Pearson

Advanced Programming in the UNIX Environment Third Edition

UNIX 环境高级编程

第3版·英文版 | 下

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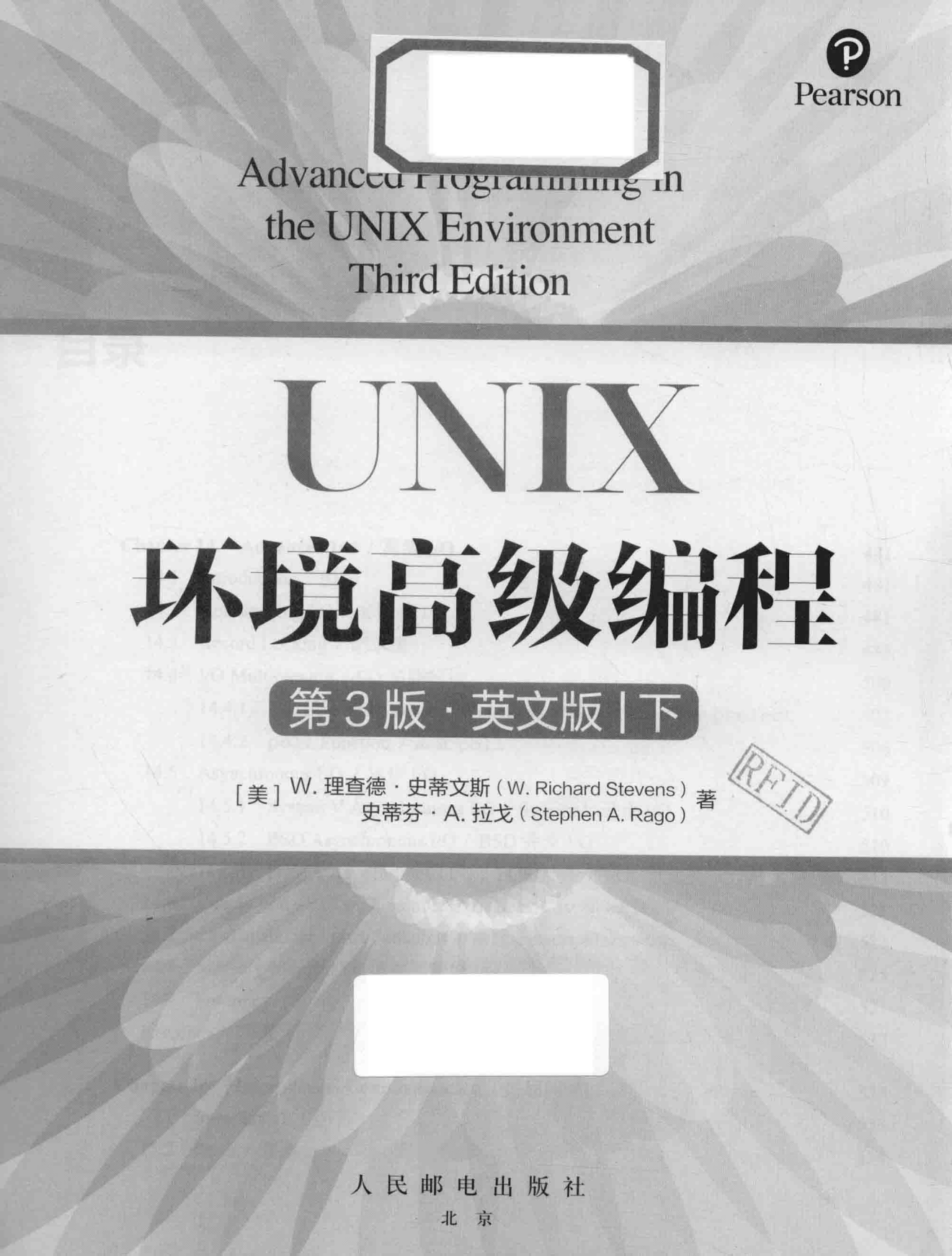
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20 多年来，严谨的 C 程序员都是依靠一本书来深入了解驱动 UNIX 和 Linux 内核的编程接口的实用知识的，这本书就是 W. Richard Stevens 所著的《UNIX 环境高级编程》。现在，Stevens 的同事 Stephen Rago 彻底更新了这本经典著作。新的第 3 版支持当今领先的系统平台，反映了最新技术进展和最佳实践，并且符合最新的 Single UNIX Specification 第 4 版（SUSv4）。

