



**AT&T**

**386 UNIX<sup>®</sup> System V  
Release 3.1**

Programmer's Guide  
Volume I

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# Introduction

## Purpose

This guide is designed to give you information about programming in a UNIX system environment. It does not attempt to teach you how to write programs. Rather, it is intended to supplement texts on programming languages by concentrating on the other elements that are part of getting programs into operation.

## Audience and Prerequisite Knowledge

As the title suggests, we are addressing programmers, especially those who have not worked extensively with the UNIX system. No special level of programming involvement is assumed. We hope the book will be useful to people who write only an occasional program as well as those who work on or manage large application development projects.

Programmers in the expert class, or those engaged in developing system software, may find this guide lacks the depth of information they need. For them we recommend the *Programmer's Reference Manual*.

Knowledge of terminal use, of a UNIX system editor, and of the UNIX system directory/file structure is assumed. If you feel shaky about your mastery of these basic tools, you might want to look over the *User's Guide* before tackling this one. The material is organized into two volumes and nineteen chapters.

## The C Connection

The UNIX system supports many programming languages, and C compilers are available on many different operating systems. Nevertheless, the relationship between the UNIX operating system and C has always been and remains very close. Most of the code in the UNIX operating system is C, and over the years many organizations using the UNIX system have come to use C for an increasing portion of their application code. Thus, while this guide is intended to be useful to you no matter what language(s) you are using, you will find that, unless there is a specific language-dependent point to be made, the examples assume you are programming in C.

## Hardware/Software Dependencies

The text reflects the way things work on your computer running UNIX System V at the Release 3.1 level. If you find commands that work a little differently in your UNIX system environment, it may be because you are running under a different release of the software. If some commands do not seem to exist at all, they may be members of packages not installed on your system. Appendix A describes the command packages available on your computer. If you do find yourself trying to execute a non-existent command, check Appendix A, then talk to the administrators of your system.

## Notation Conventions

Whenever the text includes examples of output from the computer and/or commands entered by you, we follow the standard notation scheme that is common throughout UNIX system documentation:

- Commands that you type in from your terminal are shown in **bold** type.
- Text that is printed on your terminal by the computer is shown in `constant width` type. Constant width type is also used for code samples because it allows the most accurate representation of spacing. Spacing is often a matter of coding style, but is sometimes critical.
- Comments added to a display to show that part of the display has been omitted are shown in *italic* type and are indented to separate them from the text that represents computer output or input. Comments that explain the input or output are shown in the same type font as the rest of the display.

Italics are also used to show substitutable values, such as, *filename*, when the format of a command is shown.

- There is an implied RETURN at the end of each command and menu response you enter. Where you may be expected to enter only a RETURN (as in the case where you are accepting a menu default), the symbol `<CR>` is used.

- In cases where you are expected to enter a control character, it is shown as, for example, **CTRL-D**. This means that you press the **d** key on your keyboard while holding down the **CTRL** key.
- The dollar sign, **\$**, and pound sign, **#**, symbols are the standard default prompt signs for an ordinary user and **root**. **\$** means you are logged in as an ordinary user. **#** means you are logged in as **root**.
- When the **#** prompt is used in an example, it means the command illustrated may be used only by **root**.

## Command References

When commands are mentioned in a section of the text for the first time, a reference to the manual section where the command is formally described is included in parentheses: **command**(section). Numbered sections are located in the following manuals:

Sections (1, 1M), (7), (8) *User's/System Administrator's Reference Manual*

Sections (1), (2), (3), (4), (5) *Programmer's Reference Manual*

## Information in the Examples

While every effort has been made to present displays of information just as they appear on your terminal, it is possible that your system may produce slightly different output. Some displays depend on a particular machine configuration that may differ from yours. Changes between releases of the UNIX system software may cause small differences in what appears on your terminal.

Where complete code samples are shown, we have tried to make sure they compile and work as represented. Where code fragments are shown, while we cannot say that they have been compiled, we have attempted to maintain the same standards of coding accuracy for them.







# Overview

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# 1

## Programming in A UNIX System Environment: An Overview

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# Introduction

The 1983 Turing Award of the Association for Computing Machinery was given jointly to Ken Thompson and Dennis Ritchie, the two men who first designed and developed the UNIX operating system. The award citation said, in part:

"The success of the UNIX system stems from its tasteful selection of a few key ideas and their elegant implementation. The model of the UNIX system has led a generation of software designers to new ways of thinking about programming. The genius of the UNIX system is its framework which enables programmers to stand on the work of others."

As programmers working in a UNIX system environment, why should we care what Thompson and Ritchie did? Does it have any relevance for us today?

It does because if we understand the thinking behind the system design and the atmosphere in which it flowered, it can help us become productive UNIX system programmers more quickly.

## The Early Days

You may already have read about how Ken Thompson came across a DEC PDP-7 machine sitting unused in a hallway at AT&T Bell Laboratories, and how he and Dennis Ritchie and a few of their colleagues used that as the original machine for developing a new operating system that became UNIX.

The important thing to realize, however, is that what they were trying to do was fashion a pleasant computing environment for themselves. It was not, "Let's get together and build an operating system that will attract world-wide attention."

The sequence in which elements of the system fell into place is interesting. The first piece was the file system, followed quickly by its organization into a hierarchy of directories and files. The view of everything, data stores, programs, commands, directories, even devices, as files of one type or another was critical, as was the idea of a file as a one-dimensional array of bytes with no other structure implied. The cleanness and simplicity of this way of looking at files has been a major contributing factor to a computer environment that programmers and other users have found comfortable to work in.

The next element was the idea of processes, with one process being able to create another and communicate with it. This innovative way of looking at running programs as processes led easily to the practice (quintessentially UNIX) of reusing code by calling it from another process. With the addition of commands to manipulate files and an assembler to produce executable programs, the system was essentially able to function on its own.

The next major development was the acquisition of a DEC PDP-11 and the installation of the new system on it. This has been described by Ritchie as a stroke of good luck, in that the PDP-11 was to become a hugely successful machine, its success to some extent adding momentum to the acceptance of the system that began to be known by the name of UNIX.

By 1972 the innovative idea of pipes (connecting links between processes whereby the output of one becomes the input of the next) had been incorporated into the system, the operating system had been recoded in higher level languages (first B, then C), and had been dubbed with the name UNIX (coined by Brian Kernighan). By this point, the "pleasant computing environment" sought by Thompson and Ritchie was a reality; but some other things were going on that had a strong influence on the character of the product then and today.

It is worth pointing out that the UNIX system came out of an atmosphere that was totally different from that in which most commercially successful operating systems are produced. The more typical atmosphere is that described by Tracy Kidder in *The Soul of a New Machine*. In that case, dozens of talented programmers worked at white heat, in an atmosphere of extremely tight security, against murderous deadlines. By contrast, the UNIX system could be said to have had about a ten year gestation period. From the beginning it attracted the interest of a growing number of brilliant specialists, many of whom found in the UNIX system an environment that allowed them to pursue research and development interests of their own, but who in turn contributed additions to the body of tools available for succeeding ranks of UNIX programmers.

Beginning in 1971, the system began to be used for applications within AT&T Bell Laboratories, and shortly thereafter (1974) was made available at low cost and without support to colleges and universities. These versions, called research versions and identified with Arabic numbers up through 7, occasionally grew on their own and fed back to the main system additional innovative tools. The widely-used screen editor **vi**(1), for example, was added to the UNIX system by William Joy at the University of California, Berkeley. In 1979 acceding to commercial demand, AT&T began offering supported

versions (called development versions) of the UNIX system. These are identified with Roman numerals and often have interim release numbers appended. The current development version, for example, is UNIX System V Release 3.0.

Versions of the UNIX system being offered now by AT&T are coming from an environment more closely related, perhaps, to the standard software factory. Features are being added to new releases in response to the expressed needs of the market place. The essential quality of the UNIX system, however, remains as the product of the innovative thinking of its originators and the collegial atmosphere in which they worked. This quality has on occasion been referred to as the UNIX philosophy, but what is meant is the way in which sophisticated programmers have come to work with the UNIX system.

## **UNIX System Philosophy Simply Stated**

For as long as you are writing programs on a UNIX system you should keep this motto hanging on your wall:

```
* * * * *
*
*      Build on the work of others      *
*
* * * * *
```

Unlike computer environments where each new project is like starting with a blank canvas, on a UNIX system a good percentage of any programming effort is lying there in **bins**, and **lbins**, and **/usr/bins**, not to mention **etc**, waiting to be used.

The features of the UNIX system (pipes, processes, and the file system) contribute to this reusability, as does the history of sharing and contributing that extends back to 1969. You risk missing the essential nature of the UNIX system if you do not put this to work.

---

# UNIX System Tools and Where You Can Read About Them

The term "UNIX system tools" can stand some clarification. In the narrowest sense, it means an existing piece of software used as a component in a new task. In a broader context, the term is often used to refer to elements of the UNIX system that might also be called features, utilities, programs, filters, commands, languages, functions, and so on. It gets confusing because any of the things that might be called by one or more of these names can be, and often are, used in the narrow way as part of the solution to a programming problem.

## Tools Covered and Not Covered in this Guide

The *Programmer's Guide* is about tools used in the process of creating programs in a UNIX system environment, so let us take a minute to talk about which tools we mean, which ones are not going to be covered in this book, and where you might find information about those not covered here. Actually, the subject of things not covered in this guide might be even more important to you than the things that are. We could not possibly cover everything you ever need to know about UNIX system tools in this one volume.

Tools not covered in this text:

- the **login** procedure
- UNIX system editors and how to use them
- how the file system is organized and how you move around in it
- shell programming

Information about these subjects can be found in the *User's Guide* and a number of commercially available texts.

Tools covered here can be classified as follows:

- utilities for getting programs running
- utilities for organizing software development projects
- specialized languages



- debugging and analysis tools
- compiled language components that are not part of the language syntax, for example, standard libraries, systems calls, and functions.

## **The Shell as a Prototyping Tool**

Any time you log in to a UNIX system machine you are using the shell. The shell is the interactive command interpreter that stands between you and the UNIX system kernel, but that is only part of the story. Because of its ability to start processes, direct the flow of control, field interrupts and redirect input and output, it is a full-fledged programming language. Programs that use these capabilities are known as shell procedures or shell scripts.

Much innovative use of the shell involves stringing together commands to be run under the control of a shell script. The dozens and dozens of commands that can be used in this way are documented in the *User's Reference Manual*. Time spent with the *User's Reference Manual* can be rewarding. Look through it when you are trying to find a command with just the right option to handle a knotty programming problem. The more familiar you become with the commands described in the manual pages, the more you will be able to take full advantage of the UNIX system environment.

It is not our purpose here to instruct you in shell programming. What we want to stress here is the important part that shell procedures can play in developing prototypes of full-scale applications. While understanding all the nuances of shell programming can be a fairly complex task, getting a shell procedure up and running is far less time-consuming than writing, compiling, and debugging compiled code.

This ability to get a program into production quickly is what makes the shell a valuable tool for program development. Shell programming allows you to "build on the work of others" to the greatest possible degree, since it allows you to piece together major components simply and efficiently. Many times even large applications can be done using shell procedures. Even if the application is initially developed as a prototype system for testing purposes rather than being put into production, many months of work can be saved.

With a prototype for testing, the range of possible user errors can be determined—something that is not always easy to plan out when an application is being designed. The method of dealing with strange user input can be worked out inexpensively, avoiding large re-coding problems.

A common occurrence in the UNIX system environment is to find that an available UNIX system tool can accomplish with a couple of lines of instructions what might take a page and a half of compiled code. Shell procedures can intermix compiled modules and regular UNIX system commands to let you take advantage of work that has gone before.

---

## Three Programming Environments

We distinguish among three programming environments to emphasize that the information needs and the way in which UNIX system tools are used differ from one environment to another. We do not intend to imply a hierarchy of skill or experience. Highly-skilled programmers with years of experience can be found in the "single-user" category, and relative newcomers can be members of an application development or systems programming team.

### Single-User Programmer

Programmers in this environment are writing programs only to ease the performance of their primary job. The resulting programs might well be added to the stock of programs available to the community in which the programmer works. This is similar to the atmosphere in which the UNIX system thrived; someone develops a useful tool and shares it with the rest of the organization. Single-user programmers may not have externally imposed requirements, or co-authors, or project management concerns. The programming task itself drives the coding very directly. One advantage of a timesharing system such as UNIX is that people with programming skills can be set free to work on their own without having to go through formal project approval channels and perhaps wait for months for a programming department to solve their problems.

Single-user programmers need to know how to:

- select an appropriate language
- compile and run programs
- use system libraries
- analyze programs
- debug programs
- keep track of program versions

Most of the information to perform these functions at the single-user level can be found in Chapter 2.

### Application Programming

Programmers working in this environment are developing systems for the benefit of other, non-programming users. Most large commercial computer applications still involve a team of applications development programmers. They may be employees of the end-user organization or they may work for a software development firm. Some of the people working in this environment may be more in the project management area than working programmers.

Information needs of people in this environment include all the topics in Chapter 2, plus additional information on:

- software control systems
- file and record locking
- communication between processes
- shared memory
- advanced debugging techniques

These topics are discussed in Chapter 3.

### Systems Programmers

These are programmers engaged in writing software tools that are part of, or closely related to the operating system itself. The project may involve writing a new device driver, a data base management system or an enhancement to the UNIX system kernel. In addition to knowing their way around the operating system source code and how to make changes and enhancements to it, they need to be thoroughly familiar with all the topics covered in Chapters 2 and 3.

---

## Summary

In this overview chapter we have described the way that the UNIX system developed and the effect that has on the way programmers now work with it. We have described what is and is not to be found in the other chapters of this guide to help programmers. We have also suggested that in many cases programming problems may be easily solved by taking advantage of the UNIX system interactive command interpreter known as the shell. Finally, we identified three programming environments in the hope that it will help orient the reader to the organization of the text in the remaining chapters.





# Programming Basics



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# 2 Programming Basics

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# Introduction

The information in this chapter is for anyone just learning to write programs to run in a UNIX system environment. In Chapter 1 we identified one group of UNIX system users as single-user programmers. People in that category, particularly those who are not deeply interested in programming, may find that this chapter (plus related reference manuals) tells them as much as they need to know about coding and running programs on a UNIX system computer.

Programmers whose interest does run deeper, who are part of an application development project, or who are producing programs on one UNIX system computer that are being ported to another, should view this chapter as a starter package.

---

# Choosing a Programming Language

How do you decide which programming language to use in a given situation? One answer could be, "I always code in HAIRBOL, because that's the language I know best." Actually, in some circumstances that is a legitimate answer. But assuming more than one programming language is available to you, that different programming languages have their strengths and weaknesses, and assuming that once you have learned to use one programming language it becomes relatively easy to learn to use another, you might approach the problem of language selection by asking yourself questions like the following:

- What is the nature of the task this program is to do?  
Does the task call for the development of a complex algorithm, or is this a simple procedure that has to be done on a lot of records?
- Does the programming task have many separate parts?  
Can the program be subdivided into separately compilable functions, or is it one module?
- How soon does the program have to be available?  
Is it needed right now, or do I have enough time to work out the most efficient process possible?
- What is the scope of its use?  
Am I the only person who will use this program, or is it going to be distributed to the whole world?
- Is there a possibility the program will be ported to other systems?
- What is the life expectancy of the program?  
Is it going to be used just a few times, or will it still be going strong five years from now?

## Supported Languages in a UNIX System Environment

By "supported languages" we mean those offered by AT&T for use on your computer running UNIX System V Release 3.1. Since these are separately purchasable items, not all of them will necessarily be installed on

your machine. On the other hand, you may have languages available on your machine that came from another source and are not mentioned in this discussion. Be that as it may, in this section and the one to follow we give brief descriptions of the nature of (a) C programming language, and (b) a number of special purpose languages.

## **C Language**

The C language is intimately associated with the UNIX system since it was originally developed for use in recoding the UNIX system kernel. If you need to use a lot of UNIX system function calls for low-level I/O, memory or device management, or inter-process communication, C language is a logical first choice. Most programs, however, do not require such direct interfaces with the operating system, so the decision to choose C might better be based on one or more of the following characteristics:

- a variety of data types: character, integer, long integer, float, and double
- low-level constructs (most of the UNIX system kernel is written in C)
- derived data types such as arrays, functions, pointers, structures, and unions
- multi-dimensional arrays
- scaled pointers and the ability to do pointer arithmetic
- bit-wise operators
- a variety of flow-of-control statements: if, if-else, switch, while, do-while, and for
- a high degree of portability

C is a language that lends itself readily to structured programming. It is natural in C to think in terms of functions. The next logical step is to view each function as a separately compilable unit. This approach (coding a program in small pieces) eases the job of making changes and/or improvements. If this begins to sound like the UNIX system philosophy of building new programs from existing tools, it is not just coincidence. As you create functions for one program, you will surely find that many can be picked up or quickly revised for another program.

A difficulty with C is that it takes a fairly concentrated use of the language over a period of several months to reach your full potential as a C programmer. If you are a casual programmer, you might make life easier for yourself if you choose a less demanding language.

### Assembly Language

The closest approach to machine language, assembly language is specific to the particular computer on which your program is to run. High-level languages are translated into the assembly language for a specific processor as one step of the compilation. The most common need to work in assembly language arises when you want to do some task that is not within the scope of a high-level language. Since assembly language is machine-specific, programs written in it are not portable.

### Special Purpose Languages

In addition to the above formal programming languages, the UNIX system environment frequently offers one or more of the special purpose languages listed below.

NOTE

Since UNIX system utilities and commands are packaged in functional groupings, it is possible that not all the facilities mentioned will be available on all systems.

### **awk**

**awk** (its name is an acronym constructed from the initials of its developers) scans an input file for lines that match pattern(s) described in a specification file. On finding a line that matches a pattern, **awk** performs actions also described in the specification. It is not uncommon that an **awk** program can be written in a couple of lines to do functions that would take a couple of pages to describe in a programming language like FORTRAN or C. For example, consider a case where you have a set of records that consist of a key field and a second field that represents a quantity. You have sorted the records by the key field, and you now want to add the quantities for records with duplicate keys and output a file in which no keys are duplicated.



The pseudo-code for such a program might look like this:

```

Read the first record into a hold area;
Read additional records until EOF;
{
  If the key matches the key of the record in the hold area,
  add the quantity to the quantity field of the held record;
  If the key does not match the key of the held record,
  write the held record,
  move the new record to the hold area;
}
At EOF, write out the last record from the hold area.

```

An **awk** program to accomplish this task would look like this:

```

      { qty[$1] += $2 }
END   { for (key in qty) print key, qty[key] }

```

This illustrates only one characteristic of **awk**; its ability to work with associative arrays. With **awk**, the input file does not have to be sorted, which is a requirement of the pseudo-program.

## lex

**lex** is a lexical analyzer that can be added to C programs. A lexical analyzer is interested in the vocabulary of a language rather than its grammar, which is a system of rules defining the structure of a language. **lex** can produce C language subroutines that recognize regular expressions specified by the user, take some action when a regular expression is recognized, and pass the output stream on to the next program.

## yacc

**yacc** (Yet Another Compiler Compiler) is a tool for describing an input language to a computer program. **yacc** produces a C language subroutine that parses an input stream according to rules laid down in a specification file. The **yacc** specification file establishes a set of grammar rules together with actions to be taken when tokens in the input match the rules. **lex** may be used with **yacc** to control the input process and pass tokens to the parser that applies the grammar rules.

### M4

**M4** is a macro processor that can be used as a preprocessor for assembly language and C programs. It is described in Section (1) of the *Programmer's Reference Manual*.

### **bc and dc**

**bc** enables you to use a computer terminal as you would a programmable calculator. You can edit a file of mathematical computations and call **bc** to execute them. The **bc** program uses **dc**. You can use **dc** directly, if you want, but it takes a little getting used to since it works with reverse Polish notation. That means you enter numbers into a stack followed by the operator. **bc** and **dc** are described in Section (1) of the *User's Reference Manual*.

### **curses**

Actually a library of C functions, **curses** is included in this list because the set of functions just about amounts to a sub-language for dealing with terminal screens. If you are writing programs that include interactive user screens, you will want to become familiar with this group of functions.

In addition to all the foregoing, do not overlook the possibility of using shell procedures.

---

## After Your Code Is Written

The last two steps in most compilation systems in the UNIX system environment are the assembler and the link editor. The compilation system produces assembly language code. The assembler translates that code into the machine language of the computer the program is to run on. The link editor resolves all undefined references and makes the object module executable. With most languages on the UNIX system the assembler and link editor produce files in what is known as the Common Object File Format (COFF). A common format makes it easier for utilities that depend on information in the object file to work on different machines running different versions of the UNIX system.

In the Common Object File Format an object file contains:

- a file header
- optional secondary header
- a table of section headers
- data corresponding to the section header(s)
- relocation information
- line numbers
- a symbol table
- a string table

An object file is made up of sections. Usually, there are at least two: **.text**, and **.data**. Some object files contain a section called **.bss**. (**.bss** is an assembly language pseudo-op that originally stood for "block started by symbol.") **.bss**, when present, holds uninitialized data. Options of the compilers cause different items of information to be included in the Common Object File Format. For example, compiling a program with the **-g** option adds line numbers and other symbolic information that is needed for the **sdb** (Symbolic Debugger) command to be fully effective. You can spend many years programming without having to worry too much about the contents and organization of the Common Object File Format, so we are not going into any further depth of detail at this point. Detailed information is available in Chapter 11 of this guide.

# Compiling and Link Editing

The command used for compiling depends on the language used; for C programs, `cc` both compiles and link edits.

## Compiling C Programs

To use the C compilation system you must have your source code in a file with a file name that ends in the characters `.c`, as in `mycode.c`. The command to invoke the compiler is:

```
cc mycode.c
```

If the compilation is successful, the process proceeds through the link edit stage and the result will be an executable file by the name of `a.out`.

Several options to the `cc` command are available to control its operation. The most used options are:

- `-c` causes the compilation system to suppress the link edit phase. This produces an object file (`mycode.o`) that can be link edited at a later time with a `cc` command without the `-c` option.
- `-g` causes the compilation system to generate special information about variables and language statements used by the symbolic debugger `sdb`. If you are going through the stage of debugging your program, use this option.
- `-O` causes the inclusion of an additional optimization phase. This option is logically incompatible with the `-g` option. You would normally use `-O` after the program has been debugged, to reduce the size of the object file and increase execution speed.
- `-p` causes the compilation system to produce code that works in conjunction with the `prof(1)` command to produce a runtime profile of where the program is spending its time. Useful in identifying which routines are candidates for improved code.
- `-o outfile` tells `cc` to tell the link editor to use the specified name for the executable file, rather than the default `a.out`.

Other options can be used with **cc**. Check the *Programmer's Reference Manual*.

If you enter the **cc** command using a file name that ends in **.s**, the compilation system treats it as assembly language source code and bypasses all the steps ahead of the assembly step.

## **Compiler Diagnostic Messages**

The C compiler generates error messages for statements that do not compile. The messages are generally quite understandable, but in common with most language compilers they sometimes point several statements beyond where the actual error occurred. For example, if you inadvertently put an extra **;** at the end of an **if** statement, a subsequent **else** will be flagged as a syntax error. In the case where a block of several statements follows the **if**, the line number of the syntax error caused by the **else** will start you looking for the error well past where it is. Unbalanced curly braces, **{ }**, are another common producer of syntax errors.

## **Link Editing**

The **ld** command invokes the link editor directly. The typical user, however, seldom invokes **ld** directly. A more common practice is to use a language compilation control command (such as **cc**) that invokes **ld**. The link editor combines several object files into one, performs relocation, resolves external symbols, incorporates startup routines, and supports symbol table information used by **sdb**. You may, of course, start with a single object file rather than several. The resulting executable module is left in a file named **a.out**.

Any file named on the **ld** command line that is not an object file (typically, a name ending in **o**) is assumed to be an archive library or a file of link editor directives. The **ld** command has some 16 options. We are going to describe four of them. These options should be fed to the link editor by specifying them on the **cc** command line if you are doing both jobs with the single command, which is the usual case.

**-o outfile** provides a name to be used to replace **a.out** as the name of the output file. Obviously, the name **a.out** is of only temporary usefulness. If you know the name you want to use to invoke your program, you can provide it here. Of course, it may be equally convenient to do this:

**mv a.out progname**

when you want to give your program a less temporary name.

- lx** directs the link editor to search a library **libx.a**, where *x* is up to nine characters. For C programs, **libc.a** is automatically searched if the **cc** command is used. The **-lx** option is used to bring in libraries not normally in the search path such as **libm.a**, the math library. The **-lx** option can occur more than once on a command line, with different values for the *x*. A library is searched when its name is encountered, so the placement of the option on the command line is important. The safest place to put it is at the end of the command line. The **-lx** option is related to the **-L** option.
- L dir** changes the **libx.a** search sequence to search in the specified directory before looking in the default library directories, usually **/lib** or **/usr/lib**. This is useful if you have different versions of a library and you want to point the link editor to the correct one. It works on the assumption that once a library has been found no further searching for that library is necessary. Because **-L** diverts the search for the libraries specified by **-lx** options, it must precede such options on the command line.
- u symname** enters *symname* as an undefined symbol in the symbol table. This is useful if you are loading entirely from an archive library, because initially the symbol table is empty and needs an unresolved reference to force the loading of the first routine.

When the link editor is called through **cc**, a startup routine (typically **/lib/crt0.o** for C programs) is linked with your program. This routine calls **exit(2)** after execution of the main program.

The link editor accepts a file containing link editor directives. The details of the link editor command language can be found in Chapter 12.

---

# The Interface Between a Programming Language and the UNIX System

When a program is run in a computer, it depends on the operating system for a variety of services. Some of the services such as bringing the program into main memory and starting the execution are completely transparent to the program. They are, in effect, arranged for in advance by the link editor when it marks an object module as executable. As a programmer you seldom need to be concerned about such matters.

Other services, however, such as input/output, file management, and storage allocation do required work on the part of the programmer. These connections between a program and the UNIX operating system are what is meant by the term UNIX system/language interface. The topics included in this section are:

- How arguments are passed to a program
- System calls and subroutines
- Header files and libraries
- Input/Output
- Processes
- Error Handling, Signals, and Interrupts

## Why C Is Used to Illustrate the Interface

Throughout this section C programs are used to illustrate the interface between the UNIX system and programming languages, because C programs make more use of the interface mechanisms than other high-level languages. What is really being covered in this section then is the UNIX system/C Language interface. The way that other languages deal with these topics is described in the user's guides for those languages.

## How Arguments Are Passed to a Program

Information or control data can be passed to a C program as arguments on the command line. When the program is run as a command, arguments on the command line are made available to the function **main** in two parameters, an argument count and an array of pointers to character strings. (Every C program is required to have an entry module by the name of **main**.) Since the argument count is always given, the program does not have to know in advance how many arguments to expect. The character strings pointed at by elements of the array of pointers contain the argument information.

The arguments are presented to the program traditionally as **argc** and **argv**, although any names you choose will work. **argc** is an integer that gives the count of the number of arguments. Since the command itself is considered to be the first argument, **argv[0]**, the count is always at least one. **argv** is an array of pointers to character strings (arrays of characters terminated by the null character `\0`).

If you plan to pass runtime parameters to your program, you need to include code to deal with the information. Two possible uses of runtime parameters are:

- as control data. Use the information to set internal flags that control the operation of the program.
- to provide a variable file name to the program.

Figures 2-1 and 2-2 show program fragments that illustrate these uses.



```
#include <stdio.h>

main(argc, argv)
    int argc;
    char *argv[];
{
    void exit();
    int oflag = FALSE;
    int pflag = FALSE;          /* Function Flags */
    int rflag = FALSE;
    int ch;

    while ((ch = getopt(argc,argv, "opr")) != EOF)
    {
        /* For options present, set flag to TRUE */
        /* If no options present, print error message */

        switch (ch)
        {
            case 'o':
                oflag = 1;
                break;
            case 'p':
                pflag = 1;
                break;
            case 'r':
                rflag = 1;
                break;
            default:
                (void)fprintf(stderr,
                    "Usage: %s [-opr]\n", argv[0]);
                exit(2);
        }
    }
    .
    .
    .
}
```

Figure 2-1: Using Command Line Arguments to Set Flags

```
#include <stdio.h>

main(argc, argv)
int argc;
char *argv[];
{
    FILE *fopen(), *fin;
    void perror(), exit();

    if (argc > 1)
    {
        if ((fin = fopen(argv[1], "r")) == NULL)
        {
            /* First string (%s) is program name (argv[0]) */
            /* Second string (%s) is name of file that could */
            /* not be opened (argv[1]) */

            (void)fprintf(stderr,
                "%s: cannot open %s: ",
                argv[0], argv[1]);
            perror("");
            exit(2);
        }
    }
    .
    .
    .
}
```

Figure 2-2: Using `argv[n]` Pointers to Pass a File Name

---

The shell, which makes arguments available to your program, considers an argument to be any non-blank characters separated by blanks or tabs. Characters enclosed in double quotes ("abc def") are passed to the program as one argument even if blanks or tabs are among the characters. It goes without saying that you are responsible for error checking and otherwise making sure the argument received is what your program expects it to be.

A third argument is also present, in addition to **argc** and **argv**. The third argument, known as **envp**, is an array of pointers to environment variables. You can find more information on **envp** in the *Programmer's Reference Manual* under **exec(2)** and **environ(5)**.

## System Calls and Subroutines

System calls are requests from a program for an action to be performed by the UNIX system kernel. Subroutines are precoded modules used to supplement the functionality of a programming language.

Both system calls and subroutines look like functions such as those you might code for the individual parts of your program. There are, however, differences between them:

- At link edit time, the code for subroutines is copied into the object file for your program; the code invoked by a system call remains in the kernel.
- At execution time, subroutine code is executed as if it was code you had written yourself; a system function call is executed by switching from your process area to the kernel.

This means that while subroutines make your executable object file larger, runtime overhead for context switching may be less and execution may be faster.

## Categories of System Calls and Subroutines

System calls divide fairly neatly into the following categories:

- file access
- file and directory manipulation
- process control
- environment control and status information

You can generally tell the category of a subroutine by the section of the *Programmer's Reference Manual* in which you find its manual page. However, the first part of Section 3 (3C and 3S) covers such a variety of subroutines it might be helpful to classify them further.

- The subroutines of sub-class 3S constitute the UNIX system/C Language standard I/O, an efficient I/O buffering scheme for C.
- The subroutines of sub-class 3C do a variety of tasks. They have in common the fact that their object code is stored in **libc.a**. They can be divided into the following categories:
  - string manipulation
  - character conversion
  - character classification
  - environment management
  - memory management

Figure 2-3 lists the functions that compose the standard I/O subroutines. Frequently, one manual page describes several related functions. The left hand column contains the name that appears at the top of the manual page; the other names in the same row are related functions described on the same manual page.

Figure 2-4 lists string-handling functions that are grouped under the heading **string(3C)** in the *Programmer's Reference Manual*.

Figure 2-5 lists macros that classify ASCII character-coded integer values. These macros are described under the heading **ctype(3C)** in Section 3 of the *Programmer's Reference Manual*.

Figure 2-6 lists functions and macros that are used to convert characters, integers, or strings from one representation to another.

Function Name(s)				Purpose
<b>close</b>	<b>fflush</b>			close or flush a stream
<b>ferror</b>	<b>feof</b>	<b>clearerr</b>	<b>fileno</b>	stream status inquiries
<b>fopen</b>	<b>freopen</b>	<b>fdopen</b>		open a stream
<b>fread</b>	<b>fwrite</b>			binary input/output
<b>fseek</b>	<b>rewind</b>	<b>ftell</b>		reposition a file pointer in a stream
<b>getc</b>	<b>getchar</b>	<b>fgetc</b>	<b>getw</b>	get a character or word from a stream
<b>gets</b>	<b>fgets</b>			get a string from a stream
<b>popen</b>	<b>pclose</b>			begin or end a pipe to/from a process
<b>printf</b>	<b>fprintf</b>	<b>sprintf</b>		print formatted output
<b>putc</b>	<b>putchar</b>	<b>fputc</b>	<b>putw</b>	put a character or word on a stream
<b>puts</b>	<b>fputs</b>			put a string on a stream
<b>scanf</b>	<b>fscanf</b>	<b>sscanf</b>		convert formatted input
<b>setbuf</b>	<b>setvbuf</b>			assign buffering to a stream
<b>system</b>				issue a command through the shell
<b>tmpfile</b>				create a temporary file
<b>tmpnam</b>	<b>tempnam</b>			create a name for a temporary file
<b>ungetc</b>				push character back into input stream
<b>vprintf</b>	<b>vfprintf</b>	<b>vsprintf</b>		print formatted output of a varargs argument list

For all functions: #include <stdio.h>

The function name shown in **bold** gives the location in the *Programmer's Reference Manual*, Section 3.

Figure 2-3: C Language Standard I/O Subroutines

---

String Operations

---

<b>strcat(s1, s2)</b>	append a copy of s2 to the end of s1.
<b>strncat(s1, s2, n)</b>	append n characters from s2 to the end of s1.
<b>strcmp(s1, s2)</b>	compare two strings. Returns an integer less than, greater than, or equal to 0 to show that s1 is lexicographically less than, greater than, or equal to s2.
<b>strncmp(s1, s2, n)</b>	compare n characters from the two strings. Results are otherwise identical to strcmp.
<b>strcpy(s1, s2)</b>	copy s2 to s1, stopping after the null character (\0) has been copied.
<b>strncpy(s1, s2, n)</b>	copy n characters from s2 to s1. s2 will be truncated if it is longer than n, or padded with null characters if it is shorter than n.
<b>strdup(s)</b>	returns a pointer to a new string that is a duplicate of the string pointed to by s.
<b>strchr(s, c)</b>	returns a pointer to the first occurrence of character c in string s, or a NULL pointer if c is not in s.
<b>strrchr(s, c)</b>	returns a pointer to the last occurrence of character c in string s, or a NULL pointer if c is not in s.
<b>strlen(s)</b>	returns the number of characters in s up to the first null character.
<b>strpbrk(s1, s2)</b>	returns a pointer to the first occurrence in s1 of any character from s2, or a NULL pointer if no character from s2 occurs in s1.
<b>strspn(s1, s2)</b>	returns the length of the initial segment of s1, which consists entirely of characters from s2.
<b>strcspn(s1, s2)</b>	returns the length of the initial segment of s1, which consists entirely of characters not from s2.
<b>strtok(s1, s2)</b>	look for occurrences of s2 within s1.

For all functions: #include <string.h>

**string.h** provides extern definitions of the string functions.

Figure 2-4: String Operations

---

**Classify Characters**

<b>isalpha(c)</b>	is <i>c</i> a letter
<b>isupper(c)</b>	is <i>c</i> an uppercase letter
<b>islower(c)</b>	is <i>c</i> a lowercase letter
<b>isdigit(c)</b>	is <i>c</i> a digit [0-9]
<b>isxdigit(c)</b>	is <i>c</i> a hexadecimal digit [0-9], [A-F] or [a-f]
<b>isalnum(c)</b>	is <i>c</i> an alphanumeric (letter or digit)
<b>isspace(c)</b>	is <i>c</i> a space, tab, carriage return, new-line, vertical tab, or form-feed
<b>ispunct(c)</b>	is <i>c</i> a punctuation character (neither control nor alphanumeric)
<b>isprint(c)</b>	is <i>c</i> a printing character, code 040 (space) through 0176 (tilde)
<b>isgraph(c)</b>	same as isprint except false for 040 (space)
<b>iscntrl(c)</b>	is <i>c</i> a control character (less than 040) or a delete character (0177)
<b>isascii(c)</b>	is <i>c</i> an ASCII character (code less than 0200)

For all functions: #include <ctype.h>

Nonzero return == true; zero return == false

Figure 2-5: Classifying ASCII Character-Coded Integer Values

---

Function Name(s)		Purpose	
a64l	l64a	convert between long integer and base-64 ASCII string	
ecvt	fcvt	gcvrt	convert floating-point number to string
l3tol	l3tol		convert between 3-byte integer and long integer
strtod	atof		convert string to double-precision number
strtol	atol	atoi	convert string to integer

conv(3C):	Translate Characters
<b>toupper</b>	lowercase to uppercase
<b>_toupper</b>	macro version of toupper
<b>tolower</b>	uppercase to lowercase
<b>_tolower</b>	macro version of tolower
<b>toascii</b>	turn off all bits that are not part of a standard ASCII character; intended for compatibility with other systems

For all **conv(3C)** macros: #include <ctype.h>

Figure 2-6: Conversion Functions and Macros

---



## Where the Manual Pages Can Be Found

System calls are listed alphabetically in Section 2 of the *Programmer's Reference Manual*. Subroutines are listed in Section 3. We have described earlier what is in the first subsection of Section 3. The remaining subsections of Section 3 are:

- 3M—functions that make up the Math Library, **libm**
- 3X—various specialized functions
- 3N—Networking Support Utilities

## How System Calls and Subroutines Are Used in C Programs

Information about the proper way to use system calls and subroutines is given on the manual page, but you have to know what you are looking for before it begins to make sense. To illustrate, a typical manual page [for `gets(3S)`] is shown in Figure 2-7.

### NAME

gets, fgets - get a string from a stream

### SYNOPSIS

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

```
char *gets (s)
```

```
char *s;
```

```
char *fgets (s, n, stream)
```

```
char *s;
```

```
int n;
```

```
FILE *stream;
```

### DESCRIPTION

*Gets* reads characters from the standard input stream, *stdin*, into the array pointed to by *s*, until a new-line character is read or an end-of-file condition is encountered. The new-line character is discarded and the string is terminated with a null character.

*Fgets* reads characters from the *stream* into the array pointed to by *s*, until *n-1* characters are read, or a new-line character is read and transferred to *s*, or an end-of-file condition is encountered. The string is then terminated with a null character.

### SEE ALSO

ferror(3S),

fopen(3S),

fread(3S),

getc(3S),

scanf(3S).

### DIAGNOSTICS

If end-of-file is encountered and no characters have been read, no characters are transferred to *s* and a NULL pointer is returned. If a read error occurs, such as trying to use these functions on a file that has not been opened for reading, a NULL pointer is returned. Otherwise *s* is returned.

Figure 2-7: Manual Page for `gets(3S)`

---

As you can see from the illustration, two related functions are described on this page: **gets** and **fgets**. Each function gets a string from a stream in a slightly different way. The DESCRIPTION section tells how each operates.

It is the SYNOPSIS section, however, that contains the critical information about how the function (or macro) is used in your program. Notice in Figure 2-7 that the first line in the SYNOPSIS is

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

This means that to use **gets** or **fgets** you must bring the standard I/O header file into your program (generally right at the top of the file). There is something in **stdio.h** that is needed when you use the described functions. Figure 2-9 shows a version of **stdio.h**. Check it to see if you can understand what **gets** or **fgets** uses.

The next thing shown in the SYNOPSIS section of a manual page that documents system calls or subroutines is the formal declaration of the function. The formal declaration tells you:

■ **the type of object returned by the function**

In our example, both **gets** and **fgets** return a character pointer.

■ **the object or objects the function expects to receive when called**

These are the things enclosed in the parentheses of the function. **gets** expects a character pointer. (The DESCRIPTION section sheds light on what the tokens of the formal declaration stand for.)

■ **how the function is going to treat those objects**

The declaration

```
char *s;
```

in **gets** means that the token **s** enclosed in the parentheses will be considered to be a pointer to a character string. Bear in mind that in the C language, when passed as an argument, the name of an array is converted to a pointer to the beginning of the array.

We have chosen a simple example here in **gets**. If you want to test yourself on something a little more complex, try working out the meaning of the elements of the **fgets** declaration.

While we are on the subject of **fgets**, there is another piece of C esoterica that we will explain. Notice that the third parameter in the **fgets** declaration is referred to as **stream**. A **stream**, in this context, is a file with its associated buffering. It is declared to be a pointer to a defined type FILE. Where is FILE defined? Right! In **stdio.h**.

To finish off this discussion of the way you use functions described in the *Programmer's Reference Manual* in your own code, in Figure 2-8 we show a program fragment in which **gets** is used.

```
#include <stdio.h>

main()
{
    char sarray[80];

    for(;;)
    {
        if (gets(sarray) != NULL)
            .
            /* Do something with the string */
            .
    }
}
```

Figure 2-8: How **gets** Is Used in a Program

---

You might ask, "Where is **gets** reading from?" The answer is, "From the standard input." That generally means from something being keyed in from the terminal where the command was entered to get the program running, or output from another command that was piped to **gets**. How do we know that? The DESCRIPTION section of the **gets** manual page says, "**gets** reads characters from the standard input...." Where is the standard input defined?

In `stdio.h`.

```
#ifndef _NFILE
#define _NFILE20

#define BUFSIZ1024
#define _SBFSIZ 8

typedef struct {
    int          _cnt;
    unsigned char *_ptr;
    unsigned char *_base;
    char         _flag;
    char         _file;
} FILE;

#define _IOFBF          0000 /* _IOLBF means that a file's output */
#define _IOREAD        0001 /* will be buffered line by line. */
#define _IOWRT         0002 /* In addition to being flags, _IONBF,*/
#define _IONBF         0004 /* _IOLBF and IOFBF are possible */
#define _IOMYBUF       0010 /* values for "type" in setvbuf. */
#define _IOEOF         0020
#define _IOERR         0040
#define _IOLBF         0100
#define _IORW          0200

#ifndef NULL
#define NULL          0
#endif
#ifndef EOF
#define EOF           (-1)
#endif
#endif
```

Figure 2-9: A Version of `stdio.h` (Sheet 1 of 2)

```
#define stdin          (&_iob[0])
#define stdout        (&_iob[1])
#define stderr        (&_iob[2])

#define _bufend(p)     _bufendtab[(p)->_file]
#define _bufsiz(p)     (_bufend(p) - (p)->_base)

#ifndef lint
#define getc(p)         (--(p)->_cnt < 0 ? _filbuf(p) : (int) *(p)->_ptr++)
#define putc(x, p)     (--(p)->_cnt < 0 ?
                        _flsbuf((unsigned char) (x), (p)) :
                        (int) (*(p)->_ptr++ = (unsigned char) (x)))
#define getchar()      getc(stdin)
#define putchar(x)     putc(x, stdout)
#define clearerr(p)    ((void) ((p)->_flag &= (_IOERR | _IOEOF)))
#define feof(p)        ((p)->_flag & _IOEOF)
#define ferror(p)      ((p)->_flag & _IOERR)
#define fileno(p)      (p)->_file
#endif

extern FILE      _iob[_NFILE];
extern FILE      *fopen(), *fdopen(), *freopen(), *popen(), *tmpfile();
extern long      ftell();
extern void      rewind(), setbuf();
extern char      *ctermid(), *cuserid(), *fgets(), *gets(), *tempnam(), *tmpnam();
extern unsigned char *_bufendtab[];

#define L_ctermid      9
#define L_cuserid      9
#define P_tmpdir       "/usr/tmp/"
#define L_tmpnam       (sizeof(P_tmpdir) + 15)
#endif
```

Figure 2-9: A Version of `stdio.h` (Sheet 2 of 2)

## Header Files and Libraries

In the earlier parts of this chapter there have been frequent references to **stdio.h**, and a version of the file itself is shown in Figure 2-9. **stdio.h** is the most commonly used header file in the UNIX system/C environment, but there are many others.

Header files carry definitions and declarations that are used by more than one function. Header file names traditionally have the suffix **.h**, and are brought into a program at compile time by the C-preprocessor. The preprocessor does this because it interprets the **#include** statement in your program as a directive; as indeed it is. All keywords preceded by a pound sign (#) at the beginning of the line are treated as preprocessor directives. The two most commonly used directives are **#include** and **#define**. We have already seen that the **#include** directive is used to call in (and process) the contents of the named file. The **#define** directive is used to replace a name with a token-string. For example,

```
#define _NFILE 20
```

sets to 20 the number of files a program can have open at one time. See **cpp(1)** for the complete list.

In the pages of the *Programmer's Reference Manual* there are about 45 different **.h** files named. The format of the **#include** statement for all these shows the file name enclosed in angle brackets (<>), as in

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

The angle brackets tell the C preprocessor to look in the standard places for the file. In most systems the standard place is in the **/usr/include** directory. If you have some definitions or external declarations that you want to make available in several files, you can create a **.h** file with any editor, store it in a convenient directory and make it the subject of a **#include** statement such as the following:

```
#include "../defs/rec.h"
```

It is necessary, in this case, to provide the relative path name of the file and enclose it in quotation marks (" "). Fully-qualified path names (those that begin with /) can create portability and organizational problems. An alternative to long or fully-qualified path names is to use the **-Idir** preprocessor option when you compile the program. This option directs the preprocessor to search for **#include** files whose names are enclosed in " ", first in the directory of the file being compiled, then in the directories named in the **-I** option(s), and finally in directories on the standard list. In addition, all **#include** files whose names are enclosed in angle brackets (< >) are first searched for in the list of directories named in the **-I** option and finally in the directories on the standard list.

## Object File Libraries

It is common practice in UNIX system computers to keep modules of compiled code (object files) in archives; by convention, designated by a **.a** suffix. System calls from Section 2, and the subroutines in Section 3, subsections 3C and 3S, of the *Programmer's Reference Manual* that are functions (as distinct from macros) are kept in an archive file by the name of **libc.a**. In most systems, **libc.a** is found in the directory **/lib**. Many systems also have a directory **/usr/lib**. Where both **/lib** and **/usr/lib** occur, **/usr/lib** is apt to be used to hold archives that are related to specific applications.

During the link edit phase of the compilation and link edit process, copies of some of the object modules in an archive file are loaded with your executable code. By default the **cc** command that invokes the C compilation system causes the link editor to search **libc.a**. If you need to point the link editor to other libraries that are not searched by default, you do it by naming them explicitly on the command line with the **-l** option. The format of the **-l** option is **-lx** where **x** is the library name, and can be up to nine characters. For example, if your program includes functions from the **curses** screen control package, the option

**-lcurses**

will cause the link editor to search for **/lib/libcurses.a** or **/usr/lib/libcurses.a** and use the first one it finds to resolve references in your program.



In cases where you want to direct the order in which archive libraries are searched, you may use the **-L** *dir* option. Assuming the **-L** option appears on the command line ahead of the **-l** option, it directs the link editor to search the named directory for **libx.a** before looking in **/lib** and **/usr/lib**. This is particularly useful if you are testing out a new version of a function that already exists in an archive in a standard directory. Its success is due to the fact that once having resolved a reference, the link editor stops looking. That is why the **-L** option, if used, should appear on the command line ahead of any **-l** specification.

## Input/Output

We talked some about I/O earlier in this chapter in connection with system calls and subroutines. A whole set of subroutines constitutes the C language standard I/O package, and there are several system calls that deal with the same area. In this section we want to get into the subject in a little more detail and describe for you how to deal with input and output concerns in your C programs. First off, let us briefly define what the subject of I/O encompasses. It has to do with

- creating and sometimes removing files
- opening and closing files used by your program
- transferring information from a file to your program (reading)
- transferring information from your program to a file (writing).

In this section we will describe some of the subroutines you might choose for transferring information, but the heaviest emphasis will be on dealing with files.

### Three Files You Always Have

Programs are permitted to have several files open simultaneously. The number may vary from system to system; the most common maximum is 20. **\_NFILE** in **stdio.h** specifies the number of standard I/O FILES a program is permitted to have open.

Any program automatically starts off with three files. If you will look again at Figure 2-9, about midway through you will see that **stdio.h** contains three **#define** directives that equate **stdin**, **stdout**, and **stderr** to the address of **\_iob[0]**, **\_iob[1]**, and **\_iob[2]**, respectively. The array **\_iob** holds information dealing with the way standard I/O handles streams. It is a

representation of the open file table in the control block for your program. The position in the array is a number that is also known as the file descriptor. The default in UNIX systems is to associate all three of these files with your terminal.

The real significance is that functions and macros that deal with **stdin** or **stdout** can be used in your program with no further need to open or close files. For example, **gets**, cited above, reads a string from **stdin**; **puts** writes a null-terminated string to **stdout**. There are others that do the same (in slightly different ways: character at a time, formatted, etc.). You can specify that output be directed to **stderr** by using a function such as **fprintf**. **fprintf** works the same as **printf** except that it delivers its formatted output to a named stream, such as **stderr**. You can use the shell's redirection feature on the command line to read from or write into a named file. If you want to separate error messages from ordinary output being sent to **stdout** and thence possibly piped by the shell to a succeeding program, you can do it by using one function to handle the ordinary output and a variation of the same function that names the stream to handle error messages.

### Named Files

Any files other than **stdin**, **stdout**, and **stderr** that are to be used by your program must be explicitly connected by you before the file can be read from or written to. This can be done using the standard library routine **fopen**. **fopen** takes a path name (which is the name by which the file is known to the UNIX file system), asks the system to keep track of the connection, and returns a pointer that you then use in functions that do the reads and writes.

A structure is defined in **stdio.h** with a type of **FILE**. In your program you need to have a declaration such as

```
FILE *fin;
```

The declaration says that **fin** is a pointer to a **FILE**. You can then assign the name of a particular file to the pointer with a statement in your program like this:

```
fin = fopen("filename", "r");
```

where **filename** is the path name to open. The **"r"** means that the file is to be opened for reading. This argument is known as the **mode**. As you might suspect, there are modes for reading, writing, and both reading and writing. Actually, the file open function is often included in an **if** statement that takes advantage of the fact that **fopen** returns a **NULL** pointer

if it cannot open the file. An example is:

```
if ((fin = fopen("filename", "r")) == NULL)
    (void)fprintf(stderr, "%s: Unable to open input file %s\n", argv[0], "filename");
```

Once the file has been successfully opened, the pointer **fin** is used in functions (or macros) to refer to the file. For example:

```
int c;
c = getc(fin);
```

brings in a character at a time from the file into an integer variable called **c**. The variable **c** is declared as an integer even though we are reading characters because the function **getc()** returns an integer. Getting a character is often incorporated into some flow-of-control mechanism such as:

```
while ((c = getc(fin)) != EOF)
    .
    .
    .
```

that reads through the file until EOF is returned. EOF, NULL, and the macro **getc** are all defined in **stdio.h**. **getc** and others that make up the standard I/O package keep advancing a pointer through the buffer associated with the file; the UNIX system and the standard I/O subroutines are responsible for seeing that the buffer is refilled (or written to the output file if you are producing output) when the pointer reaches the end of the buffer. All these mechanics are mercifully invisible to the program and the programmer.

The function **fclose** is used to break the connection between the pointer in your program and the path name. The pointer may then be associated with another file by another call to **fopen**. This re-use of a file descriptor for a different stream may be necessary if your program has many files to open. For output files it is good to issue an **fclose** call because the call makes sure that all output has been sent from the output buffer before disconnecting the file. The system call **exit** closes all open files for you. It also gets you completely out of your process, however, so it is safe to use only when you are sure you

are completely finished.

### **Low-Level I/O and Why You Should Not Use It**

The term low-level I/O is used to refer to the process of using system calls from Section 2 of the *Programmer's Reference Manual* rather than the functions and subroutines of the standard I/O package. We are going to postpone until Chapter 3 any discussion of when this might be advantageous. If you find as you go through the information in this chapter that it is a good fit with the objectives you have as a programmer, it is a safe assumption that you can work with C language programs in the UNIX system for a good many years without ever having a real need to use system calls to handle your I/O and file accessing problems. The reason low-level I/O is perilous is because it is more system-dependent. Your programs are less portable and probably no more efficient.

### **System Calls for Environment or Status Information**

Under some circumstances you might want to be able to monitor or control the environment in your computer. There are system calls that can be used for this purpose. Some of them are shown in Figure 2-10.

Function Name(s)	Purpose
<b>chdir</b>	change working directory
<b>chmod</b>	change access permission of a file
<b>chown</b>	change owner and group of a file
<b>getpid</b> <b>getpgrp</b> <b>getppid</b>	get process IDs
<b>getuid</b> <b>geteuid</b> <b>getgid</b>	get user IDs
<b>ioctl</b>	control device
<b>link</b> <b>unlink</b>	add or remove a directory entry
<b>mount</b> <b>umount</b>	mount or unmount a file system
<b>nice</b>	change priority of a process
<b>stat</b> <b>fstat</b>	get file status
<b>time</b>	get time
<b>ulimit</b>	get and set user limits
<b>uname</b>	get name of current UNIX system

Figure 2-10: Environment and Status System Calls

---

As you can see, many of the functions shown in Figure 2-10 have equivalent UNIX system shell commands. Shell commands can easily be incorporated into shell scripts to accomplish the monitoring and control tasks you may need to do. The functions are available, however, and may be used in C programs as part of the UNIX system/C Language interface. They are documented in Section 2 of the *Programmers' Reference Manual*.

## Processes

Whenever you execute a command in the UNIX system you are initiating a process that is numbered and tracked by the operating system. A flexible feature of the UNIX system is that processes can be generated by other processes. This happens more than you might ever be aware of. For example, when you log in to your system, you are running a process, very probably the shell. If you then use an editor such as **vi**, take the option of invoking the

shell from `vi` and execute the `ps` command; you will see a display something like that in Figure 2-11 (which shows the results of a `ps -f` command):

UID	PID	PPID	C	STIME	TTY	TIME	COMMAND
abc	24210	1	0	06:13:14	tty29	0:05	-sh
abc	24631	24210	0	06:59:07	tty29	0:13	vi c2.uli
abc	28441	28358	80	09:17:22	tty29	0:01	ps -f
abc	28358	24631	2	09:15:14	tty29	0:01	sh -i

Figure 2-11: Process Status

---

As you can see, user `abc` (who went through the steps described above) now has four processes active. It is an interesting exercise to trace the chain that is shown in the Process ID (PID) and Parent Process ID (PPID) columns. The shell that was started when user `abc` logged on is Process 24210; its parent is the initialization process (Process ID 1). Process 24210 is the parent of Process 24631, and so on.

The four processes in the example above are all UNIX system shell level commands, but you can spawn new processes from your own program. (Actually, when you issue the command from your terminal to execute a program you are asking the shell to start another process, the process being your executable object module with all the functions and subroutines that were made a part of it by the link editor.)

You might think, "Well, it's one thing to switch from one program to another when I'm at my terminal working interactively with the computer; but why would a program want to run other programs, and if one does, why wouldn't I just put everything together into one big executable module?"

Overlooking the case where your program is itself an interactive application with diverse choices for the user, your program may need to run one or more other programs based on conditions it encounters in its own processing. (If it is the end of the month, go do a trial balance, for example.) The usual reasons why it might not be practical to create one monster executable are:

- The load module may get too big to fit in the maximum process size for your system.

- You may not have control over the object code of all the other modules you want to include.

Suffice it to say, there are legitimate reasons why this creation of new processes might need to be done. There are three ways to do it:

- **system(3S)**—request the shell to execute a command.
- **exec(2)**—stop this process and start another.
- **fork(2)**—start an additional copy of this process.

### **system(3S)**

The formal declaration of the **system** function looks like this:

```
#include <stdio.h>

int system(string)
char *string;
```

The function asks the shell to treat the string as a command line. The string can therefore be the name and arguments of any executable program or UNIX system shell command. If the exact arguments vary from one execution to the next, you may want to use **sprintf** to format the string before issuing the **system** command. When the command has finished running, **system** returns the shell exit status to your program. Execution of your program waits for the completion of the command initiated by **system** and then picks up again at the next executable statement.

### **exec(2)**

**exec** is the name of a family of functions that includes **execv**, **execle**, **execve**, **execlp**, and **execvp**. They all have the function of transforming the calling process into a new process. The reason for the variety is to provide different ways of pulling together and presenting the arguments of the function. An example of one version (**execl**) might be:

```
execl("/bin/prog2", "prog", progarg1, progarg2, (char *)0);
```

For **execl** the argument list is

**/bin/prog2** path name of the new process file  
**prog** the name the new process gets in its argv[0]  
**progarg1,** arguments to *prog2* as char \*'s  
**progarg2**  
**(char \*)0** a null char pointer to mark the end of the arguments

Check the manual page in the *Programmer's Reference Manual* for the rest of the details. The key point of the **exec** family is that there is no return from a successful execution: the calling process is finished, the new process overlays the old. The new process also takes over the Process ID and other attributes of the old process. If the call to **exec** is unsuccessful, control is returned to your program with a return value of -1. You can check **errno** (see below) to learn why it failed.

### fork(2)

The **fork** system call creates a new process that is an exact copy of the calling process. The new process is known as the child process; the caller is known as the parent process. The one major difference between the two processes is that the child gets its own unique process ID. When the **fork** process has completed successfully, it returns a 0 to the child process and the child's process ID to the parent. If the idea of having two identical processes seems a little funny, consider this:

- Because the return value is different between the child process and the parent, the program can contain the logic to determine different paths.
- The child process could say, "Okay, I'm the child. I'm supposed to issue an **exec** for an entirely different program."
- The parent process could say, "My child is going to be **execing** a new process. I'll issue a **wait** until I get word that that process is finished."

To take this out of the storybook world where programs talk like people and into the world of C programming (where people talk like programs), your code might include statements like this:



```
#include <errno.h>

int ch_stat, ch_pid, status;
char *progarg1;
char *progarg2;
void exit();
extern int errno;

    if ((ch_pid = fork()) < 0)
    {
        /* Could not fork...
           check errno
           */
    }
    else if (ch_pid == 0)                                /* child */
    {
        (void)execl("/bin/prog2", "prog", progarg1, progarg2, (char *)0);
        exit(2); /* execl() failed */
    }
    else        /* parent */
    {
        while ((status = wait(&ch_stat)) != ch_pid)
        {
            if (status < 0 && errno == ECHILD)
                break;
            errno = 0;
        }
    }
}
```

Figure 2-12: Example of **fork**

---

Because the child process ID is taken over by the new **exec'd** process, the parent knows the ID. What this boils down to is a way of leaving one program to run another, returning to the point in the first program where processing left off. This is exactly what the **system(3S)** function does. As a matter of fact, **system** accomplishes it through this same procedure of **forking** and **execing**, with a **wait** in the parent.

Keep in mind that the fragment of code above includes a minimum amount of checking for error conditions. There is also potential confusion about open files and which program is writing to a file. Leaving out the possibility of named files, the new process created by the **fork** or **exec** has the three standard files that are automatically opened: **stdin**, **stdout**, and **stderr**. If the parent has buffered output that should appear before output from the child, the buffers must be flushed before the fork. Also, if the parent and the child process both read input from a stream, whatever is read by one process will be lost to the other. That is, once something has been delivered from the input buffer to a process the pointer has moved on.

### Pipes

The idea of using pipes, a connection between the output of one program and the input of another, when working with commands executed by the shell is well established in the UNIX system environment. For example, to learn the number of archive files in your system you might enter a command like:

```
echo /lib/*.a /usr/lib/*.a | wc -w
```

that first echoes all the files in **/lib** and **/usr/lib** that end in **.a**, then pipes the results to the **wc** command, which counts their number.

A feature of the UNIX system/C Language interface is the ability to establish pipe connections between your process and a command to be executed by the shell, or between two cooperating processes. The first uses the **popen(3S)** subroutine that is part of the standard I/O package; the second requires the system call **pipe(2)**.

**popen** is similar in concept to the **system** subroutine in that it causes the shell to execute a command. The difference is that once having invoked **popen** from your program, you have established an open line to a concurrently running process through a stream. You can send characters or strings to this stream with standard I/O subroutines just as you would to **stdout** or to a named file. The connection remains open until your program invokes the companion **pclose** subroutine.

A common application of this technique might be a pipe to a printer spooler. For example:

```
#include <stdio.h>

main()
{
    FILE *pptr;
    char *outstring;

    if ((pptr = popen("lp", "w")) != NULL)
    {
        for(;;)
        {
            .
            .   /* Organize output */
            .
            (void)fprintf(pptr, "%s\n", outstring);
            .
            .
            .
        }
        .
        .
        .
        pclose(pptr);
        .
        .
        .
    }
}
```

Figure 2-13: Example of a **popen** pipe

---

## Error Handling

Within your C programs you must determine the appropriate level of checking for valid data and for acceptable return codes from functions and subroutines. If you use any of the system calls described in Section 2 of the *Programmer's Reference Manual*, you have a way in which you can find out the probable cause of a bad return value.

UNIX system calls that are not able to complete successfully almost always return a value of `-1` to your program. (If you look through the system calls in Section 2, you will see that there are a few calls for which no return value is defined, but they are the exceptions.) In addition to the `-1` that is returned to the program, the unsuccessful system call places an integer in an externally declared variable, **errno**. You can determine the value in **errno** if your program contains the statement

```
#include <errno.h>
```

The value in **errno** is not cleared on successful calls, so your program should check it only if the system call returned a `-1`. Errors are described in **intro(2)** of the *Programmer's Reference Manual*.

The subroutine **perror(3C)** can be used to print an error message (on **stderr**) based on the value of **errno**.

## Signals and Interrupts

Signals and interrupts are two words for the same thing. Both words refer to messages passed by the UNIX system to running processes. Generally, the effect is to cause the process to stop running. Some signals are generated if the process attempts to do something illegal; others can be initiated by a user against his or her own processes, or by the super-user against any process.

There is a system call, **kill**, that you can include in your program to send signals to other processes running under your user-id. The format for the **kill** call is:

```
kill(pid, sig)
```

where **pid** is the process number against which the call is directed, and **sig** is an integer from 1 to 19 that shows the intent of the message. The name "kill" is something of an overstatement; not all the messages have a "drop

dead" meaning. Some of the available signals are shown in Figure 2-14 as they are defined in `<sys/signal.h>`.

```
#define SIGHUP      1  /* hangup */
#define SIGINT     2  /* interrupt (rubout) */
#define SIGQUIT    3  /* quit (ASCII FS) */
#define SIGILL     4  /* illegal instruction (not reset when caught)*/
#define SIGTRAP   5  /* trace trap (not reset when caught) */
#define SIGIOT    6  /* IOT instruction */
#define SIGABRT   6  /* used by abort, replace SIGIOT in the future */
#define SIGEMT    7  /* EMT instruction */
#define SIGFPE    8  /* floating point exception */
#define SIGKILL   9  /* kill (cannot be caught or ignored) */
#define SIGBUS   10  /* bus error */
#define SIGSEGV  11  /* segmentation violation */
#define SIGSYS   12  /* bad argument to system call */
#define SIGPIPE  13  /* write on a pipe with no one to read it */
#define SIGALRM  14  /* alarm clock */
#define SIGTERM  15  /* software termination signal from kill */
#define SIGUSR1  16  /* user defined signal 1 */
#define SIGUSR2  17  /* user defined signal 2 */
#define SIGCLD   18  /* death of a child */
#define SIGPWR   19  /* power-fail restart */

                        /* SIGWIND and SIGPHONE only used in UNIX/PC */
/*#define SIGWIND 20*/ /* window change */
/*#define SIGPHONE 21*/ /* handset, line status change */

#define SIGPOLL 22 /* pollable event occurred */

#define NSIG    23  /* The valid signal number is from 1 to NSIG-1 */
#define MAXSIG  32  /* size of u_signal[], NSIG-1 <= MAXSIG*/
                        /* MAXSIG is larger than we need now. */
                        /* In the future, we can add more signal */
                        /* number without changing user.h */
```

Figure 2-14: Signal Numbers Defined in `/usr/include/sys/signal.h`

---

The `signal(2)` system call is designed to let you code methods of dealing with incoming signals. You have a three-way choice. You can (a) accept whatever the default action is for the signal, (b) have your program ignore the signal, or (c) write a function of your own to deal with it.

---

## Analysis/Debugging

The UNIX system provides several commands designed to help you discover the causes of problems in programs and to learn about potential problems.

### Sample Program

To illustrate how these commands are used and the type of output they produce, we have constructed a sample program that opens and reads an input file and performs one to three subroutines according to options specified on the command line. This program does not do anything you could not do quite easily on your pocket calculator, but it does serve to illustrate some points. The source code is shown in Figure 2-15. The header file, **recdef.h**, is shown at the end of the source code.

