      GTK_SIGNAL_FUNC (addcd_dialog_button_clicked), NULL);

    return dialog;
}
```

- 13.** The database requires us to log in before we query it, so this function creates a dialog to enter the username and password.

```
GtkWidget *create_login_dialog()
{
    GtkWidget *dialog = gtk_dialog_new_with_buttons ("Database Login",
                                                    app,
                                                    GTK_DIALOG_MODAL,
                                                    GTK_STOCK_OK,
```

```
    GTK_RESPONSE_ACCEPT,
    GTK_STOCK_CANCEL,
    GTK_RESPONSE_REJECT,
    NULL) ;

username_entry = gtk_entry_new();
password_entry = gtk_entry_new();

gtk_entry_set_visibility(GTK_ENTRY (password_entry), FALSE);

add_widget_with_label ( GTK_CONTAINER (GTK_DIALOG (dialog)->vbox) , "Username",
                        username_entry);
add_widget_with_label ( GTK_CONTAINER (GTK_DIALOG (dialog)->vbox) , "Password",
                        password_entry);

gtk_widget_show_all(GTK_WIDGET (GTK_DIALOG (dialog)->vbox)) ;

return dialog;
}
```

Try It Out—callbacks.c

1. First, we need to include the header file and reference some global variables defined in `interface.c` so that we can read and update certain widget properties.

```
#include "app_gnome.h"

extern GtkWidget *treeview;
extern GtkWidget *app;
extern GtkWidget *appbar;
extern GtkWidget *artist_entry;
extern GtkWidget *title_entry;
extern GtkWidget *catalogue_entry;

static GtkWidget *addcd_dialog;
```

2. In `quit_app` we call `database_end` to tidy up and close the database before quitting.

```
void quit_app( GtkWidget *window, gpointer data)
{
    database_end();
    gtk_main_quit();
}
```

3. The next function pops up a simple dialog box to confirm that we wish to exit the application, returning the response as a `gboolean`.

```
gboolean confirm_exit()
{
    gint result;
    GtkWidget *dialog = gtk_message_dialog_new (NULL,
                                                GTK_DIALOG_MODAL,
                                                GTK_MESSAGE_QUESTION,
```

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```
    GTK_BUTTONS_YES_NO,  
    "Are you sure you want to quit?");  
  
result = gtk_dialog_run (GTK_DIALOG (dialog));  
gtk_widget_destroy (dialog);  
  
return (result == GTK_RESPONSE_YES);  
}
```

4. `delete_event_handler` is a callback function that we connect to the `Gdk delete event` of the main window. The event is emitted when we attempt to close a window, but critically before the GTK+ destroy signal is sent.

```
gboolean delete_event_handler ( GtkWidget *window, GdkEvent *event, gpointer data)  
{  
    return !confirm_exit();  
}
```

5. When we want to add a CD to the database, the next function is called when a button is clicked on the add CD dialog. If we clicked on Ok, we copy the strings into a non-const `char` array and pass the data in it to the MySQL interface function `add_cd`.

```
void addcd_dialog_button_clicked (GtkDialog * dialog, gint response, gpointer userdata)  
{  
    const gchar *artist_const;  
    const gchar *title_const;  
    const gchar *catalogue_const;  
    gchar artist[200];  
    gchar title[200];  
    gchar catalogue[200];  
    gint *cd_id;  
  
    if (response == GTK_RESPONSE_ACCEPT)  
    {  
        artist_const = gtk_entry_get_text (GTK_ENTRY (artist_entry));  
        title_const = gtk_entry_get_text (GTK_ENTRY (title_entry));  
        catalogue_const = gtk_entry_get_text (GTK_ENTRY (catalogue_entry));  
  
        strcpy (artist, artist_const);  
        strcpy (title, title_const);  
        strcpy (catalogue, catalogue_const);  
  
        add_cd (artist, title, catalogue, cd_id);  
    }  
  
    addcd_dialog = NULL;  
    gtk_widget_destroy (GTK_WIDGET (dialog));  
}
```

6. This is the heart of the application: retrieving the search results and populating the GtkTreeView.

```

void on_search_button_clicked (GtkButton *button, gpointer userdata)
{
    struct cd_search_st cd_res;
    struct current_cd_st cd;
    struct current_tracks_st ct;
    gint res1, res2, res3;
    gchar track_title[110];
    const gchar *search_string_const;
    gchar search_string[200];
    gchar search_text[200];
    gint i = 0, j = 0;

    GtkTreeStore *tree_store;
    GtkTreeIter parent_iter, child_iter;

    memset(&track_title, 0, sizeof(track_title));

```

7. Here we get the search string from the entry widget, copy into a non-const variable, and fetch the matching CD IDs.

```

search_string_const = gtk_entry_get_text(GTK_ENTRY (userdata));
strcpy (search_string, search_string_const);
res1 = find_cds(search_string, &cd_res);

```

8. Next we update the appbar to display a message informing the user the result of the search.

```

sprintf(search_text, " Displaying %d result(s) for search string ' %s '",
        MIN(res1, MAX_CD_RESULT), search_string);
gnome_appbar_push (GNOME_APPBAR( appbar), search_text);

```

9. Now we have the search results and can populate the GtkTreeStore with the results. For each CD ID we need to fetch the corresponding current_cd_st struct that contains the title and author of the CD and then fetch the list of its tracks. We limit the number of entries to MAX_CD_RESULT defined in app_mysql.h to ensure we don't overfill the GtkTreeStore.

```

tree_store = gtk_tree_store_new (N_COLUMNS,
                                G_TYPE_STRING,
                                G_TYPE_STRING,
                                G_TYPE_STRING);

while (i < res1 && i < MAX_CD_RESULT)
{
    res2 = get_cd(cd_res.cd_id[i], &cd);

    /* Add a new row to the model */
    gtk_tree_store_append (tree_store, &parent_iter, NULL);
    gtk_tree_store_set (tree_store, &parent_iter,
                        COLUMN_TITLE, cd.title,
                        COLUMN_ARTIST, cd.artist_name,
                        COLUMN_CATALOGUE, cd.catalogue, -1
                        );

```

```
res3 = get_cd_tracks(cd_res.cd_id[i++], &ct);
j = 0;
/* Populate the tree with the current cd's tracks */
while (j < res3)
{
    sprintf(track_title, " Track %d. ", j+1);
    strcat(track_title, ct.track[j++]);

    gtk_tree_store_append (tree_store, &child_iter, &parent_iter);
    gtk_tree_store_set (tree_store, &child_iter,
                        COLUMN_TITLE, track_title, -1);
}
}

gtk_tree_view_set_model (GTK_TREE_VIEW (treeview), GTK_TREE_MODEL(tree_store));
}
```

- 10.** The addcd dialog is nonmodal. Therefore, we check to see if it's already active before creating and showing it.

```
void on_addcd_activate (GtkMenuItem * menuitem, gpointer user_data)
{
    if (addcd_dialog != NULL)
        return;

    addcd_dialog = create_addcd_dialog();
    gtk_widget_show_all (addcd_dialog);

}

gboolean close_app ( GtkWidget * window, gpointer data)
{
    gboolean exit;

    if ((exit = confirm_exit()))
    {
        quit_app(NULL, NULL);
    }
    return exit;
}
```

- 11.** When we click the About button, a standard GNOME about box pops up.

```
void on_about_activate (GtkMenuItem * menuitem, gpointer user_data)
{
    const char * authors[] = {"Wrox Press", NULL};
    GtkWidget *about = gnome_about_new ("CD Database", "1.0",
                                         "(c) Wrox Press",
                                         "Beginning Linux Programming",
                                         (const char ** ) authors, NULL,
                                         "Translators", NULL);
    gtk_widget_show(about);
}
```

Try It Out—main.c

- After the include statements, we reference username and password entry boxes from interface.c.

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

#include "app_gnome.h"

extern GtkWidget *username_entry;
extern GtkWidget *password_entry;

gint main(gint argc, gchar *argv[])
{
    GtkWidget *main_window;
    GtkWidget *login_dialog;
    const char *user_const;
    const char *pass_const;
    gchar username[100];
    gchar password[100];
    gint result;
```

- We initialize the GNOME libraries as usual, then create and display the main window and our login dialog.

```
gnome_program_init ("CdDatabase", "0.1", LIBGNOMEUI_MODULE,
                    argc, argv,
                    GNOME_PARAM_APP_DATADIR, "",
                    NULL);
main_window = create_main_window();
gtk_widget_show_all(main_window);

login_dialog = create_login_dialog();
```

- We loop until the user enters a correct username-password combination. The user can quit by clicking Cancel, in which case she is then asked to confirm the action.

```
while (1)
{
    result = gtk_dialog_run (GTK_DIALOG (login_dialog));

    if (result != GTK_RESPONSE_ACCEPT)
    {
        if (confirm_exit())
            return 0;
        else
            continue;
    }
    user_const = gtk_entry_get_text(GTK_ENTRY (username_entry));
    pass_const = gtk_entry_get_text(GTK_ENTRY (password_entry));
    strcpy(username, user_const);
    strcpy(password, pass_const);

    if (database_start(username, password) == TRUE)
        break;
```

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4. If database_start fails, we display an error message and the logon dialog is shown again.

```
GtkWidget * error_dialog = gtk_message_dialog_new (GTK_WINDOW(main_window),
                                                 GTK_DIALOG_DESTROY_WITH_PARENT,
                                                 GTK_MESSAGE_ERROR,
                                                 GTK_BUTTONS_CLOSE,
                                                 "Could not log on! - Check Username and
                                                 Password");
gtk_dialog_run (GTK_DIALOG (error_dialog));
gtk_widget_destroy (error_dialog);
}

gtk_widget_destroy (login_dialog);
gtk_main();

return 0;
}
```

5. We'll write a makefile to compile this application.

```
all: app

app: app_mysql.c callbacks.c interface.c main.c app_gnome.h app_mysql.h
     gcc -o app -I/usr/include/mysql app_mysql.c callbacks.c interface.c main.c -
     lmysqlclient `pkg-config --cflags --libs libgnomeui-2.0` 

clean:
rm -f app
```

6. Now we just use the make command to compile the CD application:

```
make -f Makefile
```

When we run app, we should get our CD application—GNOME style (see Figure 16-15)!

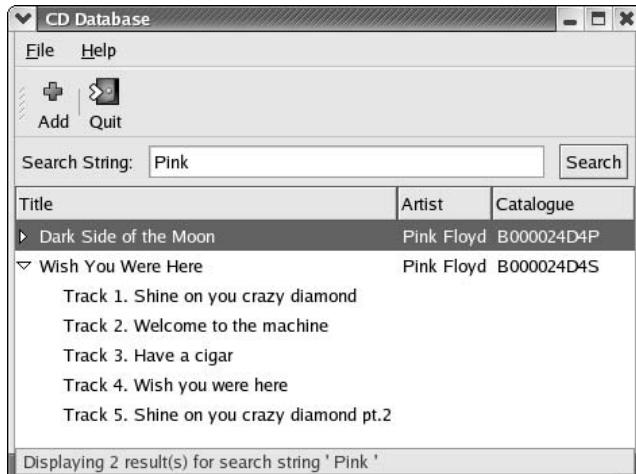


Figure 16-15

Summary

In this chapter, you've learned about programming with the GTK+/Gnome libraries to produce professional-looking GUI applications. First, we looked at the X Window System and how toolkits fit into the picture and then saw briefly how GTK+ works under the hood with its object system and signal/callback mechanism.

We then moved on to look at the API of GTK+ widgets, showing simple and more advanced examples in action in several program listings. In looking at the `GnomeApp` widget, we saw how to easily create menus using helper macros. Finally, we saw how to create modal and nonmodal dialog boxes to interact with the user.

Last, we created a GNOME/GTK+ GUI for our CD database, enabling us to log on to the database, search for CDs, and add CDs to the database.

In Chapter 17, we'll look at the rival toolkit to GTK+ and learn how to program KDE using Qt.

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Programming KDE Using Qt

In Chapter 16, we looked at the GNOME/GTK+ GUI libraries for creating graphical user interfaces under X. These libraries are only half of the story; the other big player on the GUI scene in Linux is KDE/Qt, and in this chapter we'll look at these libraries and see how they shape up against the competition.

Qt is written in C++, the standard language to write Qt/KDE applications in, so in this chapter we'll be obliged to take a diversion from our usual C and get our hands dirty with C++. You might like to take this opportunity to refresh your memory on C++, especially reminding yourself of the principles of derivation, encapsulation, method overloading, and virtual functions.

In this chapter, we'll be covering

- An introduction to Qt
- Installing Qt
- Getting started
- Signal/slot mechanism
- Qt widgets
- Dialogs
- Menus and toolbars with KDE
- Building our CD database application with KDE/Qt

Introducing KDE and Qt

KDE (K Desktop Environment) is an open source desktop environment based on the Qt GUI library. A host of applications and utilities are part of KDE, including a complete office suite, a Web browser, and even a fully featured IDE for programming KDE/Qt applications. Industry

recognition of how advanced KDE's applications are came when Apple chose to use KDE's Web browser as the core of an alternative Web browser for Mac OS X, called Safari, that's faster and offers more functionality than Internet Explorer for Macintosh.

The KDE project's homepage is at <http://www.kde.org>, where you can find detailed information, download KDE and KDE applications, find documentation, join mailing lists, and get other developer information.

The latest version of KDE at the time of writing is 3.1, and as this is the version that ships with current Linux distributions, we'll assume you have KDE 3.1 installed.

From a programmer's perspective, KDE offers dozens of KDE widgets, usually derived from their Qt counterparts to provide enhancements and greater ease of use. KDE widgets offer greater integration with the KDE desktop than we get if we use Qt alone; for example, we get session management.

Qt is a mature, cross-platform GUI toolkit written in C++. Qt is the brainchild of Trolltech, a Norwegian company that develops, markets, and supports Qt and Qt-related software for the commercial market. Trolltech loudly touts the cross-platform capabilities of Qt, which is undeniably impressive; Qt has native support on Linux and Unix derivatives, Windows, Mac OS X, and even embedded platforms, which gives Qt a great competitive advantage over its rivals.

Trolltech currently sells the commercial versions of Qt at a prohibitively high price for the casual user or hobbyist. Fortunately, Trolltech realizes the value in offering a zero-price version to the free software community, and therefore they offer a Qt Free edition for Linux, Windows, and MacOS. In return for a free version of Qt, Trolltech gets a large user install base, a large programmer community, and a high profile for its product.

Qt Free is licensed under the GPL, which means we can program using the Qt libraries and distribute our own GPL software free of charge. As far as we can tell, the two main differences between Qt Free and Qt Professional are the lack of support and the fact that you can't use Qt software in commercial applications. Trolltech's Web site at <http://www.trolltech.com> has all the API documentation that we need.

Installing Qt

Unless you have a particular reason to compile from source, it's easiest to find a binary package or RPM for your distribution. Red Hat Linux 9 ships with `qt-3.1.1-6.i386.rpm`, which we can install using the following command:

```
$ rpm -Uvh qt-3.1.1-6.i386.rpm
```

We can also install it with the package manager application (see Figure 17-1).



Figure 17-1

If you do want to download the source code and build Qt yourself, you can get the latest source from the Trolltech FTP site at <ftp://ftp.trolltech.com/qt/source/>. The source package comes with extensive instructions on how to compile and install Qt in the INSTALL file in the tarred package.

```
$ cd /usr/local
$ tar -xvzf qt-x11-free-3.2.0.tar.gz
$ ./configure
$ make
```

You'll also need to add a line to `/etc/ld.so.conf`:

```
/usr/lib/qt3/lib
```

When Qt is properly installed, the `QTDIR` environment variable should be set to the Qt installation directory. You can check that this is the case as follows:

```
$ echo $QTDIR
/usr/lib/qt3
```

Also make sure the `lib` directory is added to `/etc/ld.so.conf`.

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Then run the following command as superuser:

```
$ ldconfig
```

Let's try out the simplest Qt program and make sure our installation is working properly.

Try It Out—QMainWindow

Type this program and call it `qt1.cpp`:

```
#include <qapplication.h>
#include <qmainwindow.h>

int main(int argc, char **argv)
{
    QApplication app(argc, argv);
    QMainWindow window();
    app.setMainWidget(window);
    window.show();
    return app.exec();
}
```

To compile, we'll need to include the Qt `include` and `lib` directories:

```
$ g++ -o qt1 qt1.cpp -I$QTDIR/include -L$QTDIR/lib -lqt
```

When we run our application, we should get a Qt window (see Figure 17-2).

```
$ ./qt1
```



Figure 17-2

How It Works

Unlike GTK+, there's no all-encompassing `qt.h` header file, so we must explicitly include header files for each object we use.

The first object we encounter is `QApplication`. This is the main Qt object we must construct, passing in the command line arguments before we begin. Each Qt application must have one and only one

`QApplication` object that we must create before doing anything else. `QApplication` deals with under-the-hood Qt operations such as event handling, string localization, and controlling the look and feel.

There are two `QApplication` methods we use: `setMainWindow`, which sets the main widget of our application, and `exec`, which starts the event loop running. `exec` doesn't return until either `QApplication::quit()` is called or the main widget is closed.

`QMainWindow` is the Qt base window widget that has support for menus, a toolbar, and a status bar. It'll be featured a great deal in this chapter as you learn how to extend it and add widgets to create an interface.

We'll now introduce the mechanism of event-driven programming and add a `PushButton` widget to our application.

Signals and Slots

As we saw in Chapter 16, signals and signal handling are the primary mechanisms a GUI application uses to respond to user input and are central features of all GUI libraries. Qt's signal-handling mechanism consists of *signals* and *slots*, which are Qt's names for signals and callback functions in GTK+.

Note that a Qt signal is quite separate from a UNIX signal, as discussed in Chapter 11.

Let's remind ourselves how event-driven programming works. A GUI consists of menus, toolbars, buttons, entry boxes, and many other GUI elements that are collectively known as widgets. When the user interacts with a widget, for example activating a menu item or entering some text in an entry box, the widget will emit a named signal such as `clicked`, `text_changed`, or `key_pressed`. We'll usually want to do something in response to the user's action, such as save a document or quit the application, and we do this by connecting a signal to a callback function or, in Qt parlance, a slot.

Using signals and slots in Qt is rather special—Qt defines two new aptly named pseudo-keywords, `signals` and `slots`, to identify in our code the signals and slots of the class. This is great for readability and code maintenance, but it means we must pass our code through a separate pre-processing stage to search and replace these pseudo-keywords with additional C++ code.

There are some restrictions to how signals and slots can be used in Qt, but these are not significantly limiting:

- ❑ Signals and slots must be member functions of a class derived from `QObject`.
- ❑ If using multiple inheritance, `QObject` must appear first in the class list.
- ❑ A `Q_OBJECT` statement must appear in the class declaration.
- ❑ Signals cannot be used in templates.
- ❑ Function pointers cannot be used as arguments to signals and slots.
- ❑ Signals and slots cannot be overridden and upgraded to public status.

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Since we need to write our signals and slots in a descendant of `QObject`, it is logical to create our interface by extending and customizing a widget, since `QWidget`, the base Qt widget, is derived from `QObject`. In Qt, we nearly always create our interfaces by extending widgets such as `QMainWindow`.

A typical class definition `MyWindow.h` for our GUI will look something like this:

```
class MyWindow : public QMainWindow
{
    Q_OBJECT
public:
    MyWindow();
    virtual ~MyWindow();

signals:
    void aSignal();

private slots:
    void doSomething();
}
```

Our class derives from `QMainWindow`, which provides functionality for the main window in our application. Similarly we'll subclass `QDialog` when we want a dialog box. First is the `Q_OBJECT` statement that acts as a marker for the preprocessor, followed by the usual constructor and destructor prototypes. Next are the signal and slot definitions.

We have one signal and one slot, both with no arguments. To emit `aSignal()`, all we need to do is call `emit` somewhere in our code:

```
emit aSignal();
```

That's it—everything else is handled by Qt. We don't even need an `aSignal()` implementation.

To use slots, we must connect them to a signal. This is done with the appropriately named static `connect` method in the `QObject` class:

```
bool QObject::connect (const QObject * sender, const char * signal,
                      const QObject * receiver, const char * member)
```

We simply pass in the object that owns the signal (the sender), the signal function, the object that owns the slot (the receiver), and finally the name of the slot.

In our `MyWindow` example, if we wanted to connect the `clicked` signal of a `QPushButton` widget to our `doSomething` slot, we'd write

```
connect (button, SIGNAL(clicked()), this, SLOT(doSomething()));
```

Note that we must use `SIGNAL` and `SLOT` macros to surround the signal and slot functions. Just as in GTK+, we can connect any number of slots to a given signal and also connect a slot to any number of signals by multiple `connect` calls. If `connect` fails for any reason, it returns FALSE.

All that remains is to implement our slot, and this takes the form of an ordinary member function.

```
void MyWindow::doSomething()
{
    // Slot code
}
```

Try It Out—Signals and Slots

Now that we've seen the principles of signals and slots, let's put this to use with an example. We'll extend `QMainWindow` and add a button. We'll connect the button's `clicked` signal to a slot.

1. Type this class declaration, and call it `ButtonWindow.h`.

```
#include <qmainwindow.h>

class ButtonWindow : public QMainWindow
{
    Q_OBJECT

public:
    ButtonWindow(QWidget *parent = 0, const char *name = 0);
    virtual ~ButtonWindow();

private slots:
    void Clicked();

};

};
```

2. Next is the class implementation, `ButtonWindow.cpp`:

```
#include "ButtonWindow.moc"
#include <QPushButton.h>
#include <QApplication.h>
#include <iostream>
```

3. In the constructor, we set the window title, create the button, and connect the button's `clicked` signal to our slot. `setCaption` is a `QMainWindow` method that unsurprisingly sets the window title.

```
ButtonWindow::ButtonWindow(QWidget *parent, const char *name)
    : QMainWindow(parent, name)
{
    this->setCaption("This is the window Title");
    QPushButton *button = new QPushButton("Click Me!", this, "Button1");
    button->setGeometry(50,30,70,20);
    connect (button, SIGNAL(clicked()), this, SLOT(Clicked()));
}
```

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4. Qt manages the destruction of widgets automatically, so our destructor is empty:

```
ButtonWindow::~ButtonWindow()
{
}
```

5. Next, the slot implementation:

```
void ButtonWindow::Clicked(void)
{
    std::cout << "clicked!\n";
}
```

6. Finally, in main we just create an instance of our ButtonWindow, set it as our application's main window, and show the window on screen.

```
int main(int argc, char **argv)
{
    QApplication app(argc, argv);
    ButtonWindow *window = new ButtonWindow();

    app.setMainWidget(window);
    window->show();

    return app.exec();
}
```

7. Before we can compile this example, we need to run the preprocessor on the header file. This preprocessor program is called the Meta Object Compiler (moc) and should be present in the Qt package. Run moc on ButtonWindow.h, saving the output as ButtonWindow.moc:

```
$ moc ButtonWindow.h -o ButtonWindow.moc
```

Now we can compile as usual, linking in the moc output:

```
$ g++ -o button ButtonWindow.cpp -I$QTDIR/include -L$QTDIR/lib -lqt
```

When we run the program, we get the example shown in Figure 17-3.

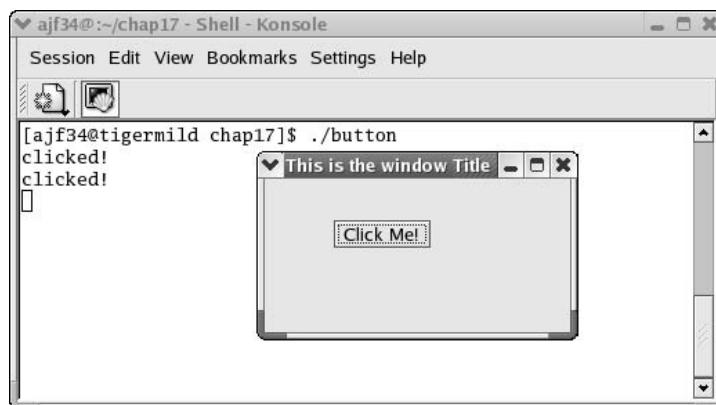


Figure 17-3

How It Works

We've introduced a new widget and some new functions here, so let's take a look at these. `QPushButton` is a simple button widget that can hold a label and bitmap graphic and can be activated by the user clicking with the mouse or using the keyboard.

The constructor of `QPushButton` that we use is quite simple:

```
QPushButton::QPushButton(const QString &text, QWidget *parent, const char* name=0 )
```

The first argument is the text of the button label, then the parent widget, and last the name of the button used internally by Qt.

The parent parameter is common to all `QWidgets`, and the parent widget controls when it is displayed and destroyed, and various other characteristics. Passing `NULL` as the parent argument denotes that the widget is top-level and creates a blank window to contain it. In our example we pass the current `ButtonWindow` object using `this`, which adds the button to the `ButtonWindow` main area.

The name argument sets the name of the widget for use internally by Qt. If Qt encounters an error, then the widget name will be printed in the error message, so it's a good idea to choose the appropriate widget, as it's a great timesaver when debugging.

You might have noticed that we rather crudely added the `QPushButton` to the `ButtonWindow` by using the parent parameter of the `QPushButton` constructor. We didn't specify the positioning, size, border, or anything like that. If we want precise control over widget layout, which is critical in creating an attractive interface, we must use Qt's layout objects. Let's take a look at these now.

There are a number of ways to arrange the positioning and layout of widgets in Qt. We've already seen using absolute coordinates by calling `setGeometry`, but this is rarely used, since the widgets don't scale and adjust to fit the window if it is resized.

The preferred method of arranging widgets is by using the `QLayout` classes or box widgets, which intelligently resize, after we've given them hints on margins and spacing between widgets.

The key difference between the `QLayout` classes and box widgets is that layout objects are *not* widgets.

The layout classes derive from `QObject` and not `QWidget`, so we are constrained in how we can use them. We cannot, for instance, make a `QVBoxLayout` a central widget of a `QMainWindow`.

Box widgets (e.g., `QHBox` and `QVBox`), by contrast, *are* derived from `QWidget`, and therefore we can treat them as ordinary widgets. You might well wonder why Qt has both `QLayouts` and `QBox` widgets with duplicate functionality. Actually `QBox` widgets are just for convenience, and in essence wrap a `QLayout` within a `QWidget`. `QLayouts` have the advantage of automatically resizing, whereas widgets must be manually resized by calling `QWidget::resizeEvent()`.

The `QLayout` subclasses `QVBoxLayout` and `QHBoxLayout` are the most popular way of creating an interface, and the ones you will most often see in Qt code.

`QVBoxLayout` and `QHBoxLayout` are invisible container objects that hold other widgets and layouts in a vertical and a horizontal orientation, respectively. We can create arbitrarily complex arrangements of widgets because we can nest layouts by placing a horizontal layout as an element inside a vertical layout, for example.

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There are three QVBoxLayout constructors of interest (QHBoxLayout has an identical API).

```
QVBoxLayout::QVBoxLayout (QWidget *parent, int margin, int spacing, const char *name)
QVBoxLayout::QVBoxLayout (QLayout *parentLayout, int spacing, const char * name)
QVBoxLayout::QVBoxLayout (int spacing, const char *name)
```

The parent of the QLayout can be either a widget or another QLayout. If we specify no parent, then we can only add the layout to another QLayout later, using the addLayout method.

margin and spacing set the empty space in pixels placed around the outside of the QLayout and in between individual widgets.

Once we've created our QLayout, we add child widgets or layouts using a couple of methods:

```
QBoxLayout::addWidget (QWidget *widget, int stretch = 0, int alignment = 0 )
QBoxLayout::addLayout (QLayout *layout, int stretch = 0)
```

Try It Out—Using QBoxLayout Classes

Let's see the QBoxLayout classes in action by arranging QLabel widgets in a QMainWindow.

1. First, type the header file, LayoutWindow.h.

```
#include <qmainwindow.h>

class LayoutWindow : public QMainWindow
{
    Q_OBJECT

public:
    LayoutWindow(QWidget *parent = 0, const char *name = 0);
    virtual ~LayoutWindow();
};
```

2. Now type the implementation, LayoutWindow.cpp.

```
#include <qapplication.h>
#include <qlabel.h>
#include <qlayout.h>

#include "LayoutWindow.moc"

LayoutWindow::LayoutWindow(QWidget *parent, const char *name) : QMainWindow(parent,
name)
{
    this->setCaption("Layouts");
```

3. We need to create a dummy QWidget to hold our QHBoxLayout because we cannot add a QLayout directly to a QMainWindow.

```
QWidget *widget = new QWidget(this);
setCentralWidget(widget);
```

```
QHBoxLayout *horizontal = new QHBoxLayout(widget, 5, 10, "horizontal");
QVBoxLayout *vertical = new QVBoxLayout();

QLabel* label1 = new QLabel("Top", widget, "textLabel1" );
QLabel* label2 = new QLabel("Bottom", widget, "textLabel2");
QLabel* label3 = new QLabel("Right", widget, "textLabel3");

vertical->addWidget(label1);
vertical->addWidget(label2);
horizontal->addLayout(vertical);
horizontal->addWidget(label3);
resize( 150, 100 );
}

LayoutWindow::~LayoutWindow()
{
}

int main(int argc, char **argv)
{
    QApplication app(argc, argv);
    LayoutWindow *window = new LayoutWindow();

    app.setMainWidget(window);
    window->show();

    return app.exec();
}
```

As before, we need to run `moc` on the header file before compiling:

```
$ moc LayoutWindow.h -o LayoutWindow.moc
$ g++ -o layout LayoutWindow.cpp -I$QTDIR/include -L$QTDIR/lib -lqt
```

When we run this program, we get our arrangement of `QLabels` (see Figure 17-4). Try resizing the window and see how the labels expand and shrink to fit the available space.

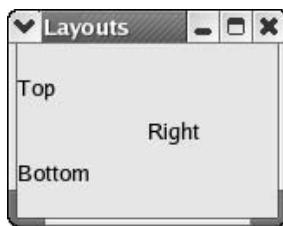


Figure 17-4

We've covered the basic principles of using Qt—signals and slots, `moc`, and layouts—so it's time to investigate the widgets more closely.

Qt Widgets

There are widgets for every occasion in Qt, and looking at them all would take up the rest of the book. In this section we'll take a look at the common Qt widgets, including data entry widgets, buttons, combo box, and list widgets.

QLineEdit

QLineEdit is Qt's single-line text entry widget. We use it for inputting brief amounts of text, which we can limit using an input mask to fit a template or, for the ultimate control, we can apply a validator function. QLineEdit has editing features, enabling us to select parts of the text, cut and paste, undo, redo, and the like from both a user's perspective and using the API.

The constructors and most useful methods are

```
#include <qlineedit.h>

QLineEdit::QlineEdit (QWidget *parent, const char* name = 0 )
QLineEdit::QlineEdit (const QString &contents, QWidget *parent,const char *name = 0
)
QLineEdit::QlineEdit (const QString &contents, const QString &inputMask,
QWidget *parent, const char *name = 0 )

void      setInputMask (const QString &inputMask)
void      insert (const QString &newText )
bool     isModified (void)
void      setMaxLength (int length)
void      setReadOnly (bool read)
void      setText (const QString &text)
QString   text (void)
void      setEchoMode(EchoMode mode)
```

In the constructors, we set the parent widget and widget name as usual with parent and name.

An interesting property is `EchoMode`, which determines how the text appears in the widget.

It can take one of three values:

- `QLineEdit::Normal`: Display inputted characters (default)
- `QLineEdit::Password`: Display asterisks in place of characters
- `QLineEdit::NoEcho`: Display nothing

We set the mode using the `setEchoMode` :

```
lineEdit->setEchoMode(QLineEdit::Password) ;
```

An enhancement introduced in Qt 3.2 is `inputMask`, which restricts input according to the mask rule.

`inputMask` is a string made up of characters, each of which corresponds to a rule that accepts a certain range of characters. If you're familiar with regular expressions, then `inputMask` uses much the same principle.

There are two sorts of `inputMask` characters: those that denote a certain character must be present, and those that, if a character is present, restrict it to fall under the rule.

| Meaning | Required Character | Optional Characters |
|---------------------|--------------------|---------------------|
| ASCII A–Z, a–z | A | a |
| ASCII A–Z, a–z, 0–9 | N | n |
| Any character | X | x |
| Numeric 0–9 | 9 | 0 |
| Numeric 1–9 | D | d |

Our `inputMask` is a string made up from a combination of these characters, optionally terminated by a semicolon. There are further special characters that also have meaning:

| | |
|---|---|
| # | Plus/minus permitted but not required. |
| > | Converts following input to uppercase. |
| < | Converts following input to lowercase. |
| ! | Stops converting case. |
| \ | Escape character to use special characters as separators. |

All other characters in the `inputMask` act as separators in the `QLineEdit`.

Here are some examples of masks and their allowed input:

| | |
|-------------------|--|
| "AAAAAA-999D" | Allows Athens-2004 but not Sydney-2000 or Atlanta-1996. |
| "AAAAnn-99-99;" | Allows March-03-12 but not May-03-12 or September-03-12. |
| "000.000.000.000" | Allows IP address, for example, 192.168.0.1. |

Try It Out—`QLineEdit`

Now let's see `QLineEdit` in action.

1. First, the header file, `LineEdit.h`:

```
#include <qmainwindow.h>
#include <qlineedit.h>
#include <qstring.h>
```

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```
class LineEdit : public QMainWindow
{
    Q_OBJECT

public:
    LineEdit(QWidget *parent = 0, const char *name = 0);
    QLineEdit *password_entry;

private slots:
    void Clicked();
};
```

- 2.** LineEdit.cpp is the now-familiar class implementation file:

```
#include "LineEdit.moc"
#include <QPushButton.h>
#include <QApplication.h>
#include <QLabel.h>
#include <QLayout.h>
#include <iostream>

LineEdit::LineEdit(QWidget *parent, const char *name) : QMainWindow(parent, name)
{
    QWidget *widget = new QWidget(this);
    setCentralWidget(widget);
```

- 3.** We'll use a QGridLayout to arrange the widgets. We specify the number of rows and columns, the margin settings, and the spacing.

```
QGridLayout *grid = new QGridLayout(widget, 3, 2, 10, 10, "grid");

QLineEdit *username_entry = new QLineEdit( widget, "username_entry");
password_entry = new QLineEdit( widget, "password_entry");
password_entry->setEchoMode(QLineEdit::Password);

grid->addWidget(new QLabel("Username", widget, "userlabel"), 0, 0, 0);
grid->addWidget(new QLabel("Password", widget, "passwordlabel"), 1, 0, 0);

grid->addWidget(username_entry, 0, 1, 0);
grid->addWidget(password_entry, 1, 1, 0);

QPushButton *button = new QPushButton ("Ok", widget, "button");
grid->addWidget(button, 2, 1, Qt::AlignRight);

resize( 350, 200 );

connect (button, SIGNAL(clicked()), this, SLOT(Clicked()));

void LineEntry::Clicked(void)
{
    std::cout << password_entry->text() << "\n";
}

int main(int argc, char **argv)
```

```

{
    QApplication app(argc,argv);
    LineEntry *window = new LineEntry();

    app.setMainWidget(window);
    window->show();

    return app.exec();
}

```

When we run this program, we get the example shown in Figure 17-5.