Rago 保留了使本书前版成为经典之作的精髓和方法。他在 Stevens 原著的基础上，从基础的文件、目录和进程讲起，并给诸如信号处理和终端 I/O 之类的先进技术保留较大的篇幅。他还深入讨论了线程和多线程编程、使用套接字接口驱动进程间通信（IPC）等方面的内容。

这一版涵盖了 70 多个新接口，包括 POSIX 异步 I/O、旋转锁、屏障（barrier）和 POSIX 信号量。此外，这一版删除了许多过时的接口，保留了一些广泛使用的接口。书中几乎所有实例都已经在主流的 4 个平台上测试过，包括 Solaris10、Mac OS X 10.6.8（Darwin 10.8.0）、FreeBSD 8.0 和 Ubuntu 12.04（基于 Linux 3.2）。

与前两版一样，读者仍可以通过实例学习，这些实例包括了 1 万多行可下载的 ISO C 源代码，书中通过简明但完整的程序阐述了 400 多个系统调用和函数，清楚地说明它们的用法、参数和返回值。为了使读者能融会贯通，书中还提供了几个贯穿整章的案例，每个案例都根据现在的技术环境进行了全面更新。

本书帮助几代程序员写出了可靠、强大、高性能的代码。第 3 版根据当今主流系统进行更新，更具实用价值。


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14

Advanced I/O

14.1 Introduction

This chapter covers numerous topics and functions that we lump under the term *advanced I/O*: nonblocking I/O, record locking, I/O multiplexing (the `select` and `poll` functions), asynchronous I/O, the `readv` and `writev` functions, and memory-mapped I/O (`mmap`). We need to cover these topics before describing interprocess communication in Chapter 15, Chapter 17, and many of the examples in later chapters.

14.2 Nonblocking I/O

In Section 10.5, we said that system calls are divided into two categories: the "slow" ones and all the others. The slow system calls are those that can block forever. They include

- Reads that can block the caller forever if data isn't present with certain file types (pipes, terminal devices, and network devices)
- Writes that can block the caller forever if the data can't be accepted immediately by these same file types (e.g., no room in the pipe, network flow control)
- Opens that block until some condition occurs on certain file types (such as an open of a terminal device that waits until an attached modem answers the phone, or an open of a FIFO for writing only, when no other process has the FIFO open for reading)
- Reads and writes of files that have mandatory record locking enabled

- Certain `ioctl` operations
- Some of the interprocess communication functions (Chapter 15)

We also said that system calls related to disk I/O are not considered slow, even though the read or write of a disk file can block the caller temporarily.

Nonblocking I/O lets us issue an I/O operation, such as an `open`, `read`, or `write`, and not have it block forever. If the operation cannot be completed, the call returns immediately with an error noting that the operation would have blocked.

There are two ways to specify nonblocking I/O for a given descriptor.

1. If we call `open` to get the descriptor, we can specify the `O_NONBLOCK` flag (Section 3.3).
2. For a descriptor that is already open, we call `fcntl` to turn on the `O_NONBLOCK` file status flag (Section 3.14). Figure 3.12 shows a function that we can call to turn on any of the file status flags for a descriptor.

