6

Devices

Linux, like most operating systems, interacts with hardware devices via modularized software components called *device drivers*. A device driver hides the peculiarities of a hardware device's communication protocols from the operating system and allows the system to interact with the device through a standardized interface.

Under Linux, device drivers are part of the kernel and may be either linked statically into the kernel or loaded on demand as kernel modules. Device drivers run as part of the kernel and aren't directly accessible to user processes. However, Linux provides a mechanism by which processes can communicate with a device driver—and through it with a hardware device—via file-like objects. These objects appear in the file system, and programs can open them, read from them, and write to them practically as if they were normal files. Using either Linux's low-level I/O operations (see Appendix B, "Low-Level I/O") or the standard C library's I/O operations, your programs can communicate with hardware devices through these file-like objects.

Linux also provides several file-like objects that communicate directly with the kernel rather than with device drivers. These aren't linked to hardware devices; instead, they provide various kinds of specialized behavior that can be of use to application and system programs.

Exercise Caution When Accessing Devices!

The techniques in this chapter provide direct access to device drivers running in the Linux kernel, and through them to hardware devices connected to the system. Use these techniques with care because misuse can cause impair or damage the GNU/Linux system.

See especially the sidebar "Dangers of Block Devices."

6.1 Device Types

Device files aren't ordinary files—they do not represent regions of data on a disk-based file system. Instead, data read from or written to a device file is communicated to the corresponding device driver, and from there to the underlying device. Device files come in two flavors:

- A *character device* represents a hardware device that reads or writes a serial stream of data bytes. Serial and parallel ports, tape drives, terminal devices, and sound cards are examples of character devices.
- A *block device* represents a hardware device that reads or writes data in fixed-size blocks. Unlike a character device, a block device provides random access to data stored on the device. A disk drive is an example of a block device.

Typical application programs will never use block devices. While a disk drive is represented as block devices, the contents of each disk partition typically contain a file system, and that file system is mounted into GNU/Linux's root file system tree. Only the kernel code that implements the file system needs to access the block device directly; application programs access the disk's contents through normal files and directories.

Dangers of Block Devices

Block devices provide direct access to disk drive data. Although most GNU/Linux systems are configured to prevent nonroot processes from accessing these devices directly, a root process can inflict severe damage by changing the contents of the disk. By writing to a disk block device, a program can modify or destroy file system control information and even a disk's partition table and master boot record, thus rendering a drive or even the entire system unusable. Always access these devices with great care.

Applications sometimes make use of character devices, though. We'll discuss several of them in the following sections.

6.2 Device Numbers

Linux identifies devices using two numbers: the *major device number* and the *minor device number*. The major device number specifies which driver the device corresponds to. The correspondence from major device numbers to drivers is fixed and part of the Linux kernel sources. Note that the same major device number may correspond to

two different drivers, one a character device and one a block device. Minor device numbers distinguish individual devices or components controlled by a single driver. The meaning of a minor device number depends on the device driver.

For example, major device no. 3 corresponds to the primary IDE controller on the system. An IDE controller can have two devices (disk, tape, or CD-ROM drives) attached to it; the "master" device has minor device no. 0, and the "slave" device has minor device no. 64. Individual partitions on the master device (if the device supports partitions) are represented by minor device numbers 1, 2, 3, and so on. Individual partitions on the slave device are represented by minor device numbers 65, 66, 67, and so on.

Major device numbers are listed in the Linux kernel sources documentation. On many GNU/Linux distributions, this documentation can be found in `/usr/src/linux/Documentation/devices.txt`. The special entry `/proc/devices` lists major device numbers corresponding to active device drivers currently loaded into the kernel. (See Chapter 7, "The `/proc` File System," for more information about `/proc` file system entries.)

6.3 Device Entries

A device entry is in many ways the same as a regular file. You can move it using the `mv` command and delete it using the `rm` command. If you try to copy a device entry using `cp`, though, you'll read bytes from the device (if the device supports reading) and write them to the destination file. If you try to overwrite a device entry, you'll write bytes to the corresponding device instead.

You can create a device entry in the file system using the `mknod` command (invoke `man 1 mknod` for the man page) or the `mknod` system call (invoke `man 2 mknod` for the man page). Creating a device entry in the file system doesn't automatically imply that the corresponding device driver or hardware device is present or available; the device entry is merely a portal for communicating with the driver, if it's there. Only superuser processes can create block and character devices using the `mknod` command or the `mknod` system call.

To create a device using the `mknod` command, specify as the first argument the path at which the entry will appear in the file system. For the second argument, specify `b` for a block device or `c` for a character device. Provide the major and minor device numbers as the third and fourth arguments, respectively. For example, this command makes a character device entry named `lp0` in the current directory. The device has major device no. 6 and minor device no. 0. These numbers correspond to the first parallel port on the Linux system.

```
% mknod ./lp0 c 6 0
```

Remember that only superuser processes can create block and character devices, so you must be logged in as `root` to invoke this command successfully.

The `ls` command displays device entries specially. If you invoke `ls` with the `-l` or `-o` options, the first character on each line of output specifies the type of the entry. Recall that `-` (a hyphen) designates a normal file, while `d` designates a directory. Similarly, `b` designates a block device, and `c` designates a character device. For the latter two, `ls` prints the major and minor device numbers where it would the size of an ordinary file. For example, we can display the block device that we just created:

```
% ls -l lp0
crw-r-----    1 root     root       6,   0 Mar  7 17:03 lp0
```

In a program, you can determine whether a file system entry is a block or character device and then retrieve its device numbers using `stat`. See Section B.2, "`stat`," in Appendix B, for instructions.

To remove the entry, use `rm`. This doesn't remove the device or device driver; it simply removes the device entry from the file system.

```
% rm ./lp0
```

6.3.1 The */dev* Directory

By convention, a GNU/Linux system includes a directory `/dev` containing the full complement of character and block device entries for devices that Linux knows about. Entries in `/dev` have standardized names corresponding to major and minor device numbers.

For example, the master device attached to the primary IDE controller, which has major and minor device numbers 3 and 0, has the standard name `/dev/hda`. If this device supports partitions, the first partition on it, which has minor device no. 1, has the standard name `/dev/hda1`. You can check that this is true on your system:

```
% ls -l /dev/hda /dev/hda1
brw-rw----    1 root     disk       3,   0 May  5  1998 /dev/hda
brw-rw----    1 root     disk       3,   1 May  5  1998 /dev/hda1
```

Similarly, `/dev` has an entry for the parallel port character device that we used previously:

```
% ls -l /dev/lp0
crw-rw----    1 root     daemon     6,   0 May  5  1998 /dev/lp0
```

In most cases, you should not use `mknod` to create your own device entries. Use the entries in `/dev` instead. Non-superuser programs have no choice but to use preexisting device entries because they cannot create their own. Typically, only system administrators and developers working with specialized hardware devices will need to create device entries. Most GNU/Linux distributions include facilities to help system administrators create standard device entries with the correct names.

6.3.2 Accessing Devices by Opening Files

How do you use these devices? In the case of character devices, it can be quite simple: Open the device as if it were a normal file, and read from or write to it. You can even use normal file commands such as `cat`, or your shell's redirection syntax, to send data to or from the device.

For example, if you have a printer connected to your computer's first parallel port, you can print files by sending them directly to `/dev/lp0`.[1] To print the contents of `document.txt`, invoke the following:

```
% cat document.txt > /dev/lp0
```

You must have permission to write to the device entry for this to succeed; on many GNU/Linux systems, the permissions are set so that only `root` and the system's printer daemon (`lpd`) can write to the file. Also, what comes out of your printer depends on how your printer interprets the contents of the data you send it. Some printers will print plain text files that are sent to them,[2] while others will not. PostScript printers will render and print PostScript files that you send to them.

In a program, sending data to a device is just as simple. For example, this code fragment uses low-level I/O functions to send the contents of a buffer to `/dev/lp0`.

```
int fd = open ("/dev/lp0", O_WRONLY);
write (fd, buffer, buffer_length);
close (fd);
```

6.4 Hardware Devices

Some common block devices are listed in Table 6.1. Device numbers for similar devices follow the obvious pattern (for instance, the second partition on the first SCSI drive is `/dev/sda2`). It's occasionally useful to know which devices these device names correspond to when examining mounted file systems in `/proc/mounts` (see Section 7.5, "Drives, Mounts, and File Systems," in Chapter 7, for more about this).

Table 6.1 **Partial Listing of Common Block Devices**

Device	Name	Major	Minor
First floppy drive	`/dev/fd0`	2	0
Second floppy drive	`/dev/fd1`	2	1
Primary IDE controller, master device	`/dev/hda`	3	0
Primary IDE controller, master device, first partition	`/dev/hda1`	3	1

continues

1. Windows users will recognize that this device is similar to the magic Windows file `LPR1`.
2. Your printer may require explicit carriage return characters, ASCII code 14, at the end of each line, and may require a form feed character, ASCII code 12, at the end of each page.

Table 6.1 **Continued**

Device	Name	Major	Minor
Primary IDE controller, secondary device	`/dev/hdb`	3	64
Primary IDE controller, secondary device, first partition	`/dev/hdb1`	3	65
Secondary IDE controller, master device	`/dev/hdc`	22	0
Secondary IDE controller, secondary device	`/dev/hdd`	22	64
First SCSI drive	`/dev/sda`	8	0
First SCSI drive, first partition	`/dev/sda1`	8	1
Second SCSI disk	`/dev/sdb`	8	16
Second SCSI disk, first partition	`/dev/sdb1`	8	17
First SCSI CD-ROM drive	`/dev/scd0`	11	0
Second SCSI CD-ROM drive	`/dev/scd1`	11	1

Table 6.2 lists some common character devices.

Table 6.2 **Some Common Character Devices**

Device	Name	Major	Minor
Parallel port 0	`/dev/lp0` or `/dev/par0`	6	0
Parallel port 1	`/dev/lp1` or `/dev/par1`	6	1
First serial port	`/dev/ttyS0`	4	64
Second serial port	`/dev/ttyS1`	4	65
IDE tape drive	`/dev/ht0`	37	0
First SCSI tape drive	`/dev/st0`	9	0
Second SCSI tape drive	`/dev/st1`	9	1
System console	`/dev/console`	5	1
First virtual terminal	`/dev/tty1`	4	1
Second virtual terminal	`/dev/tty2`	4	2
Process's current terminal device	`/dev/tty`	5	0
Sound card	`/dev/audio`	14	4

You can access certain hardware components through more than one character device; often, the different character devices provide different semantics. For example, when you use the IDE tape device `/dev/ht0`, Linux automatically rewinds the tape in the drive when you close the file descriptor. You can use the device `/dev/nht0` to access the same tape drive, except that Linux will not automatically rewind the tape when you close the file descriptor. You sometimes might see programs using `/dev/cua0` and similar devices; these are older interfaces to serial ports such as `/dev/ttyS0`.

Occasionally, you'll want to write data directly to character devices—for example:

- A terminal program might access a modem directly through a serial port device. Data written to or read from the devices is transmitted via the modem to a remote computer.
- A tape backup program might write data directly to a tape device. The backup program could implement its own compression and error-checking format.
- A program can write directly to the first virtual terminal[3] writing data to `/dev/tty1`.

  Terminal windows running in a graphical environment, or remote login terminal sessions, are not associated with virtual terminals; instead, they're associated with pseudo-terminals. See Section 6.6, "PTYs," for information about these.
- Sometimes a program needs to access the terminal device with which it is associated.

  For example, your program may need to prompt the user for a password. For security reasons, you might want to ignore redirection of standard input and output and always read the password from the terminal, no matter how the user invokes the command. One way to do this is to open `/dev/tty`, which always corresponds to the terminal device associated with the process that opens it. Write the prompt message to that device, and read the password from it. By ignoring standard input and output, this prevents the user from feeding your program a password from a file using shell syntax such as this:

  ```
  % secure_program < my-password.txt
  ```

  If you need to authenticate users in your program, you should learn about GNU/Linux's PAM facility. See Section 10.5, "Authenticating Users," in Chapter 10, "Security," for more information.
- A program can play sounds through the system's sound card by sending audio data to `/dev/audio`. Note that the audio data must be in Sun audio format (usually associated with the `.au` extension).

  For example, many GNU/Linux distributions come with the classic sound file `/usr/share/sndconfig/sample.au`. If your system includes this file, try playing it by invoking the following:

  ```
  % cat /usr/share/sndconfig/sample.au > /dev/audio
  ```

  If you're planning on using sound in your program, though, you should investigate the various sound libraries and services available for GNU/Linux. The Gnome windowing environment uses the Enlightenment Sound Daemon (EsounD), at `http://www.tux.org/~ricdude/EsounD.html`. KDE uses aRts, at `http://space.twc.de/~stefan/kde/arts-mcop-doc/`. If you use one of these sound systems instead of writing directly to `/dev/audio`, your program will cooperate better with other programs that use the computer's sound card.

3. On most GNU/Linux systems, you can switch to the first virtual terminal by pressing Ctrl+Alt+F1. Use Ctrl+Alt+F2 for the second virtual terminal, and so on.

6.5 Special Devices

Linux also provides several character devices that don't correspond to hardware devices. These entries all use the major device no. 1, which is associated with the Linux kernel's memory device instead of a device driver.

6.5.1 */dev/null*

The entry `/dev/null`, the *null device*, is very handy. It serves two purposes; you are probably familiar at least with the first one:

- Linux discards any data written to `/dev/null`. A common trick is to specify `/dev/null` as an output file in some context where the output is unwanted.

  For example, to run a command and discard its standard output (without printing it or writing it to a file), redirect standard output to `/dev/null`:

  ```
  % verbose_command > /dev/null
  ```

- Reading from `/dev/null` always results in an end-of-file. For instance, if you open a file descriptor to `/dev/null` using `open` and then attempt to `read` from the file descriptor, `read` will read no bytes and will return 0. If you copy from `/dev/null` to another file, the destination will be a zero-length file:

  ```
  % cp /dev/null empty-file
  % ls -l empty-file
  -rw-rw----    1 samuel   samuel          0 Mar  8 00:27 empty-file
  ```

6.5.2 */dev/zero*

The device entry `/dev/zero` behaves as if it were an infinitely long file filled with 0 bytes. As much data as you'd try to read from `/dev/zero`, Linux "generates" enough 0 bytes.

To illustrate this, let's run the hex dump program presented in Listing B.4 in Section B.1.4, "Reading Data," of Appendix B. This program prints the contents of a file in hexadecimal form.

```
% ./hexdump /dev/zero
0x000000 : 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x000010 : 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x000020 : 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x000030 : 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
...
```

Hit Ctrl+C when you're convinced that it will go on indefinitely.

Memory mapping `/dev/zero` is an advanced technique for allocating memory. See Section 5.3.5, "Other Uses for `mmap`," in Chapter 5, "Interprocess Communication," for more information, and see the sidebar "Obtaining Page-Aligned Memory" in Section 8.9, "`mprotect`: Setting Memory Permissions," in Chapter 8, "Linux System Calls," for an example.

6.5.3 */dev/full*

The entry `/dev/full` behaves as if it were a file on a file system that has no more room. A write to `/dev/full` fails and sets `errno` to `ENOSPC`, which ordinarily indicates that the written-to device is full.

For example, you can try to write to `/dev/full` using the `cp` command:

```
% cp /etc/fstab /dev/full
cp: /dev/full: No space left on device
```

The `/dev/full` entry is primarily useful to test how your program behaves if it runs out of disk space while writing to a file.

6.5.4 Random Number Devices

The special devices `/dev/random` and `/dev/urandom` provide access to the Linux kernel's built-in random number–generation facility.

Most software functions for generating random numbers, such as the `rand` function in the standard C library, actually generate *pseudorandom* numbers. Although these numbers satisfy some properties of random numbers, they are reproducible: If you start with the same seed value, you'll obtain the same sequence of pseudorandom numbers every time. This behavior is inevitable because computers are intrinsically deterministic and predictable. For certain applications, though, this behavior is undesirable; for instance, it is sometimes possible to break a cryptographic algorithm if you can obtain the sequence of random numbers that it employs.

To obtain better random numbers in computer programs requires an external source of randomness. The Linux kernel harnesses a particularly good source of randomness: *you!* By measuring the time delay between your input actions, such as keystrokes and mouse movements, Linux is capable of generating an unpredictable stream of high-quality random numbers. You can access this stream by reading from `/dev/random` and `/dev/urandom`. The data that you read is a stream of randomly generated bytes.

The difference between the two devices exhibits itself when Linux exhausts its store of randomness. If you try to read a large number of bytes from `/dev/random` but don't generate any input actions (you don't type, move the mouse, or perform a similar action), Linux blocks the read operation. Only when you provide some randomness does Linux generate some more random bytes and return them to your program.

For example, try displaying the contents of `/dev/random` using the `od` command.[4] Each row of output shows 16 random bytes.

4. We use `od` here instead of the `hexdump` program presented in Listing B.4, even though they do pretty much the same thing, because `hexdump` terminates when it runs out of data, while `od` waits for more data to become available. The `-t x1` option tells `od` to print file contents in hexadecimal.

```
% od -t x1 /dev/random
0000000 2c 9c 7a db 2e 79 3d 65 36 c2 e3 1b 52 75 1e 1a
0000020 d3 6d 1e a7 91 05 2d 4d c3 a6 de 54 29 f4 46 04
0000040 b3 b0 8d 94 21 57 f3 90 61 dd 26 ac 94 c3 b9 3a
0000060 05 a3 02 cb 22 0a bc c9 45 dd a6 59 40 22 53 d4
```

The number of lines of output that you see will vary—there may be quite a few—but the output will eventually pause when Linux exhausts its store of randomness. Now try moving your mouse or typing on the keyboard, and watch additional random numbers appear. For even better randomness, let your cat walk on the keyboard.

A read from `/dev/urandom`, in contrast, will never block. If Linux runs out of randomness, it uses a cryptographic algorithm to generate pseudorandom bytes from the past sequence of random bytes. Although these bytes are random enough for many purposes, they don't pass as many tests of randomness as those obtained from `/dev/random`.

For instance, if you invoke the following, the random bytes will fly by forever, until you kill the program with Ctrl+C:

```
% od -t x1 /dev/urandom
0000000 62 71 d6 3e af dd de 62 c0 42 78 bd 29 9c 69 49
0000020 26 3b 95 bc b9 6c 15 16 38 fd 7e 34 f0 ba ce c3
0000040 95 31 e5 2c 8d 8a dd f4 c4 3b 9b 44 2f 20 d1 54
...
```

Using random numbers from `/dev/random` in a program is easy, too. Listing 6.1 presents a function that generates a random number using bytes read from in `/dev/random`. Remember that `/dev/random` blocks a read until there is enough randomness available to satisfy it; you can use `/dev/urandom` instead if fast execution is more important and you can live with the potential lower quality of random numbers.

Listing 6.1 **(*random_number.c*) Function to Generate a Random Number Using */dev/random***

```
#include <assert.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <fcntl.h>
#include <unistd.h>

/* Return a random integer between MIN and MAX, inclusive.  Obtain
   randomness from /dev/random.  */

int random_number (int min, int max)
{
  /* Store a file descriptor opened to /dev/random in a static
     variable.  That way, we don't need to open the file every time
     this function is called.  */
  static int dev_random_fd = -1;
```

```
  char* next_random_byte;
  int bytes_to_read;
  unsigned random_value;

  /* Make sure MAX is greater than MIN.  */
  assert (max > min);

  /* If this is the first time this function is called, open a file
     descriptor to /dev/random.  */
  if (dev_random_fd == -1) {
    dev_random_fd = open ("/dev/random", O_RDONLY);
    assert (dev_random_fd != -1);
  }

  /* Read enough random bytes to fill an integer variable.  */
  next_random_byte = (char*) &random_value;
  bytes_to_read = sizeof (random_value);
  /* Loop until we've read enough bytes.  Because /dev/random is filled
     from user-generated actions, the read may block and may only
     return a single random byte at a time.  */
  do {
    int bytes_read;
    bytes_read = read (dev_random_fd, next_random_byte, bytes_to_read);
    bytes_to_read -= bytes_read;
    next_random_byte += bytes_read;
  } while (bytes_to_read > 0);

  /* Compute a random number in the correct range.  */
  return min + (random_value % (max - min + 1));
}
```

6.5.5 Loopback Devices

A *loopback device* enables you to simulate a block device using an ordinary disk file. Imagine a disk drive device for which data is written to and read from a file named `disk-image` rather than to and from the tracks and sectors of an actual physical disk drive or disk partition. (Of course, the file `disk-image` must reside on an actual disk, which must be larger than the simulated disk.) A loopback device enables you to use a file in this manner.

Loopback devices are named `/dev/loop0`, `/dev/loop1`, and so on. Each can be used to simulate a single block device at one time. Note that only the superuser can set up a loopback device.

A loopback device can be used in the same way as any other block device. In particular, you can construct a file system on the device and then mount that file system as you would mount the file system on an ordinary disk or partition. Such a file system, which resides in its entirety within an ordinary disk file, is called a *virtual file system*.

To construct a virtual file system and mount it with a loopback device, follow these steps:

1. Create an empty file to hold the virtual file system. The size of the file will be the apparent size of the loopback device after it is mounted.