The output produced by the various analysis and debugging tools illustrated in this section may vary slightly from one installation to another. The *Programmer's Reference Manual* is a good source of additional information about the contents of the reports.

```
        /* Main module -- restate.c */

#include <stdio.h>
#include "recdef.h"

#define TRUE    1
#define FALSE   0

main(argc, argv)
int argc;
char *argv[];
{
    FILE *fopen(), *fin;
    void exit();
    int getopt();
    int oflag = FALSE;
    int pflag = FALSE;
    int rflag = FALSE;
    int ch;
    struct rec first;
    extern int opterr;
    extern float oppty(), pft(), rfe();

        /* restate.c is continued on the next page */
```

Figure 2-15: Source Code for Sample Program (Sheet 1 of 4)

---



```
/* restate.c continued */

if (argc < 2)
{
    (void) fprintf(stderr, "%s: Must specify option\n", argv[0]);
    (void) fprintf(stderr, "Usage: %s -rpo\n", argv[0]);
    exit(2);
}

opterr = FALSE;
while ((ch = getopt(argc, argv, "opr")) != EOF)
{
    switch(ch)
    {
        {
        case 'o':
            oflag = TRUE;
            break;
        case 'p':
            pflag = TRUE;
            break;
        case 'r':
            rflag = TRUE;
            break;
        default:
            (void) fprintf(stderr, "Usage: %s -rpo\n", argv[0]);
            exit(2);
        }
    }
}

if ((fin = fopen("info", "r")) == NULL)
{
    (void) fprintf(stderr, "%s: cannot open input file %s\n", argv[0], "info");
    exit(2);
}
```

Figure 2-15: Source Code for Sample Program (Sheet 2 of 4)

```
        /* restate.c continued */

if (fscanf(fin, "%s%f%f%f%f%f",first.pname,&first.ppx,
&first.dp,&first.i,&first.c,&first.t,&first.spx) != 7)
{
    (void) fprintf(stderr,"%s: cannot read first record from %s\n",
        argv[0],"info");
    exit(2);
}

printf("Property: %s\n",first.pname);

if(oflag)
    printf("Opportunity Cost: $%#5.2f\n",oppty(&first));

if(pflag)
    printf("Anticipated Profit(loss): $%#7.2f\n",pft(&first));

if(rflag)
    printf("Return on Funds Employed: %#3.2F%%\n",rfe(&first));
}

        /* End of Main Module -- restate.c */

        /* Opportunity Cost -- oppty.c */
#include "recdef.h"

float
oppty(ps)
struct rec *ps;
{
    return(ps->i/12 * ps->t * ps->dp);
}
```

Figure 2-15: Source Code for Sample Program (Sheet 3 of 4)

---

```
/* Profit -- pft.c */

#include "reodef.h"

float
pft(ps)
struct rec *ps;
{
    return(ps->spx - ps->ppx + ps->c);
}

/* Return on Funds Employed -- rfe.c */

#include "reodef.h"

float
rfe(ps)
struct rec *ps;
{
    return(100 * (ps->spx - ps->c) / ps->spx);
}

/* Header File -- reodef.h */

struct rec {          /* To hold input */
    char pname[25];
    float ppx;
    float dp;
    float i;
    float c;
    float t;
    float spx;
};
```

Figure 2-15: Source Code for Sample Program (Sheet 4 of 4)

## **cflow**

**cflow** produces a chart of the external references in C, **yacc**, **lex**, and assembly language files. Using the modules of our sample program, the command

**cflow restate.c oppty.c pft.c rfe.c**

produces the output shown in Figure 2-16.

```
1  main: int(), <restate.c 11>
2      fprintf: <>
3      exit: <>
4      getopt: <>
5      fopen: <>
6      fscanf: <>
7      printf: <>
8      oppty: float(), <oppty.c 7>
9      pft: float(), <pft.c 7>
10     rfe: float(), <rfe.c 8>
```

Figure 2-16: **cflow** Output, No Options

---

The `-r` option looks at the caller: callee relationship from the other side. It produces the output shown in Figure 2-17.

```
1  exit: <>
2      main : <>
3  fopen: <>
4      main : 2
5  fprintf: <>
6      main : 2
7  fscanf: <>
8      main : 2
9  getopt: <>
10     main : 2
11 main: int(), <restate.c 11>
12 oppty: float(), <oppty.c 7>
13     main : 2
14 pft: float(), <pft.c 7>
15     main : 2
16 printf: <>
17     main : 2
18 rfe: float(), <rfe.c 8>
19     main : 2
```

Figure 2-17: `cflow` Output, Using `-r` Option

---

The `-ix` option causes external and static data symbols to be included. Our sample program has only one such symbol, `opterr`. The output is shown in Figure 2-18.

```
1  main: int(), <restate.c 11>
2    fprintf: <>
3    exit: <>
4    opterr: <>
5    getopt: <>
6    fopen: <>
7    fscanf: <>
8    printf: <>
9    optty: float(), <oppty.c 7>
10   pft: float(), <pft.c 7>
11   rfe: float(), <rfe.c 8>
```

Figure 2-18: `cflow` Output, Using `-ix` Option

---

Combining the `-r` and the `-ix` options produces the output shown in Figure 2-19.

```
1  exit: <>
2      main : <>
3  fopen: <>
4      main : 2
5  fprintf: <>
6      main : 2
7  fscanf: <>
8      main : 2
9  getopt: <>
10     main : 2
11 main: int(), <restate.c 11>
12 oppty: float(), <oppty.c 7>
13     main : 2
14 opterr: <>
15     main : 2
16 pft: float(), <pft.c 7>
17     main : 2
18 printf: <>
19     main : 2
20 rfe: float(), <rfe.c 8>
21     main : 2
```

Figure 2-19: `cflow` Output, Using `-r` and `-ix` Options

## `ctrace`

`ctrace` lets you follow the execution of a C program statement by statement. `ctrace` takes a `.c` file as input and inserts statements in the source code to print out variables as each program statement is executed. You must direct the output of this process to a temporary `.c` file. The temporary file is then used as input to `cc`. When the resulting `a.out` file is executed, it produces output that can tell you a lot about what is going on in your program.

Options give you the ability to limit the number of times through loops. You can also include functions in your source file that turn the trace off and on so you can limit the output to portions of the program that are of particular interest.

**ctrace** accepts only one source code file as input. To use our sample program to illustrate, it is necessary to execute the following four commands:

```
ctrace restate.c > ct.main.c  
ctrace oppty.c > ct.op.c  
ctrace pft.c > ct.p.c  
ctrace rfe.c > ct.r.c
```

The names of the output files are completely arbitrary. Use any names that are convenient for you. The names must end in **.c**, since the files are used as input to the C compilation system.

```
cc -o ct.run ct.main.c ct.op.c ct.p.c ct.r.c
```

Now the command

```
ct.run -opr
```

produces the output shown in Figure 2-20. The command above will cause the output to be directed to your terminal (**stdout**). It is probably a good idea to direct it to a file or to a printer so you can refer to it.



```
8 main(argc, argv)
23 if (argc < 2)
    /* argc == 2 */
30 opterr = FALSE;
    /* FALSE == 0 */
    /* opterr == 0 */
31 while ((ch = getopt(argc,argv,"opr")) != EOF)
    /* argc == 2 */
    /* argv == 15729316 */
    /* ch == 111 or 'o' or "t" */
32 {
33     switch(ch)
        /* ch == 111 or 'o' or "t" */
35     case 'o':
36         oflag = TRUE;
            /* TRUE == 1 or "h" */
            /* oflag == 1 or "h" */
37         break;
48 }
31 while ((ch = getopt(argc,argv,"opr")) != EOF)
    /* argc == 2 */
    /* argv == 15729316 */
    /* ch == 112 or 'p' */
32 {
33     switch(ch)
        /* ch == 112 or 'p' */
38     case 'p':
39         pflag = TRUE;
            /* TRUE == 1 or "h" */
            /* pflag == 1 or "h" */
40         break;
48 }
```

Figure 2-20: ctrace Output (Sheet 1 of 3)

```
31 while ((ch = getopt(argc,argv,"opr")) != EOF)
    /* argc == 2 */
    /* argv == 15729316 */
    /* ch == 114 or 'r' */
32 {
33     switch(ch)
        /* ch == 114 or 'r' */
41     case 'r':
42         rflag = TRUE;
            /* TRUE == 1 or "h" */
            /* rflag == 1 or "h" */
43         break;
44     }
31 while ((ch = getopt(argc,argv,"opr")) != EOF)
    /* argc == 2 */
    /* argv == 15729316 */
    /* ch == -1 */
49 if ((fin = fopen("info","r")) == NULL)
    /* fin == 140200 */
54 if (fscanf(fin, "%s%f%f%f%f",first.pname,&first.ppx,
    &first.dp,&first.i,&first.c,&first.t,&first.spx) != 7)
    /* fin == 140200 */
    /* first.pname == 15729528 */
61 printf("Property: %s0,first.pname);
    /* first.pname == 15729528 or "Linden_Place" */ Property: Linden_Place

63 if(oflag)
    /* oflag == 1 or "h" */
64     printf("Opportunity Cost: $%#5.2f0,oppty(&first));
5 oppty(ps)
8 return(ps->i/12 * ps->t * ps->dp);
    /* ps->i == 1069044203 */
    /* ps->t == 1076494336 */
    /* ps->dp == 1088765312 */ Opportunity Cost: $4476.87
```

Figure 2-20: ctrace Output (Sheet 2 of 3)

---

```

66  if(pflag)
    /* pflag == 1 or "h" */
67      printf("Anticipated Profit(loss): %#7.2f0,pft(&first));
5  pft(ps)
8  return(ps->spk - ps->ppk + ps->c);
    /* ps->spk == 1091649040 */
    /* ps->ppk == 1091178464 */
    /* ps->c == 1087409536 */  Anticipated Profit(loss): $85950.00

69  if(rflag)
    /* rflag == 1 or "h" */
70      printf("Return on Funds Employed: %#3.2f%%0,rfe(&first));
6  rfe(ps)
9  return(100 * (ps->spk - ps->c) / ps->spk);
    /* ps->spk == 1091649040 */
    /* ps->c == 1087409536 */  Return on Funds Employed: 94.00%

/* return */

```

Figure 2-20: **ctrace** Output (Sheet 3 of 3)

Using a program that runs successfully is not the optimal way to demonstrate **ctrace**. It would be more helpful to have an error in the operation that could be detected by **ctrace**. This utility might be most useful in cases where the program runs to completion, but the output is not as expected.

## cxref

**cxref** analyzes a group of C source code files and builds a cross-reference table of the automatic, static, and global symbols in each file. The command

```
cxref -c -o cx.op restate.c oppty.c pft.c rfe.c
```

produces the output shown in Figure 2-21 in a file named, in this case, **cx.op**. The **-c** option causes the reports for the four **.c** files to be combined in one cross-reference file.

```

restate.c:

oppty.c:

pft.c:

rfe.c:

SYMBOL          FILE          FUNCTION      LINE

BUFSIZ          /usr/include/stdio.h  --            *9
EOF             /usr/include/stdio.h  --            49 *50
               restate.c           --            31
FALSE          restate.c           --            *6 15 16 17 30
FILE           /usr/include/stdio.h  --            *29 73 74
               restate.c           main          12
L_ctermid      /usr/include/stdio.h  --            *80
L_cuserid      /usr/include/stdio.h  --            *81
L_tmpnam       /usr/include/stdio.h  --            *83
NULL          /usr/include/stdio.h  --            46 *47
               restate.c           --            49
P_tmpdir       /usr/include/stdio.h  --            *82
TRUE           restate.c           --            *5 36 39 42
_IOEOF         /usr/include/stdio.h  --            *41
_IOERR         /usr/include/stdio.h  --            *42
_IOFBF        /usr/include/stdio.h  --            *36
_IOLBF        /usr/include/stdio.h  --            *43
_IOMYBUF      /usr/include/stdio.h  --            *40
_IONBF        /usr/include/stdio.h  --            *39
_IOREAD       /usr/include/stdio.h  --            *37
_IORW         /usr/include/stdio.h  --            *44
_IOWRT        /usr/include/stdio.h  --            *38
_NFILE        /usr/include/stdio.h  --            2 *3 73
_SBFSIZ       /usr/include/stdio.h  --            *16

```

Figure 2-21: cxref Output, Using -c Option (Sheet 1 of 5)

SYMBOL	FILE	FUNCTION	LINE
<u>base</u>	/usr/include/stdio.h	--	*26
<u>bufend()</u>	/usr/include/stdio.h	--	*57
<u>bufendtab</u>	/usr/include/stdio.h	--	*78
<u>bufsiz()</u>	/usr/include/stdio.h	--	*58
<u>cnt</u>	/usr/include/stdio.h	--	*20
<u>file</u>	/usr/include/stdio.h	--	*28
<u>flag</u>	/usr/include/stdio.h	--	*27
<u>job</u>	/usr/include/stdio.h	--	*73
<u>ptr</u>	restate.c	main	25 26 45 51 57
argc	/usr/include/stdio.h	--	*21
	restate.c	--	8
	restate.c	main	*9 23 31
argv	restate.c	--	8
	restate.c	main	*10 25 26 31 45 51 57
c	./reconf.h	--	*6
	pft.c	pft	8
	restate.c	main	55
	rfe.c	rfe	9
ch	restate.c	main	*18 31 33
clearerr()	/usr/include/stdio.h	--	*67
ctermid()	/usr/include/stdio.h	--	*77
cuserid()	/usr/include/stdio.h	--	*77
dp	./reconf.h	--	---*4
	oppty.c	oppty	8
	restate.c	main	55
exit()	restate.c	main	*13 27 46 52 58
fdopen()	/usr/include/stdio.h	--	*74

Figure 2-21: cxref Output, Using -c Option (Sheet 2 of 5)

SYMBOL	FILE	FUNCTION	LINE
feof()			
	/usr/include/stdio.h	--	*68
ferror()			
	/usr/include/stdio.h	--	*69
fgets()			
	/usr/include/stdio.h	--	*77
fileno()			
	/usr/include/stdio.h	--	*70
fin	restate.c	main	*12 49 54
first	restate.c	main	*19 54 55 61 64 67 70
fopen()			
	/usr/include/stdio.h	--	*74
	restate.c	main	12 49
fprintf	restate.c	main	25 26 45 51 57
freopen()			
	/usr/include/stdio.h	--	*74
fscanf	restate.c	main	54
ftell()			
	/usr/include/stdio.h	--	*75
getc()			
	/usr/include/stdio.h	--	*61
getchar()			
	/usr/include/stdio.h	--	*65
getopt()			
	restate.c	main	*14 31
gets()			
	/usr/include/stdio.h	--	*77
i	./reodef.h	--	*5
	oppty.c	oppty	8
	restate.c	main	55
lint	/usr/include/stdio.h	--	60
main()			
	restate.c	--	*8

Figure 2-21: **cxref** Output, Using **-c** Option (Sheet 3 of 5)

---

SYMBOL	FILE	FUNCTION	LINE
oflag	restate.c	main	*15 36 63
oppty()	oppty.c	--	*5
	restate.c	main	*21 64
opterr	restate.c	main	*20 30
p	/usr/include/stdio.h	--	*57 *58 *61 62
*62 63 64 67 *67 68 *68 69 *69 70 *70			
pdp11	/usr/include/stdio.h	--	11
pflag	restate.c	main	*16 39 66
pft()	pft.c	--	*5
	restate.c	main	*21 67
pname	./redef.h	--	*2
	restate.c	main	54 61
popen()	/usr/include/stdio.h	--	*74
ppx	./redef.h	--	*3
	pft.c	pft	8
	restate.c	main	54
printf	restate.c	main	61 64 67 70
ps	oppty.c	--	5
	oppty.c	oppty	*6 8
	pft.c	--	5
	pft.c	pft	*6 8
	rfe.c	--	6
	rfe.c	rfe	*7 9
putc()	/usr/include/stdio.h	--	*62
putchar()	/usr/include/stdio.h	--	*66
rec	./redef.h	--	*1
	oppty.c	oppty	6
	pft.c	pft	6
	restate.c	main	19
	rfe.c	rfe	7

Figure 2-21: cxref Output, Using -c Option (Sheet 4 of 5)

SYMBOL	FILE	FUNCTION	LINE
rewind()	/usr/include/stdio.h	--	*76
rfe()	restate.c	main	*21 70
	rfe.c	--	*6
rflag	restate.c	main	*17 42 69
setbuf()	/usr/include/stdio.h	--	*76
spx	./redef.h	--	*8
	pft.c	pft	8
	restate.c	main	55
	rfe.c	rfe	9
stderr	/usr/include/stdio.h	--	*55
	restate.c	--	25 26 45 51 57
stdin	/usr/include/stdio.h	--	*53
stdout	/usr/include/stdio.h	--	*54
t	./redef.h	--	*7
	oppty.c	oppty	8
	restate.c	main	55
tempnam()	/usr/include/stdio.h	--	*77
tmpfile()	/usr/include/stdio.h	--	*74
tmpnam()	/usr/include/stdio.h	--	*77
u370	/usr/include/stdio.h	--	5
u3b	/usr/include/stdio.h	--	8 19
u3b5	/usr/include/stdio.h	--	8 19
vax	/usr/include/stdio.h	--	8 19
x	/usr/include/stdio.h	--	*62 63 64 66 *66

Figure 2-21: cxref Output, Using -c Option (Sheet 5 of 5)



## lint

**lint** looks for features in a C program that are apt to cause execution errors, that are wasteful of resources, or that create problems of portability. The following command produces the output shown in Figure 2-22:

```
lint restate.c oppty.c pft.c rfe.c
```

```
restate.c:

restate.c
=====
(71) warning: main() returns random value to invocation environment
oppty.c:
pft.c:
rfe.c:

=====
function returns value which is always ignored
printf
```

Figure 2-22: **lint** Output

**lint** has options that will produce additional information. Check the *User's Reference Manual*. The error messages give you the line numbers of some items you may want to review.

## **prof**

**prof** produces a report on the amount of execution time spent in various portions of your program and the number of times each function is called. The program must be compiled with the **-p** option. When a program that was compiled with that option is run, a file called **mon.out** is produced. **mon.out** and **a.out** (or whatever name identifies your executable file) are input to the **prof** command.

The sequence of steps needed to produce a profile report for our sample program is as follows:

Step 1: Compile the programs with the **-p** option:

```
cc -p restate.c oppty.c pft.c rfe.c
```

Step 2: Run the program to produce a file **mon.out**.

```
a.out -opr
```

Step 3: Execute the **prof** command:

```
prof a.out
```

The example of the output of this last step is shown in Figure 2-23. The figures may vary from one run to another. You will also notice that programs of very small size, like that used in the example, produce statistics that are not overly helpful.

---

%Time	Seconds	Cumsecs	#Calls	msec/call	Name
50.0	0.03	0.03	3	8.	fcvt
20.0	0.01	0.04	6	2.	atof
20.0	0.01	0.05	5	2.	write
10.0	0.00	0.05	1	5.	fwrite
0.0	0.00	0.05	1	0.	monitor
0.0	0.00	0.05	1	0.	creat
0.0	0.00	0.05	4	0.	printf
0.0	0.00	0.05	2	0.	profil
0.0	0.00	0.05	1	0.	fscanf
0.0	0.00	0.05	1	0.	__doscan
0.0	0.00	0.05	1	0.	oppty
0.0	0.00	0.05	1	0.	__filbuf
0.0	0.00	0.05	3	0.	strchr
0.0	0.00	0.05	1	0.	strcmp
0.0	0.00	0.05	1	0.	ldexp
0.0	0.00	0.05	1	0.	getenv
0.0	0.00	0.05	1	0.	fopen
0.0	0.00	0.05	1	0.	__findiop
0.0	0.00	0.05	1	0.	open
0.0	0.00	0.05	1	0.	main
0.0	0.00	0.05	1	0.	read
0.0	0.00	0.05	1	0.	strcpy
0.0	0.00	0.05	14	0	ungetc
0.0	0.00	0.05	4	0.	__doprnt
0.0	0.00	0.05	1	0.	pft
0.0	0.00	0.05	1	0.	rfe
0.0	0.00	0.05	4	0.	__xflsbuf
0.0	0.00	0.05	1	0.	__wrtchk
0.0	0.00	0.05	2	0.	__findbuf
0.0	0.00	0.05	2	0.	isatty
0.0	0.00	0.05	2	0.	ioctl
0.0	0.00	0.05	1	0.	malloc
0.0	0.00	0.05	1	0.	memchr
0.0	0.00	0.05	1	0.	memcpy
0.0	0.00	0.05	2	0.	sbrk
0.0	0.00	0.05	4	0.	getopt

Figure 2-23: prof Output

### size

**size** produces information on the number of bytes occupied by the three sections (text, data, and bss) of a common object file when the program is brought into main memory to be run. Here are the results of one invocation of the **size** command with our object file as an argument.

```
11832 + 3872 + 2240 = 17944
```

Do not confuse this number with the number of characters in the object file that appears when you do an **ls -l** command. That figure includes the symbol table and other header information that is not used at run time.

### strip

**strip** removes the symbol and line number information from a common object file. When you issue this command, the number of characters shown by the **ls -l** command approaches the figure shown by the **size** command, but still includes some header information that is not counted as part of the .text, .data, or .bss section. After the **strip** command has been executed, it is no longer possible to use the file with the **sdb** command.

### sdb

**sdb** stands for Symbolic Debugger, which means you can use the symbolic names in your program to pinpoint where a problem has occurred. You can use **sdb** to debug C programs. There are two basic ways to use **sdb**: by running your program under control of **sdb**, or by using **sdb** to rummage through a core image file left by a program that failed. The first way lets you see what the program is doing up to the point at which it fails (or to skip around the failure point and proceed with the run). The second method lets you check the status at the moment of failure, which may or may not disclose the reason the program failed.

Chapter 15 contains a tutorial on **sdb** that describes the interactive commands you can use to work your way through your program. For the time being we want to tell you just a couple of key things you need to do when using it.

1. Compile your program(s) with the **-g** option, which causes additional information to be generated for use by **sdb**.
2. Run your program under **sdb** with the command:

**sdb myprog - srcdir**

where **myprog** is the name of your executable file (**a.out** is the default), and **srcdir** is an optional list of the directories where source code for your modules may be found. The dash between the two arguments keeps **sdb** from looking for a core image file.

---

# Program Organizing Utilities

The following three utilities are helpful in keeping your programming work organized effectively.

## The **make** Command

When you have a program that is made up of more than one module of code you begin to run into problems of keeping track of which modules are up-to-date and which need to be recompiled when changes are made in another module. The **make** command is used to ensure that dependencies between modules are recorded so that changes in one module results in the re-compilation of dependent programs. Even control of a program as simple as the one shown in Figure 2-15 is made easier through the use of **make**.

The **make** utility requires a description file that you create with an editor. The description file (also referred to by its default name: **makefile**) contains the information used by **make** to keep a target file current. The target file is typically an executable program. A description file contains three types of information:

- dependency information    tells the **make** utility the relationship between the modules that comprise the target program.
- executable commands        needed to generate the target program. **make** uses the dependency information to determine which executable commands should be passed to the shell for execution.
- macro definitions            provide a shorthand notation within the description file to make maintenance easier. Macro definitions can be overridden by information from the command line when the **make** command is entered.

The **make** command works by checking the "last changed" time of the modules named in the description file. When **make** finds a component that has been changed more recently than modules that depend on it, the specified commands (usually compilations) are passed to the shell for execution.

The **make** command takes three kinds of arguments: options, macro definitions, and target file names. If no description file name is given as an option on the command line, **make** searches the current directory for a file named **makefile** or **Makefile**. Figure 2-24 shows a **makefile** for our sample program.

```
OBJECTS = restate.o oppty.o pft.o rfe.o
all: restate
restate: $(OBJECTS)
        $(CC) $(CFLAGS) $(LDFLAGS) $(OBJECTS) -o restate

$(OBJECTS): ../redef.h

clean:
        rm -f $(OBJECTS)

clobber: clean
        rm -f restate
```

Figure 2-24: **make** Description File

---

The following things are worth noticing in this description file:

- It identifies the target, **restate**, as being dependent on the four object modules. Each of the object modules in turn is defined as being dependent on the header file, **redef.h**, and by default, on its corresponding source file.
- A macro, **OBJECTS**, is defined as a convenient shorthand for referring to all of the component modules.

Whenever testing or debugging results in a change to one of the components of **restate**, for example, a command such as the following should be entered:

```
make CFLAGS=-g restate
```

This has been a very brief overview of the **make** utility. There is more on **make** in Chapter 3, and a detailed description of **make** can be found in Chapter 13.

## The Archive

The most common use of an archive file, although not the only one, is to hold object modules that make up a library. The library can be named on the link editor command line (or with a link editor option on the **cc** command line). This causes the link editor to search the symbol table of the archive file when attempting to resolve references.

The **ar** command is used to create an archive file, to manipulate its contents and to maintain its symbol table. The structure of the **ar** command is a little different from the normal UNIX system arrangement of command line options. When you enter the **ar** command you include a one-character key from the set **drqtpmx** that defines the type of action you intend. The key may be combined with one or more additional characters from the set **vuaibcls** that modify the way the requested operation is performed. The makeup of the command line is

```
ar -key [posname] afile [name]...
```

where *posname* is the name of a member of the archive and may be used with some optional key characters to make sure that the files in your archive are in a particular order. The *afile* argument is the name of your archive file. By convention, the suffix **.a** is used to indicate the named file is an archive file. (**libc.a**, for example, is the archive file that contains many of the object files of the standard C subroutines.) One or more *names* may be furnished. These identify files that are subjected to the action specified in the *key*.

We can make an archive file to contain the modules used in our sample program, **restate**. The command to do this is

```
ar -rv rste.a restate.o oppty.o pft.o rfe.o
```

If these are the only **.o** files in the current directory, you can use shell metacharacters as follows:

```
ar -rv rste.a *.o
```



Either command will produce this feedback:

```
a - restate.o
a - oppty.o
a - pft.o
a - rfe.o
ar: creating rste.a
```

The **nm** command is used to get a variety of information from the symbol table of common object files. The object files can be, but do not have to be, in an archive file. Figure 2-25 shows the output of this command when executed with the **-f** (for full) option on the archive we just created. The object files were compiled with the **-g** option.

## Program Organizing Utilities

---

Symbols from rste.a[restate.o]

Name	Value	Class	Type	Size	Line	Section
.ofake			strtag	struct	16	
restate.c		file				
_cnt	0	strmem	int			
_ptr	4	strmem	*Uchar			
_base	8	strmem	*Uchar			
_flag	12	strmem	char			
_file	13	strmem	char			
.eos		endstr		16		
rec		strtag	struct	52		
pname	0	strmem	char[25]	25		
ppx	28	strmem	float			
dp	32	strmem	float			
i	36	strmem	float			
c	40	strmem	float			
t	44	strmem	float			
spx	48	strmem	float			
.eos		endstr		52		
main	0	extern	int( )	520		.text
.bf	10	fcn			11	.text
argc	0	argm't	int			
argv	4	argm't	**char			
fin	0	auto	*struct-.ofake	16		
oflag	4	auto	int			
pflag	8	auto	int			
rflag	12	auto	int			
ch	16	auto	int			

Figure 2-25: nm Output, with -f Option (Sheet 1 of 5)

---

Symbols from rste.a[restate.o]

Name	Value	Class	Type	Size	Line	Section
first	20	auto	struct-rec	52		
.ef	518	fcn			61	.text
FILE		typedef	struct-.0fake	16		
.text	0	static		31	39	.text
.data	520	static			4	.data
.bss	824	static				.bss
_iob	0	extern				
fprintf	0	extern				
exit	0	extern				
opterr	0	extern				
getopt	0	extern				
fopen	0	extern				
fscanf	0	extern				
printf	0	extern				
oppty	0	extern				
pft	0	extern				
rfe	0	extern				

Figure 2-25: **nm** Output, with **-f** Option (Sheet 2 of 5)

Symbols from rste.a[oppty.o]

Name	Value	Class	Type	Size	Line	Section
oppty.c		file				
rec		strtag	struct	52		
pname	0	strmem	char[25]	25		
ppx	28	strmem	float			
dp	32	strmem	float			
i	36	strmem	float			
c	40	strmem	float			
t	44	strmem	float			
spx	48	strmem	float			
.eos		endstr		52		
oppty	0	extern	float()	64		.text
.bf	10	fcn			7	.text
ps	0	argm't	*struct-rec	52		
.ef	62	fcn			3	.text
.text	0	static		4	1	.text
.data	64	static				.data
.bss	72	static				.bss

Figure 2-25: **nm** Output, with **-f** Option (Sheet 3 of 5)

---

Symbols from rste.a[pft.o]

Name	Value	Class	Type	Size	Line	Section
pft.c		file				
rec		strtag	struct	52		
pname	0	strmem	char[25]	25		
ppx	28	strmem	float			
dp	32	strmem	float			
i	36	strmem	float			
c	40	strmem	float			
t	44	strmem	float			
spx	48	strmem	float			
..eos		endstr		52		
pft	0	extern	float()	60		.text
..bf	10	fcn			7	.text
ps	0	argm't	*struct-rec	52		
..ef	58	fcn			3	.text
..text	0	static		4		.text
..data	60	static				.data
..bss	60	static				.bss

Figure 2-25: **nm** Output, with **-f** Option (Sheet 4 of 5)

---

Symbols from rste.a[rfe.o]

Name	Value	Class	Type	Size	Line	Section
rfe.c		file				
rec		strtag	struct	52		
pname	0	strmem	char[25]	25		
ppx	28	strmem	float			
dp	32	strmem	float			
i	36	strmem	float			
c	40	strmem	float			
t	44	strmem	float			
spx	48	strmem	float			
.eos		endstr		52		
rfe	0	extern	float()	68		.text
.bf	10	fcn			8	.text
ps	0	argm't	*struct-rec	52		
.ef	64	fcn			3	.text
.text	0	static		4	1	.text
.data	68	static				.data
.bss	76	static				.bss

Figure 2-25: **nm** Output, with **-f** Option (Sheet 5 of 5)

---

For **nm** to work on an archive file all of the contents of the archive have to be object modules. If you have stored other things in the archive, you will get the message:

```
nm: rste.a bad magic
```

when you try to execute the command.

## **Use of SCCS by Single-User Programmers**

The UNIX system Source Code Control System (SCCS) is a set of programs designed to keep track of different versions of programs. When a program has been placed under control of SCCS, only a single copy of any one version of the code can be retrieved for editing at a given time. When

program code is changed and the program returned to SCCS, only the changes are recorded. Each version of the code is identified by its SID, or **SCCS ID**entifying number. By specifying the SID when the code is extracted from the SCCS file, it is possible to return to an earlier version. If an early version is extracted with the intent of editing it and returning it to SCCS, a new branch of the development tree is started. The set of programs that make up SCCS appear as UNIX system commands. The commands are:

- admin**
- get**
- delta**
- prs**
- rmdel**
- cdc**
- what**
- sccsdiff**
- comb**
- val**

It is most common to think of SCCS as a tool for project control of large programming projects. It is, however, entirely possible for any individual user of the UNIX system to set up a private SCCS system. Chapter 14 is an SCCS user's guide.







# Application Programming

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# 3 Application Programming

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---

# Introduction

This chapter deals with programming where the objective is to produce sets of programs (applications) that will run on a UNIX system computer.

The chapter begins with a discussion of how the ground rules change as you move up the scale from writing programs that are essentially for your own private use (we have called this single-user programming), to working as a member of a programming team developing an application that is to be turned over to others to use.

There is a section on how the criteria for selecting appropriate programming languages may be influenced by the requirements of the application.

The next three sections of the chapter deal with a number of loosely-related topics that are of importance to programmers working in the application development environment. Most of these mirror topics that were discussed in Chapter 2, Programming Basics, but here we try to point out aspects of the subject that are particularly pertinent to application programming. They are covered under the following headings:

- **Advanced Programming Tools**

- deals with such topics as File and Record Locking, Interprocess Communication, and programming terminal screens.

- **Programming Support Tools**

- covers the Common Object File Format, link editor directives, shared libraries, Symbolic Debugger (**sdb**), and **lint**.

- **Project Control Tools**

- includes some discussion of **make** and SCCS.

The chapter concludes with a description of a sample application called **liber** that uses several of the components described in earlier portions of the chapter.

---

# Application Programming

The characteristics of the application programming environment that make it different from single-user programming have at their base the need for interaction and for sharing of information.

## Numbers

Perhaps the most obvious difference between application programming and single-user programming is in the quantities of the components. Not only are applications generally developed by teams of programmers, but the number of separate modules of code can grow into the hundreds on even a fairly simple application.

When more than one programmer works on a project, there is a need to share such information as:

- the operation of each function
- the number, identity, and type of arguments expected by a function
- if pointers are passed to a function, are the objects being pointed to modified by the called function, and what is the lifetime of the pointed-to object
- the data type returned by a function

In an application, there is an odds-on possibility that the same function can be used in many different programs, by many different programmers. The object code needs to be kept in a library accessible to anyone on the project who needs it.

## Portability

When you are working on a program to be used on a single model of a computer, your concerns about portability are minimal. In application development, on the other hand, a desirable objective often is to produce code that will run on many different UNIX system computers. Some of the things that affect portability will be touched on later in this chapter.

## **Documentation**

A single-user program has modest needs for documentation. There should be enough to remind the program's creator how to use it, and what the intent was in portions of the code.

On an application development project there is a significant need for two types of internal documentation:

- comments throughout the source code that enable successor programmers to understand easily what is happening in the code. Applications can be expected to have a useful life of 5 or more years, and frequently need to be modified during that time. It is not realistic to expect that the same person who wrote the program will always be available to make modifications. Even if that does happen, the comments will make the maintenance job a lot easier.
- hard-copy descriptions of functions should be available to all members of an application development team. Without them it is difficult to keep track of available modules, which can result in the same function being written over again.

Unless end-users have clear, readily-available instructions in how to install and use an application they either will not do it at all (if that is an option) or do it improperly.

The microcomputer software industry has become ever more keenly aware of the importance of good end-user documentation. There are cases on record where the success of a software package has been attributed in large part to the fact that it had exceptionally good documentation. There are also cases where a pretty good piece of software was not widely used due to the inaccessibility of its manuals. There appears to be no truth to the rumor that in one or two cases, end-users have thrown the software away and just read the manual.

## **Project Management**

Without effective project management, an application development project is in trouble. This subject will not be dealt with in this guide, except to mention the following three things that are vital functions of project management:

- tracking dependencies between modules of code
- dealing with change requests in a controlled way
- seeing that milestone dates are met.



---

# Language Selection

In this section we talk about some of the considerations that influence the selection of programming languages and describe three of the special purpose languages that are part of the UNIX system environment.

## Influences

In single-user programming the choice of language is often a matter of personal preference; a language is chosen because it is the one the programmer feels most comfortable with.

An additional set of considerations comes into play when making the same decision for an application development project.

Is there an existing standard within the organization that should be observed?

A firm may decide to emphasize one language because a good supply of programmers is available who are familiar with it.

Does one language have better facilities for handling the particular algorithm?

One would like to see all language selection based on such objective criteria, but it is often necessary to balance this against the skills of the organization.

Is there an inherent compatibility between the language and the UNIX operating system?

This is sometimes the impetus behind selecting C for programs destined for a UNIX system machine.

Are there existing tools that can be used?

If parsing of input lines is an important phase of the application, perhaps a parser generator such as **yacc** should be employed to develop what the application needs.

Does the application integrate other software into the whole package?

If, for example, a package is to be built around an existing data base management system, there may be constraints on the variety of languages the data base management system can accommodate.

## Special Purpose Languages

The UNIX system contains a number of tools that can be included in the category of special purpose languages. Three that are especially interesting are **awk**, **lex**, and **yacc**.

### What awk Is Like

The **awk** utility scans an ASCII input file record by record, looking for matches to specific patterns. When a match is found, an action is taken. Patterns and their accompanying actions are contained in a specification file referred to as the program. The program can be made up of a number of statements. However, since each statement has the potential for causing a complex action, most **awk** programs consist of only a few. The set of statements may include definitions of the pattern that separates one record from another (a newline character, for example), and what separates one field of a record from the next (white space, for example). It may also include actions to be performed before the first record of the input file is read, and other actions to be performed after the final record has been read. All statements in between are evaluated in order, for each record in the input file. To paraphrase the action of a simple **awk** program, it would go something like this:

Look through the input file.

Every time you see this specific pattern, do this action.

A more complex **awk** program might be paraphrased like this:

First do some initialization.

Then, look through the input file.

Every time you see this specific pattern, do this action.

Every time you see this other pattern, do another action.

After all the records have been read, do these final things.

The directions for finding the patterns and for describing the actions can get pretty complicated, but the essential idea is as simple as the two sets of statements above.

One of the strong points of **awk** is that once you are familiar with the language syntax, programs can be written very quickly. They do not always run very fast, however, so they are seldom appropriate if you want to run the same program repeatedly on a large quantities of records. In such a case, it is likely to be better to translate the program to a compiled language.

### **How awk Is Used**

One typical use of **awk** would be to extract information from a file and print it out in a report. Another might be to pull fields from records in an input file, arrange them in a different order, and pass the resulting rearranged data to a function that adds records to your data base. There is an example of a use of **awk** in the sample application at the end of this chapter.

### **Where to Find More Information**

The manual page for **awk** is in Section (1) of the *User's/System Administrator's Reference Manual*. Chapter 4 of this guide contains a description of the **awk** syntax and a number of examples showing ways in which **awk** may be used.

### **What lex and yacc Are Like**

The utilities **lex** and **yacc** are often mentioned in the same breath because they perform complementary parts of what can be viewed as a single task: making sense out of input. The two utilities also share the common characteristic of producing source code for C language subroutines from specifications that appear on the surface to be quite similar.

Recognizing input is a recurring problem in programming. Input can be from various sources. In a language compiler, for example, the input is normally contained in a file of source language statements. The UNIX system shell language most often receives its input from a person keying in commands from a terminal. Frequently, information coming out of one program is fed into another where it must be evaluated.

The process of input recognition can be subdivided into two tasks: lexical analysis and parsing, and that is where **lex** and **yacc** come in. In both utilities, the specifications cause the generation of C language subroutines that deal with streams of characters; **lex** generates subroutines that do lexical analysis while **yacc** generates subroutines that do parsing.

To describe those two tasks in dictionary terms:

Lexical analysis has to do with identifying the words or vocabulary of a language as distinguished from its grammar or structure.

Parsing is the act of describing units of the language grammatically. Students in elementary school are often taught to do this with sentence diagrams.

Of course, the important thing to remember here is that in each case the rules for our lexical analysis or parsing are those we set down ourselves in the **lex** or **yacc** specifications. Because of this, the dividing line between lexical analysis and parsing sometimes becomes fuzzy.

The fact that **lex** and **yacc** produce C language source code means that these parts of what may be a large programming project can be separately maintained. The generated source code is processed by the C compiler to produce an object file. The object file can be link edited with others to produce programs that then perform whatever process follows from the recognition of the input.

### How lex Is Used

A **lex** subroutine scans a stream of input characters and waves a flag each time it identifies something that matches one or another of its rules. The waved flag is referred to as a token. The rules are stated in a format that closely resembles the one used by the UNIX system text editor for regular expressions. For example,

```
[ \t]+
```

describes a rule that recognizes a string of one or more blanks or tabs (without mentioning any action to be taken). A more complete statement of that rule might have this notation:

```
[ \t]+ ;
```

which, in effect, says to ignore white space. It carries this meaning because no action is specified when a string of one or more blanks or tabs is recognized. The semicolon marks the end of the statement.

Another rule, one that does take some action, could be stated like this:

```
[0-9]+ {
    i = atoi(yytext);
    return(NBR);
}
```

This rule depends on several things:

NBR must have been defined as a token in an earlier part of the **lex** source code called the declaration section. (It may be in a header file which is **#include**'d in the declaration section.)

**i** is declared as an **extern int** in the declaration section.

It is a characteristic of **lex** that things it finds are made available in a character string called **yytext**.

Actions can make use of standard C syntax. Here, the standard C subroutine, **atoi**, is used to convert the string to an integer.

What this rule boils down to is **lex** saying, "Hey, I found the kind of token we call NBR, and its value is now in **i**."

To review the steps of the process:

1. The **lex** specification statements are processed by the **lex** utility to produce a file called **lex.yy.c**. (This is the standard name for a file generated by **lex**, just as **a.out** is the standard name for the executable file generated by the link editor.)
2. **lex.yy.c** is transformed by the C compiler (with a **-c** option) into an object file called **lex.yy.o** that contains a subroutine called **yylex()**.
3. **lex.yy.o** is link edited with other subroutines. Presumably one of those subroutines will call **yylex()** with a statement such as:

```
while((token = yylex()) != 0)
```

and other subroutines (or even **main**) will deal with what comes back.

### Where to Find More Information

The manual page for **lex** is in Section (1) of the *Programmer's Reference Manual*. A tutorial on **lex** is contained in Chapter 5 of this guide.

### How yacc Is Used

The **yacc** subroutines are produced by pretty much the same series of steps as **lex**:

1. The **yacc** specification is processed by the **yacc** utility to produce a file called **y.tab.c**.
2. **y.tab.c** is compiled by the C compiler producing an object file, **y.tab.o**, that contains the subroutine **yyparse()**. A significant difference is that **yyparse()** calls a subroutine called **yylex()** to perform lexical analysis.
3. The object file **y.tab.o** may be link edited with other subroutines, one of which will be called **yylex()**.

There are two things worth noting about this sequence:

1. The parser generated by the **yacc** specifications calls a lexical analyzer to scan the input stream and return tokens.
2. While the lexical analyzer is called by the same name as one produced by **lex**, it does not have to be the product of a **lex** specification. It can be any subroutine that does the lexical analysis.

What really differentiates these two utilities is the format for their rules. As noted above, **lex** rules are regular expressions like those used by UNIX system editors. **yacc** rules are chains of definitions and alternative definitions, written in Backus-Naur form, accompanied by actions. The rules may refer to other rules defined further down the specification. Actions are sequences of C language statements enclosed in braces. They frequently contain numbered variables that enable you to reference values associated with parts of the rules.

An example might make that easier to understand:

```

%token  NUMBER
%%
expr    : numb                { $$ = $1; }
        | expr '+' expr      { $$ = $1 + $3; }
        | expr '-' expr      { $$ = $1 - $3; }
        | expr '*' expr      { $$ = $1 * $3; }
        | expr '/' expr      { $$ = $1 / $3; }
        | '(' expr ')'       { $$ = $2; }
        ;
numb    : NUMBER             { $$ = $1; }
        ;

```

This fragment of a **yacc** specification shows

- **NUMBER** identified as a token in the declaration section
- the start of the rules section indicated by the pair of percent signs
- a number of alternate definitions for *expr* separated by the **|** sign and terminated by the semicolon
- actions to be taken when a rule is matched
- within actions, numbered variables used to represent components of the rule:
  - \$\$\$ means the value to be returned as the value of the whole rule
  - \$*n* means the value associated with the *n*th component of the rule, counting from the left
- *numb* defined as meaning the token **NUMBER**. This is a trivial example that illustrates that one rule can be referenced within another, as well as within itself.

As with **lex**, the compiled **yacc** object file will generally be link edited with other subroutines that handle processing that takes place after the parsing—or even ahead of it.

### **Where to Find More Information**

The manual page for **yacc** is in Section (1) of the *Programmer's Reference Manual*. A detailed description of **yacc** may be found in Chapter 6 of this guide.



---

## Advanced Programming Tools

In Chapter 2 we described the use of such basic elements of programming in the UNIX system environment as the standard I/O library, header files, system calls and subroutines. In this section we introduce tools that are more apt to be used by members of an application development team than by a single-user programmer. The section contains material on the following topics:

- memory management
- file and record locking
- interprocess communication
- programming terminal screens.

### Memory Management

There are situations where a program needs to ask the operating system for blocks of memory. It may be, for example, that a number of records have been extracted from a data base and need to be held for some further processing. Rather than writing them out to a file on secondary storage and then reading them back in again, it is likely to be a great deal more efficient to hold them in memory for the duration of the process. (This is not to ignore the possibility that portions of memory may be paged out before the program is finished; but such an occurrence is not pertinent to this discussion.) There are two C language subroutines available for acquiring blocks of memory and they are both called **malloc**. One of them is **malloc(3C)**, the other is **malloc(3X)**. Each has several related functions that do specialized tasks in the same area. They are:

- **free**—to inform the system that space is being relinquished
- **realloc**—to change the size and possibly move the block
- **calloc**—to allocate space for an array and initialize it to zeros

In addition, **malloc(3X)** has a function, **mallopt**, that provides for control over the space allocation algorithm, and a structure, **mallinfo**, from which the program can get information about the usage of the allocated space.

**malloc(3X)** runs faster than the other version. It is loaded by specifying

**-lmalloc**

on the **cc(1)** or **ld(1)** command line to direct the link editor to the proper library. When you use **malloc(3X)**, your program should contain the statement

```
#include <malloc.h>
```

where the values for **mallopt** options are defined.

See the *Programmer's Reference Manual* for the formal definitions of the two **mallocs**.

## File and Record Locking

The provision for locking files, or portions of files, is primarily used to prevent the sort of error that can occur when two or more users of a file try to update information at the same time. The classic example is the airlines reservation system where two ticket agents each assign a passenger to Seat A, Row 5 on the 5 o'clock flight to Detroit. A locking mechanism is designed to prevent such mishaps by blocking Agent B from even seeing the seat assignment file until Agent A's transaction is complete.

File locking and record locking are really the same thing, except that file locking implies the whole file is affected; record locking means that only a specified portion of the file is locked. (Remember, in the UNIX system, file structure is undefined; a record is a concept of the programs that use the file.)

Two types of locks are available: read locks and write locks. If a process places a read lock on a file, other processes can also read the file but all are prevented from writing to it, that is, changing any of the data. If a process places a write lock on a file, no other processes can read or write in the file until the lock is removed. Write locks are also known as exclusive locks. The term shared lock is sometimes applied to read locks.

Another distinction needs to be made between mandatory and advisory locking. Mandatory locking means that the discipline is enforced automatically for the system calls that read, write, or create files. This is done through a permission flag established by the file's owner (or the super-user). Advisory locking means that the processes that use the file take the responsibility for setting and removing locks as needed. Thus mandatory may sound like a simpler and better deal, but it is not so. The mandatory locking capability is

included in the system to comply with an agreement with */usr/group*, an organization that represents the interests of UNIX system users. The principal weakness in the mandatory method is that the lock is in place only while the single system call is being made. It is extremely common for a single transaction to require a series of reads and writes before it can be considered complete. In cases like this, the term atomic is used to describe a transaction that must be viewed as an indivisible unit. The preferred way to manage locking in such a circumstance is to make certain the lock is in place before any I/O starts, and that it is not removed until the transaction is done. That calls for locking of the advisory variety.

### **How File and Record Locking Works**

The system call for file and record locking is `fcntl(2)`. Programs should include the line

```
#include <fcntl.h>
```

to bring in the header file shown in Figure 3-1.

```
/* Flag values accessible to open(2) and fcntl(2) */
/* (The first three can only be set by open) */
#define O_RDONLY 0
#define O_WRONLY 1
#define O_RDWR 2
#define O_NDELAY 04 /* Non-blocking I/O */
#define O_APPEND 010 /* append (writes guaranteed at the end) */
#define O_SYNC 020 /* synchronous write option */

/* Flag values accessible only to open(2) */
#define O_CREAT 00400 /* open with file create (uses third open arg)*/
#define O_TRUNC 01000 /* open with truncation */
#define O_EXCL 02000 /* exclusive open */

/* fcntl(2) requests */
#define F_DUPFD 0 /* Duplicate fildes */
#define F_GETFD 1 /* Get fildes flags */
#define F_SETFD 2 /* Set fildes flags */
#define F_GETFL 3 /* Get file flags */
#define F_SETFL 4 /* Set file flags */
#define F_GETLK 5 /* Get file lock */
#define F_SETLK 6 /* Set file lock */
#define F_SETLKW 7 /* Set file lock and wait */
#define F_CHKFL 8 /* Check legality of file flag changes */

/* file segment locking set data type - information passed to system by user */
struct flock {
    short l_type;
    short l_whence;
    long l_start;
    long l_len; /* len = 0 means until end of file */
    short l_sysid;
    short l_pid;
};

/* file segment locking types */
/* Read lock */
#define F_RDLCK 01
/* Write lock */
#define F_WRLCK 02
/* Remove lock(s) */
#define F_UNLCK 03
```

Figure 3-1: The `fcntl.h` Header File

The format of the **fcntl(2)** system call is

```
int fcntl(fildes, cmd, arg)
int fildes, cmd, arg;
```

*fildes* is the file descriptor returned by the **open** system call. In addition to defining tags that are used as the commands on **fcntl** system calls, **fcntl.h** includes the declaration for a *struct flock* that is used to pass values that control where locks are to be placed.

## **lockf**

A subroutine, **lockf(3)**, can also be used to lock sections of a file or an entire file. The format of **lockf** is:

```
#include <unistd.h>

int lockf (fildes, function, size)
int fildes, function;
long size;
```

*fildes* is the file descriptor; *function* is one of four control values defined in **unistd.h** that let you lock, unlock, test and lock, or simply test to see if a lock is already in place. *size* is the number of contiguous bytes to be locked or unlocked. The section of contiguous bytes can be either forward or backward from the current offset in the file. [You can arrange to be somewhere in the middle of the file by using the **lseek(2)** system call.]

## **Where to Find More Information**

There is an example of file and record locking in the sample application at the end of this chapter. The manual pages that apply to this facility are **fcntl(2)**, **fcntl(5)**, **lockf(3)**, and **chmod(2)** in the *Programmer's Reference Manual*. Chapter 7 of this guide is a detailed discussion of the subject with a number of examples.

## **Interprocess Communications**

In Chapter 2 we described **forking** and **execing** as methods of communicating between processes. Business applications running on a UNIX system computer often need more sophisticated methods. In applications, for example, where fast response is critical, a number of processes may be brought up at the start of a business day to be constantly available to handle transactions

on demand. This cuts out initialization time that can add seconds to the time required to deal with the transaction. To go back to the ticket reservation example again for a moment, if a customer calls to reserve a seat on the 5 o'clock flight to Detroit, you do not want to have to say, "Yes, sir. Just hang on a minute while I start up the reservations program." In transaction-driven systems, the normal mode of processing is to have all the components of the application standing by waiting for some sort of an indication that there is work to do.

To meet requirements of this type the UNIX system offers a set of nine system calls and their accompanying header files, all under the umbrella name of Interprocess Communications (IPC).

The IPC system calls come in sets of three; one set each for messages, semaphores, and shared memory. These three terms define three different styles of communication between processes:

- |               |   |
|---------------|---|
| messages      | communication is in the form of data stored in a buffer. The buffer can be either sent or received.   |
| semaphores    | communication is in the form of positive integers with a value between 0 and 32,767. Semaphores may be contained in an array the size of which is determined by the system administrator. The default maximum size for the array is 25. |
| shared memory | communication takes place through a common area of main memory. One or more processes can attach a segment of memory and as a consequence can share whatever data is placed there.  |

The sets of IPC system calls are:

<b>msgget</b>	<b>semget</b>	<b>shmget</b>
<b>msgctl</b>	<b>semctl</b>	<b>shmctl</b>
<b>msgop</b>	<b>semop</b>	<b>shmop</b>

### IPC get Calls

The **get** calls each return to the calling program an identifier for the type of IPC facility that is being requested.

## **IPC ctl Calls**

The **ctl** calls provide a variety of control operations that include obtaining (**IPC\_STAT**), setting (**IPC\_SET**), and removing (**IPC\_RMID**) the values in data structures associated with the identifiers picked up by the **get** calls.

## **IPC op Calls**

The **op** manual pages describe calls that are used to perform the particular operations characteristic of the type of IPC facility being used. **msgop** has calls that send or receive messages. **semop** (the only one of the three that is actually the name of a system call) is used to increment or decrement the value of a semaphore, among other functions. **shmop** has calls that attach or detach shared memory segments.

## **Where to Find More Information**

An example of the use of some IPC features is included in the sample application at the end of this chapter. The system calls are all located in Section (2) of the **Programmer's Reference Manual**. Do not overlook **intro(2)**. It includes descriptions of the data structures that are used by IPC facilities. A detailed description of IPC, with many code examples that use the IPC system calls, is contained in Chapter 9 of this guide.

## **Programming Terminal Screens**

The facility for setting up terminal screens to meet the needs of your application is provided by two parts of the UNIX system. The first of these, **terminfo**, is a data base of compiled entries that describe the capabilities of terminals and the way they perform various operations.

The **terminfo** data base normally begins at the **/usr/lib/terminfo** directory. Members of this directory are themselves directories, generally with single-character names that are the first character in the name of the terminal. The compiled files of operating characteristics are at the next level down the hierarchy. For example, the entry for a Teletype 5425 is located in both the file **/usr/lib/terminfo/5/5425** and the file **/usr/lib/terminfo/t/tty5425**.

Describing the capabilities of a terminal can be a painstaking task. Quite a good selection of terminal entries is included in the **terminfo** data base that comes with your computer. However, if you have a type of terminal that is not already described in the data base, the best way to proceed is to find a description of one that comes close to having the same capabilities as yours

and building on that one. There is a routine (**setupterm**) in **curses(3X)** that can be used to print out descriptions from the data base. Once you have worked out the code that describes the capabilities of your terminal, the **tic(1M)** command is used to compile the entry and add it to the data base.

### **curses**

After you have made sure that the operating capabilities of your terminal are a part of the **terminfo** data base, you can then proceed to use the routines that make up the **curses(3X)** package to create and manage screens for your application.

The **curses** library includes functions to:

- define portions of your terminal screen as windows
- define pads that extend beyond the borders of your physical terminal screen and let you see portions of the pad on your terminal
- read input from a terminal screen into a program
- write output from a program to your terminal screen
- manipulate the information in a window in a virtual screen area and then send it to your physical screen.

### **Where to Find More Information**

In the sample application at the end of this chapter, we show how you might use **curses** routines. Chapter 10 of this guide contains a tutorial on the subject. The manual pages for **curses** are in Section (3X), and those for **terminfo** are in Section (4) of the *Programmer's Reference Manual*.



---

## Programming Support Tools

This section covers UNIX system components that are part of the programming environment, but that have a highly specialized use. We refer to such things as:

- link edit command language
- Common Object File Format
- libraries
- Symbolic Debugger
- **lint** as a portability tool.

### Link Editor Command Language

The link editor command language is for use when the default arrangement of the **ld** output will not do the job. The default locations for the standard Common Object File Format sections are described in **a.out(4)** in the *Programmer's Reference Manual*.

On an 80386 Computer, when an **a.out** file is loaded into memory for execution, the text segment starts at location 0x0, and the data section starts at the next segment boundary after the end of the text. The stack begins at 0xBFFFFFFF and grows to lower memory addresses.

The link editor command language provides directives for describing different arrangements. The two major types of link editor directives are **MEMORY** and **SECTIONS**. **MEMORY** directives can be used to define the boundaries of configured and unconfigured sections of memory within a machine, to name sections, and to assign specific attributes (read, write, execute, and initialize) to portions of memory. **SECTIONS** directives, among a lot of other functions, can be used to bind sections of the object file to specific addresses within the configured portions of memory.

Why would you want to be able to do those things? Well, the truth is that in the majority of cases you do not have to worry about it.

The need to control the link editor output becomes more urgent under two, possibly related, sets of circumstances.

1. Your application is large and consists of a lot of object files.
2. The hardware your application is to run on is tight for space.

### Where to Find More Information

Chapter 12 of this guide gives a detailed description of the subject.

## Common Object File Format

The details of the Common Object File Format have never been looked on as stimulating reading. In fact, they have been recommended to hard-core insomniacs as preferred bedtime fare. However, if you are going to break into the ranks of really sophisticated UNIX system programmers, you are going to have to get a good grasp of COFF. A knowledge of COFF is fundamental to using the link editor command language. It is also good background knowledge for tasks such as:

- setting up archive libraries or shared libraries
- using the Symbolic Debugger

The following system header files contain definitions of data structures of parts of the Common Object File Format:

<code>&lt;syms.h&gt;</code>	symbol table format
<code>&lt;linenum.h&gt;</code>	line number entries
<code>&lt;ldfcn.h&gt;</code>	COFF access routines
<code>&lt;filehdr.h&gt;</code>	file header for a common object file
<code>&lt;a.out.h&gt;</code>	common assembler and link editor output
<code>&lt;scnhdr.h&gt;</code>	section header for a common object file
<code>&lt;reloc.h&gt;</code>	relocation information for a common object file
<code>&lt;storclass.h&gt;</code>	storage classes for common object files

The object file access routines are described below under the heading "The Object File Library."

## **Where to Find More Information**

Chapter 11 of this guide gives a detailed description of COFF.

## **Libraries**

A library is a collection of related object files and/or declarations that simplify programming effort. Programming groups involved in the development of applications often find it convenient to establish private libraries. For example, an application with a number of programs using a common data base can keep the I/O routines in a library that is searched at link edit time.

Prior to Release 3.0 of the UNIX System V the libraries, whether system supplied or application developed, were collections of common object format files stored in an archive (*filename.a*) file that was searched by the link editor to resolve references. Files in the archive that were needed to satisfy unresolved references became a part of the resulting executable.

Beginning with Release 3.0, shared libraries are supported. Shared libraries are similar to archive libraries in that they are collections of object files that are acted upon by the link editor. The difference, however, is that shared libraries perform a static linking between the file in the library and the executable that is the output of **ld**. The result is a saving of space, because all executables that need a file from the library share a single copy. We go into shared libraries later in this section.

In Chapter 2 we described many of the functions that are found in the standard C library, **libc.a**. The next two sections describe two other libraries, the object file library and the math library.

### **The Object File Library**

The object file library provides functions for the access and manipulation of object files. Some functions locate portions of an object file such as the symbol table, the file header, sections, and line number entries associated with a function. Other functions read these types of entries into memory. The need to work at this level of detail with object files occurs most often in the development of new tools that manipulate object files. For a description of the format of an object file, see "The Common Object File Format" in Chapter 11. This library consists of several portions.

The functions (see Figure 3-2) reside in `/lib/libld.a` and are loaded during the compilation of a C language program by the `-l` command line option:

```
cc file -lld
```

which causes the link editor to search the object file library. The argument `-lld` must appear after all files that reference functions in `libld.a`.

The following header files must be included in the source code.

```
#include <stdio.h>
#include <a.out.h>
#include <ldfcn.h>
```

<b>Function</b>	<b>Reference</b>	<b>Brief Description</b>
<b>ldaclose</b>	<b>ldclose(3X)</b>	Close object file being processed.
<b>ldahread</b>	<b>ldahread(3X)</b>	Read archive header.
<b>ldaopen</b>	<b>ldopen(3X)</b>	Open object file for reading.
<b>ldclose</b>	<b>ldclose(3X)</b>	Close object file being processed.
<b>ldfhread</b>	<b>ldfhread(3X)</b>	Read file header of object file being processed.
<b>ldgetname</b>	<b>ldgetname(3X)</b>	Retrieve the name of an object file symbol table entry.
<b>ldlinit</b>	<b>ldlread(3X)</b>	Prepare object file for reading line number entries via <b>ldlitem</b> .
<b>ldlitem</b>	<b>ldlread(3X)</b>	Read line number entry from object file after <b>ldlinit</b> .
<b>ldlread</b>	<b>ldlread(3X)</b>	Read line number entry from object file.
<b>ldlseek</b>	<b>ldlseek(3X)</b>	Seeks to the line number entries of the object file being processed.
<b>ldnlseek</b>	<b>ldlseek(3X)</b>	Seeks to the line number entries of the object file being processed given the name of a section.
<b>ldnrseek</b>	<b>ldrseek(3X)</b>	Seeks to the relocation entries of the object file being processed given the name of a section.
<b>ldnshread</b>	<b>ldshread(3X)</b>	Read section header of the named section of the object file being processed.

Figure 3-2: Object File Library Functions (Sheet 1 of 2)

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<b>Function</b>	<b>Reference</b>	<b>Brief Description</b>
<b>ldnsseek</b>	<b>ldsseek(3X)</b>	Seeks to the section of the object file being processed given the name of a section.
<b>ldohseek</b>	<b>ldohseek(3X)</b>	Seeks to the optional file header of the object file being processed.
<b>ldopen</b>	<b>ldopen(3X)</b>	Open object file for reading.
<b>ldrseek</b>	<b>ldrseek(3X)</b>	Seeks to the relocation entries of the object file being processed.
<b>ldshread</b>	<b>ldshread(3X)</b>	Read section header of an object file being processed.
<b>ldsseek</b>	<b>ldsseek(3X)</b>	Seeks to the section of the object file being processed.
<b>ldtbindex</b>	<b>ldtbindex(3X)</b>	Returns the long index of the symbol table entry at the current position of the object file being processed.
<b>ldtbread</b>	<b>ldtbread(3X)</b>	Reads a specific symbol table entry of the object file being processed.
<b>ldtbseek</b>	<b>ldtbseek(3X)</b>	Seeks to the symbol table of the object file being processed.
<b>sgetl</b>	<b>sputl(3X)</b>	Access long integer data in a machine-independent format.
<b>sputl</b>	<b>sputl(3X)</b>	Translate a long integer into a machine-independent format.

Figure 3-2: Object File Library Functions (Sheet 2 Of 2)

---

## **Common Object File Interface Macros (ldfcn.h)**

The interface between the calling program and the object file access routines is based on the defined type `LDFILE`, which is in the header file `ldfcn.h` [see `ldfcn(4)`]. The primary purpose of this structure is to provide uniform access to both simple object files and to object files that are members of an archive file.

The function `ldopen(3X)` allocates and initializes the `LDFILE` structure and returns a pointer to the structure. The fields of the `LDFILE` structure may be accessed individually through the following macros:

- `TYPE`—returns the magic number of the file, which is used to distinguish between archive files and object files that are not part of an archive.
- `IOPTR`—returns the file pointer, which was opened by `ldopen(3X)` and is used by the input/output functions of the C library.
- `OFFSET`—returns the file address of the beginning of the object file. This value is non-zero only if the object file is a member of the archive file.
- `HEADER`—accesses the file header structure of the object file.

Additional macros are provided to access an object file. These macros parallel the input/output functions in the C library; each macro translates a reference to an `LDFILE` structure into a reference to its file descriptor field. The available macros are described in `ldfcn(4)` in the *Programmer's Reference Manual*.

## **The Math Library**

The math library package consists of functions and a header file. The functions are located and loaded during the compilation of a C language program by the `-l` option on a command line, as follows:

```
cc file -lm
```

This option causes the link editor to search the math library, `libm.a`. In addition to the request to load the functions, the header file of the math library should be included in the program being compiled. This is accomplished by including the line:

```
#include <math.h>
```

near the beginning of each file that uses the routines.

The functions are grouped into the following categories:

- trigonometric functions
- Bessel functions
- hyperbolic functions
- miscellaneous functions

### **Trigonometric Functions**

These functions are used to compute angles (in radian measure), sines, cosines, and tangents. All of these values are expressed in double-precision.

<b>Function</b>	<b>Reference</b>	<b>Brief Description</b>
<b>acos</b>	<b>trig(3M)</b>	Return arc cosine.
<b>asin</b>	<b>trig(3M)</b>	Return arc sine.
<b>atan</b>	<b>trig(3M)</b>	Return arc tangent.
<b>atan2</b>	<b>trig(3M)</b>	Return arc tangent of a ratio.
<b>cos</b>	<b>trig(3M)</b>	Return cosine.
<b>sin</b>	<b>trig(3M)</b>	Return sine.
<b>tan</b>	<b>trig(3M)</b>	Return tangent.

### **Bessel Functions**

These functions calculate Bessel functions of the first and second kinds of several orders for real values. The Bessel functions are **j0**, **j1**, **jn**, **y0**, **y1**, and **yn**. The functions are located in section **bessel(3M)**.

### **Hyperbolic Functions**

These functions are used to compute the hyperbolic sine, cosine, and tangent for real values.

<b>Function</b>	<b>Reference</b>	<b>Brief Description</b>
<b>cosh</b>	<b>sinh(3M)</b>	Return hyperbolic cosine.
<b>sinh</b>	<b>sinh(3M)</b>	Return hyperbolic sine.
<b>tanh</b>	<b>sinh(3M)</b>	Return hyperbolic tangent.



**Miscellaneous Functions**

These functions cover a wide variety of operations, such as natural logarithm, exponential, and absolute value. In addition, several are provided to truncate the integer portion of double-precision numbers.

<b>Function</b>	<b>Reference</b>	<b>Brief Description</b>
<b>ceil</b>	<b>floor(3M)</b>	Returns the smallest integer not less than a given value.
<b>exp</b>	<b>exp(3M)</b>	Returns the exponential function of a given value.
<b>fabs</b>	<b>floor(3M)</b>	Returns the absolute value of a given value.
<b>floor</b>	<b>floor(3M)</b>	Returns the largest integer not greater than a given value.
<b>fmod</b>	<b>floor(3M)</b>	Returns the remainder produced by the division of two given values.
<b>gamma</b>	<b>gamma(3M)</b>	Returns the natural log of the absolute value of the result of applying the gamma function to a given value.
<b>hypot</b>	<b>hypot(3M)</b>	Return the square root of the sum of the squares of two numbers.
<b>log</b>	<b>exp(3M)</b>	Returns the natural logarithm of a given value.
<b>log10</b>	<b>exp(3M)</b>	Returns the logarithm base ten of a given value.
<b>matherr</b>	<b>matherr(3M)</b>	Error-handling function.
<b>pow</b>	<b>exp(3M)</b>	Returns the result of a given value raised to another given value.
<b>sqrt</b>	<b>exp(3M)</b>	Returns the square root of a given value.

### Shared Libraries

As noted above, beginning with UNIX System V Release 3.0, shared libraries are supported. Not only are some system libraries (**libc** and the networking library) available in both archive and shared library form, but also applications have the option of creating private application shared libraries.

The reason why shared libraries are desirable is that they save space, both on disk and in memory. With an archive library, when the link editor goes to the archive to resolve a reference, it takes a copy of the object file that it needs for the resolution and binds it into the **a.out** file. From that point on the copied file is a part of the executable, whether it is in memory to be run or sitting in secondary storage. If you have a lot of executables that use, say, **printf** (which just happens to require much of the standard I/O library) you can be talking about a sizeable amount of space.

With a shared library, the link editor does not copy code into the executable files. When the operating system starts a process that uses a shared library, it maps the shared library contents into the address space of the process. Only one copy of the shared code exists, and many processes can use it at the same time.

This fundamental difference between archives and shared libraries has another significant aspect. When code in an archive library is modified, all existing executables are unaffected. They continue using the older version until they are re-link edited. When code in a shared library is modified, all programs that share that code use the new version the next time they are executed.

All this may sound like a really terrific deal, but as with most things in life there are complications. To begin with, in the paragraphs above we did not give you quite all the facts. For example, each process that uses shared library code gets its own copy of the entire data region of the library. It is actually only the text region that is really shared. So the truth is that shared libraries can add space to executing **a.out**'s even though the chances are good that they will cause more shrinkage than expansion. What this means is that when there is a choice between using a shared library and an archive, you should not use the shared library unless it saves space. If you were using a shared **libc** to access only **strcmp**, for example, you would pick up more in shared library data than you would save by sharing the text.