> Earlier versions of System V used the flag `O_NDELAY` to specify nonblocking mode. These versions of System V returned a value of 0 from the `read` function if there wasn't any data to be read. Since this use of a return value of 0 overlapped with the normal UNIX System convention of 0 meaning the end of file, POSIX.1 chose to provide a nonblocking flag with a different name and different semantics. Indeed, with these older versions of System V, when we get a return of 0 from `read`, we don't know whether the call would have blocked or whether the end of file was encountered. We'll see that POSIX.1 requires that `read` return –1 with `errno` set to `EAGAIN` if there is no data to read from a nonblocking descriptor. Some platforms derived from System V support both the older `O_NDELAY` and the POSIX.1 `O_NONBLOCK`, but in this text we'll use only the POSIX.1 feature. The older `O_NDELAY` is intended for backward compatibility and should not be used in new applications.
>
> 4.3BSD provided the `FNDELAY` flag for `fcntl`, and its semantics were slightly different. Instead of affecting only the file status flags for the descriptor, the flags for either the terminal device or the socket were also changed to be nonblocking, thereby affecting all users of the terminal or socket, not just the users sharing the same file table entry (4.3BSD nonblocking I/O worked only on terminals and sockets). Also, 4.3BSD returned `EWOULDBLOCK` if an operation on a nonblocking descriptor could not complete without blocking. Today, BSD-based systems provide the POSIX.1 `O_NONBLOCK` flag and define `EWOULDBLOCK` to be the same as `EAGAIN`. These systems provide nonblocking semantics consistent with other POSIX-compatible systems: changes in file status flags affect all users of the same file table entry, but are independent of accesses to the same device through other file table entries. (Refer to Figures 3.7 and 3.9.)

Example

Let's look at an example of nonblocking I/O. The program in Figure 14.1 reads up to 500,000 bytes from the standard input and attempts to write it to the standard output. The standard output is first set to be nonblocking. The output is in a loop, with the results of each `write` being printed on the standard error. The function `clr_fl` is similar to the function `set_fl` that we showed in Figure 3.12. This new function simply clears one or more of the flag bits.

```
#include "apue.h"
#include <errno.h>
#include <fcntl.h>

char    buf[500000];

int
main(void)
{
    int     ntowrite, nwrite;
    char    *ptr;

    ntowrite = read(STDIN_FILENO, buf, sizeof(buf));
    fprintf(stderr, "read %d bytes\n", ntowrite);

    set_fl(STDOUT_FILENO, O_NONBLOCK);  /* set nonblocking */

    ptr = buf;
    while (ntowrite > 0) {
        errno = 0;
        nwrite = write(STDOUT_FILENO, ptr, ntowrite);
        fprintf(stderr, "nwrite = %d, errno = %d\n", nwrite, errno);

        if (nwrite > 0) {
            ptr += nwrite;
            ntowrite -= nwrite;
        }
    }

    clr_fl(STDOUT_FILENO, O_NONBLOCK);  /* clear nonblocking */

    exit(0);
}
```

Figure 14.1 Large nonblocking `write`

If the standard output is a regular file, we expect the `write` to be executed once:

```
$ ls -l /etc/services                                   print file size
-rw-r--r--  1 root     677959 Jun 23  2009 /etc/services
$ ./a.out < /etc/services > temp.file                   try a regular file first
read 500000 bytes
nwrite = 500000, errno = 0                              a single write
$ ls -l temp.file                                       verify size of output file
-rw-rw-r--  1 sar      500000 Apr  1 13:03 temp.file
```

But if the standard output is a terminal, we expect the `write` to return a partial count sometimes and an error at other times. This is what we see:

```
$ ./a.out < /etc/services 2>stderr.out          output to terminal
                                                lots of output to terminal ...
$ cat stderr.out
read 500000 bytes
nwrite = 999, errno = 0
nwrite = -1, errno = 35
nwrite = -1, errno = 35
nwrite = -1, errno = 35
nwrite = -1, errno = 35
nwrite = 1001, errno = 0
nwrite = -1, errno = 35
nwrite = 1002, errno = 0
nwrite = 1004, errno = 0
nwrite = 1003, errno = 0
nwrite = 1003, errno = 0
nwrite = 1005, errno = 0
nwrite = -1, errno = 35                         61 of these errors
   :
nwrite = 1006, errno = 0
nwrite = 1004, errno = 0
nwrite = 1005, errno = 0
nwrite = 1006, errno = 0
nwrite = -1, errno = 35                         108 of these errors
   :
nwrite = 1006, errno = 0
nwrite = 1005, errno = 0
nwrite = 1005, errno = 0
nwrite = -1, errno = 35                         681 of these errors
   :
                                                and so on ...
nwrite = 347, errno = 0
```