   One convenient way to construct a file of a fixed size is with the `dd` command. This command copies blocks (by default, 512 bytes each) from one file to another. The `/dev/zero` file is a convenient source of bytes to copy from.

   To construct a 10MB file named `disk-image`, invoke the following:

   ```
   % dd if=/dev/zero of=/tmp/disk-image count=20480
   20480+0 records in
   20480+0 records out
   % ls -l /tmp/disk-image
   -rw-rw----    1 root     root     10485760 Mar  8 01:56 /tmp/disk-image
   ```

2. The file that you've just created is filled with 0 bytes. Before you mount it, you must construct a file system. This sets up the various control structures needed to organize and store files, and builds the root directory.

   You can build any type of file system you like in your disk image. To construct an `ext2` file system (the type most commonly used for Linux disks), use the `mke2fs` command. Because it's usually run on a block device, not an ordinary file, it asks for confirmation:

   ```
   % mke2fs -q /tmp/disk-image
   mke2fs 1.18, 11-Nov-1999 for EXT2 FS 0.5b, 95/08/09
   disk-image is not a block special device.
   Proceed anyway? (y,n) y
   ```

   The `-q` option suppresses summary information about the newly created file system. Leave this option out if you're curious about it.

   Now `disk-image` contains a brand-new file system, as if it were a freshly initialized 10MB disk drive.

3. Mount the file system using a loopback device. To do this, use the `mount` command, specifying the disk image file as the mount device. Also specify `loop=`*`loopback-device`* as a mount option, using the `-o` option to `mount` to tell `mount` which loopback device to use.

   For example, to mount our `disk-image` file system, invoke these commands. Remember, only the superuser may use a loopback device. The first command creates a directory, `/tmp/virtual-fs`, to use as the mount point for the virtual file system.

   ```
   % mkdir /tmp/virtual-fs
   % mount -o loop=/dev/loop0 /tmp/disk-image /tmp/virtual-fs
   ```

   Now your disk image is mounted as if it were an ordinary 10MB disk drive.

   ```
   % df -h /tmp/virtual-fs
   Filesystem             Size  Used Avail Use% Mounted on
   /tmp/disk-image        9.7M   13k  9.2M   0% /tmp/virtual-fs
   ```

   You can use it like any other disk:

   ```
   % cd /tmp/virtual-fs
   % echo 'Hello, world!' > test.txt
   % ls -l
   total 13
   drwxr-xr-x    2 root     root         12288 Mar  8 02:00 lost+found
   -rw-rw----    1 root     root            14 Mar  8 02:12 test.txt
   % cat test.txt
   Hello, world!
   ```

   Note that `lost+found` is a directory that was automatically added by `mke2fs`.[5]

5. If the file system is ever damaged, and some data is recovered but not associated with a file, it is placed in `lost+found`.

When you're done, unmount the virtual file system.

```
% cd /tmp
% umount /tmp/virtual-fs
```

You can delete `disk-image` if you like, or you can mount it later to access the files on the virtual file system. You can also copy it to another computer and mount it there—the whole file system that you created on it will be intact.

Instead of creating a file system from scratch, you can copy one directly from a device. For instance, you can create an image of the contents of a CD-ROM simply by copying it from the CD-ROM device.

If you have an IDE CD-ROM drive, use the corresponding device name, such as `/dev/hda`, described previously. If you have a SCSI CD-ROM drive, the device name will be `/dev/scd0` or similar. Your system may also have a symbolic link `/dev/cdrom` that points to the appropriate device. Consult your `/etc/fstab` file to determine what device corresponds to your computer's CD-ROM drive.

Simply copy that device to a file. The resulting file will be a complete disk image of the file system on the CD-ROM in the drive—for example:

```
% cp /dev/cdrom /tmp/cdrom-image
```

This may take several minutes, depending on the CD-ROM you're copying and the speed of your drive. The resulting image file will be quite large—as large as the contents of the CD-ROM.

Now you can mount this CD-ROM image without having the original CD-ROM in the drive. For example, to mount it on `/mnt/cdrom`, use this line:

```
% mount -o loop=/dev/loop0 /tmp/cdrom-image /mnt/cdrom
```

Because the image is on a hard disk drive, it'll perform much faster than the actual CD-ROM disk. Note that most CD-ROMs use the file system type `iso9660`.

6.6 PTYs

If you run the `mount` command with no command-line arguments, which displays the file systems mounted on your system, you'll notice a line that looks something like this:

```
none on /dev/pts type devpts (rw,gid=5,mode=620)
```

This indicates that a special type of file system, `devpts`, is mounted at `/dev/pts`. This file system, which isn't associated with any hardware device, is a "magic" file system that is created by the Linux kernel. It's similar to the `/proc` file system; see Chapter 7 for more information about how this works.

Like the `/dev` directory, `/dev/pts` contains entries corresponding to devices. But unlike `/dev`, which is an ordinary directory, `/dev/pts` is a special directory that is created dynamically by the Linux kernel. The contents of the directory vary with time and reflect the state of the running system.

The entries in `/dev/pts` correspond to *pseudo-terminals* (or *pseudo-TTYs*, or *PTYs*). Linux creates a PTY for every new terminal window you open and displays a corresponding entry in `/dev/pts`. The PTY device acts like a terminal device—it accepts input from the keyboard and displays text output from the programs that run in it. PTYs are numbered, and the PTY number is the name of the corresponding entry in `/dev/pts`.

You can display the terminal device associated with a process using the `ps` command. Specify `tty` as one of the fields of a custom format with the `-o` option. To display the process ID, TTY, and command line of each process sharing the same terminal, invoke `ps -o pid,tty,cmd`.

6.6.1 A PTY Demonstration

For example, you can determine the PTY associated with a given terminal window by invoking in the window this command:

```
% ps -o pid,tty,cmd
  PID TT       CMD
28832 pts/4    bash
29287 pts/4    ps -o pid,tty,cmd
```

This particular terminal window is running in PTY 4.

The PTY has a corresponding entry in `/dev/pts`:

```
% ls -l /dev/pts/4
crw--w----    1 samuel   tty      136,   4 Mar  8 02:56 /dev/pts/4
```

Note that it is a character device, and its owner is the owner of the process for which it was created.

You can read from or write to the PTY device. If you read from it, you'll hijack keyboard input that would otherwise be sent to the program running in the PTY. If you write to it, the data will appear in that window.

Try opening a new terminal window, and determine its PTY number by invoking `ps -o pid,tty,cmd`. From another window, write some text to the PTY device. For example, if the new terminal window's PTY number is 7, invoke this command from another window:

```
% echo 'Hello, other window!' > /dev/pts/7
```

The output appears in the new terminal window. If you close the new terminal window, the entry `7` in `/dev/pts` disappears.

If you invoke `ps` to determine the TTY from a text-mode virtual terminal (press Ctrl+Alt+F1 to switch to the first virtual terminal, for instance), you'll see that it's running in an ordinary terminal device instead of a PTY:

```
% ps -o pid,tty,cmd
  PID TT       CMD
29325 tty1     -bash
29353 tty1     ps -o pid,tty,cmd
```

6.7 *ioctl*

The `ioctl` system call is an all-purpose interface for controlling hardware devices. The first argument to `ioctl` is a file descriptor, which should be opened to the device that you want to control. The second argument is a request code that indicates the operation that you want to perform. Various request codes are available for different devices. Depending on the request code, there may be additional arguments supplying data to `ioctl`.

Many of the available requests codes for various devices are listed in the `ioctl_list` man page. Using `ioctl` generally requires a detailed understanding of the device driver corresponding to the hardware device that you want to control. Most of these are quite specialized and are beyond the scope of this book. However, we'll present one example to give you a taste of how `ioctl` is used.

Listing 6.2 **(*cdrom-eject.c*) Eject a CD-ROM**

```
#include <fcntl.h>
#include <linux/cdrom.h>
#include <sys/ioctl.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

int main (int argc, char* argv[])
{
  /* Open a file descriptor to the device specified on the command line.  */
  int fd = open (argv[1], O_RDONLY);
  /* Eject the CD-ROM.  */
  ioctl (fd, CDROMEJECT);
  /* Close the file descriptor.  */
  close (fd);

  return 0;
}
```

Listing 6.2 presents a short program that ejects the disk in a CD-ROM drive (if the drive supports this). It takes a single command-line argument, the CD-ROM drive device. It opens a file descriptor to the device and invokes `ioctl` with the request code `CDROMEJECT`. This request, defined in the header `<linux/cdrom.h>`, instructs the device to eject the disk.

For example, if your system has an IDE CD-ROM drive connected as the master device on the secondary IDE controller, the corresponding device is `/dev/hdc`. To eject the disk from the drive, invoke this line:

```
% ./cdrom-eject /dev/hdc
```

7

The */proc* File System

TRY INVOKING THE `mount` COMMAND WITHOUT ARGUMENTS—this displays the file systems currently mounted on your GNU/Linux computer. You'll see one line that looks like this:

```
none on /proc type proc (rw)
```

This is the special `/proc` *file system*. Notice that the first field, `none`, indicates that this file system isn't associated with a hardware device such as a disk drive. Instead, `/proc` is a window into the running Linux kernel. Files in the `/proc` file system don't correspond to actual files on a physical device. Instead, they are magic objects that behave like files but provide access to parameters, data structures, and statistics in the kernel. The "contents" of these files are not always fixed blocks of data, as ordinary file contents are. Instead, they are generated on the fly by the Linux kernel when you read from the file. You can also change the configuration of the running kernel by writing to certain files in the `/proc` file system.

Let's look at an example:

```
% ls -l /proc/version
-r--r--r--    1 root     root            0 Jan 17 18:09 /proc/version
```

Note that the file size is zero; because the file's contents are generated by the kernel, the concept of file size is not applicable. Also, if you try this command yourself, you'll notice that the modification time on the file is the current time.

What's in this file? The contents of /proc/version consist of a string describing the Linux kernel version number. It contains the version information that would be obtained by the uname system call, described in Chapter 8, "Linux System Calls," in Section 8.15, "uname," plus additional information such as the version of the compiler that was used to compile the kernel. You can read from /proc/version like you would any other file. For instance, an easy way to display its contents is with the cat command.

```
% cat /proc/version
Linux version 2.2.14-5.0 (root@porky.devel.redhat.com) (gcc version egcs-2.91.
66 19990314/Linux (egcs-1.1.2 release)) #1 Tue Mar 7 21:07:39 EST 2000
```

The various entries in the /proc file system are described extensively in the proc man page (Section 5). To view it, invoke this command:

```
% man 5 proc
```

In this chapter, we'll describe some of the features of the /proc file system that are most likely to be useful to application programmers, and we'll give examples of using them. Some of the features of /proc are handy for debugging, too.

If you're interested in exactly how /proc works, take a look at the source code in the Linux kernel sources, under /usr/src/linux/fs/proc/.

7.1 Extracting Information from */proc*

Most of the entries in /proc provide information formatted to be readable by humans, but the formats are simple enough to be easily parsed. For example, /proc/cpuinfo contains information about the system CPU (or CPUs, for a multiprocessor machine). The output is a table of values, one per line, with a description of the value and a colon preceding each value.

For example, the output might look like this:

```
% cat /proc/cpuinfo
processor       : 0
vendor_id       : GenuineIntel
cpu family      : 6
model           : 5
model name      : Pentium II (Deschutes)
stepping        : 2
cpu MHz         : 400.913520
cache size      : 512 KB
fdiv_bug        : no
hlt_bug         : no
sep_bug         : no
f00f_bug        : no
coma_bug        : no
fpu             : yes
fpu_exception   : yes
cpuid level     : 2
wp              : yes
flags           : fpu vme de pse tsc msr pae mce cx8 apic sep
mtrr pge mca cmov pat pse36 mmx fxsr
bogomips        : 399.77
```

We'll describe the interpretation of some of these fields in Section 7.3.1, "CPU Information."

A simple way to extract a value from this output is to read the file into a buffer and parse it in memory using `sscanf`. Listing 7.1 shows an example of this. The program includes the function `get_cpu_clock_speed` that reads from `/proc/cpuinfo` into memory and extracts the first CPU's clock speed.

Listing 7.1 **(*clock-speed.c*) Extract CPU Clock Speed from */proc/cpuinfo***

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

/* Returns the clock speed of the system's CPU in MHz, as reported by
   /proc/cpuinfo.  On a multiprocessor machine, returns the speed of
   the first CPU.  On error returns zero.  */

float get_cpu_clock_speed ()
{
  FILE* fp;
  char buffer[1024];
  size_t bytes_read;
  char* match;
  float clock_speed;

  /* Read the entire contents of /proc/cpuinfo into the buffer.  */
  fp = fopen ("/proc/cpuinfo", "r");
  bytes_read = fread (buffer, 1, sizeof (buffer), fp);
  fclose (fp);
  /* Bail if read failed or if buffer isn't big enough.  */
  if (bytes_read == 0 || bytes_read == sizeof (buffer))
    return 0;
  /* NUL-terminate the text.  */
  buffer[bytes_read] = '\0';
  /* Locate the line that starts with "cpu MHz".  */
  match = strstr (buffer, "cpu MHz");
  if (match == NULL)
    return 0;
  /* Parse the line to extract the clock speed.  */
  sscanf (match, "cpu MHz : %f", &clock_speed);
  return clock_speed;
}


int main ()
{
  printf ("CPU clock speed: %4.0f MHz\n", get_cpu_clock_speed ());
  return 0;
}
```

Be aware, however, that the names, semantics, and output formats of entries in the /proc file system might change in new Linux kernel revisions. If you use them in a program, you should make sure that the program's behavior degrades gracefully if the /proc entry is missing or is formatted unexpectedly.

7.2 Process Entries

The /proc file system contains a directory entry for each process running on the GNU/Linux system. The name of each directory is the process ID of the corresponding process.[1] These directories appear and disappear dynamically as processes start and terminate on the system. Each directory contains several entries providing access to information about the running process. From these process directories the /proc file system gets its name.

Each process directory contains these entries:

- cmdline contains the argument list for the process. The cmdline entry is described in Section 7.2.2, "Process Argument List."
- cwd is a symbolic link that points to the current working directory of the process (as set, for instance, with the chdir call).
- environ contains the process's environment. The environ entry is described in Section 7.2.3, "Process Environment."
- exe is a symbolic link that points to the executable image running in the process. The exe entry is described in Section 7.2.4, "Process Executable."
- fd is a subdirectory that contains entries for the file descriptors opened by the process. These are described in Section 7.2.5, "Process File Descriptors."
- maps displays information about files mapped into the process's address. See Chapter 5, "Interprocess Communication," Section 5.3, "Mapped Memory," for details of how memory-mapped files work. For each mapped file, maps displays the range of addresses in the process's address space into which the file is mapped, the permissions on these addresses, the name of the file, and other information.

  The maps table for each process displays the executable running in the process, any loaded shared libraries, and other files that the process has mapped in.
- root is a symbolic link to the root directory for this process. Usually, this is a symbolic link to /, the system root directory. The root directory for a process can be changed using the chroot call or the chroot command.[2]

1. On some UNIX systems, the process IDs are padded with zeros. On GNU/Linux, they are not.

2. The chroot call and command are outside the scope of this book. See the chroot man page in Section 1 for information about the command (invoke man 1 chroot), or the chroot man page in Section 2 (invoke man 2 chroot) for information about the call.

- `stat` contains lots of status and statistical information about the process. These are the same data as presented in the `status` entry, but in raw numerical format, all on a single line. The format is difficult to read but might be more suitable for parsing by programs.

  If you want to use the `stat` entry in your programs, see the `proc` man page, which describes its contents, by invoking `man 5 proc`.
- `statm` contains information about the memory used by the process. The `statm` entry is described in Section 7.2.6, "Process Memory Statistics."
- `status` contains lots of status and statistical information about the process, formatted to be comprehensible by humans. Section 7.2.7, "Process Statistics," contains a description of the `status` entry.
- The `cpu` entry appears only on SMP Linux kernels. It contains a breakdown of process time (user and system) by CPU.

Note that for security reasons, the permissions of some entries are set so that only the user who owns the process (or the superuser) can access them.

7.2.1 */proc/self*

One additional entry in the `/proc` file system makes it easy for a program to use `/proc` to find information about its own process. The entry `/proc/self` is a symbolic link to the `/proc` directory corresponding to the current process. The destination of the `/proc/self` link depends on which process looks at it: Each process sees its own process directory as the target of the link.

For example, the program in Listing 7.2 reads the target of the `/proc/self` link to determine its process ID. (We're doing it this way for illustrative purposes only; calling the `getpid` function, described in Chapter 3, "Processes," in Section 3.1.1, "Process IDs," is a much easier way to do the same thing.) This program uses the `readlink` system call, described in Section 8.11, "`readlink`: Reading Symbolic Links," to extract the target of the symbolic link.

Listing 7.2 **(*get-pid.c*) Obtain the Process ID from */proc/self***

```
#include <stdio.h>
#include <sys/types.h>
#include <unistd.h>

/* Returns the process ID of the calling processes, as determined from
   the /proc/self symlink.  */

pid_t get_pid_from_proc_self ()
{
  char target[32];
  int pid;
  /* Read the target of the symbolic link.  */
  readlink ("/proc/self", target, sizeof (target));
```

continues

Listing 7.2 **Continued**

```
  /* The target is a directory named for the process ID.  */
  sscanf (target, "%d", &pid);
  return (pid_t) pid;
}

int main ()
{
  printf ("/proc/self reports process id %d\n",
          (int) get_pid_from_proc_self ());
  printf ("getpid() reports process id %d\n", (int) getpid ());
  return 0;
}
```

7.2.2 Process Argument List

The `cmdline` entry contains the process argument list (see Chapter 2, "Writing Good GNU/Linux Software," Section 2.1.1, "The Argument List"). The arguments are presented as a single character string, with arguments separated by NULs. Most string functions expect that the entire character string is terminated with a single NUL and will not handle NULs embedded within strings, so you'll have to handle the contents specially.

> **NUL vs. NULL**
>
> NUL is the character with integer value 0. It's different from NULL, which is a pointer with value 0.
>
> In C, a character string is usually terminated with a NUL character. For instance, the character string `"Hello, world!"` occupies 14 bytes because there is an implicit NUL after the exclamation point indicating the end of the string.
>
> NULL, on the other hand, is a pointer value that you can be sure will never correspond to a real memory address in your program.
>
> In C and C++, NUL is expressed as the character constant `'\0'`, or `(char) 0`. The definition of NULL differs among operating systems; on Linux, it is defined as `((void*)0)` in C and simply `0` in C++.

In Section 2.1.1, we presented a program in Listing 2.1 that printed out its own argument list. Using the `cmdline` entries in the `/proc` file system, we can implement a program that prints the argument of another process. Listing 7.3 is such a program; it prints the argument list of the process with the specified process ID. Because there may be several NULs in the contents of `cmdline` rather than a single one at the end, we can't determine the length of the string with `strlen` (which simply counts the number of characters until it encounters a NUL). Instead, we determine the length of `cmdline` from `read`, which returns the number of bytes that were read.

Listing 7.3 (*print-arg-list.c*) **Print the Argument List of a Running Process**

```
#include <fcntl.h>
#include <stdio.h>
#include <stdlib.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

/* Prints the argument list, one argument to a line, of the process
   given by PID.  */

void print_process_arg_list (pid_t pid)
{
  int fd;
  char filename[24];
  char arg_list[1024];
  size_t length;
  char* next_arg;

  /* Generate the name of the cmdline file for the process. */
  snprintf (filename, sizeof (filename), "/proc/%d/cmdline", (int) pid);
  /* Read the contents of the file. */
  fd = open (filename, O_RDONLY);
  length = read (fd, arg_list, sizeof (arg_list));
  close (fd);
  /* read does not NUL-terminate the buffer, so do it here. */
  arg_list[length] = '\0';

  /* Loop over arguments.  Arguments are separated by NULs. */
  next_arg = arg_list;
  while (next_arg < arg_list + length) {
    /* Print the argument.  Each is NUL-terminated, so just treat it
       like an ordinary string.  */
    printf ("%s\n", next_arg);
    /* Advance to the next argument.  Since each argument is
       NUL-terminated, strlen counts the length of the next argument,
       not the entire argument list.  */
    next_arg += strlen (next_arg) + 1;
  }
}

int main (int argc, char* argv[])
{
  pid_t pid = (pid_t) atoi (argv[1]);
  print_process_arg_list (pid);
  return 0;
}
```

For example, suppose that process 372 is the system logger daemon, `syslogd`.