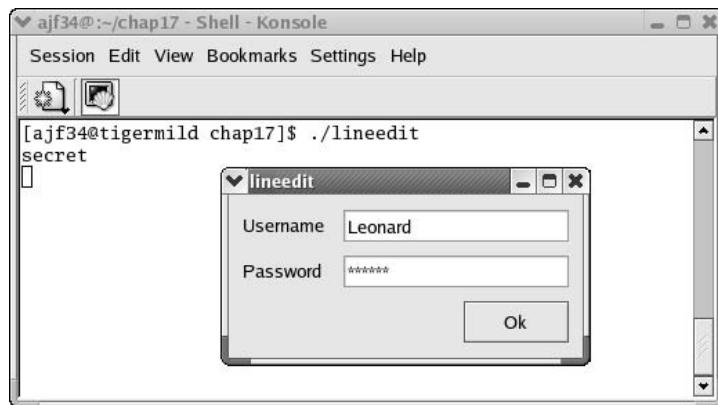


Figure 17-5

How It Works

We've created two `QLineEdit` widgets, made one a password entry by setting the `EchoMode`, and printed its contents when we click on the `PushButton`. Note that we've introduced the `QGridLayout` widget, which is very useful for laying out widgets in a grid pattern. When we add a widget to the grid, we pass the row and column number, starting at 0, 0 for the top left cell.

Qt Buttons

Buttons widgets are ubiquitous widgets, and they vary little in appearance, usage, and API from toolkit to toolkit. It's no surprise that Qt offers standard `PushButton`, `CheckBox`, and `RadioButton` variants.

QPushButton—The Button Base Class

Button widgets in Qt all derive from the abstract `QPushButton` class. This class has methods to query and toggle the on/off state of the button and to set the button's text or pixmap.

We should never need to instantiate a `QPushButton` widget itself (don't get confused between a `QPushButton` and `QPushbutton!`), so we needn't show the constructors; however, here are the useful member functions:

```
#include <qbutton.h>

virtual void QPushButton::setText ( const QString & )
```

```
virtual void QButton::setPixmap ( const QPixmap & )
bool QButton::isToggleButton () const
virtual void QButton::setDown ( bool )
bool QButton::isDown () const
bool QButton::isOn () const
enum QButton::ToggleState { Off, NoChange, On }
ToggleState QButton::state () const
```

The `isDown` and `isOn` functions are identical in meaning. They both return TRUE if the button is pressed or activated.

Often, we'll want to disable or gray out an option if it isn't currently available. We can disable any widget including `QButtons` by calling `QWidget::setEnabled(FALSE)`.

There are three subclasses of `QButton` that we're interested in:

- ❑ `QPushButton`: Simple button widget that performs some action when clicked
- ❑ `QCheckBox`: Button widget that can toggle between on and off states to indicate some option
- ❑ `QRadioButton`: Button widget normally used in groups where only one button can be active in a group at a time

QPushButton

`QPushButton` is the standard generic button that contains text such as "Ok" or "Cancel" and/or a pixmap icon. Like all `QButtons`, it emits the `clicked` signal when it's activated, and we'll usually use this to connect a slot and perform some action.

We've already used `QPushButton` in our examples, and there's really only one other thing of interest to say about this simplest of Qt widgets. `QPushButton` can be switched from a stateless button into a toggle button (i.e., can be turned on or off) by calling `setToggleButton`. (If you recall from the last chapter, GTK+ has separate widgets for the purpose.)

For completeness, here are the constructors and useful methods:

```
#include <QPushButton.h>

QPushButton (QWidget *parent, const char *name = 0)
QPushButton (const QString &text, QWidget *parent, const char *name = 0)
QPushButton (const QIconSet &icon, const QString &text,
            QWidget *parent, const char * name = 0 )

void QPushButton::setToggleButton (bool);
```

QCheckBox

`QCheckBox` is a button that has state; that is, it can be turned on or off. The appearance of `QCheckBox` depends on the current windowing style (Motif, Windows, etc.) but is usually drawn as a ticked box with text to the right.

`QCheckBox` can also be set by us to be a third, in-between state that indicates "no change." This is useful in the rare occasions when we can't read the state of the option the `QCheckBox` represents (and therefore

set the QCheckBox on or off ourselves), but still want to give the user a chance to leave it unchanged as well as actively set it on or off.

```
#include <qcheckbox.h>

QCheckBox (QWidget *parent, const char *name = 0 )
QCheckBox (const QString &text, QWidget *parent, const char *name = 0 )

bool QCheckBox::isChecked ()
void QCheckBox::setTristate ( bool y = TRUE )
bool QCheckBox::isTristate ()
```

QRadioButton

Radio buttons are toggle buttons used to represent exclusive choices when we can select only one option out of a group of options presented (think back to those old car radios, where only one station button could be pressed in at a time). QRadioButtons themselves are hardly any different from QcheckBoxes, since the grouping and exclusivity are all handled by the QButtonGroup class, the main difference being that radio buttons appear as round buttons rather than ticked boxes.

QButtonGroup is a widget that makes handling groups of buttons easier by providing convenience methods.

```
#include <qbuttongroup.h>

QButtonGroup (QWidget *parent = 0, const char * name = 0 )
QButtonGroup (const QString & title, QWidget * parent = 0, const char * name = 0 )

int insert (QPushButton *button, int id = -1)
void remove (QPushButton *button)
int id (QPushButton *button) const
int count () const
int selectedId () const
```

Using a QButtonGroup couldn't be simpler; it even offers an optional frame around the buttons if we use the title constructor.

We add a button to a QButtonGroup using either `insert`, or by specifying the QButtonGroup as the parent widget of the button. We can specify an `id` with `insert` to uniquely identify each button in the group. This is especially useful when querying which button is selected, as `selectedId` returns the `id` of the selected button.

All QRadioButtons we add to the group are automatically set to be exclusive.

The QRadioButton constructors and one unique method shouldn't be too surprising:

```
#include <qradiobutton.h>

QRadioButton (QWidget *parent, const char *name = 0 )
QRadioButton (const QString &text, QWidget *parent, const char *name = 0 )

bool QRadioButton::isChecked ()
```

Try It Out—QButtons

Let's put this knowledge to some use, with a Qt buttons example.

1. Type Buttons.h:

```
#include <qmainwindow.h>
#include <qcheckbox.h>
#include <qbutton.h>
#include <qradiobutton.h>

class Buttons : public QMainWindow
{
    Q_OBJECT

public:
    Buttons(QWidget *parent = 0, const char *name = 0);
```

2. We'll query the state of our buttons later in the slot function, so declare the button pointers as private in the class definition, as well as a helper function PrintActive:

```
private:
    void PrintActive(QButton *button);
    QCheckBox *checkbox;
    QRadioButton *radiobutton1, *radiobutton2;

private slots:
    void Clicked();

};
```

3. Here's Buttons.cpp:

```
#include "Buttons.moc"
#include <qbuttongroup.h>

#include <QPushButton.h>

#include <QApplication.h>
#include <QLabel.h>
#include <QLayout.h>

#include <iostream>

Buttons::Buttons(QWidget *parent, const char *name) : QMainWindow(parent, name)
{
    QWidget *widget = new QWidget(this);
    setCentralWidget(widget);

    QVBoxLayout *vbox = new QVBoxLayout(widget, 5, 10, "vbox");

    checkbox = new QCheckBox("CheckButton", widget, "check");
    vbox->addWidget(checkbox);
```

4. Here we create a QButtonGroup for our two radio buttons:

```

QButtonGroup *buttongroup = new QButtonGroup(0);

radiobutton1 = new QRadioButton("RadioButton1", widget, "radio1");
buttongroup->insert(radiobutton1);
vbox->addWidget(radiobutton1);

radiobutton2 = new QRadioButton("RadioButton2", widget, "radio2");
buttongroup->insert(radiobutton2);
vbox->addWidget(radiobutton2);

QPushButton *button = new QPushButton ("Ok", widget, "button");
vbox->addWidget(button);

resize( 350, 200 );

connect (button, SIGNAL(clicked()), this, SLOT(Clicked()));
}

```

5. Next is a convenience method for printing the state of the given QPushButton:

```

void Buttons::PrintActive(QButton *button)
{
    if (button->isOn())
        std::cout << button->name() << " is checked\n";
    else
        std::cout << button->name() << " is not checked\n";
}

void Buttons::Clicked(void)
{
    PrintActive(checkbox);
    PrintActive(radiobutton1);
    PrintActive(radiobutton2);
    std::cout << "\n";
}

int main(int argc, char **argv)
{
    QApplication app(argc, argv);
    Buttons *window = new Buttons();

    app.setMainWidget(window);
    window->show();

    return app.exec();
}

```

QComboBox

Radio buttons are an excellent way of enabling the user to select from a small number of options, say six or fewer. When we have more than six, things start to get out of hand and it becomes increasingly so as the number of options increases to keep the window to a sensible size. A perfect solution is to use an entry box with drop-down menu, also known as a combo box. The options appear when we click and

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reveal the menu, and the number of options is limited only by how practical it becomes to search through the list.

`QComboBox` combines the functionality of a `QLineEdit`, `QPushButton`, and dropdown menus, enabling the user to pick a single option from an unlimited choice of options.

A `QComboBox` can be either read/write or read-only; if it is read/write the user can type an alternative to the options offered; otherwise the user is limited to select from the drop-down list.

When we create a `QComboBox`, we can specify whether it's read/write or read-only as a boolean in the constructor:

```
QComboBox *combo = new QComboBox(TRUE, parent, "widgetname");
```

Passing `TRUE` sets the `QComboBox` to Read/Write mode. The other parameters are the usual parent widget pointer and widget name.

Like all Qt widgets, `QComboBox` is flexible in the way we can use it and it offers a good deal of functionality. We can add options individually or as a set, either as `QString`s or using traditional `char*` format.

To insert a single item, we call `insertItem`:

```
combo->insertItem(QString("An Item"), 1);
```

This takes a `QString` object and a position index. Here, the value of 1 sets the item to be first in the list. To add it to the end, we just pass any negative integer.

More usually we'll add several items at a time, and for this we can use the `QStringList` class, or, as we do here, as a `char*` array:

```
char* weather[] = {"Thunder", "Lightning", "Rain", 0};  
combo->insertStrList(weather, 3);
```

Again, we can specify an index for the inserted items in the list.

If the `QComboBox` is read/write, then values that the user types in can be automatically added to the list of options. This is a useful time-saving feature that saves the user from repeated typing if he or she wants to select the same typed-in value more than once.

`InsertionPolicy` controls where the new entry is added in the option list:

| | |
|---------------------------------------|--|
| <code>QComboBox::AtTop</code> | Inserts the new entry as the first option in the list. |
| <code>QComboBox::AtBottom</code> | Inserts the new entry as the last option. |
| <code>QComboBox::AtCurrent</code> | Replaces the previously selected option. |
| <code>QComboBox::BeforeCurrent</code> | Inserts the entry before the previously selected option. |
| <code>QComboBox::AfterCurrent</code> | Inserts the entry after the previously selected option. |
| <code>QComboBox::NoInsertion</code> | New entry is not inserted into option list. |

To set the policy, we call the `setInsertionPolicy` method on the `QComboBox`:

```
combo->setInsertionPolicy(QComboBox::AtTop);
```

Let's take a peek at the constructors and a selection of the `QComboBox` methods:

```
#include <qcombobox.h>

QComboBox (QWidget *parent = 0, const char *name = 0)
QComboBox (bool readwrite, QWidget *parent = 0, const char *name = 0)

int      count ()
void    insertQStringList (const QStringList &list, int index = -1)
void    insertQStringList (const QStringList &list, int index = -1)
void    insertQStringList (const QStringList *list, int index = -1)
void    insertQStringList (const char **strings, int numStrings = -1, int index = -1)
void    insertItem (const QString &t, int index = -1)
void    removeItem (int index)
virtual void setCurrentItem (int index)
QString currentText ()
virtual void setCurrentText (const QString &)
void    setEditable (bool)
```

`count` returns the number of options in the list. `QStringList` and `QStringList` are Qt string collection classes we can use to add options. We can remove options using `removeItem`, get and set the current option using `currentText` and `setCurrentText`, and toggle the editable state using `setEditable`.

`QComboBox` emits the `textChanged(QString&)` signal whenever a new option is selected, passing the newly selected option as an argument.

Try It Out—`QComboBox`

Let's have a go at using `QComboBox`, and see how signals and slots with parameters work in action. We'll create a `ComboBox` class that inherits `QMainWindow`. It'll have two `QComboBoxes`, one read/write and one read-only, and we'll connect to the `textChanged` signal to get the currently selected value each time it changes.

For the sake of brevity, we won't write out the `ComboBox.h` header file; we'll just look at the class implementation instead.

1. The interface consists of two `QComboBox` widgets, one editable and the other read-only. We populate both widgets with the same list of items:

```
#include "ComboBox.moc"

#include <qlayout.h>
#include <iostream>

ComboBox::ComboBox(QWidget *parent, const char *name) : QMainWindow(parent, name)
{
    QWidget *widget = new QWidget(this);
    setCentralWidget(widget);
```

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```
QVBoxLayout *vbox = new QVBoxLayout(widget, 5, 10,"vbox");

QComboBox *editablecombo = new QComboBox(TRUE, widget, "editable");
vbox->addWidget(editablecombo);
QComboBox *readonlycombo = new QComboBox(FALSE, widget, "readonly");
vbox->addWidget(readonlycombo);

static const char* items[] = { "Macbeth", "Twelfth Night", "Othello", 0 };
editablecombo->insertStrList (items);
readonlycombo->insertStrList (items);

connect (editablecombo, SIGNAL(textChanged(const QString&)),
          this, SLOT(Changed(const QString&)));
resize( 350, 200 );

}
```

2. This is our slot function. Note the `QString` parameter `s` that's passed by the signal.

```
void ComboBox::Changed(const QString& s)
{
    std::cout << s << "\n";
}

int main(int argc, char **argv)
{
    QApplication app(argc,argv);
    ComboBox *window = new ComboBox();

    app.setMainWidget(window);
    window->show();

    return app.exec();
}
```

You can see the newly selected options printed out on the command line in Figure 17-6.

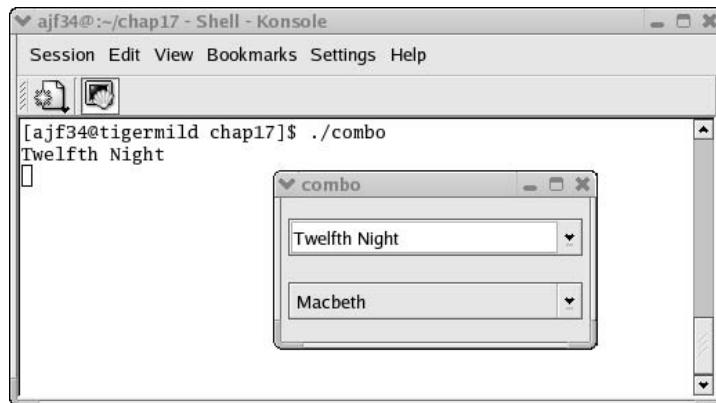


Figure 17-6

QListView

Lists and trees in Qt are provided by the `QListView` widget. `QListView` displays both plain lists and hierarchical data divided into rows and columns. It's perfect for displaying things like directory structures, as the child elements can be expanded and contracted by clicking the plus and minus boxes, just like a file viewer.

Unlike the GTK+ `ListView` widget, `QListView` handles both the data and the view, which makes for ease of use if not outstanding flexibility.

With `QListView`, we can select rows or individual cells; then we cut and paste the data, sort by column and have `QCheckBox` widgets rendered in cells. There's a great amount of functionality built in—all we need to do as programmers is add data and set up some formatting rules.

Creating a `QListView` is done in the usual fashion, specifying the parent and widget name:

```
QListView *view = new QListView(parent, "name");
```

To set column headings, we use the aptly named `addColumn` method:

```
view->addColumn("Left Column", width1); // Fixed width
view->addColumn("Right Column"); // Width autosizes
```

The column's width is set in pixels or, if omitted, defaults to the width of the widest element in the column. The column will then autosize as elements are added and removed.

Data is added to the `QListView` using a `QListViewItem` object to represent a row of data. All we need do is pass the `QListView` and row elements to the constructor, and it's appended to the view for us:

```
QListViewItem *toplevel = new QListViewItem(view, "Left Data", "Right Data");
```

The first parameter is either a `QListView`, as in this case, or another `QListViewItem`. If we pass a `QListViewItem`, the row appears as the child of that `QListViewItem`. The tree structure is therefore formed by passing the `QListView` for top-level nodes and then successive `QListViewItems` for the child nodes.

The remaining parameters are the data for each column that default to `NULL` if not specified.

Adding a child node is then just a case of passing in the top-level pointer. If we aren't adding further child nodes to a `QListViewItem`, we needn't store the returned pointer:

```
new QListViewItem(toplevel, "Left Data", "Right Data"); // A Child of toplevel
```

If we look at the `QListViewItem` API, we can see the methods to traverse the tree, should we wish to modify particular rows:

```
#include <qlistview.h>

virtual void    insertItem ( QListViewItem * newChild )
virtual void    setText ( int column, const QString & text )
```

```
virtual QString text ( int column ) const
QListViewItem *firstChild () const
QListViewItem *nextSibling () const
QListViewItem *parent () const
QListViewItem *itemAbove ()
QListViewItem *itemBelow ()
```

We can get the first row in the tree by calling `firstChild` on the `QListView` itself. We can then repeatedly call `firstChild` and `nextSibling` to return parts or the entire tree:

This code snippet prints out the first column of all the top-level nodes:

```
QListViewItem *child = view->firstChild();
while(child)
{
    cout << myChild->text(1) << "\n";
    myChild = myChild->nextSibling();
}
```

You can find all the details about `QListView`, `QListViewItem`, and `QCheckListView` in the Qt API documentation.

Try It Out—`QListView`

Now let's put everything together and write a short example of a `QListView` widget.

We'll skip the header file as before and see the class implementation:

```
#include "ListView.moc"

ListView::ListView(QWidget *parent, const char *name) : QMainWindow(parent, name)
{
    listview = new QListView(this, "listview1");

    listview->addColumn("Artist");
    listview->addColumn("Title");
    listview->addColumn("Catalogue");

    listview->setRootIsDecorated(TRUE);

    QListViewItem *toplevel = new QListViewItem(listview, "Avril Lavigne",
                                                "Let Go", "AVCD01");

    new QListViewItem(toplevel, "Complicated");
    new QListViewItem(toplevel, "Sk8er Boi");

    setCentralWidget(listview);
}

int main(int argc, char **argv)
{
    QApplication app(argc, argv);
    ListView *window = new ListView();
```

```

    app.setMainWidget(window);
    window->show();

    return app.exec();
}

```

After compiling and running the ListView example, we see the QListView widget in action as shown in Figure 17-7.

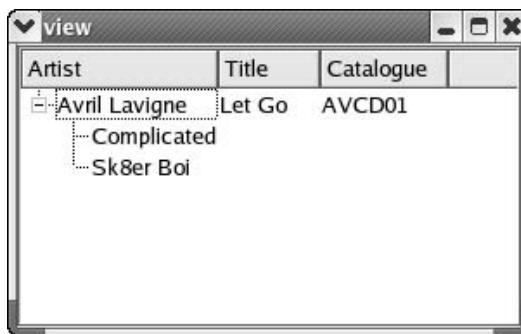


Figure 17-7

Note how the child rows are indented with respect to their parent. The plus and minus boxes indicating there are hidden or collapsible rows are not present by default; here we set them with `setRootIsDecorated`.

Dialogs

Up until now, we've been subclassing `QMainWindow` to create our interfaces. `QMainWindow` is appropriate for the primary window in our application, but for short-lived dialogs, we should look at using the `QDialog` widget.

Dialogs are useful whenever we want the user to input specific information for a particular task, or impart small amounts of information to the user, such as a warning or error message. It's preferable to subclass `QDialog` for these tasks because we get convenience methods for running the dialog and purpose-designed signals and slots to handle the user response.

As well as the usual modal and nonmodal (or modeless in Qt-speak) dialogs, Qt also offers a semimodal dialog box. Let's remind ourselves of the differences between modal and nonmodal, and define semi-modal while we're at it:

- ❑ **Modal dialog box:** Blocks input to all other windows to force the user to respond to the dialog. Useful for grabbing an immediate response from the user and displaying critical error messages.
- ❑ **Nonmodal dialog box:** Nonblocking window that operates normally with other windows in the application. Useful for search or input windows where we might want to copy and paste values to and from the main window, for instance.

- **Semimodal dialog box:** A modal dialog that does not have its own event loop. This enables control to be returned to the application, but to still have input blocked to anything other than the dialog box. A semimodal dialog is useful in the rare occasions when we have a progress meter indicate the progress of time-consuming critical operation that we want to give the user the opportunity to cancel. Since it doesn't have its own event loop, we must call `QApplication::processEvents` periodically to update the dialog.

QDialog

`QDialog` is the base dialog class in Qt that provides `exec` and `show` methods for handling modal and nonmodal dialogs, has an integral `QLayout` we can use, and has several signals and slots useful for responding to button presses.

We'll normally create a class for our dialog, inherit from `QDialog`, and add widgets to create the dialog interface:

```
#include <qdialog.h>

MyDialog::MyDialog(QWidget *parent, const char *name) : QDialog(parent, name)
{
    QHBoxLayout *hbox = new QHBoxLayout(this);

    hbox->addWidget(new QLabel("Enter your name"));
    hbox->addWidget(new QLineEdit());
    hbox->addWidget(ok_pushButton);
    hbox->addWidget(cancel_pushButton);

    connect (ok_pushButton, SIGNAL(clicked()), this, SLOT(accept()));
    connect (cancel_pushButton, SIGNAL(clicked()), this, SLOT(reject()));
}
```

Unlike with the `QMainWindow`, we can directly specify `MyDialog` as the parent of our `QLayout` object without creating a dummy `QWidget` and using that as the parent.

`QDialog` has two slots—`accept` and `reject`—that we use to indicate the dialog result. This result is returned to us by the `exec` method. Normally, we'll connect Ok and Cancel buttons to the slots, as we do in `MyDialog`.

Modal Dialogs

To use our dialog as a modal dialog, we call `exec`, which brings up the dialog and returns either the `QDialog::Accepted` or `QDialog::Rejected` according to which slot was activated.

```
MyDialog *dialog = new MyDialog(this, "mydialog");
if (dialog->exec() == QDialog::Accepted)
{
    // User clicked 'Ok'
    doSomething();
}
else
{
```

```
// user clicked 'Cancel' or dialog killed  
doSomethingElse();  
}  
delete dialog;
```

The dialog is automatically hidden when the `exec` returns, but we still delete the object from memory.

Note that all processing blocks when `exec` is called, so if there is any time-critical code in your application then a nonmodal or semimodal dialog is more appropriate.

Nonmodal Dialogs

Nonmodal dialogs are little different from ordinary main windows, the key change being that they position themselves over their parent window, share their taskbar entry and hide automatically when the `accept` or `reject` slot is called.

To display a nonmodal dialog we call `show` as we would a `QMainWindow`:

```
MyDialog *dialog = new MyDialog(this, "mydialog");  
dialog->show();
```

`show` displays the dialog and immediately returns to continue the processing loop. To handle button presses we need to write and connect to slots:

```
MyDialog::MyDialog(QWidget *parent, const char *name) : QDialog(parent, name)  
{  
    ...  
    connect (ok_pushButton, SIGNAL(clicked()), this, SLOT(OkClicked()));  
    connect (cancel_pushButton, SIGNAL(clicked()), this, SLOT(CancelClicked()));  
}  
  
MyDialog::OkClicked()  
{  
    //Do some processing  
}  
MyDialog::CancelClicked()  
{  
    //Do some other processing  
}
```

The dialog is again automatically hidden when a button is pressed, as with a modal dialog.

Semimodal Dialog

To create a semimodal dialog we must set the `modal` flag in the `QDialog` constructor and use the `show` method.

```
QDialog (QWidget *parent=0, const char *name=0, bool modal=FALSE, WFlags f=0)
```

The reason we didn't set `modal` to `TRUE` with the modal dialog is that calling `exec` forces the dialog to be modal regardless of this flag.

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Our dialog constructor will look something like this:

```
MySMDialog::MySMDialog(QWidget *parent, const char *name) : QDialog(parent, name,
TRUE)
{
    ...
}
```

Once we've got our dialog defined, we call `show` as normal and then progress with our processing, periodically calling `QApplication::processEvents` to keep the dialog updated.

```
MySMDialog *dialog = MySMDialog(this, "semimodal");
dialog->show();
while (processing)
{
    doSomeProcessing();
    app->processEvents();
    if (dialog->wasCancelled())
        break;
}
```

We check that the dialog hasn't been canceled before continuing processing. Note that `wasCancelled` isn't part of `QDialog`—we have to provide that ourselves.

Qt provides ready-made subclasses of `QDialog`, specialized for particular tasks such as a File selection, text entry, progress meter, and message box. Using these widgets whenever we can saves us a lot of trouble.

QMessageBox

A `QMessageBox` is a modal dialog that displays a simple message with an icon and buttons. The icon depends on the severity of the message, which can be regular information or warnings and other critical information.

The `QMessageBox` class has static methods to create and show each of these three types:

```
#include <qmessagebox.h>

int information (QWidget *parent, const QString &caption, const QString &text,
                 int button0, int button1=0, int button2=0)
int warning      (QWidget *parent, const QString &caption, const QString &text,
                 int button0, int button1, int button2=0)
int critical     (QWidget *parent, const QString &caption, const QString &text,
                 int button0, int button1, int button2=0)
```

We can choose buttons from a list of stock `QMessageBox` buttons, which match up with the returned value of the static methods:

- `QMessageBox::Ok`
- `QMessageBox::Cancel`
- `QMessageBox::Yes`

- QMessageBox::No
- QMessageBox::Abort
- QMessageBox::Retry
- QMessageBox::Ignore

A typical use of QMessageBox will look something like this:

```
int result = QMessageBox::information(this,
                                      "Engine Room Query", "Do you wish to engage the HyperDrive?",
                                      QMessageBox::Yes | QMessageBox::Default,
                                      QMessageBox::No | QMessageBox::Escape);

switch (result) {
    case QMessageBox::Yes:
        hyperdrive->engage();
        break;
    case QMessageBox::No:
        // do something else
        break;
}
```

We OR the button codes with Default and Escape to set the default actions when the Enter (or Return) and Escape buttons are pressed on the keyboard. Figure 17-8 shows the resulting dialog.

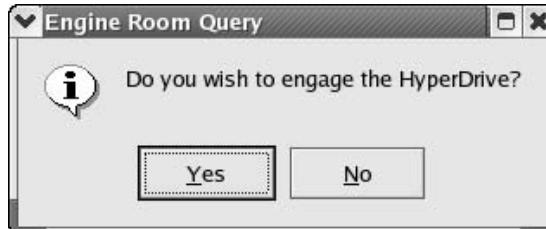


Figure 17-8

QInputDialog

QInputDialog is useful for inputting single values from the user, which can either be text, an option from a drop-down list, an integer, or a floating point value. The **QInputDialog** class has static methods like **QMessageBox** that are a bit of a handful as they have many parameters, but fortunately most have default values.

```
#include <qinputdialog.h>

QString getText  (const QString &caption, const QString &label,
                  QLineEdit::EchoMode mode=QLineEdit::Normal,
                  const QString &text=QString::null, bool * ok = 0,
                  QWidget * parent = 0, const char * name = 0)
```

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```
QString getItem (const QString &caption, const QString &label,
                 const QStringList &list, int current=0, bool editable=TRUE,
                 bool * ok=0, QWidget * parent = 0, const char * name=0)

int getInteger (const QString &caption, const QString &label, int num=0,
                int from = -2147483647, int to = 2147483647, int step = 1,
                bool * ok = 0, QWidget * parent = 0, const char * name = 0)

double getDouble (const QString &caption, const QString &label, double num = 0,
                  double from = -2147483647, double to = 2147483647,
                  int decimals = 1, bool * ok = 0, QWidget * parent = 0,
                  const char * name = 0 )
```

To input a line of text, we can write this:

```
bool result;
QString text = QInputDialog::getText("Question", "What is your Quest?:",
                                      QLineEdit::Normal,
                                      QString::null, &result, this, "input");

if (result) {
    doSomething(text);
} else {
// user pressed cancel
}
```

QInputDialog is made up of a QLineEdit widget and Ok and Cancel buttons, as we see in Figure 17-9.

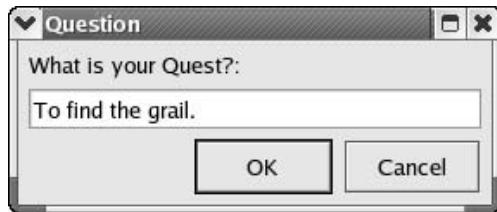


Figure 17-9

getText employs a QLineEdit that we can set the EchoMode of. We can specify default text or set it empty as we do here. Every QInputDialog has Ok and Cancel buttons, and passes a bool pointer to the method to indicate which button was pressed—result is TRUE if the user presses Ok.

getItem offers the user a list of options through a QComboBox.

```
bool result;
QStringList options;
options << "London" << "New York" << "Paris";
QString city = QInputDialog::getItem("Holiday", "Please select a destination:",
                                    options, 1, TRUE, &result, this, "combo");

if (result)
    selectDestination(city);
```

The resulting dialog is shown in Figure 17-10.

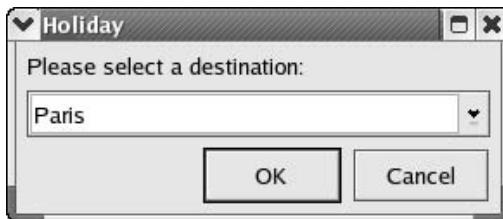


Figure 17-10

`getInteger` and `getDouble` work in much the same way, so we won't expand on them here.

Using qmake to Simplify Writing Makefiles

Compiling applications with both the KDE and Qt libraries becomes quite a chore since our makefile gets ever more complicated with the need to use `moc` and having libraries here, there, and everywhere. Fortunately, Qt comes with a utility called `qmake` to create makefiles for us.

If you've used Qt before, you may be familiar with `tmake`—an earlier (and now deprecated) incarnation of `qmake` that shipped with previous versions of Qt.

`qmake` takes a `.pro` file as input. This file contains the very basic information that the compilation requires, such as the sources, headers, target binary, and KDE/Qt library locations.

A typical KDE `.pro` file looks like this:

```
TARGET = app
MOC_DIR = moc
OBJECTS_DIR = obj
INCLUDEPATH = /usr/include/kde
QMAKE_LIBDIR_X11 += /usr/lib
QMAKE_LIBS_X11 += -lkdeui -lkdecore
SOURCES = main.cpp window.cpp
HEADERS = window.h
```

We specify the target binary, temporary `moc` and object directories, the KDE library path, and the sources and headers to build from. Note that the location of the KDE header and library files depends on your distribution. SuSe users should set `INCLUDEPATH` to `/opt/kde3/include` and `QMAKE_LIBS_X11` to `/opt/kde3/lib`.

```
$ qmake file.pro -o Makefile
```

Then we can run `make` as normal; it's that straightforward. For a KDE/Qt program of any complexity, we should use `qmake` to simplify the build routine.

Menus and Toolbars

As a demonstration of the power of KDE widgets, we've saved menus and toolbars to describe last, as they're a pretty good example of how the KDE libraries save us time and effort.

Usually in GUI libraries, menu items and toolbar items are distinct elements, each with their own item widgets. We have to create separate objects for each entry and keep track of changes; for example disabling certain options individually.

The KDE programmers came up with a better solution. Instead of this detached approach, KDE defines a `KAction` widget to represent an action that the application can perform. This action could be opening a new document, saving a file, or showing a help box.

The `KAction` is given text, a keyboard accelerator, an icon, and a slot that's called when the `KAction` is activated.

```
KAction *new_file = new KAction("New", "filenew", KstdAccel::key(KstdAccel::New),
                                this, SLOT(newFile()), this, "newaction");
```

The `KAction` can then be plugged into a menu and toolbar without any further description:

```
new_file->plug(a_menu);
new_file->plug(a_toolbar);
```

We've now created a New menu and toolbar entry that calls `newFile` when clicked.

Now if we need to disable the `KAction`—say if we don't want the user to be able to create a new file—the call is centralized.

```
new_file->setEnabled(FALSE);
```

That's all there is to menus and toolbars with KDE—it's very easy indeed. Let's look at the `KAction` constructor:

```
#include <kde/kaction.h>

KAction (const QString &text, const KShortcut &cut, const QObject *receiver,
          const char *slot, QObject *parent, const char *name = 0)
```

KDE provides us with standard `KAction` objects to make sure text, icons, and keyboard accelerators are standard between KDE applications:

```
#include <kde/kaction.h>

KAction * openNew (const QObject *recv, const char *slot, KActionCollection*
parent,
                  const char *name = 0)
KAction * save ...
KAction * saveAs ...
KAction * revert ...
KAction * close ...
```

```
KAction * print ...
etc...
```

Each standard action takes the same parameters: the slot receiver and function, a KactionCollection, and the KAction name. The KActionCollection object manages the KActions in a window, and we can get the current object using the actionCollection method of KMainWindow:

```
KAction *saveas = KStdAction::saveAs(this, SLOT(saveAs()), actionCollection(),
                                     "saveas");
```

Try It Out—A KDE Application with Menus and Toolbars

Let's try using KActions in a KDE application with this next example.