On this system, the `errno` of 35 is `EAGAIN`. The amount of data accepted by the terminal driver varies from system to system. The results will also vary depending on how you are logged in to the system: on the system console, on a hard-wired terminal, on a network connection using a pseudo terminal. If you are running a windowing system on your terminal, you are also going through a pseudo terminal device. □

In this example, the program issues more than 9,000 `write` calls, even though only 500 are needed to output the data. The rest just return an error. This type of loop, called *polling*, is a waste of CPU time on a multiuser system. In Section 14.4, we'll see that I/O multiplexing with a nonblocking descriptor is a more efficient way to do this.

Sometimes, we can avoid using nonblocking I/O by designing our applications to use multiple threads (see Chapter 11). We can allow individual threads to block in I/O calls if we can continue to make progress in other threads. This can sometimes simplify the design, as we shall see in Chapter 21; at other times, however, the overhead of synchronization can add more complexity than is saved from using threads.

14.3 Record Locking

What happens when two people edit the same file at the same time? In most UNIX systems, the final state of the file corresponds to the last process that wrote the file. In some applications, however, such as a database system, a process needs to be certain that it alone is writing to a file. To provide this capability for processes that need it, commercial UNIX systems provide record locking. (In Chapter 20, we develop a database library that uses record locking.)

Record locking is the term normally used to describe the ability of a process to prevent other processes from modifying a region of a file while the first process is reading or modifying that portion of the file. Under the UNIX System, "record" is a misnomer; the UNIX kernel does not have a notion of records in a file. A better term is *byte-range locking*, given that it is a range of a file (possibly the entire file) that is locked.

History

One of the criticisms of early UNIX systems was that they couldn't be used to run database systems, because they did not support locking portions of files. As UNIX systems found their way into business computing environments, various groups added support for record locking (differently, of course).

Early Berkeley releases supported only the `flock` function. This function locks only entire files, not regions of a file.

Record locking was added to System V Release 3 through the `fcntl` function. The `lockf` function was built on top of this, providing a simplified interface. These functions allowed callers to lock arbitrary byte ranges in a file, ranging from the entire file down to a single byte within the file.

POSIX.1 chose to standardize on the `fcntl` approach. Figure 14.2 shows the forms of record locking provided by various systems. Note that the Single UNIX Specification includes `lockf` in the XSI option.

System	Advisory	Mandatory	`fcntl`	`lockf`	`flock`
SUS	•		•	XSI	
FreeBSD 8.0	•		•	•	•
Linux 3.2.0	•	•	•	•	•
Mac OS X 10.6.8	•		•	•	•
Solaris 10	•	•	•	•	•

Figure 14.2 Forms of record locking supported by various UNIX systems

We describe the difference between advisory locking and mandatory locking later in this section. In this text, we describe only the POSIX.1 `fcntl` locking.

Record locking was originally added to Version 7 in 1980 by John Bass. The system call entry into the kernel was a function named `locking`. This function provided mandatory record locking and propagated through many versions of System III. Xenix systems picked up this function, and some Intel-based System V derivatives, such as OpenServer 5, continued to support it in a Xenix-compatibility library.