```
% ps 372
  PID TTY      STAT   TIME COMMAND
  372 ?        S      0:00 syslogd -m 0
% ./print-arg-list 372
syslogd
-m
0
```

In this case, `syslogd` was invoked with the arguments `-m 0`.

7.2.3 Process Environment

The `environ` entry contains a process's environment (see Section 2.1.6, "The Environment"). As with `cmdline`, the individual environment variables are separated by NULs. The format of each element is the same as that used in the `environ` variable, namely *`VARIABLE=value`*.

Listing 7.4 presents a generalization of the program in Listing 2.3 in Section 2.1.6. This version takes a process ID number on its command line and prints the environment for that process by reading it from `/proc`.

Listing 7.4 **(*print-environment.c*) Display the Environment of a Process**

```
#include <fcntl.h>
#include <stdio.h>
#include <stdlib.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

/* Prints the environment, one environment variable to a line, of the
   process given by PID.  */

void print_process_environment (pid_t pid)
{
  int fd;
  char filename[24];
  char environment[8192];
  size_t length;
  char* next_var;

  /* Generate the name of the environ file for the process. */
  snprintf (filename, sizeof (filename), "/proc/%d/environ", (int) pid);
  /* Read the contents of the file. */
  fd = open (filename, O_RDONLY);
  length = read (fd, environment, sizeof (environment));
  close (fd);
  /* read does not NUL-terminate the buffer, so do it here. */
  environment[length] = '\0';
```

```
  /* Loop over variables.  Variables are separated by NULs. */
  next_var = environment;
  while (next_var < environment + length) {
    /* Print the variable.  Each is NUL-terminated, so just treat it
       like an ordinary string.  */
    printf ("%s\n", next_var);
    /* Advance to the next variable.  Since each variable is
       NUL-terminated, strlen counts the length of the next variable,
       not the entire variable list.  */
    next_var += strlen (next_var) + 1;
  }
}

int main (int argc, char* argv[])
{
  pid_t pid = (pid_t) atoi (argv[1]);
  print_process_environment (pid);
  return 0;
}
```

7.2.4 Process Executable

The `exe` entry points to the executable file being run in a process. In Section 2.1.1, we explained that typically the program executable name is passed as the first element of the argument list. Note, though, that this is purely conventional; a program may be invoked with any argument list. Using the `exe` entry in the `/proc` file system is a more reliable way to determine which executable is running.

One useful technique is to extract the path containing the executable from the `/proc` file system. For many programs, auxiliary files are installed in directories with known paths relative to the main program executable, so it's necessary to determine where that executable actually is. The function `get_executable_path` in Listing 7.5 determines the path of the executable running in the calling process by examining the symbolic link `/proc/self/exe`.

Listing 7.5 (*get-exe-path.c*) **Get the Path of the Currently Running Program Executable**

```
#include <limits.h>
#include <stdio.h>
#include <string.h>
#include <unistd.h>

/* Finds the path containing the currently running program executable.
   The path is placed into BUFFER, which is of length LEN.  Returns
   the number of characters in the path, or -1 on error.  */
```

continues

Listing 7.5 **Continued**

```
size_t get_executable_path (char* buffer, size_t len)
{
  char* path_end;
  /* Read the target of /proc/self/exe.  */
  if (readlink ("/proc/self/exe", buffer, len) <= 0)
    return -1;
  /* Find the last occurrence of a forward slash, the path separator.  */
  path_end = strrchr (buffer, '/');
  if (path_end == NULL)
    return -1;
  /* Advance to the character past the last slash.  */
  ++path_end;
  /* Obtain the directory containing the program by truncating the
     path after the last slash.  */
  *path_end = '\0';
  /* The length of the path is the number of characters up through the
     last slash.  */
  return (size_t) (path_end - buffer);
}

int main ()
{
  char path[PATH_MAX];
  get_executable_path (path, sizeof (path));
  printf ("this program is in the directory %s\n", path);
  return 0;
}
```

7.2.5 Process File Descriptors

The `fd` entry is a subdirectory that contains entries for the file descriptors opened by a process. Each entry is a symbolic link to the file or device opened on that file descriptor. You can write to or read from these symbolic links; this writes to or reads from the corresponding file or device opened in the target process. The entries in the `fd` subdirectory are named by the file descriptor numbers.

Here's a neat trick you can try with `fd` entries in `/proc`. Open a new window, and find the process ID of the shell process by running `ps`.

```
% ps
  PID TTY          TIME CMD
 1261 pts/4    00:00:00 bash
 2455 pts/4    00:00:00 ps
```

In this case, the shell (`bash`) is running in process 1261. Now open a second window, and look at the contents of the `fd` subdirectory for that process.

```
% ls -l /proc/1261/fd
total 0
lrwx------    1 samuel   samuel         64 Jan 30 01:02 0 -> /dev/pts/4
lrwx------    1 samuel   samuel         64 Jan 30 01:02 1 -> /dev/pts/4
lrwx------    1 samuel   samuel         64 Jan 30 01:02 2 -> /dev/pts/4
```

(There may be other lines of output corresponding to other open file descriptors as well.) Recall that we mentioned in Section 2.1.4, "Standard I/O," that file descriptors 0, 1, and 2 are initialized to standard input, output, and error, respectively. Thus, by writing to `/proc/1261/fd/1`, you can write to the device attached to `stdout` for the shell process—in this case, the pseudo TTY in the first window. In the second window, try writing a message to that file:

```
% echo "Hello, world." >> /proc/1261/fd/1
```

The text appears in the first window.

File descriptors besides standard input, output, and error appear in the `fd` subdirectory, too. Listing 7.6 presents a program that simply opens a file descriptor to a file specified on the command line and then loops forever.

Listing 7.6 **(*open-and-spin.c*) Open a File for Reading**

```
#include <fcntl.h>
#include <stdio.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

int main (int argc, char* argv[])
{
  const char* const filename = argv[1];
  int fd = open (filename, O_RDONLY);
  printf ("in process %d, file descriptor %d is open to %s\n",
          (int) getpid (), (int) fd, filename);
  while (1);
  return 0;
}
```

Try running it in one window:

```
%  ./open-and-spin /etc/fstab
in process 2570, file descriptor 3 is open to /etc/fstab
```

In another window, take a look at the `fd` subdirectory corresponding to this process in `/proc`.

```
% ls -l /proc/2570/fd
total 0
lrwx------    1 samuel   samuel         64 Jan 30 01:30 0 -> /dev/pts/2
```

```
lrwx------    1 samuel   samuel         64 Jan 30 01:30 1 -> /dev/pts/2
lrwx------    1 samuel   samuel         64 Jan 30 01:30 2 -> /dev/pts/2
lr-x------    1 samuel   samuel         64 Jan 30 01:30 3 -> /etc/fstab
```

Notice the entry for file descriptor 3, linked to the file `/etc/fstab` opened on this descriptor.

File descriptors can be opened on sockets or pipes, too (see Chapter 5 for more information about these). In such a case, the target of the symbolic link corresponding to the file descriptor will state "socket" or "pipe" instead of pointing to an ordinary file or device.

7.2.6 Process Memory Statistics

The `statm` entry contains a list of seven numbers, separated by spaces. Each number is a count of the number of pages of memory used by the process in a particular category. The categories, in the order the numbers appear, are listed here:

- The total process size
- The size of the process resident in physical memory
- The memory shared with other processes—that is, memory mapped both by this process and at least one other (such as shared libraries or untouched copy-on-write pages)
- The text size of the process—that is, the size of loaded executable code
- The size of shared libraries mapped into this process
- The memory used by this process for its stack
- The number of dirty pages—that is, pages of memory that have been modified by the program

7.2.7 Process Statistics

The `status` entry contains a variety of information about the process, formatted for comprehension by humans. Among this information is the process ID and parent process ID, the real and effective user and group IDs, memory usage, and bit masks specifying which signals are caught, ignored, and blocked.

7.3 Hardware Information

Several of the other entries in the `/proc` file system provide access to information about the system hardware. Although these are typically of interest to system configurators and administrators, the information may occasionally be of use to application programmers as well. We'll present some of the more useful entries here.

7.3.1 CPU Information

As shown previously, `/proc/cpuinfo` contains information about the CPU or CPUs running the GNU/Linux system. The Processor field lists the processor number; this is 0 for single-processor systems. The Vendor, CPU Family, Model, and Stepping fields enable you to determine the exact model and revision of the CPU. More useful, the Flags field shows which CPU flags are set, which indicates the features available in this CPU. For example, "mmx" indicates the availability of the extended MMX instructions.[3]

Most of the information returned from `/proc/cpuinfo` is derived from the `cpuid` x86 assembly instruction. This instruction is the low-level mechanism by which a program obtains information about the CPU. For a greater understanding of the output of `/proc/cpuinfo`, see the documentation of the `cpuid` instruction in Intel's *IA-32 Intel Architecture Software Developer's Manual, Volume 2: Instruction Set Reference*. This manual is available from `http://developer.intel.com/design`.

The last element, `bogomips`, is a Linux-specific value. It is a measurement of the processor's speed spinning in a tight loop and is therefore a rather poor indicator of overall processor speed.

7.3.2 Device Information

The `/proc/devices` file lists major device numbers for character and block devices available to the system. See Chapter 6, "Devices," for information about types of devices and device numbers.

7.3.3 PCI Bus Information

The `/proc/pci` file lists a summary of devices attached to the PCI bus or buses. These are actual PCI expansion cards and may also include devices built into the system's motherboard, plus AGP graphics cards. The listing includes the device type; the device and vendor ID; a device name, if available; information about the features offered by the device; and information about the PCI resources used by the device.

7.3.4 Serial Port Information

The `/proc/tty/driver/serial` file lists configuration information and statistics about serial ports. Serial ports are numbered from 0.[4] Configuration information about serial ports can also be obtained, as well as modified, using the `setserial` command. However, `/proc/tty/driver/serial` displays additional statistics about each serial port's interrupt counts.

3. See the *IA-32 Intel Architecture Software Developer's Manual* for documentation about MMX instructions, and see Chapter 9, "Inline Assembly Code," in this book for information on how to use these and other special assembly instructions in GNU/Linux programs.

4. Note that under DOS and Windows, serial ports are numbered from 1, so `COM1` corresponds to serial port number 0 under Linux.

For example, this line from /proc/tty/driver/serial might describe serial port 1 (which would be COM2 under Windows):

```
1: uart:16550A port:2F8 irq:3 baud:9600 tx:11 rx:0
```

This indicates that the serial port is run by a 16550A-type UART, uses I/O port 0x2f8 and IRQ 3 for communication, and runs at 9,600 baud. The serial port has seen 11 transmit interrupts and 0 receive interrupts.

See Section 6.4, "Hardware Devices," for information about serial devices.

7.4 Kernel Information

Many of the entries in /proc provide access to information about the running kernel's configuration and state. Some of these entries are at the top level of /proc; others are under /proc/sys/kernel.

7.4.1 Version Information

The file /proc/version contains a long string describing the kernel's release number and build version. It also includes information about how the kernel was built: the user who compiled it, the machine on which it was compiled, the date it was compiled, and the compiler release that was used—for example:

```
% cat /proc/version
Linux version 2.2.14-5.0 (root@porky.devel.redhat.com) (gcc version
egcs-2.91.66 19990314/Linux (egcs-1.1.2 release)) #1 Tue Mar 7
21:07:39 EST 2000
```

This indicates that the system is running a 2.2.14 release of the Linux kernel, which was compiled with EGCS release 1.1.2. (EGCS, the *Experimental GNU Compiler System*, was a precursor to the current GCC project.)

The most important items in this output, the OS name and kernel version and revision, are available in separate /proc entries as well. These are /proc/sys/kernel/ostype, /proc/sys/kernel/osrelease, and /proc/sys/kernel/version, respectively.

```
% cat /proc/sys/kernel/ostype
Linux
% cat /proc/sys/kernel/osrelease
2.2.14-5.0
% cat /proc/sys/kernel/version
#1 Tue Mar 7 21:07:39 EST 2000
```

7.4.2 Hostname and Domain Name

The /proc/sys/kernel/hostname and /proc/sys/kernel/domainname entries contain the computer's hostname and domain name, respectively. This information is the same as that returned by the uname system call, described in Section 8.15.

7.4.3 Memory Usage

The `/proc/meminfo` entry contains information about the system's memory usage. Information is presented both for physical memory and for swap space. The first three lines present memory totals, in bytes; subsequent lines summarize this information in kilobytes—for example:

```
% cat /proc/meminfo
        total:    used:    free:  shared: buffers:  cached:
Mem:  529694720 519610368 10084352 82612224 10977280 82108416
Swap: 271392768 44003328 227389440
MemTotal:    517280 kB
MemFree:       9848 kB
MemShared:    80676 kB
Buffers:      10720 kB
Cached:       80184 kB
BigTotal:         0 kB
BigFree:          0 kB
SwapTotal:   265032 kB
SwapFree:    222060 kB
```

This shows 512MB physical memory, of which about 9MB is free, and 258MB of swap space, of which 216MB is free. In the row corresponding to physical memory, three other values are presented:

- The Shared column displays total shared memory currently allocated on the system (see Section 5.1, "Shared Memory").
- The Buffers column displays the memory allocated by Linux for block device buffers. These buffers are used by device drivers to hold blocks of data being read from and written to disk.
- The Cached column displays the memory allocated by Linux to the page cache. This memory is used to cache accesses to mapped files.

You can use the `free` command to display the same memory information.

7.5 Drives, Mounts, and File Systems

The `/proc` file system also contains information about the disk drives present in the system and the file systems mounted from them.

7.5.1 File Systems

The `/proc/filesystems` entry displays the file system types known to the kernel. Note that this list isn't very useful because it is not complete: File systems can be loaded and unloaded dynamically as kernel modules. The contents of `/proc/filesystems` list only file system types that either are statically linked into the kernel or are currently loaded. Other file system types may be available on the system as modules but might not be loaded yet.

7.5.2 Drives and Partitions

The /proc file system includes information about devices connected to both IDE controllers and SCSI controllers (if the system includes them).

On typical systems, the /proc/ide subdirectory may contain either or both of two subdirectories, ide0 and ide1, corresponding to the primary and secondary IDE controllers on the system.[5] These contain further subdirectories corresponding to physical devices attached to the controllers. The controller or device directories may be absent if Linux has not recognized any connected devices. The full paths corresponding to the four possible IDE devices are listed in Table 7.1.

Table 7.1 **Full Paths Corresponding to the Four Possible IDE Devices**

Controller	Device	Subdirectory
Primary	Master	/proc/ide/ide0/hda/
Primary	Slave	/proc/ide/ide0/hdb/
Secondary	Master	/proc/ide/ide1/hdc/
Secondary	Slave	/proc/ide/ide1/hdd/

See Section 6.4, "Hardware Devices," for more information about IDE device names.

Each IDE device directory contains several entries providing access to identification and configuration information for the device. A few of the most useful are listed here:

- model contains the device's model identification string.
- media contains the device's media type. Possible values are disk, cdrom, tape, floppy, and UNKNOWN.
- capacity contains the device's capacity, in 512-byte blocks. Note that for CD-ROM devices, the value will be $2^{31} - 1$, not the capacity of the disk in the drive. Note that the value in capacity represents the capacity of the entire physical disk; the capacity of file systems contained in partitions of the disk will be smaller.

For example, these commands show how to determine the media type and device identification for the master device on the secondary IDE controller. In this case, it turns out to be a Toshiba CD-ROM drive.

```
% cat /proc/ide/ide1/hdc/media
cdrom
% cat /proc/ide/ide1/hdc/model
TOSHIBA CD-ROM XM-6702B
```

5. If properly configured, the Linux kernel can support additional IDE controllers. These are numbered sequentially from ide2.

If SCSI devices are present in the system, `/proc/scsi/scsi` contains a summary of their identification values. For example, the contents might look like this:

```
% cat /proc/scsi/scsi
Attached devices:
Host: scsi0 Channel: 00 Id: 00 Lun: 00
  Vendor: QUANTUM  Model: ATLAS_V__9_WLS   Rev: 0230
  Type:   Direct-Access                   ANSI SCSI revision: 03
Host: scsi0 Channel: 00 Id: 04 Lun: 00
  Vendor: QUANTUM  Model: QM39100TD-SW     Rev: N491
  Type:   Direct-Access                   ANSI SCSI revision: 02
```

This computer contains one single-channel SCSI controller (designated "scsi0"), to which two Quantum disk drives are connected, with SCSI device IDs 0 and 4.

The `/proc/partitions` entry displays the partitions of recognized disk devices. For each partition, the output includes the major and minor device number, the number of 1024-byte blocks, and the device name corresponding to that partition.

The `/proc/sys/dev/cdrom/info` entry displays miscellaneous information about the capabilities of CD-ROM drives. The fields are self-explanatory:

```
%  cat /proc/sys/dev/cdrom/info
CD-ROM information, Id: cdrom.c 2.56 1999/09/09

drive name:  hdc
drive speed:  48
drive # of slots:  0
Can close tray:  1
Can open tray:  1
Can lock tray:  1
Can change speed:  1
Can select disk:  0
Can read multisession:  1
Can read MCN:  1
Reports media changed:  1
Can play audio:  1
```

7.5.3 Mounts

The `/proc/mounts` file provides a summary of mounted file systems. Each line corresponds to a single *mount descriptor* and lists the mounted device, the mount point, and other information. Note that `/proc/mounts` contains the same information as the ordinary file `/etc/mtab`, which is automatically updated by the `mount` command.

These are the elements of a mount descriptor:

- The first element on the line is the mounted device (see Chapter 6). For special file systems such as the `/proc` file system, this is `none`.
- The second element is the *mount point*, the place in the root file system at which the file system contents appear. For the root file system itself, the mount point is listed as `/`. For swap drives, the mount point is listed as `swap`.

- The third element is the file system type. Currently, most GNU/Linux systems use the `ext2` file system for disk drives, but DOS or Windows drives may be mounted with other file system types, such as `fat` or `vfat`. Most CD-ROMs contain an `iso9660` file system. See the man page for the `mount` command for a list of file system types.
- The fourth element lists mount flags. These are options that were specified when the mount was added. See the man page for the `mount` command for an explanation of flags for the various file system types.

In `/proc/mounts`, the last two elements are always 0 and have no meaning.

See the man page for `fstab` for details about the format of mount descriptors.[6] GNU/Linux includes functions to help you parse mount descriptors; see the man page for the `getmntent` function for information on using these.

7.5.4 Locks

Section 8.3, "`fcntl`: Locks and Other File Operations," describes how to use the `fcntl` system call to manipulate read and write locks on files. The `/proc/locks` entry describes all the file locks currently outstanding in the system. Each row in the output corresponds to one lock.

For locks created with `fcntl`, the first two entries on the line are `POSIX ADVISORY`. The third is `WRITE` or `READ`, depending on the lock type. The next number is the process ID of the process holding the lock. The following three numbers, separated by colons, are the major and minor device numbers of the device on which the file resides and the *inode* number, which locates the file in the file system. The remainder of the line lists values internal to the kernel that are not of general utility.

Turning the contents of `/proc/locks` into useful information takes some detective work. You can watch `/proc/locks` in action, for instance, by running the program in Listing 8.2 to create a write lock on the file `/tmp/test-file`.

```
% touch /tmp/test-file
% ./lock-file /tmp/test-file
file /tmp/test-file
opening /tmp/test-file
locking
locked; hit enter to unlock...
```

In another window, look at the contents of `/proc/locks`.

```
% cat /proc/locks
1: POSIX  ADVISORY  WRITE 5467 08:05:181288 0 2147483647 d1b5f740 00000000
dfea7d40 00000000 00000000
```

6. The `/etc/fstab` file lists the static mount configuration of the GNU/Linux system.

There may be other lines of output, too, corresponding to locks held by other programs. In this case, 5467 is the process ID of the `lock-file` program. Use `ps` to figure out what this process is running.

```
% ps 5467
  PID TTY      STAT   TIME COMMAND
 5467 pts/28   S      0:00 ./lock-file /tmp/test-file
```

The locked file, `/tmp/test-file`, resides on the device that has major and minor device numbers 8 and 5, respectively. These numbers happen to correspond to `/dev/sda5`.

```
% df /tmp
Filesystem           1k-blocks      Used Available Use% Mounted on
/dev/sda5              8459764   5094292   2935736  63% /
% ls -l /dev/sda5
brw-rw----    1 root     disk       8,   5 May  5  1998 /dev/sda5
```

The file `/tmp/test-file` itself is at inode 181,288 on that device.

```
% ls --inode /tmp/test-file
 181288 /tmp/test-file
```

See Section 6.2, "Device Numbers," for more information about device numbers.

7.6 System Statistics

Two entries in `/proc` contain useful system statistics. The `/proc/loadavg` file contains information about the system load. The first three numbers represent the number of *active tasks* on the system—processes that are actually running—averaged over the last 1, 5, and 15 minutes. The next entry shows the instantaneous current number of *runnable tasks*—processes that are currently scheduled to run rather than being blocked in a system call—and the total number of processes on the system. The final entry is the process ID of the process that most recently ran.

The `/proc/uptime` file contains the length of time since the system was booted, as well as the amount of time since then that the system has been idle. Both are given as floating-point values, in seconds.