1. First we start with the header file KDEMenu.h. KDEMenu is a subclass of KMainWindow, itself a subclass of QMainWindow. KMainWindow handles session management within KDE and has an integral toolbar and status bar.

```
#include <kmainwindow.h>

class KDEMenu : public KMainWindow
{
    Q_OBJECT

public:
    KDEMenu(const char * name = 0);

private slots:
    void newFile();
    void aboutApp();
};
```

2. In KDEMenu.cpp, we start with #include directives for the widgets we'll be using.

```
#include "KDEMenu.h"

#include <kapp.h>
#include <kaction.h>
#include <kstdaccel.h>
#include <kmenubar.h>
#include <kaboutdialog.h>
```

3. In the constructor, we create three KAction widgets. new_file is created using a manual definition and quit_action and help_action use standard KAction definitions:

```
KDEMenu::KDEMenu(const char *name = 0) : KMainWindow (0L, name )
{
    KAction *new_file = new KAction("New", "filenew", KstdAccel::key(KstdAccel::New),
                                    this, SLOT(newFile()), this, "newaction");

    KAction *quit_action = KStdAction::quit(KApplication::kApplication(),
                                         SLOT(quit()), actionCollection());

    KAction *help_action = KStdAction::aboutApp(this, SLOT(aboutApp()),
                                                actionCollection());
```

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4. We create two top-level menus and insert them into the KApplication menuBar:

```
QPopupMenu *file_menu = new QPopupMenu;
QPopupMenu *help_menu = new QPopupMenu;

menuBar()->insertItem("&File", file_menu);
menuBar()->insertItem("&Help", help_menu);
```

5. Now we plug the actions in the menus and toolbar, inserting a separator line between new_file and quit_action:

```
new_file->plug(file_menu);
file_menu->insertSeparator();
quit_action->plug(file_menu);
help_action->plug(help_menu);

new_file->plug(toolBar());
quit_action->plug(toolBar());
}
```

6. Finally some slot definitions: aboutApp creates a KAbout Dialog to display information about the program. Note that the quit slot is defined as part of KApplication.

```
void KDEMenu::newFile()
{
    // Create new File
}

void KDEMenu::aboutApp()
{
    KAboutDialog *about = new KAboutDialog(this, "dialog");
    about->setAuthor(QString("A. N. Author"), QString("an@email.net"),
                      QString("http://url.com"), QString("work"));
    about->setVersion("1.0");
    about->show();
}

int main(int argc, char **argv)
{
    KApplication app( argc, argv, "cdapp" );
    KDEMenu *window = new KDEMenu("kdemenu");

    app.setMainWidget(window);
    window->show();

    return app.exec();
}
```

7. Next we need a menu.pro file for qmake:

```
TARGET  = kdemenu
MOC_DIR = moc
OBJECTS_DIR = obj
INCLUDEPATH = /usr/include/kde
```

```

QMAKE_LIBDIR_X11 += -L$KDEDIR/lib
QMAKE_LIBS_X11 += -lkdeui -lkdecore
SOURCES = KDEMenu.cpp
HEADERS = KDEMenu.h

```

8. Now we run qmake to create our Makefile, compile, and run.

```

$ qmake menu.prop -o Makefile
$ make
$ ./kdemenu

```

Figures 17-11 and 17-12 show how our menus and toolbar buttons appear in the window.

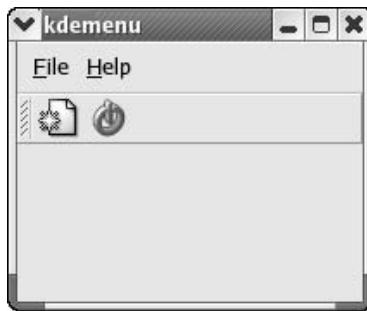


Figure 17-11

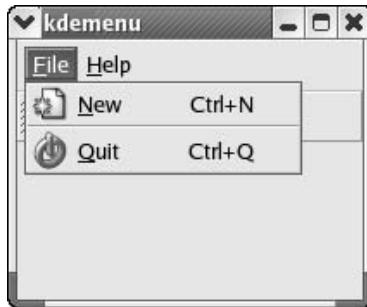


Figure 17-12

And that's it! We've finished our tour of Qt and KDE looking at the basic elements of all GUI applications, windows, layouts, buttons, dialogs, and menus. There are countless Qt and KDE widgets we haven't covered, from QColorDialog—a color-choosing dialog—to KHTML—a Web browser widget—all fully documented on the Trolltech and KDE Web sites.

CD Database Application Using KDE/Qt

It's time to turn our attention to our CD application once again, now that we can use the power of KDE/Qt to bring it to life. We'll follow the same layout we created in Chapter 16 and code similar functionality.

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Let's remind ourselves what we want our CD database application to do:

- Log on to the database from the GUI
- Search for a CD
- Display CD and track information
- Add a CD to the database
- Display an About window

Try It Out—MainWindow

We'll start off with coding the main window of our application, which contains the search entry widget and search result list.

1. Start by typing in `MainWindow.h`. Since the window contains a `QLineEdit` widget for searching for CDs and a `QListView` to display the results, we need to include the `qlistview.h` and `qlineedit.h` header files.

```
#include <kmainwindow.h>
#include <qlistview.h>
#include <qlineedit.h>

class MainWindow : public KMainWindow
{
    Q_OBJECT

public:
    MainWindow (const char *name);

public slots:
    void doSearch();
    void AddCd();

private:
    QListView *list;
    QLineEdit *search_entry;

};
```

2. `MainWindow.cpp` is the most complicated part of our program. In the constructor, we create the main window interface and connect the necessary signals to our slots. As usual, we start off with the `#include` files:

```
#include "MainWindow.h"
#include "AddCdDialog.h"
#include "app_mysql.h"

#include <qvbox.h>
#include <qlineedit.h>
#include <QPushButton.h>
#include <QLabel.h>
```

```
#include <qlistview.h>
#include <kapp.h>
#include <kmenubar.h>
#include <klocale.h>
#include <kpopupmenu.h>
#include <kstatusbar.h>
#include <kaction.h>
#include <kstdaccel.h>

#include <string.h>

MainWindow::MainWindow ( const char * name ) : KMainWindow ( 0L, name )
{
    setCaption("CD Database");
}
```

- 3.** Now we create our menu and toolbar entries using the KAction widget:

```
KAction *addcd_action = new KAction("&Add CD", "filenew",
                                   KStdAccel::key(KStdAccel::New),
                                   this,
                                   SLOT(AddCd()),
                                   this);

KAction *quit_action = KStdAction::quit(KApplication::kApplication(),
                                       SLOT(quit()), actionCollection());

QPopupMenu * filemenu = new QPopupMenu;
QString about = ("CD App\n\n"
                  "(C) 2003 Wrox Press\n"
                  "email@email.com\n");

QPopupMenu * helpmenu = helpMenu(about);
menuBar()->insertItem( "&File", filemenu );
menuBar()->insertItem(i18n("&Help"), helpmenu);

addcd_action->plug(filemenu);
filemenu->insertSeparator();
quit_action->plug(filemenu);

addcd_action->plug(toolBar());
quit_action->plug(toolBar());
```

- 4.** In the interest of variety, we'll use QBox layout widgets instead of the usual QLayout classes.

```
QVBox *vbox = new QVBox (this);
QHBox *hbox = new QHBox (vbox);

QLabel *label = new QLabel(hbox);
label->setText( "Search Text:" );

search_entry = new QLineEdit ( hbox );
QPushButton *button = new QPushButton( "Search", hbox );
```

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5. Next up is the `QListView` widget, which occupies the majority of the window area. Then we connect the requisite signals to our `doSearch` slot to perform the CD database search. The KMainWindow status bar is made visible by adding an empty message.

```
list = new QListView( vbox, "name", 0L);
list->setRootIsDecorated(TRUE);
list->addColumn("Title");
list->addColumn("Artist");
list->addColumn("Catalogue");

connect(button, SIGNAL(clicked()), this, SLOT(doSearch()));
connect(search_entry, SIGNAL(returnPressed()), this, SLOT(doSearch()));

statusBar()->message("");
setCentralWidget(vbox);
resize(300,400);
}
```

6. The `doSearch` Slot is the business end of the application. It reads the search string and fetches all matching CDs and their tracks. The logic is identical to the GNOME/GTK+ `doSearch` function in Chapter 16.

```
void MainWindow::doSearch()
{
    cd_search_st *cd_res = new cd_search_st;
    current_cd_st *cd = new current_cd_st;
    struct current_tracks_st ct;
    int res1, i, j, res2, res3;
    char track_title[110];
    char search_text[100];
    char statusBar_text[200];
    QListWidgetItem *cd_item;

    strcpy(search_text, search_entry->text());
```

7. Fetch the matching CD ids and update the status bar to display the search results.

```
res1 = find_cds(search_text, cd_res);
sprintf(statusBar_text, " Displaying %d result(s) for search string ' %s '",
       res1, search_text);
statusBar()->message(statusBar_text);

i = 0;
list->clear();
```

8. For each id, get the CD information, insert into the `QListView`, and get all tracks for this CD.

```
while (i < res1) {

    res2 = get_cd(cd_res->cd_id[i], cd);

    cd_item = new QListWidgetItem(list, cd->title, cd->artist_name, cd->catalogue);
```

```
res3 = get_cd_tracks(cd_res->cd_id[i++], &ct);
j = 0;
/* Populate the tree with the current cd's tracks */
while (j < res3) {

    sprintf(track_title, " Track %d. ", j+1);
    strcat(track_title, ct.track[j++]);

    new QListViewItem(cd_item, track_title);
}
}
```

9. The AddCd slot is called when the addcd_action menu item or toolbar button is activated.

```
void MainWindow::AddCd()
{
    AddCdDialog *dialog = new AddCdDialog(this);
    dialog->show();
}
```

The result is shown in Figure 17-13.



Figure 17-13

Try It Out—AddCdDialog

To add a CD to the database, we'll need to code a dialog with the necessary fields we need to input.

1. Type the following and call it `AddCdDialog.h`. Note that `AddCdDialog` inherits from `KDialogBase`, the KDE dialog widget.

```
#include <kdialogbase.h>
#include <qlineedit.h>
```

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```
class AddCdDialog : public KDialogBase
{
    Q_OBJECT

public:
    AddCdDialog (QWidget *parent);

private:
    QLineEdit *artist_entry, *title_entry, *catalogue_entry;

public slots:
    void okClicked();
};
```

2. Next is `AddCdDialog.cpp`, which calls the `add_cd` function from the MySQL interface code in the `okClicked` slot:

```
#include "AddCdDialog.h"
#include "app_mysql.h"

#include <qlayout.h>
#include <qlabel.h>

AddCdDialog::AddCdDialog( QWidget *parent)
    : KDialogBase( parent, "AddCD", false, "Add CD",
        KDialogBase::Ok|KDialogBase::Cancel, KDialogBase::Ok, true )
{

    QWidget *widget = new QWidget(this);
    setMainWidget(widget);

    QGridLayout *grid = new QGridLayout(widget,3,2,10, 5,"grid");

    grid->addWidget(new QLabel("Artist", widget, "artistlabel"), 0, 0, 0);
    grid->addWidget(new QLabel("Title", widget, "titlelabel"), 1, 0, 0);
    grid->addWidget(new QLabel("Catalogue", widget, "cataloguelabel"), 2, 0, 0);

    artist_entry = new QLineEdit( widget, "artist_entry");
    title_entry = new QLineEdit( widget, "title_entry");
    catalogue_entry = new QLineEdit( widget, "catalogue_entry");

    grid->addWidget(artist_entry, 0,1, 0);
    grid->addWidget(title_entry, 1,1, 0);
    grid->addWidget(catalogue_entry, 2,1, 0);

    connect (this, SIGNAL(okClicked()), this, SLOT(okClicked()));
}

void AddCdDialog::okClicked()
{
    char artist[200];
    char title[200];
    char catalogue[200];
    int cd_id = 0;
```

```

strcpy(artist, artist_entry->text());
strcpy(title, title_entry->text());
strcpy(catalogue, catalogue_entry->text());
add_cd(artist, title, catalogue, &cd_id);

}

```

Figure 17-14 shows the AddCdDialog in action.

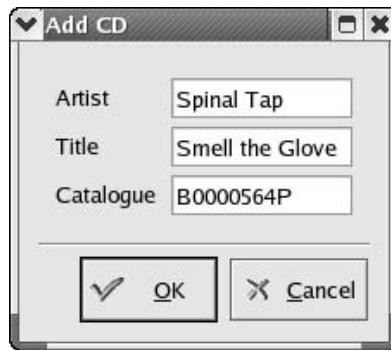


Figure 17-14

Try It Out—LogonDialog

Of course, we can't query the database without first logging on, so we need a simple dialog to enter our credentials. We'll call this class LogonDialog. (Yes, another subtle and imaginative title!)

1. First, the header file. Type this, calling it LogonDialog.h. Note that for variety this time we inherit from QDialog rather than KDialogBase.

```

#include <qdialog.h>
#include <qlineedit.h>

class LogonDialog : public QDialog
{
    Q_OBJECT

public:
    LogonDialog (QWidget *parent = 0, const char *name = 0);
    QString getUsername();
    QString getPassword();

private:
    QLineEdit *username_entry, *password_entry;
};


```

2. Rather than encapsulating the database_start call in LogonDialog.cpp, we have better methods for the username and password. Here's LogonDialog.cpp:

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```
#include "LogonDialog.h"
#include "app_mysql.h"

#include <QPushButton.h>
#include <QLayout.h>
#include <QLabel.h>

LogonDialog::LogonDialog( QWidget *parent, const char *name): QDialog(parent, name)
{
    QGridLayout *grid = new QGridLayout(this, 3, 2, 10, 5,"grid");

    grid->addWidget(new QLabel("Username", this, "username_label"), 0, 0, 0);
    grid->addWidget(new QLabel("Password", this, "password_label"), 1, 0, 0);

    username_entry = new QLineEdit( this, "username_entry");
    password_entry = new QLineEdit( this, "password_entry");
    password_entry->setEchoMode(QLineEdit::Password);

    grid->addWidget(username_entry, 0, 1, 0);
    grid->addWidget(password_entry, 1, 1, 0);

    QPushButton *button = new QPushButton ("Ok", this, "button");
    grid->addWidget(button, 2, 1,Qt::AlignRight);

    connect (button, SIGNAL(clicked()), this, SLOT(accept()));

}

QString LogonDialog::getUsername()
{
    if (username_entry == NULL)
        return NULL;

    return username_entry->text();
}

QString LogonDialog::getPassword()
{
    if (password_entry == NULL)
        return NULL;

    return password_entry->text();
}
```

Figure 17-15 shows how the dialog will look.



Figure 17-15

Try It Out—main.cpp

The only remaining code is the `main` function that we place in a separate source file, `main.cpp`.

1. In `main.cpp`, we open a `LogonDialog` and get a successful logon from `database_start`. If logging on isn't successful, we display a `QMessageBox`, or if we try to exit the `LogonDialog`, we ask the user to confirm that he wants to quit.

```
#include "MainWindow.h"
#include "app_mysql.h"
#include "LogonDialog.h"

#include <kapp.h>
#include <qmessagebox.h>

int main( int argc, char **argv )
{
    char username[100];
    char password[100];

    KApplication a( argc, argv, "cdapp" );

    LogonDialog *dialog = new LogonDialog();

    while (1)
    {
        if (dialog->exec() == QDialog::Accepted)
        {
            strcpy(username, dialog->getUsername());
            strcpy(password, dialog->getPassword());

            if (database_start(username, password))
                break;

            QMessageBox::information(0, "Title",
                                   "Could not Logon: Check username and/or password",
                                   QMessageBox::Ok);
            continue;
        }
        else
        {
            if (QMessageBox::information(0, "Title",
                                       "Are you sure you want to quit?",
                                       QMessageBox::Yes, QMessageBox::No)
                == QMessageBox::Yes)
            {
                return 0;
            }
        }
    }
    delete dialog;

    MainWindow *window = new MainWindow( "Cd App" );
    window->resize( 600, 400 );
}
```

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```
a.setMainWidget( window );
window->show();

return a.exec();
}
```

2. All that remains is to write a .pro file to pass to qmake. Call this cdapp.pro:

```
TARGET = app
MOC_DIR = moc
OBJECTS_DIR = obj
INCLUDEPATH = /usr/include/kde /usr/include/mysql
QMAKE_LIBDIR_X11 += -/usr/lib
QMAKE_LIBS_X11 += -lkdeui -lkdecore -lmysqlclient
SOURCES = MainWindow.cpp main.cpp app_mysql.cpp AddCdDialog.cpp LogonDialog.cpp
HEADERS = MainWindow.h app_mysql.h AddCdDialog.h LogonDialog.h
```

Note that we've cheated slightly and simply renamed app_mysql.c to app_mysql.cpp; therefore, we treat it like an ordinary C++ source file. This avoids the (minor) complication of having to link a C object file to C++.

```
$ qmake cdapp.pro -o Makefile
$ make
$ ./app
```

If all is well, we should have a working CD database!

You might like to try implementing the other functions in the MySQL interface, such as adding tracks to CDs or deleting CDs, to get a closer understanding of KDE/Qt. You'll need to create dialog boxes, new menu entries, and toolbar entries, and you'll have to write the underlying logic. Give it a shot!

Summary

In this chapter, you've learned about using the Qt GUI library and seen KDE widgets in action. You've seen that Qt is a C++ library that uses a signal/slot mechanism to implement event-driven programming. We took a tour of the basic Qt widgets and wrote several example programs to demonstrate how to use them in practice. Finally, we implemented a GUI front end to our CD application using KDE/Qt.

18

Device Drivers

Up until now, we've been concentrating on writing application code. We've looked at the libraries available to application programmers that allow them to access hardware and devices attached to the machine—file systems, memory, network connections, and so on. All of these libraries allow your applications to make demands on the *kernel*—the core of the operating system.

To round off this book, we're going to take a look at the kernel from the inside. In order to fulfill those demands from applications, the kernel relies upon *device drivers* to talk to all the different types of devices it might encounter. This enables the kernel to present a uniform interface to applications, regardless of the underlying technology. The file system is an obvious example; you can use the same commands to operate on files, whether the files are stored on an IDE hard drive, a SCSI drive, a CD-ROM, a floppy, or even a RAM disk. This shows device drivers at work.

In this chapter, we will be covering the following main topics:

- What device drivers are, what do they do, and how to write them
- Character devices and how they work
- Timing in the kernel
- Memory management as applied to peripheral devices
- I/O ports and how to use them to talk to your devices
- Block devices and how they work
- Debugging the kernel and kernel modules

Writing Device Drivers

Writing device code, while not necessarily more difficult than writing application code, requires you to learn some new libraries and consider different sorts of problems than you have so far encountered in application space. In this chapter, you'll be writing code that forms part of the kernel itself. It's important to understand that, while in application space, the kernel provides a safety net

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for your mistakes; however, when you're working in kernel space, there is no safety net. Kernel code has the power to monopolize control of the computer, preventing any other processes from executing, so you have to write code that doesn't abuse that power and that behaves as a good neighbor to other processes.

In writing kernel modules for Linux, you have the immense advantage that the entire body of kernel source code is available for you to look at, modify, and reuse in your own code. Throughout this chapter, we'll point you to the source code of various header files and modules for further information. It is impossible to overemphasize the importance of the source code as a source of information, good coding advice, and ideas.

In this chapter, we focus on Intel's 80x86 architecture (or just x86). That said, the accompanying modules have also been tested on a Compaq Alpha and so are known to be reasonably portable. In recent years, portability has become a great focus of kernel development, and almost all of the kernel driver API is very portable. Some code will never be completely portable, but if nothing is stated about portability in a section, it should work regardless of what particular machine you are working with. Other differences exist between these two platforms and others, which we will try to outline more extensively in the "Portability" section later in the chapter. So, while the majority of the code in this chapter will work on other architectures, we will do our best to clearly point out what parts are platform-dependent (mainly due to differences in the hardware architecture) as we come across them.

Devices

A device can be just about any part of a computer, either directly built into the core of it or as an add-on peripheral such as a SCSI controller, extra serial ports, a network adapter, and much more. Usually, you are concerned with the latter when writing new device drivers, such as adding support for that flashy new video adapter you just bought.

Device drivers are the software that control devices and export a usable interface that allows other programs to interact with a particular device. A device driver doesn't necessarily control a physical hardware peripheral. An example of this is `/dev/random` (which spits out random data, more on this later in the chapter) and `/dev/vcs` (current virtual console). These devices have no connection to real hardware, but they are a way of getting data from the kernel to applications and are usually named *software devices*.

Device drivers are a layer between the kernel and the hardware that it controls. As such, a device driver is a very useful abstraction because it greatly simplifies the kernel: Instead of having the kernel talk to each device itself, which would increase its size and decrease its speed, the kernel exports a well-defined interface and leaves the task of interacting directly with devices to the individual device drivers. This also means that the kernel proper can be (and is) written without knowledge of the various different devices that will be developed later on, as long as they can be accommodated within the framework of the defined models. So, for example, adding support for a new file system to the Linux kernel doesn't require a total rewrite and can be done relatively easily and with reuse of existing code. The file system, for example, is split into a generic virtual file system, VFS, that the specific file systems register themselves with. All the major parts of the kernel are designed this way—the CD-ROM subsystem, the SCSI layer, and others (Figure 18-1). This provides a good level of modularity and eases the development of new device drivers. Another important aspect of device drivers is providing a consistent and familiar

interface to the application-level programmer. A well-written device driver allows the application programmer to treat the I/O device as a file using standard techniques. This interface design is an important part of the design philosophy of Linux and other UNIX-like operating systems.

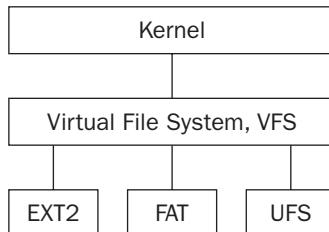


Figure 18-1

Device Classes

Device drivers can be split into different classes according to their behavior. The two basic types are character- and block-oriented devices. *Character devices* are read byte-by-byte sequentially, and access to them is not cached by the buffer system. Imagine how data or audio is read from a tape in a continuous stream—this is how character devices serve data. *Block devices*, on the other hand, allow random access, are read in multiples of their block size, and are accessed through the buffer cache system. In contrast to other UNIX flavors, the Linux kernel does allow data that is not a multiple of the device block size to be read and so that difference is purely academic.

Most device drivers are accessed through the file system; an exception is network devices that have no file entries on Linux like on some other UNIX variants. `/dev` is populated with the device special files, and its contents look almost like any other directory:

```

$ ls -l /dev
...
brw-rw---- 1 root      disk        22,      1 May  5 1998 hdc1
crw-rw---- 1 root      daemon     6,       0 May  5 1998 lp0
...
$ 
  
```

Two things that make device special files different from regular files are the `c` and `b` *flags* that classify the device as either a character or block device, respectively. The distinction between these two types of devices is clear in this example: It would not make any sense to allow random access to a printer, for instance. By contrast, being able to copy a file from a disk without resorting to reading the entire hard drive from the beginning is essential. Device special files do not have to be located in the `/dev` directory, but this is tradition and keeps the system orderly. Some UNIX systems contain directories under `/dev` for the disk subsystem, for example, but Linux generally just has one big, messy directory.

The numbers following the owner and group of the special file, respectively, indicate the major and minor number of the device. The *major number* indicates a specific device and the *minor number* an instance within the device. In the preceding example listing of `/dev`, `hdc1` has a major number of 22 and a minor number of 1. Major number 22 is the official number for the second IDE controller, and the IDE subsystem identifies partitions on the master and slave device according to the minor number. In fact, you could choose any name you wish for the special files; the kernel only cares about the type and the major number.

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New special files are created with the `mknod` system call, which can be invoked by the utility of the same name. The syntax for `mknod` is

```
mknod name type major minor.
```

So to create the above `lp0` entry, you have to be root and type

```
# mknod /dev/lp0 c 6 0  
#
```

Most of the arguments are self-explanatory, so we will just mention that `type` corresponds to the class of the device—`b` for block devices and `c` for character devices. More information can be found in the man page for `mknod`.

User and Kernel Space

The first thing to come to grips with is the difference between programming device drivers and writing normal user space applications. Linux operates in two modes: *user mode* and *supervisor mode*. We will call the latter *kernel mode* from now on because this is the descriptive explanation of what is really going on. In this context, *mode* describes a change in the way the processor itself actually handles instructions and permissions. Intel's x86 ($x \geq 3$) names its execution modes Ring 0, 1, 2, and 3, with Ring 0 being the most privileged mode and vice versa. In Linux, Ring 0 signifies kernel-mode execution and Ring 3 user-mode; the other modes are unused. Other architectures have similar features but name their execution modes differently. We won't bore you with the tedious hardware details, but the gist of it is that the mode a process operates in places certain restrictions on what it is allowed to do. Processes running in user space are, among other things, not allowed to directly access hardware and execute certain instructions.

When you are writing an ordinary program, you use certain functions that you take for granted, such as `printf` and `strcpy`. These are part of the standard C library, `libc`, and have defined prototypes in appropriate header files. User space applications are (usually) linked against `libc`, and these symbols are resolved at run time. Kernel modules, on the other hand, are linked against the kernel and are therefore restricted to using the functions that it exports. A device driver built as a kernel module is not run in the ordinary sense, and so module symbols are resolved when you attempt to load the module into the kernel.

There are several issues concerning good practice when writing kernel-level code that you should be aware of. Following are some of the rules to live by; some are black and white, while others leave room for interpretation:

- ❑ Don't use floating-point arithmetic. The kernel does not save the processor's floating-point states when switching modes, so if you do this you have to save the state yourself. There is usually no good reason to do so.
- ❑ Don't busy wait in your driver. A user space application can never completely monopolize the CPU, but a loop spinning for a second inside the kernel will appear to hang the system during that time and prevent any real work from being done.
- ❑ Keep the code as clean and comprehensible as possible. Don't try to be too clever. Debugging, as we will see later, is much harder in kernel space. Drivers often need precise timing when dealing with hardware; even adding a print statement might mess up the timing and hide an obscure bug.

What Goes Where?

You will need to decide what to implement as a module and what to keep in user space. The general consensus is that if you can code it in user space, don't do it in kernel space! There are several reasons why this is excellent advice. Mistakes happen, and while an error in user space might only cause a core dump, an error in the kernel might hang the computer completely. Bloating the kernel space with unnecessary code is not good practice, either. Providing the necessary application hooks in a kernel module will often yield the best result when speed or timing is not a critical issue. It will also give you the advantage of having the standard user space libraries available to link against.

Building Modules

Compiling a kernel module is no more difficult than what you are used to with ordinary applications. The examples that accompany this book are all supplied with makefiles for you to inspect. The basic procedure for compiling a kernel module is something on the order of

```
gcc -D__KERNEL__ -D__SMP__ -DMODULE -DMODVERSIONS -I/usr/src/linux/include -Wall
     -O2 -o module.o -c module.c
```

If you have never paid much attention to a kernel build, this may look a bit overwhelming. Most of the above defines can be handled directly from within the module by reading the settings from the kernel. Let's look at what each of them does.

| | |
|--------------------------|---|
| <code>__KERNEL__</code> | Not all kernel header files are used only by the kernel itself. Some user space applications include them, but parts of them are kernel-specific and thus need to be hidden from user space. Code that will be inserted into the kernel has to define <code>__KERNEL__</code> to see the whole thing. |
| <code>__SMP__</code> | The kernel can be compiled for either SMP (Symmetric Multi Processor, meaning systems that have more than one CPU) or UP (Uni Processor) machines. A module that will be inserted in an SMP kernel must define <code>__SMP__</code> . |
| <code>MODULE</code> | Must be defined for code that is compiled as a kernel module. |
| <code>MODVERSIONS</code> | A safeguard against kernel and module incompatibilities. A more comprehensive explanation follows. |

The rest of the `gcc` command line options are not kernel-specific, and you have probably seen them used before. The `-O` switch tells `gcc` how much optimization to perform at compile time. Kernel modules must be compiled with an optimization level of `O2` or higher to use functions that are inlined by the kernel, such as `outb`. Levels higher than `O2` may work, but we don't recommend them. All warnings are turned on, as this is good practice for any kind of program, not just kernel modules.

`/usr/src/linux` is the preferred place to keep your Linux kernel tree, but it is not a requirement and you can store it anywhere you want. The `-I` (include path) option given to `gcc` above tells it to include this path when searching for includes. Header files that are specific to the kernel are located in the `include/` directory of the kernel tree, so when we write

```
#include <linux/module.h>
```

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we are including the file `/usr/src/linux/include/linux/module.h`. There are two directories of importance inside the `include/` directory, one of them being `linux/` and the other `asm/`. The former contains platform-independent files, while the latter is a symbolic link to `asm-arch/` where `arch` is `i386` or `alpha`, for example. This link is created when configuring and building the kernel, and symbolic links to both include directories are made to `/usr/include/linux` and `/usr/include/asm`, correspondingly.

The `MODVERSIONS` define is used on kernels running with function versioning. This is a measure used to prevent modules from being loaded into an incompatible kernel, which could either cause malfunctioning or kernel crashes in the worst cases. When modules are compiled, they are built against the current kernel version you are running at the time and can usually only be loaded on exactly that version. A kernel running with versioning will suffix exported functions with checksum information based on the interface that it exports. This provides a secure way of knowing that the underlying API has not changed since the module was built. You can check whether you are running a versioned kernel by inspecting `/proc/ksyms`, which contains the symbols exported on the running kernel. If the exported functions have a suffix similar to `_Rxxxxxx`, versioning is enabled. This will look something like

```
$ cat /proc/ksyms
...
c0115728 printk_Rsmp_1b7d4074
c01d3ed0 sprintf_Rsmp_3c2c5af5
...
$
```

The actual function names of the above are `printk` and `sprintf`. The listing shows that we're currently running an SMP kernel with module versioning enabled. To be able to resolve these names, a module must include the `linux/modversions.h` file.

Name space is another issue that you may not have paid particular attention to before, unless you have worked with a big project. When developing device drivers, you should be careful about polluting the global kernel name space. An excellent way to avoid clashes, which is adopted by the vast majority of the kernel developers, is to prefix exported functions with the name of your driver. Still, exporting only functions and variables that are going to be used by other drivers is another important practice. Declaring global variables and functions static achieves this beautifully but has other side effects. Other variables and functions are explicitly exported with the macro `EXPORT_SYMBOL`, which adds them to the kernel's global symbol table. You generally only need to worry about this if you plan on splitting your driver across several modules or otherwise expose internals for others to use. Of course, keeping global name space pollution to a minimum is always a good idea. The syntax is straightforward:

| | |
|---|--|
| <code>EXPORT_SYMBOL(name)</code> | Export the variable or function name. |
| <code>EXPORT_SYMBOL_NOVERS(name)</code> | Export the variable or function name, but don't include module versioning even if defined. |
| <code>EXPORT_NO_SYMBOLS</code> | Don't export any symbols. |

The declarations must be made outside of any functions—in an include file or at the end of the module code, for example. The macros are defined in `linux/module.h` if you are curious. `EXPORT_SYMBOLTAB` must be defined prior to using any of these macros.

Data Types

Linux runs on a lot of different architectures, some 32-bit and some 64-bit. There are even ports of Linux to 16-bit architectures. Therefore, it is important not to make assumptions about the size of a given type of variable. Linux defines standard types that have a given size on any platform.

| | |
|--|---|
| <code>__u8, __u16, __u32, __u64</code> | Unsigned and signed variables between char and 64-bit long in size. |
| <code>__s8, __s16, __s32, __s64</code> | |

If you need a specifically sized variable, use one of the preceding types. They also look much nicer in the code and make it more readable when you browse the driver source a couple of months later. There are also the special types that are passed to driver entry points, for example.

```
ssize_t schar_read(..., size_t count, loff_t *offset)
```

`ssize_t` and `size_t` are examples of types that serve a specific purpose within the kernel; we'll look at exactly what purpose later in the chapter. Usually these types are acted upon directly, and therefore you don't need to worry too much about the particular size. The various types are described in `linux/types.h` and `asm/posix_types.h`, so look them up if you need a hint as to what size they are `typedefed` to. When you do need to assign them to the compiler's integral types, remember to use an appropriate cast. `gcc` is quite picky about size mismatches and will warn you about possible problems.

Try It Out—A Kernel Module

Now is an excellent time to dive in and create your very first module. In keeping with past tradition, "hello, kernel" seems like the thing to do. Don't worry—it's the last time we'll revisit this bit of programming history in this book.

1. Let's start off with the following file, `hello.c`:

```
#include <linux/module.h>

#if defined(CONFIG_SMP)
#define __SMP__
#endif

#if defined(CONFIG_MODVERSIONS)
#define MODVERSIONS
#include <linux/modversions.h>
#endif

#include <linux/kernel.h>

static __init int init_module(void)
{
    printk(KERN_DEBUG "Hello, kernel!\n");
    return 0;
}

static __exit void cleanup_module(void)
{
    printk(KERN_DEBUG "Good-bye, kernel!\n");
}
```

The `_init` and `_exit` declarations are special kernel macros designed to tell the kernel to flag these functions for special handling in cases where they are compiled in statically rather than included as parts of modules. The `_init` declaration allows the kernel to reclaim the space used by initialization functions, while the `_exit` declaration tells the kernel to just plain ignore the function altogether. If you're only going to write your device driver as a module, with no possibility that it will be included statically, it is perfectly safe to leave these special declarations out.

The kernel equivalent of `printf` is `printk`. They are similar in usage, but the latter does not support printing of floating point. The `KERN_DEBUG` define given to `printk` sets the priority of the printed message. The possible values are defined by `linux/kernel.h` as follows:

```
#define KERN_EMERG      "<0>"      /* system is unusable */
#define KERN_ALERT       "<1>"      /* action must be taken immediately      */
#define KERN_CRIT        "<2>"      /* critical conditions */
#define KERN_ERR         "<3>"      /* error conditions */
#define KERN_WARNING     "<4>"      /* warning conditions */
#define KERN_NOTICE      "<5>"      /* normal but significant condition */
#define KERN_INFO         "<6>"      /* informational */
#define KERN_DEBUG        "<7>"      /* debug-level messages */
```

So we could have written

```
printk("<7> Hello, kernel!\n");
```

instead, but we think you will agree that using the predefined levels makes the code easier to read. The log-level setting controls which messages will actually be printed on the console and/or appended to the `syslog`. This is controlled by `syslogd` and can usually be set up in `/etc/syslog.conf`. As it is written, you will probably not be able to see the messages directly. Instead, they are stored in the kernel buffer allocated for these kinds of messages. The program `dmesg` will show you what is currently stored in there (lots of messages from your last boot, most likely).

Apart from `printk`, though, there shouldn't be anything too unfamiliar here; we'll look at what's new a bit later in the chapter. For now, let's compile the module with this command in the directory where you created the `hello.c` file:

```
$ gcc -D__KERNEL__ -I/usr/src/linux/include -DMODULE -Wall -O2 -c hello.c -o
hello.o
$
```

2. Now let's try to insert the module into the kernel. Modules are loaded with the `insmod` (insert module) command, usually found in `/sbin/`. You must be root to insert and remove a module, as this would otherwise be a serious security breach if anybody were allowed to meddle with the kernel! Make sure that you are root and try the module out:

```
# insmod hello.o
#
```

3. No error messages so far, so how do we verify that the module has been inserted successfully? We can check the very end of the `dmesg` readout of the kernel buffer with this command:

```
# dmesg | tail
Hello, kernel!
#
```

4. We can see the message from our module there in the kernel buffer. To prove that the module is loaded, `lsmod` (list modules) can be run. It lists the modules that are currently inserted.

```
# lsmod
Module           Size  Used by
...
hello           176    0  (unused)
...
#
```

5. Not surprisingly, `hello` is listed with the other modules. `lsmod` also lists the size and usage count of each loaded module. We will get into usage counts a little later. For now, let's get rid of the `hello` module again. The `rmmod` (remove module) command will detach a module from the kernel.