`fcntl` Record Locking

Let's repeat the prototype for the `fcntl` function from Section 3.14.

```
#include <fcntl.h>

int fcntl(int fd, int cmd, ... /* struct flock *flockptr */ );
```

Returns: depends on *cmd* if OK (see following), –1 on error

For record locking, *cmd* is `F_GETLK`, `F_SETLK`, or `F_SETLKW`. The third argument (which we'll call *flockptr*) is a pointer to an `flock` structure.

```
struct flock {
  short  l_type;   /* F_RDLCK, F_WRLCK, or F_UNLCK */
  short  l_whence; /* SEEK_SET, SEEK_CUR, or SEEK_END */
  off_t  l_start;  /* offset in bytes, relative to l_whence */
  off_t  l_len;    /* length, in bytes; 0 means lock to EOF */
  pid_t  l_pid;    /* returned with F_GETLK */
};
```

This structure describes

- The type of lock desired: `F_RDLCK` (a shared read lock), `F_WRLCK` (an exclusive write lock), or `F_UNLCK` (unlocking a region)
- The starting byte offset of the region being locked or unlocked (`l_start` and `l_whence`)
- The size of the region in bytes (`l_len`)
- The ID (`l_pid`) of the process holding the lock that can block the current process (returned by `F_GETLK` only)

Numerous rules apply to the specification of the region to be locked or unlocked.

- The two elements that specify the starting offset of the region are similar to the last two arguments of the `lseek` function (Section 3.6). Indeed, the `l_whence` member is specified as `SEEK_SET`, `SEEK_CUR`, or `SEEK_END`.
- Locks can start and extend beyond the current end of file, but cannot start or extend before the beginning of the file.
- If `l_len` is 0, it means that the lock extends to the largest possible offset of the file. This allows us to lock a region starting anywhere in the file, up through and including any data that is appended to the file. (We don't have to try to guess how many bytes might be appended to the file.)
- To lock the entire file, we set `l_start` and `l_whence` to point to the beginning of the file and specify a length (`l_len`) of 0. (There are several ways to specify the beginning of the file, but most applications specify `l_start` as 0 and `l_whence` as `SEEK_SET`.)

We previously mentioned two types of locks: a shared read lock (`l_type` of `F_RDLCK`) and an exclusive write lock (`F_WRLCK`). The basic rule is that any number of processes can have a shared read lock on a given byte, but only one process can have an exclusive write lock on a given byte. Furthermore, if there are one or more read locks on a byte, there can't be any write locks on that byte; if there is an exclusive write lock on a byte, there can't be any read locks on that byte. We show this compatibility rule in Figure 14.3.

		Request for	
		read lock	write lock
Region currently has	no locks	OK	OK
	one or more read locks	OK	denied
	one write lock	denied	denied

Figure 14.3 Compatibility between different lock types

The compatibility rule applies to lock requests made from different processes, not to multiple lock requests made by a single process. If a process has an existing lock on a range of a file, a subsequent attempt to place a lock on the same range by the same process will replace the existing lock with the new one. Thus, if a process has a write lock on bytes 16–32 of a file and then tries to place a read lock on bytes 16–32, the request will succeed, and the write lock will be replaced by a read lock.

To obtain a read lock, the descriptor must be open for reading; to obtain a write lock, the descriptor must be open for writing.

We can now describe the three commands for the `fcntl` function.

`F_GETLK` Determine whether the lock described by *flockptr* is blocked by some other lock. If a lock exists that would prevent ours from being created, the information on that existing lock overwrites the information pointed to by *flockptr*. If no lock exists that would prevent ours from being created, the structure pointed to by *flockptr* is left unchanged except for the `l_type` member, which is set to `F_UNLCK`.

`F_SETLK` Set the lock described by *flockptr*. If we are trying to obtain a read lock (`l_type` of `F_RDLCK`) or a write lock (`l_type` of `F_WRLCK`) and the compatibility rule prevents the system from giving us the lock (Figure 14.3), `fcntl` returns immediately with `errno` set to either `EACCES` or `EAGAIN`.

> Although POSIX allows an implementation to return either error code, all four implementations described in this text return `EAGAIN` if the locking request cannot be satisfied.

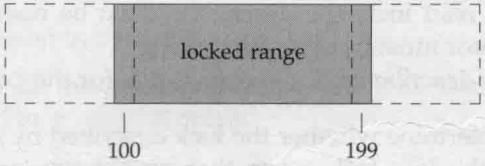
This command is also used to clear the lock described by *flockptr* (`l_type` of `F_UNLCK`).