```
% cat /proc/uptime
3248936.18 3072330.49
```

The program in Listing 7.7 extracts the uptime and idle time from the system and displays them in friendly units.

Listing 7.7 **(*print-uptime.c*) Print the System Uptime and Idle Time**

```
#include <stdio.h>

/* Summarize a duration of time to standard output.  TIME is the
   amount of time, in seconds, and LABEL is a short descriptive label.  */

void print_time (char* label, long time)
{
```

continues

Listing 7.7 **Continued**

```
  /* Conversion constants.  */
  const long minute = 60;
  const long hour = minute * 60;
  const long day = hour * 24;
  /* Produce output.  */
  printf ("%s: %ld days, %ld:%02ld:%02ld\n", label, time / day,
          (time % day) / hour, (time % hour) / minute, time % minute);
}

int main ()
{
  FILE* fp;
  double uptime, idle_time;
  /* Read the system uptime and accumulated idle time from /proc/uptime.  */
  fp = fopen ("/proc/uptime", "r");
  fscanf (fp, "%lf %lf\n", &uptime, &idle_time);
  fclose (fp);
  /* Summarize it.  */
  print_time ("uptime   ", (long) uptime);
  print_time ("idle time", (long) idle_time);
  return 0;
}
```

The `uptime` command and the `sysinfo` system call (see Section 8.14, "`sysinfo`: Obtaining System Statistics") also can obtain the system's uptime. The `uptime` command also displays the load averages found in `/proc/loadavg`.

8

Linux System Calls

So far, we've presented a variety of functions that your program can invoke to perform system-related functions, such as parsing command-line options, manipulating processes, and mapping memory. If you look under the hood, you'll find that these functions fall into two categories, based on how they are implemented.

- A *library function* is an ordinary function that resides in a library external to your program. Most of the library functions we've presented so far are in the standard C library, `libc`. For example, `getopt_long` and `mkstemp` are functions provided in the C library.

  A call to a library function is just like any other function call. The arguments are placed in processor registers or onto the stack, and execution is transferred to the start of the function's code, which typically resides in a loaded shared library.

- A *system call* is implemented in the Linux kernel. When a program makes a system call, the arguments are packaged up and handed to the kernel, which takes over execution of the program until the call completes. A system call isn't an ordinary function call, and a special procedure is required to transfer control to the kernel. However, the GNU C library (the implementation of the standard C library provided with GNU/Linux systems) wraps Linux system calls with functions so that you can call them easily. Low-level I/O functions such as `open` and `read` are examples of system calls on Linux.

> The set of Linux system calls forms the most basic interface between programs and the Linux kernel. Each call presents a basic operation or capability.
>
> Some system calls are very powerful and can exert great influence on the system. For instance, some system calls enable you to shut down the Linux system or to allocate system resources and prevent other users from accessing them. These calls have the restriction that only processes running with superuser privilege (programs run by the root account) can invoke them. These calls fail if invoked by a nonsuperuser process.

Note that a library function may invoke one or more other library functions or system calls as part of its implementation.

Linux currently provides about 200 different system calls. A listing of system calls for your version of the Linux kernel is in `/usr/include/asm/unistd.h`. Some of these are for internal use by the system, and others are used only in implementing specialized library functions. In this chapter, we'll present a selection of system calls that are likely to be the most useful to application and system programmers.

Most of these system calls are declared in `<unistd.h>`.

8.1 Using *strace*

Before we start discussing system calls, it will be useful to present a command with which you can learn about and debug system calls. The `strace` command traces the execution of another program, listing any system calls the program makes and any signals it receives.

To watch the system calls and signals in a program, simply invoke `strace`, followed by the program and its command-line arguments. For example, to watch the system calls that are invoked by the `hostname`[1] command, use this command:

```
% strace hostname
```

This produces a couple screens of output. Each line corresponds to a single system call. For each call, the system call's name is listed, followed by its arguments (or abbreviated arguments, if they are very long) and its return value. Where possible, `strace` conveniently displays symbolic names instead of numerical values for arguments and return values, and it displays the fields of structures passed by a pointer into the system call. Note that `strace` does *not* show ordinary function calls.

In the output from `strace hostname`, the first line shows the `execve` system call that invokes the `hostname` program:[2]

```
execve("/bin/hostname", ["hostname"], [/* 49 vars */]) = 0
```

1. `hostname` invoked without any flags simply prints out the computer's hostname to standard output.

2. In Linux, the `exec` family of functions is implemented via the `execve` system call.

The first argument is the name of the program to run; the second is its argument list, consisting of only a single element; and the third is its environment list, which `strace` omits for brevity. The next 30 or so lines are part of the mechanism that loads the standard C library from a shared library file.

Toward the end are system calls that actually help do the program's work. The `uname` system call is used to obtain the system's hostname from the kernel,

```
uname({sys="Linux", node="myhostname", ...}) = 0
```

Observe that `strace` helpfully labels the fields (`sys` and `node`) of the structure argument. This structure is filled in by the system call—Linux sets the `sys` field to the operating system name and the `node` field to the system's hostname. The `uname` call is discussed further in Section 8.15, "`uname`."

Finally, the `write` system call produces output. Recall that file descriptor 1 corresponds to standard output. The third argument is the number of characters to write, and the return value is the number of characters that were actually written.

```
write(1, "myhostname\n", 11)            = 11
```

This may appear garbled when you run `strace` because the output from the `hostname` program itself is mixed in with the output from `strace`.

If the program you're tracing produces lots of output, it is sometimes more convenient to redirect the output from `strace` into a file. Use the option `-o` *`filename`* to do this.

Understanding all the output from `strace` requires detailed familiarity with the design of the Linux kernel and execution environment. Much of this is of limited interest to application programmers. However, some understanding is useful for debugging tricky problems or understanding how other programs work.

8.2 *access*: Testing File Permissions

The `access` system call determines whether the calling process has access permission to a file. It can check any combination of read, write, and execute permission, and it can also check for a file's existence.

The `access` call takes two arguments. The first is the path to the file to check. The second is a bitwise or of `R_OK`, `W_OK`, and `X_OK`, corresponding to read, write, and execute permission. The return value is 0 if the process has all the specified permissions. If the file exists but the calling process does not have the specified permissions, `access` returns –1 and sets `errno` to `EACCES` (or `EROFS`, if write permission was requested for a file on a read-only file system).

If the second argument is `F_OK`, `access` simply checks for the file's existence. If the file exists, the return value is 0; if not, the return value is –1 and `errno` is set to `ENOENT`. Note that `errno` may instead be set to `EACCES` if a directory in the file path is inaccessible.

The program shown in Listing 8.1 uses `access` to check for a file's existence and to determine read and write permissions. Specify the name of the file to check on the command line.

Listing 8.1 **(*check-access.c*) Check File Access Permissions**

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

int main (int argc, char* argv[])
{
  char* path = argv[1];
  int rval;

  /* Check file existence.  */
  rval = access (path, F_OK);
  if (rval == 0)
    printf ("%s exists\n", path);
  else {
    if (errno == ENOENT)
      printf ("%s does not exist\n", path);
    else if (errno == EACCES)
      printf ("%s is not accessible\n", path);
    return 0;
  }

  /* Check read access.  */
  rval = access (path, R_OK);
  if (rval == 0)
    printf ("%s is readable\n", path);
  else
    printf ("%s is not readable (access denied)\n", path);

  /* Check write access.  */
  rval = access (path, W_OK);
  if (rval == 0)
    printf ("%s is writable\n", path);
  else if (errno == EACCES)
    printf ("%s is not writable (access denied)\n", path);
  else if (errno == EROFS)
    printf ("%s is not writable (read-only filesystem)\n", path);
  return 0;
}
```

For example, to check access permissions for a file named `README` on a CD-ROM, invoke it like this:

```
% ./check-access /mnt/cdrom/README
/mnt/cdrom/README exists
/mnt/cdrom/README is readable
/mnt/cdrom/README is not writable (read-only filesystem)
```

8.3 *fcntl*: Locks and Other File Operations

The `fcntl` system call is the access point for several advanced operations on file descriptors. The first argument to `fcntl` is an open file descriptor, and the second is a value that indicates which operation is to be performed. For some operations, `fcntl` takes an additional argument. We'll describe here one of the most useful `fcntl` operations, file locking. See the `fcntl` man page for information about the others.

The `fcntl` system call allows a program to place a read lock or a write lock on a file, somewhat analogous to the mutex locks discussed in Chapter 5, "Interprocess Communication." A read lock is placed on a readable file descriptor, and a write lock is placed on a writable file descriptor. More than one process may hold a read lock on the same file at the same time, but only one process may hold a write lock, and the same file may not be both locked for read and locked for write. Note that placing a lock does not actually prevent other processes from opening the file, reading from it, or writing to it, unless they acquire locks with `fcntl` as well.

To place a lock on a file, first create and zero out a `struct flock` variable. Set the `l_type` field of the structure to `F_RDLCK` for a read lock or `F_WRLCK` for a write lock. Then call `fcntl`, passing a file descriptor to the file, the `F_SETLCKW` operation code, and a pointer to the `struct flock` variable. If another process holds a lock that prevents a new lock from being acquired, `fcntl` blocks until that lock is released.

The program in Listing 8.2 opens a file for writing whose name is provided on the command line, and then places a write lock on it. The program waits for the user to hit Enter and then unlocks and closes the file.

Listing 8.2 **(*lock-file.c*) Create a Write Lock with *fcntl***

```
#include <fcntl.h>
#include <stdio.h>
#include <string.h>
#include <unistd.h>

int main (int argc, char* argv[])
{
  char* file = argv[1];
  int fd;
  struct flock lock;

  printf ("opening %s\n", file);
  /* Open a file descriptor to the file.  */
  fd = open (file, O_WRONLY);
  printf ("locking\n");
  /* Initialize the flock structure.  */
  memset (&lock, 0, sizeof(lock));
  lock.l_type = F_WRLCK;
  /* Place a write lock on the file.  */
  fcntl (fd, F_SETLKW, &lock);
```

continues

Listing 8.2 **Continued**

```
  printf ("locked; hit Enter to unlock... ");
  /* Wait for the user to hit Enter.  */
  getchar ();

  printf ("unlocking\n");
  /* Release the lock.  */
  lock.l_type = F_UNLCK;
  fcntl (fd, F_SETLKW, &lock);

  close (fd);
  return 0;
}
```

Compile and run the program on a test file—say, `/tmp/test-file`—like this:

```
% cc -o lock-file lock-file.c
% touch /tmp/test-file
% ./lock-file /tmp/test-file
opening /tmp/test-file
locking
locked; hit Enter to unlock...
```

Now, in another window, try running it again on the same file.

```
% ./lock-file /tmp/test-file
opening /tmp/test-file
locking
```

Note that the second instance is blocked while attempting to lock the file. Go back to the first window and press Enter:

```
unlocking
```

The program running in the second window immediately acquires the lock.

If you prefer `fcntl` not to block if the call cannot get the lock you requested, use `F_SETLK` instead of `F_SETLKW`. If the lock cannot be acquired, `fcntl` returns –1 immediately.

Linux provides another implementation of file locking with the `flock` call. The `fcntl` version has a major advantage: It works with files on NFS[3] file systems (as long as the NFS server is reasonably recent and correctly configured). So, if you have access to two machines that both mount the same file system via NFS, you can repeat the previous example using two different machines. Run `lock-file` on one machine, specifying a file on an NFS file system, and then run it again on another machine, specifying the same file. NFS wakes up the second program when the lock is released by the first program.

3. *Network File System* (NFS) is a common network file sharing technology, comparable to Windows' shares and network drives.

8.4 *fsync* and *fdatasync*: Flushing Disk Buffers

On most operating systems, when you write to a file, the data is not immediately written to disk. Instead, the operating system caches the written data in a memory buffer, to reduce the number of required disk writes and improve program responsiveness. When the buffer fills or some other condition occurs (for instance, enough time elapses), the system writes the cached data to disk all at one time.

Linux provides caching of this type as well. Normally, this is a great boon to performance. However, this behavior can make programs that depend on the integrity of disk-based records unreliable. If the system goes down suddenly—for instance, due to a kernel crash or power outage—any data written by a program that is in the memory cache but has not yet been written to disk is lost.

For example, suppose that you are writing a transaction-processing program that keeps a journal file. The journal file contains records of all transactions that have been processed so that if a system failure occurs, the state of the transaction data can be reconstructed. It is obviously important to preserve the integrity of the journal file—whenever a transaction is processed, its journal entry should be sent to the disk drive immediately.

To help you implement this, Linux provides the `fsync` system call. It takes one argument, a writable file descriptor, and flushes to disk any data written to this file. The `fsync` call doesn't return until the data has physically been written.

The function in Listing 8.3 illustrates the use of `fsync`. It writes a single-line entry to a journal file.

Listing 8.3 **(*write_journal_entry.c*) Write and Sync a Journal Entry**

```
#include <fcntl.h>
#include <string.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

const char* journal_filename = "journal.log";

void write_journal_entry (char* entry)
{
  int fd = open (journal_filename, O_WRONLY | O_CREAT | O_APPEND, 0660);
  write (fd, entry, strlen (entry));
  write (fd, "\n", 1);
  fsync (fd);
  close (fd);
}
```

Another system call, `fdatasync` does the same thing. However, although `fsync` guarantees that the file's modification time will be updated, `fdatasync` does not; it guarantees only that the file's data will be written. This means that in principal, `fdatasync` can execute faster than `fsync` because it needs to force only one disk write instead of two.

However, in current versions of Linux, these two system calls actually do the same thing, both updating the file's modification time.

The `fsync` system call enables you to force a buffer write explicitly. You can also open a file for *synchronous I/O*, which causes all writes to be committed to disk immediately. To do this, specify the `O_SYNC` flag when opening the file with the `open` call.

8.5 *getrlimit* and *setrlimit*: Resource Limits

The `getrlimit` and `setrlimit` system calls allow a process to read and set limits on the system resources that it can consume. You may be familiar with the `ulimit` shell command, which enables you to restrict the resource usage of programs you run;[4] these system calls allow a program to do this programmatically.

For each resource there are two limits, the *hard limit* and the *soft limit*. The soft limit may never exceed the hard limit, and only processes with superuser privilege may change the hard limit. Typically, an application program will reduce the soft limit to place a throttle on the resources it uses.

Both `getrlimit` and `setrlimit` take as arguments a code specifying the resource limit type and a pointer to a `structrlimit` variable. The `getrlimit` call fills the fields of this structure, while the `setrlimit` call changes the limit based on its contents. The `rlimit` structure has two fields: `rlim_cur` is the soft limit, and `rlim_max` is the hard limit.

Some of the most useful resource limits that may be changed are listed here, with their codes:

- `RLIMIT_CPU`—The maximum CPU time, in seconds, used by a program. This is the amount of time that the program is actually executing on the CPU, which is not necessarily the same as wall-clock time. If the program exceeds this time limit, it is terminated with a `SIGXCPU` signal.
- `RLIMIT_DATA`—The maximum amount of memory that a program can allocate for its data. Additional allocation beyond this limit will fail.
- `RLIMIT_NPROC`—The maximum number of child processes that can be running for this user. If the process calls `fork` and too many processes belonging to this user are running on the system, `fork` fails.
- `RLIMIT_NOFILE`—The maximum number of file descriptors that the process may have open at one time.

See the `setrlimit` man page for a full list of system resources.

The program in Listing 8.4 illustrates setting the limit on CPU time consumed by a program. It sets a 1-second CPU time limit and then spins in an infinite loop. Linux kills the process soon afterward, when it exceeds 1 second of CPU time.

4. See the man page for your shell for more information about `ulimit`.

Listing 8.4 (*limit-cpu.c*) CPU Time Limit Demonstration

```
#include <sys/resource.h>
#include <sys/time.h>
#include <unistd.h>

int main ()
{
  struct rlimit rl;

  /* Obtain the current limits.  */
  getrlimit (RLIMIT_CPU, &rl);
  /* Set a CPU limit of 1 second.  */
  rl.rlim_cur = 1;
  setrlimit (RLIMIT_CPU, &rl);
  /* Do busy work.  */
  while (1);

  return 0;
}
```

When the program is terminated by `SIGXCPU`, the shell helpfully prints out a message interpreting the signal:

```
% ./limit_cpu
CPU time limit exceeded
```

8.6 *getrusage*: Process Statistics

The `getrusage` system call retrieves process statistics from the kernel. It can be used to obtain statistics either for the current process by passing `RUSAGE_SELF` as the first argument, or for all terminated child processes that were forked by this process and its children by passing `RUSAGE_CHILDREN`. The second argument to `rusage` is a pointer to a `struct rusage` variable, which is filled with the statistics.

A few of the more interesting fields in `struct rusage` are listed here:

- `ru_utime`—A `struct timeval` field containing the amount of *user time*, in seconds, that the process has used. User time is CPU time spent executing the user program, rather than in kernel system calls.
- `ru_stime`—A `struct timeval` field containing the amount of *system time*, in seconds, that the process has used. System time is the CPU time spent executing system calls on behalf of the process.
- `ru_maxrss`—The largest amount of physical memory occupied by the process's data at one time over the course of its execution.

The `getrusage` man page lists all the available fields. See Section 8.7, "`gettimeofday`: Wall-Clock Time," for information about `struct timeval`.

The function in Listing 8.5 prints out the current process's user and system time.

Listing 8.5 **(*print-cpu-times.c*) Display Process User and System Times**

```
#include <stdio.h>
#include <sys/resource.h>
#include <sys/time.h>
#include <unistd.h>

void print_cpu_time()
{
  struct rusage usage;
  getrusage (RUSAGE_SELF, &usage);
  printf ("CPU time: %ld.%06ld sec user, %ld.%06ld sec system\n",
          usage.ru_utime.tv_sec, usage.ru_utime.tv_usec,
          usage.ru_stime.tv_sec, usage.ru_stime.tv_usec);
}
```

8.7 *gettimeofday*: Wall-Clock Time

The `gettimeofday` system call gets the system's wall-clock time. It takes a pointer to a `struct timeval` variable. This structure represents a time, in seconds, split into two fields. The `tv_sec` field contains the integral number of seconds, and the `tv_usec` field contains an additional number of microseconds. This `struct timeval` value represents the number of seconds elapsed since the start of the *UNIX epoch*, on midnight UTC on January 1, 1970. The `gettimeofday` call also takes a second argument, which should be `NULL`. Include `<sys/time.h>` if you use this system call.

The number of seconds in the UNIX epoch isn't usually a very handy way of representing dates. The `localtime` and `strftime` library functions help manipulate the return value of `gettimeofday`. The `localtime` function takes a pointer to the number of seconds (the `tv_sec` field of `struct timeval`) and returns a pointer to a `struct tm` object. This structure contains more useful fields, which are filled according to the local time zone:

- `tm_hour`, `tm_min`, `tm_sec`—The time of day, in hours, minutes, and seconds.
- `tm_year`, `tm_mon`, `tm_day`—The year, month, and date.
- `tm_wday`—The day of the week. Zero represents Sunday.
- `tm_yday`—The day of the year.
- `tm_isdst`—A flag indicating whether daylight savings time is in effect.

The `strftime` function additionally can produce from the `struct tm` pointer a customized, formatted string displaying the date and time. The format is specified in a manner similar to `printf`, as a string with embedded codes indicating which time fields to include. For example, this format string

```
"%Y-%m-%d %H:%M:%S"
```

specifies the date and time in this form:

```
2001-01-14 13:09:42
```

Pass `strftime` a character buffer to receive the string, the length of that buffer, the format string, and a pointer to a `struct tm` variable. See the `strftime` man page for a complete list of codes that can be used in the format string. Notice that neither `localtime` nor `strftime` handles the fractional part of the current time more precise than 1 second (the `tv_usec` field of `struct timeval`). If you want this in your formatted time strings, you'll have to include it yourself.

Include `<time.h>` if you call `localtime` or `strftime`.

The function in Listing 8.6 prints the current date and time of day, down to the millisecond.

Listing 8.6 **(*print-time.c*) Print Date and Time**

```
#include <stdio.h>
#include <sys/time.h>
#include <time.h>
#include <unistd.h>

void print_time ()
{
  struct timeval tv;
  struct tm* ptm;
  char time_string[40];
  long milliseconds;

  /* Obtain the time of day, and convert it to a tm struct.  */
  gettimeofday (&tv, NULL);
  ptm = localtime (&tv.tv_sec);
  /* Format the date and time, down to a single second.  */
  strftime (time_string, sizeof (time_string), "%Y-%m-%d %H:%M:%S", ptm);
  /* Compute milliseconds from microseconds.  */
  milliseconds = tv.tv_usec / 1000;
  /* Print the formatted time, in seconds, followed by a decimal point
     and the milliseconds.  */
  printf ("%s.%03ld\n", time_string, milliseconds);
}
```

8.8 The *mlock* Family: Locking Physical Memory

The `mlock` family of system calls allows a program to lock some or all of its address space into physical memory. This prevents Linux from paging this memory to swap space, even if the program hasn't accessed it for a while.

A time-critical program might lock physical memory because the time delay of paging memory out and back may be too long or too unpredictable. High-security applications may also want to prevent sensitive data from being written out to a swap file, where they might be recovered by an intruder after the program terminates.

Locking a region of memory is as simple as calling `mlock` with a pointer to the start of the region and the region's length. Linux divides memory into *pages* and can lock only entire pages at a time; each page that contains part of the memory region specified to `mlock` is locked. The `getpagesize` function returns the system's page size, which is 4KB on x86 Linux.

For example, to allocate 32MB of address space and lock it into RAM, you would use this code:

```
const int alloc_size = 32 * 1024 * 1024;
char* memory = malloc (alloc_size);
mlock (memory, alloc_size);
```

Note that simply allocating a page of memory and locking it with `mlock` doesn't reserve physical memory for the calling process because the pages may be copy-on-write.[5] Therefore, you should write a dummy value to each page as well:

```
size_t i;
size_t page_size = getpagesize ();
for (i = 0; i < alloc_size; i += page_size)
  memory[i] = 0;
```

The write to each page forces Linux to assign a unique, unshared memory page to the process for that page.