The answer to this problem, and to others that are somewhat more complex, is to assign the responsibility for shared libraries to a central person or group within the application. The shared library developer should be the one to resolve questions of when to use shared and when to use archive system libraries. If a private library is to be built for your application, one person or organization should be responsible for its development and maintenance.

### **Where to Find More Information**

The sample application at the end of this chapter includes an example of the use of a shared library. Chapter 8 of this guide describes how shared libraries are built and maintained.

## **Symbolic Debugger**

The use of **sdb** was mentioned briefly in Chapter 2. In this section we want to say a few words about **sdb** within the context of an application development project.

**sdb** works on a process, and enables a programmer to find errors in the code. It is a tool a programmer might use while coding and unit testing a program, to make sure it runs according to its design. **sdb** would normally be used prior to the time the program is turned over, along with the rest of the application, to testers. During this phase of the application development cycle, programs are compiled with the **-g** option of **cc** to facilitate the use of the debugger. The symbol table should not be stripped from the object file. Once the programmer is satisfied that the program is error-free, **strip(1)** can be used to reduce the file storage overhead taken by the file.

If the application uses a private shared library, the possibility arises that a program bug may be located in a file that resides in the shared library. Dealing with a problem of this sort calls for coordination by the administrator of the shared library. Any change to an object file that is part of a shared library means the change affects all processes that use that file. One program's bug may be another program's feature.

### **Where to Find More Information**

Chapter 15 of this guide contains information on how to use **sdb**. The manual page is in Section (1) of the *Programmer's Reference Manual*.

## lint as a Portability Tool

It is a characteristic of the UNIX system that language compilation systems are somewhat permissive. Generally speaking it is a design objective that a compiler should run fast. Most C compilers, therefore, let some things go unflagged as long as the language syntax is observed statement by statement. This sometimes means that while your program may run, the output will have some surprises. It also sometimes means that while the program may run on the machine on which the compilation system runs, there may be real difficulties in running it on some other machine.

That is where **lint** comes in. **lint** produces comments about inconsistencies in the code. The types of anomalies flagged by **lint** are:

- cases of disagreement between the type of value expected from a called function and what the function actually returns
- disagreement between the types and number of arguments expected by functions and what the function receives
- inconsistencies that might prove to be bugs
- things that might cause portability problems

Here is an example of a portability problem that would be caught by **lint**.

Code such as this:

```
int i = lseek(fdcs, offset, whence)
```

would get by most compilers. However, **lseek** returns a long integer representing the address of a location in the file. On a machine with a 16-bit integer and a bigger **long int**, it would produce incorrect results, because **i** would contain only the last 16 bits of the value returned.

Since it is reasonable to expect that an application written for a UNIX system machine will be able to run on a variety of computers, it is important that the use of **lint** be a regular part of the application development.

## **Where to Find More Information**

Chapter 16 of this guide contains a description of **lint** with examples of the kinds of conditions it uncovers. The manual page is in Section (1) of the *Programmer's Reference Manual*.

---

## Project Control Tools

Volumes have been written on the subject of project control. It is an item of top priority for the managers of any application development team. Two UNIX system tools that can play a role in this area are described in this section.

### **make**

The **make** command is extremely useful in an application development project for keeping track of what object files need to be recompiled as changes are made to source code files. One of the characteristics of programs in a UNIX system environment is that they are made up of many small pieces, each in its own object file, that are link edited together to form the executable file. Quite a few of the UNIX system tools are devoted to supporting that style of program architecture. For example, archive libraries, shared libraries and even the fact that the **cc** command accepts **.o** files as well as **.c** files, and that it can stop short of the **ld** step and produce **.o** files instead of an **a.out**, are all important elements of modular architecture. The two main advantages of this type of programming are that

- A file that performs one function can be re-used in any program that needs it.
- When one function is changed, the whole program does not have to be recompiled.

On the flip side, however, a consequence of the proliferation of object files is an increased difficulty in keeping track of what does need to be recompiled, and what does not. **make** is designed to help deal with this problem. You use **make** by describing in a specification file, called **makefile**, the relationship (that is, the dependencies) between the different files of your program. Once having done that, you conclude a session in which possibly a number of your source code files have been changed by running the **make** command. **make** takes care of generating a new **a.out** by comparing the time-last-changed of your source code files with the dependency rules you have given it.

**make** has the ability to work with files in archive libraries or under control of the Source Code Control System (SCCS).

## **Where to Find More Information**

The **make(1)** manual page is contained in the *Programmer's Reference Manual*. Chapter 13 of this guide gives a complete description of how to use **make**.

## **SCCS**

SCCS is an abbreviation for Source Code Control System. It consists of a set of 14 commands used to track evolving versions of files. Its use is not limited to source code; any text files can be handled, so an application's documentation can also be put under control of SCCS. SCCS can:

- store and retrieve files under its control
- allow no more than a single copy of a file to be edited at one time
- provide an audit trail of changes to files
- reconstruct any earlier version of a file that may be wanted

SCCS files are stored in a special coded format. Only through commands that are part of the SCCS package can files be made available in a user's directory for editing, compiling, etc. From the point at which a file is first placed under SCCS control, only changes to the original version are stored. For example, let us say that the program, **restate**, that was used in several examples in Chapter 2, was controlled by SCCS.

## Project Control Tools

---

One of the original pieces of that program is a file called **oppty.c** that looks like this:

```
/* Opportunity Cost -- oppty.c */
#include "redef.h"

float
oppty(ps)
struct rec *ps;
{
    return(ps->i/12 * ps->t * ps->dp);
}
```

If you decide to add a message to this function, you might change the file like this:

```
/* Opportunity Cost -- oppty.c */
#include "redef.h"
#include <stdio.h>

float
oppty(ps)
struct rec *ps;
{
    (void) fprintf(stderr, "Opportunity calling\n");
    return(ps->i/12 * ps->t * ps->dp);
}
```



SCCS saves only the two new lines from the second version, with a coded notation that shows where in the text the two lines belong. It also includes a note of the version number, lines deleted, lines inserted, total lines in the file, the date and time of the change, and the login id of the person making the change.

### **Where to Find More Information**

Chapter 14 of this guide is an SCCS user's guide. SCCS commands are in Section (1) of the *Programmer's Reference Manual*.

---

## liber, A Library System

To illustrate the use of UNIX system programming tools in the development of an application, we are going to pretend we are engaged in the development of a computer system for a library. The system is known as **liber**. The early stages of system development, we assume, have already been completed; feasibility studies have been done, the preliminary design is described in the coming paragraphs. We are going to stop short of producing a complete detailed design and module specifications for our system. You will have to accept that these exist. In using portions of the system for examples of the topics covered in this chapter, we will work from these virtual specifications.

We make no claim as to the efficacy of this design. It is the way it is only in order to provide some passably realistic examples of UNIX system programming tools in use.

**liber** is a system for keeping track of the books in a library. The hardware consists of a single computer with terminals throughout the library. One terminal is used for adding new books to the data base. Others are used for checking out books and as electronic card catalogs.

The design of the system calls for it to be brought up at the beginning of the day and remain running while the library is in operation. The system has one master index that contains the unique identifier of each title in the library. When the system is running, the index resides in memory. Semaphores are used to control access to the index. In the pages that follow fragments of some of the system's programs are shown to illustrate the way they work together. The startup program performs the system initialization; opening the semaphores and shared memory; reading the index into the shared memory; and kicking off the other programs. The id numbers for the shared memory and semaphores (**shmid**, **wrtsem**, and **rdsem**) are read from a file during initialization. The programs all share the in-memory index. They attach it with the following code:

```

/* attach shared memory for index */
if ((int)(index = (INDEX *) shmat(shmid, NULL, 0)) == -1)
{
    (void) fprintf(stderr, "shmat failed: %d\n", errno);
    exit(1);
}

```

Of the programs shown, **add-books** is the only one that alters the index. The semaphores are used to ensure that no other programs will try to read the index while **add-books** is altering it. The checkout program locks the file record for the book so that each copy being checked out is recorded separately, and the book cannot be checked out at two different checkout stations at the same time.

The program fragments do not provide any details on the structure of the index or the book records in the data base.

```

/* liber.h - header file for the
 *      library system.
 */
typedef ... INDEX; /* data structure for book file index */
typedef struct { /* type of records in book file */
    char title[30];
    char author[30];
    .
    .
    .
} BOOK;
int shmid;
int wrtsem;
int rdsem;
INDEX *index;

int book_file;
BOOK book_buf;

```

*continued*

```
/* startup program */

/*
 * 1. Open shared memory for file index and read it in.
 * 2. Open two semaphores for providing exclusive write access to index.
 * 3. Stash id's for shared memory segment and semaphores in a file
 * where they can be accessed by the programs.
 * 4. Start programs: add-books, card-catalog, and checkout running
 * on the various terminals throughout the library.
 */

#include <stdio.h>
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>
#include <sys/sem.h>
#include "liber.h"

void exit();
extern int errno;

key_t key;
int shmid;
int wrtsem;
int rdsem;
FILE *ipc_file;

main()
{
    .
    .
    .
    if ((shmid = shmget(key, sizeof(INDEX), IPC_CREAT | 0666)) == -1)
    {
        (void) fprintf(stderr, "startup: shmget failed: errno=%d\n", errno);
        exit(1);
    }
    if ((wrtsem = semget(key, 1, IPC_CREAT | 0666)) == -1)
    {
        (void) fprintf(stderr, "startup: semget failed: errno=%d\n", errno);
        exit(1);
    }
}
```

*continued*

```

if ((rdsem = semget(key, 1, IPC_CREAT | 0666)) == -1)
{
    (void) fprintf(stderr, "startup: semget failed: errno=%d\n", errno);
    exit(1);
}
(void) fprintf(ipc_file, "%d\n%d\n%d\n", shmids, wrtsem, rdsem);

/*
 * Start the add-books program running on the terminal in the
 * basement. Start the checkout and card-catalog programs
 * running on the various other terminals throughout the library.
 */
.
.
.
}

/* card-catalog program*/

/*
 * 1. Read screen for author and title.
 * 2. Use semaphores to prevent reading index while it is being written.
 * 3. Use index to get position of book record in book file.
 * 4. Print book record on screen or indicate book was not found.
 * 5. Go to 1.
 */

#include <stdio.h>
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>
#include <fcntl.h>
#include "liber.h"

void exit();
extern int errno;
struct sembuf sop[1];

main() {
.
.
.

```

*continued*

```
while (1)
{
    /*
     * Read author/title/subject information from screen.
     */

    /*
     * Wait for write semaphore to reach 0 (index not being written).
     */
    sop[0].sem_op = 1;
    if (semop(wrtsem, sop, 1) == -1)
    {
        (void) fprintf(stderr, "semop failed: %d\n", errno);
        exit(1);
    }
    /*
     * Increment read semaphore so potential writer will wait
     * for us to finish reading the index.
     */
    sop[0].sem_op = 0;
    if (semop(rdsem, sop, 1) == -1)
    {
        (void) fprintf(stderr, "semop failed: %d\n", errno);
        exit(1);
    }

    /* Use index to find file pointer(s) for book(s) */

    /* Decrement read semaphore */
    sop[0].sem_op = -1;
    if (semop(rdsem, sop, 1) == -1)
    {
        (void) fprintf(stderr, "semop failed: %d\n", errno);
        exit(1);
    }

    /*
     * Now we use the file pointers found in the index to
     * read the book file. Then we print the information
     * on the book(s) to the screen.
     */
} /* while */
}
/* checkout program */
```

*continued*

```
/*
 * 1. Read screen for Dewey Decimal number of book to be checked out.
 * 2. Use semaphores to prevent reading index while it is being written.
 * 3. Use index to get position of book record in book file.
 * 4. If book not found print message on screen, otherwise lock
 *    book record and read.
 * 5. If book already checked out print message on screen, otherwise
 *    mark record "checked out" and write back to book file.
 * 6. Unlock book record.
 * 7. Go to 1.
 */

#include      <stdio.h>
#include      <sys/types.h>
#include      <sys/ipc.h>
#include      <sys/sem.h>
#include      <fcntl.h>
#include      "liber.h"

void exit();
long lseek();
extern int errno;
struct flock flk;
struct sembuf sop[1];
long bookpos;

main()
{
    .
    .
    .
    while (1)
    {
        /*
         * Read Dewey Decimal number from screen.
         */
    }
}
```

*continued*

```
/*
 * Wait for write semaphore to reach 0 (index not being written).
 */
sop[0].sem_flg = 0;
sop[0].sem_op = 0;
if (semop(wrtsem, sop, 1) == -1)
{
    (void) fprintf(stderr, "semop failed: %d\n", errno);
    exit(1);
}
/*
 * Increment read semaphore so potential writer will wait
 * for us to finish reading the index.
 */
sop[0].sem_op = 1;
if (semop(rdsem, sop, 1) == -1)
{
    (void) fprintf(stderr, "semop failed: %d\n", errno);
    exit(1);
}
/*
 * Now we can use the index to find the book's record position.
 * Assign this value to "bookpos".
 */

/* Decrement read semaphore */
sop[0].sem_op = -1;
if (semop(rdsem, sop, 1) == -1)
{
    (void) fprintf(stderr, "semop failed: %d\n", errno);
    exit(1);
}

/* Lock the book's record in book file, read the record. */
flk.l_type = F_WRLCK;
flk.l_whence = 0;
flk.l_start = bookpos;
flk.l_len = sizeof(BOOK);
if (fcntl(book_file, F_SETLK, &flk) == -1)
```



*continued*

```

    {
        (void) fprintf(stderr, "trouble locking: %d\n", errno);
        exit(1);
    }
    if (lseek(book_file, bookpos, 0) == -1)
    {
        Error processing for lseek;
    }
    if (read(book_file, &book_buf, sizeof(BOOK)) == -1)
    {
        Error processing for read;
    }

    /*
     * If the book is checked out inform the client, otherwise
     * mark the book's record as checked out and write it
     * back into the book file.
     */

    /* Unlock the book's record in book file. */
    flk.l_type = F_UNLCK;
    if (fcntl(book_file, F_SETLK, &flk) == -1)
    {
        (void) fprintf(stderr, "trouble unlocking: %d\n", errno);
        exit(1);
    }
} /* while */

/* add-books program*/

/*
 * 1. Read a new book entry from screen.
 * 2. Insert book in book file.
 * 3. Use semaphore "wrtsem" to block new readers.
 * 4. Wait for semaphore "rdsem" to reach 0.
 * 5. Insert book into index.
 * 6. Decrement wrtsem.
 * 7. Go to 1.
 */

```

*continued*

```
#include <stdio.h>
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>
#include "liber.h"

void exit();
extern int errno;
struct sembuf sop[1];
BOOK bookbuf;

main()
{
    .
    .
    .
    for (;;)
    {

        /*
         * Read information on new book from screen.
         */

        addscr(&bookbuf);

        /* write new record at the end of the bookfile.
         * Code not shown, but
         * addscr() returns a 1 if title information has
         * been entered, 0 if not.
         */

        /*
         * Increment write semaphore, blocking new readers from
         * accessing the index.
         */
        sop[0].sem_flg = 0;
        sop[0].sem_op = 1;
        if (semop(wrtsem, sop, 1) == -1)
        {
            (void) fprintf(stderr, "semop failed: %d\n", errno);
            exit(1);
        }
    }
}
```

*continued*

```

/*
 * Wait for read semaphore to reach 0 (all readers to finish
 * using the index).
 */
sop[0].sem_op = 0;
if (semop(&rdsem, sop, 1) == -1)
{
    (void) fprintf(stderr, "semop failed: %d\n", errno);
    exit(1);
}
/*
 * Now that we have exclusive access to the index we
 * insert our new book with its file pointer.
 */

/* Decrement write semaphore, permitting readers to read index. */
sop[0].sem_op = -1;
if (semop(&wrtsem, sop, 1) == -1)
{
    (void) fprintf(stderr, "semop failed: %d\n", errno);
    exit(1);
}
} /* for */
.
.
}

```

The example following, `addscr()`, illustrates two significant points about `curses` screens:

1. Information read in from a `curses` window can be stored in fields that are part of a structure defined in the header file for the application.
2. The address of the structure can be passed from another function where the record is processed.

```
        /* addscr is called from add-books.
        * The user is prompted for title
        * information.
        */

#include <curses.h>

WINDOW *cmdwin;

addscr(bb)
struct BOOK *bb;
{
    int c;

    initscr();
    nonl();
    noecho();
    cbreak();

    cmdwin = newwin(6, 40, 3, 20);
    mvprintw(0, 0, "This screen is for adding titles to the data base");
    mvprintw(1, 0, "Enter a to add; q to quit: ");
    refresh();
    for (;;)
    {
        refresh();
        c = getch();
        switch (c) {
            case 'a':
                werase(cmdwin);
                box(cmdwin, '|', '-');
                mvwprintw(cmdwin, 1, 1, "Enter title: ");
                wmove(cmdwin, 2, 1);
                echo();
                wrefresh(cmdwin);
                wgetstr(cmdwin, bb->title);
                noecho();
                werase(cmdwin);
                box(cmdwin, '|', '-');
                mvwprintw(cmdwin, 1, 1, "Enter author: ");
                wmove(cmdwin, 2, 1);
                echo();
                wrefresh(cmdwin);
                wgetstr(cmdwin, bb->author);
                noecho();
                werase(cmdwin);
```

*continued*

```
        wrefresh(cndwin);
        endwin();
        return(1);
    case 'q':
        erase();
        endwin();
        return(0);
    }
}

#
# Makefile for liber library system
#

CC = cc
CFLAGS = -O
all: startup add-books checkout card-catalog

startup: liber.h startup.c
    $(CC) $(CFLAGS) -o startup startup.c

add-books: add-books.o addscr.o
    $(CC) $(CFLAGS) -o add-books add-books.o addscr.o

add-books.o: liber.h

checkout: liber.h checkout.c
    $(CC) $(CFLAGS) -o checkout checkout.c

card-catalog: liber.h card-catalog.c
    $(CC) $(CFLAGS) -o card-catalog card-catalog.c
```





awk



---

# 4 **awk**

---

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---

# Introduction

NOTE

This chapter describes the new version of **awk** released in UNIX System V Release 3.1 and described in **nawk(1)**. An earlier version is described in **awk(1)**. The new version will become the default in the next major UNIX system release. Until then, you should read **nawk** for **awk** in this chapter.

Suppose you want to tabulate some survey results stored in a file, print various reports summarizing these results, generate form letters, reformat a data file for one application package to use with another package, or count the occurrences of a string in a file. **awk** is a programming language that makes it easy to handle these and many other tasks of information retrieval and data processing. The name **awk** is an acronym constructed from the initials of its developers; it denotes the language and also the UNIX system command you use to run an **awk** program.

**awk** is an easy language to learn. It automatically does quite a few things that you have to program for yourself in other languages. As a result, many useful **awk** programs are only one or two lines long. Because **awk** programs are usually smaller than equivalent programs in other languages, and because they are interpreted, not compiled, **awk** is also a good language for prototyping.

The first part of this chapter introduces you to the basics of **awk** and is intended to make it easy for you to start writing and running your own **awk** programs. The rest of the chapter describes the complete language and is somewhat less tutorial. For the experienced **awk** user, there's a summary of the language at the end of the chapter.

You should be familiar with the UNIX system and shell programming to use this chapter. Although you don't need other programming experience, some knowledge of the C programming language is beneficial, because many constructs found in **awk** are also found in C.

---

## Basic awk

This section provides enough information for you to write and run some of your own programs. Each topic presented is discussed in more detail in later sections.

### Program Structure

The basic operation of **awk**(1) is to scan a set of input lines one after another, searching for lines that match any of a set of patterns or conditions you specify. For each pattern, you can specify an action; this action is performed on each line that matches the pattern. Accordingly, an **awk** program is a sequence of pattern-action statements, as Figure 4-1 shows.

Structure:

```
pattern    { action }  
pattern    { action }  
...
```

Example:

```
$1 == "address" { print $2, $3 }
```

Figure 4-1: **awk** Program Structure and Example

---

The example in the figure is a typical **awk** program, consisting of one pattern-action statement. The program prints the second and third fields of each input line whose first field is **address**. In general, **awk** programs work by matching each line of input against each of the patterns in turn. For each pattern that matches, the associated action (which may involve multiple steps) is executed. Then the next line is read and the matching starts over. This process typically continues until all the input has been read.

Either the pattern or the action in a pattern-action statement may be omitted. If there is no action with a pattern, as in

```
$1 == "name"
```

the matching line is printed. If there is no pattern with an action, as in

```
{ print $1, $2 }
```

the action is performed for every input line. Since patterns and actions are both optional, actions are enclosed in braces to distinguish them from patterns.

## Usage

There are two ways to run an **awk** program. First, you can type the command line

```
awk 'pattern-action statements' optional list of input files
```

to execute the pattern-action statements on the set of named input files. For example, you could say

```
awk '{ print $1, $2 }' file1 file2
```

Notice that the pattern-action statements are enclosed in single quotes. This protects characters like **\$** from being interpreted by the shell and also allows the program to be longer than one line.

If no files are mentioned on the command line, **awk(1)** reads from the standard input. You can also specify that input comes from the standard input by using the hyphen (**-**) as one of the input files. For example,

```
awk '{ print $3, $4 }' file1 -
```

says to read input first from **file1** and then from the standard input.

The arrangement above is convenient when the **awk** program is short (a few lines). If the program is long, it is often more convenient to put it into a separate file and use the **-f** option to fetch it:

```
awk -f program file optional list of input files
```

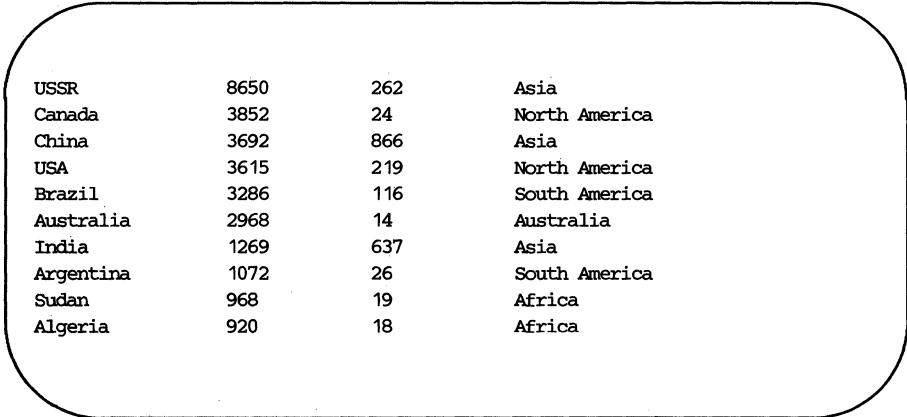
For example, the following command line says to fetch and execute **myprogram** on input from the file **file1**:

```
awk -f myprogram file1
```

## Fields

**awk** normally reads its input one line, or record, at a time; a record is, by default, a sequence of characters ending with a newline. **awk** then splits each record into fields, where, by default, a field is a string of non-blank, non-tab characters.

As input for many of the **awk** programs in this chapter, we use the file **countries**, which contains information about the ten largest countries in the world. Each record contains the name of a country, its area in thousands of square miles, its population in millions, and the continent on which it is found. (Data are from 1978; the U.S.S.R. has been arbitrarily placed in Asia.) The white space between fields is a tab in the original input; a single blank separates North and South from America .



USSR	8650	262	Asia
Canada	3852	24	North America
China	3692	866	Asia
USA	3615	219	North America
Brazil	3286	116	South America
Australia	2968	14	Australia
India	1269	637	Asia
Argentina	1072	26	South America
Sudan	968	19	Africa
Algeria	920	18	Africa

Figure 4-2: The Sample Input File **countries**

---

This file is typical of the kind of data **awk** is good at processing — a mixture of words and numbers separated into fields by blanks and tabs.

The number of fields in a record is determined by the field separator. Fields are normally separated by sequences of blanks and/or tabs, so that the first record of **countries** would have four fields, the second five, and so on. It's possible to set the field separator to just tab, so each line would have four fields, matching the meaning of the data; we'll show how to do this shortly. For the time being, we'll use the default: fields separated by blanks and/or



tabs. The first field within a line is called **\$1**, the second **\$2**, and so forth. The entire record is called **\$0**.

## Printing

If the pattern in a pattern-action statement is omitted, the action is executed for all input lines. The simplest action is to print each line; you can accomplish this with an **awk** program consisting of a single **print** statement

```
{ print }
```

so the command line

```
awk '{ print }' countries
```

prints each line of **countries**, copying the file to the standard output. The **print** statement can also be used to print parts of a record; for instance, the program

```
{ print $1, $3 }
```

prints the first and third fields of each record. Thus

```
awk '{ print $1, $3 }' countries
```

produces as output the sequence of lines:

```
USSR 262  
Canada 24  
China 866  
USA 219  
Brazil 116  
Australia 14  
India 637  
Argentina 26  
Sudan 19  
Algeria 18
```

When printed, items separated by a comma in the **print** statement are separated by the output field separator, which by default is a single blank. Each line printed is terminated by the output record separator, which by default is a newline.

NOTE

In the remainder of this chapter, we only show **awk** programs, without the command line that invokes them. Each complete program can be run either by enclosing it in quotes as the first argument of the **awk** command, or by putting it in a file and invoking **awk** with the **-f** flag, as discussed in "**awk** Command Usage." In an example, if no input is mentioned, the input is assumed to be the file **countries**.

## Formatted Printing

For more carefully formatted output, **awk** provides a C-like **printf** statement

```
printf format, expr1, expr2, . . . , exprn
```

which prints the *expr*<sub>*i*</sub>'s according to the specification in the string *format*. For example, the **awk** program

```
{ printf "%10s %6d\n", $1, $3 }
```

prints the first field (**\$1**) as a string of 10 characters (right justified), then a space, then the third field (**\$3**) as a decimal number in a six-character field, then a newline (**\n**). With input from the file **countries**, this program prints an aligned table:

USSR	262
Canada	24
China	866
USA	219
Brazil	116
Australia	14
India	637
Argentina	26
Sudan	19
Algeria	18

With **printf**, no output separators or newlines are produced automatically; you must create them yourself by using `\n` in the format specification. "The **printf** Statement" in this chapter contains a full description of **printf**.

## Simple Patterns

You can select specific records for printing or other processing by using simple patterns. **awk** has three kinds of patterns. First, you can use patterns called relational expressions that make comparisons. For example, the operator `==` tests for equality. To print the lines for which the fourth field equals the string `Asia`, we can use the program consisting of the single pattern

```
$4 == "Asia"
```

With the file **countries** as input, this program yields

USSR	8650	262	Asia
China	3692	866	Asia
India	1269	637	Asia

The complete set of comparisons is `>`, `>=`, `<`, `<=`, `==` (equal to) and `!=` (not equal to). These comparisons can be used to test both numbers and strings. For example, suppose we want to print only countries with a population greater than 100 million. The program

```
$3 > 100
```

is all that is needed. (Remember that the third field in the file **countries** is the population in millions.) It prints all lines in which the third field exceeds 100.

Second, you can use patterns called regular expressions that search for specified characters to select records. The simplest form of a regular expression is a string of characters enclosed in slashes:

```
/US/
```

This program prints each line that contains the (adjacent) letters **US** anywhere; with the file **countries** as input, it prints

```
USSR  8650  262  Asia
USA    3615  219  North America
```

We will have a lot more to say about regular expressions later in this chapter.

Third, you can use two special patterns, **BEGIN** and **END**, that match before the first record has been read and after the last record has been processed. This program uses **BEGIN** to print a title:

```
BEGIN { print "Countries of Asia:" }
/Asia/ { print "    ", $1 }
```

The output is

```
Countries of Asia:
    USSR
    China
    India
```

## Simple Actions

We have already seen the simplest action of an **awk** program: printing each input line. Now let's consider how you can use built-in and user-defined variables and functions for other simple actions in a program.

### Built-in Variables

Besides reading the input and splitting it into fields, **awk(1)** counts the number of records read and the number of fields within the current record; you can use these counts in your **awk** programs. The variable **NR** is the number of the current record, and **NF** is the number of fields in the record. So the program

```
{ print NR, NF }
```

prints the number of each line and how many fields it has, while

```
{ print NR, $0 }
```

prints each record preceded by its record number.

## User-defined Variables

Besides providing built-in variables like **NF** and **NR**, **awk** lets you define your own variables, which you can use for storing data, doing arithmetic, and the like. To illustrate, consider computing the total population and the average population represented by the data in the file **countries**:

```
{ sum = sum + $3 }
END { print "Total population is", sum, "million"
      print "Average population of", NR, "countries is", sum/NR }
```



**awk** initializes **sum** to zero before it is used.

The first action accumulates the population from the third field; the second action, which is executed after the last input, prints the sum and average:

```
Total population is 2201 million
Average population of 10 countries is 220.1
```

## Functions

**awk** has built-in functions that handle common arithmetic and string operations for you. For example, there's an arithmetic function that computes square roots. There is also a string function that substitutes one string for another. **awk** also lets you define your own functions. Functions are described in detail in the section "Actions" in this chapter.

## A Handful of Useful One-liners

Although `awk` can be used to write large programs of some complexity, many programs are not much more complicated than what we've seen so far. Here is a collection of other short programs that you may find useful and instructive. They are not explained here, but any new constructs do appear later in this chapter.

Print last field of each input line:

```
{ print $NF }
```

Print 10th input line:

```
NR == 10
```

Print last input line:

```
{ line = $0 }  
END { print line }
```

Print input lines that don't have four fields:

```
NF != 4 { print $0, "does not have 4 fields" }
```

Print input lines with more than four fields:

```
NF > 4
```

Print input lines with last field more than 4:

```
$NF > 4
```

Print total number of input lines:

```
END { print NR }
```

Print total number of fields:

```
{ nf = nf + NF }  
END { print nf }
```

Print total number of input characters:

```
{ nc = nc + length($0) }  
END { print nc + NR }
```

(Adding `NR` includes in the total the number of newlines.)

Print the total number of lines that contain the string Asia:

```
/Asia/ { nlines++ }  
END { print nlines }
```

(The statement `nlines++` has the same effect as `nlines = nlines + 1`.)

## Error Messages

If you make an error in your **awk** program, you generally get an error message. For example, trying to run the program

```
$3 < 200 { print ( $1 )
```

generates the error messages

```
awk: syntax error at source line 1
context is
    $3 < 200 { print ( >>> $1 } <<<
awk: illegal statement at source line 1
    1 extra (
```

Some errors may be detected while your program is running. For example, if you try to divide a number by zero, **awk** stops processing and reports the input record number (**NR**) and the line number in the program.

---

# Patterns

In a pattern-action statement, the pattern is an expression that selects the records for which the associated action is executed. This section describes the kinds of expressions that may be used as patterns.

## BEGIN and END

**BEGIN** and **END** are two special patterns that give you a way to control initialization and wrap-up in an **awk** program. **BEGIN** matches before the first input record is read, so any statements in the action part of a **BEGIN** are done once, before the **awk** command starts to read its first input record. The pattern **END** matches the end of the input, after the last record has been processed.

The following **awk** program uses **BEGIN** to set the field separator to tab (**\t**) and to put column headings on the output. The field separator is stored in a built-in variable called **FS**. Although **FS** can be reset at any time, usually the only sensible place is in a **BEGIN** section, before any input has been read. The program's second **printf** statement, which is executed for each input line, formats the output into a table, neatly aligned under the column headings. The **END** action prints the totals. (Notice that a long line can be continued after a comma.)

```
BEGIN { FS = "\t"
        printf "%10s %6s %5s %s\n",
               "COUNTRY", "AREA", "POP", "CONTINENT" }
{ printf "%10s %6d %5d %s\n", $1, $2, $3, $4
  area = area + $2; pop = pop + $3 }
END   { printf "\n%10s %6d %5d\n", "TOTAL", area, pop }
```

With the file **countries** as input, this program produces



COUNTRY	AREA	POP	CONTINENT
USSR	8650	262	Asia
Canada	3852	24	North America
China	3692	866	Asia
USA	3615	219	North America
Brazil	3286	116	South America
Australia	2968	14	Australia
India	1269	637	Asia
Argentina	1072	26	South America
Sudan	968	19	Africa
Algeria	920	18	Africa
TOTAL	30292	2201	

## Relational Expressions

An **awk** pattern can be any expression involving comparisons between strings of characters or numbers. **awk** has six relational operators, and two regular expression matching operators, `~` (tilde) and `!~`, which are discussed in the next section, for making comparisons. Figure 4-3 shows these operators and their meanings.

Operator	Meaning
<	less than
<=	less than or equal to
==	equal to
!=	not equal to
>=	greater than or equal to
>	greater than
~	matches
!~	does not match

Figure 4-3: **awk** Comparison Operators

---

In a comparison, if both operands are numeric, a numeric comparison is made; otherwise, the operands are compared as strings. (Every value might be either a number or a string; usually **awk** can tell what is intended. The section "Number or String?" contains more information about this.) Thus, the pattern `$3>100` selects lines where the third field exceeds 100, and the program

```
$1 >= "S"
```

selects lines that begin with the letters S through Z, namely,

```
USSR      8650   262   Asia
USA       3615   219  North America
Sudan    968     19   Africa
```

In the absence of any other information, **awk** treats fields as strings, so the program

```
$1 == $4
```

compares the first and fourth fields as strings of characters, and with the file **countries** as input, prints the single line for which this test succeeds:

```
Australia 2968 14 Australia
```

If both fields appear to be numbers, the comparisons are done numerically.

## Regular Expressions

**awk** provides more powerful patterns for searching for strings of characters than the comparisons illustrated in the previous section. These patterns are called regular expressions, and are like those in **egrep**(1) and **lex**(1). The simplest regular expression is a string of characters enclosed in slashes, like

```
/Asia/
```

This program prints all input records that contain the substring *Asia*. (If a record contains *Asia* as part of a larger string like *Asian* or *Pan-Asiatic*, it is also printed.) In general, if *re* is a regular expression, then the pattern

```
/re/
```

matches any line that contains a substring specified by the regular expression *re*.

To restrict a match to a specific field, you use the matching operators `~` (matches) and `!~` (does not match). The program

```
$4 ~ /Asia/ { print $1 }
```

prints the first field of all lines in which the fourth field matches *Asia*, while the program

```
$4 !~ /Asia/ { print $1 }
```

prints the first field of all lines in which the fourth field does not match *Asia* .

In regular expressions, the symbols

```
\ ^ $ . [ ] * + ? 0 |
```

are metacharacters with special meanings like the metacharacters in the UNIX shell. For example, the metacharacters `^` and `$` match the beginning and end, respectively, of a string, and the metacharacter `.` ("dot") matches any single character. Thus,

```
/^.$/
```

matches all records that contain exactly one character.

## Patterns

---

A group of characters enclosed in brackets matches any one of the enclosed characters; for example, `/[ABC]/` matches records containing any one of **A**, **B**, or **C** anywhere. Ranges of letters or digits can be abbreviated within brackets: `/[a-zA-Z]/` matches any single letter.

If the first character after the `[` is a `^`, this complements the class so it matches any character not in the set: `/[^a-zA-Z]/` matches any non-letter. The program

```
$2 !~ /^ [0-9 ]+$/
```

prints all records in which the second field is not a string of one or more digits (`^` for beginning of string, `[0-9]+` for one or more digits, and `$` for end of string). Programs of this nature are often used for data validation.

Parentheses `()` are used for grouping and the symbol `|` is used for alternatives. The program

```
/(apple|cherry) (pie|tart)/
```

matches lines containing any one of the four substrings `apple pie`, `apple tart`, `cherry pie`, or `cherry tart`.

To turn off the special meaning of a metacharacter, precede it by a `\` (backslash). Thus, the program

```
/b\$/
```

prints all lines containing `b` followed by a dollar sign.

In addition to recognizing metacharacters, the **awk** command recognizes the following C programming language escape sequences within regular expressions and strings:

<code>\b</code>	backspace
<code>\f</code>	formfeed
<code>\n</code>	newline
<code>\r</code>	carriage return
<code>\t</code>	tab
<code>\ddd</code>	octal value <i>ddd</i>
<code>\"</code>	quotation mark
<code>\c</code>	any other character <i>c</i> literally

For example, to print all lines containing a tab, use the program

```
^t/
```

**awk** interprets any string or variable on the right side of a `~` or `!~` as a regular expression. For example, we could have written the program

```
$2 !~ /^[0-9]+$ /
```

as

```
BEGIN      { digits = "[0-9]+$" }
$2 !~ digits
```

Suppose you wanted to search for a string of characters like `^[0-9]+$`. When a literal quoted string like `"^[0-9]+$"` is used as a regular expression, one extra level of backslashes is needed to protect regular expression meta-characters. This is because one level of backslashes is removed when a string is originally parsed. If a backslash is needed in front of a character to turn off its special meaning in a regular expression, then that backslash needs a preceding backslash to protect it in a string.

For example, suppose we want to match strings containing `b` followed by a dollar sign. The regular expression for this pattern is `b\$`. If we want to create a string to represent this regular expression, we must add one more backslash: `b\\$`. The two regular expressions on each of the following lines are equivalent:

<code>x ~ "b\\\$"</code>	<code>x ~ /b\\$/</code>
<code>x ~ "b\\$"</code>	<code>x ~ /b\$/</code>
<code>x ~ "b\$"</code>	<code>x ~ /b\$/</code>
<code>x ~ "\\t"</code>	<code>x ~ /\t/</code>

The precise form of regular expressions and the substrings they match is given in Figure 4-4. The unary operators `*`, `+`, and `?` have the highest precedence, then concatenation, and then alternation `|`. All operators are left associative. `r` stands for any regular expression.

Expression	Matches
<i>c</i>	any non-metacharacter <i>c</i>
<i>\c</i>	character <i>c</i> literally
<i>^</i>	beginning of string
<i>\$</i>	end of string
<i>.</i>	any character but newline
<i>[s]</i>	any character in set <i>s</i>
<i>[^s]</i>	any character not in set <i>s</i>
<i>r*</i>	zero or more <i>r</i> 's
<i>r+</i>	one or more <i>r</i> 's
<i>r?</i>	zero or one <i>r</i>
<i>(r)</i>	<i>r</i>
<i>r<sub>1</sub>r<sub>2</sub></i>	<i>r<sub>1</sub></i> then <i>r<sub>2</sub></i> (concatenation)
<i>r<sub>1</sub> r<sub>2</sub></i>	<i>r<sub>1</sub></i> or <i>r<sub>2</sub></i> (alternation)

Figure 4-4: *awk* Regular Expressions

---

## Combinations of Patterns

A compound pattern combines simpler patterns with parentheses and the logical operators *||* (or), *&&* (and), and *!* (not). For example, suppose we want to print all countries in Asia with a population of more than 500 million. The following program does this by selecting all lines in which the fourth field is *Asia* and the third field exceeds 500:

```
$4 == "Asia" && $3 > 500
```

The program

```
$4 == "Asia" || $4 == "Africa"
```

selects lines with *Asia* or *Africa* as the fourth field. Another way to write the latter query is to use a regular expression with the alternation operator *|*:

```
$4 ~ /^(Asia|Africa)$/
```

The negation operator **!** has the highest precedence, then **&&**, and finally **||**. The operators **&&** and **||** evaluate their operands from left to right; evaluation stops as soon as truth or falsehood is determined.

## Pattern Ranges

A pattern range consists of two patterns separated by a comma, as in

```
pat1, pat2 { ... }
```

In this case, the action is performed for each line between an occurrence of *pat*<sub>1</sub> and the next occurrence of *pat*<sub>2</sub> (inclusive). As an example, the pattern

```
/Canada/, /Brazil/
```

matches lines starting with the first line that contains the string Canada up through the next occurrence of the string Brazil:

Canada	3852	24	North America
China	3692	866	Asia
USA	3615	219	North America
Brazil	3286	116	South America

Similarly, since **FNR** is the number of the current record in the current input file (and **FILENAME** is the name of the current input file), the program

```
FNR == 1, FNR == 5 { print FILENAME, $0 }
```

prints the first five records of each input file with the name of the current input file prepended.

---

## Actions

In a pattern-action statement, the action determines what is to be done with the input records that the pattern selects. Actions frequently are simple printing or assignment statements, but they may also be a combination of one or more statements. This section describes the statements that can make up actions.

## Built-in Variables

Figure 4-5 lists the built-in variables that **awk** maintains. Some of these we have already met; others are used in this and later sections.

Variable	Meaning	Default
<b>ARGC</b>	number of command-line arguments	-
<b>ARGV</b>	array of command-line arguments	-
<b>FILENAME</b>	name of current input file	-
<b>FNR</b>	record number in current file	-
<b>FS</b>	input field separator	blank&tab
<b>NF</b>	number of fields in current record	-
<b>NR</b>	number of records read so far	-
<b>OFMT</b>	output format for numbers	%.6g
<b>OFS</b>	output field separator	blank
<b>ORS</b>	output record separator	newline
<b>RS</b>	input record separator	newline
<b>RSTART</b>	index of first character matched by <b>match()</b>	-
<b>RLENGTH</b>	length of string matched by <b>match()</b>	-
<b>SUBSEP</b>	subscript separator	" \034 "

Figure 4-5: **awk** Built-in Variables

---

## Arithmetic

Actions can use conventional arithmetic expressions to compute numeric values. As a simple example, suppose we want to print the population density for each country in the file **countries**. Since the second field is the area in thousands of square miles and the third field is the population in millions, the



expression `1000 * $3 / $2` gives the population density in people per square mile. The program

```
{ printf "%10s %6.1f\n", $1, 1000 * $3 / $2 }
```

applied to the file **countries** prints the name of each country and its population density:



```
USSR    30.3
Canada  6.2
China  234.6
USA     60.6
Brazil  35.3
Australia  4.7
India   502.0
Argentina 24.3
Sudan   19.6
Algeria 19.6
```

Arithmetic is done internally in floating point. The arithmetic operators are `+`, `-`, `*`, `/`, `%` (remainder) and `^` (exponentiation; `**` is a synonym). Arithmetic expressions can be created by applying these operators to constants, variables, field names, array elements, functions, and other expressions, all of which are discussed later. Note that **awk** recognizes and produces scientific (exponential) notation: `1e6`, `1E6`, `10e5`, and `1000000` are numerically equal.

**awk** has assignment statements like those found in the C programming language. The simplest form is the assignment statement

$$v = e$$

where  $v$  is a variable or field name, and  $e$  is an expression. For example, to compute the number of Asian countries and their total population, we could write

```
$4 == "Asia" { pop = pop + $3; n = n + 1 }
END          { print "population of", n,
               "Asian countries in millions is", pop }
```

## Actions

---

Applied to **countries**, this program produces

```
population of 3 Asian countries in millions is 1765
```

The action associated with the pattern `$4 == "Asia"` contains two assignment statements, one to accumulate population and the other to count countries. The variables are not explicitly initialized, yet everything works properly because **awk** initializes each variable with the string value "" and the numeric value 0.

The assignments in the previous program can be written more concisely using the operators `+=` and `++`:

```
$4 == "Asia"      { pop += $3; ++n }
```

The operator `+=` is borrowed from the C programming language:

```
pop += $3
```

has the same effect as

```
pop = pop + $3
```

but the `+=` operator is shorter and runs faster. The same is true of the `++` operator, which adds one to a variable.

The abbreviated assignment operators are `+=`, `-=`, `*=`, `/=`, `%=`, and `^=`. Their meanings are similar:

```
v op= e
```

has the same effect as

```
v = v op e.
```

The increment operators are `++` and `--`. As in C, they may be used as prefix (`++x`) or postfix (`x++`) operators. If `x` is 1, then `i=++x` increments `x`, then sets `i` to 2, while `i=x++` sets `i` to 1, then increments `x`. An analogous interpretation applies to prefix and postfix `--`.

Assignment and increment and decrement operators may all be used in arithmetic expressions.

We use default initialization to advantage in the following program, which finds the country with the largest population:

```
maxpop < $3 { maxpop = $3; country = $1 }  
END        { print country, maxpop }
```

Note, however, that this program would not be correct if all values of `$3` were

negative.

**awk** provides the built-in arithmetic functions shown in Figure 4-6.

<b>Function</b>	<b>Value Returned</b>
<b>atan2(y,x)</b>	arctangent of $y/x$ in the range $-\pi$ to $\pi$
<b>cos(x)</b>	cosine of $x$ , with $x$ in radians
<b>exp(x)</b>	exponential function of $x$
<b>int(x)</b>	integer part of $x$ truncated towards 0
<b>log(x)</b>	natural logarithm of $x$
<b>rand()</b>	random number between 0 and 1
<b>sin(x)</b>	sine of $x$ , with $x$ in radians
<b>sqrt(x)</b>	square root of $x$
<b>srand(x)</b>	$x$ is new seed for <b>rand()</b>

Figure 4-6: **awk** Built-in Arithmetic Functions

---

$x$  and  $y$  are arbitrary expressions. The function **rand()** returns a pseudo-random floating point number in the range (0,1), and **srand(x)** can be used to set the seed of the generator. If **srand()** has no argument, the seed is derived from the time of day.

## Strings and String Functions

A string constant is created by enclosing a sequence of characters inside quotation marks, as in "**abc**" or "**hello, everyone**". String constants may contain the C programming language escape sequences for special characters listed in "Regular Expressions" in this chapter.

String expressions are created by concatenating constants, variables, field names, array elements, functions, and other expressions. The program

```
{ print NR ":" $0 }
```

prints each record preceded by its record number and a colon, with no blanks. The three strings representing the record number, the colon, and the record are concatenated and the resulting string is printed. The concatenation operator has no explicit representation other than juxtaposition.

## Actions

---

**awk** provides the built-in string functions shown in Figure 4-7. In this table, *r* represents a regular expression (either as a string or as */r/*), *s* and *t* string expressions, and *n* and *p* integers.

Function	Description
<b>gsub</b> ( <i>r</i> , <i>s</i> )	substitute <i>s</i> for <i>r</i> globally in current record, return number of substitutions
<b>gsub</b> ( <i>r</i> , <i>s</i> , <i>t</i> )	substitute <i>s</i> for <i>r</i> globally in string <i>t</i> , return number of substitutions
<b>index</b> ( <i>s</i> , <i>t</i> )	return position of string <i>t</i> in <i>s</i> , 0 if not present
<b>length</b> ( <i>s</i> )	return length of <i>s</i>
<b>match</b> ( <i>s</i> , <i>r</i> )	return the position in <i>s</i> where <i>r</i> occurs, 0 if not present
<b>split</b> ( <i>s</i> , <i>a</i> )	split <i>s</i> into array <i>a</i> on FS, return number of fields
<b>split</b> ( <i>s</i> , <i>a</i> , <i>r</i> )	split <i>s</i> into array <i>a</i> on <i>r</i> , return number of fields
<b>sprintf</b> ( <i>fmt</i> , <i>expr-list</i> )	return <i>expr-list</i> formatted according to format string <i>fmt</i>
<b>sub</b> ( <i>r</i> , <i>s</i> )	substitute <i>s</i> for first <i>r</i> in current record, return number of substitutions
<b>sub</b> ( <i>r</i> , <i>s</i> , <i>t</i> )	substitute <i>s</i> for first <i>r</i> in <i>t</i> , return number of substitutions
<b>substr</b> ( <i>s</i> , <i>p</i> )	return suffix of <i>s</i> starting at position <i>p</i>
<b>substr</b> ( <i>s</i> , <i>p</i> , <i>n</i> )	return substring of <i>s</i> of length <i>n</i> starting at position <i>p</i>

Figure 4-7: **awk** Built-in String Functions

---

The functions **sub** and **gsub** are patterned after the substitute command in the text editor **ed**(1). The function **gsub**(*r*, *s*, *t*) replaces successive occurrences of substrings matched by the regular expression *r* with the replacement string *s* in the target string *t*. (As in **ed**, the leftmost match is used, and is made as long as possible.) It returns the number of substitutions made. The function **gsub**(*r*, *s*) is a synonym for **gsub**(*r*, *s*, **\$0**). For example, the program

```
{ gsub(/USA/, "United States"); print }
```

transcribes its input, replacing occurrences of **USA** by **United States**. The **sub** functions are similar, except that they only replace the first matching substring in the target string.

The function **index**(*s*, *t*) returns the leftmost position where the string *t* begins in *s*, or zero if *t* does not occur in *s*. The first character in a string is at position 1. For example,

```
index("banana", "an")
```

returns 2.

The **length** function returns the number of characters in its argument string; thus,

```
{ print length($0), $0 }
```

prints each record, preceded by its length. (**\$0** does not include the input record separator.) The program

```
length($1) > max { max = length($1); name = $1 }  
END { print name }
```

applied to the file **countries** prints the longest country name: **Australia**.

The **match**(*s*, *r*) function returns the position in string *s* where regular expression *r* occurs, or 0 if it does not occur. This function also sets two built-in variables **RSTART** and **RLENGTH**. **RSTART** is set to the starting position of the match in the string; this is the same value as the returned value. **RLENGTH** is set to the length of the matched string. (If a match does not occur, **RSTART** is 0, and **RLENGTH** is -1.) For example, the following program finds the first occurrence of the letter **i** followed by at most one character followed by the letter **a** in a record:

```
{ if (match($0, /i.?a/))  
    print RSTART, RLENGTH, $0 }
```

It produces the following output on the file **countries**:

17	2	USSR	8650	262	Asia
26	3	Canada	3852	24	North America
3	3	China	3692	866	Asia
24	3	USA	3615	219	North America
27	3	Brazil	3286	116	South America
8	2	Australia	2968	14	Australia
4	2	India	1269	637	Asia
7	3	Argentina	1072	26	South America
17	3	Sudan	968	19	Africa
6	2	Algeria	920	18	Africa

**NOTE**

**match()** matches the left-most longest matching string. For example, with the record

```
AsiaaaAsiaaaaaa
```

as input, the program

```
{ if (match($0, /a+/)) print RSTART, RLENGTH, $0 }
```

matches the first string of a's and sets **RSTART** to 4 and **RLENGTH** to 3.

The function **sprintf(format, expr<sub>1</sub>, expr<sub>2</sub>, . . . , expr<sub>n</sub>)** returns (without printing) a string containing *expr<sub>1</sub>*, *expr<sub>2</sub>*, . . . , *expr<sub>n</sub>* formatted according to the **printf** specifications in the string *format*. "The **printf** Statement" in this chapter contains a complete specification of the format conventions. The statement

```
x = sprintf("%10s %6d", $1, $2)
```

assigns to **x** the string produced by formatting the values of **\$1** and **\$2** as a ten-character string and a decimal number in a field of width at least six; **x** may be used in any subsequent computation.

The function **substr**(*s*, *p*, *n*) returns the substring of *s* that begins at position *p* and is at most *n* characters long. If **substr**(*s*, *p*) is used, the substring goes to the end of *s*; that is, it consists of the suffix of *s* beginning at position *p*. For example, we could abbreviate the country names in **countries** to their first three characters by invoking the program

```
{ $1 = substr($1, 1, 3); print }
```

on this file to produce

```
USS 8650 262 Asia
Can 3852 24 North America
Chi 3692 866 Asia
USA 3615 219 North America
Bra 3286 116 South America
Aus 2968 14 Australia
Ind 1269 637 Asia
Arg 1072 26 South America
Sud 968 19 Africa
Alg 920 18 Africa
```

Note that setting **\$1** in the program forces **awk** to recompute **\$0** and, therefore, the fields are separated by blanks (the default value of **OFS**), not by tabs.

Strings are stuck together (concatenated) merely by writing them one after another in an expression. For example, when invoked on file **countries**,

```
{ s = s substr($1, 1, 3) " " }
END { print s }
```

prints

```
USS Can Chi USA Bra Aus Ind Arg Sud Alg
```

by building *s* up a piece at a time from an initially empty string.

## Field Variables

The fields of the current record can be referred to by the field variables **\$1**, **\$2**, . . . , **\$NF**. Field variables share all of the properties of other variables — they may be used in arithmetic or string operations, and they may have values assigned to them. So, for example, you can divide the second field of the file **countries** by 1000 to convert the area from thousands to millions of square miles:

```
{ $2 /= 1000; print }
```

or assign a new string to a field:

```
BEGIN { FS = OFS = "\t" }  
$4 == "North America" { $4 = "NA" }  
$4 == "South America" { $4 = "SA" }  
{ print }
```

The **BEGIN** action in this program resets the input field separator **FS** and the output field separator **OFS** to a tab. Notice that the **print** in the fourth line of the program prints the value of **\$0** after it has been modified by previous assignments.

Fields can be accessed by expressions. For example, **\$(NF-1)** is the second to last field of the current record. The parentheses are needed: the value of **\$(NF-1)** is 1 less than the value in the last field.

A field variable referring to a nonexistent field, for example, **\$(NF+1)**, has as its initial value the empty string. A new field can be created, however, by assigning a value to it. For example, the following program invoked on the file **countries** creates a fifth field giving the population density:

```
BEGIN { FS = OFS = "\t" }  
{ $5 = 1000 * $3 / $2; print }
```

The number of fields can vary from record to record, but there is usually an implementation limit of 100 fields per record.



## Number or String?

Variables, fields and expressions can have both a numeric value and a string value. They take on numeric or string values according to context. For example, in the context of an arithmetic expression like

```
pop += $3
```

`pop` and `$3` must be treated numerically, so their values will be coerced to numeric type if necessary.

In a string context like

```
print $1 ":" $2
```

`$1` and `$2` must be strings to be concatenated, so they will be coerced if necessary.

In an assignment  $v = e$  or  $v op = e$ , the type of  $v$  becomes the type of  $e$ . In an ambiguous context like

```
$1 == $2
```

the type of the comparison depends on whether the fields are numeric or string, and this can only be determined when the program runs; it may well differ from record to record.

In comparisons, if both operands are numeric, the comparison is numeric; otherwise, operands are coerced to strings, and the comparison is made on the string values. All field variables are of type string; in addition, each field that contains only a number is also considered numeric. This determination is done at run time. For example, the comparison `"$1 == $2"` will succeed on any pair of the inputs

```
1    1.0    +1    0.1e+1    10E-1    001
```

but fail on the inputs

```
(null)    0
(null)    0.0
0a        0
1e50     1.0e50
```

There are two idioms for coercing an expression of one type to the other:

<i>number</i> " "	concatenate a null string to a <i>number</i> to coerce it to type string
<i>string</i> + 0	add zero to a <i>string</i> to coerce it to type numeric

Thus, to force a string comparison between two fields, say

```
$1 "" == $2 ""
```

The numeric value of a string is the value of any prefix of the string that looks numeric; thus the value of **12.34x** is 12.34, while the value of **x12.34** is zero. The string value of an arithmetic expression is computed by formatting the string with the output format conversion **OFMT**.

Uninitialized variables have numeric value 0 and string value "". Non-existent fields and fields that are explicitly null have only the string value ""; they are not numeric.

## Control Flow Statements

**awk** provides **if-else**, **while**, **do-while**, and **for** statements, and statement grouping with braces, as in the C programming language.

The **if** statement syntax is

```
if (expression) statement1 else statement2
```

The *expression* acting as the conditional has no restrictions; it can include the relational operators <, <=, >, >=, ==, and !=; the regular expression matching operators ~ and !~; the logical operators ||, &&, and !; juxtaposition for concatenation; and parentheses for grouping.

In the **if** statement, the *expression* is first evaluated. If it is non-zero and non-null, *statement*<sub>1</sub> is executed; otherwise *statement*<sub>2</sub> is executed. The **else** part is optional.

A single statement can always be replaced by a statement list enclosed in braces. The statements in the statement list are terminated by newlines or semicolons.

Rewriting the maximum population program from "Arithmetic Functions" with an **if** statement results in

```

{   if (maxpop < $3) {
        maxpop = $3
        country = $1
    }
}
END { print country, maxpop }

```

The **while** statement is exactly that of the C programming language:

**while** (*expression*) *statement*

The *expression* is evaluated; if it is non-zero and non-null the *statement* is executed and the *expression* is tested again. The cycle repeats as long as the *expression* is non-zero. For example, to print all input fields one per line,

```

{ i = 1
  while (i <= NF) {
    print $i
    i++
  }
}

```

The **for** statement is like that of the C programming language:

**for** (*expression*<sub>1</sub>; *expression*; *expression*<sub>2</sub>) *statement*

It has the same effect as

```
expression1  
while (expression) {  
    statement  
    expression2  
}
```

so

```
{ for (i = 1; i <= NF; i++) print $i }
```

does the same job as the **while** example above. An alternate version of the **for** statement is described in the next section.

The **do** statement has the form

```
do statement while (expression)
```

The *statement* is executed repeatedly until the value of the *expression* becomes zero. Because the test takes place after the execution of the *statement* (at the bottom of the loop), it is always executed at least once. As a result, the **do** statement is used much less often than **while** or **for**, which test for completion at the top of the loop.

The following example of a **do** statement prints all lines except those between *start* and *stop*.

```
/start/ {  
    do {  
        getline x  
    } while (x !~ /stop/)  
    { print }
```

The **break** statement causes an immediate exit from an enclosing **while** or **for**; the **continue** statement causes the next iteration to begin. The **next** statement causes **awk** to skip immediately to the next record and begin matching patterns starting from the first pattern-action statement.

The **exit** statement causes the program to behave as if the end of the input had occurred; no more input is read, and the **END** action, if any, is executed. Within the **END** action,

```
exit expr
```

causes the program to return the value of *expr* as its exit status. If there is no *expr*, the exit status is zero.

## Arrays

**awk** provides one-dimensional arrays. Arrays and array elements need not be declared; like variables, they spring into existence by being mentioned. An array subscript may be a number or a string.

As an example of a conventional numeric subscript, the statement

```
x[NR] = $0
```

assigns the current input line to the **NR**th element of the array **x**. In fact, it is possible in principle (though perhaps slow) to read the entire input into an array with the **awk** program

```
    { x[NR] = $0 }  
END { ... processing ... }
```

The first action merely records each input line in the array **x**, indexed by line number; processing is done in the **END** statement.

Array elements may also be named by nonnumeric values. For example, the following program accumulates the total population of Asia and Africa into the associative array **pop**. The **END** action prints the total population of these two continents.

## Actions

---

```
/Asia/      { pop["Asia"] += $3 }
/Africa/    { pop["Africa"] += $3 }
END         { print "Asian population in millions is", pop["Asia"]
             print "African population in millions is",
             pop["Africa"] }
```

On the file **countries**, this program generates

```
Asian population in millions is 1765
African population in millions is 37
```

In this program if we had used `pop[Asia]` instead of `pop["Asia"]` the expression would have used the value of the variable `Asia` as the subscript, and since the variable is uninitialized, the values would have been accumulated in `pop[""]`.

Suppose our task is to determine the total area in each continent of the file **countries**. Any expression can be used as a subscript in an array reference. Thus

```
area[$4] += $2
```

uses the string in the fourth field of the current input record to index the array `area` and in that entry accumulates the value of the second field:

```
BEGIN      { FS = "\t" }
           { area[$4] += $2 }
END        { for (name in area)
             print name, area[name] }
```

Invoked on the file **countries**, this program produces

```
Africa 1888
North America 7467
South America 4358
Asia 13611
Australia 2968
```

This program uses a form of the **for** statement that iterates over all defined subscripts of an array:

```
for (i in array) statement
```

executes *statement* with the variable *i* set in turn to each value of *i* for which *array[i]* has been defined. The loop is executed once for each defined subscript, which are chosen in a random order. Results are unpredictable when *i* or *array* is altered during the loop.

**awk** does not provide multi-dimensional arrays, but it does permit a list of subscripts. They are combined into a single subscript with the values separated by an unlikely string (stored in the variable **SUBSEP**). For example,

```
for (i = 1; i <= 10; i++)
    for (j = 1; j <= 10; j++)
        arr[i,j] = ...
```

creates an array which behaves like a two-dimensional array; the subscript is the concatenation of *i*, **SUBSEP**, and *j*.

You can determine whether a particular subscript *i* occurs in an array *arr* by testing the condition *i in arr*, as in

```
if ("Africa" in area) ...
```

This condition performs the test without the side effect of creating *area*["Africa"], which would happen if we used

```
if (area["Africa"] != "") ...
```

Note that neither is a test of whether the array *area* contains an element with value "Africa" .

It is also possible to split any string into fields in the elements of an array using the built-in function **split**. The function

```
split("s1:s2:s3", a, ":")
```

splits the string `s1:s2:s3` into three fields, using the separator `:`, and stores `s1` in `a[1]`, `s2` in `a[2]`, and `s3` in `a[3]`. The number of fields found, here three, is returned as the value of **split**. The third argument of **split** is a regular expression to be used as the field separator. If the third argument is missing, **FS** is used as the field separator.

An array element may be deleted with the **delete** statement:

```
delete arrayname[subscript]
```

## User-Defined Functions

**awk** provides user-defined functions. A function is defined as

```
function name(argument-list) {  
    statements  
}
```

The definition can occur anywhere a pattern-action statement can. The argument list is a list of variable names separated by commas; within the body of the function these variables refer to the actual parameters when the function is called. There must be no space between the function name and the left parenthesis of the argument list when the function is called; otherwise it looks like a concatenation. For example, the following program defines and tests the usual recursive factorial function (of course, using some input other than the file **countries**):



```
function fact(n) {  
    if (n <= 1)  
        return 1  
    else  
        return n * fact(n-1)  
}  
{ print $1 "! is " fact($1) }
```

Array arguments are passed by reference, as in C, so it is possible for the function to alter array elements or create new ones. Scalar arguments are passed by value, however, so the function cannot affect their values outside. Within a function, formal parameters are local variables but all other variables are global. (You can have any number of extra formal parameters that are used purely as local variables.) The **return** statement is optional, but the returned value is undefined if it is not included.

## Some Lexical Conventions

Comments may be placed in **awk** programs: they begin with the character **#** and end at the end of the line, as in

```
print x, y    # this is a comment
```

Statements in an **awk** program normally occupy a single line. Several statements may occur on a single line if they are separated by semicolons. A long statement may be continued over several lines by terminating each continued line by a backslash. (It is not possible to continue a "... " string.) This explicit continuation is rarely necessary, however, since statements continue automatically if the line ends with a comma (for example, as might occur in a **print** or **printf** statement) or after the operators **&&** and **||**.

Several pattern-action statements may appear on a single line if separated by semicolons.

---

# Output

The **print** and **printf** statements are the two primary constructs that generate output. The **print** statement is used to generate simple output; **printf** is used for more carefully formatted output. Like the shell, **awk** lets you redirect output, so that output from **print** and **printf** can be directed to files and pipes. This section describes the use of these two statements.

## The print Statement

The statement

```
print expr1, expr2, . . . , exprn
```

prints the string value of each expression separated by the output field separator followed by the output record separator. The statement

```
print
```

is an abbreviation for

```
print $0
```

To print an empty line use

```
print ""
```

## Output Separators

The output field separator and record separator are held in the built-in variables **OFS** and **ORS**. Initially, **OFS** is set to a single blank and **ORS** to a single newline, but these values can be changed at any time. For example, the following program prints the first and second fields of each record with a colon between the fields and two newlines after the second field:

```
BEGIN { OFS = ":"; ORS = "\n\n" }  
      { print $1, $2 }
```

Notice that

```
{ print $1 $2 }
```

prints the first and second fields with no intervening output field separator, because `$1 $2` is a string consisting of the concatenation of the first two fields.

## The printf Statement

**awk**'s **printf** statement is the same as that in C except that the **\*** format specifier is not supported. The **printf** statement has the general form

```
printf format, expr1, expr2, . . . , exprn
```

where *format* is a string that contains both information to be printed and specifications on what conversions are to be performed on the expressions in the argument list, as in Figure 4-8. Each specification begins with a **%**, ends with a letter that determines the conversion, and may include

- left-justify expression in its field
- width* pad field to this width as needed; fields that begin with a leading 0 are padded with zeros
- .prec* maximum string width or digits to right of decimal point

Character	Prints Expression as
<b>c</b>	single character
<b>d</b>	decimal number
<b>e</b>	<b>[-]d.dddE[+-]dd</b>
<b>f</b>	<b>[-]ddd.ddd</b>
<b>g</b>	<b>e</b> or <b>f</b> conversion, whichever is shorter, with nonsignificant zeros suppressed
<b>o</b>	unsigned octal number
<b>s</b>	string
<b>x</b>	unsigned hexadecimal number
<b>%</b>	print a <b>%</b> ; no argument is converted

Figure 4-8: **awk printf** Conversion Characters

---

## Output

---

Here are some examples of **printf** statements along with the corresponding output:

```
printf "%d", 99/2           49
printf "%e", 99/2         4.950000e+01
printf "%f", 99/2         49.500000
printf "%.2f", 99/2       49.50
printf "%g", 99/2         49.5
printf "%o", 99           143
printf "%06o", 99         000143
printf "%x", 99           63
printf "%s", "January"   |January|
printf "%10s", "January"  |  January|
printf "%-10s", "January" |January |
printf "%.3s", "January"  |Jan|
printf "%10.3s", "January" |      Jan|
printf "%-10.3s", "January" |Jan      |
printf "%%"               %
```

The default output format of numbers is **%.6g**; this can be changed by assigning a new value to **OFMT**. **OFMT** also controls the conversion of numeric values to strings for concatenation and creation of array subscripts.

## Output into Files

It is possible to print output into files instead of to the standard output by using the **>** and **>>** redirection operators. For example, the following program invoked on the file **countries** prints all lines where the population (third field) is bigger than 100 into a file called **bigpop**, and all other lines into **smallpop**:

```
$3 > 100 { print $1, $3 >"bigpop" }
$3 <= 100 { print $1, $3 >"smallpop" }
```

Notice that the file names have to be quoted; without quotes, **bigpop** and **smallpop** are merely uninitialized variables. If the output file names were created by an expression, they would also have to be enclosed in parentheses:

```
$4 ~ /North America/ { print $1 > ("tmp" FILENAME) }
```

This is because the `>` operator has higher precedence than concatenation; without parentheses, the concatenation of `tmp` and `FILENAME` would not work.