`F_SETLKW` This command is a blocking version of `F_SETLK`. (The `W` in the command name means *wait*.) If the requested read lock or write lock cannot be granted because another process currently has some part of the requested region locked, the calling process is put to sleep. The process wakes up either when the lock becomes available or when interrupted by a signal.

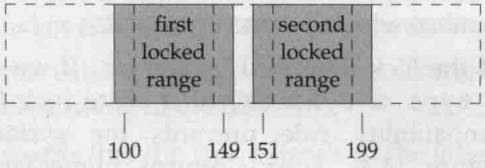
Be aware that testing for a lock with `F_GETLK` and then trying to obtain that lock with `F_SETLK` or `F_SETLKW` is not an atomic operation. We have no guarantee that, between the two `fcntl` calls, some other process won't come in and obtain the same lock. If we don't want to block while waiting for a lock to become available to us, we must handle the possible error returns from `F_SETLK`.

> Note that POSIX.1 doesn't specify what happens when one process read locks a range of a file, a second process blocks while trying to get a write lock on the same range, and a third processes then attempts to get another read lock on the range. If the third process is allowed to place a read lock on the range just because the range is already read locked, then the implementation might starve processes with pending write locks. Thus, as additional requests to read lock the same range arrive, the time that the process with the pending write-lock request has to wait is extended. If the read-lock requests arrive quickly enough without a lull in the arrival rate, then the writer could wait for a long time.

When setting or releasing a lock on a file, the system combines or splits adjacent areas as required. For example, if we lock bytes 100 through 199 and then unlock byte 150, the kernel still maintains the locks on bytes 100 through 149 and bytes 151 through 199. Figure 14.4 illustrates the byte-range locks in this situation.



File after locking bytes 100 through 199



File after unlocking byte 150

Figure 14.4 File byte-range lock diagram

If we were to lock byte 150, the system would coalesce the adjacent locked regions into a single region from byte 100 through 199. The resulting picture would be the first diagram in Figure 14.4, the same as when we started.

Example — Requesting and Releasing a Lock

To save ourselves from having to allocate an `flock` structure and fill in all the elements each time, the function `lock_reg` in Figure 14.5 handles all these details.

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

int
lock_reg(int fd, int cmd, int type, off_t offset, int whence, off_t len)
{
    struct flock    lock;

    lock.l_type = type;     /* F_RDLCK, F_WRLCK, F_UNLCK */
    lock.l_start = offset;  /* byte offset, relative to l_whence */
    lock.l_whence = whence; /* SEEK_SET, SEEK_CUR, SEEK_END */
    lock.l_len = len;       /* #bytes (0 means to EOF) */

    return(fcntl(fd, cmd, &lock));
}
```

Figure 14.5 Function to lock or unlock a region of a file

Since most locking calls are to lock or unlock a region (the command `F_GETLK` is rarely used), we normally use one of the following five macros, which are defined in `apue.h` (Appendix B).

```
#define read_lock(fd, offset, whence, len) \
            lock_reg((fd), F_SETLK, F_RDLCK, (offset), (whence), (len))
#define readw_lock(fd, offset, whence, len) \
            lock_reg((fd), F_SETLKW, F_RDLCK, (offset), (whence), (len))
#define write_lock(fd, offset, whence, len) \
            lock_reg((fd), F_SETLK, F_WRLCK, (offset), (whence), (len))
#define writew_lock(fd, offset, whence, len) \
            lock_reg((fd), F_SETLKW, F_WRLCK, (offset), (whence), (len))
#define un_lock(fd, offset, whence, len) \
            lock_reg((fd), F_SETLK, F_UNLCK, (offset), (whence), (len))
```

We have purposely defined the first three arguments to these macros in the same order as the `lseek` function. □

Example — Testing for a Lock

Figure 14.6 defines the function `lock_test` that we'll use to test for a lock.

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

pid_t
lock_test(int fd, int type, off_t offset, int whence, off_t len)
{
```