To unlock a region, call `munlock`, which takes the same arguments as `mlock`.

If you want your program's entire address space locked into physical memory, call `mlockall`. This system call takes a single flag argument: `MCL_CURRENT` locks all currently allocated memory, but future allocations are not locked; `MCL_FUTURE` locks all pages that are allocated after the call. Use `MCL_CURRENT|MCL_FUTURE` to lock into memory both current and subsequent allocations.

Locking large amounts of memory, especially using `mlockall`, can be dangerous to the entire Linux system. Indiscriminate memory locking is a good method of bringing your system to a grinding halt because other running processes are forced to compete for smaller physical memory resources and swap rapidly into and back out of memory (this is known as *thrashing*). If you lock too much memory, the system will run out of memory entirely and Linux will start killing off processes.

For this reason, only processes with superuser privilege may lock memory with `mlock` or `mlockall`. If a nonsuperuser process calls one of these functions, it will fail, return –1, and set `errno` to `EPERM`.

The `munlockall` call unlocks all memory locked by the current process, including memory locked with `mlock` and `mlockall`.

5. *Copy-on-write* means that Linux makes a private copy of a page of memory for a process only when that process writes a value somewhere into it.

A convenient way to monitor the memory usage of your program is to use the `top` command. In the output from `top`, the `SIZE` column displays the virtual address space size of each program (the total size of your program's code, data, and stack, some of which may be paged out to swap space). The `RSS` column (for *resident set size*) shows the size of physical memory that each program currently resides in. The sum of all the RSS values for all running programs cannot exceed your computer's physical memory size, and the sum of all address space sizes is limited to 2GB (for 32-bit versions of Linux).

Include `<sys/mman.h>` if you use any of the `mlock` system calls.

8.9 *mprotect*: Setting Memory Permissions

In Section 5.3, "Mapped Memory," we showed how to use the `mmap` system call to map a file into memory. Recall that the third argument to `mmap` is a bitwise or of memory protection flags `PROT_READ`, `PROT_WRITE`, and `PROT_EXEC` for read, write, and execute permission, respectively, or `PROT_NONE` for no memory access. If a program attempts to perform an operation on a memory location that is not allowed by these permissions, it is terminated with a `SIGSEGV` (segmentation violation) signal.

After memory has been mapped, these permissions can be modified with the `mprotect` system call. The arguments to `mprotect` are an address of a memory region, the size of the region, and a set of protection flags. The memory region must consist of entire pages: The address of the region must be aligned to the system's page size, and the length of the region must be a page size multiple. The protection flags for these pages are replaced with the specified value.

> **Obtaining Page-Aligned Memory**
>
> Note that memory regions returned by `malloc` are typically not page-aligned, even if the size of the memory is a multiple of the page size. If you want to protect memory obtained from `malloc`, you will have to allocate a larger memory region and find a page-aligned region within it.
>
> Alternately, you can use the `mmap` system call to bypass `malloc` and allocate page-aligned memory directly from the Linux kernel. See Section 5.3, "Mapped Memory," for details.

For example, suppose that your program allocates a page of memory by mapping `/dev/zero`, as described in Section 5.3.5, "Other Uses for `mmap`." The memory is initially both readable and writable.

```
int fd = open ("/dev/zero", O_RDONLY);
char* memory = mmap (NULL, page_size, PROT_READ | PROT_WRITE,
                     MAP_PRIVATE, fd, 0);
close (fd);
```

Later, your program could make the memory read-only by calling `mprotect`:

```
mprotect (memory, page_size, PROT_READ);
```

An advanced technique to monitor memory access is to protect the region of memory using `mmap` or `mprotect` and then handle the `SIGSEGV` signal that Linux sends to the program when it tries to access that memory. The example in Listing 8.7 illustrates this technique.

Listing 8.7 **(*mprotect.c*) Detect Memory Access Using *mprotect***

```
#include <fcntl.h>
#include <signal.h>
#include <stdio.h>
#include <string.h>
#include <sys/mman.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

static int alloc_size;
static char* memory;

void segv_handler (int signal_number)
{
  printf ("memory accessed!\n");
  mprotect (memory, alloc_size, PROT_READ | PROT_WRITE);
}

int main ()
{
  int fd;
  struct sigaction sa;

  /* Install segv_handler as the handler for SIGSEGV.  */
  memset (&sa, 0, sizeof (sa));
  sa.sa_handler = &segv_handler;
  sigaction (SIGSEGV, &sa, NULL);

  /* Allocate one page of memory by mapping /dev/zero.  Map the memory
     as write-only, initially.  */
  alloc_size = getpagesize ();
  fd = open ("/dev/zero", O_RDONLY);
  memory = mmap (NULL, alloc_size, PROT_WRITE, MAP_PRIVATE, fd, 0);
  close (fd);
  /* Write to the page to obtain a private copy.  */
  memory[0] = 0;
  /* Make the memory unwritable.  */
  mprotect (memory, alloc_size, PROT_NONE);

  /* Write to the allocated memory region.  */
  memory[0] = 1;
```

```
  /* All done; unmap the memory.  */
  printf ("all done\n");
  munmap (memory, alloc_size);
  return 0;
}
```

The program follows these steps:

1. The program installs a signal handler for `SIGSEGV`.
2. The program allocates a page of memory by mapping `/dev/zero` and writing a value to the allocated page to obtain a private copy.
3. The program protects the memory by calling `mprotect` with the `PROT_NONE` permission.
4. When the program subsequently writes to memory, Linux sends it `SIGSEGV`, which is handled by `segv_handler`. The signal handler unprotects the memory, which allows the memory access to proceed.
5. When the signal handler completes, control returns to `main`, where the program deallocates the memory using `munmap`.

8.10 *nanosleep*: High-Precision Sleeping

The `nanosleep` system call is a high-precision version of the standard UNIX `sleep` call. Instead of sleeping an integral number of seconds, `nanosleep` takes as its argument a pointer to a `struct timespec` object, which can express time to nanosecond precision. However, because of the details of how the Linux kernel works, the actual precision provided by `nanosleep` is 10 milliseconds—still better than that afforded by `sleep`. This additional precision can be useful, for instance, to schedule frequent operations with short time intervals between them.

The `struct timespec` structure has two fields: `tv_sec`, the integral number of seconds, and `tv_nsec`, an additional number of milliseconds. The value of `tv_nsec` must be less than 10^9.

The `nanosleep` call provides another advantage over `sleep`. As with `sleep`, the delivery of a signal interrupts the execution of `nanosleep`, which sets `errno` to `EINTR` and returns –1. However, `nanosleep` takes a second argument, another pointer to a `struct timespec` object, which, if not null, is filled with the amount of time remaining (that is, the difference between the requested sleep time and the actual sleep time). This makes it easy to resume the sleep operation.

The function in Listing 8.8 provides an alternate implementation of `sleep`. Unlike the ordinary system call, this function takes a floating-point value for the number of seconds to sleep and restarts the sleep operation if it's interrupted by a signal.

Listing 8.8 **(*better_sleep.c*) High-Precision Sleep Function**

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

int better_sleep (double sleep_time)
{
  struct timespec tv;
  /* Construct the timespec from the number of whole seconds...  */
  tv.tv_sec = (time_t) sleep_time;
  /* ... and the remainder in nanoseconds.  */
  tv.tv_nsec = (long) ((sleep_time - tv.tv_sec) * 1e+9);

  while (1)
  {
    /* Sleep for the time specified in tv.  If interrupted by a
       signal, place the remaining time left to sleep back into tv.  */
    int rval = nanosleep (&tv, &tv);
    if (rval == 0)
      /* Completed the entire sleep time; all done.  */
      return 0;
    else if (errno == EINTR)
      /* Interrupted by a signal.  Try again.  */
      continue;
    else
      /* Some other error; bail out.  */
      return rval;
  }
  return 0;
}
```

8.11 *readlink*: Reading Symbolic Links

The `readlink` system call retrieves the target of a symbolic link. It takes three arguments: the path to the symbolic link, a buffer to receive the target of the link, and the length of that buffer. Unusually, `readlink` does not NUL-terminate the target path that it fills into the buffer. It does, however, return the number of characters in the target path, so NUL-terminating the string is simple.

If the first argument to `readlink` points to a file that isn't a symbolic link, `readlink` sets `errno` to `EINVAL` and returns –1.

The small program in Listing 8.9 prints the target of the symbolic link specified on its command line.

Listing 8.9 **(*print-symlink.c*) Print the Target of a Symbolic Link**

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

int main (int argc, char* argv[])
{
  char target_path[256];
  char* link_path = argv[1];

  /* Attempt to read the target of the symbolic link.  */
  int len = readlink (link_path, target_path, sizeof (target_path));

  if (len == -1) {
    /* The call failed.  */
    if (errno == EINVAL)
      /* It's not a symbolic link; report that.  */
      fprintf (stderr, "%s is not a symbolic link\n", link_path);
    else
      /* Some other problem occurred; print the generic message.  */
      perror ("readlink");
    return 1;
  }
  else {
    /* NUL-terminate the target path.  */
    target_path[len] = '\0';
    /* Print it.  */
    printf ("%s\n", target_path);
    return 0;
  }
}
```

For example, here's how you could make a symbolic link and use `print-symlink` to read it back:

```
% ln -s /usr/bin/wc my_link
% ./print-symlink my_link
/usr/bin/wc
```

8.12 *sendfile*: Fast Data Transfers

The `sendfile` system call provides an efficient mechanism for copying data from one file descriptor to another. The file descriptors may be open to disk files, sockets, or other devices.

Typically, to copy from one file descriptor to another, a program allocates a fixed-size buffer, copies some data from one descriptor into the buffer, writes the buffer out to the other descriptor, and repeats until all the data has been copied. This is inefficient in both time and space because it requires additional memory for the buffer and performs an extra copy of the data into that buffer.

Using `sendfile`, the intermediate buffer can be eliminated. Call `sendfile`, passing the file descriptor to write to; the descriptor to read from; a pointer to an offset variable; and the number of bytes to transfer. The offset variable contains the offset in the input file from which the read should start (0 indicates the beginning of the file) and is updated to the position in the file after the transfer. The return value is the number of bytes transferred. Include `<sys/sendfile.h>` in your program if it uses `sendfile`.

The program in Listing 8.10 is a simple but extremely efficient implementation of a file copy. When invoked with two filenames on the command line, it copies the contents of the first file into a file named by the second. It uses `fstat` to determine the size, in bytes, of the source file.

Listing 8.10 **(*copy.c*) File Copy Using *sendfile***

```
#include <fcntl.h>
#include <stdlib.h>
#include <stdio.h>
#include <sys/sendfile.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

int main (int argc, char* argv[])
{
  int read_fd;
  int write_fd;
  struct stat stat_buf;
  off_t offset = 0;

  /* Open the input file.  */
  read_fd = open (argv[1], O_RDONLY);
  /* Stat the input file to obtain its size.  */
  fstat (read_fd, &stat_buf);
  /* Open the output file for writing, with the same permissions as the
     source file.  */
  write_fd = open (argv[2], O_WRONLY | O_CREAT, stat_buf.st_mode);
  /* Blast the bytes from one file to the other.  */
  sendfile (write_fd, read_fd, &offset, stat_buf.st_size);
  /* Close up.  */
  close (read_fd);
  close (write_fd);

  return 0;
}
```

The `sendfile` call can be used in many places to make copies more efficient. One good example is in a Web server or other network daemon, that serves the contents of a file over the network to a client program. Typically, a request is received from a socket connected to the client computer. The server program opens a local disk file to

retrieve the data to serve and writes the file's contents to the network socket. Using `sendfile` can speed up this operation considerably. Other steps need to be taken to make the network transfer as efficient as possible, such as setting the socket parameters correctly. However, these are outside the scope of this book.

8.13 *setitimer*: Setting Interval Timers

The `setitimer` system call is a generalization of the `alarm` call. It schedules the delivery of a signal at some point in the future after a fixed amount of time has elapsed.

A program can set three different types of timers with `setitimer`:

- If the timer code is `ITIMER_REAL`, the process is sent a `SIGALRM` signal after the specified wall-clock time has elapsed.
- If the timer code is `ITIMER_VIRTUAL`, the process is sent a `SIGVTALRM` signal after the process has executed for the specified time. Time in which the process is not executing (that is, when the kernel or another process is running) is not counted.
- If the timer code is `ITIMER_PROF`, the process is sent a `SIGPROF` signal when the specified time has elapsed either during the process's own execution or the execution of a system call on behalf of the process.

The first argument to `setitimer` is the timer code, specifying which timer to set. The second argument is a pointer to a `struct itimerval` object specifying the new settings for that timer. The third argument, if not null, is a pointer to another `struct itimerval` object that receives the old timer settings.

A `struct itimerval` variable has two fields:

- `it_value` is a `struct timeval` field that contains the time until the timer next expires and a signal is sent. If this is 0, the timer is disabled.
- `it_interval` is another `struct timeval` field containing the value to which the timer will be reset after it expires. If this is 0, the timer will be disabled after it expires. If this is nonzero, the timer is set to expire repeatedly after this interval.

The `struct timeval` type is described in Section 8.7, "`gettimeofday`: Wall-Clock Time."

The program in Listing 8.11 illustrates the use of `setitimer` to track the execution time of a program. A timer is configured to expire every 250 milliseconds and send a `SIGVTALRM` signal.

Listing 8.11 **(*itemer.c*) Timer Example**

```
#include <signal.h>
#include <stdio.h>
#include <string.h>
#include <sys/time.h>
```

continues

Listing 8.11 **Continued**

```
void timer_handler (int signum)
{
  static int count = 0;
  printf ("timer expired %d times\n", ++count);
}

int main ()
{
  struct sigaction sa;
  struct itimerval timer;

  /* Install timer_handler as the signal handler for SIGVTALRM.  */
  memset (&sa, 0, sizeof (sa));
  sa.sa_handler = &timer_handler;
  sigaction (SIGVTALRM, &sa, NULL);

  /* Configure the timer to expire after 250 msec...  */
  timer.it_value.tv_sec = 0;
  timer.it_value.tv_usec = 250000;
  /* ... and every 250 msec after that.  */
  timer.it_interval.tv_sec = 0;
  timer.it_interval.tv_usec = 250000;
  /* Start a virtual timer.  It counts down whenever this process is
     executing.  */
  setitimer (ITIMER_VIRTUAL, &timer, NULL);

  /* Do busy work.  */
  while (1);
}
```

8.14 *sysinfo*: Obtaining System Statistics

The `sysinfo` system call fills a structure with system statistics. Its only argument is a pointer to a `struct sysinfo`. Some of the more interesting fields of `struct sysinfo` that are filled include these:

- `uptime`—Time elapsed since the system booted, in seconds
- `totalram`—Total available physical RAM
- `freeram`—Free physical RAM
- `procs`—Number of processes on the system

See the `sysinfo` man page for a full description of `structsysinfo`. Include `<linux/kernel.h>`, `<linux/sys.h>`, and `<sys/sysinfo.h>` if you use `sysinfo`.

The program in Listing 8.12 prints some statistics about the current system.

Listing 8.12 **(*sysinfo.c*) Print System Statistics**

```
#include <linux/kernel.h>
#include <linux/sys.h>
#include <stdio.h>
#include <sys/sysinfo.h>

int main ()
{
  /* Conversion constants.  */
  const long minute = 60;
  const long hour = minute * 60;
  const long day = hour * 24;
  const double megabyte = 1024 * 1024;
  /* Obtain system statistics.  */
  struct sysinfo si;
  sysinfo (&si);
  /* Summarize interesting values.  */
  printf ("system uptime : %ld days, %ld:%02ld:%02ld\n",
          si.uptime / day, (si.uptime % day) / hour,
          (si.uptime % hour) / minute, si.uptime % minute);
  printf ("total RAM     : %5.1f MB\n", si.totalram / megabyte);
  printf ("free RAM      : %5.1f MB\n", si.freeram / megabyte);
  printf ("process count : %d\n", si.procs);
  return 0;
}
```

8.15 *uname*

The `uname` system call fills a structure with various system information, including the computer's network name and domain name, and the operating system version it's running. Pass `uname` a single argument, a pointer to a `struct utsname` object. Include `<sys/utsname.h>` if you use `uname`.

The call to `uname` fills in these fields:

- `sysname`—The name of the operating system (such as Linux).
- `release`, `version`—The Linux kernel release number and version level.
- `machine`—Some information about the hardware platform running Linux. For x86 Linux, this is i386 or i686, depending on the processor.
- `node`—The computer's unqualified hostname.
- `__domain`—The computer's domain name.

Each of these fields is a character string.

The small program in Listing 8.13 prints the Linux release and version number and the hardware information.

Listing 8.13 **(*print-uname*) Print Linux Version Number and Hardware Information**

```
#include <stdio.h>
#include <sys/utsname.h>

int main ()
{
  struct utsname u;
  uname (&u);
  printf ("%s release %s (version %s) on %s\n", u.sysname, u.release,
          u.version, u.machine);
  return 0;
}
```

9

Inline Assembly Code

TODAY, FEW PROGRAMMERS USE ASSEMBLY LANGUAGE. Higher-level languages such as C and C++ run on nearly all architectures and yield higher productivity when writing and maintaining code. For occasions when programmers need to use assembly instructions in their programs, the GNU Compiler Collection permits programmers to add architecture-dependent assembly language instructions to their programs.

GCC's inline assembly statements should not be used indiscriminately. Assembly language instructions are architecture-dependent, so, for example, programs using x86 instructions cannot be compiled on PowerPC computers. To use them, you'll require a facility in the assembly language for your architecture. However, inline assembly statements permit you to access hardware directly and can also yield faster code.

An `asm` instruction allows you to insert assembly instructions into C and C++ programs. For example, this instruction

```
asm ("fsin" : "=t" (answer) : "0" (angle));
```

is an x86-specific way of coding this C statement:[1]

```
answer = sin (angle);
```

1. The expression `sin (angle)` is usually implemented as a function call into the math library, but if you specify the `-O1` or higher optimization flag, GCC is smart enough to replace the function call with a single `fsin` assembly instruction.

Observe that unlike ordinary assembly code instructions, `asm` statements permit you to specify input and output operands using C syntax.

To read more about the x86 instruction set, which we will use in this chapter, see `http://developer.intel.com/design/pentiumii/manuals/` and `http://www.x86-64.org/documentation`.

9.1 When to Use Assembly Code

Although `asm` statements can be abused, they allow your programs to access the computer hardware directly, and they can produce programs that execute quickly. You can use them when writing operating system code that directly needs to interact with hardware. For example, `/usr/include/asm/io.h` contains assembly instructions to access input/output ports directly. The Linux source code file `/usr/src/linux/arch/i386/kernel/process.s` provides another example, using `hlt` in idle loop code. See other Linux source code files in `/usr/src/linux/arch/` and `/usr/src/linux/drivers/`.

Assembly instructions can also speed the innermost loop of computer programs. For example, if the majority of a program's running time is computing the sine and cosine of the same angles, this innermost loop could be recoded using the `fsincos` x86 instruction.[2] See, for example, `/usr/include/bits/mathinline.h`, which wraps up into macros some inline assembly sequences that speed transcendental function computation.

You should use inline assembly to speed up code only as a last resort. Current compilers are quite sophisticated and know a lot about the details of the processors for which they generate code. Therefore, compilers can often choose code sequences that may seem unintuitive or roundabout but that actually execute faster than other instruction sequences. Unless you understand the instruction set and scheduling attributes of your target processor very well, you're probably better off letting the compiler's optimizers generate assembly code for you for most operations.

Occasionally, one or two assembly instructions can replace several lines of higher-level language code. For example, determining the position of the most significant nonzero bit of a nonzero integer using the C programming languages requires a loop or floating-point computations. Many architectures, including the x86, have a single assembly instruction (`bsr`) to compute this bit position. We'll demonstrate the use of one of these in Section 9.4, "Example."

2. Algorithmic or data structure changes may be more effective in reducing a program's running time than using assembly instructions.

9.2 Simple Inline Assembly

Here we introduce the syntax of `asm` assembler instructions with an x86 example to shift a value 8 bits to the right:

```
asm ("shrl $8, %0" : "=r" (answer) : "r" (operand) : "cc");
```

The keyword `asm` is followed by a parenthetic expression consisting of sections separated by colons. The first section contains an assembler instruction and its operands. In this example, `shrl` right-shifts the bits in its first operand. Its first operand is represented by `%0`. Its second operand is the immediate constant `$8`.

The second section specifies the outputs. The instruction's one output will be placed in the C variable `answer`, which must be an lvalue. The string `"=r"` contains an equals sign indicating an output operand and an `r` indicating that `answer` is stored in a register.

The third section specifies the inputs. The C variable `operand` specifies the value to shift. The string `"r"` indicates that it is stored in a register but omits an equals sign because it is an input operand, not an output operand.

The fourth section indicates that the instruction changes the value in the condition code `cc` register.

9.2.1 Converting an *asm* to Assembly Instructions

GCC's treatment of `asm` statements is very simple. It produces assembly instructions to deal with the `asm`'s operands, and it replaces the `asm` statement with the instruction that you specify. It does not analyze the instruction in any way.