Files are opened once in an **awk** program. If `>` is used to open a file, its original contents are overwritten. But if `>>` is used to open a file, its contents are preserved and the output is appended to the file. Once the file has been opened, the two operators have the same effect.

## Output into Pipes

It is also possible to direct printing into a pipe with a command on the other end, instead of into a file. The statement

```
print | "command-line"
```

causes the output of **print** to be piped into the *command-line*.

Although we have shown them here as literal strings enclosed in quotes, the *command-line* and file names can come from variables and the return values from functions, for instance.

Suppose we want to create a list of continent-population pairs, sorted alphabetically by continent. The **awk** program below accumulates the population values in the third field for each of the distinct continent names in the fourth field in an array called `pop`. Then it prints each continent and its population, and pipes this output into the `sort` command.

```
BEGIN { FS = "\t" }
      { pop[$4] += $3 }
END   { for (c in pop)
        print c ":" pop[c] | "sort" }
```

Invoked on the file **countries**, this program yields

## Output

---

```
Africa:37
Asia:1765
Australia:14
North America:243
South America:142
```

In all of these **print** statements involving redirection of output, the files or pipes are identified by their names (that is, the pipe above is literally named `sort`), but they are created and opened only once in the entire run. So, in the last example, for all `c` in `pop`, only one `sort` pipe is open.

There is a limit to the number of files that can be open simultaneously. The statement **close**(*file*) closes a file or pipe; *file* is the string used to create it in the first place, as in

```
close("sort")
```

When opening or closing a file, different strings are different commands.

---

# Input

The most common way to give input to an **awk** program is to name on the command line the file(s) that contains the input. This is the method we've been using in this chapter. However, there are several other methods we could use, each of which this section describes.

## Files and Pipes

You can provide input to an **awk** program by putting the input data into a file, say **awkdata**, and then executing

```
awk 'program' awkdata
```

**awk** reads its standard input if no file names are given (see "Usage" in this chapter); thus, a second common arrangement is to have another program pipe its output into **awk**. For example, **egrep**(1) selects input lines containing a specified regular expression, but it can do so faster than **awk** since this is the only thing it does. We could, therefore, invoke the pipe

```
egrep 'Asia' countries | awk '...'
```

**egrep** quickly finds the lines containing **Asia** and passes them on to the **awk** program for subsequent processing.

## Input Separators

With the default setting of the field separator **FS**, input fields are separated by blanks or tabs, and leading blanks are discarded, so each of these lines has the same first field:

```
    field1  field2
  field1
field1
```

When the field separator is a tab, however, leading blanks are not discarded.

## Input

---

The field separator can be set to any regular expression by assigning a value to the built-in variable **FS**. For example,

```
BEGIN { FS = "(,[ \\t]*)|([ \\t]+)" }
```

sets it to an optional comma followed by any number of blanks and tabs. **FS** can also be set on the command line with the **-F** argument:

```
awk -F'([ \\t]*)|([ \\t]+)'
```

behaves the same as the previous example. Regular expressions used as field separators match the left-most longest occurrences (as in **sub()**), but do not match null strings.

## Multi-line Records

Records are normally separated by newlines, so that each line is a record, but this too can be changed, though only in a limited way. If the built-in record separator variable **RS** is set to the empty string, as in

```
BEGIN { RS = "" }
```

then input records can be several lines long; a sequence of empty lines separates records. A common way to process multiple-line records is to use

```
BEGIN { RS = ""; FS = "\n" }
```

to set the record separator to an empty line and the field separator to a newline. There is a limit, however, on how long a record can be; it is usually about 2500 characters. "The **getline** Function" and "Cooperation with the Shell" in this chapter show other examples of processing multi-line records.

## The getline Function

**awk**'s facility for automatically breaking its input into records that are more than one line long is not adequate for some tasks. For example, if records are not separated by blank lines, but by something more complicated, merely setting **RS** to null doesn't work. In such cases, it is necessary to manage the splitting of each record into fields in the program. Here are some suggestions.



The function **getline** can be used to read input either from the current input or from a file or pipe, by redirection analogous to **printf**. By itself, **getline** fetches the next input record and performs the normal field-splitting operations on it. It sets **NF**, **NR**, and **FNR**. **getline** returns 1 if there was a record present, 0 if the end-of-file was encountered, and -1 if some error occurred (such as failure to open a file).

To illustrate, suppose we have input data consisting of multi-line records, each of which begins with a line beginning with **START** and ends with a line beginning with **STOP**. The following **awk** program processes these multi-line records, a line at a time, putting the lines of the record into consecutive entries of an array

`f[1] f[2] ... f[nf]`

Once the line containing **STOP** is encountered, the record can be processed from the data in the `f` array:

```
/^START/ {
    f[nf=1] = $0
    while (getline && $0 !~ /^STOP/)
        f[++nf] = $0
    # now process the data in f[1]...f[nf]
    ...
}
```

Notice that this code uses the fact that **&&** evaluates its operands left to right and stops as soon as one is true.

## Input

---

The same job can also be done by the following program:

```
/^START/ && nf==0      { f[nf=1] = $0 }
nf > 1                { f[++nf] = $0 }
/^STOP/               { # now process the data in f[1]...f[nf]
                      ...
                      nf = 0
}
}
```

The statement

```
getline x
```

reads the next record into the variable **x**. No splitting is done; **NF** is not set.

The statement

```
getline <"file"
```

reads from **file** instead of the current input. It has no effect on **NR** or **FNR**, but field splitting is performed and **NF** is set. The statement

```
getline x <"file"
```

gets the next record from **file** into **x**; no splitting is done, and **NF**, **NR** and **FNR** are untouched.

NOTE

If a filename is an expression, it should be in parentheses for evaluation:

```
while ( getline x < (ARGV[1] ARGV[2]) ) { ... }
```

This is because the **<** has precedence over concatenation. Without parentheses, a statement such as

```
getline x < "tmp" FILENAME
```

sets **x** to read the file **tmp** and not **tmp <value of FILENAME>**. Also, if you use this **getline** statement form, a statement like

```
while ( getline x < file ) { ... }
```

loops forever if the file cannot be read, because **getline** returns **-1**, not zero, if an error occurs. A better way to write this test is

---

```
while ( getline x < file > 0 ) { ... }
```

It is also possible to pipe the output of another command directly into **getline**. For example, the statement

```
while ("who" | getline)
    n++
```

executes **who** and pipes its output into **getline**. Each iteration of the **while** loop reads one more line and increments the variable **n**, so after the **while** loop terminates, **n** contains a count of the number of users. Similarly, the statement

```
"date" | getline d
```

pipes the output of **date** into the variable **d**, thus setting **d** to the current date. Figure 4-9 summarizes the **getline** function.

Form	Sets
<b>getline</b>	<b>\$0, NF, NR, FNR</b>
<b>getline</b> <i>var</i>	<i>var</i> , <b>NR, FNR</b>
<b>getline</b> < <i>file</i>	<b>\$0, NF</b>
<b>getline</b> <i>var</i> < <i>file</i>	<i>var</i>
<i>cmd</i>   <b>getline</b>	<b>\$0, NF</b>
<i>cmd</i>   <b>getline</b> <i>var</i>	<i>var</i>

Figure 4-9: **getline** Function

---

## Command-line Arguments

The command-line arguments are available to an **awk** program: the array **ARGV** contains the elements **ARGV[0], . . . , ARGV[ARGC-1]**; as in C, **ARGC** is the count. **ARGV[0]** is the name of the program (generally **awk**); the remaining arguments are whatever was provided (excluding the program and any optional arguments).

## Input

---

The following command line contains an **awk** program that echoes the arguments that appear after the program name:

```
awk '
BEGIN {
    for (i = 1; i < ARGV; i++)
        printf "%s ", ARGV[i]
    printf "\n"
}' $*
```

The arguments may be modified or added to; **ARGC** may be altered. As each input file ends, **awk** treats the next non-null element of **ARGV** (up to the current value of **ARGC-1**) as the name of the next input file.

There is one exception to the rule that an argument is a file name: if it is of the form

*var=value*

then the variable *var* is set to the value *value* as if by assignment. Such an argument is not treated as a file name. If *value* is a string, no quotes are needed.

---

## Using `awk` with Other Commands and the Shell

`awk` gains its greatest power when it is used in conjunction with other programs. Here we describe some of the ways in which `awk` programs cooperate with other commands.

### The system Function

The built-in function `system(command-line)` executes the command *command-line*, which may well be a string computed by, for example, the built-in function `sprintf`. The value returned by `system` is the return status of the command executed.

For example, the program

```
$1 == "#include" { gsub(/[<>"]/, "", $2); system("cat " $2) }
```

calls the command `cat` to print the file named in the second field of every input record whose first field is `#include`, after stripping any `<`, `>` or `"` that might be present.

### Cooperation with the Shell

In all the examples thus far, the `awk` program was in a file and fetched from there using the `-f` flag, or it appeared on the command line enclosed in single quotes, as in

```
awk '{ print $1 }' . . .
```

Since `awk` uses many of the same characters as the shell does, such as `$` and `"`, surrounding the `awk` program with single quotes ensures that the shell will pass the entire program unchanged to the `awk` interpreter.

Now, consider writing a command `addr` that will search a file `addresslist` for name, address and telephone information. Suppose that `addresslist` contains names and addresses in which a typical entry is a multi-line record such as

G. R. Emlin  
600 Mountain Avenue  
Murray Hill, NJ 07974  
201-555-1234

Records are separated by a single blank line.

We want to search the address list by issuing commands like

```
addr Emlin
```

That is easily done by a program of the form

```
awk '  
BEGIN      { RS = "" }  
/Emlin/  
' addresslist
```

The problem is how to get a different search pattern into the program each time it is run.

There are several ways to do this. One way is to create a file called `addr` that contains

```
awk '  
BEGIN      { RS = "" }  
/'$1'/  
' addresslist
```

The quotes are critical here: the `awk` program is only one argument, even though there are two sets of quotes, because quotes do not nest. The `$1` is outside the quotes, visible to the shell, which therefore replaces it by the pattern `Emlin` when the command `addr Emlin` is invoked. On a UNIX system, `addr` can be made executable by changing its mode with the following command: `chmod +x addr`.

A second way to implement `addr` relies on the fact that the shell substitutes for `$` parameters within double quotes:

```
awk "  
BEGIN      { RS = \"\" }  
/$1/  
" addresslist
```

Here we must protect the quotes defining `RS` with backslashes, so that the shell passes them on to `awk`, uninterpreted by the shell. `$1` is recognized as

a parameter, however, so the shell replaces it by the pattern when the command **addr pattern** is invoked.

A third way to implement **addr** is to use **ARGV** to pass the regular expression to an **awk** program that explicitly reads through the address list with **getline**:

```
awk '
BEGIN { RS = ""
        while (getline < "addresslist")
            if ($0 ~ ARGV[1])
                print $0
    } ' $*
```

All processing is done in the **BEGIN** action.

Notice that any regular expression can be passed to **addr**; in particular, it is possible to retrieve by parts of an address or telephone number as well as by name.

---

## Example Applications

**awk** has been used in surprising ways. We have seen **awk** programs that implement database systems and a variety of compilers and assemblers, in addition to the more traditional tasks of information retrieval, data manipulation, and report generation. Invariably, the **awk** programs are significantly shorter than equivalent programs written in more conventional programming languages such as Pascal or C. In this section, we will present a few more examples to illustrate some additional **awk** programs.

### Generating Reports

**awk** is especially useful for producing reports that summarize and format information. Suppose we wish to produce a report from the file **countries** in which we list the continents alphabetically, and after each continent its countries in decreasing order of population:

Africa:	Sudan	19
	Algeria	18
Asia:	China	866
	India	637
	USSR	262
Australia:	Australia	14
North America:	USA	219
	Canada	24
South America:	Brazil	116
	Argentina	26



As with many data processing tasks, it is much easier to produce this report in several stages. First, we create a list of continent-country-population triples, in which each field is separated by a colon. This can be done with the following program **triples**, which uses an array `pop` indexed by subscripts of the form 'continent:country' to store the population of a given country. The print statement in the `END` section of the program creates the list of continent-country-population triples that are piped to the `sort` routine.

```
BEGIN { FS = "\t" }
        { pop[$4 ":" $1] += $3 }
END     { for (cc in pop)
          print cc ":" pop[cc] | "sort -t: +0 -1 +2nr" }
```

The arguments for `sort` deserve special mention. The `-t:` argument tells `sort` to use `:` as its field separator. The `+0 -1` arguments make the first field the primary sort key. In general, `+i -j` makes fields `i+1`, `i+2`, . . . , `j` the sort key. If `-j` is omitted, the fields from `i+1` to the end of the record are used. The `+2nr` argument makes the third field, numerically decreasing, the secondary sort key (`n` is for numeric, `r` for reverse order). Invoked on the file **countries**, this program produces as output

```
Africa:Sudan:19
Africa:Algeria:18
Asia:China:866
Asia:India:637
Asia:USSR:262
Australia:Australia:14
North America:USA:219
North America:Canada:24
South America:Brazil:116
South America:Argentina:26
```

This output is in the right order but the wrong format. To transform the output into the desired form we run it through a second **awk** program **format**:

```
BEGIN { FS = ":" }
{
    if ($1 != prev) {
        print "\n" $1 ":"
        prev = $1
    }
    printf "\t%-10s %6d\n", $2, $3
}
}
```

This is a control-break program that prints only the first occurrence of a continent name and formats the country-population lines associated with that continent in the desired manner. The command line

```
awk -f triples countries | awk -f format
```

gives us our desired report. As this example suggests, complex data transformation and formatting tasks can often be reduced to a few simple **awks** and **sorts**.

As an exercise, add to the population report subtotals for each continent and a grand total.

## Additional Examples

### Word Frequencies

Our first example illustrates associative arrays for counting. Suppose we want to count the number of times each word appears in the input, where a word is any contiguous sequence of non-blank, non-tab characters. The following program prints the word frequencies, sorted in decreasing order.

```
{ for (w = 1; w <= NF; w++) count[$w]++ }
END { for (w in count) print count[w], w | "sort -nr" }
```

The first statement uses the array `count` to accumulate the number of times each word is used. Once the input has been read, the second `for` loop pipes the final count along with each word into the `sort` command.

## Accumulation

Suppose we have two files, `deposits` and `withdrawals`, of records containing a name field and an amount field. For each name we want to print the net balance determined by subtracting the total withdrawals from the total deposits for each name. The net balance can be computed by the following program:

```
awk '
FILENAME == "deposits"    { balance[$1] += $2 }
FILENAME == "withdrawals" { balance[$1] -= $2 }
END                       { for (name in balance)
                           print name, balance[name]
                           } ' deposits withdrawals
```

The first statement uses the array `balance` to accumulate the total amount for each name in the file `deposits`. The second statement subtracts associated withdrawals from each total. If there are only withdrawals associated with a name, an entry for that name will be created by the second statement. The `END` action prints each name with its net balance.

## Random Choice

The following function prints (in order) `k` random elements from the first `n` elements of the array `A`. In the program, `k` is the number of entries that still need to be printed, and `n` is the number of elements yet to be examined. The decision of whether to print the `i`th element is determined by the test `rand() < k/n`.

```
function choose(A, k, n) {
    for (i = 1; n > 0; i++)
        if (rand() < k/n--) {
            print A[i]
            k--
        }
    }
}
```

## Shell Facility

The following `awk` program simulates (crudely) the history facility of the UNIX system shell. A line containing `=` re-executes the last command executed. A line beginning with `= cmd` re-executes the last command whose invocation included the string `cmd`. Otherwise, the current line is executed.

```
$1 == "=" { if (NF == 1)
             system(x[NR] = x[NR-1])
           else
             for (i = NR-1; i > 0; i--)
                 if (x[i] ~ $2) {
                     system(x[NR] = x[i])
                     break
                 }
             next }
././      { system(x[NR] = $0) }
```

## Form-letter Generation

The following program generates form letters, using a template stored in a file called `form.letter`:

```
This is a form letter.
The first field is $1, the second $2, the third $3.
The third is $3, second is $2, and first is $1.
```

and replacement text of this form:

```
field 1|field 2|field 3
one|two|three
a|b|c
```

The `BEGIN` action stores the template in the array `template`; the remaining action cycles through the input data, using `gsub` to replace template fields of the form `$n` with the corresponding data fields.

```
BEGIN {
    FS = "|"
    while (getline <"form.letter")
        line[++n] = $0
}
{
    for (i = 1; i <= n; i++) {
        s = line[i]
        for (j = 1; j <= NF; j++)
            gsub("\\\\"$j, $j, s)
        print s
    }
}
```

In all such examples, a prudent strategy is to start with a small version and expand it, trying out each aspect before moving on to the next.

---

# awk Summary

## Command Line

**awk** *program filenames*

**awk -f** *program-file filenames*

**awk -F***s* sets field separator to string *s*; **-Ft** sets separator to tab

## Patterns

**BEGIN**

**END**

*/regular expression/*

*relational expression*

*pattern && pattern*

*pattern || pattern*

*(pattern)*

*!pattern*

*pattern, pattern*

## Control Flow Statements

**if** (*expr*) *statement* [**else** *statement*]

**if** (*subscript in array*) *statement* [**else** *statement*]

**while** (*expr*) *statement*

**for** (*expr; expr; expr*) *statement*

**for** (*var in array*) *statement*

**do** *statement* **while** (*expr*)

**break**

**continue**

**next**

**exit** [*expr*]

**return** [*expr*]

## Input-output

<b>close</b> (filename)	close file
<b>getline</b>	set <b>\$0</b> from next input record; set <b>NF</b> , <b>NR</b> , <b>FNR</b>
<b>getline</b> <file	set <b>\$0</b> from next record of <i>file</i> ; set <b>NF</b>
<b>getline</b> var	set <i>var</i> from next input record; set <b>NR</b> , <b>FNR</b>
<b>getline</b> var <file	set <i>var</i> from next record of <i>file</i>
<b>print</b>	print current record
<b>print</b> expr-list	print expressions
<b>print</b> expr-list >file	print expressions on <i>file</i>
<b>printf</b> fmt, expr-list	format and print
<b>printf</b> fmt, expr-list >file	format and print on <i>file</i>
<b>system</b> (cmd-line)	execute command <i>cmd-line</i> , return status

In **print** and **printf** above, >>*file* appends to the *file*, and | *command* writes on a pipe. Similarly, *command* | **getline** pipes into **getline**. **getline** returns 0 on end of file, and -1 on error.

## Functions

```
func name(parameter list) { statement }
function name(parameter list) { statement }
function-name(expr, expr, . . .)
```

## String Functions

<b>gsub</b> ( <i>r, s, t</i> )	substitute string <i>s</i> for each substring matching regular expression <i>r</i> in string <i>t</i> , return number of substitutions; if <i>t</i> omitted, use <b>\$0</b>
<b>index</b> ( <i>s, t</i> )	return index of string <i>t</i> in string <i>s</i> , or 0 if not present
<b>length</b> ( <i>s</i> )	return length of string <i>s</i>
<b>match</b> ( <i>s, r</i> )	return position in <i>s</i> where regular expression <i>r</i> occurs, or 0 if <i>r</i> is not present
<b>split</b> ( <i>s, a, r</i> )	split string <i>s</i> into array <i>a</i> on regular expression <i>r</i> , return number of fields; if <i>r</i> omitted, <b>FS</b> is used in its place
<b>sprintf</b> ( <i>fmt, expr-list</i> )	print <i>expr-list</i> according to <i>fmt</i> , return resulting string
<b>sub</b> ( <i>r, s, t</i> )	like <b>gsub</b> except only the first matching substring is replaced
<b>substr</b> ( <i>s, i, n</i> )	return <i>n</i> -char substring of <i>s</i> starting at <i>i</i> ; if <i>n</i> omitted, use rest of <i>s</i>

## Arithmetic Functions

<b>atan2</b> ( <i>y, x</i> )	arctangent of $y/x$ in radians
<b>cos</b> ( <i>expr</i> )	cosine (angle in radians)
<b>exp</b> ( <i>expr</i> )	exponential
<b>int</b> ( <i>expr</i> )	truncate to integer
<b>log</b> ( <i>expr</i> )	natural logarithm
<b>rand</b> ()	random number between 0 and 1
<b>sin</b> ( <i>expr</i> )	sine (angle in radians)
<b>sqrt</b> ( <i>expr</i> )	square root
<b>srand</b> ( <i>expr</i> )	new seed for random number generator; use time of day if no <i>expr</i>



## Operators (Increasing Precedence)

= += -- *= /= %= ^=	assignment
?:	conditional expression
	logical OR
&&	logical AND
~ !~	regular expression match, negated match
< <= > >= != ==	relationals
<i>blank</i>	string concatenation
+ -	add, subtract
* / %	multiply, divide, mod
+ - !	unary plus, unary minus, logical negation
^	exponentiation (** is a synonym)
++ --	increment, decrement (prefix and postfix)
\$	field

## Regular Expressions (Increasing Precedence)

<i>c</i>	matches non-metacharacter <i>c</i>
\ <i>c</i>	matches literal character <i>c</i>
.	matches any character but newline
^	matches beginning of line or string
\$	matches end of line or string
[ <i>abc...</i> ]	character class matches any of <i>abc...</i>
[^ <i>abc...</i> ]	negated class matches any but <i>abc...</i> and newline
<i>r1</i>   <i>r2</i>	matches either <i>r1</i> or <i>r2</i>
<i>r1r2</i>	concatenation: matches <i>r1</i> , then <i>r2</i>
<i>r</i> +	matches one or more <i>r</i> 's
<i>r</i> *	matches zero or more <i>r</i> 's
<i>r</i> ?	matches zero or one <i>r</i> 's
( <i>r</i> )	grouping: matches <i>r</i>

## Built-in Variables

<b>ARGC</b>	number of command-line arguments
<b>ARGV</b>	array of command-line arguments (0.. <b>ARGC</b> -1)
<b>FILENAME</b>	name of current input file
<b>FNR</b>	input record number in current file
<b>FS</b>	input field separator (default blank)
<b>NF</b>	number of fields in current input record
<b>NR</b>	input record number since beginning
<b>OFMT</b>	output format for numbers (default <code>%.6g</code> )
<b>OFS</b>	output field separator (default blank)
<b>ORS</b>	output record separator (default newline)
<b>RS</b>	input record separator (default newline)
<b>RSTART</b>	index of first character matched by <b>match()</b> ; 0 if no match
<b>RLENGTH</b>	length of string matched by <b>match()</b> ; -1 if no match
<b>SUBSEP</b>	separates multiple subscripts in array elements; default <code>"\034"</code>

## Limits

Any particular implementation of **awk** enforces some limits. Here are typical values:

- 100 fields
- 2500 characters per input record
- 2500 characters per output record
- 1024 characters per individual field
- 1024 characters per printf string
- 400 characters maximum quoted string
- 400 characters in character class
- 15 open files
- 1 pipe
- numbers are limited to what can be represented on the local machine, e.g., `1e-38..1e+38`

## Initialization, Comparison, and Type Coercion

Each variable and field can potentially be a string or a number or both at any time. When a variable is set by the assignment

```
var = expr
```

its type is set to that of the expression. (Assignment includes +=, -=, etc.) An arithmetic expression is of type number, a concatenation is of type string, and so on. If the assignment is a simple copy, as in

```
v1 = v2
```

then the type of *v1* becomes that of *v2*.

In comparisons, if both operands are numeric, the comparison is made numerically. Otherwise, operands are coerced to string if necessary, and the comparison is made on strings. The type of any expression can be coerced to numeric by subterfuges such as

```
expr + 0
```

and to string by

```
expr ""
```

(that is, concatenation with a null string).

Uninitialized variables have the numeric value 0 and the string value "". Accordingly, if *x* is uninitialized,

```
if (x) ...
```

is false, and

```
if (!x) ...
```

```
if (x == 0) ...
```

```
if (x == "") ...
```

are all true. But the following is false:

```
if (x == "0") ...
```

The type of a field is determined by context when possible; for example,

```
$1++
```

clearly implies that \$1 is to be numeric, and

```
$1 = $1 " ", " $2
```

implies that \$1 and \$2 are both to be strings. Coercion is done as needed.

In contexts where types cannot be reliably determined, for example,

```
if ($1 == $2) ...
```

the type of each field is determined on input. All fields are strings; in addition, each field that contains only a number is also considered numeric.

Fields that are explicitly null have the string value " " ; they are not numeric. Non-existent fields (i.e., fields past **NF**) are treated this way, too.

As it is for fields, so it is for array elements created by **split()**.

Mentioning a variable in an expression causes it to exist, with the value " " as described above. Thus, if **arr[i]** does not currently exist,

```
if (arr[i] == "") ...
```

causes it to exist with the value " " so the **if** is satisfied. The special construction

```
if (i in arr) ...
```

determines if **arr[i]** exists without the side effect of creating it if it does not.



lex

---

# 5 lex

---

## **An Overview of lex Programming** 5-1

---

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---

# An Overview of **lex** Programming

The software tool **lex** lets you solve a wide class of problems drawn from text processing, code enciphering, compiler writing, and other areas. In text processing, you may check the spelling of words for errors; in code enciphering, you may translate certain patterns of characters into others; and in compiler writing, you may determine what the tokens (smallest meaningful sequences of characters) are in the program to be compiled. The problem common to all of these tasks is recognizing different strings of characters that satisfy certain characteristics. In the compiler writing case, creating the ability to solve the problem requires implementing the compiler's lexical analyzer; hence the name **lex**.

It is not essential to use **lex** to handle problems of this kind. You could write programs in a standard language like C to handle them, too. In fact, what **lex** does is produce such C programs. (**lex** is therefore called a program generator.) What **lex** offers you, once you acquire a facility with it, is typically a faster, easier way to create programs that perform these tasks. Its weakness is that it often produces C programs that are longer than necessary for the task at hand and that execute more slowly than they otherwise might. In many applications this is a minor consideration, and the advantages of using **lex** considerably outweigh it.

To understand what **lex** does, see the diagram in Figure 5-1. We begin with the **lex** source (often called the **lex** specification) that you, the programmer, write to solve the problem at hand. This **lex** source consists of a list of rules specifying sequences of characters (expressions) to be searched for in an input text, and the actions to take when an expression is found. The source is read by the **lex** program generator. The output of the program generator is a C program that, in turn, must be compiled by a host language C compiler to generate the executable object program that does the lexical analysis. Note that this procedure is not typically automatic—user intervention is required. Finally, the lexical analyzer program produced by this process takes as input any source file and produces the desired output, such as altered text or a list of tokens.

`lex` can also be used to collect statistical data on features of the input, such as character count, word length, number of occurrences of a word, and so forth. In later sections of this chapter, we will see

- how to write `lex` source to do some of these tasks
- how to translate `lex` source
- how to compile, link, and execute the lexical analyzer in C
- how to run the lexical analyzer program

We will then be on our way to appreciating the power that `lex` provides.

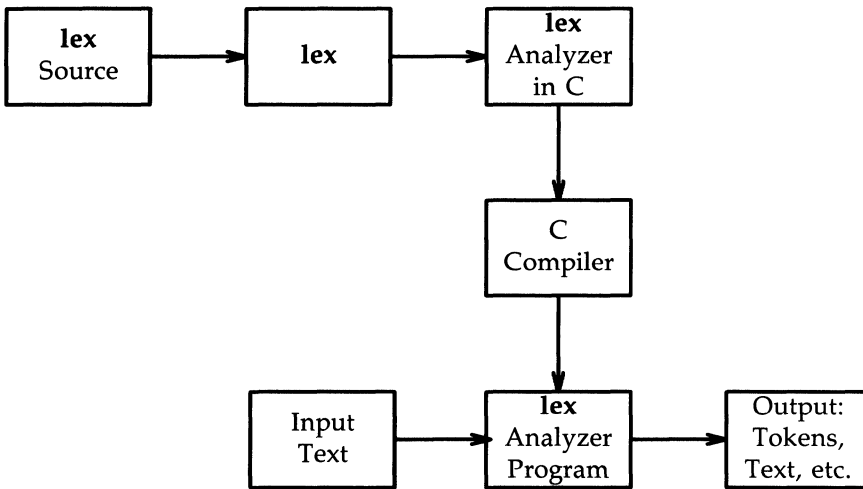


Figure 5-1: Creation and Use of a Lexical Analyzer with `lex`

---

---

# Writing lex Programs

A **lex** specification consists of at most three sections: definitions, rules, and user subroutines. The rules section is mandatory. Sections for definitions and user subroutines are optional, but if present, must appear in the indicated order.

## The Fundamentals of lex Rules

The mandatory rules section opens with the delimiter `%%`. If a subroutines section follows, another `%%` delimiter ends the rules section. If there is no second delimiter, the rules section is presumed to continue to the end of the program.

Each rule consists of a specification of the pattern sought and the action(s) to take on finding it. (Note the dual meaning of the term specification—it may mean either the entire **lex** source itself or, within it, a representation of a particular pattern to be recognized.) Whenever the input consists of patterns not sought, **lex** writes out the input exactly as it finds it. So, the simplest **lex** program is just the beginning rules delimiter, `%%`. It writes out the entire input to the output with no changes at all. Typically, the rules are more elaborate than that.

## Specifications

You specify the patterns you are interested in with a notation called regular expressions. A regular expression is formed by stringing together characters with or without operators. The simplest regular expressions are strings of text characters with no operators at all. For example,

```
apple  
orange  
pluto
```

These three regular expressions match any occurrences of those character strings in an input text. If you want to have your lexical analyzer, **a.out**, remove every occurrence of **orange** from the input text, you could specify the rule

```
orange;
```

Because you did not specify an action on the right (before the semicolon), **lex** does nothing but print out the original input text with every occurrence of this regular expression removed, that is, without any occurrence of the string **orange** at all.

Unlike **orange** above, most of the expressions that we want to search for cannot be specified so easily. The expression itself might simply be too long. More commonly, the class of desired expressions is too large; it may, in fact, be infinite. Thanks to the use of operators, we can form regular expressions signifying any expression of a certain class. The **+** operator, for instance, means one or more occurrences of the preceding expression, the **?** means 0 or 1 occurrence of the preceding expression (this is equivalent, of course, to saying that the preceding expression is optional), and **\*** means 0 or more occurrences of the preceding expression. (It may at first seem odd to speak of 0 occurrences of an expression and to need an operator to capture the idea, but it is often quite helpful. We will see an example in a moment.) So **m+** is a regular expression matching any string of **ms** such as each of the following:

```
mmmm
m
mmmmmm
mm
```

and **7\*** is a regular expression matching any string of zero or more **7s**:

```
77
77777
777
```

The string of blanks on the third line matches simply because it has no **7s** in it at all.

Brackets, **[ ]**, indicate any one character from the string of characters specified between the brackets. Thus, **[dgka]** matches a single **d**, **g**, **k**, or **a**. Note that commas are not included within the brackets. Any comma here would be taken as a character to be recognized in the input text. Ranges within a standard alphabetic or numeric order are indicated with a hyphen, **-**. The sequence **[a-z]**, for instance, indicates any lowercase letter. Somewhat more interestingly,

```
[A-Za-z0-9*&#]
```

is a regular expression that matches any letter (whether uppercase or lowercase), any digit, an asterisk, an ampersand, or a sharp character. Given the input text

```
$$$$?? ?????!!!*$$ $$$$$&+====r~~# ((
```

the lexical analyzer with the previous specification in one of its rules will recognize the `*`, `&`, `r`, and `#`, perform on each recognition whatever action the rule specifies (we have not indicated an action here), and print out the rest of the text as it stands.

The operators become especially powerful in combination. For example, the regular expression to recognize an identifier in many programming languages is

```
[a-zA-Z][0-9a-zA-Z]*
```

An identifier in these languages is defined to be a letter followed by zero or more letters or digits. That is just what the regular expression says. The first pair of brackets matches any letter. The second pair, if it were not followed by a `*`, would match any digit or letter. The two pairs of brackets with their enclosed characters would then match any letter followed by a digit or a letter. But with the asterisk, `*`, the example matches any letter followed by any number of letters or digits. In particular, it would recognize the following as identifiers:

```
e
pay
distance
pH
EngineNo99
R2D2
```

Note that it would not recognize the following as identifiers:

```
not_ideNTIFER
5times
$hello
```

because `not_ideNTIFER` has an embedded underscore; `5times` starts with a digit, not a letter; and `$hello` starts with a special character. Of course, you may want to write the specifications for these three examples as an exercise.

## Writing lex Programs

---

A potential problem with operator characters is how we can refer to them as characters to look for in our search pattern. The last example, for instance, will not recognize text with an `*` in it. **lex** solves the problem in one of two ways: a character enclosed in quotation marks or a character preceded by a `\` is taken literally, that is, as part of the text to be searched for. To use the backslash method to recognize, say, an `*` followed by any number of digits, we can use the pattern

```
\*[1-9]*
```

To recognize a `\` itself, we need two backslashes: `\\`.

### Actions

Once **lex** recognizes a string matching the regular expression at the start of a rule, it looks to the right of the rule for the action to be performed. Kinds of actions include recording the token type found and its value, if any; replacing one token with another; and counting the number of instances of a token or token type. What you want to do is write these actions as program fragments in the host language C. An action may consist of as many statements as are needed for the job at hand. You may want to print out a message noting that the text has been found or a message transforming the text in some way. Thus, to recognize the expression Amelia Earhart and to note such recognition, the rule

```
"Amelia Earhart"    printf("found Amelia");
```

would do. And to replace in a text lengthy medical terms with their equivalent acronyms, a rule such as

```
Electroencephalogram    printf("EEG");
```

would be called for. To count the lines in a text, we need to recognize end-of-lines and increment a linecounter. **lex** uses the standard escape sequences from C like `\n` for end-of-line. To count lines we might have

```
\n    lineno++;
```

where **lineno**, like other C variables, is declared in the definitions section that we discuss later.

**lex** stores every character string that it recognizes in a character array called `yytext[]`. You can print or manipulate the contents of this array as you want. Sometimes your action may consist of two or more C statements and you must (or for style and clarity, you choose to) write it on several lines. To inform **lex** that the action is for one rule only, simply enclose the C code in

braces. For example, to count the total number of all digit strings in an input text, print the running total of the number of digit strings (not their sum) and print out each one as soon as it is found, your **lex** code might be

```
+?[1-9]+          { digstringcount++;
                   printf("%d",digstringcount);
                   printf("%s", yytext); }
```

This specification matches digit strings whether they are preceded by a plus sign or not, because the **?** indicates that the preceding plus sign is optional. In addition, it will catch negative digit strings because that portion following the minus sign, **-**, will match the specification. The next section explains how to distinguish negative from positive integers.

## Advanced lex Usage

The **lex** command provides a suite of features that lets you process input text riddled with quite complicated patterns. These include rules that decide what specification is relevant, when more than one seems so at first; functions that transform one matching pattern into another; and the use of definitions and subroutines. Before considering these features, you may want to affirm your understanding thus far by examining an example drawing together several of the points already covered.

```
%%
-[0-9]+          printf("negative integer");
+?[0-9]+         printf("positive integer");
-0.[0-9]+       printf("negative fraction, no whole number part");
rail[ ]+road    printf("railroad is one word");
crook           printf("Here's a crook");
function        subprogcount++;
G[a-zA-Z]*      { printf("may have a G word here: ", yytext);
                  Gstringcount++; }
```

The first three rules recognize negative integers, positive integers, and negative fractions between 0 and -1. Use of the terminating **+** in each specification ensures that one or more digits compose the number in question. Each of the next three rules recognizes a specific pattern. The specification for **railroad** matches cases where one or more blanks intervene between the two syllables of the word. In the cases of **railroad** and **crook**, you may have simply printed a synonym rather than the messages stated. The rule recognizing a **function** increments a counter. The last rule illustrates several points:

- The braces specify an action sequence extending over several lines.
- Its action uses the **lex** array **yytext[]**, which stores the recognized character string.
- Its specification uses the **\*** to indicate that zero or more letters may follow the **G**.

### Some Special Features

Besides storing the recognized character string in **yytext[]**, **lex** automatically counts the number of characters in a match and stores it in the variable **yylen**. You may use this variable to refer to any specific character just placed in the array **yytext[]**. Remember that C numbers locations in an array starting with 0, so to print out the third digit (if there is one) in a just recognized integer, you might write

```
[1-9]+      {if (yylen > 2)
              printf("%c", yytext[2]); }
```

**lex** follows a number of high-level rules to resolve ambiguities that may arise from the set of rules that you write. *Prima facie*, any reserved word, for instance, could match two rules. In the lexical analyzer example developed later in the section on **lex** and **yacc**, the reserved word **end** could match the second rule as well as the seventh, the one for identifiers.

NOTE

**lex** follows the rule that where there is a match with two or more rules in a specification, the first rule is the one whose action will be executed.

By placing the rule for **end** and the other reserved words before the rule for identifiers, we ensure that our reserved words will be duly recognized.

Another potential problem arises from cases where one pattern you are searching for is the prefix of another. For instance, the last two rules in the lexical analyzer example above are designed to recognize **>** and **>=**. If the text has the string **>=** at one point, you might worry that the lexical analyzer would stop as soon as it recognized the **>** character to execute the rule for **>** rather than read the next character and execute the rule for **>=**.



NOTE

**lex** follows the rule that it matches the longest character string possible and executes the rule for that.

Here it would recognize the `>=` and act accordingly. As a further example, the rule would enable you to distinguish `+` from `++` in a program in C.

Still another potential problem exists when the analyzer must read characters beyond the string you are seeking because you cannot be sure you have in fact found it until you have read the additional characters. These cases reveal the importance of trailing context. The classic example here is the DO statement in FORTRAN. In the statement

```
DO 50 k = 1 , 20, 1
```

we cannot be sure that the first 1 is the initial value of the index `k` until we read the first comma. Until then, we might have the assignment statement

```
DO50k = 1
```

(Remember that FORTRAN ignores all blanks.) The way to handle this is to use the forward-looking slash, `/` (not the backslash, `\`), which signifies that what follows is trailing context, something not to be stored in `yytext[]`, because it is not part of the token itself. So the rule to recognize the FORTRAN DO statement could be

```
30/[ ]*[0-9][ ]*[a-zA-Z0-9]+=[a-zA-Z0-9]+, printf("found DO");
```

Different versions of FORTRAN have limits on the size of identifiers, here the index name. To simplify the example, the rule accepts an index name of any length.

**lex** uses the `$` as an operator to mark a special trailing context—the end of line. (It is therefore equivalent to `\n`.) An example would be a rule to ignore all blanks and tabs at the end of a line:

```
[ \t]+$ ;
```

On the other hand, if you want to match a pattern only when it starts a line, **lex** offers you the circumflex, `^`, as the operator. The formatter **nroff**, for example, demands that you never start a line with a blank, so you might want to check input to **nroff** with some such rule as:

```
^[ ]      printf("error: remove leading blank");
```

Finally, some of your action statements themselves may require your reading another character, putting one back to be read again a moment later, or writing a character on an output device. **lex** supplies three functions to handle these tasks—**input()**, **unput(c)**, and **output(c)**, respectively. One way to ignore all characters between two special characters, say between a pair of double quotation marks, would be to use **input()**, thus:

```
\ "      while (input() != '"');
```

Upon finding the first double quotation mark, the generated **a.out** will simply continue reading all subsequent characters so long as none is a quotation mark, and not again look for a match until it finds a second double quotation mark.

To handle special I/O needs, such as writing to several files, you may use standard I/O routines in C to rewrite the functions **input()**, **unput(c)**, and **output**. These and other programmer-defined functions should be placed in your subroutine section. Your new routines will then replace the standard ones. The standard **input()**, in fact, is equivalent to **getchar()**, and the standard **output(c)** is equivalent to **putchar(c)**.

There are a number of **lex** routines that let you handle sequences of characters to be processed in more than one way. These include **yymore()**, **yyless(n)**, and **REJECT**. Recall that the text matching a given specification is stored in the array **yytext[]**. In general, once the action is performed for the specification, the characters in **yytext[]** are overwritten with succeeding characters in the input stream to form the next match. The function **yymore()**, by contrast, ensures that the succeeding characters recognized are appended to those already in **yytext[]**. This lets you do one thing and then another, when one string of characters is significant and a longer one including the first is significant as well. Consider a character string bound by **B**s and interspersed with one at an arbitrary location.

```
B...B...B
```

In a simple code-deciphering situation, you may want to count the number of characters between the first and second **B**'s and add it to the number of characters between the second and third **B**. (Only the last **B** is not to be counted.) The code to do this is

```

B[^B]*      { if (flag = 0)
              save = yyleng;
              flag = 1;
              yymore();
            else {
              importantno = save + yyleng;
              flag = 0; }
            }

```

where **flag**, **save**, and **importantno** are declared (and at least **flag** initialized to 0) in the definitions section. The **flag** distinguishes the character sequence terminating just before the second **B** from that terminating just before the third.

The function **yyles(n)** lets you reset the end point of the string to be considered to the *n*th character in the original **yytext[]**. Suppose you are again in the code-deciphering business and the gimmick here is to work with only half the characters in a sequence ending with a certain one, say upper- or lower-case **Z**. The code you want might be

```

[a-zA-Y]+[Zz]      { yyles(yyleng/2);
                    ... process first half of string... }

```

Finally, the function **REJECT** lets you more easily process strings of characters even when they overlap or contain one another as parts. **REJECT** does this by immediately jumping to the next rule and its specification without changing the contents of **yytext[]**. If you want to count the number of occurrences both of the regular expression **snapdragon** and of its subexpression **dragon** in an input text, the following will do:

```

snapdragon      {countflowers++; REJECT;}
dragon          countmonsters++;

```

As an example of one pattern overlapping another, the following counts the number of occurrences of the expressions **comedian** and **diana**, even where the input text has sequences such as **comediana..**:

```

comedian      {comiccount++; REJECT;}
diana         princesscount++;

```

Note that the actions here may be considerably more complicated than simply incrementing a counter. In all cases, the counters and other necessary variables are declared in the definitions section commencing the **lex** specification.

### Definitions

The **lex** definitions section may contain any of several classes of items. The most critical are external definitions, **#include** statements, and abbreviations. Recall that for legal **lex** source this section is optional, but in most cases some of these items are necessary. External definitions have the form and function that they do in C. They declare that variables globally defined elsewhere (perhaps in another source file) will be accessed in your **lex**-generated **a.out**. Consider a declaration from an example to be developed later.

```
extern int tokval;
```

When you store an integer value in a variable declared in this way, it will be accessible in the routine, say a parser, that calls it. If, on the other hand, you want to define a local variable for use within the action sequence of one rule (as you might for the index variable for a loop), you can declare the variable at the start of the action itself right after the left brace, { .

The purpose of the **#include** statement is the same as in C: to include files of importance for your program. Some variable declarations and **lex** definitions might be needed in more than one **lex** source file. It is then advantageous to place them all in one file to be included in every file that needs them. One example occurs in using **lex** with **yacc**, which generates parsers that call a lexical analyzer. In this context, you should include the file **y.tab.h**, which may contain **#defines** for token names. Like the declarations, **#include** statements should come between **%{** and **%}**, thus:

```
%{  
#include "y.tab.h"  
extern int tokval;  
int lineno;  
%}
```

In the definitions section, after the **%}** that ends your **#include**'s and declarations, place your abbreviations for regular expressions to be used in the rules section. The abbreviation appears on the left of the line and, separated by one or more spaces, its definition or translation appears on the right. When you use abbreviations in your rules, enclose them within braces.

NOTE

The purpose of abbreviations is to avoid needless repetition in writing your specifications and to provide clarity in reading them.

As an example, reconsider the **lex** source reviewed at the beginning of this section on advanced **lex** usage. The use of definitions simplifies our later reference to digits, letters, and blanks. This is especially true if the specifications appear several times:

```

D          [0-9]
L          [a-zA-Z]
B          [ ]
%%
-[D]+      printf("negative integer");
+?[D]+     printf("positive integer");
-0.{D}+    printf("negative fraction");
G{L}*      printf("may have a G word here");
rail{B}+road printf("railroad is one word");
crook      printf("criminal");
  \\.\/{B}+  printf(".\");
  .        .
  .        .

```

The last rule, newly added to the example and somewhat more complex than the others, is used in the WRITER'S WORKBENCH Software, an AT&T software product for promoting good writing. (See the *UNIX System WRITER'S WORKBENCH Software Release 3.0 User's Guide* for information on this product.) The rule ensures that a period always precedes a quotation mark at the end of a sentence. It would change example". to example."

## Subroutines

You may want to use subroutines in **lex** for much the same reason that you do so in other programming languages. Action code that is to be used for several rules can be written once and called when needed. As with definitions, this can simplify the writing and reading of programs. The function **put\_in\_tabl()**, to be discussed in the next section on **lex** and **yacc**, is a good candidate for a subroutine.

Another reason to place a routine in this section is to highlight some code of interest or to simplify the rules section, even if the code is to be used for one rule only. As an example, consider the following routine to ignore comments in a language like C where comments occur between `/*` and `*/` :

```
/*"                skipcmnts();
.
.                /* rest of rules */
%%
skipcmnts()
{
    for(;;)
    {
        while (input() != '*');
        if (input() != '/') {
            unput(yytext[yytext-1]);
            else return;
        }
    }
}
```

There are three points of interest in this example. First, the **unput(c)** function (putting back the last character read) is necessary to avoid missing the final `/` if the comment ends unusually with a `**/`. In this case, eventually having read an `*`, the analyzer finds that the next character is not the terminal `/` and must read some more. Second, the expression `yytext[yytext-1]` picks out that last character read. Third, this routine assumes that the comments are not nested. (This is indeed the case with the C language.) If, unlike C, they are nested in the source text, after **input()**ing the first `*/` ending the inner group of comments, the **a.out** will read the rest of the comments as if they were part of the input to be searched for patterns.

Other examples of subroutines would be programmer-defined versions of the I/O routines **input()**, **unput(c)**, and **output()**, discussed above. Subroutines such as these that may be exploited by many different programs would probably do best to be stored in their own individual file or library to be called as needed. The appropriate **#include** statements would then be necessary in the definitions section.

## Using lex with yacc

If you work on a compiler project or develop a program to check the validity of an input language, you may want to use the UNIX system program tool **yacc**. **yacc** generates parsers, programs that analyze input to ensure that it is syntactically correct. (**yacc** is discussed in detail in Chapter 6 of this guide.) **lex** often forms a fruitful union with **yacc** in the compiler development context. Whether or not you plan to use **lex** with **yacc**, be sure to read this section because it covers information of interest to all **lex** programmers.

The lexical analyzer that **lex** generates (not the file that stores it) takes the name **yylex()**. This name is convenient because **yacc** calls its lexical analyzer by this very name. To use **lex** to create the lexical analyzer for the parser of a compiler, you want to end each **lex** action with the statement **return token**, where *token* is a defined term whose value is an integer. The integer value of the token returned indicates to the parser what the lexical analyzer has found. The parser, whose file is called **y.tab.c** by **yacc**, then resumes control and makes another call to the lexical analyzer when it needs another token.

In a compiler, the different values of the token indicate what, if any, reserved word of the language has been found or whether an identifier, constant, arithmetic operand, or relational operator has been found. In the latter cases, the analyzer must also specify the exact value of the token: what the identifier is, whether the constant, say, is 9 or 888, whether the operand is + or \* (multiply), and whether the relational operator is = or >. Consider the following portion of **lex** source for a lexical analyzer for some programming language perhaps slightly reminiscent of Ada:

```

begin                return(BEGIN);
end                  return(END);
while                return(WHILE);
if                   return(IF);
package              return(PACKAGE);
reverse              return(REVERSE);
loop                 return(LOOP);
[a-zA-Z][a-zA-Z0-9]* { tokval = put_in_tabl();
                       return(IDENTIFIER); }
[0-9]+               { tokval = put_in_tabl();
                       return(INTEGER); }
\+                   { tokval = PLUS;
                       return(ARITHOP); }
\-                   { tokval = MINUS;
                       return(ARITHOP); }
>                    { tokval = GREATER;
                       return(RELOP); }
>=                   { tokval = GREATEREQ;
                       return(RELOP); }

```

Despite appearances, the tokens returned and the values assigned to `tokval`, are indeed integers. Good programming style dictates that we use informative terms such as **BEGIN**, **END**, **WHILE**, and so forth to signify the integers the parser understands, rather than use the integers themselves. You establish the association by using **#define** statements in your parser calling routine in C. For example,

```

#define BEGIN 1
#define END 2
.
#define PLUS 7
.

```

If the need arises to change the integer for some token type, you then change the **#define** statement in the parser rather than hunt through the entire program, changing every occurrence of the particular integer. In using **yacc** to generate your parser, it is helpful to insert the statement

```
#include y.tab.h
```



into the definitions section of your **lex** source. The file **y.tab.h** provides **#define** statements that associate token names such as **BEGIN**, **END**, and so on with the integers of significance to the generated parser.

To indicate the reserved words in the example, the returned integer values suffice. For the other token types, the integer value of the token type is stored in the programmer-defined variable **tokval**. This variable, whose definition was an example in the definitions section, is globally defined so that the parser as well as the lexical analyzer can access it. **yacc** provides the variable **yylval** for the same purpose.

Note that the example shows two ways to assign a value to **tokval**. First, a function **put\_in\_tabl()** places the name and type of the identifier or constant in a symbol table so that the compiler can refer to it in this or a later stage of the compilation process. More to the present point, **put\_in\_tabl()** assigns a type value to **tokval** so that the parser can use the information immediately to determine the syntactic correctness of the input text. The function **put\_in\_tabl()** would be a routine that the compiler writer might place in the subroutines section discussed later. Second, in the last few actions of the example, **tokval** is assigned a specific integer indicating which operand or relational operator the analyzer recognized. If the variable **PLUS**, for instance, is associated with the integer 7 by means of the **#define** statement above, then when a **+** sign is recognized, the action assigns to **tokval** the value 7, which indicates the **+**. The analyzer indicates the general class of operator by the value it returns to the parser (in the example, the integer signified by **ARITHOP** or **RELOP**).

---

## Running `lex` under the UNIX System

As you review the following few steps, you might recall Figure 5-1 at the start of the chapter. To produce the lexical analyzer in C, run

```
lex lex.l
```

where `lex.l` is the file containing your `lex` specification. The name `lex.l` is conventionally the favorite, but you may use whatever name you want. The output file that `lex` produces is automatically called `lex.yy.c`; this is the lexical analyzer program that you created with `lex`. You then compile and link this as you would any C program, making sure that you invoke the `lex` library with the `-ll` option:

```
cc lex.yy.c -ll
```

The `lex` library provides a default `main()` program that calls the lexical analyzer under the name `yylex()`, so you need not supply your own `main()`.

If you have the `lex` specification spread across several files, you can run `lex` with each of them individually, but be sure to rename or move each `lex.yy.c` file (with `mv`) before you run `lex` on the next one. Otherwise, each will overwrite the previous one. Once you have all the generated `.c` files, you can compile all of them, of course, in one command line.

With the executable `a.out` produced, you are ready to analyze any desired input text. Suppose that the text is stored under the file name `textin` (this name is arbitrary). The lexical analyzer `a.out` by default takes input from your terminal. To have it take the file `textin` as input, use redirection, thus:

```
a.out < textin
```

By default, output will appear on your terminal. You can redirect this as well:

```
a.out < textin > textout
```

In running `lex` with `yacc`, either may be run first.

```
yacc -d grammar.y  
lex lex.l
```

spawns a parser in the file `y.tab.c`. (The `-d` option creates the file `y.tab.h`, which contains the `#define` statements that associate the `yacc`-assigned integer token values with the user-defined token names.) To compile and link the output files produced, run

```
cc lex.yy.c y.tab.c -ly -ll
```

Note that the **yacc** library is loaded (with the **-ly** option) before the **lex** library (with the **-ll** option) to ensure that the **main()** program supplied will call the **yacc** parser.

There are several options available with the **lex** command. If you use one or more of them, place them between the command name **lex** and the file name argument. If you care to see the C program, **lex.yy.c**, that **lex** generates on your terminal (the default output device), use the **-t** option.

```
lex -t lex.l
```

The **-v** option prints out for you a small set of statistics describing the so-called finite automata that **lex** produces with the C program **lex.yy.c**. (For a detailed account of finite automata and their importance for **lex**, see the Aho, Sethi, and Ullman text, *Compilers: Principles, Techniques, and Tools*, Addison-Wesley, 1986.)

**lex** uses a table (a two-dimensional array in C) to represent its finite automaton. The maximum number of states that the finite automaton requires is set by default to 500. If your **lex** source has a large number of rules or the rules are very complex, this default value may be too small. You can enlarge the value by placing another entry in the definitions section of your **lex** source, as follows:

```
%n 700
```

This entry tells **lex** to make the table large enough to handle as many as 700 states. (The **-v** option will indicate how large a number you should choose.) If you have need to increase the maximum number of state transitions beyond 2000, the designated parameter is **a**, thus:

```
%a 2800
```

Finally, check the *Programmer's Reference Manual* page on **lex** for a list of all the options available with the **lex** command. In addition, review the paper by Lesk (the originator of **lex**) and Schmidt, "Lex—A Lexical Analyzer Generator," in volume 5 of the *UNIX Programmer's Manual*, Holt, Rinehart, and Winston, 1986. It is somewhat dated, but offers several interesting examples.

This tutorial has introduced you to **lex** programming. As with any programming language, the way to master it is to write programs and then write some more.



yacc

---

# 6 yacc

---

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# Introduction

The **yacc** program provides a general tool for imposing structure on the input to a computer program. The **yacc** user prepares a specification that includes:

- a set of rules to describe the elements of the input
- code to be invoked when a rule is recognized
- either a definition or declaration of a low-level routine to examine the input

**yacc** then turns the specification into a C language function that examines the input stream. This function, called a parser, works by calling the low-level input scanner. The low-level input scanner, called a lexical analyzer, picks up items from the input stream. The selected items are known as tokens. Tokens are compared to the input construct rules, called grammar rules. When one of the rules is recognized, the user code supplied for this rule, (an action) is invoked. Actions are fragments of C language code. They can return values and make use of values returned by other actions.

The heart of the **yacc** specification is the collection of grammar rules. Each rule describes a construct and gives it a name. For example, one grammar rule might be

```
date : month_name day ',' year ;
```

where **date**, **month\_name**, **day**, and **year** represent constructs of interest; presumably, **month\_name**, **day**, and **year** are defined in greater detail elsewhere. In the example, the comma is enclosed in single quotes. This means that the comma is to appear literally in the input. The colon and semicolon merely serve as punctuation in the rule and have no significance in evaluating the input. With proper definitions, the input

```
July 4, 1776
```

might be matched by the rule.

The lexical analyzer is an important part of the parsing function. This user-supplied routine reads the input stream, recognizes the lower-level constructs, and communicates these as tokens to the parser. The lexical analyzer recognizes constructs of the input stream as terminal symbols; the parser recognizes constructs as nonterminal symbols. To avoid confusion, we will refer to terminal symbols as tokens.

## Introduction

---

There is considerable leeway in deciding whether to recognize constructs using the lexical analyzer or grammar rules. For example, the rules

```
month_name : 'J' 'a' 'n' ;
month_name : 'F' 'e' 'b' ;

...

month_name : 'D' 'e' 'c' ;
```

might be used in the above example. While the lexical analyzer only needs to recognize individual letters, such low-level rules tend to waste time and space, and may complicate the specification beyond the ability of **yacc** to deal with it. Usually, the lexical analyzer recognizes the month names and returns an indication that a **month\_name** is seen. In this case, **month\_name** is a token and the detailed rules are not needed.

Literal characters such as a comma must also be passed through the lexical analyzer and are also considered tokens.

Specification files are very flexible. It is relatively easy to add to the above example the rule

```
date : month '/' day '/' year ;
```

allowing

```
7/4/1776
```

as a synonym for

```
July 4, 1776
```

on input. In most cases, this new rule could be slipped into a working system with minimal effort and little danger of disrupting existing input.

The input being read may not conform to the specifications. With a left-to-right scan input errors are detected as early as is theoretically possible. Thus, not only is the chance of reading and computing with bad input data substantially reduced, but the bad data usually can be found quickly. Error handling, provided as part of the input specifications, permits the reentry of bad data or the continuation of the input process after skipping over the bad data.

In some cases, **yacc** fails to produce a parser when given a set of specifications. For example, the specifications may be self-contradictory, or they may require a more powerful recognition mechanism than that available to **yacc**. The former cases represent design errors; the latter cases often can be corrected by making the lexical analyzer more powerful or by rewriting some of the grammar rules. While **yacc** cannot handle all possible specifications, its power compares favorably with similar systems. Moreover, the constructs that are difficult for **yacc** to handle are also frequently difficult for human beings to handle. Some users have reported that the discipline of formulating valid **yacc** specifications for their input revealed errors of conception or design early in the program development.

The remainder of this chapter describes the following subjects:

- basic process of preparing a **yacc** specification
- parser operation
- handling ambiguities
- handling operator precedences in arithmetic expressions
- error detection and recovery
- the operating environment and special features of the parsers **yacc** produces
- suggestions to improve the style and efficiency of the specifications
- advanced topics

In addition, there are two examples and a summary of the **yacc** input syntax.

---

## Basic Specifications

Names refer to either tokens or nonterminal symbols. **yacc** requires token names to be declared as such. While the lexical analyzer may be included as part of the specification file, it is perhaps more in keeping with modular design to keep it as a separate file. Like the lexical analyzer, other subroutines may be included as well. Thus, every specification file theoretically consists of three sections: the declarations, (grammar) rules, and subroutines. Sections are separated by double percent signs, %% (the percent sign is generally used in **yacc** specifications as an escape character).

A full specification file looks like:

```
declarations
%%
rules
%%
subroutines
```

when all sections are used. The *declarations* and *subroutines* sections are optional. The smallest legal **yacc** specification is

```
%%
rules
```

Blanks, tabs, and newlines are ignored, but they may not appear in names or multicharacter reserved symbols. Comments may appear wherever a name is legal. They are enclosed in */\* ... \*/*, as in the C language.

The rules section is made up of one or more grammar rules. A grammar rule has the form

```
A : BODY ;
```

where **A** represents a nonterminal symbol, and **BODY** represents a sequence of zero or more names and literals. The colon and the semicolon are **yacc** punctuation.

Names may be of any length and may be made up of letters, dots, underscores, and digits although a digit may not be the first character of a name. Uppercase and lowercase letters are distinct. The names used in the body of a grammar rule may represent tokens or nonterminal symbols.

A literal consists of a character enclosed in single quotes, '. As in the C language, the backslash, \, is an escape character within literals, and all the C language escapes are recognized. Thus:

```
'\n'    newline
'\r'    return
'\''    single quote ( ' )
'\'\'   backslash ( \ )
'\t'    tab
'\b'    backspace
'\f'    form feed
'\xxx'  xxx in octal notation
```

are understood by **yacc**. For a number of technical reasons, the NULL character (\0 or 0) should never be used in grammar rules.

If there are several grammar rules with the same left-hand side, the vertical bar, |, can be used to avoid rewriting the left-hand side. In addition, the semicolon at the end of a rule is dropped before a vertical bar. Thus the grammar rules

```
A  : B C D ;
A  : E F  ;
A  : G   ;
```

can be given to **yacc** as

```
A  : B C D
    | E F
    | G
    ;
```

by using the vertical bar. It is not necessary that all grammar rules with the same left side appear together in the grammar rules section although it makes the input more readable and easier to change.

If a nonterminal symbol matches the empty string, this can be indicated by

```
epsilon : ;
```

The blank space following the colon is understood by **yacc** to be a nonterminal symbol named **epsilon**.

## Basic Specifications

---

Names representing tokens must be declared. This is most simply done by writing

```
%token  name1 name2 ...
```

in the declarations section. Every name not defined in the declarations section is assumed to represent a nonterminal symbol. Every nonterminal symbol must appear on the left side of at least one rule.

Of all the nonterminal symbols, the start symbol has particular importance. By default, the start symbol is taken to be the left-hand side of the first grammar rule in the rules section. It is possible and desirable to declare the start symbol explicitly in the declarations section using the `%start` keyword.

```
%start  symbol
```

The end of the input to the parser is signaled by a special token, called the end-marker. The end-marker is represented by either a zero or a negative number. If the tokens up to but not including the end-marker form a construct that matches the start symbol, the parser function returns to its caller after the end-marker is seen and accepts the input. If the end-marker is seen in any other context, it is an error.

It is the job of the user-supplied lexical analyzer to return the end-marker when appropriate. Usually the end-marker represents some reasonably obvious I/O status, such as end of file or end of record.

## Actions

With each grammar rule, the user may associate actions to be performed when the rule is recognized. Actions may return values and may obtain the values returned by previous actions. Moreover, the lexical analyzer can return values for tokens if desired.

An action is an arbitrary C language statement and as such can do input and output, call subroutines, and alter arrays and variables. An action is specified by one or more statements enclosed in curly braces, {, and }. For example:

```
A  :  '(' B ')'  
    {  
        hello( 1, "abc" );  
    }
```

and

```
XXX : YYY ZZZ
    {
      (void) printf("a message\n");
      flag = 25;
    }
```

are grammar rules with actions.

The dollar sign symbol, \$, is used to facilitate communication between the actions and the parser. The pseudo-variable \$\$ represents the value returned by the complete action. For example, the action

```
{ $$ = 1; }
```

returns the value of one; in fact, that is all it does.

To obtain the values returned by previous actions and the lexical analyzer, the action may use the pseudo-variables \$1, \$2, ... \$n. These refer to the values returned by components 1 through n of the right side of a rule, with the components being numbered from left to right. If the rule is

```
A : B C D ;
```

then \$2 has the value returned by C, and \$3 the value returned by D. The rule

```
expr : '(' expr ')' ;
```

provides a common example. One would expect the value returned by this rule to be the value of the *expr* within the parentheses. Since the first component of the action is the literal left parenthesis, the desired logical result can be indicated by

```
expr : '(' expr ')'
    {
      $$ = $2 ;
    }
```

## Basic Specifications

---

By default, the value of a rule is the value of the first element in it (**\$1**). Thus, grammar rules of the form

```
A : B ;
```

frequently need not have an explicit action. In previous examples, all the actions came at the end of rules. Sometimes, it is desirable to get control before a rule is fully parsed. **yacc** permits an action to be written in the middle of a rule as well as at the end. This action is assumed to return a value accessible through the usual **\$** mechanism by the actions to the right of it. In turn, it may access the values returned by the symbols to its left. Thus, in the rule below the effect is to set **x** to 1 and **y** to the value returned by **C**.

```
A : B
    {
        $$ = 1;
    }
    C
    {
        x = $2;
        y = $3;
    }
    ;
```

Actions that do not terminate a rule are handled by **yacc** by manufacturing a new nonterminal symbol name and a new rule matching this name to the empty string. The interior action is the action triggered by recognizing this added rule. **yacc** treats the above example as if it had been written as follows (where **\$ACT** is an empty action).



```

$ACT : /* empty */
      {
        $$ = 1;
      }
      ;

A    : B $ACT C
      {
        x = $2;
        y = $3;
      }
      ;

```

In many applications, output is not done directly by the actions. A data structure, such as a parse tree, is constructed in memory and transformations are applied to it before output is generated. Parse trees are particularly easy to construct given routines to build and maintain the tree structure desired. For example, suppose there is a C function `node` written so that the call

```
node( L, n1, n2 )
```

creates a node with label `L` and descendants `n1` and `n2` and returns the index of the newly created node. Then a parse tree can be built by supplying actions such as

```

expr : expr '+' expr
      {
        $$ = node( '+', $1, $3 );
      }

```

in the specification.

The user may define other variables to be used by the actions. Declarations and definitions can appear in the declarations section enclosed in the marks `%{` and `%}`. These declarations and definitions have global scope, so they are known to the action statements and can be made known to the lexical analyzer. For example:

```
%{ int variable = 0; %}
```

could be placed in the declarations section making **variable** accessible to all of the actions. Users should avoid names beginning with **yy** because the **yacc** parser uses only such names. In the examples shown thus far all the values are integers. A discussion of values of other types is found in the section "Advanced Topics."

## Lexical Analysis

The user must supply a lexical analyzer to read the input stream and communicate tokens (with values, if desired) to the parser. The lexical analyzer is an integer-valued function called **yylex**. The function returns an integer, the *token number*, representing the kind of token read. If there is a value associated with that token, it should be assigned to the external variable **yyval**.

The parser and the lexical analyzer must agree on these token numbers in order for communication between them to take place. The numbers may be chosen by **yacc** or the user. In either case, the **#define** mechanism of C language is used to allow the lexical analyzer to return these numbers symbolically. For example, suppose that the token name **DIGIT** has been defined in the declarations section of the **yacc** specification file. The relevant portion of the lexical analyzer might look like

```
int yylex()
{
    extern int yyval;
    int c;
    ...
    c = getchar();
    ...
    switch (c)
    {
        ...
        case '0':
        case '1':
        ...
        case '9':
            yyval = c - '0';
            return (DIGIT);
        ...
    }
    ...
}
```

to return the appropriate token.

The intent is to return a token number of DIGIT and a value equal to the numerical value of the digit. Provided that the lexical analyzer code is placed in the subroutines section of the specification file, the identifier DIGIT is defined as the token number associated with the token DIGIT.

This mechanism leads to clear, easily modified lexical analyzers. The only pitfall to avoid is using any token names in the grammar that are reserved or significant in C language or the parser. For example, the use of token names **if** or **while** will almost certainly cause severe difficulties when the lexical analyzer is compiled. The token name **error** is reserved for error handling and should not be used naively.