```
# rmmod hello
# dmesg | tail
Good-bye, kernel!
#
```

How It Works

A couple of new things were introduced here. `linux/module.h` includes another header file (among others) called `linux/config.h` that contains the options selected at the kernel compile time, as defines. This is especially convenient for us, since we can be sure that if the kernel is compiled for SMP, `CONFIG_SMP` will be defined and we can define `_SMP_` appropriately. The same thing goes for `CONFIG_MODVERSIONS`; if that is configured, we define `MODVERSIONS` and include `linux/modversions.h` to gain access to the versioning information.

As we saw, a little message is printed to the kernel buffer when the module is loaded and unloaded. The two functions we defined to perform this are the only ones needed to complete a module. `init_module` is called at load time and is responsible for setting up internal data structures, initializing the hardware, and performing any other tasks that need to be done before the device is invoked for the first time. Since the above is only a simple framework, no real work is done. Most things work both ways, and so `cleanup_module` takes care of shutting down the device and releasing any resources that the device may have occupied.

And that's it! We've built a module and successfully inserted it into the kernel. Now that we've overcome our fear of the Linux kernel, we can get on to something a little more substantial.

Character Devices

While the `hello` module in the previous section is about as simple as you can get, it doesn't really do anything interesting. Once it is loaded, you cannot interact with it and it does not export any useful functions to user space applications. As a first step beyond, let's look at a sample framework for a character-driven driver.

Character-driven drivers are device drivers that operate on characters (bytes) as the basic unit of input and output. They are accessed in a sequential, nonrandom manner. Other types of device drivers are *block-driven*, where a contiguous block of data is the basic unit of I/O, and *packet-driven* (e.g., network interface cards), where the basic unit of I/O is a packet. Block drivers can be accessed in a random fashion while character drivers cannot.

Character devices have to register themselves with the kernel and provide it with the information that enables the kernel to invoke the correct functions when applications wish to interact with the device. `register_chrdev` takes care of this and is invoked with the following syntax:

```
int register_chrdev(unsigned int major, const char *name, struct file_operations  
*fops)
```

The return value is negative in case of failure and is non-negative (either a positive integer or zero) on success, which is the case with the majority of the kernel functions. Calling the function with zero as `major` provides dynamic major number assignment. In this case, the device is registered with the next available major number, and this is returned. Using dynamic assignment is not hard, but in order to access devices you need to create the correct special files if the major has changed since the last time you loaded the module. Because of this, we will use a series of reserved major numbers in this chapter.

Majors 42 and 120–127 are set aside for local devices and thus are not to be used by production modules. Consult Documentation/devices.txt for more information, including how to acquire an official number if you ever need one.

The second parameter, `name`, is only used for registration with `/proc/devices`. It is simply the name that will show up there, nothing more. The final parameter, the file operations structure, is the most interesting. It defines how the driver communicates with the outside world—specifically, which functions it handles itself and which the kernel defaults take care of. The structure is defined in `linux/fs.h` and is a series of pointers to functions. This concept is used in numerous places in the kernel and provides a form of abstraction between the different layers and how they interact.

File Operations

Access to character and block devices goes through the file system, as we saw earlier in the chapter. This is independent of the type of device—be it directly related to file systems (a hard disk driver, for example) or totally unrelated (a parallel port driver, perhaps). Device drivers therefore need to register a set of file operations that define the specific implementation that they offer. Below is the current file operations structure with the prototypes defined. All of the possible function types are listed, although no one single module will normally need to define them all. You'll recognize the names of most of these functions as mirroring the low-level device access functions we discussed back in Chapter 3. These functions are actually where those low-level calls end up, once the kernel has identified the device that needs to be contacted to fulfill that request.

```
struct file_operations {  
    struct module *owner;  
    loff_t (*llseek) (struct file *, loff_t, int);  
    ssize_t (*read) (struct file *, char *, size_t, loff_t *);  
    ssize_t (*write) (struct file *, const char *, size_t, loff_t *);  
    int (*readdir) (struct file *, void *, filldir_t);  
    unsigned int (*poll) (struct file *, struct poll_table_struct *);  
    int (*ioctl) (struct inode *, struct file *, unsigned int, unsigned long);  
    int (*mmap) (struct file *, struct vm_area_struct *);  
    int (*open) (struct inode *, struct file *);  
    int (*flush) (struct file *);  
    int (*release) (struct inode *, struct file *);  
    int (*fsync) (struct file *, struct entry *, int datasync);  
    int (*fasync) (int, struct file *, int);  
    int (*lock) (struct file *, int, struct file_lock );
```

```

ssize_t (*readv) (struct file *, const struct iovec *, unsigned long, loff_t *);
ssize_t (*writev) (struct file *, const struct iovec *, unsigned long, loff_t *);
ssize_t (*sendpage) (struct file *, struct page *, int, size_t, loff_t *, int);
unsigned long (*get_unmapped_area) (struct file *, unsigned long, unsigned long,
                                  unsigned long, unsigned long)
}

```

Your driver can provide any combination of these functions in order to represent the functionality of its device to the kernel. Let's look at what the available functions are shown in the following table.

| | |
|---------|---|
| llseek | llseek, or lseek as it is known in user space, changes the position within the file structure. Specifically, <code>file->f_pos</code> is modified; we will look at this later when discussing the file structure. On success, it returns the new position, while failure is identified with a negative return value. |
| read | read is seen from the application point of view, so <code>read</code> actually writes data back to user space. The return value, if positive, is the number of bytes read. Negative return values indicate an error. |
| write | <code>write</code> feeds data to the device and is equivalent to <code>read</code> with respect to return values. |
| readdir | <code>readdir</code> is strictly used by file systems to look up the contents of a directory. |
| poll | <code>poll</code> allows an application to be notified of given events from the device. <code>select</code> , the equivalent in BSD UNIX, is deprecated in Linux, and <code>poll</code> should be used instead. |
| ioctl | <code>ioctl</code> , or I/O control, allows applications to control the behavior or get data from the device with the <code>ioctl</code> system call. |
| mmap | <code>mmap</code> implements memory mapping of the device's address space to user space. This can be used to provide direct access to an internal buffer or peripheral device memory space. |
| open | <code>open</code> is called when the device is opened by an application. This is the only function that is default-implemented for both character and block devices, so you can leave this undefined if you don't need or care to know when the device is opened. |
| flush | <code>flush</code> naturally flushes the buffered data. As character devices aren't buffered, this entry only makes sense for block devices. |
| release | <code>release</code> is called when the device is closed. |
| fsync | <code>fsync</code> synchronizes the in-memory state with that on the device, writing out all dirty data in the output buffer. It must not return until it's finished. This entry is also only relevant to block devices. |
| fasync | <code>fasync</code> is called when an application changes the behavior with <code>fcntl</code> . |
| lock | <code>lock</code> enables a user to lock a file—only really makes sense for file systems. |
| readv | <code>readv</code> reads data from the device into a vector of buffers described by <code>iovec</code> . |

Table continued on following page

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| | |
|-------------------|--|
| writev | writev is similar to readv but writes data from the buffers described by iovec. |
| sendpage | sendpage is used to write pages one at a time, usually in connection with a network file system. |
| get_unmapped_area | get_unmapped_area is used to determine which parts of your device are not memory mapped. |

A single device will probably never have to define all of the above methods. It is completely up to you to define the operations that make sense for your device and set the others to NULL.

When the character device is registered with the kernel, its `file_operations` structure and name is added to the global `chrdevs` array of `device_struct` structures where the major number indexes it. This is called the character device switch table.

```
struct device_struct {  
    const char *name;  
    struct file_operations *fops;  
};
```

So, by looking up `chrdevs [YOUR_MAJOR] ->fops`, the kernel knows how to talk to the device and what entry points it supports (see Figure 18-2).

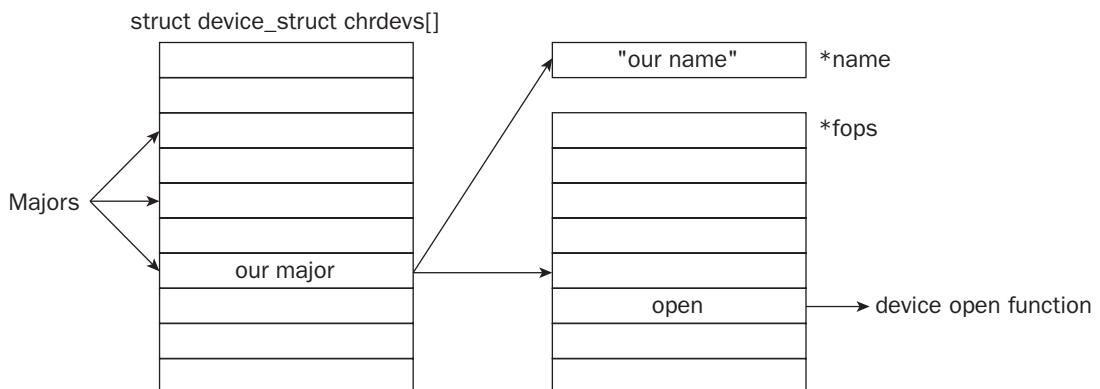


Figure 18-2

A Sample Driver: schar

Let's take a look at a sample character device driver, which we'll call `schar`. This driver implements reading and writing in its own fake way by pretending to serve data from a device that is polled at a constant interval. The polling mechanism is managed by kernel timers, which we will explain fully in the next section.

`schar.c` starts out with forwarding declarations of the functions that define our implementation of the `file_operations` structure. Then we fill it out.

```

/* forward declarations for _fops */
static ssize_t schar_read(struct file *file, char *buf, size_t count, loff_t
*offset);
static ssize_t schar_write(struct file *file, const char *buf, size_t count, loff_t
*offset);
static unsigned int schar_poll(struct file *file, poll_table *wait);
static int schar_ioctl(struct inode *inode, struct file *file, unsigned int cmd,
unsigned long arg);
static int schar_mmap(struct file *file, struct vm_area_struct *vma);
static int schar_open(struct inode *inode, struct file *file);
static int schar_release(struct inode *inode, struct file *file);

static struct file_operations schar_fops = {
    read:    schar_read,
    write:   schar_write,
    poll:    schar_poll,
    ioctl:   schar_ioctl,
    open:    schar_open,
    release: schar_release,
};

```

Some prefer the `file_operations` structure to appear at the beginning of the module, while others like it at the bottom. The latter approach would spare us from putting function prototypes at the beginning of the file. It is purely a matter of taste. Don't worry about some of the include files; we'll cross those bridges along the way.

The MSG Macro

Before we dive deeper into `schar`'s sources, we need to introduce the `MSG` macro we use throughout this chapter. It is an alternative way to print debugging statements that can prove quite handy. Instead of sprinkling the code with ugly `#ifdef` statements, we put the definition of `MSG` in the `schar.h`:

```

#define DEBUG

#ifndef DEBUG
#define MSG(string, args...) printk(KERN_DEBUG "schar:" string, ##args)
#else
#define MSG(string, args...)
#endif

```

It keeps the code looking clean and prefixes every statement with the module name. You could also easily define a bitmask of events and get finely controlled logging, if you wish. `schar` is very simple, so logging everything makes sense. Undefining `DEBUG` would effectively make `MSG` a no-op. Sometimes it would be advantageous to include even more information in the debug statement, especially for larger device driver projects. We might want to include line and file information to quickly be able to locate a specific message within the source. This could look something like this:

```

#define MSG(string, args...) printk(KERN_DEBUG \
"schar:_FILE_-__LINE__:" string, ##args)

```

It's up to you which one you prefer; all of the modules shown in this book use the former because their complexity does not warrant the extra information.

Registering the Device

As with the `hello` module, `schar` naturally also has an `init_module` entry point. It does a lot of different things—allocating memory, initializing timers and variables, and so on—but for the time being we will stick to looking at the device registration.

```
int init_module(void)
{
    int res;

    if (schar_name == NULL)
        schar_name = "schar";

    /* register device with kernel */
    res = register_chrdev(SCHAR_MAJOR, schar_name, &schar_fops);
    if (res) {
        MSG("can't register device with kernel\n");
    }
    return res;
}
```

`schar_name` can be passed in to the module as a parameter—we'll see how later on. For now, we check to see if a name has been specified and, if not, set it to a default.

`SCHAR_MAJOR` is defined in `schar.h` and is set to 42, which as we said before is one of the reserved major numbers. It doesn't matter what number you choose as long as it is not being used by any other active devices. Choosing one of the reserved majors is always safe for experimenting on your own.

```
#define SCHAR_MAJOR    42
```

We could also have used dynamic assignment of majors instead. The advantage of that approach would be that we don't have to know anything about what majors are available. The downside, at least in this context, is that we would have to create new device special files for using the module every time we load it (provided that the major returned isn't the same all the time). For this reason, we will stick to static majors. A sample implementation of dynamic registration could be easily implemented and would look something like this:

```
int major = 0, res;

res = register_chrdev(major, schar, &schar_fops);
if (res < 0) {
    MSG("can't register device with kernel\n");
    return res;
} else {
    major = res;
    MSG("device registered with major %d\n" , major);
}
```

All the sample devices in this chapter use static major numbers, and switching to dynamic assignment is left as an exercise to the reader.

After a successful call to `register_chrdev`, the device is registered with the kernel and the given file operations structure is added to the character switch table. The device should also show up in `/proc/devices` in the character device section.

Module Usage Count

The kernel needs to keep track of usage information for each module loaded in the system. If it didn't, how else would it know when it was safe to remove a module? We certainly wouldn't want a hard disk driver module to be removed while you were copying files to it; that would wreak havoc on the disk and leave the file system in an unreliable state.

There are two macros that modify the usage count, `MOD_INC_USE_COUNT` and `MOD_DEC_USE_COUNT`; the former increments the count by one, while the latter decrements it. It is up to the driver programmer to maintain a usage count that protects the module from being unloaded unexpectedly while at the same time making certain that the module can be safely removed when it is unused. The kernel will only allow unloading of modules with a usage count of zero. The `MOD_IN_USE` macro evaluates to the current usage count, but it is hardly ever needed since the kernel checks it itself before attempting to remove the module.

Open and Release

The module is now loaded and sits idle on your system until someone opens the associated device. `schar_open` is invoked when the device is opened by a process. Here, the module usage count is incremented to prevent removal of the device while it is busy.

```
static int schar_open(struct inode *inode, struct file *file)
{
    /* increment usage count */
    MOD_INC_USE_COUNT;
```

This tells the kernel that the module is now being used by one more process. If a user executes an `rmmod module_name`, the kernel returns `-EBUSY` for modules that have a usage count greater than zero (meaning that they are in use). Therefore, it is the module's own responsibility to keep the usage count up to date. We increase the usage count by one in `schar_open`, which protects the module from being unloaded while a process has it opened. When a process closes the device, we decrement the usage count to keep it in balance.

The `file` argument passed to `schar_open` is the in-kernel description of the file descriptor returned to applications. The `file` structure contains information about the mode the device is opened in. This code snippet tests whether the device is being opened for read or not, for example.

```
if (file->f_mode & FMODE_READ) {
    MSG("opened for reading\n");
    ...
```

It also includes information on where the next read should be initiated and much more. The following parts are all that are relevant to this module (and most others, in fact):

```
struct file {
    ...
    mode_t          f_mode;
```

```
loff_t          f_pos;
unsigned int    f_flags;
...
};
```

`f_mode` is the mode the device is opened in, either for reading, writing, or both. `f_flags` provides more information, some of which is relevant to device modules, such as `O_NONBLOCK` or `O_NDELAY`, for example. These flags are the ones given to the `open` call from the user space application and control the behavior of the device on read and write. You can find all the related information in `asm/fcntl.h`. `f_pos` is the position from which the next read or write operation will be performed.

The next step in `schar_open` is to set up the timer; we will look at this in the next section. `schar_open` ends up by printing the major and minor number of the opened device, extracted from the inode passed to it. Right now we have no real use for this, but later on we will examine modules that use this information to differentiate between different instances of the driver. Inodes, which we discussed in Chapter 3, identify files on disk and in memory and contain such information as owner, access time, size, type of file system, and much more. The `stat` system call gets its information by extracting it from the inode, so running `stat` on a file should give you some clue as to what data the inode provides (that are relevant outside the kernel). Look up the detailed information in `linux/fs.h`, and note how the file system type is defined in the union `u`. Linux supports a lot of file systems!

`schar_release` does nothing more than decrement the usage count by 1. There is nothing else to be done, since `schar` does not keep any memory `malloced` on a per-open basis and has no other state information that needs to be updated.

```
static int schar_release(struct inode *inode, struct file *file)
{
    MOD_DEC_USE_COUNT;
    MSG("schar_release\n");
    return 0;
}
```

Reading the Device

`schar_read` pretends to read data from the device—in fact, it reads it from an internal data queue—and pass it back to user space. `schar` keeps a global variable that keeps track of the data queue; when data is available, `schar_pool` holds the number of bytes that are in surplus. This means that if `schar_read` is invoked while `schar_pool` is zero or negative, reading processes must be made inactive until data is available.

```
static ssize_t schar_read(struct file *file, char *buf, size_t count,
                         loff_t *offset)
{
    /* if less data than requested is here, put process to sleep */
    while (count > schar_pool) {
        MSG("putting process with pid %u to sleep\n", current->pid);
        /* go to sleep, but wake up on signals */
        interruptible_sleep_on(&schar_wq);
        if (signal_pending(current)) {
            MSG("pid %u got signal\n", (unsigned)current->pid);
    }
}
```

```

        /* tell vfs about the signal */
        return -EINTR;
    }

    /* copy the data from our buffer */
    if (copy_to_user(buf, schar_buffer, count))
        return -EFAULT;

    schar_pool -= count;
    schar_data_read += count;

    MSG("want to read %u bytes, %ld bytes in queue\n", (unsigned)count,
        schar_pool);

    /* return data written */
    file->f_pos += count;
    return count;
}

```

This may seem a little daunting, but let's take it step by step. `count` is the amount of data that the reading process requested. If `count` is bigger than `schar_pool`, the read cannot be satisfied and we must put the reading process on hold until the requested data is available. `interruptible_sleep_on` changes the state of the process and adds it to the `schar_wq` wait queue. We'll look at wait queues in a moment; they provide a way for us to set the process reading the device to a nonrunning state and let the scheduler select a new process for execution. The data is served from our internal buffer and copied back to the application with the aid of `copy_to_user`, a concept that will also be detailed later on.

At the end of `schar_read`, we subtract `count` bytes from our pool, `schar_length`, and return the number of bytes read. In this case, we just return `count`, since we pretend to have written exactly as much data to the application as it asked for. This works fine with dd, for example, since we can instruct it to request exactly the number of bytes we want. Try running cp on `schar` later, and you will see what we mean; on our system, cp asks for data in blocks of 4 Kb and keeps going until 0 bytes read is returned. So you can feed `schar` as much as you want, and cp just keeps asking for more.

Don't worry if a lot of `schar_read` doesn't make much sense for now. We will look at each aspect of it one at a time in the following sections.

The current Task

There are several mentions of the `current` macro in `schar_read`. It is a macro that represents the currently running process in the form of a task structure. This means that the `current` we act upon in `schar_read` is the process that is currently reading from the device. A task structure has many elements; the complete listing can be found in `linux/sched.h`, but let's take a look at some of the fields we used here, directly or indirectly:

```

struct task_struct {
    volatile long state;
    ...
    ...
    pid_t pid;
    ...

```

```
    struct signal_struct *sig;
    sigset_t blocked;
    struct sigpending pending;
    ...
};
```

As you can see if you examine `include/linux/sched.h`, all the tasks in the system are linked in a doubly linked list. `state` signifies the current state of the process (i.e., whether it is running, stopped, or currently swapping). We'll look more at this in the discussion of wait queues. `pid` is self-explanatory—the program ID of the process. `sig` holds information regarding any signals sent to the process, and `blocked` is a mask of signals that the process itself decided to block out. Finally, `sigpending` holds information on whether the process was sent an unblocked signal and is the variable checked by `signal_pending`. So if `signal_pending` returns true, we notify the VFS and let it restart the transfer.

Wait Queues

We're using wait queues to let the current task be put to sleep when no data is available and then wake it up when new data is copied to `schar`. This frees up the system and allows it to run other processes. The scheduler will not consider the task until we wake it up again—which we'll do when the condition it sleeps on has been fulfilled. As we said, this gives our kernel code considerable power over user space applications that access it.

`schar_read` used this technique, and we'll see it again later, but let's take a more formal look at the implementation:

```
struct wait_queue {
    struct task_struct *task;
    struct wait_queue *next;
};
```

There's not much to say about the definition; it explains itself. `task` contains relevant state information in the task structure about the process being put to sleep, and `next` is a pointer to the next entry in the wait queue. With that in mind, it should be obvious that you can have as many processes sleeping on a wait queue as you want. How do we put the processes to sleep?

```
void interruptible_sleep_on(struct wait_queue **p)
long interruptible_sleep_on_timeout(struct wait_queue **p, long timeout)
```

These macros put the process to sleep with a state but allow it to wake on signals. The `_timeout` variant calls `schedule_timeout` internally and thus enables the callee to let the process wake on its own when it expires. We'll discuss how the timeout is specified later on when we come to timers.

```
void sleep_on(struct wait_queue **p)
long sleep_on_timeout(struct wait_queue **p, long timeout)
```

The semantics of these two are exactly the same as the preceding functions, except that the state is set to `TASK_UNINTERRUPTIBLE`.

If you wish to peek more at the internals, they can be found in `kernel/sched.c`.

Sooner or later, a sleeping process must be brought to life, one way or another.

```
wake_up_interruptible(struct wait_queue **p)
wake_up(struct wait_queue **p)
```

Both of these are macros that expand to `_wake_up`. The former wakes interruptible sleepers only, while the latter wakes both. However, processes that were explicitly stopped (sent a `SIGSTOP`, for example) will not be awakened.

`schar` puts readers to sleep on its wait queue, when it has no data to serve. A timer will wake them up, as would a writer, when enough data is available to satisfy the request.

```
interruptible_sleep_on(&schar_wq);
if (signal_pending(current))
    return -EINTR;
```

This structure is seen in many places throughout the kernel; we put the current process to sleep but allow it to wake up in case it is sent a signal. When `interruptible_sleep_on` returns, the process has been awakened either by an explicit call to `wake_up_interruptible` or because it received a signal. If the latter is the case, `signal_pending` returns 1 and we instruct the VFS to restart the read by returning `-EINTR` to signify an interrupted call. If we had simply used `sleep_on` to put the process to sleep, it would sleep completely uninterruptible while waiting for data, and not even a `SIGKILL` would annihilate it.

As mentioned before, we wake the readers in the timer handler and `schar_write`.

```
wake_up_interruptible(&schar_wq);
```

This wakes up all the readers sleeping on the queue. Whether that is the appropriate behavior or not depends on the situation; we may be able to satisfy only one read, so should we wake all the readers and let them race for the data? `schar` could keep a per-device-open wait queue to solve the problem. Since that would not introduce any new concepts, that exercise is left to the interested reader. Having per-device data is an interesting and useful concept by itself and will be demonstrated with the `Iomap` module later.

Writing to the Device

`schar_write` is much simpler by comparison, as it increments `schar_pool` by count and modifies `file->f_pos` to signify how much data was written to the device. The reason this is so much simpler than the read operation is that `schar` doesn't care about finding something to do with the data; it'll take as much as we throw at it. The only thing we need to do apart from this is wake up any readers, since there might be enough data available now to satisfy their read. The implementation looks like this:

```
static ssize_t schar_write(struct file *file, const char *buf,
    size_t count, off_t *offset)
{
    schar_pool += count;
    schar_data_written += count;

    /* if we were really writing - modify the file position to
       reflect the amount of data written */
    file->f_pos += count;
    if (copy_from_user(schar_buffer, buf, count))
        return -EFAULT;
```

```
/* wake up reading processes, if any */
if (schar_pool > 0) {
    wake_up_interruptible(&schar_wq);
    wake_up_interruptible(&schar_poll_read);
}

MSG("trying to write %u bytes, %ld bytes in queue now\n",
    (unsigned)count, schar_pool);

/* return data written */
return count;
}
```

Nonblocking Reads

Drivers that serve data should differentiate between blocking and nonblocking opens. If not enough data is available to satisfy a request, we ordinarily put the process to sleep and wake it once enough data is available. When the device is opened nonblocking, we should instead supply as much data as we can and return immediately without putting the process to sleep. We achieve this by adding the following to the `schar_read` function:

```
static ssize_t schar_read(struct file *file, char *buf, size_t count,
                         loff_t *offset)
...
while (count > schar_pool) {
    /* if the device is opened nonblocking, satisfy what we
       can of the request and don't put the process to sleep. */
    if (file->f_flags & O_NONBLOCK) {
        if (schar_pool > 0) {
            file->f_pos += schar_pool;
            if (copy_to_user(buf, schar_buffer, schar_pool))
                return -EFAULT;
            count = schar_length;
            schar_pool = 0;
            return count;
        } else {
            return -EAGAIN;
        }
    }
    MSG("putting process with pid %u to sleep\n", current->pid);
    /* go to sleep, but wake up on signals */
    interruptible_sleep_on(&schar_wq);
    if (signal_pending(current)) {
        MSG("pid %u got signal\n", (unsigned)current->pid);
        /* tell vfs about the signal */
        return -EINTR;
    }
}
...
}
```

`schar_read` checks `f_flags` in order to detect with what method the device was opened. If the application requested more data than what is currently in our pool, we return what is there, but if the pool is empty we return `-EAGAIN`. This is a hint to the reading process that it should try its request again later.

A device driver that only implements `read` and `write` is a bit boring. The file operation structure contains many other entry points. Now let's implement some of these in `schar` or at least explain why some of them work without even writing an explicit function in the driver to handle it.

Seeking

`schar` does not implement its own seeking function and therefore relies on the default implementation in the kernel. The default implementation is invoked if a `NULL` is registered for `llseek` in the file operations structure passed to `register_chrdev`. The kernel version can be found in `fs/read_write.c` as `default_llseek` and provides `SEEK_SET`, `SEEK_CUR` and `SEEK_END` functionality. These macros, when used with `llseek`, change the value of `file->f_pos`, the position in the file stream from which the next byte will be read. In case you want to handle the seeking yourself—if the specific device does not support seeking relative to the end, for example—you will have to provide your own `llseek` implementation. This is a typical example:

```
loff_t own_llseek(struct file *file, loff_t offset, int mode)
{
    switch (mode) {
        case 0:                                /* SEEK_SET */
            file->f_pos = offset;
            return file->f_pos;
        case 1:                                /* SEEK_CUR */
            file->f_pos += offset;
            return file->f_pos;
        case 2:                                /* SEEK_END */
            return -EINVAL;
        default:                               /* cannot happen */
            return -EINVAL;
    }
}
```

If seeking does not make sense for the device at all, an `llseek` function will have to be defined to prevent seeking. In that case, `-ESPIPE` should simply be returned, which means “illegal seek” in this respect.

```
loff_t own_llseek(struct file *file, loff_t offset, int mode)
{
    /* illegal seek */
    return -ESPIPE;
}
```

ioctl

Sometimes it can be useful to change or get the parameters from a running driver instead of reconfiguring it and running a new compile. For some devices, this is not even an option if it is constantly in use and thus cannot be removed from the system. `ioctl` is an entry point in the driver that will let you either set or retrieve settings while it is still running.

Every device in the kernel has a (somewhat) unique `ioctl` base number associated with it along with a range of commands. For example, the SCSI generic layer has `ioctl` base number `0x22` and the whole subrange of `0x00–0xff` assigned to it. Sometimes only a part of the subrange is used, as most devices won't need to support 256 commands. An `ioctl` command consists of an upper 16-bit base and a lower 16-bit command, and so the first SCSI generic command would be `0x2200`. The `ioctl` base numbers are

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documented in `Documentation/ioctl-number.txt`, although it is not quite up-to-date as of this writing. The file also includes instructions as to how to request a suitable range for your own device. We selected an available base number for `schar`—`0xbb`. The lower-level implementation is somewhat more complex than that. Ignorance is bliss, but if you are really interested, look at the definitions in `asm/ioctl.h`.

Linux distinguishes between four types of `ioctl` function calls: direct commands, read, write, or read and write. This is defined by the way the identifiers are written in the module. The different types are defined as follows:

| | |
|---|--|
| <code>_IO(base, command)</code> | Define the selected command. No data is transferred to or from the application issuing the <code>ioctl</code> . An <code>_IO</code> <code>ioctl</code> can still return an integer as long as it is positive (and thus not interpreted as an error). |
| <code>_IOR(base, command, size)</code> | A reading <code>ioctl</code> , as seen from the application. <code>size</code> is the size of the argument to be transferred back. |
| <code>_IOW(base, command, size)</code> | A writing <code>ioctl</code> , as seen from the application. <code>size</code> is the size of the argument to be transferred from user space. |
| <code>_IOWR(base, command, size)</code> | A reading and writing <code>ioctl</code> . As usual, <code>size</code> indicates the size of the argument to be transferred back and forth. |

In addition, macros are provided to check the validity of the command sent. The kernel side encoding splits the bit field into a direction, size, and command section. The information can be extracted with the following macros:

| | |
|---------------------------------|--|
| <code>_IOC_DIR(command)</code> | The direction of the command, either <code>_IOC_NONE</code> , <code>_IOC_WRITE</code> , or <code>_IOC_READ</code> , corresponding to the types mentioned a bit earlier in the section. For <code>_IOWR</code> , the value is <code>_IOC_WRITE ORed with _IOC_READ</code> . |
| <code>_IOC_TYPE(command)</code> | The <code>ioctl</code> base number part of the field, <code>0xbb</code> for <code>schar</code> . |
| <code>_IOC_NR(command)</code> | The command part of the field. |
| <code>_IOC_SIZE(command)</code> | The size of the argument, if any. |

The `ioctl` function itself is defined in the `file_operations` structure supplied when registering the module. `schar.h` defines the supported commands.

```
#define SCHAR_IOCTL_BASE          0xbb
#define SCHAR_TOGGLE_DEBUG         _IO(SCHAR_IOCTL_BASE, 0)
#define SCHAR_GET_POOL             _IOR(SCHAR_IOCTL_BASE, 1, unsigned long)
#define SCHAR_EX_TIMER_DELAY       _IOWR(SCHAR_IOCTL_BASE, 5, unsigned long)
```

The base number is sufficiently far away from anything else out there, so we shouldn't get any conflicts. These are the three different types that exist in `schar`. `SCHAR_TOGGLE_DEBUG` toggles whether debug messages should be printed or not. No parameter is specified, hence the `_IO` type. `SCHAR_GET_POOL`

returns the number of bytes currently residing in the pool, and finally `SCHAR_EX_TIMER_DELAY` sets the number of jiffies between each timer delay and returns the old setting. *Jiffies* are a time measurement within the kernel and will be covered shortly.

The `schar_ioctl` function consists almost solely of a switch statement supporting the different commands.

```
static int schar_ioctl(struct inode *inode, struct file *file,
                      unsigned int cmd, unsigned long arg)
{
    /* make sure that the command is really one of schar's */
    if (_IOC_TYPE(cmd) != SCHAR_IOCTL_BASE)
        return -ENOTTY;

    switch (cmd) {
        case SCHAR_TOGGLE_DEBUG: {
            schar_debug = !schar_debug;
            return 0;
        }
        case SCHAR_GET_POOL: {
            if (put_user(schar_pool, (unsigned long *)arg))
                return -EFAULT;
            break;
        }
        case SCHAR_EX_TIMER_DELAY: {
            unsigned long tmp = schar_timer_delay;
            if (!capable(CAP_SYS_ADMIN))
                return -EACCES;
            if (get_user(schar_timer_delay,
                         (unsigned long *)arg))
                return -EFAULT;
            if (put_user(tmp, (unsigned long *)arg))
                return -EFAULT;
            break;
        }
        default: {
            MSG("ioctl: no such command\n");
            return -ENOTTY;
        }
    }
    /* to keep gcc happy */
    return 0;
}
```

The implementation hopefully speaks for itself if you have used the `ioctl` system call before. We will look at the two calls that we've not met before a little later: `get_user` and `put_user`. For now, it should suffice to say that they copy data back and forth between user space and kernel space. The `default` case catches any commands that `schar` does not support. `-ENOTTY` is the appropriate return value for unsupported commands. This might seem a bit odd, since this historically meant “not a typewriter” and dates back to the days when the only devices were TTYs. Today, this translates to “inappropriate `ioctl` for device” when it is returned for an `ioctl` call.

Checking User Rights

`ioctls` are available for use by anyone who has access to open the device. Depending on what operations should be performed, access should not be permitted to all users. `SCHAR_EX_TIMER_DELAY` checks whether the user who opened the device is the superuser, since setting too low a timeout will expire the timer too quickly and thus effectively prevent the machine from doing any useful work. Linux has a lot of different capability personalities defined, the most significant in this case being `CAP_SYS_ADMIN`. The various `CAP_` defines are located in `linux/capability.h` with comments regarding the operations permitted.

```
int capable(int cap)
```

The check is performed by `capable`, which returns 1 if the user has the particular capability and 0 otherwise. The use of capabilities is not restricted to `ioctls` alone, but they are most frequently used there.

poll

`poll` provides a way for a process to sleep on the device waiting for a certain event to take place. This is not to be confused with a repeated check for status, as this is not what happens here. Using the `poll` system call is an efficient way of waiting for events to occur without resorting to busy looping. `schar` implements `poll` somewhat, as much as it makes sense in our case, anyway. The implementation of `poll` is very simple. Since a write to `schar` will always succeed, we only need to test for reads. A `schar_poll_read` wait queue is introduced, and if our pool of data is empty, a `poll` for read will sleep until data is available.

```
static unsigned int schar_poll(struct file *file,
                               poll_table *wait)
{
    unsigned int mask = 0;

    poll_wait(file, &schar_poll_read, wait);

    /* if the pool contains data, a read will succeed */
    if (schar_pool > 0)
        mask |= POLLIN | POLLRDNORM;

    /* a write always succeeds */
    mask |= POLLOUT | POLLWRNORM;

    return mask;
}
```

This is all it takes for `schar`! If `schar` kept an upper limit on the size of the pool, a `schar_poll_write` could easily be added and a similar check could be made for `POLLOUT`. The header file `asm/poll.h` contains the possible `poll` masks; we will cover the standard ones here.

| | |
|---------|--|
| POLLIN | The device can supply data on a succeeding read without blocking. |
| POLLOUT | The device can accept data on a succeeding write without blocking. |
| POLLERR | An error occurred. |

If you have ever used `poll` for user space applications, you should be familiar with these as they are similar when seen from the kernel.

Try It Out—Reading and Writing to schar

Okay, we've covered the basics of schar. We'll get to the timer and memory functionality soon, but before we do, let's try it out. You can download the source code for schar from the Wrox Press Web site at <http://www.wrox.com>. You can extract the archive anywhere on your system. schar is located in chapter18/schar.

1. The first thing we need to do is create an appropriate special file for schar. Recall from earlier that mknod is the command that does just that. We need to create a character special file with a major number of 42 and a minor of 0.