For example, GCC converts this program fragment

```
double foo, bar;
asm ("mycool_asm %1, %0" : "=r" (bar) : "r" (foo));
```

to these x86 assembly instructions:

```
        movl -8(%ebp),%edx
        movl -4(%ebp),%ecx
#APP
        mycool_asm %edx, %edx
#NO_APP
        movl %edx,-16(%ebp)
        movl %ecx,-12(%ebp)
```

Remember that `foo` and `bar` each require two words of stack storage on a 32-bit x86 architecture. The register `ebp` points to data on the stack.

The first two instructions copy `foo` into registers `EDX` and `ECX` on which `mycool_asm` operates. The compiler decides to use the same registers to store the answer, which is copied into `bar` by the final two instructions. It chooses appropriate registers, even reusing the same registers, and copies operands to and from the proper locations automatically.

9.3 Extended Assembly Syntax

In the subsections that follow, we describe the syntax rules for `asm` statements. Their sections are separated by colons.

We will refer to this illustrative `asm` statement, which computes the Boolean expression `x > y`:

```
asm ("fucomip %%st(1), %%st; seta %%al" :
     "=a" (result) : "u" (y), "t" (x) : "cc", "st");
```

First, `fucomip` compares its two operands `x` and `y`, and stores values indicating the result into the condition code register. Then `seta` converts these values into a 0 or 1 result.

9.3.1 Assembler Instructions

The first section contains the assembler instructions, enclosed in quotation marks. The example `asm` contains two assembly instructions, `fucomip` and `seta`, separated by semicolons. If the assembler does not permit semicolons, use newline characters (`\n`) to separate instructions.

The compiler ignores the contents of this first section, except that one level of percentage signs is removed, so `%%` changes to `%`. The meaning of `%%st(1)` and other such terms is architecture-dependent.

GCC will complain if you specify the `-traditional` option or the `-ansi` option when compiling a program containing `asm` statements. To avoid producing these errors, such as in header files, use the alternative keyword `__asm__`.

9.3.2 Outputs

The second section specifies the instructions' output operands using C syntax. Each operand is specified by an operand constraint string followed by a C expression in parentheses. For output operands, which must be lvalues, the constraint string should begin with an equals sign. The compiler checks that the C expression for each output operand is in fact an lvalue.

Letters specifying registers for a particular architecture can be found in the GCC source code, in the `REG_CLASS_FROM_LETTER` macro. For example, the `gcc/config/i386/i386.h` configuration file in GCC lists the register letters for the x86 architecture.[3] Table 9.1 summarizes these.

3. You'll need to have some familiarity with GCC's internals to make sense of this file.

Table 9.1 **Register Letters for the Intel x86 Architecture**

Register Letter	Registers That GCC May Use
R	General register (EAX, EBX, ECX, EDX, ESI, EDI, EBP, ESP)
q	General register for data (EAX, EBX, ECX, EDX)
f	Floating-point register
t	Top floating-point register
u	Second-from-top floating-point register
a	EAX register
b	EBX register
c	ECX register
d	EDX register
x	SSE register (Streaming SIMD Extension register)
y	MMX multimedia registers
A	An 8-byte value formed from EAX and EDX
D	Destination pointer for string operations (EDI)
S	Source pointer for string operations (ESI)

Multiple operands in an `asm` statement, each specified by a constraint string and a C expression, are separated by commas, as illustrated in the example `asm`'s input section. You may specify up to 10 operands, denoted `%0`, `%1`, …, `%9`, in the output and input sections. If there are no output operands but there are input operands or clobbered registers, leave the output section empty or mark it with a comment like `/* no outputs */`.

9.3.3 Inputs

The third section specifies the input operands for the assembler instructions. The constraint string for an input operand should not have an equals sign, which indicates an lvalue. Otherwise, an input operand's syntax is the same as for output operands.

To indicate that a register is both read from and written to in the same `asm`, use an input constraint string of the output operand's number. For example, to indicate that an input register is the same as the first output register number, use `0`. Output operands are numbered left to right, starting with 0. Merely specifying the same C expression for an output operand and an input operand does not guarantee that the two values will be placed in the same register.

This input section can be omitted if there are no input operands and the subsequent clobber section is empty.

9.3.4 Clobbers

If an instruction modifies the values of one or more registers as a side effect, specify the clobbered registers in the `asm`'s fourth section. For example, the `fucomip` instruction modifies the condition code register, which is denoted `cc`. Separate strings representing clobbered registers with commas. If the instruction can modify an arbitrary memory location, specify `memory`. Using the clobber information, the compiler determines which values must be reloaded after the `asm` executes. If you don't specify this information correctly, GCC may assume incorrectly that registers still contain values that have, in fact, been overwritten, which will affect your program's correctness.

9.4 Example

The x86 architecture includes instructions that determine the positions of the least significant set bit and the most significant set bit in a word. The processor can execute these instructions quite efficiently. In contrast, implementing the same operation in C requires a loop and a bit shift.

For example, the `bsrl` assembly instruction computes the position of the most significant bit set in its first operand, and places the bit position (counting from 0, the least significant bit) into its second operand. To place the bit position for `number` into `position`, we could use this `asm` statement:

```
asm ("bsrl %1, %0" : "=r" (position) : "r" (number));
```

One way you could implement the same operation in C is using this loop:

```
long i;
for (i = (number >> 1), position = 0; i != 0; ++position)
  i >>= 1;
```

To test the relative speeds of these two versions, we'll place them in a loop that computes the bit positions for a large number of values. Listing 9.1 does this using the C loop implementation. The program loops over integers, from 1 up to the value specified on the command line. For each value of `number`, it computes the most significant bit that is set. Listing 9.2 does the same thing using the inline assembly instruction. Note that in both versions, we assign the computed bit position to a volatile variable `result`. This is to coerce the compiler's optimizer so that it does not eliminate the entire bit position computation; if the result is not used or stored in memory, the optimizer eliminates the computation as "dead code."

Listing 9.1 **(*bit-pos-loop.c*) Find Bit Position Using a Loop**

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

int main (int argc, char* argv[])
{
  long max = atoi (argv[1]);
  long number;
```

```
  long i;
  unsigned position;
  volatile unsigned result;

  /* Repeat the operation for a large number of values.  */
  for (number = 1; number <= max; ++number) {
    /* Repeatedly shift the number to the right, until the result is
       zero.  Keep count of the number of shifts this requires.  */
    for (i = (number >> 1), position = 0; i != 0; ++position)
      i >>= 1;
    /* The position of the most significant set bit is the number of
       shifts we needed after the first one.  */
    result = position;
  }

  return 0;
}
```

Listing 9.2 (*bit-pos-asm.c*) **Find Bit Position Using *bsrl***

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

int main (int argc, char* argv[])
{
  long max = atoi (argv[1]);
  long number;
  unsigned position;
  volatile unsigned result;

  /* Repeat the operation for a large number of values.  */
  for (number = 1; number <= max; ++number) {
    /* Compute the position of the most significant set bit using the
       bsrl assembly instruction.  */
    asm ("bsrl %1, %0" : "=r" (position) : "r" (number));
    result = position;
  }

  return 0;
}
```

We'll compile both versions with full optimization:

```
% cc -O2 -o bit-pos-loop bit-pos-loop.c
% cc -O2 -o bit-pos-asm bit-pos-asm.c
```

Now let's run each using the `time` command to measure execution time. We'll specify a large value as the command-line argument, to make sure that each version takes at least a few seconds to run.

```
% time ./bit-pos-loop 250000000
19.51user 0.00system 0:20.40elapsed 95%CPU (0avgtext+0avgdata
0maxresident)k0inputs+0outputs (73major+11minor)pagefaults 0swaps
% time ./bit-pos-asm 250000000
3.19user 0.00system 0:03.32elapsed 95%CPU (0avgtext+0avgdata
0maxresident)k0inputs+0outputs (73major+11minor)pagefaults 0swaps
```

Notice that the version that uses inline assembly executes a great deal faster (your results for this example may vary).

9.5 Optimization Issues

GCC's optimizer attempts to rearrange and rewrite programs' code to minimize execution time even in the presence of `asm` expressions. If the optimizer determines that an `asm`'s output values are not used, the instruction will be omitted unless the keyword `volatile` occurs between `asm` and its arguments. (As a special case, GCC will not move an `asm` without any output operands outside a loop.) Any `asm` can be moved in ways that are difficult to predict, even across jumps. The only way to guarantee a particular assembly instruction ordering is to include all the instructions in the same `asm`.

Using `asm`s can restrict the optimizer's effectiveness because the compiler does not know the asms' semantics. GCC is forced to make conservative guesses that may prevent some optimizations. *Caveat emptor!*

9.6 Maintenance and Portability Issues

If you decide to use nonportable, architecture-dependent `asm` statements, encapsulating these statements within macros or functions can aid in maintenance and porting. Placing all these macros in one file and documenting them will ease porting to a different architecture, something that occurs with surprising frequency even for "throwaway" programs. Thus, the programmer will need to rewrite only one file for the different architecture.

For example, most `asm` statements in the Linux source code are grouped into `/usr/src/linux/include/asm` and `/usr/src/linux/include/asm-i386` header files, and `/usr/src/linux/arch/i386/` and `/usr/src/linux/drivers/` source files.

10 Security

Much of the power of a GNU/Linux system comes from its support for multiple users and for networking. Many people can use the system at once, and they can connect to the system from remote locations. Unfortunately, with this power comes risk, especially for systems connected to the Internet. Under some circumstances, a remote "hacker" can connect to the system and read, modify, or remove files that are stored on the machine. Or, two users on the same machine can read, modify, or remove each other's files when they should not be allowed to do so. When this happens, the system's security is said to have been *compromised*.

The Linux kernel provides a variety of facilities to ensure that these events do not take place. But to avoid security breaches, ordinary applications must be careful as well. For example, imagine that you are developing accounting software. Although you might want all users to be able to file expense reports with the system, you wouldn't want all users to be able to *approve* those reports. You might want users to be able to view their own payroll information, but you certainly wouldn't want them to be able to view everyone else's payroll information. You might want managers to be able to view the salaries of employees in their departments, but you wouldn't want them to view the salaries of employees in other departments.

To enforce these kinds of controls, you have to be very careful. It's amazingly easy to make a mistake that allows users to do something you didn't intend them to be able to do. The best approach is to enlist the help of security experts. Still, every application developer ought to understand the basics.

10.1 Users and Groups

Each Linux user is assigned a unique number, called a *user ID*, or *UID*. Of course, when you log in, you use a username rather than a user ID. The system converts your username to a particular user ID, and from then on it's only the user ID that counts.

You can actually have more than one username for the same user ID. As far as the system is concerned, the user IDs, not the usernames, matter. There's no way to give one username more power than another if they both correspond to the same user ID.

You can control access to a file or other resource by associating it with a particular user ID. Then only the user corresponding to that user ID can access the resource. For example, you can create a file that only you can read, or a directory in which only you can create new files. That's good enough for many simple cases.

Sometimes, however, you want to share a resource among multiple users. For example, if you're a manager, you might want to create a file that any manager can read but that ordinary employees cannot. Linux doesn't allow you to associate multiple user IDs with a file, so you can't just create a list of all the people to whom you want to give access and attach them all to the file.

You can, however, create a *group*. Each group is assigned a unique number, called a *group ID*, or *GID*. Every group contains one or more user IDs. A single user ID can be a member of lots of groups, but groups can't contain other groups; they can contain only users. Like users, groups have names. Also like usernames, however, the group names don't really matter; the system always uses the group ID internally.

Continuing our example, you could create a `managers` group and put the user IDs for all the managers in this group. You could then create a file that can be read by anyone in the `managers` group but not by people who aren't in the group. In general, you can associate only one group with a resource. There's no way to specify that users can access a file only if they're in either group 7 or group 42, for example.

If you're curious to see what your user ID is and what groups you are in, you can use the `id` command. For example, the output might look like this:

```
% id
uid=501(mitchell) gid=501(mitchell) groups=501(mitchell),503(csl)
```

The first part shows you that the user ID for the user who ran the command was 501. The command also figures out what the corresponding username is and displays that in parentheses. The command shows that user ID 501 is actually in two groups: group 501 (called `mitchell`) and group 503 (called `csl`). You're probably wondering why group 501 appears twice: once in the `gid` field and once in the `groups` field. We'll explain this later.

10.1.1 The Superuser

One user account is very special.[1] This user has user ID 0 and usually has the username `root`. It is also sometimes referred to as the *superuser* account. The `root` user can do just about anything: read any file, remove any file, add new users, turn off network access, and so forth. Lots of special operations can be performed only by processes running with root privilege—that is, running as user `root`.

The trouble with this design is that a lot of programs need to be run by `root` because a lot of programs need to perform one of these special operations. If any of these programs misbehaves, chaos can result. There's no effective way to contain a program when it's run by `root`; it can do *anything*. Programs run by root must be written very carefully.

10.2 Process User IDs and Process Group IDs

Until now, we've talked about commands being executed by a particular user. That's not quite accurate because the computer never really knows which user is using it. If Eve learns Alice's username and password, then Eve can log in as Alice, and the computer will let Eve do everything that Alice can do. The system knows only which user ID is in use, not which user is typing the commands. If Alice can't be trusted to keep her password to herself, for example, then nothing you do as an application developer will prevent Eve from accessing Alice's files. The responsibility for system security is shared among the application developer, the users of the system, and the administrators of the system.

Every process has an associated user ID and group ID. When you invoke a command, it typically runs in a process whose user and group IDs are the same as your user and group IDs. When we say that a user performs an operation, we really mean that a process with the corresponding user ID performs that operation. When the process makes a system call, the kernel decides whether to allow the operation to proceed. It makes that determination by examining the permissions associated with the resources that the process is trying to access and by checking the user ID and group ID associated with the process trying to perform the action.

Now you know what that middle field printed by the `id` command is all about. It's showing the group ID of the current process. Even though user 501 is in multiple groups, the current process can have only one group ID. In the example shown previously, the current group ID is 501.

If you have to manipulate user IDs and group IDs in your program (and you will, if you're writing programs that deal with security), then you should use the `uid_t` and `gid_t` types defined in `<sys/types.h>`. Even though user IDs and group IDs are essentially just integers, avoid making any assumptions about how many bits are used in these types or perform arithmetic operations on them. Just treat them as opaque handles for user and group identity.

1. The fact that there is only one special user gave AT&T the name for its UNIX operating system. In contrast, an earlier operating system that had multiple special users was called MULTICS. GNU/Linux, of course, is mostly compatible with UNIX.

To get the user ID and group ID for the current process, you can use the `geteuid` and `getegid` functions, declared in `<unistd.h>`. These functions don't take any parameters, and they always work; you don't have to check for errors. Listing 10.1 shows a simple program that provides a subset of the functionality provide by the `id` command:

Listing 10.1 **(*simpleid.c*) Print User and Group IDs**

```
#include <sys/types.h>
#include <unistd.h>
#include <stdio.h>

int main()
{
  uid_t uid = geteuid ();
  gid_t gid = getegid ();
  printf ("uid=%d gid=%d\n", (int) uid, (int) gid);
  return 0;
}
```

When this program is run (by the same user who ran the real `id` program) the output is as follows:

```
% ./simpleid
uid=501 gid=501
```

10.3 File System Permissions

A good way to see users and groups in action is to look at file system permissions. By examining how the system associates permissions with each file and then seeing how the kernel checks to see who is allowed to access which files, the concepts of user ID and group ID should become clearer.

Each file has exactly one *owning user* and exactly one *owning group*. When you create a new file, the file is owned by the user and group of the creating process.[2]

The basic things that you can do with files, as far as Linux is concerned, are *read* from them, *write* to them, and *execute* them. (Note that creating a file and removing a file are not considered things you can do with the file; they're considered things you can do with the directory containing the file. We'll get to this a little later.) If you can't read a file, Linux won't let you examine the file's contents. If you can't write a file, you can't change its contents. If there's a program file for which you do not have execute permission, you cannot run the program.

2. Actually, there are some rare exceptions, involving *sticky bits*, discussed later in Section 10.3.2, "Sticky Bits."

Linux enables you to designate which of these three actions—reading, writing, and executing—can be performed by the owning user, owning group, and everybody else. For example, you could say that the owning user can do anything she wants with the file, that anyone in the owning group can read and execute the file (but not write to it), and that nobody else can access the file at all.

You can view these *permission bits* interactively with the `ls` command by using the `-l` or `-o` options and programmatically with the `stat` system call. You can set the *permission bits* interactively with the `chmod` program[3] or programmatically with the system call of the same name. To look at the permissions on a file named `hello`, use `ls -l hello`. Here's how the output might look:

```
% ls -l hello
-rwxr-x---    1 samuel   csl         11734 Jan 22 16:29 hello
```

The `samuel` and `csl` fields indicate that the owning user is `samuel` and that the owning group is `csl`.

The string of characters at the beginning of the line indicates the permissions associated with the file. The first dash indicates that this is a normal file. It would be `d` for a directory, or it can be other letters for special kinds of files such as devices (see Chapter 6, "Devices") or named pipes (see Chapter 5, "Interprocess Communication," Section 5.4, "Pipes"). The next three characters show permissions for the owning user; they indicate that `samuel` can read, write, and execute the file. The next three characters show permissions for members of the `csl` group; these members are allowed only to read and execute the file. The last three characters show permissions for everyone else; these users are not allowed to do anything with `hello`.

Let's see how this works. First, let's try to access the file as the user `nobody`, who is not in the `csl` group:

```
% id
uid=99(nobody) gid=99(nobody) groups=99(nobody)
% cat hello
cat: hello: Permission denied
% echo hi > hello
sh: ./hello: Permission denied
% ./hello
sh: ./hello: Permission denied
```

We can't read the file, which is why `cat` fails; we can't write to the file, which is why `echo` fails; and we can't run the file, which is why `./hello` fails.

3. You'll sometimes see the permission bits for a file referred to as the file's *mode*. The name of the `chmod` command is short for "change mode."

Things are better if we are accessing the file as `mitchell`, who is a member of the `csl` group:

```
% id
uid=501(mitchell) gid=501(mitchell) groups=501(mitchell),503(csl)
% cat hello
#!/bin/bash
echo "Hello, world."
% ./hello
Hello, world.
% echo hi > hello
bash: ./hello: Permission denied
```

We can list the contents of the file, and we can run it (it's a simple shell script), but we still can't write to it.

If we run as the owner (`samuel`), we can even overwrite the file:

```
% id
uid=502(samuel) gid=502(samuel) groups=502(samuel),503(csl)
% echo hi > hello
% cat hello
hi
```

You can change the permissions associated with a file only if you are the file's owner (or the superuser). For example, if you now want to allow everyone to execute the file, you can do this:

```
% chmod o+x hello
% ls -l hello
-rwxr-x--x    1 samuel   csl             3 Jan 22 16:38 hello
```

Note that there's now an `x` at the end of the first string of characters. The `o+x` bit means that you want to add the execute permission for other people (not the file's owner or members of its owning group). You could use `g-w` instead, to remove the write permission from the group. See the man page in section 1 for `chmod` for details about this syntax:

```
% man 1 chmod
```

Programmatically, you can use the `stat` system call to find the permissions associated with a file. This function takes two parameters: the name of the file you want to find out about, and the address of a data structure that is filled in with information about the file. See Appendix B, "Low-Level I/O," Section B.2, "`stat`," for a discussion of other information that you can obtain with `stat`. Listing 10.2 shows an example of using `stat` to obtain file permissions.

Listing 10.2 **(*stat-perm.c*) Determine File Owner's Write Permission**

```
#include <stdio.h>
#include <sys/stat.h>

int main (int argc, char* argv[])
{
  const char* const filename = argv[1];
  struct stat buf;
```

```
  /* Get file information.  */
  stat (filename, &buf);
  /* If the permissions are set such that the file's owner can write
     to it, print a message.  */
  if (buf.st_mode & S_IWUSR)
    printf ("Owning user can write `%s'.\n", filename);
  return 0;
}
```

If you run this program on our `hello` program, it says:

```
% ./stat-perm hello
Owning user can write 'hello'.
```

The `S_IWUSR` constant corresponds to write permission for the owning user. There are other constants for all the other bits. For example, `S_IRGRP` is read permission for the owning group, and `S_IXOTH` is execute permission for users who are neither the owning user nor a member of the owning group. If you store permissions in a variable, use the typedef `mode_t` for that variable. Like most system calls, `stat` will return `-1` and set `errno` if it can't obtain information about the file.

You can use the `chmod` function to change the permission bits on an existing file. You call `chmod` with the name of the file you want to change and the permission bits you want set, presented as the bitwise or of the various permission constants mentioned previously. For example, this next line would make `hello` readable and executable by its owning user but would disable all other permissions associated with `hello`:

```
chmod ("hello", S_IRUSR | S_IXUSR);
```

The same permission bits apply to directories, but they have different meanings. If a user is allowed to read from a directory, the user is allowed to see the list of files that are present in that directory. If a user is allowed to write to a directory, the user is allowed to add or remove files from the directory. Note that a user may remove files from a directory if she is allowed to write to the directory, *even if she does not have permission to modify the file she is removing*. If a user is allowed to execute a directory, the user is allowed to enter that directory and access the files therein. Without execute access to a directory, a user is not allowed to access the files in that directory independent of the permissions on the files themselves.