In the default situation, token numbers are chosen by **yacc**. The default token number for a literal character is the numerical value of the character in the local character set. Other names are assigned token numbers starting at 257. If the **yacc** command is invoked with the **-d** option, a file called **y.tab.h** is generated. **y.tab.h** contains **#define** statements for the tokens.

## Basic Specifications

---

If the user prefers to assign the token numbers, the first appearance of the token name or literal in the declarations section must be followed immediately by a nonnegative integer. This integer is taken to be the token number of the name or literal. Names and literals not defined this way are assigned default definitions by **yacc**. The potential for duplication exists here. Care must be taken to make sure that all token numbers are distinct.

For historical reasons, the end-marker must have token number 0 or negative. This token number cannot be redefined by the user. Thus, all lexical analyzers should be prepared to return 0 or a negative number as a token upon reaching the end of their input.

A very useful tool for constructing lexical analyzers is the **lex** utility. Lexical analyzers produced by **lex** are designed to work in close harmony with **yacc** parsers. The specifications for these lexical analyzers use regular expressions instead of grammar rules. **lex** can be easily used to produce quite complicated lexical analyzers, but there remain some languages (such as FORTRAN), which do not fit any theoretical framework and whose lexical analyzers must be crafted by hand.

---

## Parser Operation

The **yacc** command turns the specification file into a C language procedure, which parses the input according to the specification given. The algorithm used to go from the specification to the parser is complex and will not be discussed here. The parser itself, though, is relatively simple and understanding its usage will make treatment of error recovery and ambiguities easier.

The parser produced by **yacc** consists of a finite state machine with a stack. The parser is also capable of reading and remembering the next input token (called the look-ahead token). The current state is always the one on the top of the stack. The states of the finite state machine are given small integer labels. Initially, the machine is in state 0 (the stack contains only state 0) and no look-ahead token has been read.

The machine has only four actions available—**shift**, **reduce**, **accept**, and **error**. A step of the parser is done as follows:

1. Based on its current state, the parser decides if it needs a look-ahead token to choose the action to be taken. If it needs one and does not have one, it calls **yylex** to obtain the next token.
2. Using the current state and the look-ahead token if needed, the parser decides on its next action and carries it out. This may result in states being pushed onto the stack or popped off of the stack and in the look-ahead token being processed or left alone.

The shift action is the most common action the parser takes. Whenever a shift action is taken, there is always a look-ahead token. For example, in state 56 there may be an action

```
IF shift 34
```

which says, in state 56, if the look-ahead token is IF, the current state (56) is pushed down on the stack, and state 34 becomes the current state (on the top of the stack). The look-ahead token is cleared.

The **reduce** action keeps the stack from growing without bounds. The **reduce** actions are appropriate when the parser has seen the right-hand side of a grammar rule and is prepared to announce that it has seen an instance of the rule replacing the right side by the left side. It may be necessary to consult the look-ahead token to decide whether or not to **reduce** (usually it is not necessary). In fact, the default action (represented by a dot) is often a **reduce** action.

## Parser Operation

---

The **reduce** actions are associated with individual grammar rules. Grammar rules are also given small integer numbers, and this leads to some confusion. The action

```
. reduce 18
```

refers to grammar rule 18, while the action

```
IF shift 34
```

refers to state 34.

Suppose the rule

```
A : x y z ;
```

is being reduced. The **reduce** action depends on the left-hand symbol (A in this case) and the number of symbols on the right-hand side (three in this case). To reduce, first pop off the top three states from the stack. (In general, the number of states popped equals the number of symbols on the right side of the rule.) In effect, these states were the ones put on the stack while recognizing x, y, and z and no longer serve any useful purpose. After popping these states, a state is uncovered, which was the state the parser was in before beginning to process the rule. Using this uncovered state and the symbol on the left side of the rule, perform what is in effect a shift of **A**. A new state is obtained, pushed onto the stack, and parsing continues.\* There are significant differences between the processing of the left-hand symbol and an ordinary shift of a token, however, so this action is called a **goto** action. In particular, the look-ahead token is cleared by a shift but is not affected by a **goto**. In any case, the uncovered state contains an entry such as

```
A goto 20
```

causing state 20 to be pushed onto the stack and become the current state.

In effect, the **reduce** action turns back the clock in the parse popping the states off the stack to go back to the state where the right side of the rule was first seen. The parser then behaves as if it had seen the left side at that time. If the right-hand side of the rule is empty, no states are popped off of the stacks. The uncovered state is in fact the current state.

The **reduce** action is also important in the treatment of user-supplied actions and values. When a rule is reduced, the code supplied with the rule is executed before the stack is adjusted. In addition to the stack holding the states, another stack running in parallel with it holds the values returned from the lexical analyzer and the actions. When a **shift** takes place, the external variable **yyval** is copied onto the value stack. After the return from the user

code, the reduction is carried out. When the **goto** action is done, the external variable **yyval** is copied onto the value stack. The pseudo-variables **\$1**, **\$2**, etc., refer to the value stack.

The other two parser actions are conceptually much simpler. The **accept** action indicates that the entire input has been seen and that it matches the specification. This action appears only when the look-ahead token is the end-marker and indicates that the parser has successfully done its job. The **error** action, on the other hand, represents a place where the parser can no longer continue parsing according to the specification. The input tokens it has seen (together with the look-ahead token) cannot be followed by anything that would result in a legal input. The parser reports an error and attempts to recover the situation and resume parsing. The error recovery (as opposed to the detection of error) will be discussed later.

Consider the following as a **yacc** specification:

```
%token DING DONG DELL
%%
rhyme : sound place
      ;
sound : DING DONG
      ;
place : DELL
      ;
```

When **yacc** is invoked with the **-v** option, a file called **y.output** is produced with a human-readable description of the parser. The **y.output** file corresponding to the above grammar (with some statistics stripped off the end) follows.

```
state 0
    $accept : _rhyme $end

    DING shift 3
    . error

    rhyme goto 1
    sound goto 2

state 1
    $accept : rhyme_$end

    $end accept
    . error

state 2
    rhyme : sound_place

    DELL shift 5
    . error

    place goto 4

state 3
    sound : DING_DONG

    DONG shift 6
    . error

state 4
    rhyme : sound place_ (1)

    . reduce 1

state 5
    place : DELL_ (3)

    . reduce 3

state 6
    sound : DING DONG_ (2)

    . reduce 2
```



The actions for each state are specified, and there is a description of the parsing rules being processed in each state. The `_` character is used to indicate what has been seen and what is yet to come in each rule. The following input

```
DING DONG DELL
```

can be used to track the operations of the parser. Initially, the current state is state 0. The parser needs to refer to the input in order to decide between the actions available in state 0, so the first token, DING, is read and becomes the look-ahead token. The action in state 0 on DING is **shift 3**, state 3 is pushed onto the stack, and the look-ahead token is cleared. State 3 becomes the current state. The next token, DONG, is read and becomes the look-ahead token. The action in state 3 on the token DONG is **shift 6**, state 6 is pushed onto the stack, and the look-ahead is cleared. The stack now contains 0, 3, and 6. In state 6, without even consulting the look-ahead, the parser reduces by

```
sound : DING DONG
```

which is rule 2. Two states, 6 and 3, are popped off of the stack uncovering state 0. Consulting the description of state 0 (looking for a **goto** on **sound**),

```
sound goto 2
```

is obtained. State 2 is pushed onto the stack and becomes the current state.

In state 2, the next token, DELL, must be read. The action is **shift 5**, so state 5 is pushed onto the stack, which now has 0, 2, and 5 on it, and the look-ahead token is cleared. In state 5, the only action is to reduce by rule 3. This has one symbol on the right-hand side, so one state, 5, is popped off, and state 2 is uncovered. The **goto** in state 2 on **place** (the left side of rule 3) is state 4. Now, the stack contains 0, 2, and 4. In state 4, the only action is to reduce by rule 1. There are two symbols on the right, so the top two states are popped off, uncovering state 0 again. In state 0, there is a **goto** on **rhyme** causing the parser to enter state 1. In state 1, the input is read and the end-marker is obtained indicated by **\$end** in the **y.output** file. The action in state 1 (when the end-marker is seen) successfully ends the parse.

The reader is urged to consider how the parser works when confronted with such incorrect strings as DING DONG DONG, DING DONG, DING DONG DELL DELL, etc. A few minutes spent with this and other simple examples is repaid when problems arise in more complicated contexts.

---

## Ambiguity and Conflicts

A set of grammar rules is ambiguous if there is some input string that can be structured in two or more different ways. For example, the grammar rule

$$\text{expr} : \text{expr} \text{'-' } \text{expr}$$

is a natural way of expressing the fact that one way of forming an arithmetic expression is to put two other expressions together with a minus sign between them. Unfortunately, this grammar rule does not completely specify the way that all complex inputs should be structured. For example, if the input is

$$\text{expr} - \text{expr} - \text{expr}$$

the rule allows this input to be structured as either

$$(\text{expr} - \text{expr}) - \text{expr}$$

or as

$$\text{expr} - (\text{expr} - \text{expr})$$

(The first is called left association, the second right association.)

**yacc** detects such ambiguities when it is attempting to build the parser. Given the input

$$\text{expr} - \text{expr} - \text{expr}$$

consider the problem that confronts the parser. When the parser has read the second *expr*, the input seen

$$\text{expr} - \text{expr}$$

matches the right side of the grammar rule above. The parser could reduce the input by applying this rule. After applying the rule, the input is reduced to **expr** (the left side of the rule). The parser would then read the final part of the input

$$- \text{expr}$$

and again reduce. The effect of this is to take the left associative interpretation.

Alternatively, if the parser sees

$$\text{expr} - \text{expr}$$

it could defer the immediate application of the rule and continue reading the input until

$$\text{expr} - \text{expr} - \text{expr}$$

is seen. It could then apply the rule to the rightmost three symbols reducing them to *expr*, which results in

$$\text{expr} - \text{expr}$$

being left. Now the rule can be reduced once more. The effect is to take the right associative interpretation. Thus, having read

$$\text{expr} - \text{expr}$$

the parser can do one of two legal things, a shift or a reduction. It has no way of deciding between them. This is called a **shift-reduce** conflict. It may also happen that the parser has a choice of two legal reductions. This is called a **reduce-reduce** conflict. Note that there are never any **shift-shift** conflicts.

When there are **shift-reduce** or **reduce-reduce** conflicts, **yacc** still produces a parser. It does this by selecting one of the valid steps wherever it has a choice. A rule describing the choice to make in a given situation is called a disambiguating rule.

**yacc** invokes two default disambiguating rules:

1. In a **shift-reduce** conflict, the default is to do the shift.
2. In a **reduce-reduce** conflict, the default is to reduce by the earlier grammar rule (in the **yacc** specification).

Rule 1 implies that reductions are deferred in favor of shifts when there is a choice. Rule 2 gives the user rather crude control over the behavior of the parser in this situation, but **reduce-reduce** conflicts should be avoided when possible.

Conflicts may arise because of mistakes in input or logic or because the grammar rules (while consistent) require a more complex parser than **yacc** can construct. The use of actions within rules can also cause conflicts if the action must be done before the parser can be sure which rule is being recognized. In these cases, the application of disambiguating rules is inappropriate and leads to an incorrect parser. For this reason, **yacc** always reports the number of **shift-reduce** and **reduce-reduce** conflicts resolved by Rule 1 and Rule 2.

## Ambiguity and Conflicts

---

In general, whenever it is possible to apply disambiguating rules to produce a correct parser, it is also possible to rewrite the grammar rules so that the same inputs are read but there are no conflicts. For this reason, most previous parser generators have considered conflicts to be fatal errors. Our experience has suggested that this rewriting is somewhat unnatural and produces slower parsers. Thus, **yacc** will produce parsers even in the presence of conflicts.

As an example of the power of disambiguating rules, consider

```
stat  :  IF '(' cond ')' stat
      |  IF '(' cond ')' stat ELSE stat
      ;
```

which is a fragment from a programming language involving an **if-then-else** statement. In these rules, **IF** and **ELSE** are tokens, *cond* is a nonterminal symbol describing conditional (logical) expressions, and *stat* is a nonterminal symbol describing statements. The first rule will be called the simple **if** rule and the second, the **if-else** rule.

These two rules form an ambiguous construction because input of the form

```
IF ( C1 ) IF ( C2 ) S1 ELSE S2
```

can be structured according to these rules in two ways

```
IF ( C1 )
{
    IF ( C2 )
        S1
}
ELSE
    S2
```

or

```
IF ( C1 )
{
    IF ( C2 )
        S1
    ELSE
        S2
}
```

where the second interpretation is the one given in most programming languages having this construct; each ELSE is associated with the last preceding un-ELSE'd IF. In this example, consider the situation where the parser has seen

```
IF ( C1 ) IF ( C2 ) S1
```

and is looking at the ELSE. It can immediately reduce by the simple **if** rule to get

```
IF ( C1 ) stat
```

and then read the remaining input

```
ELSE S2
```

and reduce

```
IF ( C1 ) stat ELSE S2
```

by the **if-else** rule. This leads to the first of the above groupings of the input.

On the other hand, the ELSE may be shifted, S2 read, and then the right-hand portion of

```
IF ( C1 ) IF ( C2 ) S1 ELSE S2
```

can be reduced by the if-else rule to get

```
IF ( C1 ) stat
```

which can be reduced by the simple **if** rule. This leads to the second of the above groupings of the input which is usually desired.

Once again, the parser can do two valid things—there is a **shift-reduce** conflict. The application of disambiguating rule 1 tells the parser to shift in this case, which leads to the desired grouping.

This **shift-reduce** conflict arises only when there is a particular current input symbol, ELSE, and particular inputs, such as

```
IF ( C1 ) IF ( C2 ) S1
```

have already been seen. In general, there may be many conflicts, and each one will be associated with an input symbol and a set of previously read inputs. The previously read inputs are characterized by the state of the parser.

## Ambiguity and Conflicts

---

The conflict messages of **yacc** are best understood by examining the verbose (**-v**) option output file. For example, the output corresponding to the above conflict state might be

```
23: shift-reduce conflict (shift 45, reduce 18) on ELSE
```

```
state 23
```

```
stat : IF ( cond ) stat_      (18)
```

```
stat : IF ( cond ) stat_ELSE stat
```

```
ELSE  shift 45
```

```
.      reduce 18
```

where the first line describes the conflict—giving the state and the input symbol. The ordinary state description gives the grammar rules active in the state and the parser actions. Recall that the underline marks the portion of the grammar rules, which has been seen. Thus in the example, in state 23 the parser has seen input corresponding to

```
IF ( cond ) stat
```

and the two grammar rules shown are active at this time. The parser can do two possible things. If the input symbol is **ELSE**, it is possible to shift into state 45. State 45 will have, as part of its description, the line

```
stat : IF ( cond ) stat ELSE_stat
```

because the **ELSE** will have been shifted in this state. In state 23, the alternative action (describing a dot, **.**) is to be done if the input symbol is not mentioned explicitly in the actions. In this case, if the input symbol is not **ELSE**, the parser reduces to

```
stat : IF '(' cond ')' stat
```

by grammar rule 18.

Once again, notice that the numbers following shift commands refer to other states, while the numbers following reduce commands refer to grammar rule numbers. In the **y.output** file, the rule numbers are printed in parentheses after those rules, which can be reduced. In most states, there is a reduce action possible in the state and this is the default command. The user who encounters unexpected **shift-reduce** conflicts will probably want to look at the verbose output to decide whether the default actions are appropriate.

---

# Precedence

There is one common situation where the rules given above for resolving conflicts are not sufficient. This is in the parsing of arithmetic expressions. Most of the commonly used constructions for arithmetic expressions can be naturally described by the notion of precedence levels for operators, together with information about left or right associativity. It turns out that ambiguous grammars with appropriate disambiguating rules can be used to create parsers that are faster and easier to write than parsers constructed from unambiguous grammars. The basic notion is to write grammar rules of the form

```
expr : expr OP expr
```

and

```
expr : UNARY expr
```

for all binary and unary operators desired. This creates a very ambiguous grammar with many parsing conflicts. As disambiguating rules, the user specifies the precedence or binding strength of all the operators and the associativity of the binary operators. This information is sufficient to allow **yacc** to resolve the parsing conflicts in accordance with these rules and construct a parser that realizes the desired precedences and associativities.

The precedences and associativities are attached to tokens in the declarations section. This is done by a series of lines beginning with a **yacc** keyword: **%left**, **%right**, or **%nonassoc**, followed by a list of tokens. All of the tokens on the same line are assumed to have the same precedence level and associativity; the lines are listed in order of increasing precedence or binding strength. Thus:

```
%left '+' '-'  
%left '*' '/'
```

describes the precedence and associativity of the four arithmetic operators. Plus and minus are left associative and have lower precedence than star and slash, which are also left associative. The keyword **%right** is used to describe right associative operators, and the keyword **%nonassoc** is used to describe operators, like the operator **.LT.** in FORTRAN, that may not associate with themselves. Thus:

```
A .LT. B .LT. C
```



is illegal in FORTRAN and such an operator would be described with the keyword **%nonassoc** in **yacc**. As an example of the behavior of these declarations, the description

```

%right '='
%left '+' '-'
%left '*' '/'

%%

expr  :  expr '=' expr
      |  expr '+' expr
      |  expr '-' expr
      |  expr '*' expr
      |  expr '/' expr
      |  NAME
      ;

```

might be used to structure the input

$$a = b = c*d - e - f*g$$

as follows

$$a = ( b = ( ((c*d)-e) - (f*g) ) )$$

in order to perform the correct precedence of operators. When this mechanism is used, unary operators must, in general, be given a precedence. Sometimes a unary operator and a binary operator have the same symbolic representation but different precedences. An example is unary and binary minus,  $-$ .

Unary minus may be given the same strength as multiplication, or even higher, while binary minus has a lower strength than multiplication. The keyword, **%prec**, changes the precedence level associated with a particular grammar rule. The keyword **%prec** appears immediately after the body of the grammar rule, before the action or closing semicolon, and is followed by a token name or literal. It causes the precedence of the grammar rule to become that of the following token name or literal. For example, the rules

```
%left '+' '-'
%left '*' '/'

%%

expr : expr '+' expr
     | expr '-' expr
     | expr '*' expr
     | expr '/' expr
     | '-' expr %prec '*'
     | NAME
     ;
```

might be used to give unary minus the same precedence as multiplication.

A token declared by `%left`, `%right`, and `%nonassoc` need not be, but may be, declared by `%token` as well.

Precedences and associativities are used by `yacc` to resolve parsing conflicts. They give rise to the following disambiguating rules:

1. Precedences and associativities are recorded for those tokens and literals that have them.
2. A precedence and associativity is associated with each grammar rule. It is the precedence and associativity of the last token or literal in the body of the rule. If the `%prec` construction is used, it overrides this default. Some grammar rules may have no precedence and associativity associated with them.
3. When there is a **reduce-reduce** conflict or there is a **shift-reduce** conflict and either the input symbol or the grammar rule has no precedence and associativity, then the two default disambiguating rules given at the beginning of the section are used, and the conflicts are reported.

4. If there is a **shift-reduce** conflict and both the grammar rule and the input character have precedence and associativity associated with them, then the conflict is resolved in favor of the action—**shift** or **reduce**—associated with the higher precedence. If precedences are equal, then associativity is used. Left associative implies **reduce**; right associative implies **shift**; nonassociating implies **error**.

Conflicts resolved by precedence are not counted in the number of **shift-reduce** and **reduce-reduce** conflicts reported by **yacc**. This means that mistakes in the specification of precedences may disguise errors in the input grammar. It is a good idea to be sparing with precedences and use them in a cookbook fashion until some experience has been gained. The **y.output** file is very useful in deciding whether the parser is actually doing what was intended.

---

## Error Handling

Error handling is an extremely difficult area, and many of the problems are semantic ones. When an error is found, for example, it may be necessary to reclaim parse tree storage, delete or alter symbol table entries, and/or, typically, set switches to avoid generating any further output.

It is seldom acceptable to stop all processing when an error is found. It is more useful to continue scanning the input to find further syntax errors. This leads to the problem of getting the parser restarted after an error. A general class of algorithms to do this involves discarding a number of tokens from the input string and attempting to adjust the parser so that input can continue.

To allow the user some control over this process, **yacc** provides the token name **error**. This name can be used in grammar rules. In effect, it suggests places where errors are expected and recovery might take place. The parser pops its stack until it enters a state where the token **error** is legal. It then behaves as if the token **error** were the current look-ahead token and performs the action encountered. The look-ahead token is then reset to the token that caused the error. If no special error rules have been specified, the processing halts when an error is detected.

In order to prevent a cascade of error messages, the parser, after detecting an error, remains in error state until three tokens have been successfully read and shifted. If an error is detected when the parser is already in error state, no message is given, and the input token is quietly deleted.

As an example, a rule of the form

```
stat : error
```

means that on a syntax error the parser attempts to skip over the statement in which the error is seen. More precisely, the parser scans ahead, looking for three tokens that might legally follow a statement and start processing at the first of these. If the beginnings of statements are not sufficiently distinctive, it may make a false start in the middle of a statement and end up reporting a second error where there is in fact no error.

Actions may be used with these special error rules. These actions might attempt to reinitialize tables, reclaim symbol table space, etc.

Error rules such as these mentioned are very general but difficult to control. Rules such as

```
stat : error ';' ;
```

are somewhat easier. Here, when there is an error, the parser attempts to skip over the statement but does so by skipping to the next semicolon. All tokens after the error and before the next semicolon cannot be shifted and are discarded. When the semicolon is seen, this rule will be reduced and any cleanup action associated with it performed.

Another form of **error** rule arises in interactive applications where it may be desirable to permit a line to be reentered after an error. The following example

```
input : error '\n'
      {
        (void) printf( "Reenter last line: " );
      }
      input
      {
        $$ = $4;
      }
      ;
```

is one way to do this. There is one potential difficulty with this approach. The parser must correctly process three input tokens before it admits that it has correctly resynchronized after the error. If the reentered line contains an error in the first two tokens, the parser deletes the offending tokens and gives no message. This is clearly unacceptable. For this reason, there is a mechanism that can force the parser to believe that error recovery has been accomplished. The statement

```
yyerrok ;
```

in an action resets the parser to its normal mode. The last example can be rewritten as:

```
input : error '\n'
      {
        yyerrork;
        (void) printf( "Reenter last line: " );
      }
      input
    {
      $$ = $4;
    }
  ;
```

As previously mentioned, the token seen immediately after the **error** symbol is the input token at which the error was discovered. Sometimes, this is inappropriate; for example, an error recovery action might take upon itself the job of finding the correct place to resume input. In this case, the previous look-ahead token must be cleared. The statement

```
yyclearin ;
```

in an action will have this effect. For example, suppose the action after **error** were to call some sophisticated resynchronization routine (supplied by the user) that attempted to advance the input to the beginning of the next valid statement. After this routine is called, the next token returned by **yylex** is presumably the first token in a legal statement. The old illegal token must be discarded and the **error** state reset. A rule similar to the following example could perform this.

```
stat : error
     {
       resynch();
       yyerrok ;
       yyclearin;
     }
     ;
```

These mechanisms are admittedly crude but do allow for a simple, fairly effective recovery of the parser from many errors. Moreover, the user can get control to deal with the error actions required by other portions of the program.

---

# The yacc Environment

When the user inputs a specification to **yacc**, the output is a file of C language subroutines, called **y.tab.c**. The function produced by **yacc** is called **yyparse()**; it is an integer-valued function. When it is called, it in turn repeatedly calls **yylex()**, the lexical analyzer supplied by the user (see "Lexical Analysis"), to obtain input tokens. Eventually, an error is detected, **yyparse()** returns the value 1, and no error recovery is possible, or the lexical analyzer returns the end-marker token and the parser accepts. In this case, **yyparse()** returns the value 0.

The user must provide a certain amount of environment for this parser in order to obtain a working program. For example, as with every C language program, a routine called **main()** must be defined that eventually calls **yyparse()**. In addition, a routine called **yyerror()** is needed to print a message when a syntax error is detected.

These two routines must be supplied in one form or another by the user. To ease the initial effort of using **yacc**, a library has been provided with default versions of **main()** and **yyerror()**. The library is accessed by a **-ly** argument to the **cc(1)** command or to the loader. The source codes

```
main()
{
    return (yyparse());
}
```

and

```
# include <stdio.h>

yyerror(s)
    char *s;
{
    (void) fprintf(stderr, "%s\n", s);
}
```

show the triviality of these default programs. The argument to **yyerror()** is a string containing an error message, usually the string **syntax error**. The average application wants to do better than this. Ordinarily, the program should keep track of the input line number and print it along with the message when a syntax error is detected. The external integer variable **yychar** contains the look-ahead token number at the time the error was detected. This may be of some interest in giving better diagnostics. Since the **main()** routine is



probably supplied by the user (to read arguments, etc.), the **yacc** library is useful only in small projects or in the earliest stages of larger ones.

The external integer variable **yydebug** is normally set to 0. If it is set to a nonzero value, the parser will output a verbose description of its actions, including a discussion of the input symbols read and what the parser actions are. It is possible to set this variable by using **sdb**.

---

# Hints for Preparing Specifications

This part contains miscellaneous hints on preparing efficient, easy to change, and clear specifications. The individual subsections are more or less independent.

## Input Style

It is difficult to provide rules with substantial actions and still have a readable specification file. The following are a few style hints.

1. Use all uppercase letters for token names and all lowercase letters for nonterminal names. This is useful in debugging.
2. Put grammar rules and actions on separate lines. It makes editing easier.
3. Put all rules with the same left side together. Put the left side in only once and let all following rules begin with a vertical bar.
4. Put a semicolon only after the last rule with a given left-hand side and put the semicolon on a separate line. This allows new rules to be easily added.
5. Indent rule bodies by one tab stop and action bodies by two tab stops.
6. Put complicated actions into subroutines defined in separate files.

Example 1 is written following this style, as are the examples in this section (where space permits). The user must decide about these stylistic questions. The central problem, however, is to make the rules visible through the morass of action code.

## Left Recursion

The algorithm used by the `yacc` parser encourages so called left recursive grammar rules. Rules of the form

```
name : name rest_of_rule ;
```

match this algorithm. These rules such as

```
list  :  item
      |  list ',' item
      ;
```

and

```
seq   :  item
      |  seq item
      ;
```

frequently arise when writing specifications of sequences and lists. In each of these cases, the first rule will be reduced for the first item only; and the second rule will be reduced for the second and all succeeding items.

With right recursive rules, such as

```
seq   :  item
      |  item seq
      ;
```

the parser is a bit bigger; and the items are seen and reduced from right to left. More seriously, an internal stack in the parser is in danger of overflowing if a very long sequence is read. Thus, the user should use left recursion whenever reasonable.

It is worth considering if a sequence with zero elements has any meaning, and if so, consider writing the sequence specification as

```
seq   :  /* empty */
      |  seq item
      ;
```

using an empty rule. Once again, the first rule would always be reduced exactly once before the first item was read, and then the second rule would be reduced once for each item read. Permitting empty sequences often leads to increased generality. However, conflicts might arise if **yacc** is asked to decide which empty sequence it has seen when it has not seen enough to know!

### Lexical Tie-Ins

Some lexical decisions depend on context. For example, the lexical analyzer might want to delete blanks normally, but not within quoted strings, or names might be entered into a symbol table in declarations but not in expressions. One way of handling these situations is to create a global flag that is examined by the lexical analyzer and set by actions. For example,

```
%{
    int dflag;
%}
... other declarations ...

%%

prog : decls stats
    ;

decls : /* empty */
    {
        dflag = 1;
    }
    | decls declaration
    ;

stats : /* empty */
    {
        dflag = 0;
    }
    | stats statement
    ;

... other rules ...
```

specifies a program that consists of zero or more declarations followed by zero or more statements. The flag **dflag** is now 0 when reading statements and 1 when reading declarations, except for the first token in the first statement.

This token must be seen by the parser before it can tell that the declaration section has ended and the statements have begun. In many cases, this single token exception does not affect the lexical scan.

This kind of back-door approach can be elaborated to a noxious degree. Nevertheless, it represents a way of doing some things that are difficult, if not impossible, to do otherwise.

## **Reserved Words**

Some programming languages permit you to use words like **if**, which are normally reserved as label or variable names, provided that such use does not conflict with the legal use of these names in the programming language. This is extremely hard to do in the framework of **yacc**. It is difficult to pass information to the lexical analyzer telling it this instance of **if** is a keyword and that instance is a variable. The user can make a stab at it using the mechanism described in the last subsection, but it is difficult.

A number of ways of making this easier are under advisement. Until then, it is better that the keywords be reserved, i.e., forbidden for use as variable names. There are powerful stylistic reasons for preferring this.

---

## Advanced Topics

This part discusses a number of advanced features of `yacc`.

### Simulating error and accept in Actions

The parsing actions of **error** and **accept** can be simulated in an action by use of macros `YYACCEPT` and `YYERROR`. The `YYACCEPT` macro causes `yyparse()` to return the value 0; `YYERROR` causes the parser to behave as if the current input symbol had been a syntax error; `yterror()` is called, and error recovery takes place. These mechanisms can be used to simulate parsers with multiple end-markers or context sensitive syntax checking.

### Accessing Values in Enclosing Rules

An action may refer to values returned by actions to the left of the current rule. The mechanism is simply the same as with ordinary actions, a dollar sign followed by a digit.

```

sent  : adj noun verb adj noun
      {
        look at the sentence ...
      }
      ;
adj   : THE
      {
        $$ = THE;
      }
      | YOUNG
      {
        $$ = YOUNG;
      }
      ...
      ;
noun  : DOG
      {
        $$ = DOG;
      }
      | CRONE
      {
        if( $0 == YOUNG )
        {
          (void) printf( "what?\n" );
        }
        $$ = CRONE;
      }
      ;
      ...

```

In this case, the digit may be 0 or negative. In the action following the word `CRONE`, a check is made that the preceding token shifted was not `YOUNG`. Obviously, this is only possible when a great deal is known about what might precede the symbol **noun** in the input. There is also a distinctly unstructured flavor about this. Nevertheless, at times this mechanism prevents a great deal of trouble especially when a few combinations are to be excluded from an otherwise regular structure.

## Support for Arbitrary Value Types

By default, the values returned by actions and the lexical analyzer are integers. **yacc** can also support values of other types including structures. In addition, **yacc** keeps track of the types and inserts appropriate union member names so that the resulting parser is strictly type checked. **yacc** value stack is declared to be a **union** of the various types of values desired. The user declares the union and associates union member names with each token and nonterminal symbol having a value. When the value is referenced through a **\$\$** or **\$n** construction, **yacc** will automatically insert the appropriate union name so that no unwanted conversions take place. In addition, type checking commands such as **lint** are far more silent.

There are three mechanisms used to provide for this typing. First, there is a way of defining the union. This must be done by the user since other sub-routines, notably the lexical analyzer, must know about the union member names. Second, there is a way of associating a union member name with tokens and nonterminals. Finally, there is a mechanism for describing the type of those few values where **yacc** cannot easily determine the type.

To declare the union, the user includes

```
%union
{
    body of union ...
}
```

in the declaration section. This declares the **yacc** value stack and the external variables **yyval** and **yyval** to have type equal to this union. If **yacc** was invoked with the **-d** option, the union declaration is copied onto the **y.tab.h** file as **YYSTYPE**.

Once **YYSTYPE** is defined, the union member names must be associated with the various terminal and nonterminal names. The construction

```
<name>
```

is used to indicate a union member name. If this follows one of the keywords **%token**, **%left**, **%right**, or **%nonassoc**, the union member name is associated with the tokens listed. Thus, saying

```
%left <optype> '+' '-'
```



causes any reference to values returned by these two tokens to be tagged with the union member name **optype**. Another keyword, **%type**, is used to associate union member names with nonterminals. Thus, one might say

```
%type <nodetype> expr stat
```

to associate the union member **nodetype** with the nonterminal symbols **expr** and **stat**.

There remain a couple of cases where these mechanisms are insufficient. If there is an action within a rule, the value returned by this action has no *a priori* type. Similarly, reference to left context values (such as **\$0**) leaves **yacc** with no easy way of knowing the type. In this case, a type can be imposed on the reference by inserting a union member name between **<** and **>** immediately after the first **\$**. The example

```
rule : aaa
      {
        $<intval>$ = 3;
      }
      bbb
    {
      fun( $<intval>2, $<other>0 );
    }
    ;
```

shows this usage. This syntax has little to recommend it, but the situation arises rarely.

A sample specification is given in Example 2. The facilities in this subsection are not triggered until they are used. In particular, the use of **%type** will turn on these mechanisms. When they are used, there is a fairly strict level of checking. For example, use of **\$n** or **\$\$** to refer to something with no defined type is diagnosed. If these facilities are not triggered, the **yacc** value stack is used to hold **ints**.

## yacc Input Syntax

This section has a description of the **yacc** input syntax as a **yacc** specification. Context dependencies, etc. are not considered. Ironically, although **yacc** accepts an LALR(1) grammar, the **yacc** input specification language is most naturally specified as an LR(2) grammar; the sticky part comes when an identifier is seen in a rule immediately following an action. If this identifier is followed by a colon, it is the start of the next rule; otherwise, it is a continuation of the current rule, which just happens to have an action embedded in it. As implemented, the lexical analyzer looks ahead after seeing an identifier and decides whether the next token (skipping blanks, newlines, and comments, etc.) is a colon. If so, it returns the token `C_IDENTIFIER`. Otherwise, it returns `IDENTIFIER`. Literals (quoted strings) are also returned as `IDENTIFIERS` but never as part of `C_IDENTIFIERS`.

```

/* grammar for the input to yacc */

/* basic entries */
%token    IDENTIFIER /* includes identifiers and literals */
%token    C_IDENTIFIER /* identifier (but not literal) followed by a : */
%token    NUMBER      /* [0-9]+ */

/* reserved words: %type=>TYPE %left=>LEFT,etc. */

%token    LEFT RIGHT NONASSOC TOKEN PREC TYPE START UNION

%token    MARK /* the %% mark */
%token    LCURL /* the %{ mark */
%token    RCURL /* the %} mark */

/* ASCII character literals stand for themselves */

%token    spec

%%

spec :    defs MARK rules tail
      ;

```

*continued*

```
tail : MARK
    {
        In this action, eat up the rest of the file
    }
    | /* empty: the second MARK is optional */
    ;

defs : /* empty */
    | defs def
    ;

def : START IDENTIFIER
    | UNION
    {
        Copy union definition to output
    }
    | LCURL
    {
        Copy C code to output file
    }
    | RCURL
    | rword tag nlist
    ;

rword : TOKEN
    | LEFT
    | RIGHT
    | NONASSOC
    | TYPE
    ;

tag : /* empty: union tag is optional */
    | '<' IDENTIFIER '>'
    ;

nlist : nmo
    | nlist nmo
    | nlist ',' nmo
    ;
```

*continued*

```
nmno : IDENTIFIER      /* Note: literal illegal with % type */
      | IDENTIFIER NUMBER /* Note: illegal with % type */
      ;

/* rule section */

rules : C_IDENTIFIER rbody prec
       | rules rule
       ;
rule  : C_IDENTIFIER rbody prec
       | '|' rbody prec
       ;

rbody : /* empty */
       | rbody IDENTIFIER
       | rbody act
       ;

act   : '{'
       {
           Copy action translate $$ etc.
       }
       '}'
       ;

prec  : /* empty */
       | PREC IDENTIFIER
       | PREC IDENTIFIER act
       | prec ';'
       ;
```

---

# Examples

## 1. A Simple Example

This example gives the complete **yacc** applications for a small desk calculator; the calculator has 26 registers labeled **a** through **z** and accepts arithmetic expressions made up of the operators

**+**, **-**, **\***, **/**, **%** (mod operator), **&** (bitwise and), **|** (bitwise or),  
and assignments.

If an expression at the top level is an assignment, only the assignment is done; otherwise, the expression is printed. As in the C language, an integer that begins with 0 (zero) is assumed to be octal; otherwise, it is assumed to be decimal.

As an example of a **yacc** specification, the desk calculator does a reasonable job of showing how precedence and ambiguities are used and demonstrates simple recovery. The major oversimplifications are that the lexical analyzer is much simpler than for most applications, and the output is produced immediately line by line. Note the way that decimal and octal integers are read in by grammar rules. This job is probably better done by the lexical analyzer.

```
%{
# include <stdio.h>
# include <ctype.h>

int regs[26];
int base;

%}

%start list

%token DIGIT LETTER

%left '|'
%left '&'
%left '+' '-'
%left '*' '/' '%'
```

*continued*

```
%left UMINUS /* supplies precedence for unary minus */

%%      /* beginning of rules section */

list    : /* empty */
        | list stat '\n'
        | list error '\n'
        {
          yyerrorok;
        }
        ;

stat    : expr
        {
          (void) printf( "%d\n", $1 );
        }
        | LETTER '=' expr
        {
          regs[$1] = $3;
        }
        ;

expr    : '(' expr ')'
        {
          $$ = $2;
        }
        | expr '+' expr
        {
          $$ = $1 + $3;
        }
        | expr '-' expr
        {
          $$ = $1 - $3;
        }
        | expr '*' expr
        {
          $$ = $1 * $3;
        }
        | expr '/' expr
        {
          $$ = $1 / $3;
        }
        | exp '%' expr
```

*continued*

```

    {
        $$ = $1 % $3;
    }
    | expr '&' expr
    {
        $$ = $1 & $3;
    }
    | expr '|' expr
    {
        $$ = $1 | $3;
    }
    | '-' expr %prec UMINUS
    {
        $$ = -$2;
    }
    | LETTER
    {
        $$ = reg[$1];
    }
    | number
    ;

number : DIGIT
    {
        $$ = $1; base = ($1==0) ? 8 ; 10;
    }
    | number DIGIT
    {
        $$ = base * $1 + $2;
    }
    ;

%%
/* beginning of subroutines section */

int yylex( ) /* lexical analysis routine */
{
    /* return LETTER for lowercase letter, */
    /* yyval = 0 through 25 */
    /* returns DIGIT for digit, yyval = 0 through 9 */
    /* all other characters are returned immediately */

```

*continued*

```
int c;
    /*skip blanks*/
while ((c = getchar()) == ' ')
    ;

    /* c is now nonblank */

if (islower(c))
{
    yynlval = c - 'a';
    return (LETTER);
}
if (isdigit(c))
}
    yynlval = c - '0';
    return (DIGIT);

}
return (c);
}
```

## 2. An Advanced Example

This section gives an example of a grammar using some of the advanced features. The desk calculator example in Example 1 is modified to provide a desk calculator that does floating point interval arithmetic. The calculator understands floating point constants; the arithmetic operations +, -, \*, /, and unary - a through z. Moreover, it also understands intervals written

(X,Y)

where X is less than or equal to Y. There are 26 interval valued variables A through Z that may also be used. The usage is similar to that in Example 1; assignments return no value and print nothing while expressions print the (floating or interval) value.



This example explores a number of interesting features of **yacc** and C. Intervals are represented by a structure consisting of the left and right end-point values stored as doubles. This structure is given a type name, **INTERVAL**, by using **typedef**. The **yacc** value stack can also contain floating point scalars and integers (used to index into the arrays holding the variable values). Notice that the entire strategy depends strongly on being able to assign structures and unions in C language. In fact, many of the actions call functions that return structures as well.

It is also worth noting the use of **YYERROR** to handle error conditions—division by an interval containing 0 and an interval presented in the wrong order. The error recovery mechanism of **yacc** is used to throw away the rest of the offending line.

In addition to the mixing of types on the value stack, this grammar also demonstrates an interesting use of syntax to keep track of the type (for example, scalar or interval) of intermediate expressions. Note that scalar can be automatically promoted to an interval if the context demands an interval value. This causes a large number of conflicts when the grammar is run through **yacc**: 18 **shift-reduce** and 26 **reduce-reduce**. The problem can be seen by looking at the two input lines.

```
2.5 + (3.5 - 4.)
```

and

```
2.5 + (3.5, 4)
```

Notice that the 2.5 is to be used in an interval value expression in the second example, but this fact is not known until the comma is read. By this time, 2.5 is finished, and the parser cannot go back and change its mind. More generally, it might be necessary to look ahead an arbitrary number of tokens to decide whether to convert a scalar to an interval. This problem is evaded by having two rules for each binary interval valued operator—one when the left operand is a scalar and one when the left operand is an interval. In the second case, the right operand must be an interval, so the conversion will be applied automatically. Despite this evasion, there are still many cases where the conversion may be applied or not, leading to the above conflicts. They are resolved by listing the rules that yield scalars first in the specification file; in this way, the conflict will be resolved in the direction of keeping scalar valued expressions scalar valued until they are forced to become intervals.

## Examples

---

This way of handling multiple types is very instructive. If there were many kinds of expression types instead of just two, the number of rules needed would increase dramatically and the conflicts even more dramatically. Thus, while this example is instructive, it is better practice in a more normal programming language environment to keep the type information as part of the value and not as part of the grammar.

Finally, a word about the lexical analysis. The only unusual feature is the treatment of floating point constants. The C language library routine `atof()` is used to do the actual conversion from a character string to a double-precision value. If the lexical analyzer detects an error, it responds by returning a token that is illegal in the grammar provoking a syntax error in the parser and thence error recovery.

```
%{  
  
#include <stdio.h>  
#include <ctype.h>  
  
typedef struct interval  
{  
    double lo, hi;  
} INTERVAL;  
  
INTERVAL vmul(), vdiv();  
  
double atof();  
  
double dreg[26];  
INTERVAL vreg[26];  
  
%}  
  
%start line  
  
%union  
{  
    int ival;  
    double dval;  
    INTERVAL vval;  
}  
  
%token <ival> DREG VREG /* indices into dreg, vreg arrays */
```

*continued*

```

%token <dval> CONST      /* floating point constant */

%type <dval> dexp        /* expression */

%type <vval> vexp        /* interval expression */

/* precedence information about the operators */

%left '+' '-'
%left '*' '/'
%left UMINUS /* precedence for unary minus */

%% /* beginning of rules section */

lines : /* empty */
      | lines line
      ;
line  : dexp '\n'
      {
          (void) printf("%15.8f\n", $1);
      }
      | vexp '\n'
      {
          (void) printf("%15.8f, %15.8f\n", $1.lo, $1.hi);
      }
      | DREG '=' dexp '\n'
      {
          dreg[$1] = $3;
      }
      | VREG '=' vexp '\n'
      {
          vreg[$1] = $3;
      }
      | error '\n'
      {
          yyerror;
      }
      ;

dexp  : CONST

```

*continued*

```
| DREG
{
    $$ = dreg[$1];
}
| dexp '+' dexp
{
    $$ = $1 + $3;
}
| dexp '-' dexp
{
    $$ = $1 - $3;
}
| dexp '*' dexp
{
    $$ = $1 * $3;
}
| dexp '/' dexp
{
    $$ = $1 / $3;
}
| '-' dexp %prec UMINUS
{
    $$ = -$2;
}
| '(' dexp ')'
{
    $$ = $2;
}
;

vexp : dexp
{
    $$ .hi = $$ .lo = $1;
}
| '(' dexp ',' dexp ')'
{
    $$ .lo = $2;
    $$ .hi = $4;
    if( $$ .lo > $$ .hi )
```

*continued*

```
        {
            (void) printf("interval out of order \n");
            YYERROR;
        }
    }
| VREG
{
    $$ = vreg[$1];
}
| vexp '+' vexp
{
    $$ .hi = $1 .hi + $3 .hi;
    $$ .lo = $1 .lo + $3 .lo;
}
| dexp '+' vexp
{
    $$ .hi = $1 + $3 .hi;
    $$ .lo = $1 + $3 .lo;
}
| vexp '-' vexp
{
    $$ .hi = $1 .hi - $3 .lo;
    $$ .lo = $1 .lo - $3 .hi;
}
| dexp '-' vdep
{
    $$ .hi = $1 - $3 .lo;
    $$ .lo = $1 - $3 .hi
}
| vexp '*' vexp
{
    $$ = vmul( $1 .lo, $ .hi, $3 )
}
| dexp '*' vexp
{
    $$ = vmul( $1, $1, $3 )
}
| vexp '/' vexp
```

*continued*

```
{
    if( dcheck( $3 ) ) YYERROR;
    $$ = vdiv( $1.lo, $1.hi, $3 )
}
| dexp '/' vexp
{
    if( dcheck( $3 ) ) YYERROR;
    $$ = vdiv( $1.lo, $1.hi, $3 )
}
| '-' vexp %prec UMINUS
{
    $$ .hi = -$2.lo; $$ .lo = -$2.hi
}
| '(' vexp ')'
}
    $$ = $2
}
;

%%
/* beginning of subroutines section */

# define BSZ 50 /* buffer size for floating point number */

/* lexical analysis */

int yylex( )
{
    register int c;

    /* skip over blanks */
    while ((c = getchar()) == ' ')
        ;
    if (isupper(c))
    {
        yylval.ival = c - 'A'
        return (VREG);
    }
    if (islower(c))
```

*continued*

```
{
    yylval.ival = c - 'a',
    return( DREG );
}

/* gobble up digits. points, exponents */

if (isdigit(c) || c == '.')
{
    char buf[BSZ+1], *cp = buf;
    int dot = 0, exp = 0;

    for(; (cp - buf) < BSZ ; ++cp, c = getchar())
    {
        *cp = c;
        if (isdigit(c))
            continue;
        if (c == '.')
        {
            if (dot++ || exp)
                return ('.'); /* will cause syntax error */
            continue;
        }
        if (c == 'e')
        {
            if (exp++)
                return ('e'); /* will cause syntax error */
            continue;
        }
        /* end of number */
        break;
    }

    *cp = ' ';
    if (cp - buf >= BSZ)
        (void) printf("constant too long - truncated\n");
    else
        ungetc(c, stdin); /* push back last char read */
    yylval.dval = atof(buf);
    return (CONST);
}
```

*continued*

```
        return (c);
    }
    INTERVAL
    hilo(a, b, c, d)
        double a, b, c, d;
    {
        /* returns the smallest interval containing a, b, c, and d */

        /* used by */ routine */
        INTERVAL v;

        if (a > b)
        {
            v.hi = a;
            v.lo = b;
        }
        else
        {
            v.hi = b;
            v.lo = a;
        }
        if (c > d)
        {
            if (c > v.hi)
                v.hi = c;
            if (d < v.lo)
                v.lo = d;
        }
        else
        {
            if (d > v.hi)
                v.hi = d;
            if (c < v.lo)
                v.lo = c;
        }
        return (v);
    }
}
```



*continued*

```
INTERVAL
vmul(a, b, v)
    double a, b;
    INTERVAL v;

{
    return (hilo(a * v.hi, a * v.lo, b * v.hi, b * v.lo));
}
dcheck(v)
    INTERVAL v;

{
    if (v.hi >= 0. && v.lo <= 0.)
    {
        (void) printf("divisor interval contains 0.\n");
        return (1);
    }
    return (0);
}

INTERVAL
vdiv(a, b, v)
    double a, b;
    INTERVAL v;

{
    return (hilo(a / v.hi, a / v.lo, b / v.hi, b / v.lo));
}
```





## File and Record Locking

---

# 7 File and Record Locking

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## Introduction

Mandatory and advisory file and record locking both are available on current releases of the UNIX system. The intent of this capability is to provide a synchronization mechanism for programs accessing the same stores of data simultaneously. Such processing is characteristic of many multiuser applications, and the need for a standard method of dealing with the problem has been recognized by standards advocates like */usr/group*, an organization of UNIX system users from businesses and campuses across the country.

Advisory file and record locking can be used to coordinate self-synchronizing processes. In mandatory locking, the standard I/O subroutines and I/O system calls enforce the locking protocol. In this way, at the cost of a little efficiency, mandatory locking double-checks the programs against accessing the data out of sequence.

The remainder of this chapter describes how file and record locking capabilities can be used. Examples are given for the correct use of record locking. Misconceptions about the amount of protection that record locking affords are dispelled. Record locking should be viewed as a synchronization mechanism, not a security mechanism.

The manual pages for the **fcntl(2)** system call, the **lockf(3)** library function, and **fcntl(5)** data structures and commands are referred to throughout this section. You should read them before continuing.

---

# Terminology

Before discussing how record locking should be used, let us first define a few terms.

## Record

A contiguous set of bytes in a file. The UNIX operating system does not impose any record structure on files. This may be done by the programs that use the files.

## Cooperating Processes

Processes that work together in some well defined fashion to accomplish the tasks at hand. Processes that share files must request permission to access the files before using them. File access permissions must be carefully set to restrict non-cooperating processes from accessing those files. The term process will be used interchangeably with cooperating process to refer to a task obeying such protocols.

## Read (Share) Locks

These are used to gain limited access to sections of files. When a read lock is in place on a record, other processes may also read lock that record, in whole or in part. No other process, however, may have or obtain a write lock on an overlapping section of the file. If a process holds a read lock it may assume that no other process will be writing or updating that record at the same time. This access method also permits many processes to read the given record. This might be necessary when searching a file, without the contention involved if a write or exclusive lock were to be used.

## Write (Exclusive) Locks

These are used to gain complete control over sections of files. When a write lock is in place on a record, no other process may read or write lock that record, in whole or in part. If a process holds a write lock it may assume that no other process will be reading or writing that record at the same time.

## Advisory Locking

A form of record locking that does not interact with the I/O subsystem [that is, **creat(2)**, **open(2)**, **read(2)**, and **write(2)**]. The control over records is accomplished by requiring an appropriate record lock request before I/O operations. If appropriate requests are always made by all processes accessing the file, then the accessibility of the file will be controlled by the interaction of these requests. Advisory



locking depends on the individual processes to enforce the record locking protocol; it does not require an accessibility check at the time of each I/O request.

#### Mandatory Locking

A form of record locking that does interact with the I/O subsystem. Access to locked records is enforced by the **creat(2)**, **open(2)**, **read(2)**, and **write(2)** system calls. If a record is locked, then access of that record by any other process is restricted according to the type of lock on the record. The control over records should still be performed explicitly by requesting an appropriate record lock before I/O operations, but an additional check is made by the system before each I/O operation to ensure the record locking protocol is being honored. Mandatory locking offers an extra synchronization check, but at the cost of some additional system overhead.

---

## File Protection

There are access permissions for UNIX system files to control who may read, write, or execute such a file. These access permissions may only be set by the owner of the file or by the super-user. The permissions of the directory in which the file resides can also affect the ultimate disposition of a file. Note that if the directory permissions allow anyone to write in it, then files within the directory may be removed, even if those files do not have read, write, or execute permission for that user. Any information that is worth protecting is worth protecting properly. If your application warrants the use of record locking, make sure that the permissions on your files and directories are set properly. A record lock, even a mandatory record lock, will only protect the portions of the files that are locked. Other parts of these files might be corrupted if proper precautions are not taken.

Only a known set of programs and/or administrators should be able to read or write a data base. This can be done easily by setting the set-group-ID bit [see `chmod(1)`] of the data base accessing programs. The files can then be accessed by a known set of programs that obey the record locking protocol. An example of such file protection, although record locking is not used, is the `mail(1)` command. In that command only the particular user and the `mail` command can read and write in the unread mail files.

## Opening a File for Record Locking

The first requirement for locking a file or segment of a file is having a valid open file descriptor. If read locks are to be done, then the file must be opened with at least read accessibility and likewise for write locks and write accessibility. For our example we will open our file for both read and write access:

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

int fd; /* file descriptor */
char *filename;

main(argc, argv)
int argc;
char *argv[];
{
    extern void exit(), perror();

    /* get data base file name from command line and open the
     * file for read and write access.
     */
    if (argc < 2) {
        (void) fprintf(stderr, "usage: %s filename\n", argv[0]);
        exit(2);
    }
    filename = argv[1];
    fd = open(filename, O_RDWR);
    if (fd < 0) {
        perror(filename);
        exit(2);
    }
    .
    .
    .
}
```

The file is now open for us to perform both locking and I/O functions. We then proceed with the task of setting a lock.

## Setting a File Lock

There are several ways for us to set a lock on a file. In part, these methods depend upon how the lock interacts with the rest of the program. There are also questions of performance as well as portability. Two methods will be given here, one using the **fcntl(2)** system call, the other using the */usr/group* standards compatible **lockf(3)** library function call.

Locking an entire file is just a special case of record locking. For both these methods the concept and the effect of the lock are the same. The file is locked starting at a byte offset of zero (0) until the end of the maximum file size. This point extends beyond any real end of the file so that no lock can be placed on this file beyond this point. To do this the value of the size of the lock is set to zero. The code using the **fcntl(2)** system call is as follows:

```
#include <fcntl.h>
#define MAX_TRY 10
int try;
struct flock lck;

try = 0;

/* set up the record locking structure, the address of which
 * is passed to the fcntl system call.
 */
lck.l_type = F_WRLCK; /* setting a write lock */
lck.l_whence = 0; /* offset l_start from beginning of file */
lck.l_start = 0L;
lck.l_len = 0L; /* until the end of the file address space */

/* Attempt locking MAX_TRY times before giving up.
 */
while (fcntl(fd, F_SETLK, &lck) < 0) {
    if (errno == EAGAIN || errno == EACCES) {
        /* there might be other errors cases in which
         * you might try again.
         */
        if (++try < MAX_TRY) {
            (void) sleep(2);
            continue;
        }
        (void) fprintf(stderr, "File busy try again later!\n");
        return;
    }
    perror("fcntl");
    exit(2);
}
.
.
.
```

## File Protection

---

This portion of code tries to lock a file. This task is attempted several times until one of the following things happens:

- the file is locked
- an error occurs
- it gives up trying because `MAX_TRY` has been exceeded.

To perform the same task using the `lockf(3)` function, the code is as follows:

```
#include <unistd.h>
#define MAX_TRY 10
int try;
try = 0;

/* make sure the file pointer
 * is at the beginning of the file.
 */
lseek(fd, 0L, 0);

/* Attempt locking MAX_TRY times before giving up.
 */
while (lockf(fd, F_TLOCK, 0L) < 0) {
if (errno == EAGAIN || errno == EACCES) {
/* there might be other errors cases in which
 * you might try again.
 */
if (++try < MAX_TRY) {
sleep(2);
continue;
}
(void) fprintf(stderr, "File busy try again later!\n");
return;
}
perror("lockf");
exit(2);
}
.
.
.
```

It should be noted that the `lockf(3)` example appears to be simpler, but the `fcntl(2)` example exhibits additional flexibility. Using the `fcntl(2)` method, it is possible to set the type and start of the lock request simply by setting a few structure variables. `lockf(3)` merely sets write (exclusive) locks; an additional system call [`lseek(2)`] is required to specify the start of the lock.

## Setting and Removing Record Locks

Locking a record is done the same way as locking a file except for the differing starting point and length of the lock. We will now try to solve an interesting and real problem. There are two records (these records may be in the same or different file) that must be updated simultaneously so that other processes get a consistent view of this information. (This type of problem comes up, for example, when updating the interrecord pointers in a doubly linked list.) To do this you must decide the following questions:

- What do you want to lock?
- For multiple locks, in what order do you want to lock and unlock the records?
- What do you do if you succeed in getting all the required locks?
- What do you do if you fail to get all the locks?

In managing record locks, you must plan a failure strategy if one cannot obtain all the required locks. It is because of contention for these records that we have decided to use record locking in the first place. Different programs might:

- wait a certain amount of time and try again
- abort the procedure and warn the user
- let the process sleep until signaled that the lock has been freed
- some combination of the above.

Let us now look at our example of inserting an entry into a doubly linked list. For the example, we will assume that the record after which the new record is to be inserted has a read lock on it already. The lock on this record must be changed or promoted to a write lock so that the record may be edited.

Promoting a lock (generally from read lock to write lock) is permitted if no other process is holding a read lock in the same section of the file. If there are processes with pending write locks that are sleeping on the same section of the file, the lock promotion succeeds and the other (sleeping) locks wait. Promoting (or demoting) a write lock to a read lock carries no restrictions. In either case, the lock is merely reset with the new lock type. Because the



`/usr/group lockf` function does not have read locks, lock promotion is not applicable to that call. An example of record locking with lock promotion follows:

```

struct record {
    .
    /* data portion of record */
    .
    long prev; /* index to previous record in the list */
    long next; /* index to next record in the list */
};

/* Lock promotion using fcntl(2)
 * When this routine is entered it is assumed that there are read
 * locks on "here" and "next".
 * If write locks on "here" and "next" are obtained:
 *   Set a write lock on "this".
 *   Return index to "this" record.
 * If any write lock is not obtained:
 *   Restore read locks on "here" and "next".
 *   Remove all other locks.
 *   Return a -1.
 */
long
set3lock (this, here, next)
long this, here, next;
{
    struct flock lck;

    lck.l_type = F_WRLCK; /* setting a write lock */
    lck.l_whence = 0; /* offset l_start from beginning of file */
    lck.l_start = here;
    lck.l_len = sizeof(struct record);

    /* promote lock on "here" to write lock */
    if (fcntl(fd, F_SETLKW, &lck) < 0) {
        return (-1);
    }
    /* lock "this" with write lock */
    lck.l_start = this;
    if (fcntl(fd, F_SETLKW, &lck) < 0) {
        /* Lock on "this" failed;
         * demote lock on "here" to read lock.
         */
        lck.l_type = F_RDLCK;
    }
}

```

*continued*

```
lck.l_start = here;
(void) fcntl(fd, F_SETLKW, &lck);
return (-1);
}
/* promote lock on "next" to write lock */
lck.l_start = next;
if (fcntl(fd, F_SETLKW, &lck) < 0) {
/* Lock on "next" failed;
 * demote lock on "here" to read lock,
 */
lck.l_type = F_RDLCK;
lck.l_start = here;
(void) fcntl(fd, F_SETLK, &lck);
/* and remove lock on "this".
 */
lck.l_type = F_UNLCK;
lck.l_start = this;
(void) fcntl(fd, F_SETLK, &lck);
return (-1); /* cannot set lock, try again or quit */
}

return (this);
}
```

The locks on these three records were all set to wait (sleep) if another process was blocking them from being set. This was done with the `F_SETLKW` command. If the `F_SETLK` command was used instead, the `fcntl` system calls would fail if blocked. The program would then have to be changed to handle the blocked condition in each of the error return sections.

Let us now look at a similar example using the `lockf` function. Since there are no read locks, all (write) locks will be referenced generically as locks.

```
/* Lock promotion using lockf(3)
 * When this routine is entered it is assumed that there are
 * no locks on "here" and "next".
 * If locks are obtained:
 *   Set a lock on "this".
 *   Return index to "this" record.
 * If any lock is not obtained:
 *   Remove all other locks.
 *   Return a -1.
 */

#include <unistd.h>

long
set3lock (this, here, next)
long this, here, next;

{

    /* lock "here" */
    (void) lseek(fd, here, 0);
    if (lockf(fd, F_LOCK, sizeof(struct record)) < 0) {
        return (-1);
    }
    /* lock "this" */
    (void) lseek(fd, this, 0);
    if (lockf(fd, F_LOCK, sizeof(struct record)) < 0) {
        /* Lock on "this" failed.
         * Clear lock on "here".
         */
        (void) lseek(fd, here, 0);
        (void) lockf(fd, F_ULOCK, sizeof(struct record));
        return (-1);
    }

    /* lock "next" */
    (void) lseek(fd, next, 0);
    if (lockf(fd, F_LOCK, sizeof(struct record)) < 0) {

        /* Lock on "next" failed.
         * Clear lock on "here",
         */
        (void) lseek(fd, here, 0);
```

*continued*

```
(void) lockf(fd, F_ULOCK, sizeof(struct record));

/* and remove lock on "this".
 */
(void) lseek(fd, this, 0);
(void) lockf(fd, F_ULOCK, sizeof(struct record));
return (-1); /* cannot set lock, try again or quit */

}

return (this);
}
```

Locks are removed in the same manner as they are set, only the lock type is different (`F_UNLCK` or `F_ULOCK`). An unlock cannot be blocked by another process and will only affect locks that were placed by this process. The unlock only affects the section of the file defined in the previous example by `lck`. It is possible to unlock or change the type of lock on a subsection of a previously set lock. This may cause an additional lock (two locks for one system call) to be used by the operating system. This occurs if the subsection is from the middle of the previously set lock.

## Getting Lock Information

One can determine which processes, if any, are blocking a lock from being set. This can be used as a simple test or as a means to find locks on a file. A lock is set up as in the previous examples and the `F_GETLK` command is used in the `fcntl` call. If the lock passed to `fcntl` would be blocked, the first blocking lock is returned to the process through the structure passed to `fcntl`. That is, the lock data passed to `fcntl` is overwritten by blocking lock information. This information includes two pieces of data that have not been discussed yet, `L_pid` and `L_sysid`, that are only used by `F_GETLK`. (For systems that do not support a distributed architecture, the value in `L_sysid` should be ignored.) These fields uniquely identify the process holding the lock.

If a lock passed to `fcntl` using the `F_GETLK` command would not be blocked by another process' lock, then the `l_type` field is changed to `F_UNLCK` and the remaining fields in the structure are unaffected. Let us use this capability to print all the segments locked by other processes. Note that if there are several read locks over the same segment, only one of these will be found.