```
# mknod /dev/schar c 42 0
#
```

2. Go to the source of the schar module and type **make** inside the directory and press Enter. The compile should complete without errors or warnings. The finished module then resides in the same directory as schar.o. Insert the module:

```
# insmod schar.o
#
```

3. The device should now be registered with the kernel and ready to serve. Verify this by examining the /proc/devices file as explained previously or type **dmesg** and notice how schar welcomes us at the end.

```
$ dmesg | tail -n1
schar: module loaded
$
```

4. Now let's copy a file to schar and see what happens. You can choose any file you'd like, but try a small text file if you have one handy or can create one for this purpose. It would be a good idea to have a separate terminal window open to repeatedly run dmesg to follow schar's output. Here we list the output from dmesg below each command. If cp asks you if it's okay to overwrite /dev/schar, just say yes.

```
$ cp small_file /dev/schar
schar: opened for writing
schar: major: 42 minor: 0
schar: trying to write 4096 bytes, 4096 bytes in queue now
schar: trying to write 4096 bytes, 8192 bytes in queue now
schar: trying to write 3241 bytes, 11433 bytes in queue now
schar: release
```

First, we go through schar_open, which is responsible for the first two lines of output. Then schar_write is entered, and the 11,433-byte file we copied to the device is written in chunks of 4,096 bytes at a time. When the write has finished, schar_release is entered and the write of the file is completed.

5. Data is now available to be read from schar, so let's copy some of it back:

```
$ cp /dev/schar out_file
schar: opened for reading
schar: major: 42 minor: 0
schar: want to read 4096 bytes, 7337 bytes in queue
```

```
schar: want to read 4096 bytes, 3241 bytes in queue
schar: putting process with pid 757 to sleep
schar: pid 757 got signal
```

Again, `schar_open` is the entry point, but this time `schar_read` is entered next. Data is read in chunks of 4,096 bytes again; we can satisfy two reads of 4 Kb before the pool contains less than what `cp` asks for. This is where we put the reader (`cp`) to sleep until more data becomes available. We got impatient and ended the read with a Ctrl+C, which sent a signal to the process, hence the last line of output.

It is important to note that the 4-Kb chunks we serve data in above are not a schar limit, but rather the design of cp. We could just as well serve data in 1b or 16-Kb chunks instead.

Try It Out—`ioctl`

So we can write data to `schar` and read data back. Let's now try and play with some of the other functions we included.

1. Make sure that the `schar` module is built and loaded. Create a file called `schar_ioctl.c` in the directory containing the sources to `schar`.

```
#include <stdio.h>
#include <fcntl.h>
#include <sys/ioctl.h>

#include "schar.h"

int main(int argc, char *argv[])
{
    int fd = open("/dev/schar", O_RDWR);

    /* complain if the open failed */
    if (fd == -1) {
        perror("open");
        return 1;
    }

    /* complain if the ioctl call failed */
    if (ioctl(fd, SCHAR_TOGGLE_DEBUG) == -1) {
        perror("ioctl");
        return 2;
    }

    printf("schar debug toggled\n");

    return 0;
}
```

2. Compile the program and execute it with the following two lines:

```
$ cc -o schar_ioctl schar_ioctl.c
$ ./schar_ioctl
schar debug toggled
$
```

3. If `schar` was loaded with debugging enabled (as it defaults to), it should now stop printing informative messages about opens, reads, and such. Try the copy commands we used earlier and check `dmmsg`. You should see that debugging output is no longer arriving in the kernel buffer.

Module Parameters

Linux provides an easy way to add parameter options for modules, which can be supplied at module load time with either `modprobe` or `insmod`. `schar` has most of its user-definable parameters set up this way.

```
MODULE_PARM(variable, type)
```

`variable` is the variable parameter set, and `type` is a string comprising the length and type of the parameter. They can be placed anywhere in the module outside of functions but are usually placed after the global variable declarations near the top. Let's look at an example from `schar`:

```
MODULE_PARM(schar_debug, "1b");
```

The type string "`1b`" signifies that this is a byte value of length 1. The length can also be supplied with both a minimum and maximum size; "`5-10b`" would then mean that `schar_debug` was a byte size array with a minimum of 5 and a maximum of 10 items. If no length argument is given, a length of 1 is assumed. Four other types are defined besides byte size.

| | |
|---|--------|
| h | short |
| i | int |
| l | long |
| s | string |

It is also possible to supply a descriptive text of the various module parameters. This information can be extracted with `modinfo` and gives the user a chance to see what parameters are supported without diving into the actual source of the module.

```
MODULE_PARM_DESC(schar_debug, "Enable debugging messages");
```

The preceding line is used to describe the meaning of the `schar_debug` variable exported prior with `MODULE_PARM` declaration. Finally, a general description and author field can be filled out.

```
MODULE_DESCRIPTION("Sample character driver");
MODULE_AUTHOR("Jens Axboe");
```

`modinfo` supports several options that let you extract the information you need.

Try It Out—`modinfo`

Let's try it out and list some of the module-parameter information stored in a compiled `schar` module. Make sure that you are in the directory containing the built `schar` module:

```
$ modinfo -p schar.o
schar_name string, description "Name of device"
schar_debug byte, description "Enable debugging messages"
```

```
schar_inc int, description "Byte increase in pool per timer fire"  
schar_timer_delay long, description "Timer ticks between timer fire"  
schar_pool_min long, description "Timer fill pool minimum in bytes"
```

The `-p` parameter asks `modinfo` to print information about the parameter that the module can be fed at load time—its name, type, and a description of the option.

proc File System Interface

The `proc` file system works much like a real file system in that it is mounted and reading or writing is accomplished by using standard file utilities. The data read from a file is generated on the fly by the module or kernel and can provide run time statistics and other relevant information. Writable files can be used to change configuration or behavior of the driver. Adding a `proc` file system entry to `schar` thus allows users to retrieve information from the running module without having to issue `ioctl` commands through a program.

sysctl

The best place to register an entry is under the `/proc/sys` directory. Then, entries can be retrieved with either `cat`, for example, or the `sysctl` system call. Devices should register themselves under the `dev/` directory, and this is exactly what `schar` does: It creates a `schar` subdirectory and an entry called `0` inside it. The entries are defined in an array of `ctl_table` structures stacked on top of each other until the chain is complete. The root (`/proc/sys/dev`) is set up with `/proc/sys/dev/schar` as a directory entry child, and finally `/proc/sys/dev/schar/0` is added. Here's the code from `schar.c`:

```
/* sysctl entries */  
static char schar_proc_string[SCHAR_MAX_SYSCTL];  
static struct ctl_table_header *schar_root_header = NULL;  
static int schar_read_proc(ctl_table *ctl, int write, struct file *file,  
    void *buffer, size_t *lenp);  
  
static ctl_table schar_sysctl_table[] = {  
    { DEV_SCHAR_ENTRY, /* binary id */  
        "0", /* name */  
        &schar_proc_string, /* data */  
        SCHAR_MAX_SYSCTL, /* max size of output */  
        0644, /* mode */  
        0, /* child - none */  
        &schar_read_proc }, /* set up text */  
    { 0 }  
};  
  
static ctl_table schar_dir[] = {  
    { DEV_SCHAR, /* /proc/dev/schar */  
        "schar", /* name */  
        NULL,  
        0,  
        0555,  
        schar_sysctl_table }, /* the child */  
    { 0 }  
};  
  
static ctl_table schar_root_dir[] = {  
    { CTL_DEV, /* /proc/dev */  
        }
```

```

    "dev",                      /* name */
    NULL,
    0,
    0555,
    schar_dir },                /* the child */
{ 0 }
};

```

`DEV_SCHAR_ENTRY` is the binary ID used when issuing a `sysctl` system call and should be unique. `schar_proc_string` is the data returned to reading processes and is no longer than `SCHAR_MAX_SYSCTL` bytes in length. The implementation is very simple and merely consists of copying the statistics generated to a dedicated buffer—`schar_proc_string`—that is generated by `schar_read_proc` when the read takes place.

Once the appropriate tables have been set up, the entry is registered with the `proc` file system. A `ctl_table_header` is returned or 0 in the unlikely scenario that no memory was available.

```

schar_root_header = register_sysctl_table(schar_root_dir, 0);
schar_root_dir->child->de->owner = THIS_MODULE;

```

The last line sets up the owner of the entry to be `THIS_MODULE`, which is a macro referring to, naturally enough, this module. With this, we make an effort to protect our entry. Allowing just anyone to delete our entry anytime they liked could lead to problems such as a kernel fault (also known as an Oops; we will look at these in the section on debugging).

`proc_dosstring` does the rest of the job for us, copying the data to user space and modifying the file position. The arguments remain untouched and are simply passed along.

```

return proc_dosstring(ctl, write, file, buffer, lenp);

```

`schar` is not very careful with regards to `proc` or `sysctl` support in the kernel. If this was a production module, the implementation should be protected by adding the necessary define checks, something on the order of

```

#endif CONFIG_SYSCTL
...
#endif

```

around the relevant pieces of code. Otherwise, the module would fail to compile on a kernel build without `sysctl` support, albeit that is an extremely rare scenario.

Writable Entries

The entry registered by `schar` only provides information to the user and as such is read-only. The mode setup does permit writing, however, and in that case the written string is merely printed to the logs.

```

if (write) {
    char *tmp = (char *) get_free_page(GFP_KERNEL);
    MSG("proc: someone wrote %u bytes\n", *lenp);
    if (tmp) {
        if (!copy_from_user(tmp, buffer, *lenp))
            MSG("proc: %s", tmp);
    }
}

```

```
        free_page((unsigned long)tmp);
        file->f_pos += *lenp;
    }
    return 0;
}
```

A write argument is passed to the registered handler indicating whether the access was for reading or writing. In the latter case, the data is copied to us and printed.

It should not be hard to add a function to parse the input and change the configuration appropriately. Another alternative is to create numerous entries, each holding one of `schar`'s configuration options (much like the other `/proc/sys` entries), and thus provide the possibility of simply echoing changes directly to the separate files. It would then even be possible to use `proc_dostring` for both input and output. The `sysctl` abstraction does lend itself more in this direction, but learning about both should provide you with the necessary tools to further pursue the `proc` file systems. Besides, it is a two-for-one deal, since registering a `sysctl` table also takes care of setting up the `proc` file system entry. `kernel/sysctl.c` is a great place to look for more information.

How `schar` Behaves

`schar` keeps an internal count of how many bytes are either in surplus or in demand in the `schar_pool` variable. A negative value means that a reader is currently starved of `schar_pool` bytes, while a positive value signifies the opposite. Writing to the device will add the bytes written to the pool for later consumption. `schar` keeps a kernel timer running that adds `SCHAR_INC` bytes to `schar_pool` at `SCHAR_TIMER_DELAY` intervals while a reader is waiting for data. A write to the device will always succeed, but if a reader requests more data than what is currently in the pool, it is added to `schar`'s wait queue and woken up every time the timer handler runs. It prints relevant information to the logs, so give it a try to get a feel for how the internals work.

`schar` keeps a free page of memory as an internal buffer and copies read and written data to and from there. It serves no particular purpose other than to demonstrate how data is moved between kernel and user space—a concept we will look at much more closely later.

While `schar` is useless by itself, it exposes the basic skeleton for a character-driven device driver. We used a kernel timer to feed the pool to emulate the feel of a polled device. Polling is needed if the device is unable to provide feedback to the driver in the form of interrupts, a concept we will look at later when looking at interrupt-driven character drivers.

Time and Jiffies

The kernel keeps track of time passing in the global `jiffies` variable. You may consider this the kernel's heartbeat because for every timer tick that goes by, `jiffies` is incremented by one. The define `HZ` controls the rate of the ticks and can be modified at your will in `<asm/param.h>`.

Beware that changing this will require a recompile of existing modules (and the kernel, of course) and will break applications that depend on its default value.

Most platforms set this to 100, giving us a heartbeat rate of one every 10 milliseconds. Increasing the value may give you better interactive performance at the expense of spending more time in the scheduler, but leaving it at 100 is probably a safe bet. Every now and then, discussions arise debating whether HZ should be changed since it has stayed the same since Linux was first introduced. So far, it is not conclusive if increasing it will give better performance on today's faster processors.

You might end up programming devices where you want to detect whether an operation was completed within a given amount of time or not. Some devices do not support raising interrupts upon completion and thus must be handled via some form of polling for status. This is usually only the case with old or badly designed hardware; modern devices should support some kind of event notification. Busy looping should never be considered good device driver programming practice. If you do need to resort to these dirty measures, make sure that it only runs in the odd case (i.e., during device probing or similar instances). In these cases, the most used construct is a variant of the following:

```
unsigned long timeout = jiffies + PROBE_TIMEOUT;
do {
    do_command(PROBE);
    stat = get_status();
} while (stat == BUSY && time_before(jiffies, timeout));

if (time_after_eq(jiffies, timeout))
    printk("operation timed out.\n");
```

Now you might be wondering what the `time_before` and `time_after_eq` functions do and why we didn't just compare `timeout` and `jiffies` directly. Well, Linux is such a stable operating system that it is not that unusual to have machines running a very long time between reboots. Given that `jiffies` is defined to be an `unsigned long`, it will wrap eventually and start ticking from zero again. If `timeout` wraps when `jiffies` and `PROBE_TIMEOUT` are added, a simple test of

```
do {
    do_command(PROBE);
    stat = get_status();
} while (stat == BUSY && (jiffies < timeout));
```

would cause the loop to exit prematurely. Clearly, this isn't intended, and keeping track of wraps ourselves, albeit not that difficult, shouldn't be something that the driver writer should be bothered with. For this reason, these four macros can do the job for us safely:

| | |
|---|--|
| <code>time_before(jiffies, x)</code> | <code>wrap safe jiffies < x</code> |
| <code>time_after(jiffies, x)</code> | <code>wrap safe jiffies > x</code> |
| <code>time_before_eq(jiffies, x)</code> | <code>wrap safe jiffies <= x</code> |
| <code>time_after_eq(jiffies, x)</code> | <code>wrap safe jiffies >= x</code> |

The macros are not only useful when doing direct tests like the preceding, where the possibility of a wrap is minuscule, but also when testing for much larger values in drivers where packets are queued and then only tested for timeouts much later. That could be in a SCSI or network adapter driver code, for example. The macros are defined in `linux/timer.h`.

Chapter 18

On the issue of portability and timeouts using `jiffies`, never assume that `HZ` equals 100. This is already a false assumption on Alpha architectures, which define it as 1,024, and on rtLinux (Real Time Linux), which uses 10,000. Users are free to select any value they please, and changing `HZ` is as easy as modifying `asm/param.h` and recompiling. Therefore, make sure that constructs like the above define `PROBE_TIMEOUT` in terms of `HZ` and not a tick value alone.

Small Delays

At times, you need a finer control over time than that which `HZ` provides. Remember that `HZ` is 100 on most platforms, which will give you only an approximate resolution of 0.01 seconds. That may not seem like much, but for most hardware this is an extremely long period of time. In case you need finer resolution, `udelay` can provide up to microsecond precision.

```
/* delay for 0.5 milliseconds */
udelay(500);
```

`udelay` uses the `BogoMIPS` rating calculated at boot time, and while you cannot rely on precisely microsecond resolution, it does get fairly close. You may have wondered what the `BogoMIPS` rating shown at boot means and what it is used for; it is a calibration loop run at boot that measures a loops-per-second speed. As such, it isn't directly related to hardware speed (hence, `BogoMIPS`, for bogus), but it does provide a way to somewhat accurately offer delay operations for `udelay` and friends.

Never use `udelay` for more than a millisecond or two, as this can cause overflow on machines with high `BogoMIPS` ratings. In fact, be very certain that you really do need to delay like this! If you do need to pause for longer than this, loop a specified number of times and `udelay` a millisecond each time, like this:

```
/* delay for 10 milliseconds */
int i;
for (i = 0; i < 10; i++)
    udelay(1000);
```

You can also use `mdelay`, which is a macro that does exactly that for you:

```
/* delay for 10 milliseconds */
mdelay(10);
```

Timers

Kernel timers are an excellent way of keeping track of time in your driver. Instead of looping and busy waiting for a certain amount of time to expire, you should take advantage of the available timer functions. As we have seen above, timers can also be used to poll a device at a constant interval. Timers are implemented as a doubly linked list with the following format:

```
struct timer_list {
    struct timer_list *next;
    struct timer_list *prev;
    unsigned long expires;
```

```

    unsigned long data;
    void (*function)(unsigned long);
};

}

```

You can find this definition in `linux/timer.h`. For the sake of simplicity, you will never have to touch the `*next` and `*prev` pointers; in fact, you should not. The kernel uses these internally and does that for us. The interesting parts can be found in `kernel/sched.c`. `add_timer` takes care of acquiring the necessary locks and then calls `internal_add_timer`. This keeps the interface simple for us, and we do not actually have to be concerned with the inner workings of `internal_add_timer`. The different locking schemes will be introduced later when the issues of SMP and re-entrant code are discussed.

`init_timer` does exactly what the name hints at—initializes the timer for use. In reality, it merely updates `next` and `prev` to be null pointers so that timers added twice won't go unnoticed. This is also the technique used in `schar`'s `open` procedure to detect whether the internal timer was already set up. Let's take a closer look at the code from `schar` that shows how timers are used in that context. The timer is initialized as follows:

```
static struct timer_list schar_timer;
```

This code, from `init_module`, just prepares the timer for later use.

```
init_timer(&schar_timer);
```

`schar_open` then sets it up, provided that it hasn't already been set up by another reader.

```

if (!timer_pending(&schar_timer)) {
    schar_timer.function = &schar_timer_handler;
    mod_timer(&schar_timer, SCHAR_TIMER_DELAY);
}

```

Most important is the `timer_handler` function, a reference to which is passed to `schar_timer`'s `function` value.

```

static void schar_timer_handler(unsigned long data)
{
    /* set up timer again */
    if (schar_pool < schar_pool_min) {
        schar_pool += SCHAR_INC;
        schar_timer.expires = jiffies + schar_timer_delay;
        schar_timer.function = &schar_timer_handler;
        add_timer(&schar_timer);
        MSG("setting timer up again, %ld data now\n", schar_pool);
    }

    /* if the module is in use, we most likely have a reader waiting for
       data. wake up any processes that are waiting for data. */
    if (MOD_IN_USE && schar_pool > 0) {
        wake_up_interruptible(&schar_wq);
        wake_up_interruptible(&schar_poll_read);
    }
}

return;
}

```

The syntax is fairly straightforward, so we won't explain it to death. `data` is not used in `schar` at all, since we are only maintaining one timer with the handler. We could have added a timer for both readers and writers and let the value of `data` signify either a `SCHAR_READER` or `SCHAR_WRITER` timer. There are many other uses for `data`; it is passed to `timer_handler` as an argument so you can use it any way you please. It is also worth noting that `expires` is not relative to the current time; you need to add `jiffies` explicitly.

Timers are automatically deleted when they expire, but leaving them hanging after the module has been unloaded is an excellent way to hang the kernel. This also means that you can add the timer again from the handler itself. `cleanup_module` calls `timer_pending` to detect whether the timer has expired or not. It returns `true` if the timer hasn't fired yet and `false` otherwise. If the timer is still running, it is explicitly deleted by `del_timer`. Strictly speaking, this isn't really necessary since calling `del_timer` on a timer that has fired does no harm. We included it here merely for the sake of covering all the related timer functions.

If you need to update the timer to extend the timeout, `mod_timer` is your friend. So, instead of doing

```
del_timer(&timer1);
timer1.expires = jiffies + new_value;
add_timer(&timer1);
```

you can do

```
mod_timer(&timer1, new_value);
```

and end up with the same result in a nicer way. If the timer had already expired by the time `mod_timer` is invoked, it acts just like `add_timer` and merely adds the timer again.

Try It Out—The Timer Implementation in `schar`

`schar` periodically adds data to its internal pool by using a kernel timer. The interval can be adjusted either through an `ioctl` call or by modifying `SCHAR_TIMER_DELAY` in `schar.h`.

The timer is added when a reader opens the device and is readded from the timer handler as long as data is in demand.

```
$ cp /dev/schar out_file
schar: opened for reading
schar: major: 42 minor: 0
schar: putting process with pid 889 to sleep

schar: setting timer up again, 1024 data now
schar: putting process with pid 889 to sleep

schar: setting timer up again, 2048 data now
schar: putting process with pid 889 to sleep

schar: setting timer up again, 3072 data now
schar: putting process with pid 889 to sleep

schar: setting timer up again, 4096 data now
schar: want to read 4096 bytes, 0 bytes in queue
schar: putting process with pid 889 to sleep
```

SCHAR_INC bytes of data are added to the pool each time the handler runs—1,024 in this case. Every time the handler runs, it wakes the reading process (or processes, if you have more than one running) in case we now have enough data to satisfy the read. When the pool contains 4,096 bytes, cp can receive the first chunk of data and the procedure starts over again.

Giving Up the Processor

Instead of looping and waiting for a certain amount of time to expire, it may be beneficial to suspend execution of the current process and resume later. Changing the state of the process and calling the scheduler can accomplish this. In the listing of the Linux task structure we examined earlier, the state field was introduced. It can be assigned to any of the following values:

| | |
|----------------------|--|
| TASK_RUNNING | The task was selected by the scheduler the last time it ran and is currently in a running state. This is the state of the current process when entering the driver. |
| TASK_INTERRUPTIBLE | The task is in a state of sleep but can be woken up by signals. |
| TASK_UNINTERRUPTIBLE | The task is in a state of sleep, and signals cannot wake it up. The process is probably waiting on an event to happen, and it wouldn't make sense to let it wake before that event occurs. |

There are a few more than this, but they aren't relevant here. Look them up in `linux/sched.h` if you wish.

So before invoking the scheduler, `current->state` should be set to either `TASK_INTERRUPTIBLE` or `TASK_UNINTERRUPTIBLE`. Which one to use depends on the condition that the process is waiting for. The latter should be used only if it wouldn't make sense to let it wake up before what it requested is ready, and putting it away in an uninterruptible state is the most logical choice. For most issues, that is not the case; if you `grep` through the Linux sources, you will find very few places that actually use `TASK_UNINTERRUPTIBLE`. One example, however, is if pages belonging to the process are being brought in from swap; we don't want the process to wake up until the task is completed.

A piece of code that demonstrates these principles is the following:

```
current->state = TASK_INTERRUPTIBLE;
schedule();
```

Now the process gets tugged away and the scheduler runs. But how do we know when the process returns? If there are no other suitable processes to run, the same task will be selected to run again and we end up at the same place almost instantly. This is where `schedule_timeout` enters the picture; you call it instead of `schedule`, and it returns the number of jiffies left to be slept. The scheduler is guaranteed not to select the process for execution before the specified timeout has expired.

```
/* put the process away for a second */
current->state = TASK_INTERRUPTIBLE;
schedule_timeout(HZ);
```

The value signifies the number of jiffies the process should sleep before being run again. The inner workings of `schedule_timeout` are rather interesting; it is implemented with the aid of a kernel timer, and the `data` argument is the address of the current process. After the timer has been added, `schedule_timeout` calls `schedule` itself. The timer function simply wakes up the process with address data. If you are interested, look in `kernel/sched.c`.

Task Queues

We have looked at how timers can be used to wake up processes at a given point in the future. While timers are handy, it could also be useful to delay work to be executed later. This becomes particularly interesting when we deal with interrupt handling routines and bottom halves, which task queues are very closely related to. For now, let's stick to task queues and defer the discussion of interrupt handling to the next section.

```
struct tq_struct {
    struct list_head list;          /* linked list of active bh's */
    unsigned long sync;             /* must be initialized to zero*/
    void (*routine)(void *);        /* function to call */
    void *data;                     /* argument to function */
};
```

The declaration is from `linux/tqueue.h`. As usual, you do not have to touch all the fields yourself. `*next` is used internally to keep the queued tasks in a linked list, and `sync` makes sure that a task is not queued twice before being run. This would corrupt the linked list, so if you attempt to queue the task twice, you will simply be ignored.

Some predefined task queues exist in the kernel, but let's first look at declaring your own queue:

```
DECLARE_TASK_QUEUE(q_task);
struct tq_struct q_run = { NULL, 0, (void *)q_task_handler,
                           &q_task };
```

This is the definition of the structure in `queues` and is pretty much taken directly from the header file. The only real difference is that we define our own function to be called and activate the task queue from there. `DECLARE_TASK_QUEUE` is a macro that initializes the queue to `NULL`. `q_task` is where we queue the tasks, and `q_run` will run `q_task_handler` when the task queue is being consumed. Adding a process to the preceding queue is done with the following:

```
queue_task(&q_run, &q_task);
```

`queue_task` can be called numerous times, and when we are ready to execute the tasks on hold on the queue, `run_task_queue` is invoked. All the tasks queued on `q_task` are then consumed.

```
run_task_queue(&q_task);
```

The Predefined Task Queues

We won't talk anymore about defining your own task queues, since the kernel provides a few for us to use and they will suffice for the most part. Therefore, you hardly ever need to handle your own.

| | |
|---------------------------|--|
| <code>tq_immediate</code> | Runs as soon as possible. We'll talk more about it in the "Interrupt Handling" section later in this chapter. |
| <code>tq_timer</code> | After each passing timer tick, <code>tq_timer</code> is run. This queue is the one the kernel uses for kernel timers internally. |
| <code>tq_scheduler</code> | Runs every time the scheduler is invoked if it contains any tasks. |
| <code>tq_disk</code> | Mostly used by the VFS and the block functions when dealing with requests. |

The first three queues are clearly the most interesting, and you should probably stay away from `tq_disk`, since it has a very specialized purpose. If we disregard `tq_disk`, we have placed them in order of how fast they will get executed after queuing (as a rule of thumb).

When you deal with the built-in task queues, you will never have to invoke `run_task_queue` on your own. Depending on which queue you use, you instead simply mark the queue after adding the task and it will be run automatically. Before we move on to looking at how to mark the queues for execution, let's take a very quick look at the implementation of bottom halves in Linux.

We will look more closely at bottom halves in the section on interrupt handling, but since they are closely related to task queues it seems appropriate to use them as an example. Basically, interrupt handlers can be split into two parts—a top and bottom half. The former receives the interrupt and takes care of immediate, basic needs such as acknowledging it to the device. The bottom half runs later and is used to defer processing of the data received in the top half. This allows Linux to process more interrupts than a single interrupt handler can manage on its own.

In fact, task queues are implemented as bottom halves in Linux. As the different bottom halves are marked active, the kernel executes them with `do_bottom_half` from the scheduler. The kernel maintains a list of possible bottom halves in `linux/interrupt.h`. Here is a snippet:

```
enum {
    TIMER_BH = 0
    TQUEUE_BH,
    ...
    IMMEDIATE_BH,
    ...
};
```

These are the older embedded bottom halves and are not directly available to modules since each of them serves a specialized purpose. If you look in the header file, you will notice that there isn't an entry for `tq_scheduler` because it does not need to be marked for execution. The first thing the scheduler does is to check whether `tq_scheduler` contains any tasks and execute them if it does. This also means that this queue is run every time the scheduler is invoked, which is dependent on many factors.

`tq_timer` is run on every timer tick if it contains any tasks and thus does not need to be marked as active either. This also means that tasks waiting on this queue are being run at interrupt time, which places certain restrictions on what they can do. Functions that are being run at interrupt time must not block or sleep, for example. This may not sound like such a hard thing to achieve, but you must also bear in mind that the entire call path of such a function is included—so you must not call other functions that might block.

The last queue that should be considered for general use is `tq_immediate`. As the name implies, the queue is run extremely fast. It is generally intended to be used as a way of deferring work for interrupt handlers, and we will use it in the interrupt handling section.

```
void init_bh(int nr,  
void (*routine)(void))
```

Enable the handling of bottom half nr by function routine.

```
void mark_bh(int nr)
```

Mark the appropriate bit in `bh_active`, which will make the scheduler run the task queue when it is invoked.

`tq_immediate` is the only queue that must be explicitly marked, since its intended use is as a bottom half. When we get to interrupt handling, some examples on how to use task queues and bottom halves will be shown.

Memory Management

Before we deal with how to allocate memory properly in a driver, let us take a brief tour of memory management in general and how Linux handles it. You have probably come across the term “virtual memory” before and may have wondered just what precisely it covered. When you allocate memory in user-space applications, you aren’t handed a private section of the RAM in your machine. While this would be a way for an operating system to handle memory allocations, it would only allow you to run as many applications as your memory could hold in total. Linux does not work this way; it pretends that much more memory is available (hence, the term “virtual memory”; it isn’t actually real) and hands out virtual addresses to applications.

The mapping between virtual and physical addresses is kept in several structures that compose the page table. The page table consists of three levels—the page directory, the page middle directory, and the page table entries, each of which provides an offset of the virtual address. This is the lowest level of memory management, and the driver writer won’t usually have to deal with the page table directly (see Figure 18-3).

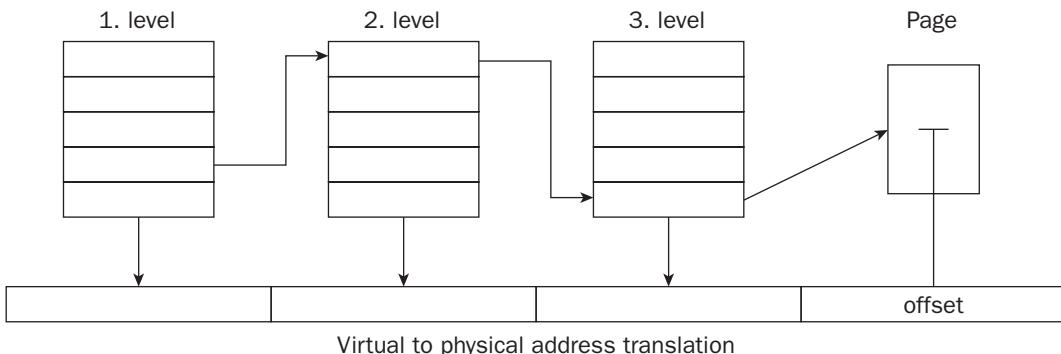


Figure 18-3

Virtual Memory Areas

Above the page table reside the virtual memory areas. These constitute a map of contiguous virtual memory addresses as handed out to an application.

```
struct vm_area_struct {
    ...
    unsigned long vm_start;
    unsigned long vm_end;
    ...
    pgprot_t vm_page_prot;
    ...
    struct vm_operations_struct *vm_ops;
    unsigned long vm_pgoff;
    struct file *vm_file;
    ...
};
```

This is a highly snipped version of the structure; you can find it in `linux/mm.h`. We will cover the members that we will actually need later on. `vm_start` and `vm_end` represent the beginning and end of the virtual memory area, and `vm_page_prot` is the protection attributes assigned to it—whether it is shared, private, executable, and so forth. `vm_ops` is similar to the `file_operations` structure used with character and block devices and forms an analogous abstraction to operation on virtual memory areas. Finally, `vm_offset` is the offset into the area, and `vm_file` is used in correlation with memory mapping of files. We'll take a much closer look at this structure when we dissect the `mmap` functions of `schar`.

The mappings made by a specific process can be seen in `/proc/<PID>/maps`. Each one corresponds to a separate `vm_area_struct`, and the size, span, and protection associated with the mapping can be read from the `proc` entry, among other things.

Address Space

The entire addressable area of memory (4 GB on 32-bit platforms) is split into two major areas—kernel space and user (or application) space. `PAGE_OFFSET` defines this split and is actually configurable in `asm/page.h`. The kernel space is located above the offset, and user space is kept below. The default for `PAGE_OFFSET` on the Intel platform is `0xc0000000` and thus provides the kernel with approximately 1 GB of memory, leaving 3 GB for user space consumption. On the Intel platform, the virtual addresses seen from the kernel are therefore a direct offset from the physical address. This isn't always the case, and primitives to convert between the two must thus be used. See Figure 18-4 for a visual representation of the address space.

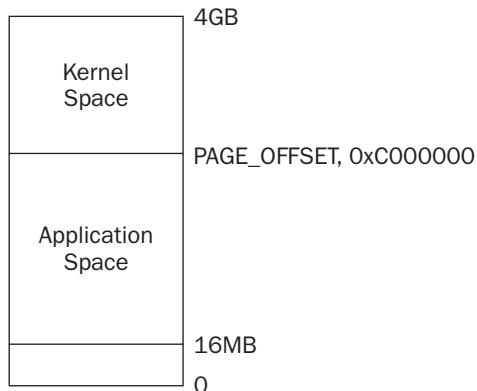


Figure 18-4

Types of Memory Locations

There are three kinds of addresses you need to be aware of as a device-driver writer:

- ❑ **Physical:** This is the “real” address, the one that is used to index the memory bus on the motherboard.
- ❑ **Virtual:** Only the CPU and the kernel (via its page tables and TLB) know about virtual addresses.
- ❑ **Bus:** All devices outside the CPU. On some platforms, this is identical to the physical addresses.

Now, if you want to talk to an add-on card, you can't hand it a virtual memory address and tell it to transfer X number of bytes to you. The card knows absolutely nothing about what addressing scheme the kernel and CPU have agreed upon since it does not have access to the page tables and thus can't make any sense of the memory address. Similarly, the kernel uses virtual addresses for everything, and accessing bus memory varies from platform to platform. Linux therefore provides convenient macros and functions to convert the three types of addresses back and forth.

```
unsigned long virt_to_phys(void *address)
void *phys_to_virt(unsigned long address)
```

```
unsigned long virt_to_bus(void *address)
void *bus_to_virt(unsigned long address)
```

Talking to a peripheral device requires the translation back and forth between virtual addresses (that the kernel knows about) and bus addresses (what the devices know about). This is regardless of the type of bus the peripheral is installed in, be it PCI, ISA, or any other. Note that jumping through the extra hoops of converting addresses is only necessary when you explicitly need to pass a pointer to a memory area directly to the device. This is the case with DMA transfers, for example. In other situations, you normally read the data from device I/O memory or I/O ports.

Getting Memory in Device Drivers

Memory is allocated in chunks of the `PAGE_SIZE` on the target machine. The Intel platform has a page size of 4 Kb, whereas the Alpha architecture uses 8-Kb-sized pages, and it is not a user-configurable option. Keep in mind that the page size varies depending on the platform. There are many ways of allocating memory for driver usage, the lowest-level one being a variant of

```
unsigned long __get_free_page
(int gfp_mask)
```

Allocate exactly one page of memory.

`gfp_mask` describes priority and attributes of the page we would like to get a hold of. The most commonly used ones in drivers are the following:

| | |
|-------------------------|--|
| <code>GFP_ATOMIC</code> | Memory should be returned, if any is available, without blocking or bringing in pages from swap. |
| <code>GFP_KERNEL</code> | Memory should be returned, if any is available, but the call may block if pages need to be swapped out. |
| <code>GFP_DMA</code> | The memory returned should be below the 16MB mark and thus suitable as a DMA buffer. This flag is only needed on ISA peripherals, as these cannot address more memory than 16MB. |

`GFP_ATOMIC` must always be specified if you wish to allocate memory at interrupt time since it is guaranteed not to schedule out the current process if a suitable page is not available. ISA boards can only see up to 16MB of memory, and hence you must specify `GFP_DMA` if you are allocating a buffer for DMA transfers on an ISA peripheral. Depending on how much memory is installed and the level of internal fragmentation, memory allocated with `GFP_DMA` may not succeed. PCI devices do not suffer under this constraint and can use any memory returned by `__get_free_page` for DMA transfers.

`__get_free_page` is actually just a special case of `__get_free_pages`.