To summarize, let's review how the kernel decides whether to allow a process to access a particular file. It checks to see whether the accessing user is the owning user, a member of the owning group, or someone else. The category into which the accessing user falls is used to determine which set of read/write/execute bits are checked. Then the kernel checks the operation that is being performed against the permission bits that apply to this user.[4]

4. The kernel may also deny access to a file if a component directory in its file path is inaccessible. For instance, if a process may not access the directory `/tmp/private/`, it may not read `/tmp/private/data`, even if the permissions on the latter are set to allow the access.

There is one important exception: Processes running as `root` (those with user ID 0) are always allowed to access any file, regardless of the permissions associated with it.

10.3.1 Security Hole: Programs Without Execute Permissions

Here's a first example of where security gets very tricky. You might think that if you disallow execution of a program, then nobody can run it. After all, that's what it means to disallow execution. But a malicious user can make a copy of the program, change the permissions to make it executable, and then run the copy! If you rely on users not being able to run programs that aren't executable but then don't prevent them from copying the programs, you have a *security hole*—a means by which users can perform some action that you didn't intend.

10.3.2 Sticky Bits

In addition to read, write, and execute permissions, there is a magic bit called the *sticky bit*.[5] This bit applies only to directories.

A directory that has the sticky bit set allows you to delete a file only if you are the owner of the file. As mentioned previously, you can ordinarily delete a file if you have write access to the directory that contains it, even if you are not the file's owner. When the sticky bit is set, you *still* must have write access to the directory, but you must also be the owner of the file that you want to delete.

A few directories on the typical GNU/Linux system have the sticky bit set. For example, the `/tmp` directory, in which any user can place temporary files, has the sticky bit set. This directory is specifically designed to be used by all users, so the directory must be writable by everyone. But it would be bad if one user could delete another user's files, so the sticky bit is set on the directory. Then only the owning user (or `root`, of course) can remove a file.

You can see the sticky bit is set because of the `t` at the end of the permission bits when you run `ls` on `/tmp`:

```
% ls -ld /tmp
drwxrwxrwt   12 root     root         2048 Jan 24 17:51 /tmp
```

The corresponding constant to use with `stat` and `chmod` is `S_ISVTX`.

If your program creates directories that behave like `/tmp`, in that lots of people put things there but shouldn't be able to remove each other's files, then you should set the sticky bit on the directory. You can set the sticky bit on a directory with the `chmod` command by invoking the following:

```
% chmod o+t directory
```

5. This name is anachronistic; it goes back to a time when setting the sticky bit caused a program to be retained in main memory even when it was done executing. The pages allocated to the program were "stuck" in memory.

To set the sticky bit programmatically, call `chmod` with the `S_ISVTX` mode flag. For example, to set the sticky bit of the directory specified by `dir_path` to those of the `/tmp` and give full read, write, and execute permissions to all users, use this call:

```
chmod (dir_path, S_IRWXU | S_IRWXG | S_IRWXO | S_ISVTX);
```

10.4 Real and Effective IDs

Until now, we've talked about the user ID and group ID associated with a process as if there were only one such user ID and one such group ID. But, actually, it's not quite that simple.

Every process really has two user IDs: the *effective user ID* and the *real user ID*. (Of course, there's also an *effective group ID* and *real group ID*. Just about everything that's true about user IDs is also true about group IDs.) Most of the time, the kernel checks only the effective user ID. For example, if a process tries to open a file, the kernel checks the effective user ID when deciding whether to let the process access the file.

The `geteuid` and `getegid` functions described previously return the effective user ID and the effective group ID. Corresponding `getuid` and `getgid` functions return the real user ID and real group ID.

If the kernel cares about only the effective user ID, it doesn't seem like there's much point in having a distinction between a real user ID and an effective user ID. However, there is one very important case in which the real user ID matters. If you want to change the effective user ID of an already running process, the kernel looks at the real user ID as well as the effective user ID.

Before looking at *how* you can change the effective user ID of a process, let's examine *why* you would want to do such a thing by looking back at our accounting package. Suppose that there's a server process that might need to look at any file on the system, regardless of the user who created it. Such a process must run as `root` because only `root` can be guaranteed to be capable of looking at any file. But now suppose that a request comes in from a particular user (say, `mitchell`) to access some file. The server process could carefully examine the permissions associated with the files in question and try to decide whether `mitchell` should be allowed to access those files. But that would mean duplicating all the processing that the kernel would normally do to check file access permissions. Reimplementing that logic would be complex, error-prone, and tedious.

A better approach is simply to temporarily change the effective user ID of the process from `root` to `mitchell` and then try to perform the operations required. If `mitchell` is not allowed to access the data, the kernel will prevent the process from doing so and will return appropriate indications of error. After all the operations taken on behalf of `mitchell` are complete, the process can restore its original effective user ID to `root`.

Programs that authenticate users when they log in take advantage of the capability to change user IDs as well. These login programs run as `root`. When the user enters a username and password, the login program verifies the username and password in the system password database. Then the login program changes both the effective user ID and the real ID to be that of the user. Finally, the login program calls `exec` to start the user's shell, leaving the user running a shell whose effective user ID and real user ID are that of the user.

The function used to change the user IDs for a process is `setreuid`. (There is, of course, a corresponding `setregid` function as well.) This function takes two arguments. The first argument is the desired real user ID; the second is the desired effective user ID. For example, here's how you would exchange the effective and real user IDs:

```
setreuid (geteuid(), getuid ());
```

Obviously, the kernel won't let just any process change its user IDs. If a process were allowed to change its effective user ID at will, then any user could easily impersonate any other user, simply by changing the effective user ID of one of his processes. The kernel will let a process running with an effective user ID of 0 change its user IDs as it sees fit. (Again, notice how much power a process running as `root` has! A process whose effective user ID is 0 can do absolutely anything it pleases.) Any other process, however, can do only one of the following things:

- Set its effective user ID to be the same as its real user ID
- Set its real user ID to be the same as its effective user ID
- Swap the two user IDs

The first alternative would be used by our accounting process when it has finished accessing files as `mitchell` and wants to return to being `root`. The second alternative could be used by a login program after it has set the effective user ID to that of the user who just logged in. Setting the real user ID ensures that the user will never be able go back to being `root`. Swapping the two user IDs is almost a historical artifact; modern programs rarely use this functionality.

You can pass -1 to either argument to `setreuid` if you want to leave that user ID alone. There's also a convenience function called `seteuid`. This function sets the effective user ID, but it doesn't modify the real user ID. The following two statements both do exactly the same thing:

```
seteuid (id);
setreuid (-1, id);
```

10.4.1 Setuid Programs

Using the previous techniques, you know how to make a `root` process impersonate another process temporarily and then return to being `root`. You also know how to make a `root` process drop all its special privileges by setting both its real user ID and its effective user ID.

Here's a puzzle: Can you, running as a non-`root` user, ever become `root`? That doesn't seem possible, using the previous techniques, but here's proof that it can be done:

```
% whoami
mitchell
% su
Password: ...
% whoami
root
```

The `whoami` command is just like `id`, except that it shows only the effective user ID, not all the other information. The `su` command enables you to become the superuser if you know the `root` password.

How does `su` work? Because we know that the shell was originally running with both its real user ID and its effective user ID set to `mitchell`, `setreuid` won't allow us to change either user ID.

The trick is that the `su` program is a *setuid* program. That means that when it is run, the effective user ID of the process will be that of the file's owner rather than the effective user ID of the process that performed the `exec` call. (The real user ID will still be that of the executing user.) To create a setuid program, you use `chmod +s` at the command line, or use the `S_ISUID` flag if calling `chmod` programmatically.[6]

For example, consider the program in Listing 10.3.

Listing 10.3 **(*setuid-test.c*) Setuid Demonstration Program**

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

int main ()
{
  printf ("uid=%d euid=%d\n", (int) getuid (), (int) geteuid ());
  return 0;
}
```

Now suppose that this program is setuid and owned by `root`. In that case, the `ls` output will look like this:

```
-rwsrws--x    1 root     root        11931 Jan 24 18:25 setuid-test
```

The `s` bits indicate that the file is not only executable (as an `x` bit would indicate) but also setuid and setgid. When we use this program, we get output like this:

```
% whoami
mitchell
% ./setuid-test
uid=501 euid=0
```

6. Of course, there is a similar notion of a setgid program. When run, its effective group ID is the same as that of the group owner of the file. Most setuid programs are also setgid programs.

Note that the effective user ID is set to 0 when the program is run.

You can use the `chmod` command with the `u+s` or `g+s` arguments to set the setuid and setgid bits on an executable file, respectively—for example:

```
% ls -l program
-rwxr-xr-x    1 samuel   csl             0 Jan 30 23:38 program
% chmod g+s program
% ls -l program
-rwxr-sr-x    1 samuel   csl             0 Jan 30 23:38 program
% chmod u+s program
% ls -l program
-rwsr-sr-x    1 samuel   csl             0 Jan 30 23:38 program
```

You can also use the `chmod` call with the `S_ISUID` or `S_ISGID` mode flags.

`su` is capable of changing the effective user ID through this mechanism. It runs initially with an effective user ID of 0. Then it prompts you for a password. If the password matches the `root` password, it sets its real user ID to be `root` as well and then starts a new shell. Otherwise, it exits, unceremoniously leaving you as a non-privileged user.

Take a look at the permissions on the `su` program:

```
% ls -l /bin/su
-rwsr-xr-x    1 root     root        14188 Mar  7  2000 /bin/su
```

Notice that it's owned by `root` and that the setuid bit is set.

Note that `su` doesn't actually change the user ID of the shell from which it was run. Instead, it starts a new shell process with the new user ID. The original shell is blocked until the new shell completes and `su` exits.

10.5 Authenticating Users

Often, if you have a setuid program, you don't want to offer its services to everyone. For example, the `su` program lets you become `root` only if you know the `root` password. The program makes you prove that you are entitled to become `root` before going ahead with its actions. This process is called *authentication*—the `su` program is checking to see that you are authentic.

If you're administering a very secure system, you probably don't want to let people log in just by typing an ordinary password. Users tend to write down passwords, and black hats tend to find them. Users tend to pick passwords that involve their birthdays, the names of their pets, and so forth.[7] Passwords just aren't all that secure.

7. It has been found that system administrators tend to pick the word *god* as their password more often than any other password. (Make of that what you will.) So, if you ever need `root` access on a machine and the sysadmin isn't around, a little divine inspiration might be just what you need.

For example, many organizations now require the use of special "one-time" passwords that are generated by special electronic ID cards that users keep with them. The same password can't be used twice, and you can't get a valid password out of the ID card without entering a PIN. So, an attacker must obtain both the physical card and the PIN to break in. In a really secure facility, retinal scans or other kinds of biometric testing are used.

If you're writing a program that must perform authentication, you should allow the system administrator to use whatever means of authentication is appropriate for that installation. GNU/Linux comes with a very useful library that makes this very easy. This facility, called *Pluggable Authentication Modules*, or *PAM*, makes it easy to write applications that authenticate their users as the system administrator sees fit.

It's easiest to see how PAM works by looking at a simple PAM application. Listing 10.4 illustrates the use of PAM.

Listing 10.4 **(*pam.c*) PAM Example**

```
#include <security/pam_appl.h>
#include <security/pam_misc.h>
#include <stdio.h>

int main ()
{
  pam_handle_t* pamh;
  struct pam_conv pamc;

  /* Set up the PAM conversation.  */
  pamc.conv = &misc_conv;
  pamc.appdata_ptr = NULL;
  /* Start a new authentication session.  */
  pam_start ("su", getenv ("USER"), &pamc, &pamh);
  /* Authenticate the user.  */
  if (pam_authenticate (pamh, 0) != PAM_SUCCESS)
    fprintf (stderr, "Authentication failed!\n");
  else
    fprintf (stderr, "Authentication OK.\n");
  /* All done.  */
  pam_end (pamh, 0);
  return 0;
}
```

To compile this program, you have to link it with two libraries: the `libpam` library and a helper library called `libpam_misc`:

```
% gcc -o pam pam.c -lpam -lpam_misc
```

This program starts off by building up a PAM *conversation object*. This object is used by the PAM library whenever it needs to prompt the user for information. The `misc_conv` function used in this example is a standard conversation function that uses the terminal for input and output. You could write your own function that pops up a dialog box, or that uses speech for input and output, or that provides even more exotic input and output methods.

The program then calls `pam_start`. This function initializes the PAM library. The first argument is a service name. You should use a name that uniquely identifies your application. For example, if your application is named whizbang, you should probably use that for the service name, too. However, the program probably won't work until the system administrator explicitly configures the system to work with your service. So, in this example, we use the su service, which says that our program should authenticate users in the same way that the `su` command does. You should *not* use this technique in a real program. Pick a real service name, and have your installation scripts help the system administrator to set up a correct PAM configuration for your application.

The second argument is the name of the user whom you want to authenticate. In this example, we use the value of the `USER` environment variable. (Normally, this is the username that corresponds to the effective user ID of the current process, but that's not always the case.) In most real programs, you would prompt for a username at this point. The third argument indicates the PAM conversation, discussed previously. The call to `pam_start` fills in the handle provided as the fourth argument. Pass this handle to subsequent calls to PAM library routines.

Next, the program calls `pam_authenticate`. The second argument enables you to pass various flags; the value 0 means to use the default options. The return value from this function indicates whether authentication succeeded.

Finally, the programs calls `pam_end` to clean up any allocated data structures.

Let's assume that the valid password for the current user is "password" (an exceptionally poor password). Then, running this program with the correct password produces the expected:

```
% ./pam
Password: password

Authentication OK.
```

If you run this program in a terminal, the password probably won't actually appear when you type it in; it's hidden to prevent others from peeking at your password over your shoulder as you type.

However, if a hacker tries to use the wrong password, the PAM library will correctly indicate failure:

```
% ./pam
Password: badguess

Authentication failed!
```

The basics covered here are enough for most simple programs. Full documentation about how PAM works is available in `/usr/doc/pam` on most GNU/Linux systems.

10.6 More Security Holes

Although this chapter will point out a few common security holes, you should by no means rely on this book to cover all possible security holes. A great many have already been discovered, and many more are out there waiting to be found. If you are trying to write secure code, there is really no substitute for having a security expert audit your code.

10.6.1 Buffer Overruns

Almost every major Internet application daemon, including the `sendmail` daemon, the `finger` daemon, the `talk` daemon, and others, has at one point been compromised through a *buffer overrun*.

If you are writing any code that will ever be run as `root`, you absolutely must be aware of this particular kind of security hole. If you are writing a program that performs any kind of interprocess communication, you should definitely be aware of this kind of security hole. If you are writing a program that reads files (or *might* read files) that are not owned by the user executing the program, you should be aware of this kind of security hole. That last criterion applies to almost every program. Fundamentally, if you're going to write GNU/Linux software, you ought to know about buffer overruns.

The idea behind a buffer overrun attack is to trick a program into executing code that it did not intend to execute. The usual mechanism for achieving this feat is to overwrite some portion of the program's process stack. The program's stack contains, among other things, the memory location to which the program will transfer control when the current function returns. Therefore, if you can put the code that you want to have executed into memory somewhere and then change the return address to point to that piece of memory, you can cause the program to execute anything. When the program returns from the function it is executing, it will jump to the new code and execute whatever is there, running with the privileges of the current process. Clearly, if the current process is running as `root`, this would be a disaster. If the process is running as another user, it's a disaster "only" for that user—and anybody else who depends on the contents of files owned by that user, and so forth.

If the program is running as a daemon and listening for incoming network connections, the situation is even worse. A daemon typically runs as `root`. If it contains buffer overrun bugs, anyone who can connect via the network to a computer running the daemon can seize control of the computer by sending a malignant sequence of data to the daemon over the network. A program that does not engage in network communications is much safer because only users who are already able to log in to the computer running the program are able to attack it.

The buggy versions of `finger`, `talk`, and `sendmail` all shared a common flaw. Each used a fixed-length string buffer, which implied a constant upper limit on the size of the string but then allowed network clients to provide strings that overflowed the buffer. For example, they contained code similar to this:

```
#include <stdio.h>

int main ()
{
  /* Nobody in their right mind would have more than 32 characters in
     their username.  Plus, I think UNIX allows only 8-character
     usernames.  So, this should be plenty of space.  */
  char username[32];
  /* Prompt the user for the username.  */
  printf ("Enter your username: ");
  /* Read a line of input.  */
  gets (username);
  /* Do other things here...  */

  return 0;
}
```

The combination of the 32-character buffer with the `gets` function permits a buffer overrun. The `gets` function reads user input up until the next newline character and stores the entire result in the `username` buffer. The comments in the code are correct in that people generally have short usernames, so no well-meaning user is likely to type in more than 32 characters. But when you're writing secure software, you must consider what a malicious attacker might do. In this case, the attacker might deliberately type in a very long username. Local variables such as `username` are stored on the stack, so by exceeding the array bounds, it's possible to put arbitrary bytes onto the stack beyond the area reserved for the `username` variable. The username will overrun the buffer and overwrite parts of the surrounding stack, allowing the kind of attack described previously.

Fortunately, it's relatively easy to prevent buffer overruns. When reading strings, you should always use a function, such as `getline`, that either dynamically allocates a sufficiently large buffer or stops reading input if the buffer is full. For example, you could use this:

```
char* username = getline (NULL, 0, stdin);
```

This call automatically uses `malloc` to allocate a buffer big enough to hold the line and returns it to you. You have to remember to call `free` to deallocate the buffer, of course, to avoid leaking memory.

Your life will be even easier if you use C++ or another language that provides simple primitives for reading input. In C++, for example, you can simply use this:

```
string username;
getline (cin, username);
```

The `username` string will automatically be deallocated as well; you don't have to remember to `free` it.[8]

Of course, buffer overruns can occur with any statically sized array, not just with strings. If you want to write secure code, you should never write into a data structure, on the stack or elsewhere, without verifying that you're not going to write beyond its region of memory.

10.6.2 Race Conditions in */tmp*

Another very common problem involves the creation of files with predictable names, typically in the `/tmp` directory. Suppose that your program `prog`, running as `root`, always creates a temporary file called `/tmp/prog` and writes some vital information there. A malicious user can create a symbolic link from `/tmp/prog` to any other file on the system. When your program goes to create the file, the `open` system call will succeed. However, the data that you write will not go to `/tmp/prog`; instead, it will be written to some arbitrary file of the attacker's choosing.

This kind of attack is said to exploit a *race condition*. There is implicitly a race between you and the attacker. Whoever manages to create the file first wins.

This attack is often used to destroy important parts of the file system. By creating the appropriate links, the attacker can trick a program running as `root` that is supposed to write a temporary file into overwriting an important system file instead. For example, by making a symbolic link to `/etc/passwd`, the attacker can wipe out the system's password database. There are also ways in which a malicious user can obtain `root` access using this technique.

One attempt at avoiding this attack is to use a randomized name for the file. For example, you could read from `/dev/random` to get some bits to use in the name of the file. This certainly makes it harder for a malicious user to guess the filename, but it doesn't make it impossible. The attacker might just create a large number of symbolic links, using many potential names. Even if she has to try 10,000 times before wining the race condition, that one time could be disastrous.

Another approach is to use the `O_EXCL` flag when calling `open`. This flag causes `open` to fail if the file already exists. Unfortunately, if you're using the Network File System (NFS), or if anyone who's using your program might ever be using NFS, that's not a sufficiently robust approach because `O_EXCL` is not reliable when NFS is in use. You can't ever really know for sure whether your code will be used on a system that uses NFS, so if you're highly paranoid, don't rely on using `O_EXCL`.

In Chapter 2, "Writing Good GNU/Linux Software," Section 2.1.7, "Using Temporary Files," we showed how to use `mkstemp` to create temporary files. Unfortunately, what `mkstemp` does on Linux is open the file with `O_EXCL` after trying to pick a name that is hard to guess. In other words, using `mkstemp` is still insecure if `/tmp` is mounted over NFS.[9] So, using `mkstemp` is better than nothing, but it's not fully secure.

8. Some programmers believe that C++ is a horrible and overly complex language. Their arguments about multiple inheritance and other such complications have some merit, but it is easier to write code that avoids buffer overruns and other similar problems in C++ than in C.

9. Obviously, if you're also a system administrator, you shouldn't mount `/tmp` over NFS.

One approach that works is to call `lstat` on the newly created file (lstat is discussed in Section B.2, "`stat`"). The `lstat` function is like `stat`, except that if the file referred to is a symbolic link, `lstat` tells you about the link, not the file to which it refers. If `lstat` tells you that your new file is an ordinary file, not a symbolic link, and that it is owned by you, then you should be okay.

Listing 10.5 presents a function that tries to securely open a file in `/tmp`. The authors of this book have not had it audited professionally, nor are we professional security experts, so there's a good chance that it has a weakness, too. We do not recommend that you use this code without getting an audit, but it should at least convince you that writing secure code is tricky. To help dissuade you, we've deliberately made the interface difficult to use in real programs. Error checking is an important part of writing secure software, so we've included error-checking logic in this example.

Listing 10.5 **(*temp-file.c*) Create a Temporary File**

```
#include <fcntl.h>
#include <stdlib.h>
#include <sys/stat.h>
#include <unistd.h>

/* Returns the file descriptor for a newly created temporary file.
   The temporary file will be readable and writable by the effective
   user ID of the current process but will not be readable or
   writable by anybody else.