```
struct flock lck;

/* Find and print "write lock" blocked segments of this file. */
(void) printf("sysid  pid type  start  length\n");
lck.l_whence = 0;
lck.l_start = 0L;
lck.l_len = 0L;
do {
    lck.l_type = F_WRLCK;
    (void) fcntl(fd, F_GETLK, &lck);
    if (lck.l_type != F_UNLCK) {
        (void) printf("%5d %5d  %c %8d %8d\n",
            lck.l_sysid,
            lck.l_pid,
            (lck.l_type == F_WRLCK) ? 'W' : 'R',
            lck.l_start,
            lck.l_len);
        /* if this lock goes to the end of the address
         * space, no need to look further, so break out.
         */
        if (lck.l_len == 0)
            break;
        /* otherwise, look for new lock after the one
         * just found.
         */
        lck.l_start += lck.l_len;
    }
} while (lck.l_type != F_UNLCK);
```

The `fcntl` function with the `F_GETLK` command will always return correctly (that is, it will not sleep or fail) if the values passed to it as arguments are valid.

The `lockf` function with the `F_TEST` command can also be used to test if there is a process blocking a lock. This function does not, however, return the information about where the lock actually is and which process owns the lock. A routine using `lockf` to test for a lock on a file follows:

```
/* find a blocked record. */

/* seek to beginning of file */
(void) lseek(fd, 0, 0L);
/* set the size of the test region to zero (0)
 * to test until the end of the file address space.
 */
if (lockf(fd, F_TEST, 0L) < 0) {
switch (errno) {
case EACCES:
case EAGAIN:
(void) printf("file is locked by another process\n");
break;
case EBADF:
/* bad argument passed to lockf */
perror("lockf");
break;
default:
(void) printf("lockf: unknown error <%d>\n", errno);
break;
}
}
```

When a process forks, the child receives a copy of the file descriptors that the parent has opened. The parent and child also share a common file pointer for each file. If the parent were to seek to a point in the file, the child's file pointer would also be at that location. This feature has important implications when using record locking. The current value of the file pointer is used as the reference for the offset of the beginning of the lock, as described by `L_start`,

when using an **Lwhence** value of 1. If both the parent and child process set locks on the same file, there is a possibility that a lock will be set using a file pointer that was reset by the other process. This problem appears in the **lockf(3)** function call as well and is a result of the */usr/group* requirements for record locking. If forking is used in a record locking program, the child process should close and reopen the file if either locking method is used. This will result in the creation of a new and separate file pointer that can be manipulated without this problem occurring. Another solution is to use the **fcntl** system call with a **Lwhence** value of 0 or 2. This makes the locking function atomic, so that even processes sharing file pointers can be locked without difficulty.

## **Deadlock Handling**

There is a certain level of deadlock detection/avoidance built into the record locking facility. This deadlock handling provides the same level of protection granted by the */usr/group* standard **lockf** call. This deadlock detection is only valid for processes that are locking files or records on a single system. Deadlocks can only potentially occur when the system is about to put a record locking system call to sleep. A search is made for constraint loops of processes that would cause the system call to sleep indefinitely. If such a situation is found, the locking system call will fail and set **errno** to the deadlock error number. If a process wishes to avoid the use of the systems deadlock detection, it should set its locks using **F\_GETLK** instead of **F\_GETLKW**.

---

## Selecting Advisory or Mandatory Locking

The use of mandatory locking is not recommended for reasons that will be made clear in a subsequent section. Whether or not locks are enforced by the I/O system calls is determined at the time the calls are made and by the state of the permissions on the file [see `chmod(2)`]. For locks to be under mandatory enforcement, the file must be a regular file with the set-group-ID bit on and the group execute permission off. If either condition fails, all record locks are advisory. Mandatory enforcement can be assured by the following code:

```
#include <sys/types.h>
#include <sys/stat.h>

int mode;
struct stat buf;
.
.
.
if (stat(filename, &buf) < 0) {
    perror("program");
    exit (2);
}
/* get currently set mode */
mode = buf.st_mode;
/* remove group execute permission from mode */
mode &= ~(S_IXEC>>3);
/* set 'set group id bit' in mode */
mode |= S_ISGID;
if (chmod(filename, mode) < 0) {
    perror("program");
    exit(2);
}
.
.
.
```



Files that are to be record locked should never have any type of execute permission set on them. This is because the operating system does not obey the record locking protocol when executing a file.

The **chmod(1)** command can also be easily used to set a file to have mandatory locking. This can be done with the command:

```
chmod +l filename
```

The **ls(1)** command was also changed to show this setting when you ask for the long listing format:

```
ls -l filename
```

causes the following to be printed:

```
-rw---l--- 1 abc      other    1048576 Dec  3 11:44 filename
```

## **Caveat Emptor—Mandatory Locking**

- Mandatory locking only protects those portions of a file that are locked. Other portions of the file that are not locked may be accessed according to normal UNIX system file permissions.
- If multiple reads or writes are necessary for an atomic transaction, the process should explicitly lock all such pieces before any I/O begins. Thus advisory enforcement is sufficient for all programs that perform in this way.
- As stated earlier, arbitrary programs should not have unrestricted access permission to files that are important enough to record lock.
- Advisory locking is more efficient because a record lock check does not have to be performed for every I/O request.

## Record Locking and Future Releases of the UNIX System

Provisions have been made for file and record locking in a UNIX system environment. In such an environment the system on which the locking process resides may be remote from the system on which the file and record locks reside. In this way multiple processes on different systems may put locks upon a single file that resides on one of these or yet another system. The record locks for a file reside on the system that maintains the file. It is also important to note that deadlock detection/avoidance is only determined by the record locks being held by and for a single system. Therefore, it is necessary that a process only hold record locks on a single system at any given time for the deadlock mechanism to be effective. If a process needs to maintain locks over several systems, it is suggested that the process avoid the **sleep-when-blocked** features of **fcntl** or **lockf** and that the process maintain its own deadlock detection. If the process uses the **sleep-when-blocked** feature, then a timeout mechanism should be provided by the process so that it does not hang waiting for a lock to be cleared.





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# 8 Shared Libraries

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## Summary

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## Introduction

Efficient use of disk storage space, memory, and computing power is becoming increasingly important. A shared library can offer savings in all three areas. For example, if constructed properly, a shared library can make **a.out** files (executable object files) smaller on disk storage and processes (**a.out** files that are executing) smaller in memory.

The first part of this chapter, "Using a Shared Library," is designed to help you use UNIX System V shared libraries. It describes what a shared library is and how to use one to build **a.out** files. It also offers advice about when and when not to use a shared library and how to determine whether an **a.out** uses a shared library.

The second part in this chapter, "Building a Shared Library," describes how to build a shared library. You do not need to read this part to use shared libraries. It addresses library developers, advanced programmers who are expected to build their own shared libraries. Specifically, this part describes how to use the UNIX system tool **mkshlib(1)** (documented in the *Programmer's Reference Manual*) and how to write C code for shared libraries on a UNIX system. An example is included. This part also describes how to use the tool **chkshlib(1)**, which helps you check the compatibility of versions of shared libraries. Read this part of the chapter only if you have to build a shared library.

NOTE

Shared libraries are a new feature of UNIX System V Release 3.0. An executable object file that needs shared libraries will not run on previous releases of UNIX System V.

---

# Using a Shared Library

If you are accustomed to using libraries to build your applications programs, shared libraries should blend into your work easily. This part of the chapter explains what shared libraries are and how and when to use them on the UNIX system.

## What is a Shared Library?

A shared library is a file containing object code that several **a.out** files may use simultaneously while executing. When a program is compiled or link edited with a shared library, the library code that defines the program's external references is not copied into the program's object file. Instead, a special section called **.lib** that identifies the library code is created in the object file. When the UNIX system executes the resulting **a.out** file, it uses the information in this section to bring the required shared library code into the address space of the process.

The implementation behind these concepts is a shared library with two pieces. The first, called the host shared library, is an archive that the link editor searches to resolve user references and to create the **.lib** section in **a.out** files. The structure and operation of this archive is the same as any archive without shared library members. For simplicity, however, in this chapter references to archives mean archive libraries without shared library members.

The second part of a shared library is the target shared library. This is the file that the UNIX system uses when running **a.out** files built with the host shared library. It contains the actual code for the routines in the library. Naturally, it must be present on the the system where the **a.out** files will be run.

A shared library offers several benefits by not copying code into **a.out** files. It can

- save disk storage space

Because shared library code is not copied into all the **a.out** files that use the code, these files are smaller and use less disk space.

- save memory

By sharing library code at run time, the dynamic memory needs of processes are reduced.



- make executable files using library code easier to maintain

As mentioned above, shared library code is brought into a process' address space at run time. Updating a shared library effectively updates all executable files that use the library, because the operating system brings the updated version into new processes. If an error in shared library code is fixed, all processes automatically use the corrected code.

Archive libraries cannot, of course, offer this benefit: changes to archive libraries do not affect executable files, because code from the libraries is copied to the files during link editing, not during execution.

"Deciding Whether to Use a Shared Library" in this chapter describes shared libraries in more detail.

## The UNIX System Shared Libraries

Shared libraries are part of the SDS core. and later releases and the C host shared library with C Programming Language Utilities 4.0 and later. The networking library included with the Networking Support Utilities is also a shared library. Other shared libraries may be available now from software vendors and in the future from AT&T.

Shared Library	Host Library Command Line Option	Target Library Pathname
C Library	<code>-lc_s</code>	<code>/shlib/libc_s</code>
Networking Library	<code>-lnsl_s</code>	<code>/shlib/libnsl_s</code>

Notice the `_s` suffix on the library names; we use it to identify both host and target shared libraries. For example, it distinguishes the standard relocatable C library `libc` from the shared C library `libc_s`. The `_s` also indicates that the libraries are statically linked.

The relocatable C library is still available with releases of the C Programming Language Utilities; this library is searched by default during the compilation or link editing of C programs. All other archive libraries from previous releases of the system are also available.

Just as you use the archive libraries' names, you must use a shared library's name when you want to use it to build your **a.out** files. You tell the link editor its name with the **-l** option, as shown below.

### Building an a.out File

You direct the link editor to search a shared library the same way you direct a search of an archive library on the UNIX system:

```
cc file.c -o file ... -llibrary_file ...
```

To direct a search of the networking library, for example, you use the following command line.

```
cc file.c -o file ... -lnsl_s ...
```

And to link all the files in your current directory together with the shared C library you'd use the following command line:

```
cc *.c -lc_s
```

Normally, you should include the **-lc\_s** argument after all other **-l** arguments on a command line. The shared C library will then be treated like the relocatable C library, which is searched by default after all other libraries specified on a command line are searched.

A shared library might be built with references to other shared libraries. That is, the first shared library might contain references to symbols that are resolved in a second shared library. In this case, both libraries must be given on the **cc** command line, in the order of the dependencies.

For example, if the library **libX.a** references symbols in the shared C library, the command line would be:

```
cc *.c -lX_s -lc_s
```

Notice that the shared library containing the references to symbols must be listed on the command line before the shared library needed to resolve those references. For more information on inter-library dependencies, see the section "Referencing Symbols in a Shared Library from Another Shared Library" later in this chapter.

Notice that the shared library containing the references to symbols must be listed on the command line before the shared library needed to resolve those references. For more information on inter-library dependencies, see the section "Referencing Symbols in a Shared Library from Another Shared Library" later in this chapter.

## **Coding an Application**

Application source code in C or assembly language is compatible with both archive libraries and shared libraries. As a result, you should not have to change the code in any applications you already have when you use a shared library with them. When coding a new application for use with a shared library, you should just observe your standard coding conventions.

However, do keep the following two points in mind, which apply when using either an archive or a shared library:

- Don't define symbols in your application with the same names as those in a library.

Although there are exceptions, you should avoid redefining standard library routines, such as **printf(3S)** and **strcmp(3C)**. Replacements that are incompatibly defined can cause any library, shared or unshared, to behave incorrectly.

- Don't use undocumented archive routines.

Use only the functions and data mentioned on the manual pages describing the routines in Section 3 of the *Programmer's Reference Manual*. For example, don't try to outsmart the **ctype** design by manipulating the underlying implementation.

## **Deciding Whether to Use a Shared Library**

You should base your decision to use a shared library on whether it saves space in disk storage and memory for your program. A well-designed shared library almost always saves space. So, as a general rule, use a shared library when it is available.

## Using a Shared Library

---

To determine what savings are gained from using a shared library, you might build the same application with both an archive and a shared library, assuming both kinds are available. Remember, that you may do this because source code is compatible between shared libraries and archive libraries. (See the above section "Coding an Application.") Then compare the two versions of the application for size and performance. For example,

```
$ cat hello.c
main()
{
    printf("Hello\n");
}
$ cc -o unshared hello.c
$ cc -o shared hello.c -lc_s
$ size unshared shared
unshared: 8680 + 1388 + 2248 = 12316
shared: 300 + 680 + 2248 = 3228
```

If the application calls only a few library members, it is possible that using a shared library could take more disk storage or memory. The following section gives a more detailed discussion about when a shared library does and does not save space.

When making your decision about using shared libraries, also remember that they are not available on UNIX System V releases prior to Release 3.0. If your program must run on previous releases, you will need to use archive libraries.

## More About Saving Space

This section is designed to help you better understand why your programs will usually benefit from using a shared library. It explains

- how shared libraries save space that archive libraries cannot

- how shared libraries are implemented on the UNIX system
- how shared libraries might increase space usage

## How Shared Libraries Save Space

To better understand how a shared library saves space, we need to compare it to an archive library.

A host shared library resembles an archive library in three ways. First, as noted earlier, both are archive files. Second, the object code in the library typically defines commonly used text symbols and data symbols. The symbols defined inside and made visible outside the library are external symbols. Note that the library may also have imported symbols, symbols that it uses but usually does not define. Third, the link editor searches the library for these symbols when linking a program to resolve its external references. By resolving the references, the link editor produces an executable version of the program, the **a.out** file.



Note that the link editor on the UNIX system is a static linking tool; static linking requires that all symbolic references in a program be resolved before the program may be executed. The link editor uses static linking with both an archive library and a shared library.

Although these similarities exist, a shared library differs significantly from an archive library. The major differences relate to how the libraries are handled to resolve symbolic references, a topic already discussed briefly.

Consider how the UNIX system handles both types of libraries during link editing. To produce an **a.out** file using an archive library, the link editor copies the library code that defines a program's unresolved external reference from the library into appropriate **.text** and **.data** sections in the program's object file. In contrast, to produce an **a.out** file using a shared library, the link editor copies from the shared library into the program's object file only a small amount of code for initialization of imported symbols. (See the section "Importing Symbols" later in the chapter for more details on imported symbols.) For the bulk of the library code, it creates a special section called **.lib** in the file that identifies the library code needed at run time and resolves the external references to shared library symbols with their correct values. When the UNIX system executes the resulting **a.out** file, it uses the information in the **.lib** section to bring the required shared library code into the address space of the process.

## Using a Shared Library

---

Figure 8-1 depicts the **a.out** files produced using a regular archive version and a shared version of the standard C library to compile the following program:

```
main()
{
  ...
  printf( "How do you like this manual?\n" );
  ...
  result = strcmp( "I do.", answer );
  ...
}
```

Notice that the shared version is smaller. Figure 8-2 depicts the process images in memory of these two files when they are executed.

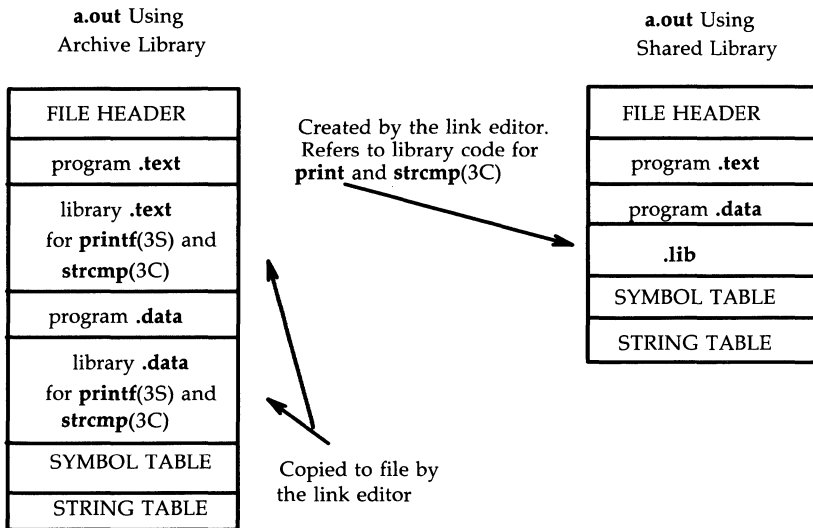


Figure 8-1: `a.out` Files Created Using an Archive Library and a Shared Library

---

Now consider what happens when several `a.out` files need the same code from a library. When using an archive library, each file gets its own copy of the code. This results in duplication of the same code on the disk and in memory when the `a.out` files are run as processes. In contrast, when a shared library is used, the library code remains separate from the code in the `a.out` files, as indicated in Figure 8-2. This separation enables all processes using the same shared library to reference a single copy of the code.

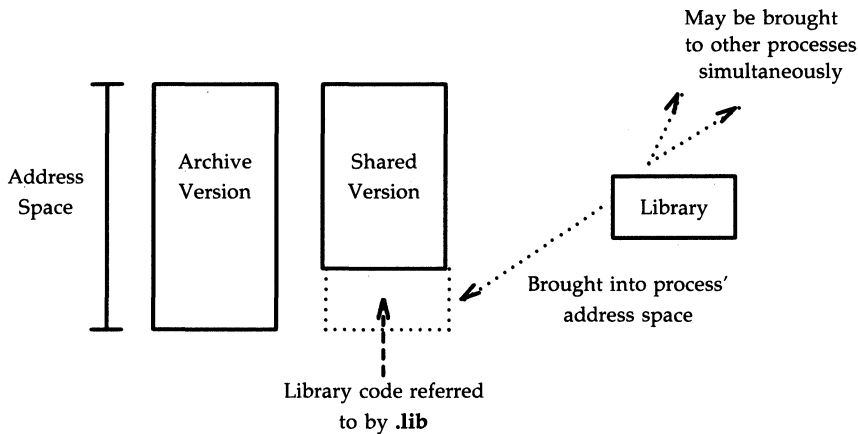


Figure 8-2: Processes Using an Archive and a Shared Library

---

### How Shared Libraries Are Implemented

Now that you have a better understanding of how shared libraries save space, you need to consider their implementation on the UNIX system to understand how they might increase space usage (this happens seldomly). The following paragraphs describe host and target shared libraries, the branch table, and then how shared libraries might increase space usage.

#### The Host Library and Target Library

As previously mentioned, every shared library has two parts: the host library used for linking that resides on the host machine and the target library used for execution that resides on the target machine. The host machine is the machine on which you build an **a.out** file; the target machine is the machine on which you run the file. Of course, the host and target may be the same machine, but they don't have to be.

The host library is just like an archive library. Each of its members (typically a complete object file) defines some text and data symbols in its symbol table. The link editor searches this file when a shared library is used during the compilation or link editing of a program.



The search is for definitions of symbols referenced in the program but not defined there. However, as mentioned earlier, the link editor does not copy the library code defining the symbols into the program's object file. Instead, it uses the library members to locate the definitions and then places symbols in the file that tell where the library code is. The result is the special section in the **a.out** file mentioned earlier (see the section "What is a Shared Library?") and shown in Figure 8-1 as **.lib**.

The target library used for execution resembles an **a.out** file. The UNIX operating system reads this file during execution if a process needs a shared library. The special **.lib** section in the **a.out** file tells which shared libraries are needed. When the UNIX system executes the **a.out** file, it uses this section to bring the appropriate library code into the address space of the process. In this way, before the process starts to run, all required library code has been made available.

Shared libraries enable the sharing of **.text** sections in the target library, which is where text symbols are defined. Although processes that use the shared library have their own virtual address spaces, they share a single physical copy of the library's text among them. That is, the UNIX system uses the same physical code for each process that attaches a shared library's text.

The target library cannot share its **.data** sections. Each process using data from the library has its own private data region (contiguous area of virtual address space that mirrors the **.data** section of the target library). Processes that share text do not share data and stack area so that they do not interfere with one another.

As suggested above, the target library is a lot like an **a.out** file, which can also share its text, but not its data. Also, a process must have execute permission for a target library to execute an **a.out** file that uses the library.

### **The Branch Table**

When the link editor resolves an external reference in a program, it gets the address of the referenced symbol from the host library. This is because a static linking loader like **ld** binds symbols to addresses during link editing. In this way, the **a.out** file for the program has an address for each referenced symbol.

What happens if library code is updated and the address of a symbol changes? Nothing happens to an **a.out** file built with an archive library, because that file already has a copy of the code defining the symbol. (Even though it isn't the updated copy, the **a.out** file will still run.) However, the change can adversely affect an **a.out** file built with a shared library. This file

has only a symbol telling where the required library code is. If the library code were updated, the location of that code might change. Therefore, if the **a.out** file ran after the change took place, the operating system could bring in the wrong code. To keep the **a.out** file current, you might have to recompile a program that uses a shared library after each library update.

To prevent the need to recompile, a shared library is implemented with a branch table on the UNIX system. A branch table associates text symbols with absolute addresses that do not change even when library code is changed. Each address labels a jump instruction to the address of the code that defines a symbol. Instead of being directly associated with the addresses of code, text symbols have addresses in the branch table.

Figure 8-3 shows two **a.out** files executing that make a call to **printf(3S)**. The process on the left was built using an archive library. It already has a copy of the library code defining the **printf(3S)** symbol. The process on the right was built using a shared library. This file references an absolute address (10) in the branch table of the shared library at run time; at this address, a jump instruction references the needed code.

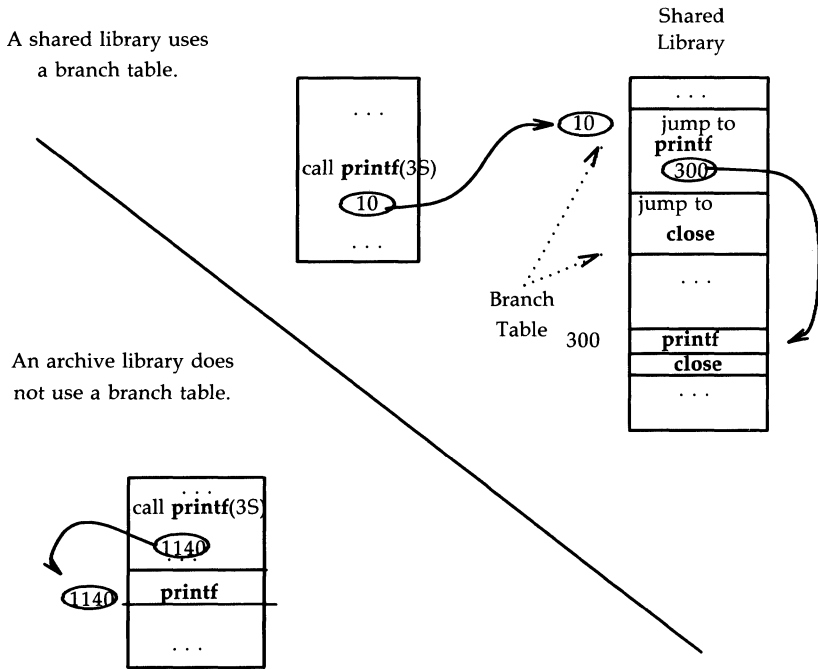


Figure 8-3: A Branch Table in a Shared Library

Data symbols do not have a mechanism to prevent a change of address between shared libraries. The tool **chkshlib(1)** compares **a.out** files with a shared library to check compatibility and help you decide if the files need to be recompiled. See "Checking Versions of Shared Libraries Using **chkshlib(1)**."

### How Shared Libraries Might Increase Space Usage

A target library might add to a process. Recall from "How Shared Libraries are Implemented" in this chapter that a shared library's target file may have both text and data regions connected to a process. While the text region is shared by all processes that use the library, the data region is not. Every process that uses the library gets its own private copy of the entire library data region. Naturally, this region adds to the process's memory

requirements. As a result, if an application uses only a small part of a shared library's text and data, executing the application might require more memory with a shared library than without one. For example, it would be unwise to use the shared C library to access only `strcmp(3C)`. Although sharing `strcmp(3C)` saves disk storage and memory, the memory cost for sharing all the shared C library's private data region outweighs the savings. The archive version of the library would be more appropriate.

A host library might add space to an `a.out` file. Recall that UNIX System V Release 3.0 uses static linking, which requires that all external references in a program be resolved before it is executed. Also recall that a shared library may have imported symbols, which are used but not defined by the library. To resolve these references, the link editor has to add to the `a.out` initialization code defining the referenced imported symbols file. This code increases the size of the `a.out` file.

## Identifying a.out Files that Use Shared Libraries

Suppose you have an executable file and you want to know whether it uses a shared library. You can use the `dump(1)` command (documented in the *Programmer's Reference Manual*) to look at the section headers for the file:

```
dump -hv a.out
```

If the file has a `.lib` section, a shared library is needed. If the `a.out` does not have a `.lib` section, it does not use shared libraries.

With a little more work, you can even tell what libraries a file uses by looking at the `.lib` section contents.

```
dump -L a.out
```

## Debugging a.out Files that Use Shared Libraries

`sdb` reads the shared libraries' symbol tables and performs as documented (in the *Programmer's Reference Manual*) using the available debugging information. The branch table is hidden so that functions in shared libraries can be referenced by their names, and the `M` command lists, among other

information, the names of shared libraries' target files used by the executable file.

Shared library data are not dumped to core files, however. So, if you encounter an error that results in a core dump and does not appear to be in your application code, you may find debugging easier if you rebuild the application with the archive version of the library used.

---

# Building a Shared Library

This part of the chapter explains how to build a shared library. It covers the major steps in the building process, the use of the UNIX system tool **mkshlib**(1) that builds the host and target libraries, and some guidelines for writing shared library code. There is an example at the end of this part which demonstrates the major features of **mkshlib** and the steps in the building process.

This part assumes that you are an advanced C programmer faced with the task of building a shared library. It also assumes you are familiar with the archive library building process. You do not need to read this part of the chapter if you only plan to use the UNIX system shared libraries or other shared libraries that have already been built.

## The Building Process

To build a shared library on the UNIX system, you have to complete six major tasks:

- Choose region addresses.
- Choose the pathname for the shared library target file.
- Select the library contents.
- Rewrite existing library code to be included in the shared library.
- Write the library specification file.
- Use the **mkshlib** tool to build the host and target libraries.

Here each of these tasks is discussed.

### Step 1: Choosing Region Addresses

The first thing you need to do is choose region addresses for your shared library.

Shared library regions on the 386 based computer correspond to memory management unit (MMU) segment size, each of which is 128 KB. The following table gives a list of the segment assignments on the 386 based computer (as of the copyright date for this guide) and shows what virtual addresses are available for libraries you might build.

80386 Computer Start Address	Contents	Target Pathname
0xA0000000	Reserved for AT&T	
...	UNIX Shared C Library AT&T Networking Library	<code>/shlib/libc_s</code> <code>/shlib/libnsl_s</code>
0xA3C00000		
0xA4000000	Generic Database Library	Unassigned
0xA4C00000		
0xA5000000	Generic Statistical Library	Unassigned
0xA5C00000		
0xA6000000	Generic User Interface Library	Unassigned
0xA6C00000		
0xA7000000	Generic Screen Handling Library	Unassigned
0xA7C00000		
0xA8000000	Generic Graphics Library	Unassigned
0xA8C00000		
0xA9000000	Generic Networking Library	Unassigned
0xA9C00000		
0xAA000000	Generic – to be defined	Unassigned
...		
0xAFC00000		
0xB0000000	For private use	Unassigned
...		
0xB7C00000		

What does this table tell you? First, the AT&T shared C library and the networking library reside at the pathnames given above and use addresses in the range reserved for AT&T. If you build a shared library that uses reserved addresses you run the risk of conflicting with future AT&T products.

Second, a number of segments are allocated for shared libraries that provide various services such as graphics, database access, and so on. These categories are intended to reduce the chance of address conflicts among commercially available libraries. Although two libraries of the same type may conflict, that doesn't matter. A single process should not usually need to use two shared libraries of the same type. If the need arises, a program can use one shared library and one archive library.

NOTE

Any number of libraries can use the same virtual addresses, even on the same machine. Conflicts occur only within a single process, not among separate processes. Thus two shared libraries can have the same region addresses without causing problems, as long as a single **a.out** file doesn't need to use both libraries.

Third, several segments are reserved for private use. If you are building a large system with many **a.out** files and processes, shared libraries might improve its performance. As long as you don't intend to release the shared libraries as separate products, you should use the private region addresses. You can put your shared libraries into these segments and avoid conflicting with commercial shared libraries. You should also use the private areas when you will own all the **a.out** files that access your shared library. Don't risk address conflicts.

NOTE

If you plan to build a commercial shared library, you are strongly encouraged to provide a compatible, relocatable archive as well. Some of your customers might not find the shared library appropriate for their applications. Others might want their applications to run on versions of the UNIX system without shared library support.

### Step 2: Choosing the Target Library Pathname

After you choose the region addresses for your shared library, you should choose the pathname for the target library. We chose **/shlib/libc\_s** for the shared C library and **/shlib/libnsl\_s** for the networking library. (As mentioned earlier, we use the **\_s** suffix in the pathnames of all statically linked shared libraries.) To choose a pathname for your shared library, consult the established list of names for your computer or see your system administrator. Also keep in mind that shared libraries needed to boot a UNIX system should normally be located in **/shlib**; other application libraries normally reside in **/usr/lib** or in private application directories. Of course, if your shared library is for personal use, you can choose any convenient pathname for the target library.



### **Step 3: Selecting Library Contents**

Selecting the contents for your shared library is the most important task in the building process. Some routines are prime candidates for sharing; others are not. For example, it's a good idea to include large, frequently used routines in a shared library but to exclude smaller routines that aren't used as much. What you include will depend on the individual needs of the programmers and other users for whom you are building the library. There are some general guidelines you should follow, however. They are discussed in the section "Choosing Library Members" in this chapter. Also see the guidelines in the following sections: "Importing Symbols," "Referencing Symbols in a Shared Library from Another Shared Library," and "Tuning the Shared Library Code."

### **Step 4: Rewriting Existing Library Code**

If you choose to include some existing code from an archive library in a shared library, changing some of the code will make the shared code easier to maintain. See the section "Changing Existing Code for the Shared Library" in this chapter.

### **Step 5: Writing the Library Specification File**

After you select and edit all the code for your shared library, you have to build the shared library specification file. The library specification file contains all the information that **mkshlib** needs to build both the host and target libraries. An example specification file is given in the section towards the end of the chapter, "An Example." Also, see the section "Using the Specification File for Compatibility" in this chapter. The contents and format of the specification file are given by the following directives (see also the **mkshlib**(1) manual page).

All directives that are followed by multi-line specifications are valid until the next directive or the end of file.

**#address** *sectname address*

Specifies the start address, *address*, of section *sectname* for the target file. This directive is typically used to specify the start addresses of the **.text** and **.data** sections.

**#target** *pathname*

Specifies the pathname, *pathname*, of the target shared library on the target machine. This is the location where the operating system looks for the shared library during

execution. Normally, *pathname* will be an absolute path-name, but it does not have to be.

This directive must be specified exactly once per specification file.

### **#branch**

Starts the branch table specifications. The lines following this directive are taken to be branch table specification lines.

Branch table specification lines have the following format:

*funcname* <white space> *position*

*funcname* is the name of the symbol given a branch table entry and *position* specifies the position of *funcname*'s branch table entry. *position* may be a single integer or a range of integers of the form *position1-position2*. Each *position* must be greater than or equal to one. The same position cannot be specified more than once, and every position from one to the highest given position must be accounted for.

If a symbol is given more than one branch table entry by associating a range of positions with the symbol or by specifying the same symbol on more than one branch table specification line, then the symbol is defined to have the address of the highest associated branch table entry. All other branch table entries for the symbol can be thought of as empty slots and can be replaced by new entries in future versions of the shared library.

Finally, only functions should be given branch table entries, and those functions must be external.

This directive must be specified exactly once per shared library specification file.

### **#objects**

Specifies the names of the object files constituting the target shared library. The lines following this directive are taken to be the list of input object files in the order they are to be loaded into the target. The list simply consists of each filename followed by a newline character. This list of objects will be used to build the shared library.

This directive must be specified exactly once per shared

library specification file.

### **#objects noload**

Specifies the ordered list of host shared libraries to be searched to resolve references to symbols not defined in the library being built and not imported. Resolution of a reference in this way requires a version of the symbol with an absolute address to be found in one of the listed libraries. It's considered an error if a non-shared version of a symbol is found during the search for a shared version of the symbol.

Each name specified is assumed to be a pathname to a host or an argument of the form **-lX**, where **libX.a** is the name of a file in the default library locations. This behavior is identical to that of **ld**, and the **-L** option can be used on the command line to specify other directories in which to locate these archives.

### **#init object**

Specifies that the object file, *object*, requires initialization code. The lines following this directive are taken to be initialization specification lines.

Initialization specification lines have the following format:

```
ptr <white space> import
```

*ptr* is a pointer to the associated imported symbol, *import*, and must be defined in the current specified object file, *object*. The initialization code generated for each such line is of the form:

```
ptr = &import;
```

All initializations for a particular object file must be given once and multiple specifications of the same object file are not allowed.

### **#hide linker [\*]**

This directive changes symbols that are normally *external* into *static* symbols, local to the library being created. A regular expression may be given [sh(1), egrep(1)], in which case all *external* symbols matching the regular

expression are hidden; the **#export** directive can be used to counter this effect for specified symbols.

The optional "\*" is equivalent to the directive

```
#hide linker  
*
```

and causes all *external* symbols to be made into *static* symbols.

All symbols specified in **#init** and **#branch** directives are assumed to be *external* symbols, and cannot be changed into *static* symbols using the **#hide** directive.

### **#export linker \***

Specifies those symbols that a regular expression in a **#hide** directive would normally cause to be hidden but that should nevertheless remain external. For example,

```
#hide linker *  
#export linker  
one  
two
```

causes all symbols except *one*, *two*, and those used in **#branch** and **#init** entries to be tagged as *static*.

**#ident string** Specifies a string, *string*, to be included in the **.comment** section of the target shared library and the **.comment** sections of every member of the host shared library.

**##** Specifies a comment. The rest of the line is ignored.

## **Step 6: Using mkshlib to Build the Host and Target**

The UNIX system command **mkshlib(1)** builds both the host and target libraries. **mkshlib** invokes other tools such as the assembler, **as(1)**, and link editor, **ld(1)**. Tools are invoked through the use of **execvp** (see **exec(2)**), which searches directories in a user's **\$PATH** environment variable. Also, prefixes to **mkshlib** are parsed in much the same manner as prefixes to the **cc(1)** command and invoked tools are given the prefix, where appropriate. For example, **3bmkshlib** invokes **3bld**. These commands all are documented in the *Programmer's Reference Manual*.

The user input to **mkshlib** consists of the library specification file and command line options. We just discussed the specification file; let's take a look at the options now. The shared library build tool has the following syntax:

**mkshlib** *-s specfil* *-t target* [*-h host*] [*-L dir...*] [*-n*] [*-q*]

- s specfil* Specifies the shared library specification file, *specfil*. This file contains all the information necessary to build a shared library.
- t target* Specifies the name, *target*, of the target shared library produced on the host machine. When *target* is moved to the target machine, it should be installed at the location given in the specification file (see the **#target** directive in the section "Writing the Library Specification File"). If the *-n* option is given, then a new target shared library will not be generated.
- h host* Specifies the name of the host shared library, *host*. If this option is not given, then the host shared library will not be produced.
- n* Prevents a new target shared library from being generated. This option is useful when producing only a new host shared library. The *-t* option must still be supplied since a version of the target shared library is needed to build the host shared library.
- L dir* Changes the algorithm of searching for the host shared libraries specified with the **#objects noload** directive to look in *dir* before looking in the default directories. The *-L* option can be specified multiple times on the command line in which case the directories given with the *-L* options are searched in the order given on the command line before the default directories.
- q* Suppresses the printing of certain warning messages.

### Guidelines for Writing Shared Library Code

Because the main advantage of a shared library over an archive library is sharing and the space it saves, these guidelines stress ways to increase sharing while avoiding the disadvantages of a shared library. The guidelines also stress upward compatibility. When appropriate, we describe our experience with building the shared C library to illustrate how following a particular guideline helped us.

We recommend that you read these guidelines once from beginning to end to get a perspective of the things you need to consider when building a shared library. Then use it as a checklist to guide your planning and decision-making.

Before we consider these guidelines, let's consider the restrictions to building a shared library common to all the guidelines. These restrictions involve static linking. Here's a summary of them, some of which are discussed in more detail later. Keep them in mind when reading the guidelines in this section:

- External symbols have fixed addresses.

If an external symbol moves, you have to re-link all **a.out** files that use the library. This restriction applies both to text and data symbols.

Use of the **#hide** directive to limit externally visible symbols can help avoid problems in this area. (See "Use **#hide** and **#export** to Limit Externally Visible Symbols" for more details).

- If the library's text changes for one process at run time, it changes for all processes.
- If the library uses a symbol directly, that symbol's run time value (address) must be known when the library is built.
- Imported symbols cannot be referenced directly.

Their addresses are not known when you build the library, and they can be different for different processes. You can use imported symbols by adding an indirection through a pointer in the library's data.

## Choosing Library Members

### Include Large, Frequently Used Routines

These routines are prime candidates for sharing. Placing them in a shared library saves code space for individual **a.out** files and saves memory, too, when several concurrent processes need the same code. **printf(3S)** and related C library routines (which are documented in the *Programmer's Reference Manual*) are good examples.

#### When we built the shared C library...

The **printf(3S)** family of routines is used frequently. Consequently, we included **printf(3S)** and related routines in the shared C library.

### Exclude Infrequently Used Routines

Putting these routines in a shared library can degrade performance, particularly on paging systems. Traditional **a.out** files contain all code they need at run time. By definition, the code in an **a.out** file is (at least distantly) related to the process. Therefore, if a process calls a function, it may already be in memory because of its proximity to other text in the process.

If the function is in the shared library, a page fault may be more likely to occur, because the surrounding library code may be unrelated to the calling process. Only rarely will any single **a.out** file use everything in the shared C library. If a shared library has unrelated functions, and unrelated processes make random calls to those functions, the locality of reference may be decreased. The decreased locality may cause more paging activity and, thereby, decrease performance. See also "Organize to Improve Locality."

### Exclude Routines that Use Much Static Data

These modules increase the size of processes. As "How Shared Libraries are Implemented" and "Deciding Whether to Use a Shared Library" explain, every process that uses a shared library gets its own private copy of the library's data, regardless of how much of the data is needed. Library data is static: it is not shared and cannot be loaded selectively with the provision that unreferenced pages may be removed from the working set.

For example, **getgrent(3C)**, which is documented in the *Programmer's Reference Manual*, is not used by many standard UNIX commands. Some versions of the module define over 1400 bytes of unshared, static data. It probably should not be included in a shared library. You can import global data, if necessary, but not local, static data.

### Exclude Routines that Complicate Maintenance

All external symbols must remain at constant addresses. The branch table makes this easy for text symbols, but data symbols don't have an equivalent mechanism. The more data a library has, the more likely some of them will have to change size. Any change in the size of external data may affect symbol addresses and break compatibility.

### Include Routines the Library Itself Needs

It usually pays to make the library self-contained. For example, **printf(3S)** requires much of the standard I/O library. A shared library containing **printf(3S)** should contain the rest of the standard I/O routines, too.





This guideline should not take priority over the others in this section. If you exclude some routine that the library itself needs based on a previous guideline, consider leaving the symbol out of the library and importing it.

## **Changing Existing Code for the Shared Library**

All C code that works in a shared library will also work in an archive library. However, the reverse is not true because a shared library must explicitly handle imported symbols. The following guidelines are meant to help you produce shared library code that is still valid for archive libraries (although it may be slightly bigger and slower). The guidelines explain how to structure data for ease of maintenance, since most compatibility problems involve restructuring data.

### **Minimize Global Data**

All external data symbols are, of course, visible to applications. This can make maintenance difficult. You should try to reduce global data, as described below.

First, try to use automatic (stack) variables. Don't use permanent storage if automatic variables work. Using automatic variables saves static data space and reduces the number of symbols visible to application processes.

Second, see whether variables really must be external. Static symbols are not visible outside the library, so they may change addresses between library versions. Only external variables must remain constant. See the section "**Use #hide and #export to Limit Externally Visible Symbols**" later in this chapter for further tips.

Third, allocate buffers at run time instead of defining them at compile time. This does two important things. It reduces the size of the library's data region for all processes and, therefore, saves memory; only the processes that actually need the buffers get them. It also allows the size of the buffer to change from one release to the next without affecting compatibility. Statically allocated buffers cannot change size without affecting the addresses of other symbols and, perhaps, breaking compatibility.

### Define Text and Global Data in Separate Source Files

Separating text from global data makes it easier to prevent data symbols from moving. If new external variables are needed, they can be added at the end of the old definitions to preserve the old symbols' addresses.

Archive libraries let the link editor extract individual members. This sometimes encourages programmers to define related variables and text in the same source file. This works fine for relocatable files, but shared libraries have a different set of restrictions. Suppose external variables were scattered throughout the library modules. Then external and static data would be intermixed. Changing static data, such as a string, like **hello** in the following example, moves subsequent data symbols, even the external symbols:

Before

```
...
int head = 0;
...
func()
{
    ...
    p = "hello";
    ...
}
...
int tail = 0;
...
```

Broken Successor

```
...
int head = 0;
...
func()
{
    ...
    p = "hello, world";
    ...
}
...
int tail = 0;
...
```

Assume the relative virtual address of **head** is 0 for both examples. The string literals will have the same address too, but they have different lengths. The old and new addresses of **tail** thus might be 12 and 20, respectively. If **tail** is supposed to be visible outside the library, the two versions will not be compatible.

NOTE

The compilation system sometimes defines and uses static data invisibly to the user (e.g. tables for switch statements). Therefore, it is a mistake to assume that because you declare no static data in your shared library that you can ignore the guideline in this section.

Adding new external variables to a shared library may change the addresses of static symbols, but this doesn't affect compatibility. An **a.out** file has no way to reference static library symbols directly, so it cannot depend on their values. Thus it pays to group all external data symbols and place them at lower addresses than the static (hidden) data. You can write the specification file to control this. In the list of object files, make the global data files first.

```
#objects
data1.o
...
lastdata.o
text1.o
text2.o
...
```

If the data modules are not first, a seemingly harmless change (such as a new string literal) can break existing **a.out** files.

Shared library users get all library data at run time, regardless of the source file organization. Consequently, you can put all external variables' definitions in a single source file without a space penalty.

### **Initialize Global Data**

Initialize external variables, including the pointers for imported symbols. Although this uses more disk space in the target shared library, the expansion is limited to a single file. **mkshlib** will give a fatal error if it finds an uninitialized external symbol.

### Using the Specification File for Compatibility

The way in which you use the directives in the specification file can affect compatibility across versions of a shared library. This section gives some guidelines on how to use the directives **#branch**, **#hide**, and **#export**.

#### Preserve Branch Table Order

You should add new functions only at the end of the branch table. After you have a specification file for the library, try to maintain compatibility with previous versions. You may add new functions without breaking old **a.out** files as long as previous assignments are not changed. This lets you distribute a new library without having to re-link all of the **a.out** files that used a previous version of the library.

#### Use #hide and #export to Limit Externally Visible Symbols

Sometimes variables (or functions) must be referenced from several object files to be included in the shared library and yet are not intended to be available to users of the shared library. That is, they must be external so that the link editor can properly resolve all references to symbols and create the target shared library, but should be hidden from the user's view to prevent their use. Such unintended and unwanted use may result in compatibility problems if the symbols move or are removed between versions of the shared library.

The **#hide** and **#export** directives are the key to resolving this dilemma. The **#hide** directive causes **mkshlib**, after resolving all references within the shared library, to alter the symbol tables of the shared library so that all specified external symbols are made static and inaccessible from user code. You can specify the symbols to be so treated individually and/or through the use of regular expressions.

The **#export** directive allows you to specify those symbols in the range of an accompanying **#hide** directive regular expression which should remain external. It is simply a convenience.

NOTE

It is a fatal error to try to explicitly name the same symbol in a **#hide** and an **#export** directive. For example, the following would result in a fatal error.

```
#hide linker
    one
#export linker
    one
```

**#export** may seem like an unnecessary feature since you could avoid specifying in the **#hide** directive those symbols that you do not want to be made static. However, its usefulness becomes apparent when the shared library to be built is complicated and there are many symbols to be made static. In these cases, it is more efficient to use regular expressions to make all external variables static and individually list those symbols you need to be external. The simple example in the section "Writing the Library Specification File" demonstrates this point.

NOTE

Symbols mentioned in the **#branch** and **#init** directives are services of the shared library, must be external symbols, and cannot be made static through the use of these directives.

### **When we built the shared C library...**

Our approach for the shared C library was to hide all data symbols by default, and then explicitly export symbols that we knew were needed. The advantage of this approach is that future changes to the libraries won't introduce new external symbols (possibly causing name collisions) unless we explicitly export the new symbols.

We chose the symbols to export by looking at a list of all the current external symbols in the shared C library and finding out what each symbol was used for. The symbols that were global but were only used in the shared C library were not exported; these symbols will be hidden from applications code. All other symbols were explicitly exported.

## **Importing Symbols**

Normally, shared library code cannot directly use symbols defined outside a library, but an escape hatch exists. You can define pointers in the data area and arrange for those pointers to be initialized to the addresses of imported symbols. Library code then accesses imported symbols indirectly, delaying symbol binding until run time. Libraries can import both text and data

symbols. Moreover, imported symbols can come from the user's code, another library, or even the library itself. In Figure 8-4, the symbols `_libc.ptr1` and `_libc.ptr2` are imported from user's code and the symbol `_libc_malloc` from the library itself.

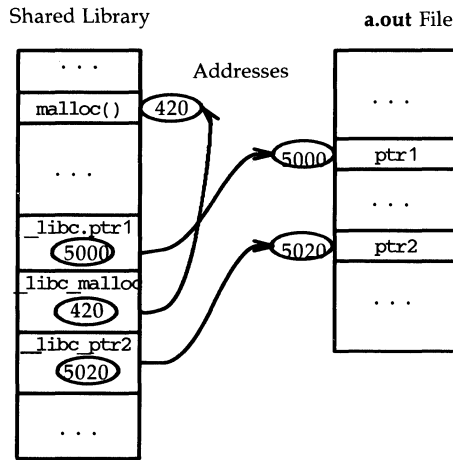


Figure 8-4: Imported Symbols in a Shared Library

---

The following guidelines describe when and how to use imported symbols.

### Imported Symbols that the Library Does Not Define

Archive libraries typically contain relocatable files, which allow undefined references. Although the host shared library is an archive, too, that archive is constructed to mirror the target library, which more closely resembles an **a.out** file. Neither target shared libraries nor **a.out** files can have unresolved references to symbols.

Consequently, shared libraries must import any symbols they use but do not define. Some shared libraries will derive from existing archive libraries. For the reasons stated above, it may not be appropriate to include all the archive's modules in the target shared library. Remember though that if you exclude a symbol from the target shared library that is referenced from the target shared library, you will have to import the excluded symbol.

**Imported Symbols that Users Must Be Able to Redefine**

Optionally, shared libraries can import their own symbols. At first this might appear to be an unnecessary complication, but consider the following. Two standard libraries, **libc** and **libmalloc**, provide a **malloc** family. Even though most UNIX commands use the **malloc** from the C library, they can choose either library or define their own.

**When we built the shared C library...**

Three possible strategies existed for the shared C library. First, we could have excluded the **malloc(3C)** family. Other library members would have needed it, and so it would have been an imported symbol. This would have worked, but it would have meant less savings.

Second, we could have included the **malloc** family and not imported it. This would have given us more savings for typical commands, but it had a price. Other library routines call **malloc** directly, and those calls could not have been overridden. If an application tried to redefine **malloc**, the library calls would not have used the alternate version. Furthermore, the link editor would have found multiple definitions of **malloc** while building the application. To resolve this the library developer would have to change source code to remove the custom **malloc**, or the developer would have to refrain from using the shared library.

Finally, we could have included **malloc** in the shared library, treating it as an imported symbol. This is what we did. Even though **malloc** is in the library, nothing else there refers to it directly; all references are through an imported symbol pointer. If the application does not redefine **malloc**, both application and library calls are routed to the library version. All calls are mapped to the alternate, if present.

You might want to permit redefinition of all library symbols in some libraries. You can do this by importing all symbols the library defines, in addition to those it uses but does not define. Although this adds a little space and time overhead to the library, the technique allows a shared library to be one

hundred percent compatible with an existing archive at link time and run time.

### Mechanics of Importing Symbols

Let's assume a shared library wants to import the symbol **malloc**. The original archive code and the shared library code appear below.

#### Archive Code

```
extern char *malloc();

export()
{
    ...
    p = malloc(n);
    ...
}
```

#### Shared Library Code

```
/* See pointers.c on next page */

extern char *(*_libc_malloc)();

export()
{
    ...
    p = (*_libc_malloc)(n);
    ...
}
```

Making this transformation is straightforward, but two sets of source code would be necessary to support both an archive and a shared library. Some simple macro definitions can hide the transformations and allow source code compatibility. A header file defines the macros, and a different version of this header file would exist for each type of library. The **-I** flag to **cc(1)** would direct the C preprocessor to look in the appropriate directory to find the desired file.



**Archive `import.h`**

```
/* empty */
```

**Shared `import.h`**

```
/*  
 * Macros for importing  
 * symbols. One #define  
 * per symbol.  
 */  
  
...  
#define malloc (*_libc_malloc)  
...  
extern char *malloc();  
...
```

These header files allow one source both to serve the original archive source and to serve a shared library, too, because they supply the indirections for imported symbols. The declaration of `malloc` in `import.h` actually declares the pointer `_libc_malloc`.

**Common Source**

```
#include "import.h"  
  
extern char *malloc();  
  
export()  
{  
    ...  
    p = malloc(n);  
    ...  
}
```

Alternatively, one can hide the `#include` with `#ifndef`:

Common Source

```
#ifndef SHLIB
#   include "import.h"
#endif

extern char *malloc();

export()
{
    ...
    p = malloc(n);
    ...
}
```

Of course the transformation is not complete. You must define the pointer `_libc_malloc`.

File `pointers.c`

```
char *(*_libc_malloc)() = 0;
```

Note that `_libc_malloc` is initialized to zero, because it is an external data symbol.

Special initialization code sets the pointers. Shared library code should not use the pointer before it contains the correct value. In the example the address of `malloc` must be assigned to `_libc_malloc`. Tools that build the shared library generate the initialization code according to the library specification file.

### Pointer Initialization Fragments

A host shared library archive member can define one or many imported symbol pointers. Regardless of the number, every imported symbol pointer should have initialization code.

This code goes into the **a.out** file and does two things. First, it creates an unresolved reference to make sure the symbol being imported gets resolved. Second, initialization fragments set the imported symbol pointers to their values before the process reaches **main**. If the imported symbol pointer can be used at run time, the imported symbol will be present, and the imported symbol pointer will be set properly.

NOTE

Initialization fragments reside in the host, not the target, shared library. The link editor copies initialization code into **a.out** files to set imported pointers to their correct values.

Library specification files describe how to initialize the imported symbol pointers. For example, the following specification line would set **\_libc\_malloc** to the address of **malloc**:

```
#init pmalloc.o
_libc_malloc  malloc
```

When **mkshlib** builds the host library, it modifies the file **pmalloc.o**, adding relocatable code to perform the following assignment statement:

```
_libc_malloc = &malloc;
```

When the link editor extracts **pmalloc.o** from the host library, the relocatable code goes into the **a.out** file. As the link editor builds the final **a.out** file, it resolves the unresolved references and collects all initialization fragments. When the **a.out** file is executed, the run time startup routines execute the initialization fragments to set the library pointers.

### **Selectively Loading Imported Symbols**

Defining fewer pointers in each archive member increases the granularity of symbol selection and can prevent unnecessary objects and initialization code from being linked into the **a.out** file. For example, if an archive member defines three pointers to imported symbols, the link editor will require definitions for all three symbols, even though only one might be needed.

You can reduce unnecessary loading by writing C source files that define imported symbol pointers singly or in related groups. If an imported symbol must be individually selectable, put its pointer in its own source file (and archive member). This will give the link editor a finer granularity to use when it resolves the reference to the symbol.

## Building a Shared Library

---

Let's look at an example. In the coarse method, a single source file might define all pointers to imported symbols:

Old `pointers.c`

```
int (*_libc_ptr1)() = 0;
char (*_libc_malloc)() = 0;
int (*_libc_ptr2)() = 0;
...
```

Allowing the loader to resolve only those references that are needed requires multiple source files and archive members. Each of the new files defines a single pointer:

File	Contents
<code>ptr1.c</code>	<code>int (*_libc_ptr1)() = 0;</code>
<code>pmalloc.c</code>	<code>char (*_libc_malloc)() = 0;</code>
<code>ptr2.c</code>	<code>int (*_libc_ptr2)() = 0;</code>

Using the three files ensures that the link editor will only look for definitions for imported symbols and load in the corresponding initialization code in cases where the symbols are actually used.

### Referencing Symbols in a Shared Library from Another Shared Library

At the beginning of the section "Importing Symbols," there was a statement that "normally shared libraries cannot directly use symbols defined outside the shared library." This is true in general, and you should import all symbols defined outside the shared library whenever possible.

Unfortunately, this is not always possible, for example when floating-point operations are performed in a shared library to be built. When such operations are encountered in any C code, the standard C compiler generates calls to functions to perform the actual operations. These functions are defined in the C library and are normally resolved invisibly to the user when an **a.out** is created since the **cc** command automatically causes the relocatable version of the C library to be searched. When building a shared library, these floating-point routine references must be resolved at the time the shared library is being built. But, the symbols cannot be imported because their names and usage are invisible.

The **#objects noload** directive has been provided to allow symbol references such as these to be resolved at the time the shared library is built, provided that the symbols are defined in another shared library. If there are unresolved references to symbols after the object files listed with the **#objects** directive have been link edited, the host shared libraries specified with the **#objects noload** directive are searched for absolute definitions of the symbols. The normal use of the directive would be to search the shared version of the C library to resolve references to floating-point routines.

For this use, the syntax in the specification file would be:

```
#objects noload
-lc_s
```

This would cause **mkshlib** to search for the host shared library **libc\_s.a** in the default library locations and to use it to resolve references to any symbols left unresolved in the shared library being built. The **-L** option can be used to cause **mkshlib** to look for the specified library in other than the default locations.

A few notes on usage are in order. When building a shared library using **#objects noload** you must make sure that for each symbol with an unresolved reference there is a version of the symbol with an absolute definition in the searched host shared libraries before any relocatable version of that symbol. **mkshlib** will give a fatal error if this is not the case because relocatable definitions do not have absolute addresses and therefore do not allow complete resolution of the target shared library.

When using a shared library built with references to symbols resolved from another shared library, both libraries must be specified on the **cc** command line. The dependent library must be specified on the command line before the libraries on which it depends. (See the section "Building an **a.out** File" for more details.) If you provide a shared library which references

symbols in another shared library, you should make sure that your documentation clearly states that users must specify both libraries when building **a.out** files.

Finally, as some of the text above hints, it is possible to use **#objects noload** to resolve references to any symbols not defined in a shared library as long as they are defined in some other shared library. We strongly encourage you to import as many symbols as possible and to use **#objects noload** only when absolutely necessary. Probably you will only need to use this feature to resolve references to floating-point routines generated by the C compiler.

Importing symbols has several important benefits over resolving references through **#objects noload**. First, importing symbols is more flexible in that it allows you to define your own version of library routines. You can define your own versions with archive versions of a library. Preserving this ability with the shared versions helps maintain compatibility.

Importing symbols also helps prevent unexpected name space collisions. The link editor will complain about multiple definitions of a symbol, references to which are resolved through the **#objects noload** mechanism, if a user of the shared library also has an external definition of the symbol.

Finally, **#objects noload** has the drawback that both the library you build and all the libraries on which it depends must be available on all the systems. Anyone who wishes to create **a.out** files using your shared library will need to use the host shared libraries. Also, the targets of all the libraries must be available on all systems on which the **a.out** files are to be run.

### Providing Archive Library Compatibility

Having compatible libraries makes it easy to substitute one for the other. In almost all cases, this can be done without makefile or source file changes. Perhaps the best way to explain this guideline is by example:

### **When we built the shared C library...**

We had an existing archive library to use as the base. This obviously gave us code for individual routines, and the archive library also gave us a model to use for the shared library itself.

We wanted the host library archive file to be compatible with the relocatable archive C library. However, we did not want the shared library target file to include all routines from the archive: including them all would have hurt performance.

Reaching these goals was, perhaps, easier than you might think. We did it by building the host library in two steps. First, we used the available shared library tools to create the host library to match exactly the target. The resulting archive file was not compatible with the archive C library at this point. Second, we added to the host library the set of relocatable objects residing in the archive C library that were missing from the host library. Although this set is not in the shared library target, its inclusion in the host library makes the relocatable and shared C libraries compatible.

## **Tuning the Shared Library Code**

Some suggestions for how to organize shared library code to improve performance are presented here. They apply to paging systems, such as UNIX System V Release 3.0. The suggestions come from the experience of building the shared C library.

The archive C library contains several diverse groups of functions. Many processes use different combinations of these groups, making the paging behavior of any shared C library difficult to predict. A shared library should offer greater benefits for more homogeneous collections of code. For example, a data base library probably could be organized to reduce system paging substantially, if its static and dynamic calling dependencies were more predictable.

### Profile the Code

To begin, profile the code that might go into the shared library.

### Choose Library Contents

Based on profiling information, make some decisions about what to include in the shared library. **a.out** file size is a static property, and paging is a dynamic property. These static and dynamic characteristics may conflict, so you have to decide whether the performance lost is worth the disk space gained. See "Choosing Library Members" in this chapter for more information.

### Organize to Improve Locality

When a function is in **a.out** files, it probably resides in a page with other code that is used more often (see "Exclude Infrequently Used Routines"). Try to improve locality of reference by grouping dynamically related functions. If every call of **funcA** generates calls to **funcB** and **funcC**, try to put them in the same page. **cflow(1)** (documented in the *Programmer's Reference Manual*) generates this static dependency information. Combine it with profiling to see what things actually are called, as opposed to what things might be called.

### Align for Paging

The key is to arrange the shared library target's object files so that frequently used functions do not unnecessarily cross page boundaries. When arranging object files within the target library, be sure to keep the text and data files separate. You can reorder text object files without breaking compatibility; the same is not true for object files that define global data. Once again, an example might best explain this guideline:



### When we built the shared C library...

Using name lists and disassemblies of the shared library target file, we determined where the page boundaries fell.

After grouping related functions, we broke them into page-sized chunks. Although some object files and functions are larger than a single page, most of them are smaller. Then we used the infrequently called functions as glue between the chunks. Because the glue between pages is referenced less frequently than the page contents, the probability of a page fault decreased.

After determining the branch table, we rearranged the library's object files without breaking compatibility. We put frequently used, unrelated functions together, because we figured they would be called randomly enough to keep the pages in memory. System calls went into another page as a group, and so on. The following example shows how to change the order of the library's object files:

Before	After
#objects	#objects
...	...
printf.o	strcmp.o
fopen.o	malloc.o
malloc.o	printf.o
strcmp.o	fopen.o
...	...

### Avoid Hardware Thrashing

You get better performance by arranging the typical process to avoid cache entry conflicts. If a heavily used library had both its text and its data segment mapped to the same cache entry, the performance penalty would be particularly severe. Every library instruction would bring the text segment information into the cache. Instructions that referenced data would flush the entry to load the data segment. Of course, the next instruction would reference text and flush the cache entry, again.

### Checking for Compatibility

The following guidelines explain how to check for upward-compatible shared libraries. Note, however, that upward compatibility may not always be an issue. Consider the case in which a shared library is one piece of a larger system and is not delivered as a separate product. In this restricted case, you can identify all **a.out** files that use a particular library. As long as you rebuild all the **a.out** files every time the library changes, the **a.out** files will run successfully, even though versions of the library are not compatible. This may complicate development, but it is possible.

### Checking Versions of Shared Libraries Using `chkshlib(1)`

Shared library developers normally want newer versions of a library to be compatible with previous ones. As mentioned before, **a.out** files will not execute properly otherwise.

If you use shared libraries, you might need to find out if different versions of a shared library are compatible, or if executable files could have been built with a particular host shared library or can run with a particular target shared library. For example, you might have a new version of a target shared library and you need to know if all the executable files that ran with the older version will run with the new one. You might need to find out if a particular target shared library can reference symbols in another shared library. A command, `chkshlib(1)`, has been provided to allow you to do these and other comparisons.

**chkshlib** takes names of target shared libraries, host shared libraries, and executable files as input, and checks to see if those files satisfy the compatibility criteria. **chkshlib** checks to see if every library symbol in the first file that needs to be matched exists in the second file and has the same address. The following table shows what types of files and how many of them **chkshlib** accepts as input.

The rows listed down represent the first input given, and the columns listed across represent any more inputs given. For example, if the first input file you give **chkshlib** is a target shared library, you must give another input file that is a target or host shared library.

	Nothing	Executable	Target	Host
Executable	OK	No	OK*	OK*
Target	No	No	OK	OK
Host	OK	No	OK	OK

\* The executable file must be one that was built using a host shared library.

A useful way to confirm this is to use **dump -L** to find out which target file(s) gets loaded when the program is run. See **dump(1)**.

\* You can also have *executable target1...targetn* and *executable host1...hostn*.

An example of a **chkshlib** command line is shown below:

```
chkshlib /shlib/libc_s /lib/libc_s.a
```

In this example, **/shlib/libc\_s** is a target shared library and **/lib/libc\_s.a** is a host shared library. **chkshlib** will check to see if executable files built with **/shlib/libc\_s.a** would be able to run with **/lib/libc\_s**.

Depending on the input it receives, **chkshlib** checks to find out if:

- an executable file will run with the given target shared library
- an executable file could have been built using the given host shared library
- an executable file produced with a given host shared library will run with a given target shared library

- an executable file that ran with an old version of a target shared library will run with a new version
- a new host shared library can replace the old host shared library; that is, executable files built with the new host shared library will run with the old target shared library
- a target shared library can reference symbols in another target shared library

To determine if files are compatible, you have to determine which library symbols in the first file need to be matched in the second file.

- For target shared libraries, the symbols of concern are all external, defined symbols with non-zero values, except for branch labels (branch labels always start with **.bt**), and the special symbols **etext**, **edata**, and **end**.
- For host shared libraries, the symbols of concern are all external absolute symbols with a non-zero value.
- For executable files, the symbols of concern are all external absolute symbols with a non-zero value except for the special symbols **etext**, **edata**, and **end**.

For two files to be compatible, the target pathnames must be identical in both files (unless the **-i** option has been specified).

The following table displays the output you will receive when you use **chkshlib** to check different combinations of files for compatibility. In this table **file1** represents the name of the first file given, and **file2,3...** represents the names of any more files given as input.

Input	Output
<b>file1</b> is executable <b>file2,3,...</b> (if any) are targets	<b>file1</b> can [may not] execute using <b>file2</b> <b>file1</b> can [may not] execute using <b>file3</b>
<b>file1</b> is executable <b>file2,3</b> are hosts	<b>file1</b> may [may not] have been produced using <b>file2</b> <b>file1</b> may [may not] have been produced using <b>file3</b>
<b>file1</b> is host <b>file2</b> (if any) is target	<b>file1</b> can [may not] produce executables which will run with <b>file2</b>
<b>file1</b> is target <b>file2</b> is host	<b>file2</b> can [may not] produce executables which will run with <b>file1</b>
both files are targets <i>or</i> both files are hosts	<b>file1</b> can [may not] replace <b>file2</b> <b>file2</b> can [may not] replace <b>file1</b>
both files are targets and <b>-n</b> option is specified*	<b>file1</b> can [may not] include <b>file2</b>

- \* The **-n** option tells **chkshlib** that the two files are target shared libraries, the first of which can reference (include) symbols in the other. See "Referencing Another Shared Library Within A Shared Library" for details.

For more information on **chkshlib**, see **chkshlib(1)**.

### When we built the shared C library...

When we built the second version of the shared C library and checked it against the first version, **chkshlib** reported that many external symbols had different values and therefore the second version could not replace the first.

Since these text symbols were not intended to be user entry points, they were not put in the branch table. So when new code was added to the shared library the addresses of these text symbols changed, and hence their values changed.

We devised the **#hide** and **#export** directives to allow us to explicitly hide the symbols we did not want to be user entry points. In fact, in the latest C Shared Library we hid all the symbols, and exported just the ones we want to be user entry points.

You cannot directly reference these functions, and these symbols will not be considered incompatible by **chkshlib** in checking the latest version of the shared C library with any subsequent version.

### **Dealing with Incompatible Libraries**

When you determine that a newer version of a library can't replace the older version, you have to deal with the incompatibility. You can deal with it in one of two ways. First, you can rebuild all the **a.out** files that use your library. If feasible, this is probably the best choice. Unfortunately, you might not be able to find those **a.out** files, let alone force their owners to rebuild them with your new library.

So your second choice is to give a different target pathname to the new version of the library. The host and target pathnames are independent; so you don't have to change the host library pathname. New **a.out** files will use your new target library, but old **a.out** files will continue to access the old library.

As the library developer, it is your responsibility to check for compatibility and, probably, to provide a new target library pathname for a new version of a library that is incompatible with older versions. If you fail to resolve compatibility problems, **a.out** files that use your library will not work properly.



You should try to avoid multiple library versions. If too many copies of the same shared library exist, they might actually use more disk space and more memory than the equivalent relocatable version would have.

## **An Example**

This section contains an example of a small specialized shared library and the process by which it is created from original source and built. We refer to the guidelines given earlier in this chapter.

### **The Original Source**

The name of the library to be built is **libmaux** (for math auxiliary library). The interface consists of three functions:

- |              |  |
|--------------|--|
| <b>logd</b>  | floating-point logarithm to a given base; defined in the file <b>log.c</b> |
| <b>polyd</b> | evaluate a polynomial; defined in the file <b>poly.c</b>                   |

## Building a Shared Library

---

**maux\_stat** return usage counts for the other two routines in a structure; defined in **stats.c**,

an external variable:

**mauxerr** set to non-zero if there is an error in the processing of any of the functions in the library and set to zero if there is no error (unlike **errno** in the C library),

and a header file:

**maux.h** declares the return types of the function and the structure returned by **maux\_stat**.

The source files before any modifications for inclusion in a shared library are given below.



```
/* log.c */
#include "maux.h"
#include <math.h>

/*
 * Return the log of "x" relative to the base "a".
 *
 *      logd(base, x) := log(x) / log(base);
 * where "log" is "log to the base E".
 */

double logd(base, x)
double base, x;
{
    extern int stats_logd;
    extern int total_calls;

    double logbase;
    double logx;

    total_calls++;
    stats_logd++;

    logbase = log((double)base);
    logx = log((double)x);
    if(logbase == -HUGE || logx == -HUGE) {
        mauxerr = 1;
        return(0);
    }
    else
        mauxerr = 0;
    return(logx/logbase);
}
```

Figure 8-5: File **log.c**

---

```
/* poly.c */

#include "maux.h"
#include <math.h>

/* Evaluate the polynomial
 *   f(x) := a[0] * (x ^ n) + a[1] * (x ^ (n-1)) + ... + a[n];
 * Note that there are N+1 coefficients!
 * This uses Horner's Method, which is:
 *   f(x) := (((((a[0]*x) + a[1])*x) + a[2]) + ...) + a[n];
 * It's equivalent, but uses many less operations and is more precise. */

double polyd(a, n, x)
double a[];
int n;
double x;
{
    extern int stats_polyd;
    extern int total_calls;
    double result;
    int i;

    total_calls++;
    stats_polyd++;
    if (n < 0) {
        mauxerr = 1;
        return(0);
    }
    result = a[0];
    for (i = 1; i <= n; i++)
    {
        result *= (double)x;
        result += (double)a[i];
    }
    mauxerr = 0;
    return(result);
}
```

Figure 8-6: File **poly.c**

---

```
/* stats.c */
#include "maux.h"

int total_calls = 0;
int stats_logd = 0;
int stats_polyd = 0;

int mauxerr;

/* Return structure with usage stats for functions in library
 * or 0 if space cannot be allocated for the structure */
struct mstats *
maux_stat()
{
    extern char * malloc();
    struct mstats * st;

    if((st = (struct mstats *) malloc(sizeof(struct mstats))) == 0)
        return(0);
    st->st_polyd = stats_polyd;
    st->st_logd = stats_logd;
    st->st_total = total_calls;
    return(st);
}
```

Figure 8-7: File **stats.c**

---

```
/*iaux.h */

struct mstats {
    int st_polyd;
    int st_logd;
    int st_total;
};

extern double polyd();
extern double logd();
extern struct mstats *iaux_stat();

extern intiauxerr;
```

Figure 8-8: Header File **iaux.h**

---

### Choosing Region Addresses and the Target Pathname

To begin, we choose the region addresses for the library's **.text** and **.data** sections from the segments reserved for private use on the 80386 Computer; note that the region addresses must be on a segment boundary (128K):

```
.text    0xB0400000
.data    0xB0800000
```

Also we choose the pathname for our target library:

```
/my/directory/libiaux_s
```

### Selecting Library Contents

This example is for illustration purposes and so we will include everything in the shared library. In a real case, it is unlikely that you would make a shared library with these three small routines unless you had many programmers using them frequently.

## Rewriting Existing Code

According to the guidelines given earlier in the chapter, we need to first minimize the global data. We realize that **total\_calls**, **stats\_logd**, and **stats\_polyd** do not need to be visible outside the library, but are needed in multiple files within the library. Hence, we will use the **#hide** directive in our specification file to make these variables static after the shared library is built.

We need to define text and global data in separate source files. The only piece of global data we have left is **mauxerr**, which we will remove from **stats.c** and put in a new file **maux\_defs.c**. We will also have to initialize it to zero since shared libraries cannot have any uninitialized variables.

Next, we notice that there are some references to symbols that we do not define in our shared library (i.e. **log** and **malloc**). We can import these symbols. To do so, we create a new header file, **import.h**, which will be included in each of **log.c**, **poly.c**, and **stats.c**. The header file defines C preprocessor macros for these symbols to make transparent the use of indirection in the actual C source files. We use the **\_libmaux\_** prefixes on the pointers to the symbols because those pointers are made external, and the use of the library name as a prefix helps prevent name conflicts.