```
unsigned long __get_free_pages(int gfp_mask, unsigned long order)
```

`gfp_mask` has the same meaning, but `order` is a new concept. Pages can only be allocated in orders of 2, so the number of pages returned is 2^{order} . The `PAGE_SHIFT` define determines the software page size and is 12 on the *x86* platform (2^{12} bytes is 4 Kb). An `order` of 0 returns one page of `PAGE_SIZE` bytes, and so forth. The kernel keeps internal lists of the different orders up to 5, which limits the maximum order to that amount, giving you a maximum of 2^5 times 4 Kb—which is equal to 128 Kb—on the *x86* platform.

You may have wondered why the functions are prefixed with `__`; there is a perfectly good explanation for this. They are actually faster variants of `get_free_page` and `get_free_pages`, respectively, and the only difference lies in the fact that the `__` versions don't clear the page before returning it. If you copy memory back to user space applications, it may be beneficial to clear the page of previous contents that could inadvertently contain sensitive information that should not be passed to another process.

`__get_free_page` and friends are quicker and, if the memory allocated is only to be used internally, clearing the pages may not be needed.

It is extremely important to free memory once you are done using it. The kernel does not reap allocated pages when the module is unloaded, and this makes it the module's complete responsibility to do its own memory management.

```
void free_page(unsigned long addr)
void free_pages(unsigned long addr,
unsigned long order)
```

Free the page(s) at memory location addr. You are expected to keep track of the size of allocated pages, since `free_pages` expects you to supply it with the order you used when allocating the memory.

kmalloc

Allocation of memory with `get_free_page` and the like is a bit troublesome and places a lot of the memory management work in the hands of the device driver. Depending on what you are aiming at using the memory for, a page-oriented scheme might not be the most appropriate. Besides, it is not that often that the size requirement fits perfectly into the scheme of allocating pages in orders of two of the page size. This can lead to a lot of wasted memory. Linux provides `kmalloc` as an alternative, which lets you allocate memory any size you want.

```
void *kmalloc(size_t size, int flags)
```

`size` is the requested amount of memory and is rounded up to the nearest multiple of the page size. The `flags` parameter consists of a mask of priorities, just like with the `get_free_page` variants. The same size restrictions apply: You can only get up to 128 kB at a time. Trying to allocate more will result in an error in the log, saying “`kmalloc: Size (135168) too large,`” for example.

```
void kfree(const void *addr)
```

`kfree` will free the memory previously allocated by `kmalloc`. If you are used to dynamically allocating memory in applications with `malloc`, you will feel right at home with `kmalloc`.

vmalloc

The third and final way to acquire memory is with `vmalloc`. While `get_free_page` and `kmalloc` both return memory that is physically contiguous, `vmalloc` provides memory that is contiguous in the virtual address space and thus serves a different purpose. It does so by allocating pages separately and manipulating the page tables.

```
void *vmalloc(unsigned long size)
void vfree(void *addr)
```

`vmalloc` allows you to allocate much larger arrays than `kmalloc`, but the returned memory can only be used from within the kernel. Regions passed to peripheral devices cannot be allocated with `vmalloc` because they are not contiguous in the physical address space. Virtual memory is only usable within the kernel/CPU context where it can be looked up in the page tables.

`vmalloc` cannot be used at interrupt time either as it may sleep, since internally `kmalloc` is called without `GFP_ATOMIC` set. This should not pose a serious problem, as it would be abnormal to need more memory than `__get_free_pages` can provide inside an interrupt handler.

All things considered, `vmalloc` is most useful for internal storage. The RAM disk module, `radimo`, shown in the “Block Devices” section later in this chapter will provide an example of `vmalloc` usage.

Transferring Data between User and Kernel Space

Applications running on the system can only access memory below the `PAGE_OFFSET` mark. This ensures that no process is allowed to overwrite memory areas managed by the kernel, which would seriously compromise system integrity, but at the same time poses problems regarding getting data back to user space. Processes running in the context of the kernel are allowed to access both regions of memory, but at the same time it must be verified that the location given by the process is within its virtual memory area.

```
int access_ok(int type, const void *addr,
             unsigned long size)
```

The above macro returns 1 if it is okay to access the desired memory range. The type of access (`VERIFY_READ` or `VERIFY_WRITE`) is specified by `type`, the starting address by `addr`, and the size of the memory region by `size`. Every transfer taking place to or from user space must make sure that the location given is a valid one. The code to do so is architecture-dependent and located in `asm/uaccess.h`.

The actual transfer of data is done by various functions, depending on the size of the transfer.

| | |
|--|--|
| <code>get_user(void *x, const void *addr)</code> | Copy <code>sizeof(addr)</code> bytes from user space address <code>addr</code> to <code>x</code> . |
| <code>put_user(void *x, const void *addr)</code> | Copy <code>sizeof(addr)</code> bytes to user space to variable <code>x</code> from <code>addr</code> . |

The type of the pointer given in `addr` must be known and cast if necessary, which is why there is no need for a size argument. The implementation is quite intricate and can be found in the aforementioned include file. Frequently they are used in implementing `ioctl` calls since those often copy single-value variables back and forth.

You may have wondered why the appropriate `access_ok` call was not included in `schar`, for example. Often the check is omitted by mistake, and the `x_user` functions therefore include the check. The return value is 0 if the copy was completed and -EFAULT in case of access violation.

```
get_user(x, addr)
```

The versions prefixed with `__` perform no checking. They are typically used when performing multiple single-value copies, where performing the access check several times is redundant.

```
char foo[2];
...
if (__access_ok(VERIFY_WRITE, arg, 2*sizeof(*arg)) {
    __put_user(foo[0], arg);
    __put_user(foo[1], arg+1);
```

```
    } else {
        return -EFAULT;
    }
```

This is a trivial case, but the idea behind it should be clear. A third version of the `x_user` family also exists. Typically, the return value is checked and `-EFAULT` is returned in the case of access violation; this leads to the introduction of the last variant.

```
void get_user_ret(x, addr, ret)
void put_user_ret(x, addr, ret)
```

The `_ret` versions return the value in `ret` for you in case of error; they don't return any error code back to you. This simplifies the programming of `ioctls` and leads to such simple code as

```
get_user_ret(tmp, (long *)arg, -EFAULT);
```

Moving More Data

Often more data needs to be copied than just single variables, and it would be very inefficient and awkward to base the code on the primitives in the preceding section. Linux provides the functions needed to transfer larger amounts of data in one go. These functions are used in `schar`'s read and write functions:

```
copy_to_user(void *to, void *from, unsigned long size)
copy_from_user(void *to, void *from, unsigned long size)
```

They copy `size` amount of bytes to and from the pointers specified. The return value is 0 in case of success and nonzero (the amount not transferred) if access is not permitted, as `copy_xx_user` also calls `access_ok` internally. An example of the usage can be found in `schar`.

```
if (copy_to_user(buf, schar_buffer, count))
    return -EFAULT;
```

As with `get_user`, nonchecking versions also exist and are prefixed in the same manner with `__`.

```
copy_to_user(void *to, void *from, unsigned long size)
copy_from_user(void *to, void *from, unsigned long size)
```

Finally, `_ret` variants are also available that return `ret` in case of access violations.

```
copy_to_user_ret(void *to, void *from, unsigned long size, int ret)
copy_from_user_ret(void *to, void *from, unsigned long size, int ret)
```

All of the preceding examples rely on being run in the context of a process. This means that using them from interrupt handlers and timer functions, for example, is strictly prohibited. In these situations the kernel functions are not working on behalf of a specific process, and there is no way to know if current is related to you in any way. In these situations it is far more advisable to copy data to a buffer maintained by the driver and later move the data to user space. Alternatively, as will be seen in the next section, memory mapping of device driver buffers can be implemented and solve the problems without resorting to an extra copy.

Simple Memory Mapping

Instead of copying data back and forth between user and kernel space incessantly, at times it is more advantageous to simply provide the applications a way to continuously view in-device memory. The concept is called *memory mapping*, and you may already have used it in applications to map entire files and read or write to them through pointers instead of using the ordinary file-oriented read or write. If not, Chapter 3 contains an explanation of what `mmap` is and how it is used in user space. In particular, many of the arguments are explained there, and they map directly to what we are going to do here.

It is not always safe or possible to copy data directly to user space. The scheduler might schedule out the process in question, which would be fatal from an interrupt handler, for example. One possible solution is to maintain an internal buffer and have such functions write and read there and later copy the data to the appropriate place. That causes additional overhead because two copies of the same data have to be made, one to the internal buffer and an extra one to the application's memory area. However, if the driver implements the `mmap` driver entry point, a given application can directly obtain a viewpoint into the driver buffer, and there is thus no need for a second copy.

`schar_mmap` is added to the `file_operations` structure to declare that we support this operation. Let's look at the `schar` implementation:

```
static int schar_mmap(struct file *file,
                      struct vm_area_struct *vma)
{
    unsigned long size;

    /* mmap flags - could be read and write, also */
    MSG("mmap: %s\n", vma->vm_flags & VM_WRITE ? "write" :
        "read");

    /* we will not accept an offset into the page */
    if(vma->vm_offset != 0) {
        MSG("mmap: offset must be 0\n");
        return -EINVAL;
    }

    /* schar_buffer is only one page */
    size = vma->vm_end - vma->vm_start;
    if (size != PAGE_SIZE) {
        MSG("mmap: wanted %lu, but PAGE_SIZE is %lu\n",
            size, PAGE_SIZE);
        return -EINVAL;
    }

    /* remap user buffer */
    if (remap_page_range(vma->vm_start,
                         virt_to_phys(schar_buffer),
                         size, vma->vm_page_prot))
        return -EAGAIN;

    return 0;
}
```

Chapter 18

We receive two arguments in the function—a file structure and the virtual memory area that will be associated with the mapping. As mentioned earlier, `vm_start` and `vm_end` signify the beginning and end of the mapping, and the total size wanted can be deduced from the difference between the two. `schar`'s buffer is only one page long, which is why mappings bigger than that are rejected. `vm_offset` would be the offset into the buffer. In this case, it wouldn't make much sense to allow an offset into a single page, and `schar_mmap` rejects the mapping if one was specified.

The final step is the most important one. `remap_page_range` updates the page tables from the `vma->vm_start` memory location with `size` being the total length in bytes. The physical address is effectively mapped into the virtual address space.

```
remap_page_range(unsigned long from, unsigned long phys_addr,
                 unsigned long size, pgprot_t prot)
```

The return value is 0 in case of success and `-ENOMEM` if it failed. The `prot` argument specifies the protection associated with the area (`MAP_SHARED` for a shared area, `MAP_PRIVATE` for a private, etc.). `schar` passes it directly from the one given to `mmap` in the application.

The page or pages being mapped must be locked so they won't be considered for other use by the kernel. Every page present in the system has an entry in the kernel tables, and we can find which page we're using based on the address and set the necessary attributes.

```
struct page *virt_to_page(void *addr)      Return the page for address.
```

`schar` allocates a page of memory and calls `mem_map_reserve` for the page returned by the `virt_to_page` function. The page is unlocked by `mem_map_unreserve` and freed in `cleanup_module` when the driver is unloaded. This order of operation is important, as `free_page` will not free a page that is reserved. The entire page structure, along with all the different flag attributes, can be found in `linux/mm.h`.

This was an example of how to access the kernel's virtual memory from user space by making `remap_page_range` do the work for us. In many cases, however, memory mapping from drivers allows access to the buffers on peripheral devices. The next section will introduce I/O memory and, among other things, will briefly touch upon how to do just that.

I/O Memory

The last kind of address space we are going to look at is I/O memory. This can be both ISA memory below the 1MB boundary or high PCI memory, but we conceptually use the same access method for both. I/O memory is not memory in the ordinary sense, but rather ports or buffers mapped into that area. A peripheral may have a status port or onboard buffers that we would like to gain access to. The sample module `I omap` gives a demonstration of these principles and can be used to read and write or memory-map a region of I/O memory.

Where I/O memory is mapped to depends highly on the platform in question. On the `x86` platform, simple pointer dereferencing can be used to access low memory, but it is not always in the physical address space and therefore must be remapped before we can get a hold of it.

```
void *ioremap(unsigned long offset, unsigned long size)
```

`ioremap` maps a physical memory location to a kernel pointer of the wanted size. `Iomap` uses it to remap the frame buffer of a graphics adapter (the main intended use for the module) to a virtual address we can access from within the driver. An `Iomap` device consists of the following:

```
struct Iomap {
    unsigned long base;
    unsigned long size;
    char *ptr;
}
```

Where `base` is the starting location of the frame buffer, `size` is the length of the buffer, and `ptr` is what `ioremap` returns. The base address can be determined from `/proc/pci`, provided you have a PCI or AGP adapter; it is the prefetchable location listed there:

```
$ cat /proc/pci
PCI devices found:
Bus 1, device 0, function 0:
    VGA compatible controller: NVidia Unknown device (rev 17).
        Vendor id=10de. Device id=29.
        Medium devsel. Fast back-to-back capable. IRQ 16. Master Capable.
Latency=64. Min Gnt=5. Max Lat=1.
        Non-prefetchable 32 bit memory at 0xdf000000 [0xdf000000].
        Prefetchable 32 bit memory at 0xe2000000 [0xe2000008].
```

Find your graphics adapter among the different PCI devices in your system and locate the memory listed as prefetchable; as you can see, that would be `0xe2000000` on this system. `Iomap` can manage up to 16 different mappings all set up through `ioctl` commands. We'll need this value when trying out `Iomap` a little later.

Once the region has been remapped, data can be read and written to. `Iomap` using byte-size functions.

```
unsigned char *readb(void *addr)
unsigned char *writeb(unsigned char data, void *addr)
```

`readb` returns the byte read from `addr`, and `writeb` writes data to specified location. The latter also returns what it wrote, if you need that functionality. In addition, doubleword and long versions exist.

```
unsigned short *readw(void *addr)
unsigned short *writew(unsigned short data, void *addr)
unsigned long *readl(void *addr)
unsigned long *	writel(unsigned long data, void *addr)
```

If `IOMAP_BYTE_WISE` is defined, this is how `Iomap` reads and writes data. As one would expect, they are not that fast when doing copies of the megabyte size since that is not their intended use. When `IOMAP_BYTE_WISE` is not defined, `Iomap` utilizes other functions to copy data back and forth.

```
void *memcpy_fromio(void *to, const void *from, unsigned long size)
void *memcpy_toio(void *to, const void *from, unsigned long size)
```

They work exactly like `memcpy` but operate on I/O memory instead. A `memset` version also exists that sets the entire region to a specific value.

```
void *memset_io(void *addr, int value, unsigned long size)
```

Iomap's read and write functions work basically just like schar's, for example, so we are not going to list them here. Data is moved between user space and the remapped I/O memory through a kernel buffer, and the file position is incremented.

At module cleanup time, the remapped regions must be undone. The pointer returned from `ioremap` is passed to `iounmap` to delete the mapping.

```
void iounmap(void *addr)
```

The data returned by the read and write functions is in little endian format, whether that is the native byte ordering on the target machine or not. This is the ordering used in PCI peripherals' configuration space, for example, and the preceding functions will byte swap the data if necessary. If data needs to be converted between the two data types, Linux includes the primitives to do so. The "Portability" section later in the chapter gives us a closer look at that.

Assignment of Devices in Iomap

Iomap keeps a global array of the possible devices created, indexed by minor numbers. This is a widely used approach to managing multiple devices and is easy to work with. The global array, `iomap_dev`, holds pointers to all the potential accessed devices. In all the device entry points, the device being acted upon is extracted from the array.

```
Iomap *idev = iomap_dev[MINOR(inode->i_rdev)];
```

In the cases where an inode is not directly passed to the function, it can be extracted from the file structure. It contains a pointer to the dentry (directory entry) associated with the file, and the inode can be found in that structure.

```
Iomap *idev = iomap_dev[MINOR(file->f_dentry->d_inode->i_rdev)];
```

I/O Memory mmap

In addition to being read and written ordinarily, Iomap supports memory mapping of the remapped I/O memory. The actual remapping of pages is very similar to schar, with the deviation that because actual physical pages are not being mapped no locking needs to be done. Remember that I/O memory is not real RAM, and thus no entries exist for it in `mem_map`.

```
remap_page_range(vma->vm_start, idev->base, size,
                  vma->vm_page_prot)
```

As with schar, `remap_page_range` is the heart of `iomap_mmap`. It does the hard work for us in setting up the page tables. The actual function doesn't require much code.

```

static int iomap_mmap(struct file *file, struct vm_area_struct *vma)
{
    Iomap *idev = iomap_dev[MINOR(file->f_dentry->d_inode->i_rdev)];
    unsigned long size;

    /* no such device */
    if (!idev->base)
        return -ENXIO;

    /* size must be a multiple of PAGE_SIZE */
    size = vma->vm_end - vma->vm_start;
    if (size % PAGE_SIZE)
        return -EINVAL;

    /* remap the range */
    if (remap_page_range(vma->vm_start, idev->base, size,
                         vma->vm_page_prot))
        return -EAGAIN;

    MSG("region mmaped\n");
    return 0;
}

```

We start by finding the specific device in the `iomap_dev` array and check whether this particular device has been set up. If it hasn't, we return an appropriate error message. We also require that the range that is going to be remapped is a multiple of the page size and return an error. If all is in order, we call `remap_page_range` and let it do its job.

Try It Out—The Iomap Module

`Iomap`'s source is also included in the code download from the Wrox Web site. Go to the `modules/omap` directory, where you should find the following files:

```

$ ls
iomap.c      iomap.h      iomap_setup.c      Makefile

```

1. As the superuser, run `make` to build the `omap` module, make two special file entries—one with minor 0 and one with minor 1—and insert the module.

```

# make
# mknod /dev/omap0 c 42 0
# mknod /dev/omap1 c 42 1
# insmod omap.o
omap: module loaded

```

2. Now we are ready to take it for a spin. `Iomap` won't do anything on its own, so we need to set up two devices to experiment with. First, you will need to dig up the base address of the frame buffer on your display adapter; examine `/proc/pci` as explained at the beginning of the "I/O Memory" section earlier in the chapter. Recall that the address was `0xe200000` on this system. We will need this now when creating a small program that sets up the two devices through `ioctl` calls. Create a file called `omap_setup.c` in the directory where the `Iomap` module sources are located, or edit the existing code, containing the following:

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```
#include <stdio.h>
#include <fcntl.h>
#include <sys/ioctl.h>

#include "iomap.h"

#define BASE    0xe2000000

int main(int argc, char *argv[])
{
    int fd1 = open("/dev/iomap0", O_RDWR);
    int fd2 = open("/dev/iomap1", O_RDWR);
    Iomap dev1, dev2;

    if (fd1 == -1 || fd2 == -1) {
        perror("open");
        return 1;
    }

    /* set up first device */
    dev1.base = BASE;
    dev1.size = 512 * 1024;
    if (ioctl(fd1, IOMAP_SET, &dev1)) {
        perror("ioctl");
        return 2;
    }

    /* set up second device, offset the size of the first device */
    dev2.base = BASE + dev1.size;
    dev2.size = 512 * 1024;
    if (ioctl(fd2, IOMAP_SET, &dev2)) {
        perror("ioctl");
        return 3;
    }

    return 0;
}
```

As you'd expect, you should change `BASE` to point to your frame buffer address! Otherwise we might end up writing to another device in your system, which could crash the system or render the affected device unusable. Compile and run the `iomap_setup` program; this should define the two devices we are going to operate on.

```
$ cc -Wall -o iomap_setup iomap_setup.c
$ ./iomap_setup
iomap: setting up minor 0
iomap: setup: 0xe2000000 extending 0x80000 bytes
iomap: setting up minor 1
iomap: setup: 0xe2080000 extending 0x80000 bytes
```

3. We have now set up two devices, one mapping 0.5MB from the start of the frame buffer and the other mapping 0.5MB from the start of the first mapping. These map directly into the graphics memory of the display adapter, and writing to them should cause a visible distortion on your screen. Before running the next few lines to try that out, make sure that you have X loaded and execute the commands from within a terminal there.

```
$ cp /dev/iomap1 /dev/iomap0
```

4. Now the effects of the above command should be apparent. The region on your monitor that corresponds to the mapping of the second device should now also appear at the top of the screen, thus creating an odd-looking X session. Continue the fun and fill the top of the monitor with garbage by copying random data to it:

```
$ dd if=/dev/random of=/dev/iomap0 bs=512 count=1024
```

I/O Ports

I/O ports are a phenomenon only seen on some platforms such as the *x86* architecture. They can be either a status port on a peripheral device or the serial port that your mouse is connected to. Data is read and written to ports in sizes according to its width. Other platforms, Alpha for example, don't have real ports but only I/O memory. On platforms like that, reading and writing to memory locations achieves access to I/O data.

Linux supports a wide variety of functions to read and write to and from I/O ports. They are all variants of the same flavor and differ mainly in how wide a port they talk to. Note that this section deals with regular I/O ports, not I/O memory, which was covered earlier in the chapter. The header file to browse for this section is `asm/io.h`; this is a very nasty file, so consider yourself warned!

A driver ought to verify that a given port can be used. Another driver might already have grabbed the port we are looking for, and we do not want to wreak havoc by outputting data that might confuse the device it handles.

```
int check_region(unsigned int from, unsigned long extent)
```

`from` is the port we are testing, and `extent` is how wide it is counted in bytes. The return value is 0 on success or nonzero if the port is already taken. Once a proper port has been found, you can go ahead and request it.

```
void request_region(unsigned int from, unsigned long extent, const char *name)
void release_region(unsigned int from, unsigned long extent)
```

The parameters are almost alike; `name` is the one that shows up in `/proc/ioports` and should be considered a device label along the lines with the `/proc/devices` entry. Ports can be 8, 16, or 32 bits wide.

```
u8 inb(unsigned int port)
u16 inw(unsigned int port)
u32 inl(unsigned int port)
```

The usage should be clear: They all read the respective size value from a port. The return value is the data read, and depending on the platform used, different types fill the size requirement. The functions for writing to ports are similar.

```
void outb(__u8 data, unsigned int port)
void outw(__u16 data, unsigned int port)
void outl(__u32 data, unsigned int port)
```

Again, the typing is a bit loose because it varies from one platform to another. Typing is not the only problem with I/O ports, as some platforms don't have regular ports but emulate them by reading and writing to memory locations instead. We won't detail this any further here; your best bet is to study some of the drivers in the kernel.

In addition, Linux provides string versions that allow you to transfer more than one datum at a time efficiently.

```
void insb(unsigned int port, void *addr, unsigned long count)
void outsb(unsigned int port, void *addr, unsigned long count)
```

`addr` is the location in memory to transfer to or from, and `count` is the number of units to transfer. Similar versions exist for word- and doubleword-size transfers with the same naming convention as the single datum functions. They are very fast and much more efficient than building a loop around the `inb`, for example.

Some platforms do not have regular I/O ports like the x86 architecture but instead implement them as a mapped region of regular memory. The above functions for talking to I/O ports are also not the only variants that exist, as different platforms have differing needs. The data returned is in little endian format, which might not be suitable, and some big endian platforms provide variants that don't byte swap the result. Inspect `asm/io.h` from the various architecture-specific directories—under `arch` in the kernel source tree—if you are curious.

Interrupt Handling

Most real hardware does not rely on polling to control the data flow. Instead, interrupts are used to signal the availability of data or other hardware conditions to the device driver and let it take the appropriate action. Writing an ISR (Interrupt Service Routine) is often surrounded by mysticism, but that can only be because people have not seen how easy it really is to do in Linux. There is nothing special about it because Linux exports a very elegant and uncomplicated interface for registering interrupt handlers and (eventually) handling interrupts as they come in.

An *interrupt* is a way for a device to get the device driver's attention and tell it that the device needs to be serviced somehow. This could be to signal that data is available for transfer or that a previously queued command has now completed and the device is ready for a new one.

How interrupts are handled internally by Linux is very architecture-dependent: It all depends on the interrupt controller that the platform is equipped with. If you are interested, you can find the necessary information in `arch/<your arch>/kernel/irq.c` file: `arch/i386/kernel/irq.c`, for example.

Interrupts that have no designated handler assigned to them are simply acknowledged and ignored by Linux. You can find a listing of what handlers are installed on your system by listing the contents of `/proc/interrupts`:

| | CPU0 | CPU1 | | |
|----|---------|---------|--------------|--------------|
| 0: | 1368447 | 1341817 | IO-APIC-edge | timer |
| 1: | 47684 | 47510 | IO-APIC-edge | keyboard |
| 2: | 0 | 0 | XT-PIC | cascade |
| 4: | 181793 | 182240 | IO-APIC-edge | serial |
| 5: | 130943 | 130053 | IO-APIC-edge | soundblaster |
| | ... | | | |

This is an incomplete listing of our system right now. The leftmost column is the interrupt number, and the next two columns represent the number of times each CPU has handled the particular interrupt. The last two items are the interrupt type and the device that registered the handler. So, the listing above reveals that CPU0 has handled 130,943 interrupts from the soundblaster device and CPU1 took care of 130,053. 0 is a special case—the timer interrupt (on the x86; other platforms are different)—and indicates the number of ticks since the system was booted. The fourth column here indicates how the interrupts are handled. This is not really important to us here, and it should suffice to know that in an SMP environment the `IO-APIC` distributes the interrupts between the CPUs. `XT-PIC` is the standard interrupt controller.

Another file you might want to look at is `/proc/stat`. It contains, among other things, the total number of interrupts that have transpired. The line of interest to us now is `intr`, which has the following format: `intr total irq0 irq1 irq2 ...`, where `total` is the sum of all interrupts, `irq0` the sum of interrupt 0, and so forth. This file might come in handy when you are experimenting with your first interrupt-driven driver because it also lists triggered interrupts that don't have a handler registered that `/proc/interrupts` doesn't.

Allocating an Interrupt

Now that we have looked at the interrupt statistics gathered in `/proc`, let's move on to how you can request your own IRQ. An explanation of the parameters follows.

```
int request_irq(unsigned int irq,
                void (*handler)(int, void *, struct pt_regs *),
                unsigned long irqflags,
                const char *devname,
                void *dev_id)
```

`request_irq` returns 0 on success, and failure is indicated by an appropriate negative error—most notably, `-EINVAL` if the IRQ is out of range and `-EBUSY` if a shared handler was requested and the `irqflags` do not match with an already installed handler.

| | |
|---|---|
| <code>irq</code> | The actual IRQ that you wish to handle. |
| <code>handler(int irq, void *dev_id, struct pt_regs *regs)</code> | When the interrupt occurs, this is the function that gets called. This is the IRQ handler. |
| <code>irqflags</code> | This controls the behavior of the interrupt. We will look more at that later. |

Table continued on following page

| | |
|---------|--|
| devname | The name that is listed in /proc/interrupts. |
| dev_id | Helps support sharing of interrupts. It is the one that is passed to the handler—the function passed as the second argument—and can thus be used if you need to pass it information. The IDE subsystem, for example, uses it to distinguish between the master and slave that it controls per interrupt. |

The `irqflags` parameter comprises several possible combinations:

| | |
|------------------|---|
| SA_INTERRUPT | A handler registered with this flag runs with all IRQs disabled. Not setting it only disables the IRQ being serviced by the handler. |
| SA_SHIRQ | Enable the IRQ line to be shared between more than one device. The drivers must also agree on the rest of the <code>irqflags</code> mask and supply the proper <code>dev_id</code> , otherwise sharing is not allowed. |
| SA_SAMPLE_RANDOM | The Linux kernel keeps an internal entropy pool managed by the random device. If the device being managed by the handler does not interrupt at a fixed rate, it may be able to contribute to the randomness of this pool and the flag should be set. Naturally, this depends heavily on the actual hardware being driven. |

The handler being registered receives three arguments when invoked. `irq` can only be considered useful if the handler manages more than one IRQ, otherwise you would already know which specific interrupt occurred. `regs` contains the imagery of the CPU registers before the interrupt occurred. It is rarely useful, but you can find the definition in `asm/ptrace.h` if you are curious. The second argument is `dev_id`, which we already covered.

Unregistering an IRQ handler is done with `free_irq`. The arguments are similar to `request_irq` and need no further explanation.

```
void free_irq(unsigned int irq, void *dev_id)
```

Getting an Appropriate IRQ

Before you can register a handler to use with your driver, you have to find out what IRQ to use. This is highly hardware dependent, both in regards to the type of peripheral device and the host bus, be it ISA, PCI, or SBUS (a host bus found on the SPARC). Regarding the former, some devices will let you read the configuration from a status port; others you may have to probe. If you are going to write a driver for a real piece of hardware, you need the programming specifications from the vendor; they will tell you how to retrieve the needed information correctly.

The most prevalent bus types are ISA and PCI (at least on the x86 platform). Although efforts have been made to partially add Plug and Play capabilities to ISA devices, ISA was invented before Plug and Play was an issue and no real standard exists. Besides, we have probably all experienced how well that works. PCI devices provide a clean and standardized way to retrieve configuration information without

resorting to nasty probing and guesswork. How to handle PCI devices is beyond the scope of this book. `linux/pci.h` is a good place to start if you want to deal with PCI, and, as always, plenty of examples exist within the Linux sources. The rest of this section will deal only with legacy devices.

If the hardware allows you to retrieve the configuration directly, you will not have to do any probing yourself. As mentioned previously, this information is located in hardware device manuals and we can't say anything generic about that. Linux provides interrupt detection for devices that don't support nicer alternatives.

```
unsigned long probe_irq_on(void)
int probe_irq_off(unsigned long mask)
```

`probe_irq_on` initiates the probing sequence, and `probe_irq_off` ends it. In between, you should put code that will trigger an IRQ from the device, and this will then be the return value from `probe_irq_off`. If more than one IRQ fired, `probe_irq_off` will return a negative value (in fact, corresponding to the first triggered IRQ found, which could provide some hint). The probing sequence will typically look something like the following:

```
int irq;
unsigned long foo;

/* clear dangling interrupts */
probe_irq_off(probe_irq_on());

foo = probe_irq_on();

/* this should provoke an interrupt from the device */
outb(TRIGGER_IRQ, PORT);

irq = probe_irq_off(foo);

if (irq > 0)
    printk("irq %d detected\n", irq);
```

This is a purely theoretical example of how you might detect the IRQ used. The value returned by `probe_irq_on` is a mask of all interrupts already in use. The interesting part is what is returned after the probe—hopefully the interrupt you need.

The IRQ Handler

Once you have the available IRQ that you need, you need to write a handler to deal with the device interrupts. The job of the handler is to acknowledge the interrupt and service the device in some way. Typically some form of data is available and should be transferred from the device, or a state change occurred and the hardware wants to let us know about it. The handler runs either with all interrupts enabled except its own or no interrupts enabled depending on whether `SA_INTERRUPT` was specified, so any interrupts from the same device are lost until the handler has finished running. We'll see later how to deal with that issue.

The normal flow of execution is halted when an interrupt occurs; the kernel stops what it is currently doing and invokes the appropriate handler registered. Interrupt handlers are different from the normal driver entry points in that they run at interrupt time and as such are not running on behalf of a specific

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process. That means that the current process typically doesn't have any relation to the driver and it shouldn't be touched. This also includes any access to user space, such as copying data back and forth.

Interrupt handlers should finish as soon as possible, or you may otherwise miss another interrupt from the device. If you share the interrupt with another device, you are also preventing interrupts from there being serviced. Although it has been mentioned before, it's important to stress that you must not block at interrupt time. If you do, the scheduler may be invoked and this is not allowed. It will inform you of such an occurrence with "Scheduling in interrupt" on the console followed by an `oops`. Nor are you allowed to sleep in the handler. In general, think carefully about how you interact with the rest of the system while running at interrupt time.

There is nothing special about interrupt handlers other than what is mentioned above, so we won't give detailed examples on how to write one. As with the probe example, here is a theoretical interrupt handler:

```
void our_intr(int irq, void *dev_id, struct pt_regs *regs)
{
    int status;

    printk("received interrupt %d\n", irq);

    /* reading status from board */
    inb(STATUS_PORT, status);

    /* we are sharing irq, check if it was our board */
    if (status & MY_IRQ_STAT)
        return;

    /* acknowledge IRQ */
    outb(STATUS_PORT, MY_ACK_IRQ);

    >transfer data from the device, if needed<

    /* schedule bottom half for execution */
    our_taskqueue.routine = (void *) (void *)our_bh;
    our_taskqueue.data = (void *)dev_id;
    queue_task(&our_taskqueue, &tq_immediate);
    mark_bh(IMMEDIATE_BH);

    return;
}
```

The first thing we do is check whether the IRQ was generated from the device the driver is managing by reading a status from a designated port on the hardware. This is one way of handling interrupt sharing. If the handler was controlling several instances of the same hardware device, we could have used `dev_id` to differentiate between them.

Bottom Halves

The handler in the previous section introduces a new concept, bottom halves. They were mentioned briefly earlier in the chapter, but they deserve a little more attention. Instead of doing all the work in the actual interrupt handler, we declare a task queue and add it to the immediate queue (thus guaranteeing very swift execution). `our_bh` is the bottom half for this device and will be consumed by the immediate

queue as soon as we return from the top half (the actual interrupt handler). The top half will most likely copy data from the device to an internal buffer and let the bottom half deal with necessary processing.

Whether keeping a separate bottom half is worth the effort depends on how much time you need to spend in the top half and if the IRQ is shared or not. As soon as the interrupt handler returns from execution, the device IRQ reporting is enabled again. Bottom halves thus run with the device IRQ active and thereby allow the handler to service more interrupts than it otherwise would have been able to. Bottom halves are atomic with respect to each other, so you don't have to worry about being re-entered. A top half, however, can be invoked while the bottom half is still executing. If a bottom half is marked while it is running, it will be run again as soon as possible, but marking it twice will still only make it run once.

Often, you need to share data between the two, since the bottom half is doing work for the top half. This requires some care. We will talk more about atomicity and re-entrancy in the next few sections.

You don't have to use `tq_immediate`, but it is usually the one used simply because it is the quickest. Since the regular bottom halves are all predefined in the kernel, this is the replacement to use if you need it.

Re-entrancy

One of the more important issues with device drivers is the issue of *re-entrancy*. We have already discussed some of the issues loosely throughout the text but only in passing, and the issue clearly needs more attention than that. Imagine having your driver opened by several processes at once. Often a driver for a real device has to maintain several internal structures that are manipulated in a myriad of places. It goes without saying that the integrity of these structures must remain intact, so how do you make sure that two processes aren't modifying the same structure at the same time? The issue is even more important as SMP systems are becoming more prevalent and having two CPUs these days is not uncommon. Linux's 2.0 kernel solved this problem by guarding the entire kernel space with a big lock, thus making sure that only one CPU at a time was spending time in the kernel. While this solution worked, it didn't scale very well as the number of CPUs increased.

During the 2.1 kernel development cycle, it became apparent that finer-grained locking was needed if Linux was to conquer machines with more than two CPUs and do it well. So instead of having one big lock and having processes acquire it upon entering kernel space, new locking primitives were introduced. Important data structures inside the kernel are now guarded with a separate lock, and having numerous processes executing inside the kernel is now possible. Sections of code that modify structures that can also be modified by others at the same time are called *critical sections*, and this is the piece of code we need to protect against re-entrancy.

As we mentioned earlier, a process running in kernel space can't be pre-empted on its own, so you can be assured that `current` won't change beneath you; they have to give up execution. This was almost true. Actually, interrupts can come in at any time and will break the current flow of execution. Of course, there is also the issue of putting processes to sleep and explicitly calling `schedule()` from within the driver; here we must also be prepared to handle the consequences of being re-entered. Does this mean that you have to guard all variables? No, luckily only global structures share the same address space. Variables local to a function reside in the kernel stack for that process and are thus distinct to each accessing process.

```
int global;

int device_open(struct inode *inode, struct file *file)
{
```

```
int local;

printf("pid = %d : ", current->pid);
printf("global = 0x%p, local = 0x%p\n", &global, &local);
...
}
```

The output of the preceding code in a module verifies that this is true; global variables are shared while local variables are different copies:

```
pid = 909 : global = 0xc18005fc, local = 0xc08d3f2c
pid = 910 : global = 0xc18005fc, local = 0xc098df2c
```

While having local variables residing in the kernel stack is a relief, it also places certain constraints on what you can fit in that space. The Linux kernel reserves approximately 7 Kb of kernel stack per process, which should be sufficient for most needs. Some of this is reserved for interrupt handling and the like; you should be careful not to overstep this limit. Should you need more than approximately 6 Kb, you must allocate it dynamically.

The classic way of guarding yourself against re-entrancy was to disable interrupts globally, do your work, and enable interrupts again. Interrupt handlers, and everything else that runs at interrupt time, work asynchronously with your driver, and structures that are modified by these handlers need to be protected against being changed while you are working with them.

```
unsigned long flags;

/* save processor flags and disable interrupts */
save_flags(flags);
cli();

_read/modify structures, critical section_

restore_flags(flags);
```

While this still works, it disables interrupts across all CPUs, and as such it is a slow and noncooperative way of guarding yourself. If the target system is guaranteed to be UP (single CPU systems), this is all you need since only one CPU can be executing kernel code. Instructions are thus guaranteed to be serialized and are therefore atomic in respect to each other.

Disabling Single Interrupts

If you know that only your own interrupt handler modifies the internal structures, it can be considered overkill to disable all interrupts in the system. All you really need is to make sure that your own handler doesn't run while you are mucking around with the interrupts. In this case, Linux provides functions to disable a single IRQ line.

```
void disable_irq(unsigned int irq);
void disable_irq_nosync(unsigned int irq);
void enable_irq(unsigned int irq);
```

The critical region can thus be placed between a `disable` and `enable` of the interrupt, and the top half will not be invoked if the interrupt line is raised. The difference between the regular `disable_irq` and the `_nosync` version is that the former guarantees that the specified IRQ is not running on any CPU before returning, while the latter will disable the specified interrupt and return even if a top-half handler is still running.

Atomicity

Instructions are said to be atomic when you know they are executed in one go (i.e., you will not be interrupted until you are done). Disabling interrupts accomplishes this, as we saw above, since no one can interrupt us in the critical section. Linux also offers atomic primitives that act on variables without the need to lock everybody else out. They are defined in `asm/atomic.h`.

```
void atomic_add(int i, volatile atomic_t *v)
void atomic_sub(int i, volatile atomic_t *v)
void atomic_inc(volatile atomic_t *v)
void atomic_dec(volatile atomic_t *v)
int atomic_dec_and_test(volatile atomic_t *v)
```

As you can see, these operate on the `atomic_t` type, which is a structure containing only a counter member. What it contains doesn't really matter, since you should only access it via the `atomic_x` functions and macros. Only then are you ensured atomicity. They are mainly used for keeping count for semaphores but can be used any way you please.

Atomic operations are often needed to prevent race conditions. A race exists when a process decides to sleep on an event based on evaluating an expression nonatomically. `schar` does not have such a construct, but it is common enough that we will give an example.

```
/* if device is busy, sleep */
if (device->stat & BUSY)
    sleep_on(&queue);
```

If the test for checking whether the device is busy is not atomic, the condition may become false after the test but before `sleep_on` is invoked. The process may sleep forever on the queue. Linux has some handy bit-testing operations that are guaranteed to execute atomically.

| | |
|---|--|
| <code>set_bit(int nr, volatile void *addr)</code> | Set, clear, or test the bit specified in <code>nr</code> from the bitmask at <code>addr</code> . |
| <code>clear_bit(int nr, volatile void *addr)</code> | |
| <code>test_bit(int nr, volatile void *addr)</code> | |

The preceding device busy test could then be implemented as

```
/* if device is busy, sleep */
if (test_bit(BUSY, &device->stat)
    sleep_on(queue);
```

and be completely race safe. There are several others, including test-and-set operations, defined in `asm/bitops.h`.

Protecting Critical Sections

Assuming that your modules are going to be run only on UP systems is clearly a very bad idea. Linux provides two variants of spin locks that can be used to protect structures against manipulation. On UP systems, this defaults to the above construct of disabling interrupts with `c1i`, while on SMP systems they only disable interrupts on the local CPU. The latter is sufficient as long as all the functions on your driver acquire the same spin lock before modifying shared structures.

Basic Spin Locks

Spin locks are one of the most basic locking primitives. A process trying to enter a critical region already protected by another process with a spin lock will “spin,” or loop, until the lock is released and can be acquired.

The different types of spin locks can be found in `asm/spinlock.h`. This is also the file to inspect if you are at all interested in how they are implemented differently in single and multiple CPU configurations. There are two basic types implemented in Linux. The first type is

```
spinlock_t our_lock = SPIN_LOCK_UNLOCKED;  
  
spin_lock(&our_lock);
```

and the second is

```
spinlock_t our_lock = SPIN_LOCK_UNLOCKED;  
unsigned long flags;  
  
spin_lock_irqsave(&our_lock, flags);
```

If the structures are not going to be modified at interrupt time, `spin_lock` is all you need. It provides safety from modification across CPUs but doesn't disable interrupts even on the local CPU. This makes it faster than `spin_lock_irqsave`, which also provides assurance against interrupt handlers.

```
spin_unlock(&our_lock);  
spin_unlock_irqrestore(&our_lock, flags);
```

These are the equivalent unlocking macros to be used when you're done modifying structures.

There are a lot more functions in `asm/spinlock.h`, including macros that allow you to test whether getting a lock will succeed before trying to acquire it, and others. If you need more functionality, you can find the needed information there.

Reader and Writer Locks

The preceding spin locks provide full locking and protect the code in between from being re-entered for any purpose. It may also be useful to further differentiate access to structures, access with the purpose of only reading data, or write access. For this purpose, Linux provides locks that allow you to acquire either read or write access, thus allowing multiple readers or a single writer to enter the critical region at the same time.

```
rwlock_t our_lock = RW_LOCK_UNLOCKED;
unsigned long flags;

read_lock(&our_lock);
read_lock_irqsave(&our_lock, flags);
write_lock(&our_lock);
write_lock_irqsave(&our_lock, flags);
```

The semantics are exactly the same as for basic spin locks, so we won't explain them further. Unlocking the region is provided by similar macros.

```
read_unlock(&our_lock);
read_unlock_irqrestore(&our_lock, flags);
write_unlock(&our_lock);
write_unlock_irqrestore(&our_lock, flags);
```

Now you know how to protect yourself effectively against the gruesome effects of re-entrancy with basic spin locks and reader/writer spin locks. In a UP environment, the non-IRQ versions all expand to no-ops (IRQ versions still disable interrupts, since they are handled as soon as they come in and therefore still run asynchronously) so you will not lose performance there, but the behavior on SMP systems is far more attractive than the basic `cli` construct.

Automated Locking

Most of the functions available to device drivers are protected internally by spin locks, courtesy of the kernel, and no extra locking is thus required. An example of such was given in the "Timers" section earlier in this chapter, where `add_timer` internally acquired the `timer_list` lock before manipulating the given timer structure. If the timer is local to the function, no locking is needed and `internal_add_timer` could be called directly. However, it is recommended to always use the "safer" variants, and this subsection is purely added in case you were wondering why no locking was used to maintain integrity of wait queues or timer lists in `schar`, for example.

Block Devices

The second class of devices covered in this book is block devices. They are entirely different creatures than character drivers in that they don't serve bytes of data, but entire blocks instead. While character drivers are usually accessed directly from applications by reading and writing to them, block device accesses go through the buffer cache in the system.

Figure 18-5 is a half-truth since only reading and writing of blocks passes through the buffer cache. `open`, `close`, and `ioctl` have normal entry points, for example.

Block devices usually host file systems and can be accessed randomly by specifying which block to read or write. This is in contrast to character drivers, which only allow sequential, nonrandom access and thus cannot be used for providing file system storage.

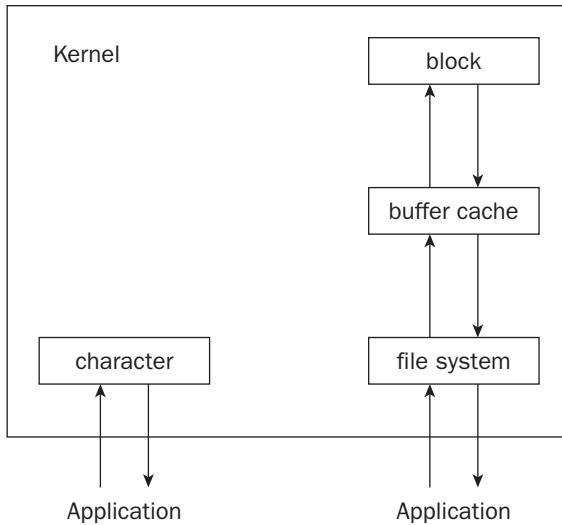


Figure 18-5

Linux does not distinguish sharply between block and character devices and even provides the same interface for both. When we were designing the first character driver, `schar`, some of the elements of the `file_operations` structure did not lend themselves to a character-oriented access scheme, exactly because the same one is used for both types of devices.

radimo—A Simple RAM Disk Module

The best way to get a little familiar with the inner workings of block devices and the underlying system they depend on is to dig in with a working example. `radimo` is a RAM disk driver that will host a file system of varying size, depending on the available memory in the system.

At the heart of every block device driver is the `request` function that receives the read and write requests and turns them into something that the device can comprehend. If we were to write an IDE driver, the `request` function would generate commands and send them to the controller to initiate the transfer of data in both directions. Several items, including the `request` function, need to be defined in a special order at the beginning of the module. The normal order of include files applies, but the items in the following table must be defined before `<linux/blk.h>` is included.

| | | |
|-------------------------------------|-----------------------------|--|
| <code>#define MAJOR_NR</code> | <code>RADIMO_MAJOR</code> | The major number of the device. This is mandatory. |
| <code>#define DEVICE_NAME</code> | <code>"radimo"</code> | The name of the device. This may be omitted and is then set to "unknown." Serves no particular function other than providing a name to be printed in case of request errors. |
| <code>#define DEVICE_REQUEST</code> | <code>radimo_request</code> | The <code>request</code> function for the device. Is also mandatory. |

| | | |
|---|------------------------------|---|
| <code>#define DEVICE_NR (device)</code> | <code>(MINOR(device))</code> | Used for partitionable devices to enable them to use the minor number for partition selection. |
| <code>#define DEVICE_ON (device) #define DEVICE_OFF (device)</code> | | Motorized devices can set this to the functions related to spinning the device up and down. When a request has ended, the block system will call the off function. <code>DEVICE_OFF</code> must be defined even as just an empty define, but <code>DEVICE_ON</code> can be omitted. |
| <code>#define DEVICE_ NO_RANDOM</code> | | If defined, the device will not contribute to system entropy. This is similar to <code>SA_SAMPLE_RANDOM</code> for interrupt handlers. |

After having defined the preceding, `linux/blk.h` can be included.

Size Issues

There are two sector sizes associated with a block device: a hardware and software sector size. The former is how the data is arranged on the physical media controlled by the device, while the latter is the arrangement within the device. By far, the majority of devices have a hardware sector size of 512 bytes, although deviants such as MO-drives do exist and typically use 2,048-byte sector sizes.

The respective sizes are set at initialization time in global arrays indexed by major number.

```
#define RADIMO_HARDS_SIZE          512
#define RADIMO_BLOCK_SIZE           1024
static int radimo_hard = RADIMO_HARDS_SIZE;
static int radimo_soft = RADIMO_BLOCK_SIZE;

...
hardsect_size[RADIMO_MAJOR] = &radimo_hard;
blksize_size[RADIMO_MAJOR] = &radimo_soft;
```

We go with the flow and use a hardware sector size of 512 bytes. It does not really matter, since `radimo` stores data in a buffer internally. The software block size can be any value, with a couple of restrictions: It has to be equal to or bigger than the hardware sector size, a multiple of the hardware sector size, and smaller than the `PAGE_SIZE`. If you neglect to set either one, 512 is assumed for the hardware sector size and 1,024 for the block size.

In addition to the sector sizes, the total size of the device is also kept in a global array. The size argument is given in kilobytes and lets the kernel return `-ENOSPC` (no space left on device) automatically.

```
blk_size[RADIMO_MAJOR] = &radimo_size;
```

If we kept several virtual devices (indexed by minor, for example) `radimo_size` and friends could be an array and thus get [MAJOR] [MINOR] indexing. The actual definition of the various block-related global structures resides in `drivers/block/ll_rw_blk.c` and also contains comments about them.

Registering a Block Device

Once the various defining is done, a file operations structure is set up. Since kernel 2.3.26, block devices have used a different setup method from character devices, so things get a little trickier. The `block_device_operations` structure was introduced to simplify some of the kernel internals and to make it easier for block device driver writers to keep track of things. Many developers are still unhappy with the block layer, and more changes are anticipated in future releases. For maximum portability, we're going to show both versions here and how to test the kernel version at compile time. For the remainder of the chapter, we're going to focus on the methods used in the 2.4 series kernel.

If you need a reference for an older version of the kernel, an older edition of this book can probably be found in your local library, but we strongly recommend that you upgrade your kernel instead.

```
#if LINUX_VERSION_CODE < 0x20326
/* This gets used if the kernel version is less than 2.3.36 */
static struct file_operations radimo_fops = {
    read:          block_read,           /* generic block read */
    write:         block_write,          /* generic block write */
    ioctl:        radimo_ioctl,
    open:         radimo_open,
    release:      radimo_release,
    check_media_change: radimo_media_change,
    revalidate:   radimo_revalidate
};

#else
/* On newer kernels, this gets used instead */
static struct block_device_operations radimo_fops = {
    open:         radimo_open,
    release:      radimo_release,
    ioctl:        radimo_ioctl,
    check_media_change: radimo_media_change,
    revalidate:   radimo_revalidate,
#endif
#if LINUX_VERSION_CODE >= 0x20414
    owner:        THIS_MODULE,
#endif
};

#endif
```

The structure sets up our communications system. There is usually no need to define our own read and write functions as the defaults set up the request and call `ll_rw_block`, which queues the requests for us to execute. The defaults can be found in `fs/block_dev.c` and `drivers/block/ll_rw_block.c`, but you don't really need to know the inner workings to be comfortable with block devices. We define our own `ioctl` function; for a block device to function properly with the standard file system utilities, there are some `ioctl` commands we have to support. We will look at them a little later. `open` and `release` serve the same purpose as with character devices, and that just leaves `radimo_media_change`.

Finally, the block device is registered much the same way as the character devices.

```

res = register_blkdev(RADIMO_MAJOR, "radimo", &radimo_fops);
if (res) {
    MSG(RADIMO_ERROR, "couldn't register block device\n");
    return res;
}

```

Media Change

Whenever a block device is being mounted, the defined `check_media_change` function is called to detect whether the medium has changed or not. Being a RAM disk driver, this can never be the case, but we will play along and pretend it can happen anyway. `radimo` sets up an internal timer that clears our storage every 60 seconds if the device is not busy. In addition, it invalidates any buffers that might be in the buffer cache in the system, forcing them to be reread instead of being served from the cache. The buffers are in fact invalidated by the VFS when we return 1 to indicate a media change, but that won't happen until mount time. Buffers might still be cached if the user simply copied the device raw with `dd` or `cp`.

`revalidate` is closely related to the media change. If a change has occurred, `radimo_media_change` returns 1 to inform the VFS of the change. Next, the `revalidate` function is called to allow the device to perform whatever it needs to update its internal device information. There is no need to implement a specific `revalidate` function if the necessary actions can be taken in the media change function. Nor does it matter what you return; the function is strictly called for your pleasure.

ioctl for Block Devices

Since block devices are used to host file systems, it seems only appropriate that all block devices should accept some standard `ioctl` commands. We looked at implementing `ioctls` earlier, and you might want to skip back if you want to have your memory refreshed. `radimo` implements the most common and standard ones.

| | |
|------------|---|
| BLKFLSBUF | Block flush buffers. Writes out all dirty buffers currently residing in the buffer cache. <code>Radimo</code> does nothing more than call <code>fsync</code> to write out dirty buffers and invalidate them. |
| BLKGETSIZE | Block get size. Returns the size of the device in units of 1,024 bytes. The various file system-related utilities (<code>fsck</code> , for instance) determine the total size by issuing this <code>ioctl</code> . If the device does not support this command, they will have to guess. |
| BLKSSZGET | Block get sector size. Returns the software sector size of the block device. |
| BLKRAGET | Block get read ahead. Returns the current read-ahead value for the device. |
| BLKRASET | Block set read ahead. Sets the read-ahead value for the device. |
| BLKRRPART | Block reread partition table. Called by <code>fdisk</code> when rewriting the partition table. <code>Radimo</code> is not partionable and does not support this command. |

The implementation is fairly straightforward so we won't list it here. There are other standard commands for block devices; find them in `linux/fs.h` if you are interested. `radimo` does not implement any device-specific commands, but if it did they would naturally be enclosed within the same `switch` statement.

The request Function

The `request` function is definitely the backbone of the block device. In contrast to character devices, which receive a stream of data, block devices process requests instead. A request is either a read or a write, and it is the job of the `request` function to either retrieve or store the data sent to it on the media it controls. Depending on the peripheral in question, the actions performed by the `request` function naturally differs a lot.

Requests are stored in lists of structures, each of which are of the type `struct request`. In the 2.2 series of stable kernels (and earlier 2.3 development kernels), the `request` function was stored in the `blk_dev` global array. Because this method allowed for only one request queue, a new method was needed to get multiqueue capabilities. Luckily, the people responsible for the block layer in the kernel made sure that even though the internals were different, only minor changes needed to be made to the device drive code. The function does not need to traverse the list itself, but instead accesses the request via the `CURRENT` macro (not to be confused with the `current` process).

The definition resides in `linux/blk.h`. The structure of the request is as follows, with the irrelevant (to our discussion of the block system) parts left out; the ones used by `radimo` will be expanded upon further when we look at its `request` function next.

| | |
|---|--|
| <code>volatile int rq_status</code> | Status of the request, either <code>RQ_ACTIVE</code> or <code>RQ_INACTIVE</code> (the SCSI subsystem does use more, however). The kernel uses the status internally while finding an unused entry in the list of requests. |
| <code>kdev_t rq_dev</code> | The device the request is for. If the driver is managing several minors, information can be extracted from here by using the <code>MINOR</code> macro. |
| <code>int cmd</code> | The type of request, either <code>READ</code> or <code>WRITE</code> . |
| <code>int errors</code> | Can be used to maintain a per-request error status count. |
| <code>unsigned long sector,</code> <code>current_nr_sectors</code> | The starting sector and number of sectors that we should act upon. |
| <code>char *buffer</code> | Where we should read/write the data. |
| <code>struct buffer_head *bh;</code> | The buffer head associated with the request. We look a bit more at buffer heads in the next section. |

These are the details of a request. `radimo` stores the data in an array allocated with `vmalloc` at `init` time and serves requests by copying the data from `CURRENT->buffer` back and forth as instructed. The sectors are thus no more than an offset into the array. `request` functions have a somewhat peculiar format. Let's look at `radimo`'s version and follow up with a few comments afterward.

```
void radimo_request(void)
{
    unsigned long offset, total;

    radimo_begin:
```

```

INIT_REQUEST;

MSG(RADIMO_REQUEST, "%s sector %lu of %lu\n",
     CURRENT->cmd == READ ? "read" : "write",
     CURRENT->sector,
     CURRENT->current_nr_sectors);

offset = CURRENT->sector * radimo_hard;
total = CURRENT->current_nr_sectors * radimo_hard;

/* access beyond end of the device */
if (total+offset > radimo_size*1024) {
    /* error in request */
    end_request(0);
    goto radimo_begin;
}

MSG(RADIMO_REQUEST, "offset = %lu, total = %lu\n", offset, total);

if (CURRENT->cmd == READ) {
    memcpy(CURRENT->buffer, radimo_storage+offset, total);
} else if (CURRENT->cmd == WRITE) {
    memcpy(radimo_storage+offset, CURRENT->buffer, total);
} else {
    /* can't happen */
    MSG(RADIMO_ERROR, "cmd == %d is invalid\n", CURRENT->cmd);
    end_request(0);
}

/* successful */
end_request(1);

/* let INIT_REQUEST return when we are done */
goto radimo_begin;
}

```

The macro `INIT_REQUEST` is responsible for quite a number of actions. First, it checks whether `CURRENT` contains a request and returns if it does not. Then, it performs a validity check of the request (is it really for this device?) and whether the proper locking of `CURRENT->bh` is in order. The first check also explains why we continuously loop around `INIT_REQUEST`; when we are done, it will return for us. The offset into our storage array is calculated by multiplying the supplied starting sector `CURRENT->sector` by our hardware sector size. The total amount of data to be transferred is found in a similar way by examining the total number of sectors that `CURRENT->current_nr_sectors` specifies. Data is then copied with a simple `memcpy` depending on what direction `CURRENT->cmd` contains.

`void end_request(int uptodate)` Ends the `CURRENT` request.

An `uptodate` value of 1 indicates that the request was successfully fulfilled. `CURRENT` is then set to the next request. If that request is also for `radimo`, control is handed back to us and `radimo_request` continues; if not, then another `request` function is brought to life.

If the request cannot be fulfilled (it could be beyond the end of the device, for example), `end_request` is invoked with a value of 0. This will generate an I/O error in the system logs, specifying the offending device and the sector that caused the error. Note that we receive the request from the generic block read and write functions only after it has already verified that the request does not exceed the boundaries. If `blk_size [RADIMO_MAJOR]` is set to NULL, the simple check is bypassed when the request is created and a read error can be provoked by accessing beyond the end of the device:

```
radimo: read sector 4096 of 2
end_request: I/O error, dev 2a:00 (radimo), sector 4096
```

The info printed is the device major and minor numbers in hexadecimal and the `DEVICE_NAME` defined.

The Buffer Cache

Blocks of data written and read from block devices get cached in the buffer cache. This improves system performance, because if a process wants to read a block of data just read or written, it can be served directly from the buffer cache instead of issuing a new read from the media. Internally this cache is a doubly linked list of buffer head structures indexed by a hash table. Although it initially does not look like we touched a buffer head in `radimo_request`, `CURRENT->buffer` is merely a pointer to the data field inside the buffer head.

If you are running `radimo` with `RADIMO_REQUEST` in the `MSG` mask, you can follow the requests as they are processed by the `request` function. Try mounting your `radimo` device and then performing an `ls` on the mount point. Take a look at the output of `dmesg` and you'll see the read requests. Now do another `ls`. You'll notice that this time there wasn't any read request; that's because the buffer cache served the request and `radimo` never saw it. The opposite can also be investigated; try writing some blocks to the device and notice how they are not processed immediately. The blocks reside in the buffer cache for some time before being flushed to the device. Even if `radimo` did not copy the data sent to it to internal storage, the device would be fully functional while the buffers still resided in the cache. The RAM disk module that comes with the kernel (`drivers/block/rd.c`) uses this principle. `Rd` does nothing to maintain internal storage, but instead marks the used buffers as locked and thus ensures that they stay in the buffer cache and are not put on the freelist.

The buffer head structure can be found in `linux/fs.h`. Going into details would be beyond the scope of this book, but let's take a look at the state flags since they are accessed indirectly by a couple of functions in `radimo`.

| | |
|---|---|
| <code>BH_Uptodate</code> | The data residing in the buffer is up-to-date with that on disk. |
| <code>BH_Dirty</code> | Data in the buffer has been modified and must be written out to disk. |
| <code>BH_Lock</code> <code>BH_Protected</code> | Buffer has been locked and cannot be put on the freelist. |
| <code>BH_Rq</code> | Unset if the buffer was invalidated. |

`invalidate_buffers` is called when we wish to remove all references to the buffers associated with `radimo` from the buffer cache. It clears all but `BH_Lock`, and the buffers are then free to be reused.

Try It Out—radimo

radimo is the final module included in the source code download. It's located, naturally, in the `modules/radimo` directory. As usual, you will need to compile and insert the module and create a corresponding special file before we can interact with the device.

```
# make
# mknod /dev/radimo b 42 0
# insmod radimo.o
radimo: loaded
radimo: sector size of 512, block size of 1024, total size = 2048Kb
```

The options printed can all be specified at load time by supplying the appropriate parameters to `insmod`. Browse back to the beginning of the `radimo` section and find them or use `modinfo` to dig them out. The defaults will do fine for this session.

Now that the module is loaded, we are ready to create a file system on the device. Any type will do, but we'll use `ext2` in this example.

```
# mke2fs /dev/radimo
# dmesg | tail -n1
radimo: ioctl: BLKGETSIZE
```

Since we implemented the `BLKGETSIZE` ioctl call in `radimo`, `mke2fs` can obtain the complete size of the device on its own. Now you can mount the file system and copy files to and from it just like you would on an ordinary hard drive.

```
# mount -t ext2 /dev/radimo /mnt/radimo
# cp /vmlinuz /mnt/radimo
```

There should be nothing new in that concept. `umount` the device and leave it alone for 60 seconds, which is the length of our `RADIMO_TIMER_DELAY` defined in `radimo.h`, to test the media change mechanism. Now try mounting it again.

```
# umount /dev/radimo; sleep 60
# mount -t ext2 /dev/radimo /mnt/radimo
mount: wrong fs type, bad option, bad superblock on /dev/radimo,
      or too many mounted file systems
# dmesg
radimo: media has changed
VFS: Disk change detected on device radimo(42,0)
radimo: revalidate
```

On the last mount, our timer handler has run and set `media_changed` to 1. This causes `radimo_media_change` to return 1 to the VFS indicating a media change; VFS prints a message confirming this and then invokes `radimo_revalidate` to let the device do any handling it might need to perform on a disk change. The end result is that the `mount` fails.

Going Further

This section was meant only as a short introduction to block devices, mainly the `request` function with related structures and `ioctl` calls. `radimo` is a very simple driver and as such does not demonstrate how block device drivers handle a real hardware peripheral. Actual hardware typically relies on interrupts to control the flow of data, and in those cases the `request` function cannot indicate whether the request completed successfully or not right away. The interrupt handler normally deals with this when the device has signaled the outcome of the operation. There are myriad examples of interrupt-driven block drivers in the kernel for you to study if you need to.

As block devices are used to host file systems, they normally support partition-based access. Linux offers generic partition support defined in the `partition` and `gendisk` structure defined in `linux/genhd.h`. The implementation can be found in `gendisk.c` in `drivers/block` where various drivers that utilize the support are also located. Adding partition support to `radimo` should not pose any significant problems and would be a good exercise in getting familiar with the generic disk subsystem. That is left as an exercise to the reader.

Most block devices in the kernel belong to a specific class, such as SCSI, IDE, or even CD-ROM drivers. While these can be considered ordinary block devices, Linux offers special interfaces for these that should be utilized. The readily available examples in the kernel along with the obtainable documentation found in `Documentation/` or the Linux Documentation Project are an invaluable resource in this situation.

Debugging

Device drivers are no different from regular programs; they are almost never bug-free.

Kernel-level code does not segmentation fault in the ordinary sense and produce nice core dumps for you to examine, so doing postmortem debugging on device drivers is very different from regular debugging. Some people might tell you that the human mind is the best debugger there is, and they are right. In this case, all we can do is go back to the source and work through it step-by-step. The great thing about Linux is that you have the entire source code available—use it. Using a debugger can be invaluable, but make sure you end up fixing the real bug and not just adding a Band-Aid or hiding the real problem.

Oops Tracing

One technique that is essential to master is Oops tracing. Most kernel bugs manifest themselves as NULL pointer dereferences, and depending on where they happen, the kernel can often continue running. This is much like a segmentation fault in applications, but it does not generate a core file. The layout of Oops is highly processor-specific, and the rest of this section will look at how the x86 version looks. The procedure for decoding the dump is basically the same for other platforms, and the information provided in this section will therefore be useful on non-x86 architectures as well. Now let's dive into an Oops.

```
Unable to handle kernel paging request at virtual address 01380083
current >tss.cr3 = 06704000, %cr3 = 06704000
*pde = 00000000
Oops: 0000
CPU:     1
```

```

EIP: 0010:[<c0144040>]
EFLAGS: 00010202
eax: c0144000 ebx: 01380083 ecx: 00000005 edx: c64e8550
esi: c64e9c20 edi: c5f17f84 ebp: 00000000 esp: c5f17f3c
ds: 0018 es: 0018 ss: 0018
Process bash (pid: 390, process nr: 32, stackpage=c5f17000)
Stack: c5f17f84 c64e859c c64e859c fffffffe c012dfaf c64e8550 c64e9c20
      c5f17f84 00000000 c60dd004 00000001 c012e17a c64e9620 c5f17f84
      c60dd000 c60dd000 c5f16000 bfffff6b0 c60dd002 00000002 000006b3
      c012e26c c60dd000 c64e9620
Call Trace: [<c012dfaf>] [<c012e17a>] [<c012e26c>] [<c012c232>] [<c0108be4>]
Code: 66 83 3b 00 74 4e 31 c9 8b 74 24 20 66 8b 4b 02 3b 4e 44 75

```

If this the first time you have come across an Oops, it might look at bit intimidating. It contains a dump of the processor registers at the time of the fault, a stack trace, a back trace of the function calls, and a listing of the machine code that caused the Oops. This information is useless if we can't map the addresses shown to actual function names. The tool `ksymoops` does this for us, among other things. It is conveniently located in the `scripts/ksymoops` subdirectory of your kernel sources. Running the preceding Oops through `ksymoops` will yield something like the text opposite.

```

Unable to handle kernel paging request at virtual address 01380083
current >tss.cr3 = 06704000, %cr3 = 06704000
*pde = 00000000
Oops: 0000
CPU: 1
EIP: 0010:[<c0144040>]
EFLAGS: 00010202
eax: c0144000 ebx: 01380083 ecx: 00000005 edx: c64e8550
esi: c64e9c20 edi: c5f17f84 ebp: 00000000 esp: c5f17f3c
ds: 0018 es: 0018 ss: 0018
Process bash (pid: 390, process nr: 32, stackpage=c5f17000)
Stack: c5f17f84 c64e859c c64e859c fffffffe c012dfaf c64e8550 c64e9c20
      c5f17f84 00000000 c60dd004 00000001 c012e17a c64e9620 c5f17f84
      c60dd000 c60dd000 c5f16000 bfffff6b0 c60dd002 00000002 000006b3
      c012e26c c60dd000 c64e9620
Call Trace: [<c012dfaf>] [<c012e17a>] [<c012e26c>] [<c012c232>] [<c0108be4>]
Code: 66 83 3b 00 74 4e 31 c9 8b 74 24 20 66 8b 4b 02 3b 4e 44 75

```

```

>>EIP: c0144040 <proc_lookup+4c/e0>
Trace: c012dfaf <real_lookup+4b/74>
Trace: c012e17a <lookup_dentry+126/1f0>
Trace: c012e26c <__namei+28/58>
Trace: c012c232 <sys_newstat+2a/8c>
Trace: c0108be4 <system_call+34/38>
Code: c0144040 <proc_lookup+4c/e0> 00000000 <_EIP>:
Code: c0144040 <proc_lookup+4c/e0> 0: 66 83 3b 00 cmpw
$0x0, (%ebx)
Code: c0144044 <proc_lookup+50/e0> 4: 74 4e je 54
<_EIP+0x54> c0144094 <proc_lookup+a0/e0>
Code: c0144046 <proc_lookup+52/e0> 6: 31 c9 xorl
%ecx, %ecx
Code: c0144048 <proc_lookup+54/e0> 8: 8b 74 24 20 movl
0x20(%esp,1), %esi

```

```
Code: c014404c <proc_lookup+58/e0>          c:    66 8b 4b 02      movw  
0x2(%ebx),%cx  
Code: c0144050 <proc_lookup+5c/e0>          10:   3b 4e 44       cmpl  
0x44(%esi),%ecx  
Code: c0144053 <proc_lookup+5f/e0>          13:   75 00       jne     15  
<_EIP+0x15> c0144055 <proc_lookup+61/e0>
```

For `ksymoops` to resolve the addresses to function names, it needs the appropriate system map for the running kernel. During the kernel building process, an updated file is placed in the root of your kernel source directory, usually `/usr/src/linux/System.map`. However, the file contains only entries for the files that are compiled in because it cannot possibly know the memory location where a particular module will be loaded later. Getting the location of modularized code can be accomplished at load time by telling `insmod` to do so by adding the `-m` parameter. Exported symbols also show up in `/proc/ksyms`.

The call trace of this particular Oops goes from `system_call` through the listed functions and ends up in `proc_lookup` where the fault occurred. The trace lists functions according to the following format.

```
<function_name+offset/length>
```

The “offset” indicates where in the function the jump was made, and “length” is the total length. The offending code is listed disassembled. At offset 0x4c into `proc_lookup`, a `compare` was made against the `ebx` register, and looking at the register dumps shows that it contains an invalid address. Now we need to locate the file that contains the function in question and find out what could be causing this. In this case, it seems reasonable that `proc_lookup` would be a part of the `proc` file system, and indeed the function is listed in `fs/proc/root.c`. The makefile in the kernel allows you to run a `make fs/proc/root.s` and get an assembler listing containing debugging information. Open `root.s` in an editor, and find `proc_lookup` and the offending operation, along with a line number in `root.c`. In this particular case, the dentry pointer passed to `proc_lookup` was completely bogus.