```
/* New header file import.h */
#define malloc    (*_libmaux_malloc)
#define log       (*_libmaux_log)

extern char * malloc();
extern double log();
```

Now, we need to define the imported symbol pointers somewhere. We have already created a file for global data **maux\_defs.c**, so we will add the definitions to it.

```
/* Data fileiaux_defs.c */  
  
intiauxerr = 0;  
double (*_libiaux_log)() = 0;  
char * (*_libiaux_malloc)() = 0;
```

Finally, we observe that there are floating-point operations in the code and we remember that the routines for these cannot be imported. (If we tried to write the specification file and build the shared library without taking this into account, **mkshlib** would give us errors about unresolved references.) This means we will have to use the **#objects noload** directive in our specification file to search the C host shared library to resolve the references.

### Writing the Specification File

This is the specification file for **libiaux**:

```
1 ##
2 ## libmaux.sl - libmaux specification lfile
3 #address .text 0x80680000
4 #address .data 0x806a0000
5 #target /my/directory/libmaux_s
6 #branch
7     polyd           1
8     logd            2
9     maux_stat       3
10 #objects
11     maux_defs.o
12     poly.o
13     log.o
14     stats.o
15 #objects noload
16     -lc_s
17 #hide linker *
18 #export linker
19     mauxerr
20 #init maux_defs.o
21     _libmaux_malloc  malloc
22     _libmaux_log     log
```

Figure 8-9: Specification File

---

Briefly, here is what the specification file does. Lines 1 and 2 are comment lines. Lines 3 and 4 give the virtual addresses for the shared library text and data regions, respectively. Line 5 gives the pathname of the shared library on the target machine. The target shared library must be installed there for **a.out** files that use it to work correctly. Line 6 contains the **#branch** directive. Line 7 through 9 specify the branch table. They assign the functions **polyd()**, **logd()**, and **maux\_stat()** to branch table entries 1, 2, and 3. Only external text symbols, such as C functions, should be placed in the branch table.

## Building a Shared Library

---

Line 10 contains the **#objects** directive. Lines 11 through 14 give the list of object files that will be used to construct the host and target shared libraries. When building the host shared library archive, each file listed here will reside in its own archive member. When building the target library, the order of object files will be preserved. The data files must be first. Otherwise, an addition of static data to **poly.o**, for example, would move external data symbols and break compatibility.

Line 15 contains the **#objects noload** directive, and line 16 gives information about where to resolve the references to the floating-point routines.

Lines 17 through 19 contain the **#hide linker** and **#export linker** directives, which tell what external symbols are to be left external after the shared library is built. Together, these **#hide** and **#export** directives say that only **mauxerr** will remain external. The symbols in the branch table and those specified in the **#init** directive will remain external by definition.

Line 20 contains the **#init** directive. Lines 21 and 22 give imported symbol information for the object file **maux\_defs.o**. You can imagine assignments of the symbol values on the right to the symbols on the left. Thus **\_libmaux** will hold a pointer to **malloc**, and so on.

## Building the Shared Library

Now, we have to compile the **.o** files as we would for any other library:

```
cc -c maux_defs.c poly.c log.c stats.c
```

Next, we need to invoke **mkshlib** to build our host and target libraries:

```
mkshlib -s libmaux.sl -t libmaux_s -h libmaux_s.a
```

Presuming all of the source files have been compiled appropriately, the **mkshlib** command line shown above will create both the host library, **libmaux\_s.a**, and the target library, **libmaux\_s**. Before any **a.out** files built with **libmaux\_s.a** can be executed, the target shared library **libmaux\_s** will have to be moved to **/my/directory/libmaux\_s** as specified in the specification file.

## Using the Shared Library

To use the shared library with a file **x.c** which contains a reference to one or more of the routines in **libmaux**, you would issue the following command line:

```
cc x.c libmaux_s.a -lm -lc_s
```



This command line causes:

- the imported symbol pointer reference to **log** to be resolved from **libm** and
- the imported symbol pointer reference to **malloc** to be resolved with the shared version from **libc\_s**.

The most important thing to note from the command line, however, is that you have to specify the C host shared library (in this case with the **-lc\_s**) on the command line since **libmaux** was built with direct references to the floating-point routines in that library.

---

## Summary

This chapter describes the UNIX system shared libraries and explains how to use them. It also explains how to build your own shared libraries. Using any shared library almost always saves disk storage space, memory, and computer power; and running the UNIX system on smaller machines makes the efficient use of these resources increasingly important. Therefore, you should normally use a shared library whenever it's available.



# Interprocess Communication

---

# 9

## Interprocess Communication

---

---

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# Introduction

The UNIX system supports three types of Inter-Process Communication (IPC):

- messages
- semaphores
- shared memory

This chapter describes the system calls for each type of IPC. Included are several example programs that show the use of the IPC system calls. All of the example programs have been compiled and run on your computer.

Since there are many ways in the C Programming Language to accomplish the same task or requirement, keep in mind that the example programs were written for clarity and not for program efficiency. Usually, system calls are embedded within a larger user-written program that makes use of a particular function that the calls provide.

---

# Messages

The message type of IPC allows processes (executing programs) to communicate through the exchange of data stored in buffers. This data is transmitted between processes in discrete portions called messages. Processes using this type of IPC can perform two operations:

- sending
- receiving

Before a message can be sent or received by a process, a process must have the UNIX system generate the necessary software mechanisms to handle these operations. A process does this by using the **msgget(2)** system call. While doing this, the process becomes the owner/creator of the message facility and specifies the initial operation permissions for all other processes, including itself. Subsequently, the owner/creator can relinquish ownership or change the operation permissions using the **msgctl(2)** system call. However, the creator remains the creator as long as the facility exists. Other processes with permission can use **msgctl()** to perform various other control functions.

Processes which have permission and are attempting to send or receive a message can suspend execution if they are unsuccessful at performing their operation. That is, a process which is attempting to send a message can wait until the process which is to receive the message is ready and vice versa. A process which specifies that execution is to be suspended is performing a "blocking message operation." A process which does not allow its execution to be suspended is performing a "nonblocking message operation."

A process performing a blocking message operation can be suspended until one of three conditions occurs:

- It is successful.
- It receives a signal.
- The facility is removed.

System calls make these message capabilities available to processes. The calling process passes arguments to a system call, and the system call either successfully or unsuccessfully performs its function. If the system call is successful, it performs its function and returns applicable information. Otherwise, a known error code (-1) is returned to the process, and an external error number variable **errno** is set accordingly.



Before a message can be sent or received, a uniquely identified message queue and data structure must be created. The unique identifier created is called the message queue identifier (**msqid**); it is used to identify or reference the associated message queue and data structure.

The message queue is used to store (header) information about each message that is being sent or received. This information includes the following for each message:

- pointer to the next message on queue
- message type
- message text size
- message text address

There is one associated data structure for the uniquely identified message queue. This data structure contains the following information related to the message queue:

- operation permissions data (operation permission structure)
- pointer to first message on the queue
- pointer to last message on the queue
- current number of bytes on the queue
- number of messages on the queue
- maximum number of bytes on the queue
- process identification (PID) of last message sender
- PID of last message receiver
- last message send time
- last message receive time
- last change time

NOTE

All include files discussed in this chapter are located in the `/usr/include` or `/usr/include/sys` directories.

## Messages

---

The C Programming Language data structure definition for message information contained in the message queue is located in the header file `/usr/include/sys/msg.h` and is as follows:

```
struct msg
{
    struct msg    *msg_next; /* ptr to next message on q */
    long         msg_type; /* message type */
    short        msg_ts; /* message text size */
    short        msg_spot; /* message text map address */
};
```

Likewise, the structure definition for the associated data structure is located in the `#include <sys/msg.h>` header file and is as follows:

```
struct msgqid_ds
{
    struct ipc_perm msg_perm; /* operation permission struct */
    struct msg    *msg_first; /* ptr to first message on q */
    struct msg    *msg_last; /* ptr to last message on q */
    ushort        msg_cbytes; /* current # bytes on q */
    ushort        msg_qnum; /* # of messages on q */
    ushort        msg_qbytes; /* max # of bytes on q */
    ushort        msg_lspid; /* pid of last msgsnd */
    ushort        msg_lrpid; /* pid of last msgrcv */
    time_t        msg_stime; /* last msgsnd time */
    time_t        msg_rtime; /* last msgrcv time */
    time_t        msg_ctime; /* last change time */
};
```

Note that the `msg_perm` member of this structure uses `ipc_perm` as a template. The breakout for the operation permissions data structure is shown in

Figure 9-1.

The definition of the **ipc\_perm** data structure is located in the header file **#include <sys/ipc.h>** and is as follows:

```
struct ipc_perm
{
    ushort   uid;    /* owner's user id */
    ushort   gid;    /* owner's group id */
    ushort   cuid;   /* creator's user id */
    ushort   cgid;   /* creator's group id */
    ushort   mode;   /* access modes */
    ushort   seq;    /* slot usage sequence number */
    key_t    key;    /* key */
};
```

Figure 9-1: **ipc\_perm** Data Structure

The structure is common for all IPC facilities.

The **msgget(2)** system call is used to perform two tasks when only the **IPC\_CREAT** flag is set in the **msgflg** argument that it receives:

- to get a new **msqid** and create an associated message queue and data structure for it
- to return an existing **msqid** that already has an associated message queue and data structure

The task performed is determined by the value of the **key** argument passed to the **msgget()** system call. For the first task, if the **key** is not already in use for an existing **msqid**, a new **msqid** is returned with an associated message queue and data structure created for the **key**. This occurs provided no system tunable parameters would be exceeded.

There is also a provision for specifying a **key** of value zero which is known as the private **key** (`IPC_PRIVATE = 0`); when specified, a new **msqid** is always returned with an associated message queue and data structure created for it unless a system tunable parameter would be exceeded. When the **ipcs** command is performed, for security reasons the **KEY** field for the **msqid** is all zeros.

For the second task, if a **msqid** exists for the **key** specified, the value of the existing **msqid** is returned. If you do not desire to have an existing **msqid** returned, a control command (`IPC_EXCL`) can be specified (set) in the **msgflg** argument passed to the system call. The details of using this system call are discussed in the "Using **msgget**" section of this chapter.

When performing the first task, the process which calls **msgget** becomes the owner/creator, and the associated data structure is initialized accordingly. Remember, ownership can be changed but the creating process always remains the creator; see the "Controlling Message Queues" section in this chapter. The creator of the message queue also determines the initial operation permissions for it.

Once a uniquely identified message queue and data structure are created, message operations [**msgop()**] and message control [**msgctl()**] can be used.

Message operations, as mentioned previously, consist of sending and receiving messages. System calls are provided for each of these operations; they are **msgsnd()** and **msgrcv()**. Refer to the "Operations for Messages" section in this chapter for details of these system calls.

Message control is done by using the **msgctl(2)** system call. It permits you to control the message facility in the following ways:

- to determine the associated data structure status for a message queue identifier (**msqid**)
- to change operation permissions for a message queue
- to change the **size (msg\_qbytes)** of the message queue for a particular **msqid**
- to remove a particular **msqid** from the UNIX operating system along with its associated message queue and data structure

Refer to the "Controlling Message Queues" section in this chapter for details of the `msgctl()` system call.

## Getting Message Queues

This section gives a detailed description of using the `msgget(2)` system call along with an example program illustrating its use.

### Using `msgget`

The synopsis found in the `msgget(2)` entry in the *Programmer's Reference Manual* is as follows:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

int msgget (key, msgflg)
key_t key;
int msgflg;
```

All of these include files are located in the `/usr/include/sys` directory of the UNIX operating system.

The following line in the synopsis informs you that `msgget()` is a function with two formal arguments that returns an integer type value upon successful completion (`msqid`).

```
int msgget (key, msgflg)
```

The next two lines declare the types of the formal arguments. `key_t` is declared by a `typedef` in the `types.h` header file to be an integer.

```
key_t key;
int msgflg;
```

## Messages

---

The integer returned from this function upon successful completion is the message queue identifier (**msqid**) that was discussed earlier.

As declared, the process calling the **msgget()** system call must supply two arguments to be passed to the formal **key** and **msgflg** arguments.

A new **msqid** with an associated message queue and data structure is provided if one of the following conditions exists:

- **key** is equal to `IPC_PRIVATE`
- **key** is passed a unique hexadecimal integer, and **msgflg** ANDed with `IPC_CREAT` is `TRUE`.

The value passed to the **msgflg** argument must be an integer type octal value and will specify the following:

- access permissions
- execution modes
- control fields (commands)

Access permissions determine the read/write attributes, and execution modes determine the user/group/other attributes of the **msgflg** argument. They are collectively referred to as "operation permissions." Figure 9-2 reflects the numeric values (expressed in octal notation) for the valid operation permissions codes.

<u>Operation Permissions</u>	<u>Octal Value</u>
Read by User	00400
Write by User	00200
Read by Group	00040
Write by Group	00020
Read by Others	00004
Write by Others	00002

Figure 9-2: Operation Permissions Codes

---

A specific octal value is derived by adding the octal values for the operation permissions desired. That is, if read by user and read/write by others is desired, the code value would be 00406 (00400 plus 00006). There are constants located in the **msg.h** header file which can be used for the user (OWNER).

Control commands are predefined constants (represented by all uppercase letters). Figure 9-3 contains the names of the constants which apply to the **msgget()** system call along with their values. They are also referred to as flags and are defined in the **ipc.h** header file.

<b>Control Command</b>	<b>Value</b>
IPC_CREAT	0001000
IPC_EXCL	0002000

Figure 9-3: Control Commands (Flags)

---

The value for the **msgflg** argument is therefore a combination of operation permissions and control commands. After determining the value for the operation permissions as previously described, the desired flag(s) can be specified. This specification is accomplished by bitwise ORing (|) them with the operation permissions; bit positions and values for the control commands in relation to those of the operation permissions make this possible. An example of determining the **msgflg** argument follows.

		<b>Octal Value</b>	<b>Binary Value</b>
IPC_CREAT	=	0 1 0 0 0	0 000 001 000 000 000
ORed by User	=	0 0 4 0 0	0 000 000 100 000 000
<b>msgflg</b>	=	0 1 4 0 0	0 000 001 100 000 000

The **msgflg** value can easily be set by using the names of the flags in conjunction with the octal operation permissions value:

```
msgqid = msgget (key, (IPC_CREAT | 0400));
msgqid = msgget (key, (IPC_CREAT | IPC_EXCL | 0400));
```

## Messages

---

As specified by the `msgget(2)` page in the *Programmer's Reference Manual*, success or failure of this system call depends upon the argument values for `key` and `msgflg` or system tunable parameters. The system call will attempt to return a new `msqid` if one of the following conditions exists:

- `key` is equal to `IPC_PRIVATE` (0)
- `key` does not already have a `msqid` associated with it, and `(msgflg & IPC_CREAT)` is TRUE (not zero).

The `key` argument can be set to `IPC_PRIVATE` in the following ways:

```
msqid = msgget (IPC_PRIVATE, msgflg);
```

or

```
msqid = msgget ( 0 , msgflg);
```

This alone will cause the system call to be attempted because it satisfies the first condition specified. Exceeding the `MSGMNI` system tunable parameter always causes a failure. The `MSGMNI` system tunable parameter determines the maximum number of unique message queues (`msqid`'s) in the UNIX operating system.

The second condition is satisfied if the value for `key` is not already associated with a `msqid` and the bitwise ANDing of `msgflg` and `IPC_CREAT` is TRUE (not zero). This means that the `key` is unique (not in use) within the UNIX operating system for this facility type and that the `IPC_CREAT` flag is set (`msgflg ! IPC_CREAT`). The bitwise ANDing (`&`), which is the logical way of testing if a flag is set, is illustrated as follows:

```
msgflg = x 1 x x x   (x = immaterial)
& IPC_CREAT = 0 1 0 0 0
result = 0 1 0 0 0   (not zero)
```

Since the result is not zero, the flag is set or TRUE.

`IPC_EXCL` is another control command used in conjunction with `IPC_CREAT` to exclusively have the system call fail if, and only if, a `msqid` exists for the specified `key` provided. This is necessary to prevent the process from thinking that it has received a new (unique) `msqid` when it has not. In other words, when both `IPC_CREAT` and `IPC_EXCL` are specified, a new `msqid` is returned if the system call is successful.



---

Refer to the `msgget(2)` page in the *Programmer's Reference Manual* for specific, associated data structure initialization for successful completion. The specific failure conditions with error names are contained there also.

## Example Program

The example program in this section (Figure 9-4) is a menu-driven program which allows all possible combinations of using the `msgget(2)` system call to be exercised.

From studying this program, you can observe the method of passing arguments and receiving return values. The user-written program requirements are pointed out.

This program begins (lines 4-8) by including the required header files as specified by the `msgget(2)` entry in the *Programmer's Reference Manual*. Note that the `errno.h` header file is included as opposed to declaring `errno` as an external variable; either method will work.

Variable names have been chosen to be as close as possible to those in the synopsis for the system call. Their declarations are self-explanatory. These names make the program more readable, and are perfectly legal since they are local to the program. Variables declared for this program and their purposes are:

- **key**—used to pass the value for the desired **key**
- **opperm**—used to store the desired operation permissions
- **flags**—used to store the desired control commands (flags)
- **opperm\_flags**—used to store the combination from the logical ORing of the **opperm** and **flags** variables; it is then used in the system call to pass the `msgflg` argument.
- **msqid**—used for returning the message queue identification number for a successful system call or the error code (-1) for an unsuccessful one.

The program begins by prompting for a hexadecimal **key**, an octal operation permissions code, and the control command combinations (flags) which are selected from a menu (lines 15-32). All possible combinations are allowed even though they might not be viable. This allows observing the errors for illegal combinations.

Next, the menu selection for the flags is combined with the operation permissions, and the result is stored at the address of the **opperm\_flags** variable (lines 36-51).

The system call is made next, and the result is stored at the address of the **msqid** variable (line 53).

Since the **msqid** variable now contains a valid message queue identifier or the error code (-1), it is tested to see if an error occurred (line 55). If **msqid** equals -1, a message indicates that an error resulted, and the external **errno** variable is displayed (lines 57 and 58).

If no error occurred, the returned message queue identifier is displayed (line 62).

The example program for the **msgget(2)** system call follows. It is suggested that the source program file be named **msgget.c** and that the executable file be named **msgget**.

When compiling C programs that use floating point operations, the **-f** option should be used on the **cc** command line. If this option is not used, the program will compile successfully, but when the program is executed, it will fail.

```
1  /*This is a program to illustrate
2  **the message get, msgget(),
3  **system call capabilities.*/

4  #include <stdio.h>
5  #include <sys/types.h>
6  #include <sys/ipc.h>
7  #include <sys/msg.h>
8  #include <errno.h>

9  /*Start of main C language program*/
10 main()
11 {
12     key_t key;           /*declare as long integer*/
13     int opperm, flags;
14     int msqid, opperm_flags;
15     /*Enter the desired key*/
16     printf("Enter the desired key in hex = ");
17     scanf("%x", &key);

18     /*Enter the desired octal operation
19     permissions.*/
20     printf("\nEnter the operation\n");
21     printf("permissions in octal = ");
22     scanf("%o", &opperm);
```

Figure 9-4: **msgget()** System Call Example (Sheet 1 of 3)

```
23      /*Set the desired flags.*/
24      printf("\nEnter corresponding number to\n");
25      printf("set the desired flags:\n");
26      printf("No flags                = 0\n");
27      printf("IPC_CREAT                  = 1\n");
28      printf("IPC_EXCL                      = 2\n");
29      printf("IPC_CREAT and IPC_EXCL          = 3\n");
30      printf("                Flags          = ");

31      /*Get the flag(s) to be set.*/
32      scanf("%d", &flags);

33      /*Check the values.*/
34      printf ("\nkey =0x%x, opperm = 0%, flags = 0%\n",
35             key, opperm, flags);

36      /*Incorporate the control fields (flags) with
37       the operation permissions*/
38      switch (flags)
39      {
40      case 0:      /*No flags are to be set.*/
41                 opperm_flags = (opperm | 0);
42                 break;
43      case 1:      /*Set the IPC_CREAT flag.*/
44                 opperm_flags = (opperm | IPC_CREAT);
45                 break;
46      case 2:      /*Set the IPC_EXCL flag.*/
47                 opperm_flags = (opperm | IPC_EXCL);
48                 break;
49      case 3:      /*Set the IPC_CREAT and IPC_EXCL flags.*/
50                 opperm_flags = (opperm | IPC_CREAT | IPC_EXCL);
51      }
}
```

Figure 9-4: **msgget()** System Call Example (Sheet 2 of 3)

---

```
52     /*Call the msgget system call.*/
53     msgqid = msgget (key, opperm_flags);

54     /*Perform the following if the call is unsuccessful.*/
55     if(msgqid == -1)
56     {
57         printf ("\nThe msgget system call failed!\n");
58         printf ("The error number = %d\n", errno);
59     }

60     /*Return the msgqid upon successful completion.*/
61     else
62         printf ("\nThe msgqid = %d\n", msgqid);
63     exit(0);
64 }
```

Figure 9-4: **msgget()** System Call Example (Sheet 3 of 3)

## Controlling Message Queues

This section gives a detailed description of using the **msgctl** system call along with an example program which allows all of its capabilities to be exercised.

### Using **msgctl**

The synopsis found in the **msgctl(2)** entry in the *Programmer's Reference Manual* is as follows:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

int msgctl (msqid, cmd, buf)
int msqid, cmd;
struct msqid_ds *buf;
```

The **msgctl()** system call requires three arguments to be passed to it, and it returns an integer value. Upon successful completion, a zero value is returned. When unsuccessful, a  $-1$  is returned.

The **msqid** variable must be a valid, non-negative, integer value. In other words, it must have already been created by using the **msgget()** system call.

The **cmd** argument can be replaced by one of the following control commands (flags):

- IPC\_STAT return the status information contained in the associated data structure for the specified **msqid**, and place it in the data structure pointed to by the **\*buf** pointer in the user memory area.
- IPC\_SET for the specified **msqid**, set the effective user and group identification, operation permissions, and the number of bytes for the message queue.
- IPC\_RMID remove the specified **msqid** along with its associated message queue and data structure.

A process must have an effective user identification of OWNER/CREATOR or super-user to perform an IPC\_SET or IPC\_RMID control command. Read permission is required to perform the IPC\_STAT control command.

---

The details of this system call are discussed in the example program for it. If you have problems understanding the logic manipulations in this program, read the "Using **msgget**" section of this chapter; it goes into more detail than what would be practical to do for every system call.

### Example Program

The example program in this section (Figure 9-5) is a menu-driven program which allows all possible combinations of using the **msgctl(2)** system call to be exercised.

From studying this program, you can observe the method of passing arguments and receiving return values. The user-written program requirements are pointed out.

This program begins (lines 5-9) by including the required header files as specified by the **msgctl(2)** entry in the *Programmer's Reference Manual*. Note in this program that **errno** is declared as an external variable, and therefore, the **errno.h** header file does not have to be included.

Variable and structure names have been chosen to be as close as possible to those in the synopsis for the system call. Their declarations are self-explanatory. These names make the program more readable, and are perfectly legal since they are local to the program. Variables declared for this program and their purpose are:

- **uid**—used to store the IPC\_SET value for the effective user identification
- **gid**—used to store the IPC\_SET value for the effective group identification
- **mode**—used to store the IPC\_SET value for the operation permissions
- **bytes**—used to store the IPC\_SET value for the number of bytes in the message queue (**msg\_qbytes**)
- **rtrn**—used to store the return integer value from the system call
- **msqid**—used to store and pass the message queue identifier to the system call
- **command**—used to store the code for the desired control command so that subsequent processing can be performed on it

- **choice**—used to determine which member is to be changed for the `IPC_SET` control command
- **msqid\_ds**—used to receive the specified message queue identifier's data structure when an `IPC_STAT` control command is performed
- **\*buf**—a pointer passed to the system call which locates the data structure in the user memory area where the `IPC_STAT` control command is to place its return values or where the `IPC_SET` command gets the values to set

Note that the **msqid\_ds** data structure in this program (line 16) uses the data structure located in the **msg.h** header file of the same name as a template for its declaration. This is a perfect example of the advantage of local variables.

The next important thing to observe is that although the **\*buf** pointer is declared to be a pointer to a data structure of the **msqid\_ds** type, it must also be initialized to contain the address of the user memory area data structure (line 17). Now that all of the required declarations have been explained for this program, this is how it works.

First, the program prompts for a valid message queue identifier which is stored at the address of the **msqid** variable (lines 19 and 20). This is required for every **msgctl** system call.

Then the code for the desired control command must be entered (lines 21-27), and it is stored at the address of the command variable. The code is tested to determine the control command for subsequent processing.

If the `IPC_STAT` control command is selected (code 1), the system call is performed (lines 37 and 38) and the status information returned is printed out (lines 39-46); only the members that can be set are printed out in this program. Note that if the system call is unsuccessful (line 106), the status information of the last successful call is printed out. In addition, an error message is displayed and the **errno** variable is printed out (lines 108 and 109). If the system call is successful, a message indicates this along with the message queue identifier used (lines 111-114).

If the `IPC_SET` control command is selected (code 2), the first thing done is to get the current status information for the message queue identifier specified (lines 50-52). This is necessary because this example program provides for changing only one member at a time, and the system call changes all of them. Also, if an invalid value happened to be stored in the user memory



area for one of these members, it would cause repetitive failures for this control command until corrected. The next thing the program does is to prompt for a code corresponding to the member to be changed (lines 53-59). This code is stored at the address of the choice variable (line 60). Now, depending upon the member picked, the program prompts for the new value (lines 66-95). The value is placed at the address of the appropriate member in the user memory area data structure, and the system call is made (lines 96-98). Depending upon success or failure, the program returns the same messages as for `IPC_STAT` above.

If the `IPC_RMID` control command (code 3) is selected, the system call is performed (lines 100-103), and the `msqid` along with its associated message queue and data structure are removed from the UNIX operating system. Note that the `*buf` pointer is not required as an argument to perform this control command, and its value can be zero or `NULL`. Depending upon the success or failure, the program returns the same messages as for the other control commands.

The example program for the `msgctl()` system call follows. It is suggested that the source program file be named `msgctl.c` and that the executable file be named `msgctl`.

When compiling C programs that use floating point operations, the `-f` option should be used on the `cc` command line. If this option is not used, the program will compile successfully, but when the program is executed, it will fail.

```
1  /*This is a program to illustrate
2  **the message control, msgctl(),
3  **system call capabilities.
4  */

5  /*Include necessary header files.*/
6  #include <stdio.h>
7  #include <sys/types.h>
8  #include <sys/ipc.h>
9  #include <sys/msg.h>

10 /*Start of main C language program*/
11 main()
12 {
13     extern int errno;
14     int uid, gid, mode, bytes;
15     int rtm, msqid, command, choice;
16     struct msqid_ds msqid_ds, *buf;
17     buf = &msqid_ds;

18     /*Get the msqid, and command.*/
19     printf("Enter the msqid = ");
20     scanf("%d", &msqid);
21     printf("\nEnter the number for\n");
22     printf("the desired command:\n");
23     printf("IPC_STAT = 1\n");
24     printf("IPC_SET = 2\n");
25     printf("IPC_RMID = 3\n");
26     printf("Entry = ");
27     scanf("%d", &command);
```

Figure 9-5: **msgctl()** System Call Example (Sheet 1 of 4)

---

```
28      /*Check the values.*/
29      printf ("\nmsqid =%d, command = %d\n",
30             msqid, command);

31      switch (command)
32      {
33      case 1: /*Use msgctl() to duplicate
34             the data structure for
35             msqid in the msqid_ds area pointed
36             to by buf and then print it out.*/
37             rtrn = msgctl(msqid, IPC_STAT,
38                          buf);
39             printf ("\nThe USER ID = %d\n",
40                    buf->msg_perm.uid);
41             printf ("The GROUP ID = %d\n",
42                    buf->msg_perm.gid);
43             printf ("The operation permissions = 0%o\n",
44                    buf->msg_perm.mode);
45             printf ("The msg_qbytes = %d\n",
46                    buf->msg_qbytes);
47             break;
48      case 2: /*Select and change the desired
49             member(s) of the data structure.*/
50             /*Get the original data for this msqid
51             data structure first.*/
52             rtrn = msgctl(msqid, IPC_STAT, buf);
53             printf ("\nEnter the number for the\n");
54             printf ("member to be changed:\n");
55             printf ("msg_perm.uid    = 1\n");
56             printf ("msg_perm.gid    = 2\n");
57             printf ("msg_perm.mode   = 3\n");
58             printf ("msg_qbytes    = 4\n");
59             printf ("Entry          = ");
```

Figure 9-5: `msgctl()` System Call Example (Sheet 2 of 4)

```
60         scanf("%d", &choice);
61         /*Only one choice is allowed per
62         pass as an illegal entry will
63         cause repetitive failures until
64         msgqid_ds is updated with
65         IPC_STAT.*/

66         switch(choice){
67         case 1:
68             printf("\nEnter USER ID = ");
69             scanf ("%d", &uid);
70             buf->msg_perm.uid = uid;
71             printf("\nUSER ID = %d\n",
72                 buf->msg_perm.uid);
73             break;
74         case 2:
75             printf("\nEnter GROUP ID = ");
76             scanf ("%d", &gid);
77             buf->msg_perm.gid = gid;
78             printf("\nGROUP ID = %d\n",
79                 buf->msg_perm.gid);
80             break;
81         case 3:
82             printf("\nEnter MODE = ");
83             scanf ("%o", &mode);
84             buf->msg_perm.mode = mode;
85             printf("\nMODE = %o\n",
86                 buf->msg_perm.mode);
87             break;
```

Figure 9-5: `msgctl()` System Call Example (Sheet 3 of 4)

---

```
88         case 4:
89             printf("\nEnter msq_bytes = ");
90             scanf("%d", &bytes);
91             buf->msg_qbytes = bytes;
92             printf("\nmsg_qbytes = %d\n",
93                 buf->msg_qbytes);
94             break;
95         }

96         /*Do the change.*/
97         rtrn = msgctl(msqid, IPC_SET,
98             buf);
99         break;

100        case 3:    /*Remove the msqid along with its
101                   associated message queue
102                   and data structure.*/
103            rtrn = msgctl(msqid, IPC_RMID, NULL);
104        }
105        /*Perform the following if the call is unsuccessful.*/
106        if(rtrn == -1)
107        {
108            printf ("\nThe msgctl system call failed!\n");
109            printf ("The error number = %d\n", errno);
110        }
111        /*Return the msqid upon successful completion.*/
112        else
113            printf ("\nMsgctl was successful for msqid = %d\n",
114                msqid);
115        exit (0);
116    }
```

Figure 9-5: `msgctl()` System Call Example (Sheet 4 of 4)

# Operations for Messages

This section gives a detailed description of using the **msgsnd(2)** and **msgrcv(2)** system calls, along with an example program which allows all of their capabilities to be exercised.

## Using msgop

The synopsis found in the **msgop(2)** entry in the *Programmer's Reference Manual* is as follows:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

int msgsnd (msqid, msgp, msgsz, msgflg)
int msqid;
struct msgbuf *msgp;
int msgsz, msgflg;

int msgrcv (msqid, msgp, msgsz, msgtyp, msgflg)
int msqid;
struct msgbuf *msgp;
int msgsz;
long msgtyp;
int msgflg;
```

## Sending a Message

The **msgsnd** system call requires four arguments to be passed to it, and it returns an integer value. Upon successful completion, a zero value is returned. When unsuccessful, a  $-1$  is returned.

The **msqid** argument must be a valid, non-negative, integer value. In other words, it must have already been created by using the **msgget()** system call.

The **msgp** argument is a pointer to a structure in the user memory area that contains the type of the message and the message to be sent.

The **msgsz** argument specifies the length of the character array in the data structure pointed to by the **msgp** argument. This is the length of the message. The maximum **size** of this array is determined by the MSGMAX system tunable parameter.

The **msg\_qbytes** data structure member can be lowered from MSGMNB by using the **msgctl()** IPC\_SET control command, but only the super-user can raise it afterwards.

The **msgflg** argument allows the "blocking message operation" to be performed if the IPC\_NOWAIT flag is not set (**msgflg & IPC\_NOWAIT = 0**); this would occur if the total number of bytes allowed on the specified message queue are in use (**msg\_qbytes** or MSGMNB), or the total system-wide number of messages on all queues is equal to the system imposed limit (MSGTQL). If the IPC\_NOWAIT flag is set, the system call will fail and return a -1.

Further details of this system call are discussed in the example program for it. If you have problems understanding the logic manipulations in this program, read the "Using **msgget**" section of this chapter; it goes into more detail than would be practical to do for every system call.

### **Receiving Messages**

The **msgrcv()** system call requires five arguments to be passed to it, and it returns an integer value. Upon successful completion, a value equal to the number of bytes received is returned. When unsuccessful, a -1 is returned.

The **msqid** argument must be a valid, non-negative, integer value; that is, it must have already been created by using the **msgget()** system call.

The **msgp** argument is a pointer to a structure in the user memory area that will receive the message type and the message text.

The **msgsz** argument specifies the length of the message to be received. If its value is less than the message in the array, an error can be returned if desired; see the **msgflg** argument.

The **msgtyp** argument is used to pick the first message on the message queue of the particular type specified. If it is equal to zero, the first message on the queue is received; if it is greater than zero, the first message of the same type is received; if it is less than zero, the lowest type that is less than or equal to its absolute value is received.

The **msgflg** argument allows the "blocking message operation" to be performed if the **IPC\_NOWAIT** flag is not set (**msgflg & IPC\_NOWAIT = 0**); this would occur if there is not a message on the message queue of the desired type (**msgtyp**) to be received. If the **IPC\_NOWAIT** flag is set, the system call will fail immediately when there is not a message of the desired type on the queue. **Msgflg** can also specify that the system call fail if the message is longer than the **size** to be received; this is done by not setting the **MSG\_NOERROR** flag in the **msgflg** argument (**msgflg & MSG\_NOERROR = 0**). If the **MSG\_NOERROR** flag is set, the message is truncated to the length specified by the **msgsz** argument of **msgrcv()**.

Further details of this system call are discussed in the example program for it. If you have problems understanding the logic manipulations in this program, read the "Using **msgget**" section of this chapter; it goes into more detail than would be practical to do for every system call.

### Example Program

The example program in this section (Figure 9-6) is a menu-driven program which allows all possible combinations of using the **msgsnd()** and **msgrcv(2)** system calls to be exercised.

From studying this program, you can observe the method of passing arguments and receiving return values. The user-written program requirements are pointed out.

This program begins (lines 5-9) by including the required header files as specified by the **msgop(2)** entry in the *Programmer's Reference Manual*. Note that in this program **errno** is declared as an external variable, and therefore, the **errno.h** header file does not have to be included.

Variable and structure names have been chosen to be as close as possible to those in the synopsis for the system call. Their declarations are self-explanatory. These names make the program more readable, and are perfectly legal since they are local to the program. Variables declared for this program and their purposes are:

- **sndbuf**—used as a buffer to contain a message to be sent (line 13); it uses the **msgbuf1** data structure as a template (lines 10-13). The **msgbuf1** structure (lines 10-13) is almost an exact duplicate of the **msgbuf** structure contained in the **msg.h** header file. The only difference is that the character array for **msgbuf1** contains the maximum message **size** (**MSGMAX**) for your computer, where in **msgbuf** it is set to one (1) to satisfy the compiler. For this reason **msgbuf** cannot be



---

used directly as a template for the user-written program. It is there so you can determine its members.

- **rcvbuf**—used as a buffer to receive a message (line 13); it uses the **msgbuf1** data structure as a template (lines 10-13).
- **\*msgp**—used as a pointer (line 13) to both the **sndbuf** and **rcvbuf** buffers
- **i**—used as a counter to input characters from the keyboard, to store them in the array, and to keep track of the message length for the **msgsnd()** system call; it is also used as a counter to output the received message for the **msgrcv()** system call.
- **c**—used to receive the input character from the **getchar()** function (line 50)
- **flag**—used to store the code of **IPC\_NOWAIT** for the **msgsnd()** system call (line 61)
- **flags**—used to store the code of the **IPC\_NOWAIT** or **MSG\_NOERROR** flags for the **msgrcv()** system call (line 117)
- **choice**—used to store the code for sending or receiving (line 30)
- **rtrn**—used to store the return values from all system calls
- **msqid**—used to store and pass the desired message queue identifier for both system calls
- **msgsz**—used to store and pass the **size** of the message to be sent or received
- **msgflg**—used to pass the value of flag for sending or the value of flags for receiving
- **msgtyp**—used for specifying the message type for sending, or used to pick a message type for receiving.

Note that a **msqid\_ds** data structure is set up in the program (line 21) with a pointer which is initialized to point to it (line 22); this will allow the data structure members that are affected by message operations to be observed. They are observed by using the **msgctl()** (**IPC\_STAT**) system call to get them for the program to print them out (lines 80-92 and lines 161-168).

The first thing the program prompts for is whether to send or receive a message. A corresponding code must be entered for the desired operation, and it is stored at the address of the choice variable (lines 23-30). Depending upon the code, the program proceeds as in the following **msgsnd** or **msgrcv** sections.

### **msgsnd**

When the code is to send a message, the **msgp** pointer is initialized (line 33) to the address of the send data structure, **sndbuf**. Next, a message type must be entered for the message; it is stored at the address of the variable **msgtyp** (line 42), and then (line 43) it is put into the **mtype** member of the data structure pointed to by **msgp**.

The program now prompts for a message to be entered from the keyboard and enters a loop of getting and storing into the **mtext** array of the data structure (lines 48-51). This will continue until an end of file is recognized, which for the **getchar()** function is a control-d (CTRL-D) immediately following a carriage return (<CR>). When this happens, the **size** of the message is determined by adding one to the **i** counter (lines 52 and 53) as it stored the message beginning in the zero array element of **mtext**. Keep in mind that the message also contains the terminating characters, and the message will therefore appear to be three characters short of **msgsz**.

The message is immediately echoed from the **mtext** array of the **sndbuf** data structure to provide feedback (lines 54-56).

The next and final thing that must be decided is whether to set the **IPC\_NOWAIT** flag. The program does this by requesting that a code of a 1 be entered for yes or anything else for no (lines 57-65). It is stored at the address of the flag variable. If a 1 is entered, **IPC\_NOWAIT** is logically ORed with **msgflg**; otherwise, **msgflg** is set to zero.

The **msgsnd()** system call is performed (line 69). If it is unsuccessful, a failure message is displayed along with the error number (lines 70-72). If it is successful, the returned value is printed which should be zero (lines 73-76).

Every time a message is successfully sent, there are three members of the associated data structure which are updated. They are described as follows:

- msg\_qnum** represents the total number of messages on the message queue; it is incremented by one.
- msg\_lspid** contains the Process Identification (PID) number of the last process sending a message; it is set accordingly.

**msg\_stime** contains the time in seconds since January 1, 1970, Greenwich Mean Time (GMT) of the last message sent; it is set accordingly.

These members are displayed after every successful message send operation (lines 79-92).

**msgrcv**

If the code specifies that a message is to be received, the program continues execution as in the following paragraphs.

The **msgp** pointer is initialized to the **rcvbuf** data structure (line 99).

Next, the message queue identifier of the message queue from which to receive the message is requested, and it is stored at the address of **msgqid** (lines 100-103).

The message type is requested, and it is stored at the address of **msgtyp** (lines 104-107).

The code for the desired combination of control flags is requested next, and it is stored at the address of **flags** (lines 108-117). Depending upon the selected combination, **msgflg** is set accordingly (lines 118-133).

Finally, the number of bytes to be received is requested, and it is stored at the address of **msgsz** (lines 134-137).

The **msgrcv()** system call is performed (line 144). If it is unsuccessful, a message and error number is displayed (lines 145-148). If successful, a message indicates so, and the number of bytes returned is displayed followed by the received message (lines 153-159).

When a message is successfully received, there are three members of the associated data structure which are updated; they are described as follows:

**msg\_qnum** contains the number of messages on the message queue; it is decremented by one.

**msg\_lrpid** contains the process identification (PID) of the last process receiving a message; it is set accordingly.

**msg\_rtime** contains the time in seconds since January 1, 1970, Greenwich Mean Time (GMT) that the last process received a message; it is set accordingly.

The example program for the **msgop()** system calls follows. It is suggested that the program be put into a source file called **msgop.c** and then into an executable file called **msgop**.

When compiling C programs that use floating point operations, the **-f** option should be used on the **cc** command line. If this option is not used, the program will compile successfully, but when the program is executed it will fail. The **-f** option is not required, however, for your computer.

```
1  /*This is a program to illustrate
2  **the message operations, msgop(),
3  **system call capabilities.
4  */

5  /*Include necessary header files.*/
6  #include <stdio.h>
7  #include <sys/types.h>
8  #include <sys/ipc.h>
9  #include <sys/msg.h>

10 struct msgbuf1 {
11     long  mtype;
12     char  mtext[8192];
13 } sndbuf, rcvbuf, *msgp;

14 /*Start of main C language program*/
15 main()
16 {
17     extern int errno;
18     int i, c, flag, flags, choice;
19     int rtrn, msqid, msgsz, msgflg;
20     long mtype, msgtyp;
21     struct msqid_ds msqid_ds, *buf;
22     buf = &msqid_ds;
```

Figure 9-6: `msgop()` System Call Example (Sheet 1 of 7)

```
23      /*Select the desired operation.*/
24      printf("Enter the corresponding\n");
25      printf("code to send or\n");
26      printf("receive a message:\n");
27      printf("Send          = 1\n");
28      printf("Receive       = 2\n");
29      printf("Entry         = ");
30      scanf("%d", &choice);

31      if(choice == 1) /*Send a message.*/
32      {
33          msgp = &sndbuf; /*Point to user send structure.*/

34          printf("\nEnter the msqid of\n");
35          printf("the message queue to\n");
36          printf("handle the message = ");
37          scanf("%d", &msqid);

38          /*Set the message type.*/
39          printf("\nEnter a positive integer\n");
40          printf("message type (long) for the\n");
41          printf("message = ");
42          scanf("%d", &msgtyp);
43          msgp->mtype = msgtyp;

44          /*Enter the message to send.*/
45          printf("\nEnter a message: \n");

46          /*A control-d (^d) terminates as
47          EOF.*/
```

Figure 9-6: **msgop()** System Call Example (Sheet 2 of 7)

---

```
48      /*Get each character of the message
49         and put it in the mtext array.*/
50      for(i = 0; ((c = getchar()) != EOF); i++)
51          sndbuf.mtext[i] = c;

52      /*Determine the message size.*/
53      msgsz = i + 1;

54      /*Echo the message to send.*/
55      for(i = 0; i < msgsz; i++)
56          putchar(sndbuf.mtext[i]);

57      /*Set the IPC_NOWAIT flag if
58         desired.*/
59      printf("\nEnter a 1 if you want the\n");
60      printf("the IPC_NOWAIT flag set: ");
61      scanf("%d", &flag);
62      if(flag == 1)
63          msgflg |= IPC_NOWAIT;
64      else
65          msgflg = 0;

66      /*Check the msgflg.*/
67      printf("\nmsgflg = 0x%x\n", msgflg);

68      /*Send the message.*/
69      rtrn = msgsnd(msqid, msgp, msgsz, msgflg);
70      if(rtrn == -1)
71          printf("\nMsgsnd failed. Error = %d\n",
72              errno);
73      else {
74          /*Print the value of test which
75             should be zero for successful.*/
76          printf("\nValue returned = %d\n", rtrn);
```

Figure 9-6: `msgop()` System Call Example (Sheet 3 of 7)

```
77         /*Print the size of the message
78         sent.*/
79         printf("\nMsgsz = %d\n", msgsz);

80         /*Check the data structure update.*/
81         msgctl(msqid, IPC_STAT, buf);

82         /*Print out the affected members.*/

83         /*Print the incremented number of
84         messages on the queue.*/
85         printf("\nThe msg_qnum = %d\n",
86         buf->msg_qnum);
87         /*Print the process id of the last sender.*/
88         printf("The msg_lspid = %d\n",
89         buf->msg_lspid);
90         /*Print the last send time.*/
91         printf("The msg_stime = %d\n",
92         buf->msg_stime);
93     }
94 }

95 if(choice == 2) /*Receive a message.*/
96 {
97     /*Initialize the message pointer
98     to the receive buffer.*/
99     msgp = &rcvbuf;

100     /*Specify the message queue which contains
101     the desired message.*/
102     printf("\nEnter the msqid = ");
103     scanf("%d", &msqid);
```

Figure 9-6: `msgop()` System Call Example (Sheet 4 of 7)

---



```
104      /*Specify the specific message on the queue
105         by using its type.*/
106      printf("\nEnter the msgtyp = ");
107      scanf("%d", &msgtyp);

108      /*Configure the control flags for the
109         desired actions.*/
110      printf("\nEnter the corresponding code\n");
111      printf("to select the desired flags: \n");
112      printf("No flags           = 0\n");
113      printf("MSG_NOERROR           = 1\n");
114      printf("IPC_NOWAIT             = 2\n");
115      printf("MSG_NOERROR and IPC_NOWAIT = 3\n");
116      printf("                Flags     = ");
117      scanf("%d", &flags);

118      switch(flags) {
119          /*Set msgflg by ORing it with the appropriate
120             flags (constants).*/
121      case 0:
122          msgflg = 0;
123          break;
124      case 1:
125          msgflg |= MSG_NOERROR;
126          break;
127      case 2:
128          msgflg |= IPC_NOWAIT;
129          break;
130      case 3:
131          msgflg |= MSG_NOERROR | IPC_NOWAIT;
132          break;
133      }
```

Figure 9-6: `msgop()` System Call Example (Sheet 5 of 7)

```
134      /*Specify the number of bytes to receive.*/
135      printf("\nEnter the number of bytes\n");
136      printf("to receive (msgsz) = ");
137      scanf("%d", &msgsz);

138      /*Check the values for the arguments.*/
139      printf("\nmsqid = %d\n", msqid);
140      printf("\nmsgtyp = %d\n", msgtyp);
141      printf("\nmsgsz = %d\n", msgsz);
142      printf("\nmsgflg = 0%o\n", msgflg);

143      /*Call msgrcv to receive the message.*/
144      rtm = msgrcv(msqid, msgp, msgsz, msgtyp, msgflg);

145      if(rtm == -1) {
146          printf("\nMsgrcv failed. ");
147          printf("Error = %d\n", errno);
148      }
149      else {
150          printf ("\nMsgctl was successful\n");
151          printf("for msqid = %d\n",
152              msqid);

153          /*Print the number of bytes received,
154             it is equal to the return
155             value.*/
156          printf("Bytes received = %d\n", rtm);
```

---

Figure 9-6: **msgop()** System Call Example (Sheet 6 of 7)

---

```
157             /*Print the received message.*/
158             for(i = 0; i<=rtrn; i++)
159                 putchar(rcvbuf.mtext[i]);
160         }
161         /*Check the associated data structure.*/
162         msgctl(msqid, IPC_STAT, buf);
163         /*Print the decremented number of messages.*/
164         printf("\nThe msg_qnum = %d\n", buf->msg_qnum);
165         /*Print the process id of the last receiver.*/
166         printf("The msg_lrpid = %d\n", buf->msg_lrpid);
167         /*Print the last message receive time*/
168         printf("The msg_rtime = %d\n", buf->msg_rtime);
169     }
170 }
```

Figure 9-6: **msgop()** System Call Example (Sheet 7 of 7)

---

# Semaphores

The semaphore type of IPC allows processes to communicate through the exchange of semaphore values. A semaphore is a positive integer (0 through 32,767). Since many applications require the use of more than one semaphore, the UNIX operating system has the ability to create sets or arrays of semaphores. A semaphore set can contain one or more semaphores up to a limit set by the system administrator. The tunable parameter, SEMMSL has a default value of 25. Semaphore sets are created by using the **semget(2)** system call.

The process performing the **semget(2)** system call becomes the owner/creator, determines how many semaphores are in the set, and sets the operation permissions for the set, including itself. This process can subsequently relinquish ownership of the set or change the operation permissions using the **semctl()**, semaphore control, system call. The creating process always remains the creator as long as the facility exists. Other processes with permission can use **semctl()** to perform other control functions.

Provided a process has alter permission, it can manipulate the semaphore(s). Each semaphore within a set can be manipulated in two ways with the **semop(2)** system call (which is documented in the *Programmer's Reference Manual*):

- incremented
- decremented

To increment a semaphore, an integer value of the desired magnitude is passed to the **semop(2)** system call. To decrement a semaphore, a minus (-) value of the desired magnitude is passed.

The UNIX operating system ensures that only one process can manipulate a semaphore set at any given time. Simultaneous requests are performed sequentially in an arbitrary manner.

A process can test for a semaphore value to be greater than a certain value by attempting to decrement the semaphore by one more than that value. If the process is successful, then the semaphore value is greater than that certain value. Otherwise, the semaphore value is not. While doing this, the process can have its execution suspended (IPC\_NOWAIT flag not set) until the semaphore value would permit the operation (other processes increment the semaphore), or the semaphore facility is removed.

The ability to suspend execution is called a "blocking semaphore operation." This ability is also available for a process which is testing for a semaphore to become zero or equal to zero; only read permission is required for this test, and it is accomplished by passing a value of zero to the **semop(2)** system call.

On the other hand, if the process is not successful and the process does not request to have its execution suspended, it is called a "nonblocking semaphore operation." In this case, the process is returned a known error code (-1), and the external **errno** variable is set accordingly.

The blocking semaphore operation allows processes to communicate based on the values of semaphores at different points in time. Remember also that IPC facilities remain in the UNIX operating system until removed by a permitted process or until the system is reinitialized.

Operating on a semaphore set is done by using the **semop(2)**, semaphore operation, system call.

When a set of semaphores is created, the first semaphore in the set is semaphore number zero. The last semaphore number in the set is one less than the total in the set.

An array of these "blocking/nonblocking operations" can be performed on a set containing more than one semaphore. When performing an array of operations, the "blocking/nonblocking operations" can be applied to any or all of the semaphores in the set. Also, the operations can be applied in any order of semaphore number. However, no operations are done until they can all be done successfully. This requirement means that preceding changes made to semaphore values in the set must be undone when a "blocking semaphore operation" on a semaphore in the set cannot be completed successfully; no changes are made until they can all be made. For example, if a process has successfully completed three of six operations on a set of ten semaphores but is "blocked" from performing the fourth operation, no changes are made to the set until the fourth and remaining operations are successfully performed. Additionally, any operation preceding or succeeding the "blocked" operation, including the blocked operation, can specify that at such time that all operations can be performed successfully, that the operation be undone. Otherwise, the operations are performed and the semaphores are changed, or one "nonblocking operation" is unsuccessful and none are changed. All of this is commonly referred to as being "atomically performed."

The ability to undo operations requires the UNIX operating system to maintain an array of "undo structures" corresponding to the array of semaphore operations to be performed. Each semaphore operation which is to be undone has an associated adjust variable used for undoing the operation, if necessary.

Remember, any unsuccessful "nonblocking operation" for a single semaphore or a set of semaphores causes immediate return with no operations performed at all. When this occurs, a known error code (-1) is returned to the process, and the external variable **errno** is set accordingly.

System calls make these semaphore capabilities available to processes. The calling process passes arguments to a system call, and the system call either successfully or unsuccessfully performs its function. If the system call is successful, it performs its function and returns the appropriate information. Otherwise, a known error code (-1) is returned to the process, and the external variable **errno** is set accordingly.

## Using Semaphores

Before semaphores can be used (operated on or controlled) a uniquely identified **data structure** and **semaphore set** (array) must be created. The unique identifier is called the semaphore identifier (**semid**); it is used to identify or reference a particular data structure and semaphore set.

The semaphore set contains a predefined number of structures in an array, one structure for each semaphore in the set. The number of semaphores (**nsems**) in a semaphore set is user-selectable. The following members are in each structure within a semaphore set:

- semaphore text map address
- process identification (PID) performing last operation
- number of processes awaiting the semaphore value to become greater than its current value
- number of processes awaiting the semaphore value to equal zero

There is one associated data structure for the uniquely identified semaphore set. This data structure contains information related to the semaphore set as follows:

- operation permissions data (operation permissions structure)
- pointer to first semaphore in the set (array)
- number of semaphores in the set
- last semaphore operation time
- last semaphore change time

The C Programming Language data structure definition for the semaphore set (array member) is located in the **#include <sys/sem.h>** header file and is as follows:

```
struct sem
{
    ushort  semval;      /* semaphore text map address */
    short   sempid;     /* pid of last operation */
    ushort  semncnt;    /* # awaiting semval > cval */
    ushort  semzcnt;    /* # awaiting semval = 0 */
};
```

Likewise, the structure definition for the associated semaphore data structure is also located in the **#include <sys/sem.h>** header file and is as follows:

```
struct semid_ds
{
    struct ipc_perm sem_perm; /* operation permission struct */
    struct sem      *sem_base; /* ptr to first semaphore in set */
    ushort         sem_nsems; /* # of semaphores in set */
    time_t         sem_otime; /* last semop time */
    time_t         sem_ctime; /* last change time */
};
```

Note that the **sem\_perm** member of this structure uses **ipc\_perm** as a template. The breakout for the operation permissions data structure is shown in Figure 9-1.

The **ipc\_perm** data structure is the same for all IPC facilities, and it is located in the **#include <sys/ipc.h>** header file. It is shown in the "Messages" section.

The **semget(2)** system call is used to perform two tasks when only the **IPC\_CREAT** flag is set in the **semflg** argument that it receives:

- to get a new **semid** and create an associated data structure and semaphore set for it
- to return an existing **semid** that already has an associated data structure and semaphore set

The task performed is determined by the value of the **key** argument passed to the **semget(2)** system call. For the first task, if the **key** is not already in use for an existing **semid**, a new **semid** is returned with an associated data structure and semaphore set created for it provided no system tunable parameter would be exceeded.

There is also a provision for specifying a **key** of value zero (0) which is known as the private **key** (**IPC\_PRIVATE = 0**); when specified, a new **semid** is always returned with an associated data structure and semaphore set created for it unless a system tunable parameter would be exceeded. When the **ipcs** command is performed, the **KEY** field for the **semid** is all zeros.



When performing the first task, the process which calls **semget()** becomes the owner/creator, and the associated data structure is initialized accordingly. Remember, ownership can be changed, but the creating process always remains the creator; see the "Controlling Semaphores" section in this chapter. The creator of the semaphore set also determines the initial operation permissions for the facility.

For the second task, if a **semid** exists for the **key** specified, the value of the existing **semid** is returned. If it is not desired to have an existing **semid** returned, a control command (**IPC\_EXCL**) can be specified (set) in the **semflg** argument passed to the system call. The system call will fail if it is passed a value for the number of semaphores (**nsems**) that is greater than the number actually in the set; if you do not know how many semaphores are in the set, use 0 for **nsems**. The details of using this system call are discussed in the "Using **semget**" section of this chapter.

Once a uniquely identified semaphore set and data structure are created, semaphore operations [**semop(2)**] and semaphore control [**semctl()**] can be used.

Semaphore operations consist of incrementing, decrementing, and testing for zero. A single system call is used to perform these operations. It is called **semop()**. Refer to the "Operations on Semaphores" section in this chapter for details of this system call.

Semaphore control is done by using the **semctl(2)** system call. These control operations permit you to control the semaphore facility in the following ways:

- to return the value of a semaphore
- to set the value of a semaphore
- to return the process identification (PID) of the last process performing an operation on a semaphore set
- to return the number of processes waiting for a semaphore value to become greater than its current value
- to return the number of processes waiting for a semaphore value to equal zero
- to get all semaphore values in a set and place them in an array in user memory

## Semaphores

---

- to set all semaphore values in a semaphore set from an array of values in user memory
- to place all data structure member values, status, of a semaphore set into user memory area
- to change operation permissions for a semaphore set
- to remove a particular **semid** from the UNIX operating system along with its associated data structure and semaphore set.

Refer to the "Controlling Semaphores" section in this chapter for details of the **semctl(2)** system call.

## Getting Semaphores

This section contains a detailed description of using the **semget(2)** system call along with an example program illustrating its use.

### Using **semget**

The synopsis found in the **semget(2)** entry in the *Programmer's Reference Manual* is as follows:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>

int semget (key, nsems, semg)
key_t key;
int nsems, semg;
```

The following line in the synopsis informs you that **semget()** is a function with three formal arguments that returns an integer type value upon successful completion (**semid**).

```
int semget (key, nsems, semflg)
```

The next two lines declare the types of the formal arguments. **key\_t** is declared by a **typedef** in the **types.h** header file to be an integer.

```
key_t key;  
int nsems, semflg;
```

The integer returned from this system call upon successful completion is the semaphore set identifier (**semid**) that was discussed earlier.

As declared, the process calling the **semget()** system call must supply three arguments to be passed to the formal **key**, **nsems**, and **semflg** arguments.

A new **semid** with an associated semaphore set and data structure is provided if one of the following conditions exists:

- **key** is equal to **IPC\_PRIVATE**
- **key** is passed a unique hexadecimal integer, and **semflg** ANDed with **IPC\_CREAT** is **TRUE**.

The value passed to the **semflg** argument must be an integer type octal value and will specify the following:

- access permissions
- execution modes
- control fields (commands)

Access permissions determine the read/alter attributes, and execution modes determine the user/group/other attributes of the **semflg** argument. They are collectively referred to as "operation permissions." Figure 9-7 reflects the numeric values (expressed in octal notation) for the valid operation permissions codes.

<u>Operation Permissions</u>	<u>Octal Value</u>
Read by User	00400
Alter by User	00200
Read by Group	00040
Alter by Group	00020
Read by Others	00004
Alter by Others	00002

Figure 9-7: Operation Permissions Codes

---

A specific octal value is derived by adding the octal values for the operation permissions desired. That is, if read by user and read/alter by others is desired, the code value would be 00406 (00400 plus 00006). There are constants **#define**'d in the **sem.h** header file which can be used for the user (OWNER). They are:

```
SEM_A    0200    /* alter permission by owner */
SEM_R    0400    /* read permission by owner */
```

Control commands are predefined constants (represented by all uppercase letters). Figure 9-8 contains the names of the constants which apply to the **semget(2)** system call along with their values. They are also referred to as flags and are defined in the **ipc.h** header file.

<u>Control Command</u>	<u>Value</u>
IPC_CREAT	0001000
IPC_EXCL	0002000

Figure 9-8: Control Commands (Flags)

---

The value for the **semflg** argument is, therefore, a combination of operation permissions and control commands. After determining the value for the operation permissions as previously described, the desired flag(s) can be specified. This specification is accomplished by bitwise ORing (!) them with the operation permissions; bit positions and values for the control commands in relation to those of the operation permissions make this possible. An example of determining the **semflg** argument follows.

		Octal Value	Binary Value
IPC_CREAT	=	0 1 0 0 0	0 000 001 000 000 000
CW! ORed by User	=	0 0 4 0 0	0 000 000 100 000 000
<b>semflg</b>	=	0 1 4 0 0	0 000 001 100 000 000

The **semflg** value can easily be set by using the names of the flags in conjunction with the octal operation permissions value:

```
semid = semget (key, nsems, (IPC_CREAT | 0400));
semid = semget (key, nsems, (IPC_CREAT | IPC_EXCL | 0400));
```

As specified by the **semget(2)** entry in the *Programmer's Reference Manual*, success or failure of this system call depends upon the actual argument values for **key**, **nsems**, **semflg** or system tunable parameters. The system call will attempt to return a new **semid** if one of the following conditions exists:

- **key** is equal to `IPC_PRIVATE (0)`
- **key** does not already have a **semid** associated with it, and **(semflg & IPC\_CREAT)** is TRUE (not zero).

The **key** argument can be set to `IPC_PRIVATE` in the following ways:

```
semid = semget (IPC_PRIVATE, nsems, semflg);
```

or

```
semid = semget ( 0, nsems, semflg);
```

This alone will cause the system call to be attempted because it satisfies the first condition specified. Exceeding the `SEMMNI`, `SEMMNS`, or `SEMMSL` system-tunable parameters will always cause a failure. The `SEMMNI` system-tunable parameter determines the maximum number of unique semaphore sets (**semid**'s) in the UNIX operating system. The `SEMMNS` system-tunable parameter determines the maximum number of semaphores in all semaphore sets system wide. The `SEMMSL` system-tunable parameter determines the maximum number of semaphores in each semaphore set.

The second condition is satisfied if the value for **key** is not already associated with a **semid** and the bitwise ANDing of **semflg** and `IPC_CREAT` is TRUE (not zero). This means that the **key** is unique (not in use) within the UNIX operating system for this facility type and that the `IPC_CREAT` flag is set (**semflg** | `IPC_CREAT`). The bitwise ANDing (&), which is the logical way of testing if a flag is set, is illustrated as follows:

```
semflg = x 1 x x x   (x = immaterial)
& IPC_CREAT = 0 1 0 0 0
result = 0 1 0 0 0   (not zero)
```

Since the result is not zero, the flag is set or TRUE. `SEMMNI`, `SEMMNS`, and `SEMMSL` apply here also, just as for condition one.

`IPC_EXCL` is another control command used in conjunction with `IPC_CREAT` to exclusively have the system call fail if, and only if, a **semid** exists for the specified **key** provided. This is necessary to prevent the process from thinking that it has received a new (unique) **semid** when it has not. In other words, when both `IPC_CREAT` and `IPC_EXCL` are specified, a new **semid** is returned if the system call is successful. Any value for **semflg** returns a new **semid** if the **key** equals zero (`IPC_PRIVATE`) and no system-tunable parameters are exceeded.

Refer to the `semget(2)` manual page for specific, associated data structure initialization for successful completion.

### Example Program

The example program in this section (Figure 9-9) is a menu-driven program which allows all possible combinations of using the `semget(2)` system call to be exercised.

From studying this program, you can observe the method of passing arguments and receiving return values. The user-written program requirements are pointed out.

This program begins (lines 4-8) by including the required header files as specified by the `semget(2)` entry in the *Programmer's Reference Manual*. Note that the `errno.h` header file is included as opposed to declaring `errno` as an external variable; either method will work.

Variable names have been chosen to be as close as possible to those in the synopsis for the system call. Their declarations are self-explanatory. These names make the program more readable, and are perfectly legal since they are local to the program. Variables declared for this program and their purpose are:

- **key**—used to pass the value for the desired **key**
- **opperm**—used to store the desired operation permissions
- **flags**—used to store the desired control commands (flags)
- **opperm\_flags**—used to store the combination from the logical ORing of the **opperm** and **flags** variables; it is then used in the system call to pass the **semflg** argument.
- **semid**—used for returning the semaphore set identification number for a successful system call or the error code (-1) for an unsuccessful one.

The program begins by prompting for a hexadecimal **key**, an octal operation permissions code, and the control command combinations (flags) which are selected from a menu (lines 15-32). All possible combinations are allowed even though they might not be viable. This allows observing the errors for illegal combinations.

Next, the menu selection for the flags is combined with the operation permissions, and the result is stored at the address of the **opperm\_flags** variable (lines 36-52).

Then, the number of semaphores for the set is requested (lines 53-57), and its value is stored at the address of **nsems**.

The system call is made next, and the result is stored at the address of the **semid** variable (lines 60 and 61).

Since the **semid** variable now contains a valid semaphore set identifier or the error code (-1), it is tested to see if an error occurred (line 63). If **semid** equals -1, a message indicates that an error resulted and the external **errno** variable is displayed (lines 65 and 66). Remember that the external **errno** variable is only set when a system call fails; it should only be tested immediately following system calls.

## Semaphores

---

If no error occurred, the returned semaphore set identifier is displayed (line 70).

The example program for the `semget(2)` system call follows. It is suggested that the source program file be named `semget.c` and that the executable file be named `semget`.