That was the easy part. Now you have to find out how on earth that could have happened. It might be a valid thing to do, and in that case a check should probably be added. However, it is far more plausible that the driver being created is at fault. In this case, the Oops occurred while we were testing the `proc` implementation in `schar`. The problem was that while someone was accessing the `proc` entry, the module was removed, and the directory entry associated with it was freed. The next time the entry was looked up, the dentry passed was no longer valid. `schar` was fixed to increment its module usage count when the `proc` entry was busy and the problem was solved.

Debugging Modules

Unfortunately it is not possible to single-step kernel code like ordinary applications, at least not right out of the box. The best way to go about debugging your own modules is to strategically add `printk` statements in troublesome areas and work your way down from there. Beware that obscure bugs may be hidden by a simple `printk` statement, either because it changes the timing or the alignment of data slightly. But try it and see what happens. If it hangs, find out where and print critical variables. An Oops can be decoded using the techniques demonstrated above, and `ksymoops` includes `/proc/ksyms` by default and can thus also decode any functions exported by the modules loaded. During development, it is advisable to export all possible functions and variables to make sure that `ksymoops` will catch them. The section on integrated debugging will explore further options.

The Magic Key

The most unfortunate bugs are the ones that crash the system completely. In these situations, the magic Sys Rq key, or System Attention Key (SAK), can be of great assistance. This handy feature was added during the 2.1 kernel development cycle, and you can enable the option when configuring the kernel. It doesn't add any overhead to normal system operation and might be the only way to resolve a complete hang, so whether you are doing kernel development or not, always leave it enabled. You activate the different commands by pressing Alt+Sys Rq and a command key. The different commands are documented in Documentation/sysrq.txt; here we will examine the *p* command. So go ahead and press Alt+Sys Rq+P:

```
SysRq: Show Regs
```

```
EIP: 0010:[:<c0107cd0>] EFLAGS: 00003246
EAX: 0000001f EBX: c022a000 ECX: c022a000 EDX: c0255378
ESI: c0255300 EDI: c0106000 EBP: 000000a0 DS: 0018 ES: 0018
CR0: 8005003b CR2: 4000b000 CR3: 00101000
```

This is a listing of the processor state, complete with flags and registers. **EIP**, the instruction pointer, shows where the kernel is currently executing, so you need to look up this value in the symbol map for your kernel. The closest matches for our kernel are

```
c0107c8c T cpu_idle
c0107ce4 T sys_idle
```

which reveals that the kernel was currently executing `cpu_idle`. If a driver gets stuck in an endless loop, Alt+Sys Rq+P will tell you exactly where, assuming that the scheduler is still running. The system might also be completely hung, and in that case the Alt+Sys Rq+P cannot help you.

Kernel Debugger—`kdb`

There is a way to debug a running kernel safely that has minimal impact on normal system operation. It does require patching of the kernel for the *x86* platform, however, as the features are not yet included there—although they might be in the future. Some of the other platforms provide similar features without the need to patch the kernel. Snoop around in the kernel configuration or search the Internet, if necessary.

As of this writing, the kdb project is maintained by SGI, so you can try searching their Web site to find a kdb kernel patch that is compatible with the kernel you are running.

The debugger can be invoked in different places. At boot, you can pass the `kdb` parameter to LILO, and the debugger will be started as soon as possible. During system operation, the debugger can be entered manually by pressing the Pause key and is invoked automatically when an Oops occurs. From within the debugger, you can inspect and modify CPU registers and process variables, single-step execution, set breakpoints, and much more.

The patch comes with quite a few man pages explaining how to use it so we won't go into detail here. The debugger is fairly simple to use, although it is not as pleasant to work with as `gdb` and does not

provide the same degree of functionality. This is to be expected for a built-in debugger, but having said that, it still is a very handy tool. Entering the debugger, setting a breakpoint, and then having the debugger automatically invoked when it is reached provide an excellent way to single-step your module without affecting general system performance that much.

Remote Debugging

After Chapter 9, you’re familiar with `gdb` and how to use it with ordinary applications. With the `kgdb` kernel patches, a running kernel can be debugged over a serial line from `gdb` just like any other program. This approach requires two machines—a master, where the controlling `gdb` is run from, and a slave being debugged. A null-modem cable connects the two machines, and it is probably a good idea to test the connection with Minicom or a similar terminal program to make sure that the link is fully functional and reliable.

After having patched the kernel on the slave, recompiled, and rebooted, the machine runs just like before until an accompanying debug script is invoked. A breakpoint is defined in the kernel, and upon executing the script, the slave is halted and control passed to the master. From there, you can use `gdb` like you are used to; the slave machine is resumed with “continue” and can be stopped with `Ctrl+C` again or when it hits a breakpoint.

The `kdb` patches also offer serial line debugging, but if you have two machines set up, using the `kgdb` patches offers the advantage of providing the interface through the vastly more powerful `gdb`. Whether you need that extra functionality or not is up to you.

General Notes on Debugging

While the various ways to debug the kernel differ in one way or another, they all have some points in common. Generally, you will have to be very careful with breakpoints. If you are using an integrated debugger, setting breakpoints in some of the keyboard handling is not a very good idea (for obvious reasons)—likewise with debugging via a network connection and enabling a breakpoint in the driver or somewhere in the network stack. It might work and it might not, but be prepared to hit the big red switch and enjoy a cup of coffee while `fsck` runs! Some drivers rely on precise timing and single stepping; those will probably not work either. This also applies to interrupt and timer handlers. Be prepared to handle crashes until you get the hang of kernel debugging and know where *not* to place breakpoints.

In our experience, having a dedicated machine for testing and debugging provides the most flexible solution. It does not have to be an expensive solution either; we have an old 486 hooked up to our main workstation that boots over the network and mounts its root file system through NFS. The test machine contains nothing more than a motherboard with little RAM, a network adapter, floppy, and a cheap graphics adapter. The development is kept on the workstation while trial runs and debugging are done on the test machine alone. If it happens to crash, a reboot takes only about half a minute with no file system check necessary, and we can keep editing sources undisturbed on the workstation. Hook up a serial cable and remote debugging the test machine is a cinch.

Portability

The device driver created should naturally run on as many platforms as possible. Luckily the exposed API is very portable, and the problems that arise are mainly due to platform differences. Most of the portability issues have been mentioned in the sections where most of the problems arise. This section will look a little more closely at some of these and introduce a few others.

Data Types

The brief “Data Types” section near the beginning of the chapter listed the `_uXX` and `_sXX` data types. It is always a good idea to use these when a specific size of variable is needed, since there is no guarantee that a `long` is the same size on all platforms, for example.

Endianess

Platforms like the Intel x86 or Alpha use little-endian byte orientation, which means that the most and least significant byte values are swapped. Power PC and SPARC CPUs are some of the big-endian platforms that Linux runs on, however, and they store the data in that order. This is how C views the world and what is most easily read by humans. In most cases, you do not need to worry about the target endianess, but if you are building or retrieving data with a specific orientation, converting between the two will be needed. For big endian, `_BIG_ENDIAN_BITFIELD` is defined and `_LITTLE_ENDIAN_BITFIELD` for little-endian platforms, so the relevant code can be placed inside define checks.

```
#if defined( _LITTLE_ENDIAN_BITFIELD)
    byteval = x >> 8;
#else
    byteval = x & 0xff;
#endif
```

Linux also provides primitives to ease the conversion of variables. These are defined in `linux/byte-order/generic.h` and come in many different flavors. Some of the most common (for Intel, at least) are the following:

| | |
|--|---|
| <code>unsigned long cpu_to_be32 (unsigned long x) unsigned short cpu_to_be16 (unsigned short x)</code> | Convert the variable <code>x</code> from the CPU native ordering to big endian. |
| <code>unsigned long be32_to_cpu (unsigned long x) unsigned short be16_to_cpu (unsigned short x)</code> | Convert big-endian variable <code>x</code> to CPU native ordering. |

There are numerous other functions to satisfy the conversion of 16-, 32-, and 64-bit variables to either type of byte ordering; they can all be found in the aforementioned include file.

Alignment

A piece of data is said to be properly aligned when it resides at a memory address that a processor can access in an efficient manner. It is dependent on the type of the processor under which conditions that it considers data to be unaligned and what happens when it is accessed; the consequences are either a slowdown in execution for the architecture that allows unaligned access or failure for one that does not.

```
get_unaligned(ptr)  
put_unaligned(val, ptr)
```

Access unaligned data.

If you need to access data that is known to be misaligned, use the above macros. They are defined in `<asm/unaligned.h>`. For the architectures that directly support unaligned access, they expand to general pointer dereferencing.

Other possible portability problems have been mentioned throughout the text where they belong, and you should not encounter any that were not listed either here or there. Portable code is beautiful code, so keep it that way!

Anatomy of the Kernel Source

We hope you've enjoyed your introduction to kernel programming. The road is steep and rocky, and one of the largest obstacles is knowing where to find that specific piece in the kernel you need to understand. We've tried to give pointers to the most important aspects, but this is no substitute for reading the only up-to-date and most complete documentation there is—the kernel source itself. If you find a need for information not provided here, point yourself toward the kernel source and `grep` like you've never grepped before. You'll find what you need.

Since writing about the Linux kernel is writing about a moving target, whenever you encounter a difference between the kernel and what is written here, trust the kernel. That is the beauty and the glory of Open Souce projects—that the source is always there, free for you to browse at will. Some of the kernel developers are extremely gifted programmers, and looking over their examples is always time well spent, even if you have no intention of ever writing your own device driver.

With this chapter, the examples in the kernel source, and the technical documentation for your device, you should be able to get started on your very own device driver, and perhaps even finally be able to hook up that old eight-inch floppy drive you've got in the garage. How to find media for it is “an exercise left for the student.”

Figure 18-6 shows you a view of the Linux kernel “from 30,000 feet.” We have omitted large parts, but this is the basic structure of the kernel. You are encouraged to go look for yourself.

| | |
|-------|---|
| linux | |
| | arch (architecture dependent code) |
| | drivers |
| | block (block devices) |
| | cdrom (generic drivers and uniform layer) |
| | char (character devices) |
| | macintosh |
| | misc (mostly parallel port) |
| | net (network drivers) |
| | pci (PCI subsystem) |
| | sbus (SBUS subsystem (SPARC)) |
| | scsi (drivers and sound subsystem) |
| | sound (drivers and sound subsystem) |
| | video (mostly framebuffer drivers) |
| | fs (vfs and all other file systems) |
| | include |
| | asm (symlink to appropriate platform, e.g. asm-alpha) |
| | linux |
| | init (where it all begins) |
| | ipc (Inter Process Communication) |
| | kernel |
| | lib (string functions, et al) |
| | mm (the memory management subsystem) |
| | modules |
| | net (the network subsystem) |
| | scripts (various useful tools) |

Figure 18-6

Summary

In this chapter, we looked at the basic anatomy of a device driver. We looked at how character devices register themselves with the kernel, how they use a `file_operations` structure to define what operations and access methods they support, and how to implement basic character device drivers as modules. We then looked at some of the visible entry points the driver provides besides just read and write and how the kernel provides defaults for those we choose not to implement.

Chapter 18

Next up was `ioctls`—I/O controls—and how they are implemented, followed by a brief introduction to the `/proc` file system and `sysctl` entries. Interspersed in strategic locations throughout the chapter we found information on timing, queues, interrupt handling, and a few other common device driver tasks. We rounded out the chapter with an overview of block device drivers, kernel Oops tracing, and a few notes on portability.

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Standards for Linux

Linux started as just a kernel. Unfortunately, a kernel on its own is not very useful; programs are needed for logging in, managing files, compiling new programs, and so forth. To make a useful system, tools were added from the GNU project. These were clones of familiar programs available on the UNIX and UNIX-like systems around at the time. Making Linux look and feel like UNIX set the first standards for Linux, providing a familiar environment for C programmers.

Different UNIX (and later Linux) vendors added proprietary extensions to the commands and utilities they made available, and the layout of the file systems they used varied slightly. It became difficult to create applications that would work on more than one system. Even worse, a programmer could not even rely on system facilities being provided in the same way or configuration files being maintained in the same place.

It was clear that some standardization was needed to prevent the UNIX systems from fragmenting, and some excellent UNIX standardization work is now in place.

Over time not only have these standards moved forward, but Linux itself has been enhanced at an impressive speed by the community. As Linux has progressed, it, and the GCC compiler collection, has not only tracked the relevant standards rather well, but has also defined new standards as existing standards have been found to be insufficient.

In this final chapter, we are going to look at these standards, pointing out areas that you should be aware of if you want not only to write applications that work on your Linux systems through upgrades, but also to create code that will be portable to other Linux distributions, and maybe even other UNIX-style systems, so that you can share your programs with others.

In particular, we will be looking at

- ❑ The C programming language standard
- ❑ The UNIX standards, particularly the POSIX standard developed by the IEEE and the Single UNIX Specification developed by the Open Group
- ❑ Work by the Free Standards Group, particularly the Linux Standard Base, which defines a standard Linux file system layout

A good starting place for standards relating to Linux is the Free Standards Group, whose Web site can be found at <http://www.freestandards.org>.

We are not going to look in detail at the contents of the standards; many of them are as long as this book. We are going to point out the key standards you should know about, give you a little historic background on how those standards arose, and help you decide which standards you might find helpful when writing your own programs.

The C Programming Language

The programming language C is the de facto language for programming Linux, so in order to write portable C programs for Linux, it's worth understanding a little of its origins, how it has changed, and, most important, how to check that your program is conforming correctly to standards.

A Brief History Lesson

For those not enamored of history, don't worry; since this book is about programming, not history, we will keep this discussion very brief.

The C programming language dates from around 1970 and was based, in part, on the earlier programming language BCPL and extensions to the "B" language B. Dennis M. Ritchie wrote a reference manual for the language in 1974, and C was used as the basis for a rewrite of the UNIX kernel on a PDP-11 around the same time. In 1978 Brian W. Kernighan and Ritchie wrote the classic reference book for the language, *The C Programming Language*, which, updated for changes to the C language, is still in print today.

The language became very popular very quickly, influenced no doubt in part by the rapid growth in the popularity of UNIX, but also by its own power and clean syntax. The C language syntax continued to evolve by consensus, but as it diverged further and further from the language described in the original book, it became clear that a standard that was both consistent with current usage, and more precise, was needed.

In 1983 ANSI established the X3J11 standards committee to develop a clean and concise definition of the language. Along the way they made some minor additions to the language, particularly giving it the very welcome ability to declare the type of parameters, but in general the committee simply clarified and rationalized the existing definition of what constituted common usage of the language. The standard was finally published in 1989 as the ANSI standard Programming Language C, X3.159-1989, or more briefly C89, or sometimes C90. (This later became an ISO standard, ISO/IEC 9899:1990, Programming Languages—C. The two standards are technically identical.)

As with most standards, publication did not end the work of the committee, which continued work on clarifying minor discrepancies found in the specification, and in 1993 started work on the next version of the standard, dubbed C9X. The committee also published minor corrections and updates to the current standard in 1994, 1995, and 1996.

The new edition of the standard just made it into the 1990s, and officially become the C99 standard; it was adopted by ISO as ISO/IEC 9899:1999. More information can be found at http://www.x3.org/incits/tc_home/j11.htm.

The GNU Compiler Collection

After developing the Emacs editor (yes, we love Emacs), the GNU project's next major accomplishment, as discussed in Chapter 1, was a completely free C compiler, gcc, with the first official version released in 1987.

Originally, gcc was the GNU C Compiler, but since the same basic compiler framework now supports C, C++, Object-C, FORTRAN, Java, and ADA, the definition has been adjusted to the more appropriate GNU Compiler Collection.

gcc has always been, and looks set to remain, the standard compiler for Linux, and C or C++ the primary language for writing programs on Linux. The gcc home page can be found at <http://gcc.gnu.org/>.

The GNU C compiler has always been good at accurately tracking the developing C standard, although it does allow some extensions, and there are inevitably slight delays, as with almost all compilers, between the standard's becoming available and compilers that exactly implement that specification. Occasionally the opposite happens, and gcc anticipates that a standard will change slightly, which can also be quite confusing. gcc has a number of command line and other options that allow you to specify the version of C standard you wish gcc to conform to, as well as other options to control just how pernickety you would like the compiler to be.

gcc Options

Now that we know a little of the background of the C standard, we can look at the options the gcc compiler gives us for ensuring that the C (or C++) we write conforms accurately to the language standard. There are three ways we can ensure our C code is both in conformity with standards and clean: options that control the version of the standard we intend to be compatible with, defines to control header files, and warning options that invoke more stringent checking of the code.

gcc has a huge range of options, and we will look here only at the options we consider most important. The full list of options can be found on the gcc manual pages. We also look briefly at some additional `#define` options that can be used; these must normally be set in your source code before any `#include` lines or defined on the gcc command line. You might wonder why so many options are required for selecting the standard to use, rather than simply a flag that says enforce the current standard. The reason is that many older programs rely on the historic behavior of the compiler and would require significant reworking to update them to the latest standards. Rarely, if ever, do we want a compiler update to start breaking working code. As the standards change, it's important to be able to work against a defined standard, even if that is not always the very latest version of the standard.

Even if you are just writing a small program for personal use, when maybe conforming to standards doesn't seem that important, it can often be worth turning on more of gcc's warnings, to let the compiler find a mistake in your code before you even run the program. This is always more efficient than stepping through code in the debugger wondering where the problem might be. The compiler has many options that go well beyond simple checking for conformance to standards, such as the ability to spot code that does conform to the standard but may have dubious semantics. For example, there may be an order of execution that will allow a variable to be accessed before it is initialized.

If you do need to write code for other people to use, then—having selected the level of standards compliance and compiler warning you think appropriate—it's very important to put in that extra bit of effort to ensure that your code compiles with no warnings at all. If you allow some warnings to appear and make it a habit just to ignore them, then one day a more serious warning will appear that you may miss. If your code always compiles completely clean, a new warning will be obvious. Clean compiling code is a good habit to get into.

Compiler Options for Standards Tracking

These options are passed to gcc on the command line; we show only the most important options here.

- ❑ **-ansi:** This is the most important standards option, and tells the compiler to work to the C89 standard of the language. It turns off certain gcc extensions that are incompatible with the standard and also defines the macro `_STRICT_ANSI_`, which turns off some gcc extensions in header files that are incompatible with the standard. Later versions of the compiler may change the language standard targeted.
- ❑ **-std=:** This option allows more fine-grained control of the standard in use by supplying a parameter that sets the exact standard required. The main options are
 - ❑ c89 or iso9899:1990 supports the more common c89 standard.
 - ❑ c99 or iso9899:1999 supports the latest c99 standard, although as of gcc 3.3 support is not yet complete.
 - ❑ gnu89 supports the c89 standard, but allows GNU extensions and some c99 features as well.

Define Options for Standard Tracking

These are constants (`#defines`) that can either be set by options on the compiler command line or, alternatively, as definitions in the source code. We generally suggest using the compiler command line for these options.

- ❑ `_STRICT_ANSI_`: Force the use of ISO standard C.
- ❑ `_POSIX_C_SOURCE=2`: Turn on features defined by the IEEE Std 1003.1 and 1003.2 standards. We will mention these standards again later in this chapter.
- ❑ `_BSD_SOURCE`: This enables BSD-type features.
- ❑ `_GNU_SOURCE`: Allows a wide range of features, including GNU extensions.
- ❑ `_RE-ENTRANT`: As we saw in Chapter 12, this ensures that functions are made re-entrant, and is required for programs using threads.

Compiler Options for Warnings

These options are passed to the compiler on the command line. Again we just list the main options; a full list can be found in the gcc manual pages.

- ❑ **-pedantic:** This is the most powerful compiler option for checking clean C code. Apart from turning on the option to check for standard conformant C, it also turns off some traditional C constructs that are not permitted by the standard, and disables all the GNU extensions to the standard. This is the option to use if you want your C code to be as portable as possible. The downside is that the compiler is very fussy indeed about your code being clean, and sometimes it can require you to think very carefully in order to get rid of the last few warnings.

- ❑ **-Wformat:** Checks that the arguments types to the `printf` family of functions are correct.
- ❑ **-Wparentheses:** Checks that parentheses are always provided, even in some circumstances where they are not needed. This is quite a useful option for checking that initialization of complex structures is as intended.
- ❑ **-Wswitch-default:** Checks that all switch statements have a default case, which is generally good coding practice.
- ❑ **-Wunused:** Checks a variety of cases such as static functions declared but never defined, unused parameters, and discarded results.
- ❑ **-Wall:** Turns on most of gcc's warnings, including all of the preceding -W options (it does not select `-pedantic`) and is a good way to keep your code clean.

There are many, many more warning options; see the gcc Web pages for the full details. In general we would suggest you use -Wall; it's a good compromise between checking for good quality code and having the compiler generate so many trivial warnings it becomes a serious impediment to keeping the number of warnings from the compiler to zero.

Interfaces and the LSB

We are now going to move up a level from the raw C code and look at the interfaces (system functions) provided by the operating system. This level of standardization has various components: the functions provided by libraries and the system calls provided by the underlying operating system. In both of these there are two levels of detail: which interfaces are present and the definition of what an interface does.

The definitive document in this area for Linux is The Linux Standards Base (LSB), which can be found at <http://www.linuxbase.org>.

There is a list of distributions that have passed the certification to say they conform, which can be found at http://www.opengroup.org/lsb/cert/cert_proplist.tpl. Both the Red Hat and SuSE Linux distributions we have used in the writing of this book are listed as certified, as are many other distributions of Linux.

This specification covers a number of areas, but also refers to some external standards for particular interface definitions. The areas covered by the LSB are

- ❑ Object formats for binary compatibility
- ❑ Dynamic linking standards
- ❑ Standard libraries, both base libraries and the X Window System libraries
- ❑ The shell and other command line programs
- ❑ The execution environment, including users and groups
- ❑ System initialization and run levels

In this chapter, we are really only interested in the standard libraries, users, and system initialization, so those are the areas we will look at here.

LSB Standard Libraries

The Linux Standard Base defines the interfaces that must be present in two ways. For some functions, primarily those that are implemented by the GNU C library or tend to be Linux-only standards, it defines the interface and its behavior. For other interfaces, mostly those that come from Linux being UNIX-like, the specification simply states that a particular interface must be present and must behave as defined by another standard, usually that of the Common Application Environment (CAE) or more commonly The Single UNIX Specification, which is available from The Open Group, <http://www.opengroup.org>. Some parts are available (currently registration is required) on the Web at <http://www.unix.org/online.html>.

Unfortunately, the underlying standards for Linux, the UNIX standards, have a rather complex past, and rather too many standards to choose from, although mostly the various versions of the standards are closely compatible.

A Brief History Lesson

UNIX started in the late 1960s at AT&T Bell Laboratories, when Ken Thompson and Dennis Ritchie wrote an operating system, originally intended only for their personal use, that they called Unics. The name somehow changed into UNIX. AT&T allowed universities to have the source code for their own research, and UNIX quickly became extremely popular because of its very clean design and powerful concept. The fact that the source code was available must also have been a significant incentive because it allowed people to make changes and experiment.

The BSD operating system was a variant that came out of work done at the University of California at Berkeley, where a lot of work was being done on networking.

When AT&T started to make UNIX commercial, which occurred mostly around the mid 1980s, it termed its releases UNIX System, and the most popular was UNIX System V.

Many other variants also appeared, far too numerous to list here, all of which had slight differences from and additions to the base standards, as companies have tried to add value by making proprietary extensions.

Things started to get really complicated when AT&T sold its UNIX business to Novell, which, in 1994, decided to exit the UNIX business. Novell sold the UNIX business in two parts: the trademark and specification to X/OPEN Company (now The Open Group) and the source code to SCO.

In 1988 the IEEE (<http://www.ieee.org>) issued the first of a set of standards: the POSIX, or 1003, standards, which were intended to be a definitive portable interface specification for computer environments. Although it's a good and well-defined standard, POSIX is also very much a core specification and is quite limited in scope.

In 1994 the X/OPEN Company, a vendor-neutral organization, produced a much larger set of specifications, the X/OPEN CAE, or Common Applications Environment, which is a superset of the IEEE POSIX standards and is technically identical to it in many areas. The X/OPEN company later merged with the OSF to found The Open Group; its home page is at <http://www.opengroup.org/>. The CAE standard was updated and released in 2002 as The Single UNIX Specification, Version 3, available from The Open Group.

It is this specification to which the Linux standards base most frequently refers.

Using the LSB Standard for Libraries

That's enough about history of the standards, what does this mean for people writing C (or C++) programs that they want to be portable?

First you should check that the library function you are using is listed in the LSB specification. If it isn't there, you may well be doing something that is not going to port easily, and you should look for a standard way of performing whatever you are trying to achieve. You might like to try the `apropos` Linux command, which searches the online manual pages for appropriate references.

Second, and more difficult, is to check that the function behavior you are using is part of the specification, and you are not relying on behavior that is not specified. You may have to refer to the Single UNIX Specification to do this if the function usage is not defined by the LSB.

A particularly good place to check for undefined or possibly erroneous behavior is the online Linux manuals. Many of the pages have a BUGS section, which is an invaluable source of information about where a particular call in Linux may not perfectly implement the standards or where there are known defects or oddities in behavior.

LSB Users and Groups

This section of the specification is nice and brief, and very easy to understand. Following are a few of the specifications:

- It tells us never to read files like `/etc/password` directly, but to always use the standard library calls such as `getpwent`.
- It tells us that there must be a user called `root` in the root group, and that `root` is an administrative user with full privileges. We also discover that there are a number of optional user and group names that should never be used by standard applications; they are intended for use by distributions.
- It warns us that only user IDs from 500 and up should be used by real users; the lower numbers are reserved.

Generally, that is about all most Linux programmers need to know about the standards for users.

LSB System Initialization

The area of system initialization has always, at least to us, been an annoyance of subtle differences between distributions.

Linux has inherited from UNIX-like operating systems the idea of run levels that define the services that are running at any time. For Linux, the usual definitions are given in the following table.

| Run Level | Used for |
|-----------|---|
| 0 | Halt. Used as a logical state to change to when the system is shut down. |
| 1 | Single user mode, directories other than <code>/</code> may not be mounted, and networking will not be enabled. It is normally used for system maintenance. |

Table continued on following page

Chapter 19

| Run Level | Used for |
|-----------|---|
| 2 | Multiuser mode; however, networking is not enabled. |
| 3 | Normal multiuser mode with networking, using a text mode login screen. |
| 4 | Reserved. |
| 5 | Normal multiuser mode with networking, using an <code>xdm</code> type graphical login screen. |
| 6 | A pseudo-level used for rebooting. |

The LSB lists these levels but doesn't require them to be used, although they are very common.

Accompanying these run levels is a set of initialization scripts used to start, stop, and restart services. Previously these have lived in various locations under `/etc`, often `/etc/init.d` or `/etc/rc.d/init.d`. This variation was often a source of confusion, as people who changed distributions could no longer find the initialization scripts where they expected to find them, and install programs failed while trying to put initialization scripts in the wrong directory.

The LSB 1.3 defines the location of these initialization scripts as `/etc/init.d`, though it does allow this to be a link to a different location; indeed, on Red Hat 9 this directory is a link to the directory `/etc/rc.d/init.d`, which was the traditional Red Hat location in many earlier versions.

Each script in `/etc/init.d` has a name that relates to the service it provides. As this is a common namespace that all services on Linux must share, it's important that names are unique. For example, life would get difficult if both MySQL and PostgreSQL decided to call their scripts "database." To avoid this conflict there is—you guessed it—another set of standards. This is "The Linux Assigned Names And Numbers Authority" (LANANA), which can be found at <http://www.lanana.org/>. Fortunately, you need to know very little about it except that they keep a list of registered names for scripts, and thereby make life easier for users of Linux systems.

An initialization script must take a parameter that controls what it should do. The defined parameters are as follows:

| Parameter | Meaning |
|---------------------------|--|
| <code>start</code> | Start (or restart) the service. |
| <code>stop</code> | Stop the service. |
| <code>restart</code> | Restart the service; this is commonly implemented as simply a stop followed by a start of the service. |
| <code>reload</code> | This should reset the service, reloading any parameters, without actually stopping the service. Not all services can support this option, so this parameter may not be accepted by all scripts, or may be accepted but have no effect. |
| <code>force-reload</code> | This attempts to cause a reload if the service supports it, but if not, it does a restart. |

| Parameter | Meaning |
|-----------|--|
| status | This prints a textual message about the status of the service and returns a status code that can be used to determine the status of the service. |

All commands return 0 on success, or an error code indicating the reason for failure. In the case of status, 0 is returned if the service is running; all other codes indicate the service is not running for some reason.

The Filesystem Hierarchy Standard

The last of the standards we are going to look at in this chapter is the Filesystem Hierarchy Standard (FHS), which can be found at <http://www.pathname.com/fhs/>.

The purpose of this standard is to define standard places in the Linux file system, so that developers and users alike can have reasonable expectations of where to find things. Long-time users of the various UNIX-like operating systems have long bemoaned the subtle differences between the way file systems are laid out, and the FHS provides a way for Linux distributions to avoid going down the same fragmented path.

The arrangement of files in a Linux system may seem at first to be a semi-arbitrary arrangement of files and directories, based on historic practice. To an extent that's true, but over the years the layout has evolved for good reasons into the hierarchy we see today. The general idea is to separate files and directories into three groups:

- ❑ Files and directories that are unique to a particular system running Linux, such as start-up scripts and configuration files
- ❑ Files and directories that are read-only and may be shared between systems running Linux, such as application executables
- ❑ Directories that are read/write, but may be shared between systems running Linux or other operating systems, such as user home directories

In this book, we are not overly interested in sharing files among different versions of Linux, although, where a network of Linux machines is in use, it can be an excellent way of ensuring that only a single copy of the key program directories exists, and of sharing that among many machines. This is particularly useful for diskless workstations.

The top-level structure is defined by FHS to have several mandatory subdirectories and a small number of optional directories, as in the following table.

| Directory | Required? | Use |
|-----------|-----------|------------------------------------|
| /bin | Y | Important system binary files. |
| /boot | Y | Files required to boot the system. |
| /dev | Y | Devices. |
| /etc | Y | System configuration files. |

Table continued on following page

| Directory | Required? | Use |
|-----------|-----------|--|
| /home | N | Directories for user files. |
| /lib | Y | Standard libraries. |
| /mnt | Y | A convenient point to temporarily mount devices, such as CD-ROMs and flash memory sticks. |
| /opt | Y | Additional application software. |
| /root | N | Files for the root user. |
| /sbin | Y | Important system binary files which are required during system startup. |
| /tmp | Y | Temporary files. |
| /usr | Y | A secondary hierarchy. Traditionally user files were also stored here, but that is now considered bad practice, and /usr should not be writable by ordinary users. |
| /var | Y | Variable data, such as log files. |

In addition, there can be other directories starting with `lib`, although this is not common. You will also usually see a `/lost+found` directory (for file system recovery by `fsck`) and a `/proc` directory, which is a pseudo file system, providing a mapping into the current running system. The `/proc` file system is mentioned by the current version of FHS standard, but is not required to be present. Details of the `/proc` system are generally beyond the scope of this book, though we took a brief tour in Chapter 4.

We will look briefly at the purposes of each of the standard subdirectories of the `/` (root) directory.

`/bin`

This contains binary files that can be used both by the root user and ordinary users, but are essential to operation in single-user mode, when some other directory structures may not be mounted. For example, core commands such as `cat` and `ls` would normally be found in here, as will `sh`.

`/boot`

This directory is used for files required during booting of the Linux system. It is frequently quite small, less than 100 MB, and often a separate partition. This is handy on PC-based systems, where there are frequently BIOS limitations on the active partition, requiring it to be in the first 2 G or 4 G of the disk. Having this as a separate partition allows more flexibility when deciding how to lay out the rest of the disk partitions.

`/dev`

This contains the special device files that map to hardware. For example, `/dev/hda` will be mapped to the first IDE disk.

/etc

This contains configuration files. Historically some binaries could also be found in here, but that is no longer true on most Linux systems. The best-known file in the /etc directory is probably `passwd`, which contains information on users. Other useful files are `fstab`, listing mount options; `hosts`, listing IP to host name mappings, and the `httpd` directory, which contains configuration for the Apache server.

/home

This is a directory for user files. Normally each user will have a single directory under this directory with the same name as their login, and this will be their default login directory. For example, after logging in, the user `rick` will almost certainly find himself in the `/home/rick` directory.

/lib

This contains essential shared libraries and kernel modules, specifically those that will be required while the system is booting or in single user mode.

/mnt

This is simply a convenient place for mounting additional file systems temporarily. Normally there will be subdirectories for the different devices, such as `/cdrom` and `/floppy`.

/opt

This is a directory for software vendors to use when adding software applications. By convention, distributions generally don't use it for software they distribute as part of the standard distribution, but leave it free for third-party vendors to use. Generally, vendors will create a subdirectory with their name, and then further subdirectories such as `/bin` and `/lib` for files specific to their application.

By convention, most Open Source Linux packages use `/usr/local` for installation.

/root

This is for files used by the root user. It is not in the `/home` directory part of the tree, because that may not be mounted in single-user mode.

/sbin

This is used for commands normally used only by the system administrator, and required while the system is booting or in single user mode. Commands such as `fsck`, `halt`, and `swapon` live here.

/tmp

This is used for temporary files. It is usually, but not always, cleared when the system is booted.

/usr

This is a rather complex secondary file system, generally containing all the system-type commands and libraries not required during system booting or in single user mode. It has many subdirectories, such as /bin, /lib, /X11R6 and /local.

In the early days, UNIX also had subdirectories for logs, mail spooling, and the like. These have all now been removed from the /usr directory and placed in the /var directory. This has the advantage that /usr can now be a mountable file system, and in particular can be mounted read-only most of the time. When /usr is mounted read-only, it can be shared to other systems across a network and is less vulnerable to corruption should the system stop in an uncontrolled manner, perhaps because the power failed.

/var

This contains data that changes frequently, such as spool files for printing, application log files, and mail-spooling directories.

Further Reading about Standards

There are, of course, many more things to consider if you want to write, and deploy, a fully portable Linux application.

Do you want to localize your application so that it works with different languages and locales? Even if you stick to English, there are still the issues of currency, number separators, date formats, and many other considerations. There are, you guessed it, people working on those standards; you can see their work at <http://www.openi18n.org/>.

Another consideration is what options, library versions, and so forth the target system has installed. Fortunately, this problem is getting less acute, largely thanks to the standardization work we have looked at in this chapter, but it can still be a difficult problem. There are a pair of GNU tools which help considerably with this problem: `autoconf` and `automake`. Although you may not have used them directly, you have almost certainly seen the benefits of them when installing software from source, when you typed `./configure ; make`.

The use of these tools is beyond the scope of this book, but you can find more about them on the GNU Web pages <http://www.gnu.org/software/autoconf/> and <http://www.gnu.org/software/automake>.

Summary

In this final chapter, we have looked briefly at some of the many standards that are helping to make Linux an easier platform to program for, and ensure that the many different distributions of Linux conform to some basic standards. Conforming to standards helps to make life easier for us, its programmers and users, and we urge you to use the standards and to encourage others to do so.

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