```
1  /*This is a program to illustrate
2  **the semaphore get, semget(),
3  **system call capabilities.*/

4  #include <stdio.h>
5  #include <sys/types.h>
6  #include <sys/ipc.h>
7  #include <sys/sem.h>
8  #include <errno.h>

9  /*Start of main C language program*/
10 main()
11 {
12     key_t key;    /*declare as long integer*/
13     int opperm, flags, nsems;
14     int semid, opperm_flags;

15     /*Enter the desired key*/
16     printf("\nEnter the desired key in hex = ");
17     scanf("%x", &key);

18     /*Enter the desired octal operation
19     permissions.*/
20     printf("\nEnter the operation\n");
21     printf("permissions in octal = ");
22     scanf("%o", &opperm);
```

Figure 9-9: `semget()` System Call Example (Sheet 1 of 3)

---



```
23      /*Set the desired flags.*/
24      printf("\nEnter corresponding number to\n");
25      printf("set the desired flags:\n");
26      printf("No flags          = 0\n");
27      printf("IPC_CREAT          = 1\n");
28      printf("IPC_EXCL           = 2\n");
29      printf("IPC_CREAT and IPC_EXCL = 3\n");
30      printf("          Flags      = ");
31      /*Get the flags to be set.*/
32      scanf("%d", &flags);

33      /*Error checking (debugging)*/
34      printf ("\nkey =0x%x, opperm = 0%, flags = 0%\n",
35             key, opperm, flags);
36      /*Incorporate the control fields (flags) with
37         the operation permissions.*/
38      switch (flags)
39      {
40      case 0: /*No flags are to be set.*/
41             opperm_flags = (opperm | 0);
42             break;
43      case 1: /*Set the IPC_CREAT flag.*/
44             opperm_flags = (opperm | IPC_CREAT);
45             break;
46      case 2: /*Set the IPC_EXCL flag.*/
47             opperm_flags = (opperm | IPC_EXCL);
48             break;
49      case 3: /*Set the IPC_CREAT and IPC_EXCL
50             flags.*/
51             opperm_flags = (opperm | IPC_CREAT | IPC_EXCL);
52      }
```

Figure 9-9: `semget()` System Call Example (Sheet 2 of 3)

```
53     /*Get the number of semaphores for this set.*/
54     printf("\nEnter the number of\n");
55     printf("desired semaphores for\n");
56     printf("this set (25 max) = ");
57     scanf("%d", &nsems);

58     /*Check the entry.*/
59     printf("\nNsems = %d\n", nsems);

60     /*Call the semget system call.*/
61     semid = semget(key, nsems, opperm_flags);

62     /*Perform the following if the call is unsuccessful.*/
63     if(semid == -1)
64     {
65         printf("The semget system call failed!\n");
66         printf("The error number = %d\n", errno);
67     }
68     /*Return the semid upon successful completion.*/
69     else
70         printf("\nThe semid = %d\n", semid);
71     exit(0);
72 }
```

Figure 9-9: `semget()` System Call Example (Sheet 3 of 3)

---

## Controlling Semaphores

This section contains a detailed description of using the `semctl(2)` system call along with an example program which allows all of its capabilities to be exercised.

## Using semctl

The synopsis found in the **semctl(2)** entry in the *Programmer's Reference Manual* is as follows:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>

int semctl (semid, semnum, cmd, arg)
int semid, cmd;
int semnum;
union semun
{
    int val;
    struct semid_ds *bu;
    ushort array[];
} arg;
```

The **semctl(2)** system call requires four arguments to be passed to it, and it returns an integer value.

The **semid** argument must be a valid, non-negative, integer value that has already been created by using the **semget(2)** system call.

The **semnum** argument is used to select a semaphore by its number. This relates to array (atomically performed) operations on the set. When a set of semaphores is created, the first semaphore is number 0, and the last semaphore has the number of one less than the total in the set.

The **cmd** argument can be replaced by one of the following control commands (flags):

- GETVAL—return the value of a single semaphore within a semaphore set
- SETVAL—set the value of a single semaphore within a semaphore set

- **GETPID**—return the Process Identifier (PID) of the process that performed the last operation on the semaphore within a semaphore set
- **GETNCNT**—return the number of processes waiting for the value of a particular semaphore to become greater than its current value
- **GETZCNT**—return the number of processes waiting for the value of a particular semaphore to be equal to zero
- **GETALL**—return the values for all semaphores in a semaphore set
- **SETALL**—set all semaphore values in a semaphore set
- **IPC\_STAT**—return the status information contained in the associated data structure for the specified **semid**, and place it in the data structure pointed to by the **\*buf** pointer in the user memory area; **arg.buf** is the union member that contains the value of **buf**.
- **IPC\_SET**—for the specified semaphore set (**semid**), set the effective user/group identification and operation permissions.
- **IPC\_RMID**—remove the specified (**semid**) semaphore set along with its associated data structure.

A process must have an effective user identification of OWNER/CREATOR or super-user to perform an **IPC\_SET** or **IPC\_RMID** control command. Read/alter permission is required as applicable for the other control commands.

The **arg** argument is used to pass the system call the appropriate union member for the control command to be performed:

- **arg.val**
- **arg.buf**
- **arg.array**

The details of this system call are discussed in the example program for it. If you have problems understanding the logic manipulations in this program, read the "Using **semget**" section of this chapter; it goes into more detail than would be practical to do for every system call.

## Example Program

The example program in this section (Figure 9-10) is a menu-driven program which allows all possible combinations of using the `semctl(2)` system call to be exercised.

From studying this program, you can observe the method of passing arguments and receiving return values. The user-written program requirements are pointed out.

This program begins (lines 5-9) by including the required header files as specified by the `semctl(2)` entry in the *Programmer's Reference Manual*. Note that in this program `errno` is declared as an external variable, and therefore the `errno.h` header file does not have to be included.

Variable, structure, and union names have been chosen to be as close as possible to those in the synopsis for the system call. Their declarations are self-explanatory. These names make the program more readable, and are perfectly legal since they are local to the program. Variables declared for this program and their purpose are:

- **semid\_ds**—used to receive the specified semaphore set identifier's data structure when an `IPC_STAT` control command is performed
- **c**—used to receive the input values from the `scanf(3S)` function, (line 117) when performing a `SETALL` control command
- **i**—used as a counter to increment through the union `arg.array` when displaying the semaphore values for a `GETALL` (lines 97-99) control command, and when initializing the `arg.array` when performing a `SETALL` (lines 115-119) control command
- **length**—used as a variable to test for the number of semaphores in a set against the `i` counter variable (lines 97 and 115)
- **uid**—used to store the `IPC_SET` value for the effective user identification
- **gid**—used to store the `IPC_SET` value for the effective group identification
- **mode**—used to store the `IPC_SET` value for the operation permissions
- **rtrn**—used to store the return integer from the system call which depends upon the control command or a `-1` when unsuccessful

- **semid**—used to store and pass the semaphore set identifier to the system call
- **semnum**—used to store and pass the semaphore number to the system call
- **cmd**—used to store the code for the desired control command so that subsequent processing can be performed on it
- **choice**—used to determine which member (**uid**, **gid**, **mode**) for the `IPC_SET` control command is to be changed
- **arg.val**—used to pass the system call a value to set (`SETVAL`) or to store (`GETVAL`) a value returned from the system call for a single semaphore (union member)
- **arg.buf**—a pointer passed to the system call which locates the data structure in the user memory area where the `IPC_STAT` control command is to place its return values, or where the `IPC_SET` command gets the values to set (union member)
- **arg.array**—used to store the set of semaphore values when getting (`GETALL`) or initializing (`SETALL`) (union member).

Note that the **semid\_ds** data structure in this program (line 14) uses the data structure located in the **sem.h** header file of the same name as a template for its declaration. This is a perfect example of the advantage of local variables.

The **arg** union (lines 18-22) serves three purposes in one. The compiler allocates enough storage to hold its largest member. The program can then use the union as any member by referencing union members as if they were regular structure members. Note that the array is declared to have 25 elements (0 through 24). This number corresponds to the maximum number of semaphores allowed per set (`SEMMSL`), a system tunable parameter.

The next important program aspect to observe is that although the **\*buf** pointer member (**arg.buf**) of the union is declared to be a pointer to a data structure of the **semid\_ds** type, it must also be initialized to contain the address of the user memory area data structure (line 24). Because of the way this program is written, the pointer does not need to be reinitialized later. If it was used to increment through the array, it would need to be reinitialized just before calling the system call.

Now that all of the required declarations have been presented for this program, this is how it works.

First, the program prompts for a valid semaphore set identifier, which is stored at the address of the **semid** variable (lines 25-27). This is required for all **semctl(2)** system calls.

Then, the code for the desired control command must be entered (lines 28-42), and the code is stored at the address of the **cmd** variable. The code is tested to determine the control command for subsequent processing.

If the GETVAL control command is selected (code 1), a message prompting for a semaphore number is displayed (lines 49 and 50). When it is entered, it is stored at the address of the **semnum** variable (line 51). Then, the system call is performed, and the semaphore value is displayed (lines 52-55). If the system call is successful, a message indicates this along with the semaphore set identifier used (lines 195, 196); if the system call is unsuccessful, an error message is displayed along with the value of the external **errno** variable (lines 191-193).

If the SETVAL control command is selected (code 2), a message prompting for a semaphore number is displayed (lines 56 and 57). When it is entered, it is stored at the address of the **semnum** variable (line 58). Next, a message prompts for the value to which the semaphore is to be set, and it is stored as the **arg.val** member of the union (lines 59 and 60). Then, the system call is performed (lines 61, 63). Depending upon success or failure, the program returns the same messages as for GETVAL above.

If the GETPID control command is selected (code 3), the system call is made immediately since all required arguments are known (lines 64-67), and the PID of the process performing the last operation is displayed. Depending upon success or failure, the program returns the same messages as for GETVAL above.

If the GETNCNT control command is selected (code 4), a message prompting for a semaphore number is displayed (lines 68-72). When entered, it is stored at the address of the **semnum** variable (line 73). Then, the system call is performed, and the number of processes waiting for the semaphore to become greater than its current value is displayed (lines 74-77). Depending upon success or failure, the program returns the same messages as for GETVAL above.

If the GETZCNT control command is selected (code 5), a message prompting for a semaphore number is displayed (lines 78-81). When it is entered, it is stored at the address of the **semnum** variable (line 82). Then the system call is performed, and the number of processes waiting for the semaphore value to become equal to zero is displayed (lines 83-86). Depending upon success or failure, the program returns the same messages as for GETVAL above.

If the GETALL control command is selected (code 6), the program first performs an IPC\_STAT control command to determine the number of semaphores in the set (lines 88-93). The length variable is set to the number of semaphores in the set (line 91). Next, the system call is made and, upon success, the **arg.array** union member contains the values of the semaphore set (line 96). Now, a loop is entered which displays each element of the **arg.array** from zero to one less than the value of length (lines 97-103). The semaphores in the set are displayed on a single line, separated by a space. Depending upon success or failure, the program returns the same messages as for GETVAL above.

If the SETALL control command is selected (code 7), the program first performs an IPC\_STAT control command to determine the number of semaphores in the set (lines 106-108). The length variable is set to the number of semaphores in the set (line 109). Next, the program prompts for the values to be set and enters a loop which takes values from the keyboard and initializes the **arg.array** union member to contain the desired values of the semaphore set (lines 113-119). The loop puts the first entry into the array position for semaphore number zero and ends when the semaphore number that is filled in the array equals one less than the value of length. The system call is then made (lines 120-122). Depending upon success or failure, the program returns the same messages as for GETVAL above.

If the IPC\_STAT control command is selected (code 8), the system call is performed (line 127), and the status information returned is printed out (lines 128-139); only the members that can be set are printed out in this program. Note that if the system call is unsuccessful, the status information of the last successful one is printed out. In addition, an error message is displayed, and the **errno** variable is printed out (lines 191 and 192).

If the IPC\_SET control command is selected (code 9), the program gets the current status information for the semaphore set identifier specified (lines 143-146). This is necessary because this example program provides for changing only one member at a time, and the **semctl(2)** system call changes all of them. Also, if an invalid value happened to be stored in the user memory



area for one of these members, it would cause repetitive failures for this control command until corrected. The next thing the program does is to prompt for a code corresponding to the member to be changed (lines 147-153). This code is stored at the address of the choice variable (line 154). Now, depending upon the member picked, the program prompts for the new value (lines 155-178). The value is placed at the address of the appropriate member in the user memory area data structure, and the system call is made (line 181). Depending upon success or failure, the program returns the same messages as for GETVAL above.

If the IPC\_RMID control command (code 10) is selected, the system call is performed (lines 183-185). The **semid** along with its associated data structure and semaphore set is removed from the UNIX operating system. Depending upon success or failure, the program returns the same messages as for the other control commands.

The example program for the **semctl(2)** system call follows. It is suggested that the source program file be named **semctl.c** and that the executable file be named **semctl**.

```
1  /*This is a program to illustrate
2  **the semaphore control, semctl(),
3  **system call capabilities.
4  */

5  /*Include necessary header files.*/
6  #include <stdio.h>
7  #include <sys/types.h>
8  #include <sys/ipc.h>
9  #include <sys/sem.h>

10 /*Start of main C language program*/
11 main()
12 {
13     extern int errno;
14     struct semid_ds semid_ds;
15     int c, i, length;
16     int uid, gid, mode;
17     int retrn, semid, semnum, cmd, choice;
18     union semun {
19         int val;
20         struct semid_ds *buf;
21         ushort array[25];
22     } arg;

23     /*Initialize the data structure pointer.*/
24     arg.buf = &semid_ds;
```

Figure 9-10: `semctl()` System Call Example (Sheet 1 of 7)

---

```
25      /*Enter the semaphore ID.*/
26      printf("Enter the semid = ");
27      scanf("%d", &semid);

28      /*Choose the desired command.*/
29      printf("\nEnter the number for\n");
30      printf("the desired cmd:\n");
31      printf("GETVAL      = 1\n");
32      printf("SETVAL      = 2\n");
33      printf("GETPID      = 3\n");
34      printf("GETINCNT   = 4\n");
35      printf("GETZCNT    = 5\n");
36      printf("GETALL     = 6\n");
37      printf("SETALL     = 7\n");
38      printf("IPC_STAT   = 8\n");
39      printf("IPC_SET    = 9\n");
40      printf("IPC_RMID   = 10\n");
41      printf("Entry      = ");
42      scanf("%d", &cmd);

43      /*Check entries.*/
44      printf ("\nsemid =%d, cmd = %d\n\n",
45             semid, cmd);

46      /*Set the command and do the call.*/
47      switch (cmd)
48      {
```

Figure 9-10: `semctl()` System Call Example (Sheet 2 of 7)

```
49     case 1: /*Get a specified value.*/
50         printf("\nEnter the semnum = ");
51         scanf("%d", &semnum);
52         /*Do the system call.*/
53         retrn = semctl(semid, semnum, GETVAL, 0);
54         printf("\nThe semval = %d\n", retrn);
55         break;
56     case 2: /*Set a specified value.*/
57         printf("\nEnter the semnum = ");
58         scanf("%d", &semnum);
59         printf("\nEnter the value = ");
60         scanf("%d", &arg.val);
61         /*Do the system call.*/
62         retrn = semctl(semid, semnum, SETVAL, arg.val);
63         break;
64     case 3: /*Get the process ID.*/
65         retrn = semctl(semid, 0, GETPID, 0);
66         printf("\nThe sempid = %d\n", retrn);
67         break;
68     case 4: /*Get the number of processes
69             waiting for the semaphore to
70             become greater than its current
71             value.*/
72         printf("\nEnter the semnum = ");
73         scanf("%d", &semnum);
74         /*Do the system call.*/
75         retrn = semctl(semid, semnum, GETNCNT, 0);
76         printf("\nThe semncnt = %d", retrn);
77         break;
```

Figure 9-10: **semctl()** System Call Example (Sheet 3 of 7)

---

```
78     case 5: /*Get the number of processes
79             waiting for the semaphore
80             value to become zero.*/
81     printf("\nEnter the semnum = ");
82     scanf("%d", &semnum);
83     /*Do the system call.*/
84     retrn = semctl(semid, semnum, GETZCNT, 0);
85     printf("\nThe semzcnt = %d", retrn);
86     break;

87     case 6: /*Get all of the semaphores.*/
88     /*Get the number of semaphores in
89             the semaphore set.*/
90     retrn = semctl(semid, 0, IPC_STAT, arg.buf);
91     length = arg.buf->sem_nsems;
92     if(retrn == -1)
93         goto ERROR;
94     /*Get and print all semaphores in the
95             specified set.*/
96     retrn = semctl(semid, 0, GETALL, arg.array);
97     for (i = 0; i < length; i++)
98     {
99         printf("%d", arg.array[i]);
100        /*Separate each
101            semaphore.*/
102        printf("%c", ' ');
103    }
104    break;
```

Figure 9-10: `semctl()` System Call Example (Sheet 4 of 7)

```
105     case 7: /*Set all semaphores in the set.*/
106         /*Get the number of semaphores in
107            the set.*/
108         retrn = semctl(semid, 0, IPC_STAT, arg.buf);
109         length = arg.buf->sem_nsems;
110         printf("Length = %d\n", length);
111         if(retrn == -1)
112             goto ERROR;
113         /*Set the semaphore set values.*/
114         printf("\nEnter each value:\n");
115         for(i = 0; i < length ; i++)
116             {
117                 scanf("%d", &c);
118                 arg.array[i] = c;
119             }
120         /*Do the system call.*/
121         retrn = semctl(semid, 0, SETALL, arg.array);
122         break;

123     case 8: /*Get the status for the semaphore set.*/
124         /*Get and print the current status values.*/
125         retrn = semctl(semid, 0, IPC_STAT, arg.buf);
126         printf ("\nThe USER ID = %d\n",
127             arg.buf->sem_perm.uid);
128         printf ("The GROUP ID = %d\n",
129             arg.buf->sem_perm.gid);
130         printf ("The operation permissions = 0%o\n",
131             arg.buf->sem_perm.mode);
132         printf ("The number of semaphores in set = %d\n",
133             arg.buf->sem_nsems);
134         printf ("The last semop time = %d\n",
135             arg.buf->sem_otime);
136         printf ("The last semop time = %d\n",
137             arg.buf->sem_otime);
```

Figure 9-10: `semctl()` System Call Example (Sheet 5 of 7)

---

```
138     printf ("The last change time = %d\n",
139             arg.buf->sem_ctime);
140     break;

141     case 9: /*Select and change the desired
142             member of the data structure.*/
143             /*Get the current status values.*/
144             retm = semctl(semid, 0, IPC_STAT, arg.buf);
145             if(retm == -1)
146                 goto ERROR;
147             /*Select the member to change.*/
148             printf("\nEnter the number for the\n");
149             printf("member to be changed:\n");
150             printf("sem_perm.uid   = 1\n");
151             printf("sem_perm.gid   = 2\n");
152             printf("sem_perm.mode  = 3\n");
153             printf("Entry       = ");
154             scanf("%d", &choice);
155             switch(choice){

156                 case 1: /*Change the user ID.*/
157                     printf("\nEnter USER ID = ");
158                     scanf ("%d", &uid);
159                     arg.buf->sem_perm.uid = uid;
160                     printf("\nUSER ID = %d\n",
161                             arg.buf->sem_perm.uid);
162                     break;

163                 case 2: /*Change the group ID.*/
164                     printf("\nEnter GROUP ID = ");
165                     scanf("%d", &gid);
166                     arg.buf->sem_perm.gid = gid;
167                     printf("\nGROUP ID = %d\n",
168                             arg.buf->sem_perm.gid);
169                     break;
```

Figure 9-10: `semctl()` System Call Example (Sheet 6 of 7)

```
170         case 3: /*Change the mode portion of
171                 the operation
172                     permissions.*/
173             printf("\nEnter MODE = ");
174             scanf("%o", &mode);
175             arg.buf->sem_perm.mode = mode;
176             printf("\nMODE = 0%o\n",
177                 arg.buf->sem_perm.mode);
178             break;
179         }
180         /*Do the change.*/
181         retrn = semctl(semid, 0, IPC_SET, arg.buf);
182         break;
183     case 10: /*Remove the semid along with its
184             data structure.*/
185         retrn = semctl(semid, 0, IPC_RMID, 0);
186     }
187     /*Perform the following if the call is unsuccessful.*/
188     if(retrn == -1)
189     {
190     ERROR:
191         printf ("\n\nThe semctl system call failed!\n");
192         printf ("The error number = %d\n", errno);
193         exit(0);
194     }
195     printf ("\n\nThe semctl system call was successful\n");
196     printf ("for semid = %d\n", semid);
197     exit (0);
198 }
```

Figure 9-10: **semctl()** System Call Example (Sheet 7 of 7)

---



## Operations on Semaphores

This section contains a detailed description of using the **semop(2)** system call along with an example program which allows all of its capabilities to be exercised.

### Using semop

The synopsis found in the **semop(2)** entry in the *Programmer's Reference Manual* is as follows:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>

int semop (semid, sops, nsops)
int semid;
struct sembuf **sops;
unsigned nsops;
```

The **semop(2)** system call requires three arguments to be passed to it, and it returns an integer value. Upon successful completion, a zero value is returned. When unsuccessful, a  $-1$  is returned.

The **semid** argument must be a valid, non-negative, integer value; that is, it must have already been created by using the **semget(2)** system call.

The **sops** argument is a pointer to an array of structures in the user memory area that contains the following for each semaphore to be changed:

- the semaphore number
- the operation to be performed
- the control command (flags)

The **\*\*sops** declaration means that a pointer can be initialized to the address of the array, or the array name can be used since it is the address of the first element of the array. **Sembuf** is the *tag* name of the data structure used as the template for the structure members in the array; it is located in the **#include <sys/sem.h>** header file.

The **nsops** argument specifies the length of the array (the number of structures in the array). The maximum **size** of this array is determined by the SEMOPM system tunable parameter. Therefore, a maximum of SEMOPM operations can be performed for each **semop(2)** system call.

The semaphore number determines the particular semaphore within the set on which the operation is to be performed.

The operation to be performed is determined by the following:

- a positive integer value means to increment the semaphore value by its value
- a negative integer value means to decrement the semaphore value by its value
- a value of zero means to test if the semaphore is equal to zero

The following operation commands (flags) can be used:

- **IPC\_NOWAIT**—this operation command can be set for any operations in the array. The system call will return unsuccessfully without changing any semaphore values at all if any operation for which **IPC\_NOWAIT** is set cannot be performed successfully. The system call will be unsuccessful when trying to decrement a semaphore more than its current value, or when testing for a semaphore to be equal to zero when it is not.
- **SEM\_UNDO**—this operation command allows any operations in the array to be undone when any operation in the array is unsuccessful and does not have the **IPC\_NOWAIT** flag set. That is, the blocked operation waits until it can perform its operation; and when it and all succeeding operations are successful, all operations with the **SEM\_UNDO** flag set are undone. Remember, no operations are performed on any semaphores in a set until all operations are successful. Undoing is accomplished by using an array of adjust values for the operations that are to be undone when the blocked operation and all subsequent operations are successful.

## Example Program

The example program in this section (Figure 9-11) is a menu-driven program which allows all possible combinations of using the **semop(2)** system call to be exercised.

From studying this program, you can observe the method of passing arguments and receiving return values. The user-written program requirements are pointed out.

This program begins (lines 5-9) by including the required header files as specified by the **shmop(2)** entry in the *Programmer's Reference Manual*. Note that in this program **errno** is declared as an external variable, and therefore, the **errno.h** header file does not have to be included.

Variable and structure names have been chosen to be as close as possible to those in the synopsis for the system call. Their declarations are self-explanatory. These names make the program more readable, and are perfectly legal since they are local to the program. Variables declared for this program and their purpose are:

- **sembuf[10]**—used as an array buffer (line 14) to contain a maximum of ten **sembuf** type structures; ten equals SEMOPM, the maximum number of operations on a semaphore set for each **semop(2)** system call.
- **\*sops**—used as a pointer (line 14) to **sembuf[10]** for the system call and for accessing the structure members within the array
- **rtrn**—used to store the return values from the system call
- **flags**—used to store the code of the IPC\_NOWAIT or SEM\_UNDO flags for the **semop(2)** system call (line 60)
- **i**—used as a counter (line 32) for initializing the structure members in the array, and used to print out each structure in the array (line 79)
- **nsops**—used to specify the number of semaphore operations for the system call—must be less than or equal to SEMOPM
- **semid**—used to store the desired semaphore set identifier for the system call

First, the program prompts for a semaphore set identifier that the system call is to perform operations on (lines 19-22). `semid` is stored at the address of the `semid` variable (line 23).

A message is displayed requesting the number of operations to be performed on this set (lines 25-27). The number of operations is stored at the address of the `nsops` variable (line 28).

Next, a loop is entered to initialize the array of structures (lines 30-77). The semaphore number, operation, and operation command (flags) are entered for each structure in the array. The number of structures equals the number of semaphore operations (`nsops`) to be performed for the system call, so `nsops` is tested against the `i` counter for loop control. Note that `sops` is used as a pointer to each element (structure) in the array, and `sops` is incremented just like `i`. `sops` is then used to point to each member in the structure for setting them.

After the array is initialized, all of its elements are printed out for feedback (lines 78-85).

The `sops` pointer is set to the address of the array (lines 86 and 87). `sembuf` could be used directly, if desired, instead of `sops` in the system call.

The system call is made (line 89), and depending upon success or failure, a corresponding message is displayed. The results of the operation(s) can be viewed by using the `semctl()` GETALL control command.

The example program for the `semop(2)` system call follows. It is suggested that the source program file be named `semop.c` and that the executable file be named `semop`.

```
1  /*This is a program to illustrate
2  **the semaphore operations, semop(),
3  **system call capabilities.
4  */

5  /*Include necessary header files.*/
6  #include <stdio.h>
7  #include <sys/types.h>
8  #include <sys/ipc.h>
9  #include <sys/sem.h>
10 /*Start of main C language program*/
11 main()
12 {
13     extern int errno;
14     struct sembuf sembuf[10], *sops;
15     char string[];
16     int retrn, flags, sem_num, i, semid;
17     unsigned nsops;
18     sops = sembuf; /*Pointer to array sembuf.*/

19     /*Enter the semaphore ID.*/
20     printf("\nEnter the semid of\n");
21     printf("the semaphore set to\n");
22     printf("be operated on = ");
23     scanf("%d", &semid);
24     printf("\nsemid = %d", semid);
```

Figure 9-11: **semop(2)** System Call Example (Sheet 1 of 4)

```
25      /*Enter the number of operations.*/
26      printf("\nEnter the number of semaphore\n");
27      printf("operations for this set = ");
28      scanf("%d", &nsops);
29      printf("\nnsops = %d", nsops);

30      /*Initialize the array for the
31         number of operations to be performed.*/
32      for(i = 0; i < nsops; i++, sops++)
33      {

34          /*This determines the semaphore in
35             the semaphore set.*/
36          printf("\nEnter the semaphore\n");
37          printf("number (sem_num) = ");
38          scanf("%d", &sem_num);
39          sops->sem_num = sem_num;
40          printf("\nThe sem_num = %d", sops->sem_num);

41          /*Enter a (-)number to decrement,
42             an unsigned number (no +) to increment,
43             or zero to test for zero. These values
44             are entered into a string and converted
45             to integer values.*/
46          printf("\nEnter the operation for\n");
47          printf("the semaphore (sem_op) = ");
48          scanf("%s", string);
49          sops->sem_op = atoi(string);
50          printf("\nsem_op = %d\n", sops->sem_op);
```

---

Figure 9-11: **semop(2)** System Call Example (Sheet 2 of 4)

```
51      /*Specify the desired flags.*/
52      printf("\nEnter the corresponding\n");
53      printf("number for the desired\n");
54      printf("flags:\n");
55      printf("No flags           = 0\n");
56      printf("IPC_NOWAIT           = 1\n");
57      printf("SEM_UNDO             = 2\n");
58      printf("IPC_NOWAIT and SEM_UNDO = 3\n");
59      printf("           Flags      = ");
60      scanf("%d", &flags);

61      switch(flags)
62      {
63      case 0:
64          sops->sem_flg = 0;
65          break;
66      case 1:
67          sops->sem_flg = IPC_NOWAIT;
68          break;
69      case 2:
70          sops->sem_flg = SEM_UNDO;
71          break;
72      case 3:
73          sops->sem_flg = IPC_NOWAIT | SEM_UNDO;
74          break;
75      }
76      printf("\nFlags = 0%o\n", sops->sem_flg);
77  }
```

Figure 9-11: **semop(2)** System Call Example (Sheet 3 of 4)

```
78      /*Print out each structure in the array.*/
79      for(i = 0; i < nsops; i++)
80      {
81          printf("\nsem_num = %d\n", sembuf[i].sem_num);
82          printf("sem_op = %d\n", sembuf[i].sem_op);
83          printf("sem_flg = %o\n", sembuf[i].sem_flg);
84          printf("%c", ' ');
85      }

86      sops = sembuf; /*Reset the pointer to
87                    sembuf[0].*/

88      /*Do the semop system call.*/
89      retm = semop(semid, sops, nsops);
90      if(retm == -1) {
91          printf("\nSemop failed. ");
92          printf("Error = %d\n", errno);
93      }
94      else {
95          printf ("\nSemop was successful\n");
96          printf("for semid = %d\n", semid);

97          printf("Value returned = %d\n", retm);
98      }
99  }
```

Figure 9-11: **semop(2)** System Call Example (Sheet 4 of 4)

---



---

# Shared Memory

The shared memory type of IPC allows two or more processes (executing programs) to share memory and consequently the data contained there. This is done by allowing processes to set up access to a common virtual memory address space. This sharing occurs on a segment basis, which is memory management hardware dependent.

This sharing of memory provides the fastest means of exchanging data between processes.

A process initially creates a shared memory segment facility using the **shmget(2)** system call. Upon creation, this process sets the overall operation permissions for the shared memory segment facility, sets its size in bytes, and can specify that the shared memory segment is for reference only (read-only) upon attachment. If the memory segment is not specified to be for reference only, all other processes with appropriate operation permissions can read from or write to the memory segment.

There are two operations that can be performed on a shared memory segment:

- **shmat(2)** — shared memory attach
- **shmdt(2)** — shared memory detach

Shared memory attach allows processes to associate themselves with the shared memory segment if they have permission. They can then read or write as allowed.

Shared memory detach allows processes to disassociate themselves from a shared memory segment. Therefore, they lose the ability to read from or write to the shared memory segment.

The original owner/creator of a shared memory segment can relinquish ownership to another process using the **shmctl(2)** system call. However, the creating process remains the creator until the facility is removed or the system is reinitialized. Other processes with permission can perform other functions on the shared memory segment using the **shmctl(2)** system call.

System calls, which are documented in the *Programmer's Reference Manual*, make these shared memory capabilities available to processes. The calling process passes arguments to a system call, and the system call either successfully or unsuccessfully performs its function. If the system call is successful, it performs its function and returns the appropriate information. Otherwise, a known error code (-1) is returned to the process, and the external variable `errno` is set accordingly.

## Using Shared Memory

The sharing of memory between processes occurs on a virtual segment basis. There is one and only one instance of an individual shared memory segment existing in the UNIX operating system at any point in time.

Before sharing of memory can be realized, a uniquely identified shared memory segment and data structure must be created. The unique identifier created is called the shared memory identifier (**shmid**); it is used to identify or reference the associated data structure. The data structure includes the following for each shared memory segment:

- operation permissions
- segment size
- segment descriptor
- process identification performing last operation
- process identification of creator
- current number of processes attached
- in memory number of processes attached
- last attach time
- last detach time
- last change time

The C Programming Language data structure definition for the shared memory segment data structure is located in the `/usr/include/sys/shm.h` header file. It is as follows:

```

/*
**  There is a shared mem id data structure for
**  each segment in the system.
*/

struct shm_id_ds {
    struct ipc_perm    shm_perm;        /* operation permission struct */
    int                shm_segsz;      /* segment size */
    struct region      *shm_reg;       /* ptr to region structure */
    char               pad[4];         /* for swap compatibility */
    ushort             shm_lpid;       /* pid of last shmop */
    ushort             shm_cpid;       /* pid of creator */
    ushort             shm_nattch;     /* used only for shminfo */
    ushort             shm_cnattch;    /* used only for shminfo */
    time_t             shm_atime;      /* last shmat time */
    time_t             shm_dtime;      /* last shmdt time */
    time_t             shm_ctime;      /* last change time */
};

```

Note that the **shm\_perm** member of this structure uses **ipc\_perm** as a template. The breakout for the operation permissions data structure is shown in Figure 9-1.

The **ipc\_perm** data structure is the same for all IPC facilities, and it is located in the **#include <sys/ipc.h>** header file. It is shown in the introduction section of "Messages."

Figure 9-12 is a table that shows the shared memory state information.

Lock Bit	Swap Bit	Allocated Bit	Implied State
0	0	0	Unallocated Segment
0	0	1	Incore
0	1	0	Unused
0	1	1	On Disk
1	0	1	Locked Incore
1	1	0	Unused
1	0	0	Unused
1	1	1	Unused

Figure 9-12: Shared Memory State Information

---

The implied states of Figure 9-12 are as follows:

- **Unallocated Segment**—the segment associated with this segment descriptor has not been allocated for use.
- **Incore**—the shared segment associated with this descriptor has been allocated for use. Therefore, the segment does exist and is currently resident in memory.
- **On Disk**—the shared segment associated with this segment descriptor is currently resident on the swap device.
- **Locked Incore**—the shared segment associated with this segment descriptor is currently locked in memory and will not be a candidate for swapping until the segment is unlocked. Only the super-user may lock and unlock a shared segment.
- **Unused**—this state is currently unused and should never be encountered by the normal user in shared memory handling.

The **shmget(2)** system call is used to perform two tasks when only the **IPC\_CREAT** flag is set in the **shmflg** argument that it receives:

- to get a new **shmid** and create an associated shared memory segment data structure for it
- to return an existing **shmid** that already has an associated shared memory segment data structure

The task performed is determined by the value of the **key** argument passed to the **shmget(2)** system call. For the first task, if the **key** is not already in use for an existing **shmid**, a new **shmid** is returned with an associated shared memory segment data structure created for it provided no system tunable parameters would be exceeded.

There is also a provision for specifying a **key** of value zero which is known as the private **key** (**IPC\_PRIVATE = 0**); when specified, a new **shmid** is always returned with an associated shared memory segment data structure created for it unless a system tunable parameter would be exceeded. When the **ipcs** command is performed, the **KEY** field for the **shmid** is all zeros.

For the second task, if a **shmid** exists for the **key** specified, the value of the existing **shmid** is returned. If it is not desired to have an existing **shmid** returned, a control command (**IPC\_EXCL**) can be specified (set) in the **shmflg** argument passed to the system call. The details for using this system call are discussed in the "Using **shmget**" section of this chapter.

When performing the first task, the process that calls **shmget** becomes the owner/creator, and the associated data structure is initialized accordingly. Remember, ownership can be changed, but the creating process always remains the creator; see the "Controlling Shared Memory" section in this chapter. The creator of the shared memory segment also determines the initial operation permissions for it.

Once a uniquely identified shared memory segment data structure is created, shared memory segment operations [**shmop()**] and control [**shmctl(2)**] can be used.

Shared memory segment operations consist of attaching and detaching shared memory segments. System calls are provided for each of these operations; they are **shmat(2)** and **shmdt(2)**. Refer to the "Operations for Shared Memory" section in this chapter for details of these system calls.

## Shared Memory

---

Shared memory segment control is done by using the **shmctl(2)** system call. It permits you to control the shared memory facility in the following ways:

- by determining the associated data structure status for a shared memory segment (**shmid**)
- by changing operation permissions for a shared memory segment
- by removing a particular **shmid** from the UNIX operating system along with its associated shared memory segment data structure
- by locking a shared memory segment in memory
- by unlocking a shared memory segment.

Refer to the "Controlling Shared Memory" section in this chapter for details of the **shmctl(2)** system call.

## Getting Shared Memory Segments

This section gives a detailed description of using the **shmget(2)** system call along with an example program illustrating its use.

### Using shmget

The synopsis found in the **shmget(2)** entry in the *Programmer's Reference Manual* is as follows:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>

int shmget (key, size, shmflg)
key_t key;
int size, shmflg;
```

All of these include files are located in the `/usr/include/sys` directory of the UNIX operating system. The following line in the synopsis informs you that `shmget(2)` is a function with three formal arguments that returns an integer type value, upon successful completion (`shmid`).

```
int shmget (key, size, shmflg)
```

The next two lines declare the types of the formal arguments. The variable `key_t` is declared by a `typedef` in the `types.h` header file to be an integer.

```
key_t key;  
int size, shmflg;
```

The integer returned from this function upon successful completion is the shared memory identifier (`shmid`) that was discussed earlier.

As declared, the process calling the `shmget(2)` system call must supply three arguments to be passed to the formal `key`, `size`, and `shmflg` arguments.

A new `shmid` with an associated shared memory data structure is provided if one of the following conditions exists:

- `key` is equal to `IPC_PRIVATE`
- `key` is passed a unique hexadecimal integer, and `shmflg` ANDed with `IPC_CREAT` is `TRUE`.

The value passed to the `shmflg` argument must be an integer type octal value and will specify the following:

- access permissions
- execution modes
- control fields (commands)

Access permissions determine the read/write attributes, and execution modes determine the user/group/other attributes of the `shmflg` argument. They are collectively referred to as "operation permissions." Figure 9-13 reflects the numeric values (expressed in octal notation) for the valid operation permissions codes.

<u>Operation Permissions</u>	<u>Octal Value</u>
Read by User	00400
Write by User	00200
Read by Group	00040
Write by Group	00020
Read by Others	00004
Write by Others	00002

Figure 9-13: Operation Permissions Codes

---

A specific octal value is derived by adding the octal values for the operation permissions desired. That is, if read by user and read/write by others is desired, the code value would be 00406 (00400 plus 00006). There are constants located in the **shm.h** header file which can be used for the user (OWNER). They are as follows:

<code>SHM_R</code>	0400
<code>SHM_W</code>	0200

Control commands are predefined constants (represented by all uppercase letters). Figure 9-14 contains the names of the constants that apply to the **shmget()** system call along with their values. They are also referred to as flags and are defined in the **ipc.h** header file.

<u>Control Command</u>	<u>Value</u>
<code>IPC_CREAT</code>	0001000
<code>IPC_EXCL</code>	0002000

Figure 9-14: Control Commands (Flags)

---

The value for the **shmflg** argument is, therefore, a combination of operation permissions and control commands. After determining the value for the operation permissions as previously described, the desired flag(s) can be specified. This specification is accomplished by bitwise ORing (**|**) them with the operation permissions; bit positions and values for the control commands in relation to those of the operation permissions make this possible. An example of determining the **shmflg** argument follows.



		Octal Value	Binary Value
IPC_CREAT	=	0 1 0 0 0	0 000 001 000 000 000
ORed by User	=	0 0 4 0 0	0 000 000 100 000 000
shmflg	=	0 1 4 0 0	0 000 001 100 000 000

The **shmflg** value can easily be set by using the names of the flags in conjunction with the octal operation permissions value:

```
shmld = shmget (key, size, (IPC_CREAT | 0400));
shmld = shmget (key, size, (IPC_CREAT | IPC_EXCL | 0400));
```

As specified by the **shmget(2)** entry in the *Programmer's Reference Manual*, success or failure of this system call depends upon the argument values for **key**, **size**, and **shmflg** or system tunable parameters. The system call will attempt to return a new **shmld** if one of the following conditions exists:

- **key** is equal to `IPC_PRIVATE (0)`.
- **key** does not already have a **shmld** associated with it, and (**shmflg** & `IPC_CREAT`) is TRUE (not zero).

The **key** argument can be set to `IPC_PRIVATE` in the following ways:

```
shmld = shmget (IPC_PRIVATE, size, shmflg);
```

or

```
shmld = shmget ( 0 , size, shmflg);
```

This alone will cause the system call to be attempted because it satisfies the first condition specified. Exceeding the `SHMMNI` system tunable parameter always causes a failure. The `SHMMNI` system tunable parameter determines the maximum number of unique shared memory segments (**shmls**) in the UNIX operating system.

The second condition is satisfied if the value for **key** is not already associated with a **shmld** and the bitwise ANDing of **shmflg** and `IPC_CREAT` is TRUE (not zero). This means that the **key** is unique (not in use) within the UNIX operating system for this facility type and that the `IPC_CREAT` flag is set (**shmflg** & `IPC_CREAT`). The bitwise ANDing (&), which is the logical way of testing if a flag is set, is illustrated as follows:

## Shared Memory

---

```
shmflg = x 1 x x x    (x = immaterial)
& IPC_CREAT = 0 1 0 0 0
result = 0 1 0 0 0    (not zero)
```

Because the result is not zero, the flag is set or TRUE. SHMMNI applies here also, just as for condition one.

IPC\_EXCL is another control command used in conjunction with IPC\_CREAT to exclusively have the system call fail if, and only if, a **shm**id exists for the specified **key** provided. This is necessary to prevent the process from thinking that it has received a new (unique) **shm**id when it has not. In other words, when both IPC\_CREAT and IPC\_EXCL are specified, a unique **shm**id is returned if the system call is successful. Any value for **shmflg** returns a new **shm**id if the **key** equals zero (IPC\_PRIVATE).

The system call will fail if the value for the **size** argument is less than SHMMIN or greater than SHMMAX. These tunable parameters specify the minimum and maximum shared memory segment **sizes**.

Refer to the **shmget(2)** manual page for specific, associated data structure initialization for successful completion. The specific failure conditions with error names are contained there also.

### Example Program

The example program in this section (Figure 9-15) is a menu-driven program which allows all possible combinations of using the **shmget(2)** system call to be exercised.

From studying this program, you can observe the method of passing arguments and receiving return values. The user-written program requirements are pointed out.

This program begins (lines 4-7) by including the required header files as specified by the **shmget(2)** entry in the *Programmer's Reference Manual*. Note that the **errno.h** header file is included as opposed to declaring **errno** as an external variable; either method will work.

Variable names have been chosen to be as close as possible to those in the synopsis for the system call. Their declarations are self-explanatory. These names make the program more readable, and are perfectly legal since they are local to the program. Variables declared for this program and their purposes are:

- **key**—used to pass the value for the desired **key**
- **opperm**—used to store the desired operation permissions
- **flags**—used to store the desired control commands (flags)
- **opperm\_flags**—used to store the combination from the logical ORing of the **opperm** and **flags** variables; it is then used in the system call to pass the **shmflg** argument.
- **shmid**—used for returning the message queue identification number for a successful system call or the error code (-1) for an unsuccessful one
- **size**—used to specify the shared memory segment size.

The program begins by prompting for a hexadecimal **key**, an octal operation permissions code, and the control command combinations (flags) which are selected from a menu (lines 14-31). All possible combinations are allowed even though they might not be viable. This allows observing the errors for illegal combinations.

Next, the menu selection for the flags is combined with the operation permissions, and the result is stored at the address of the **opperm\_flags** variable (lines 35-50).

A display then prompts for the **size** of the shared memory segment, and it is stored at the address of the **size** variable (lines 51-54).

The system call is made next, and the result is stored at the address of the **shmid** variable (line 56).

Since the **shmid** variable now contains a valid message queue identifier or the error code (-1), it is tested to see if an error occurred (line 58). If **shmid** equals -1, a message indicates that an error resulted and the external **errno** variable is displayed (lines 60 and 61).

If no error occurred, the returned shared memory segment identifier is displayed (line 65).

The example program for the **shmget(2)** system call follows. It is suggested that the source program file be named **shmget.c** and that the executable file be named **shmget**.

When compiling C programs that use floating point operations, the `-f` option should be used on the `cc` command line. If this option is not used, the program will compile successfully, but when the program is executed, it will fail.

```
1  /*This is a program to illustrate
2  **the shared memory get, shmget(),
3  **system call capabilities.**/

4  #include    <sys/types.h>
5  #include    <sys/ipc.h>
6  #include    <sys/shm.h>
7  #include    <errno.h>

8  /*Start of main C language program*/
9  main()
10 {
11     key_t key;           /*declare as long integer*/
12     int opperm, flags;
13     int shmId, size, opperm_flags;
14     /*Enter the desired key*/
15     printf("Enter the desired key in hex = ");
16     scanf("%x", &key);

17     /*Enter the desired octal operation
18     permissions.*/
19     printf("\nEnter the operation\n");
20     printf("permissions in octal = ");
21     scanf("%o", &opperm);
```

Figure 9-15: `shmget(2)` System Call Example (Sheet 1 of 3)

---

```
22     /*Set the desired flags.*/
23     printf("\nEnter corresponding number to\n");
24     printf("set the desired flags:\n");
25     printf("No flags           = 0\n");
26     printf("IPC_CREAT             = 1\n");
27     printf("IPC_EXCL                = 2\n");
28     printf("IPC_CREAT and IPC_EXCL   = 3\n");
29     printf("           Flags        = ");
30     /*Get the flag(s) to be set.*/
31     scanf("%d", &flags);

32     /*Check the values.*/
33     printf ("\nkey =0x%x, opperm = 0%, flags = 0%\n",
34           key, opperm, flags);

35     /*Incorporate the control fields (flags) with
36       the operation permissions*/
37     switch (flags)
38     {
39     case 0: /*No flags are to be set.*/
40         opperm_flags = (opperm | 0);
41         break;
42     case 1: /*Set the IPC_CREAT flag.*/
43         opperm_flags = (opperm | IPC_CREAT);
44         break;
45     case 2: /*Set the IPC_EXCL flag.*/
46         opperm_flags = (opperm | IPC_EXCL);
47         break;
48     case 3: /*Set the IPC_CREAT and IPC_EXCL flags.*/
49         opperm_flags = (opperm | IPC_CREAT | IPC_EXCL);
50     }
```

Figure 9-15: `shmget(2)` System Call Example (Sheet 2 of 3)

```
51     /*Get the size of the segment in bytes.*/
52     printf ("\nEnter the segment");
53     printf ("\nsize in bytes = ");
54     scanf ("%d", &size);

55     /*Call the shmget system call.*/
56     shmid = shmget (key, size, operm_flags);

57     /*Perform the following if the call is unsuccessful.*/
58     if(shmid == -1)
59     {
60         printf ("\nThe shmget system call failed!\n");
61         printf ("The error number = %d\n", errno);
62     }
63     /*Return the shmid upon successful completion.*/
64     else
65         printf ("\nThe shmid = %d\n", shmid);
66     exit(0);
67 }
```

Figure 9-15: **shmget(2)** System Call Example (Sheet 3 of 3)

---

## **Controlling Shared Memory**

This section gives a detailed description of using the **shmctl(2)** system call along with an example program which allows all of its capabilities to be exercised.

## Using shmctl

The synopsis found in the **shmctl(2)** entry in the *Programmer's Reference Manual* is as follows:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>

int shmctl (shmids, cmd, buf)
int shmids, cmd;
struct shmids *buf;
```

The **shmctl(2)** system call requires three arguments to be passed to it, and it returns an integer value. Upon successful completion, a zero value is returned. When unsuccessful, a  $-1$  is returned.

The **shmids** variable must be a valid, non-negative, integer value. In other words, it must have already been created by using the **shmget(2)** system call.

The **cmd** argument can be replaced by one of following control commands (flags):

- **IPC\_STAT**—return the status information contained in the associated data structure for the specified **shmids** and place it in the data structure pointed to by the **\*buf** pointer in the user memory area
- **IPC\_SET**—for the specified **shmids**, set the effective user and group identification, and operation permissions
- **IPC\_RMID**—remove the specified **shmids** along with its associated shared memory segment data structure
- **SHM\_LOCK**—lock the specified shared memory segment in memory; must be super-user
- **SHM\_UNLOCK**—unlock the shared memory segment from memory; must be super-user.

A process must have an effective user identification of OWNER/CREATOR or super-user to perform an IPC\_SET or IPC\_RMID control command. Only the super-user can perform a SHM\_LOCK or SHM\_UNLOCK control command. A process must have read permission to perform the IPC\_STAT control command.

The details of this system call are discussed in the example program for it. If you have problems understanding the logic manipulations in this program, read the "Using **shmget**" section of this chapter; it goes into more detail than would be practical to do for every system call.

### Example Program

The example program in this section (Figure 9-16) is a menu-driven program which allows all possible combinations of using the **shmctl(2)** system call to be exercised.

From studying this program, you can observe the method of passing arguments and receiving return values. The user-written program requirements are pointed out.

This program begins (lines 5-9) by including the required header files as specified by the **shmctl(2)** entry in the *Programmer's Reference Manual*. Note in this program that **errno** is declared as an external variable, and therefore, the **errno.h** header file does not have to be included.

Variable and structure names have been chosen to be as close as possible to those in the synopsis for the system call. Their declarations are self-explanatory. These names make the program more readable, and are perfectly legal since they are local to the program. Variables declared for this program and their purposes are:

- **uid**—used to store the IPC\_SET value for the effective user identification
- **gid**—used to store the IPC\_SET value for the effective group identification
- **mode**—used to store the IPC\_SET value for the operation permissions
- **rtrn**—used to store the return integer value from the system call
- **shmid**—used to store and pass the shared memory segment identifier to the system call



- **command**—used to store the code for the desired control command so that subsequent processing can be performed on it
- **choice**—used to determine which member for the `IPC_SET` control command is to be changed
- **shmid\_ds**—used to receive the specified shared memory segment identifier's data structure when an `IPC_STAT` control command is performed
- **\*buf**—a pointer passed to the system call which locates the data structure in the user memory area where the `IPC_STAT` control command is to place its return values or where the `IPC_SET` command gets the values to set.

Note that the **shmid\_ds** data structure in this program (line 16) uses the data structure located in the **shm.h** header file of the same name as a template for its declaration. This is an example of the advantage of local variables.

The next important thing to observe is that although the **\*buf** pointer is declared to be a pointer to a data structure of the **shmid\_ds** type, it must also be initialized to contain the address of the user memory area data structure (line 17).

Now that all of the required declarations have been explained for this program, this is how it works.

First, the program prompts for a valid shared memory segment identifier which is stored at the address of the **shmid** variable (lines 18-20). This is required for every **shmctl(2)** system call.

Then, the code for the desired control command must be entered (lines 21-29), and it is stored at the address of the command variable. The code is tested to determine the control command for subsequent processing.

If the `IPC_STAT` control command is selected (code 1), the system call is performed (lines 39 and 40) and the status information returned is printed out (lines 41-71). Note that if the system call is unsuccessful (line 146), the status information of the last successful call is printed out. In addition, an error message is displayed and the **errno** variable is printed out (lines 148 and 149). If the system call is successful, a message indicates this along with the shared memory segment identifier used (lines 151-154).

If the `IPC_SET` control command is selected (code 2), the first thing to do is get the current status information for the message queue identifier specified (lines 90-92). This is necessary because this example program provides for changing only one member at a time, and the system call changes all of them. Also, if an invalid value happened to be stored in the user memory area for one of these members, it would cause repetitive failures for this control command until corrected. The next thing the program does is to prompt for a code corresponding to the member to be changed (lines 93-98). This code is stored at the address of the choice variable (line 99). Now, depending upon the member picked, the program prompts for the new value (lines 105-127). The value is placed at the address of the appropriate member in the user memory area data structure, and the system call is made (lines 128-130). Depending upon success or failure, the program returns the same messages as for `IPC_STAT` above.

If the `IPC_RMID` control command (code 3) is selected, the system call is performed (lines 132-135), and the `shmid` along with its associated message queue and data structure are removed from the UNIX operating system. Note that the `*buf` pointer is not required as an argument to perform this control command and its value can be zero or `NULL`. Depending upon success or failure, the program returns the same messages as for the other control commands.

If the `SHM_LOCK` control command (code 4) is selected, the system call is performed (lines 137 and 138). Depending upon success or failure, the program returns the same messages as for the other control commands.

If the `SHM_UNLOCK` control command (code 5) is selected, the system call is performed (lines 140-142). Depending upon success or failure, the program returns the same messages as for the other control commands.

The example program for the `shmctl(2)` system call follows. It is suggested that the source program file be named `shmctl.c` and that the executable file be named `shmctl`.

When compiling C programs that use floating point operations, the `-f` option should be used on the `cc` command line. If this option is not used, the program will compile successfully, but when the program is executed it will fail. The `-f` option is not required, however, on your computer.

```
1  /*This is a program to illustrate
2  **the shared memory control, shmctl(),
3  **system call capabilities.
4  */

5  /*Include necessary header files.*/
6  #include <stdio.h>
7  #include <sys/types.h>
8  #include <sys/ipc.h>
9  #include <sys/shm.h>

10 /*Start of main C language program*/
11 main()
12 {
13     extern int errno;
14     int uid, gid, mode;
15     int rtrn, shmid, command, choice;
16     struct shmctl_ds shmctl_ds, *buf;
17     buf = &shmctl_ds;

18     /*Get the shmid, and command.*/
19     printf("Enter the shmid = ");
20     scanf("%d", &shmid);
21     printf("\nEnter the number for\n");
22     printf("the desired command:\n");
```

Figure 9-16: **shmctl(2)** System Call Example (Sheet 1 of 6)

---

```
23     printf("IPC_STAT   = 1\n");
24     printf("IPC_SET    = 2\n");
25     printf("IPC_RMID   = 3\n");
26     printf("SHM_LOCK   = 4\n");
27     printf("SHM_UNLOCK = 5\n");
28     printf("Entry     = ");
29     scanf("%d", &command);

30     /*Check the values.*/
31     printf ("\nshmid =%d, command = %d\n",
32            shmids, command);

33     switch (command)
34     {
35     case 1: /*Use shmctl() to duplicate
36            the data structure for
37            shmids in the shmids area pointed
38            to by buf and then print it out.*/
39            rtm = shmctl(shmids, IPC_STAT,
40                       buf);
41            printf ("\nThe USER ID = %d\n",
42                   buf->shm_perm.uid);
43            printf ("The GROUP ID = %d\n",
44                   buf->shm_perm.gid);
45            printf ("The creator's ID = %d\n",
46                   buf->shm_perm.cuid);
47            printf ("The creator's group ID = %d\n",
48                   buf->shm_perm.cgid);
49            printf ("The operation permissions = 0%o\n",
50                   buf->shm_perm.mode);
51            printf ("The slot usage sequence\n");
```

Figure 9-16: **shmctl(2)** System Call Example (Sheet 2 of 6)

---

```
52     printf ("number = 0%k\n",
53             buf->shm_perm.seq);
54     printf ("The key= 0%k\n",
55             buf->shm_perm.key);
56     printf ("The segment size = %d\n",
57             buf->shm_segsz);
58     printf ("The pid of last shmop = %d\n",
59             buf->shm_lpid);
60     printf ("The pid of creator = %d\n",
61             buf->shm_cpid);
62     printf ("The current # attached = %d\n",
63             buf->shm_nattch);
64     printf("The in memory # attached = %d\n",
65             buf->shm_cnattach);
66     printf("The last shmat time = %d\n",
67             buf->shm_atime);
68     printf("The last shmdt time = %d\n",
69             buf->shm_dtime);
70     printf("The last change time = %d\n",
71             buf->shm_ctime);
72     break;

/* Lines 73 - 87 deleted */
```

Figure 9-16: **shmctl(2)** System Call Example (Sheet 3 of 6)

```
88     case 2: /*Select and change the desired
89             member(s) of the data structure.*/

90         /*Get the original data for this shmid
91            data structure first.*/
92         rtn = shmctl(shmid, IPC_STAT, buf);

93         printf("\nEnter the number for the\n");
94         printf("member to be changed:\n");
95         printf("shm_perm.uid   = 1\n");
96         printf("shm_perm.gid   = 2\n");
97         printf("shm_perm.mode  = 3\n");
98         printf("Entry       = ");
99         scanf("%d", &choice);
100        /*Only one choice is allowed per
101           pass as an illegal entry will
102           cause repetitive failures until
103           shmid_ds is updated with
104           IPC_STAT.*/
```

Figure 9-16: `shmctl(2)` System Call Example (Sheet 4 of 6)

---

```
105     switch(choice){
106     case 1:
107         printf("\nEnter USER ID = ");
108         scanf ("%d", &uid);
109         buf->shm_perm.uid = uid;
110         printf("\nUSER ID = %d\n",
111             buf->shm_perm.uid);
112         break;

113     case 2:
114         printf("\nEnter GROUP ID = ");
115         scanf ("%d", &gid);
116         buf->shm_perm.gid = gid;
117         printf("\nGROUP ID = %d\n",
118             buf->shm_perm.gid);
119         break;

120     case 3:
121         printf("\nEnter MODE = ");
122         scanf ("%o", &mode);
123         buf->shm_perm.mode = mode;
124         printf("\nMODE = 0%o\n",
125             buf->shm_perm.mode);
126         break;
127     }
128     /*Do the change.*/
129     rtrn = shmctl(shmid, IPC_SET,
130         buf);
131     break;
```

Figure 9-16: shmctl() System Call Example (Sheet 5 of 6)

```
132     case 3: /*Remove the shmid along with its
133             associated
134             data structure.*/
135         rtn = shmctl(shmid, IPC_RMID, NULL);
136         break;

137     case 4: /*Lock the shared memory segment*/
138         rtn = shmctl(shmid, SHM_LOCK, NULL);
139         break;
140     case 5: /*Unlock the shared memory
141             segment.*/
142         rtn = shmctl(shmid, SHM_UNLOCK, NULL);
143         break;
144     }
145     /*Perform the following if the call is unsuccessful.*/
146     if(rtn == -1)
147     {
148         printf ("\nThe shmctl system call failed!\n");
149         printf ("The error number = %d\n", errno);
150     }
151     /*Return the shmid upon successful completion.*/
152     else
153         printf ("\nShmctl was successful for shmid = %d\n",
154             shmid);
155     exit (0);
156 }
```

Figure 9-16: **shmctl(2)** System Call Example (Sheet 6 of 6)

---



## Operations for Shared Memory

This section gives a detailed description of using the **shmat(2)** and **shmdt(2)** system calls, along with an example program which allows all of their capabilities to be exercised.

### Using shmop

The synopsis found in the **shmop(2)** entry in the *Programmer's Reference Manual* is as follows:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>

char *shmat (shmid, shmaddr, shmflg)
int shmid;
char *shmaddr;
int shmflg;

int shmdt (shmaddr)
char *shmaddr;
```

### Attaching a Shared Memory Segment

The **shmat(2)** system call requires three arguments to be passed to it, and it returns a character pointer value.

The system call can be cast to return an integer value. Upon successful completion, this value will be the address in core memory where the process is attached to the shared memory segment. When unsuccessful the value will be a `-1`.

## Shared Memory

---

The **shmid** argument must be a valid, non-negative, integer value. In other words, it must have already been created by using the **shmget(2)** system call.

The **shmaddr** argument can be zero or user-supplied when passed to the **shmat(2)** system call. If it is zero, the UNIX operating system picks the address of where the shared memory segment will be attached. If it is user-supplied, the address must be a valid address that the UNIX operating system would pick. The following table illustrates some typical address ranges for your computer:

80286	80386
0x01F70000	0x80400000
0x02070000	0x80800000
0x020F0000	0x80C00000
0x02170000	0x81000000

Note that these addresses are in chunks of 0x80000 hexadecimal (for the 80286 Computer) and 0x1000 hexadecimal (for the 80386 Computer). It would be wise to let the operating system pick addresses so as to improve portability.

The **shmflg** argument is used to pass the SHM\_RND and SHM\_RDONLY flags to the **shmat()** system call.

Further details are discussed in the example program for **shmop()**. If you have problems understanding the logic manipulations in this program, read the "Using **shmget**" section of this chapter; it goes into more detail than would be practical to do for every system call.

### Detaching Shared Memory Segments

The **shmdt(2)** system call requires one argument to be passed to it, and it returns an integer value. Upon successful completion, zero is returned. When unsuccessful, a -1 is returned.

Further details of this system call are discussed in the example program. If you have problems understanding the logic manipulations in this program, read the "Using **shmget**" section of this chapter; it goes into more detail than would be practical to do for every system call.

## Example Program

The example program in this section (Figure 9-17) is a menu-driven program which allows all possible combinations of using the **shmat(2)** and **shmdt(2)** system calls to be exercised.

From studying this program, you can observe the method of passing arguments and receiving return values. The user-written program requirements are pointed out.

This program begins (lines 5-9) by including the required header files as specified by the **shmop(2)** entry in the *Programmer's Reference Manual*. Note that in this program **errno** is declared as an external variable, and therefore, the **errno.h** header file does not have to be included.

Variable and structure names have been chosen to be as close as possible to those in the synopsis for the system call. Their declarations are self-explanatory. These names make the program more readable, and are perfectly legal since they are local to the program. Variables declared for this program and their purposes are as follows:

- **flags**—used to store the codes of SHM\_RND or SHM\_RDONLY for the **shmat(2)** system call
- **addr**—used to store the address of the shared memory segment for the **shmat(2)** and **shmdt(2)** system calls
- **i**—used as a loop counter for attaching and detaching
- **attach**—used to store the desired number of attach operations
- **shmid**—used to store and pass the desired shared memory segment identifier
- **shmflg**—used to pass the value of flags to the **shmat(2)** system call
- **retrn**—used to store the return values from both system calls
- **detach**—used to store the desired number of detach operations.

This example program combines both the **shmat(2)** and **shmdt(2)** system calls. The program prompts for the number of attachments and enters a loop until they are done for the specified shared memory identifiers. Then, the program prompts for the number of detachments to be performed and enters a loop until they are done for the specified shared memory segment addresses.

### **shmat**

The program prompts for the number of attachments to be performed, and the value is stored at the address of the `attach` variable (lines 17-21).

A loop is entered using the `attach` variable and the `i` counter (lines 23-70) to perform the specified number of attachments.

In this loop, the program prompts for a shared memory segment identifier (lines 24-27) and it is stored at the address of the `shmidx` variable (line 28). Next, the program prompts for the address where the segment is to be attached (lines 30-34), and it is stored at the address of the `addr` variable (line 35). Then, the program prompts for the desired flags to be used for the attachment (lines 37-44), and the code representing the flags is stored at the address of the `flags` variable (line 45). The `flags` variable is tested to determine the code to be stored for the `shmflg` variable used to pass them to the `shmat(2)` system call (lines 46-57). The system call is made (line 60). If successful, a message stating so is displayed along with the attach address (lines 66-68). If unsuccessful, a message stating so is displayed and the error code is displayed (lines 62, 63). The loop then continues until it finishes.

### **shmdt**

After the `attach` loop completes, the program prompts for the number of detach operations to be performed (lines 71-75), and the value is stored at the address of the `detach` variable (line 76).

A loop is entered using the `detach` variable and the `i` counter (lines 78-95) to perform the specified number of detachments.

In this loop, the program prompts for the address of the shared memory segment to be detached (lines 79-83), and it is stored at the address of the `addr` variable (line 84). Then, the `shmdt(2)` system call is performed (line 87). If successful, a message stating so is displayed along with the address that the segment was detached from (lines 92 and 93). If unsuccessful, the error number is displayed (line 89). The loop continues until it finishes.

The example program for the `shmop(2)` system calls follows. It is suggested that the program be put into a source file called `shmop.c` and then into an executable file called `shmop`.

When compiling C programs that use floating point operations, the `-f` option should be used on the `cc` command line. If this option is not used, the program will compile successfully, but when the program is executed, it will fail. The `-f` option is not required, however, on your computer.

```
1  /*This is a program to illustrate
2  **the shared memory operations, shmop(),
3  **system call capabilities.
4  */

5  /*Include necessary header files.*/
6  #include <stdio.h>
7  #include <sys/types.h>
8  #include <sys/ipc.h>
9  #include <sys/shm.h>
10 /*Start of main C language program*/
11 main()
12 {
13     extern int errno;
14     int flags, addr, i, attach;
15     int shmid, shmflg, retrn, detach;

16     /*Loop for attachments by this process.*/
17     printf("Enter the number of\n");
18     printf("attachments for this\n");
19     printf("process (1-4).\n");
20     printf("    Attachments = ");

21     scanf("%d", &attach);
22     printf("Number of attaches = %d\n", attach);
```

Figure 9-17: **shmop()** System Call Example (Sheet 1 of 4)

---

```
23     for(i = 1; i <= attach; i++) {
24         /*Enter the shared memory ID.*/
25         printf("\nEnter the shmid of\n");
26         printf("the shared memory segment to\n");
27         printf("be operated on = ");
28         scanf("%d", &shmid);
29         printf("\nshmid = %d\n", shmid);

30         /*Enter the value for shmaddr.*/
31         printf("\nEnter the value for\n");
32         printf("the shared memory address\n");
33         printf("in hexadecimal:\n");
34         printf("      Shmaddr = ");
35         scanf("%x", &addr);
36         printf("The desired address = 0x%x\n", addr);

37         /*Specify the desired flags.*/
38         printf("\nEnter the corresponding\n");
39         printf("number for the desired\n");
40         printf("flags:\n");
41         printf("SHM_RND                = 1\n");
42         printf("SHM_RDONLY                = 2\n");
43         printf("SHM_RND and SHM_RDONLY = 3\n");
44         printf("      Flags                = ");
45         scanf("%d", &flags);
```

Figure 9-17: **shmop()** System Call Example (Sheet 2 of 4)

---

```
46         switch(flags)
47         {
48         case 1:
49             shmflg = SHM_RND;
50             break;
51         case 2:
52             shmflg = SHM_RDONLY;
53             break;
54         case 3:
55             shmflg = SHM_RND | SHM_RDONLY;
56             break;
57         }
58         printf("\nFlags = %o\n", shmflg);

59         /*Do the shmat system call.*/
60         retrn = (int)shmat(shmid, addr, shmflg);
61         if(retrn == -1) {
62             printf("\nShmat failed. ");
63             printf("Error = %d\n", errno);
64         }
65         else {
66             printf ("\nShmat was successful\n");
67             printf("for shmid = %d\n", shmid);
68             printf("The address = 0x%x\n", retrn);
69         }
70     }

71     /*Loop for detachments by this process.*/
72     printf("Enter the number of\n");
73     printf("detachments for this\n");
74     printf("process (1-4).\n");
75     printf("    Detachments = ");
```

Figure 9-17: **shmop()** System Call Example (Sheet 3 of 4)

```
76     scanf("%d", &detach);
77     printf("Number of attaches = %d\n", detach);
78     for(i = 1; i <= detach; i++) {

79         /*Enter the value for shmaddr.*/
80         printf("\nEnter the value for\n");
81         printf("the shared memory address\n");
82         printf("in hexadecimal:\n");
83         printf("          Shmaddr = ");
84         scanf("%x", &addr);
85         printf("The desired address = 0x%x\n", addr);

86         /*Do the shmdt system call.*/
87         retm = (int)shmdt(addr);
88         if(retm == -1) {
89             printf("Error = %d\n", errno);
90         }
91         else {
92             printf ("\nShmdt was successful\n");
93             printf("for address = 0%x\n", addr);

94         }
95     }
96 }
```

Figure 9-17: **shmop()** System Call Example (Sheet 4 of 4)

---





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