   Returns -1 if the temporary file could not be created.  */

int secure_temp_file ()
{
  /* This file descriptor points to /dev/random and allows us to get
     a good source of random bits.  */
  static int random_fd = -1;
  /* A random integer.  */
  unsigned int random;
  /* A buffer, used to convert from a numeric to a string
     representation of random.  This buffer has fixed size, meaning
     that we potentially have a buffer overrun bug if the integers on
     this machine have a *lot* of bits.  */
  char filename[128];
  /* The file descriptor for the new temporary file.  */
  int fd;
  /* Information about the newly created file.  */
  struct stat stat_buf;

  /* If we haven't already opened /dev/random, do so now.  (This is
     not threadsafe.)  */
  if (random_fd == -1) {
```

```
    /* Open /dev/random.  Note that we're assuming that /dev/random
       really is a source of random bits, not a file full of zeros
       placed there by an attacker.  */
    random_fd = open ("/dev/random", O_RDONLY);
    /* If we couldn't open /dev/random, give up.  */
    if (random_fd == -1)
      return -1;
  }

  /* Read an integer from /dev/random.  */
  if (read (random_fd, &random, sizeof (random)) !=
      sizeof (random))
    return -1;
  /* Create a filename out of the random number.  */
  sprintf (filename, "/tmp/%u", random);
  /* Try to open the file.  */
  fd = open (filename,
             /* Use O_EXECL, even though it doesn't work under NFS.  */
             O_RDWR | O_CREAT | O_EXCL,
             /* Make sure nobody else can read or write the file.  */
             S_IRUSR | S_IWUSR);
  if (fd == -1)
    return -1;

  /* Call lstat on the file, to make sure that it is not a symbolic
     link.  */
  if (lstat (filename, &stat_buf) == -1)
    return -1;
  /* If the file is not a regular file, someone has tried to trick
     us.  */
  if (!S_ISREG (stat_buf.st_mode))
    return -1;
  /* If we don't own the file, someone else might remove it, read it,
     or change it while we're looking at it.  */
  if (stat_buf.st_uid != geteuid () || stat_buf.st_gid != getegid ())
    return -1;
  /* If there are any more permission bits set on the file,
     something's fishy.  */
  if ((stat_buf.st_mode & ~(S_IRUSR | S_IWUSR)) != 0)
    return -1;

  return fd;
}
```

This function calls `open` to create the file and then calls `lstat` a few lines later to make sure that the file is not a symbolic link. If you're thinking carefully, you'll realize that there seems to be a race condition at this point. In particular, an attacker could remove the file and replace it with a symbolic link between the time we call `open` and the

time we call `lstat`. That won't harm us directly because we already have an open file descriptor to the newly created file, but it will cause us to indicate an error to our caller. This attack doesn't create any direct harm, but it does make it impossible for our program to get its work done. Such an attack is called a *denial-of-service* (*DoS*) attack.

Fortunately, the sticky bit comes to the rescue. Because the sticky bit is set on `/tmp`, nobody else can remove files from that directory. Of course, `root` can still remove files from `/tmp`, but if the attacker has `root` privilege, there's nothing you can do to protect your program.

If you choose to assume competent system administration, then `/tmp` will not be mounted via NFS. And if the system administrator was foolish enough to mount `/tmp` over NFS, then there's a good chance that the sticky bit isn't set, either. So, for most practical purposes, we think it's safe to use `mkstemp`. But you should be aware of these issues, and you should definitely not rely on `O_EXCL` to work correctly if the directory in use is not `/tmp`—nor you should rely on the sticky bit being set anywhere else.

10.6.3 Using *system* or *popen*

The third common security hole that every programmer should bear in mind involves using the shell to execute other programs. As a toy example, let's consider a dictionary server. This program is designed to accept connections via the Internet. Each client sends a word, and the server tells it whether that is a valid English word. Because every GNU/Linux system comes with a list of about 45,000 English words in `/usr/dict/words`, an easy way to build this server is to invoke the `grep` program, like this:

```
% grep -x word /usr/dict/words
```

Here, *`word`* is the word that the user is curious about. The exit code from `grep` will tell you whether that word appears in `/usr/dict/words`.[10]

Listing 10.6 shows how you might try to code the part of the server that invokes `grep`:

Listing 10.6 **(*grep-dictionary.c*) Search for a Word in the Dictionary**

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

/* Returns a nonzero value if and only if the WORD appears in
   /usr/dict/words.  */

int grep_for_word (const char* word)
{
  size_t length;
  char* buffer;
  int exit_code;
```

10. If you don't know about `grep`, you should look at the manual pages. It's an incredibly useful program.

```
/* Build up the string 'grep -x WORD /usr/dict/words'.  Allocate the
     string dynamically to avoid buffer overruns.  */
  length =
    strlen ("grep -x ") + strlen (word) + strlen (" /usr/dict/words") + 1;
  buffer = (char*) malloc (length);
  sprintf (buffer, "grep -x %s /usr/dict/words", word);

  /* Run the command.  */
  exit_code = system (buffer);
  /* Free the buffer.  */
  free (buffer);
  /* If grep returned 0, then the word was present in the
     dictionary.  */
  return exit_code == 0;
}
```

Note that by calculating the number of characters we need and then allocating the buffer dynamically, we're sure to be safe from buffer overruns.

Unfortunately, the use of the `system` function (described in Chapter 3, "Processes," Section 3.2.1, "Using `system`") is unsafe. This function invokes the standard system shell to run the command and then returns the exit value. But what happens if a malicious hacker sends a "word" that is actually the following line or a similar string?

```
foo /dev/null; rm -rf /
```

In that case, the server will execute this command:

```
grep -x foo /dev/null; rm -rf / /usr/dict/words
```

Now the problem is obvious. The user has turned one command, ostensibly the invocation of `grep`, into two commands because the shell treats a semicolon as a command separator. The first command is still a harmless invocation of `grep`, but the second removes all files on the entire system! Even if the server is not running as `root`, all the files that can be removed by the user running the server will be removed. The same problem can arise with `popen` (described in Section 5.4.4, "`popen` and `pclose`"), which creates a pipe between the parent and child process but still uses the shell to run the command.

There are two ways to avoid these problems. One is to use the `exec` family of functions instead of `system` or `popen`. That solution avoids the problem because characters that the shell treats specially (such as the semicolon in the previous command) are not treated specially when they appear in the argument list to an `exec` call. Of course, you give up the convenience of `system` and `popen`.

The other alternative is to validate the string to make sure that it is benign. In the dictionary server example, you would make sure that the word provided contains only alphabetic characters, using the `isalpha` function. If it doesn't contain any other characters, there's no way to trick the shell into executing a second command. Don't implement the check by looking for dangerous and unexpected characters; it's always safer to explicitly check for the characters that you know are safe rather than try to anticipate all the characters that might cause trouble.

11

A Sample GNU/Linux Application

This chapter is where it all comes together. We'll describe and implement a complete GNU/Linux program that incorporates many of the techniques described in this book. The program provides information about the system it's running on via a Web interface.

The program is a complete demonstration of some of the methods we've described for GNU/Linux programming and illustrated in shorter programs. This program is written more like "real-world" code, unlike most of the code listings that we presented in previous chapters. It can serve as a jumping-off point for your own GNU/Linux programs.

11.1 Overview

The example program is part of a system for monitoring a running GNU/Linux system. It includes these features:

- The program incorporates a minimal Web server. Local or remote clients access system information by requesting Web pages from the server via HTTP.
- The program does not serve static HTML pages. Instead, the pages are generated on the fly by modules, each of which provides a page summarizing one aspect of the system's state.

- Modules are not linked statically into the server executable. Instead, they are loaded dynamically from shared libraries. Modules can be added, removed, or replaced while the server is running.
- The server services each connection in a child process. This enables the server to remain responsive even when individual requests take a while to complete, and it shields the server from failures in modules.
- The server does not require superuser privilege to run (as long as it is not run on a privileged port). However, this limits the system information that it can collect.

We provide four sample modules that demonstrate how modules might be written. They further illustrate some of the techniques for gathering system information presented previously in this book. The `time` module demonstrates using the `gettimeofday` system call. The `issue` module demonstrates low-level I/O and the `sendfile` system call. The `diskfree` module demonstrates the use of `fork`, `exec`, and `dup2` by running a command in a child process. The `processes` module demonstrates the use of the `/proc` file system and various system calls.

11.1.1 Caveats

This program has many of the features you'd expect in an application program, such as command-line parsing and error checking. At the same time, we've made some simplifications to improve readability and to focus on the GNU/Linux-specific topics discussed in this book. Bear in mind these caveats as you examine the code.

- We don't attempt to provide a full implementation of HTTP. Instead, we implement just enough for the server to interact with Web clients. A real-world program either would provide a more complete HTTP implementation or would interface with one of the various excellent Web server implementations[1] available instead of providing HTTP services directly.
- Similarly, we don't aim for full compliance with HTML specifications (see `http://www.w3.org/MarkUp/`). We generate simple HTML output that can be handled by popular Web browsers.
- The server is not tuned for high performance or minimum resource usage. In particular, we intentionally omit some of the network configuration code that you would expect in a Web server. This topic is outside the scope of this book. See one of the many excellent references on network application development, such as *UNIX Network Programming, Volume 1: Networking APIs—Sockets and XTI,* by W. Richard Stevens (Prentice Hall, 1997), for more information.

1. The most popular open source Web server for GNU/Linux is the Apache server, available from `http://www.apache.org`.

- We make no attempt to regulate the resources (number of processes, memory use, and so on) consumed by the server or its modules. Many multiprocess Web server implementations service connections using a fixed pool of processes rather than creating a new child process for each connection.
- The server loads the shared library for a server module each time it is requested and then immediately unloads it when the request has been completed. A more efficient implementation would probably cache loaded modules.

HTTP

The *Hypertext Transport Protocol* (*HTTP*) is used for communication between Web clients and servers. The client connects to the server by establishing a connection to a well-known port (usually port 80 for Internet Web servers, but any port may be used). HTTP requests and headers are composed of plain text.

Once connected, the client sends a request to the server. A typical request is `GET /page HTTP/1.0`. The GET method indicates that the client is requesting that the server send it a Web page. The second element is the path to that page on the server. The third element is the protocol and version. Subsequent lines contain header fields, formatted similarly to email headers, which contain extra information about the client. The header ends with a blank line.

The server sends back a response indicating the result of processing the request. A typical response is `HTTP/1.0 200 OK`. The first element is the protocol version. The next two elements indicate the result; in this case, result `200` indicates that the request was processed successfully. Subsequent lines contain header fields, formatted similarly to email headers. The header ends with a blank line. The server may then send arbitrary data to satisfy the request.

Typically, the server responds to a page request by sending back HTML source for the Web page. In this case, the response headers will include `Content-type: text/html`, indicating that the result is HTML source. The HTML source follows immediately after the header.

See the HTTP specification at `http://www.w3.org/Protocols/` for more information.

11.2 Implementation

All but the very smallest programs written in C require careful organization to preserve the modularity and maintainability of the source code. This program is divided into four main source files.

Each source file exports functions or variables that may be accessed by the other parts of the program. For simplicity, all exported functions and variables are declared in a single header file, `server.h` (see Listing 11.1), which is included by the other files. Functions that are intended for use within a single compilation unit only are declared `static` and are not declared in `server.h`.

Listing 11.1 ***(server.h)* Function and Variable Declarations**

```
#ifndef SERVER_H
#define SERVER_H

#include <netinet/in.h>
#include <sys/types.h>

/*** Symbols defined in common.c  ***********************************/

/* The name of this program.  */
extern const char* program_name;

/* If nonzero, print verbose messages.  */
extern int verbose;

/* Like malloc, except aborts the program if allocation fails.  */
extern void* xmalloc (size_t size);

/* Like realloc, except aborts the program if allocation fails.  */
extern void* xrealloc (void* ptr, size_t size);

/* Like strdup, except aborts the program if allocation fails.  */
extern char* xstrdup (const char* s);

/* Print an error message for a failed call OPERATION, using the value
   of errno, and end the program.  */
extern void system_error (const char* operation);

/* Print an error message for failure involving CAUSE, including a
   descriptive MESSAGE, and end the program.  */
extern void error (const char* cause, const char* message);

/* Return the directory containing the running program's executable.
   The return value is a memory buffer that the caller must deallocate
   using free.  This function calls abort on failure.  */
extern char* get_self_executable_directory ();


/*** Symbols defined in module.c  ***********************************/

/* An instance of a loaded server module.  */
struct server_module {
  /* The shared library handle corresponding to the loaded module.  */
  void* handle;
  /* A name describing the module.  */
  const char* name;
  /* The function that generates the HTML results for this module.  */
void (* generate_function) (int);
};
```

```
/* The directory from which modules are loaded.  */
extern char* module_dir;

/* Attempt to load a server module with the name MODULE_PATH.  If a
   server module exists with this path, loads the module and returns a
   server_module structure representing it.  Otherwise, returns NULL.  */
extern struct server_module* module_open (const char* module_path);

/* Close a server module and deallocate the MODULE object.  */
extern void module_close (struct server_module* module);


/*** Symbols defined in server.c.  ***********************************/

/* Run the server on LOCAL_ADDRESS and PORT.  */
extern void server_run (struct in_addr local_address, uint16_t port);


#endif  /* SERVER_H */
```

11.2.1 Common Functions

`common.c` (see Listing 11.2) contains functions of general utility that are used throughout the program.

Listing 11.2 **(*common.c*) General Utility Functions**

```
#include <errno.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <unistd.h>

#include "server.h"

const char* program_name;

int verbose;

void* xmalloc (size_t size)
{
  void* ptr = malloc (size);
  /* Abort if the allocation failed.  */
  if (ptr == NULL)
    abort ();
  else
    return ptr;
}
```

continues

Listing 11.2 **Continued**

```
void* xrealloc (void* ptr, size_t size)
{
  ptr = realloc (ptr, size);
  /* Abort if the allocation failed.  */
  if (ptr == NULL)
    abort ();
  else
    return ptr;
}

char* xstrdup (const char* s)
{
  char* copy = strdup (s);
  /* Abort if the allocation failed.  */
  if (copy == NULL)
    abort ();
  else
    return copy;
}

void system_error (const char* operation)
{
  /* Generate an error message for errno.  */
  error (operation, strerror (errno));
}

void error (const char* cause, const char* message)
{
  /* Print an error message to stderr.  */
  fprintf (stderr, "%s: error: (%s) %s\n", program_name, cause, message);
  /* End the program.  */
  exit (1);
}

char* get_self_executable_directory ()
{
  int rval;
  char link_target[1024];
  char* last_slash;
  size_t result_length;
  char* result;

  /* Read the target of the symbolic link /proc/self/exe.  */
  rval = readlink ("/proc/self/exe", link_target, sizeof (link_target));
  if (rval == -1)
    /* The call to readlink failed, so bail.  */
    abort ();
  else
```

```
    /* NUL-terminate the target.  */
    link_target[rval] = '\0';
  /* We want to trim the name of the executable file, to obtain the
     directory that contains it.  Find the rightmost slash.  */
  last_slash = strrchr (link_target, '/');
  if (last_slash == NULL || last_slash == link_target)
    /* Something strange is going on.  */
    abort ();
  /* Allocate a buffer to hold the resulting path.  */
  result_length = last_slash - link_target;
  result = (char*) xmalloc (result_length + 1);
  /* Copy the result.  */
  strncpy (result, link_target, result_length);
  result[result_length] = '\0';
  return result;
}
```

You could use these functions in other programs as well; the contents of this file might be included in a common code library that is shared among many projects:

- `xmalloc`, `xrealloc`, and `xstrdup` are error-checking versions of the C library functions `malloc`, `realloc`, and `strdup`, respectively. Unlike the standard versions, which return a null pointer if the allocation fails, these functions immediately abort the program when insufficient memory is available.

  Early detection of memory allocation failure is a good idea. Otherwise, failed allocations introduce null pointers at unexpected places into the program. Because allocation failures are not easy to reproduce, debugging such problems can be difficult. Allocation failures are usually catastrophic, so aborting the program is often an acceptable course of action.

- The `error` function is for reporting a fatal program error. It prints a message to `stderr` and ends the program. For errors caused by failed system calls or library calls, `system_error` generates part of the error message from the value of `errno` (see Section 2.2.3, "Error Codes from System Calls," in Chapter 2, "Writing Good GNU/Linux Software").

- `get_self_executable_directory` determines the directory containing the executable file being run in the current process. The directory path can be used to locate other components of the program, which are installed in the same place at runtime. This function works by examining the symbolic link `/proc/self/exe` in the `/proc` file system (see Section 7.2.1, "`/proc/self`," in Chapter 7, "The `/proc` File System").

In addition, `common.c` defines two useful global variables:

- The value of `program_name` is the name of the program being run, as specified in its argument list (see Section 2.1.1, "The Argument List," in Chapter 2). When the program is invoked from the shell, this is the path and name of the program as the user entered it.

- The variable `verbose` is nonzero if the program is running in verbose mode. In this case, various parts of the program print progress messages to `stdout`.

11.2.2 Loading Server Modules

`module.c` (see Listing 11.3) provides the implementation of dynamically loadable server modules. A loaded server module is represented by an instance of `struct server_module`, which is defined in `server.h`.

Listing 11.3 **(*module.c*) Server Module Loading and Unloading**

```
#include <dlfcn.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

#include "server.h"

char* module_dir;

struct server_module* module_open (const char* module_name)
{
  char* module_path;
  void* handle;
  void (* module_generate) (int);
  struct server_module* module;

  /* Construct the full path of the module shared library we'll try to
     load.  */
  module_path =
    (char*) xmalloc (strlen (module_dir) + strlen (module_name) + 2);
  sprintf (module_path, "%s/%s", module_dir, module_name);

  /* Attempt to open MODULE_PATH as a shared library.  */
  handle = dlopen (module_path, RTLD_NOW);
  free (module_path);
  if (handle == NULL) {
    /* Failed; either this path doesn't exist or it isn't a shared
       library.  */
    return NULL;
  }

  /* Resolve the module_generate symbol from the shared library.  */
  module_generate = (void (*) (int)) dlsym (handle, "module_generate");
  /* Make sure the symbol was found.  */
  if (module_generate == NULL) {
```

```
    /* The symbol is missing.  While this is a shared library, it
       probably isn't a server module.  Close up and indicate failure.  */
    dlclose (handle);
    return NULL;
  }

  /* Allocate and initialize a server_module object.  */
  module = (struct server_module*) xmalloc (sizeof (struct server_module));
  module->handle = handle;
  module->name = xstrdup (module_name);
  module->generate_function = module_generate;
  /* Return it, indicating success.  */
  return module;
}

void module_close (struct server_module* module)
{
  /* Close the shared library.  */
  dlclose (module->handle);
  /* Deallocate the module name.  */
  free ((char*) module->name);
  /* Deallocate the module object.  */
  free (module);
}
```

Each module is a shared library file (see Section 2.3.2, "Shared Libraries," in Chapter 2) and must define and export a function named `module_generate`. This function generates an HTML Web page and writes it to the client socket file descriptor passed as its argument.

`module.c` contains two functions:

- `module_open` attempts to load a server module with a given name. The name normally ends with the `.so` extension because server modules are implemented as shared libraries. This function opens the shared library with `dlopen` and resolves a symbol named `module_generate` from the library with `dlsym` (see Section 2.3.6, "Dynamic Loading and Unloading," in Chapter 2). If the library can't be opened, or if `module_generate` isn't a name exported by the library, the call fails and `module_open` returns a null pointer. Otherwise, it allocates and returns a module object.
- `module_close` closes the shared library corresponding to the server module and deallocates the `struct server_module` object.

`module.c` also defines a global variable `module_dir`. This is the path of the directory in which `module_open` attempts to find shared libraries corresponding to server modules.

11.2.3 The Server

`server.c` (see Listing 11.4) is the implementation of the minimal HTTP server.

Listing 11.4 **(*server.c*) Server Implementation**

```
#include <arpa/inet.h>
#include <assert.h>
#include <errno.h>
#include <netinet/in.h>
#include <signal.h>
#include <stdio.h>
#include <string.h>
#include <sys/types.h>
#include <sys/socket.h>
#include <sys/wait.h>
#include <unistd.h>

#include "server.h"

/* HTTP response and header for a successful request.  */

static char* ok_response =
  "HTTP/1.0 200 OK\n"
  "Content-type: text/html\n"
  "\n";

/* HTTP response, header, and body, indicating that we didn't
   understand the request.  */

static char* bad_request_response =
  "HTTP/1.0 400 Bad Request\n"
  "Content-type: text/html\n"
  "\n"
  "<html>\n"
  " <body>\n"
  "  <h1>Bad Request</h1>\n"
  "  <p>This server did not understand your request.</p>\n"
  " </body>\n"
  "</html>\n";

/* HTTP response, header, and body template, indicating that the
   requested document was not found.  */

static char* not_found_response_template =
  "HTTP/1.0 404 Not Found\n"
  "Content-type: text/html\n"
  "\n"
  "<html>\n"
  " <body>\n"
  "  <h1>Not Found</h1>\n"
```

```
  "  <p>The requested URL %s was not found on this server.</p>\n"
  " </body>\n"
  "</html>\n";

/* HTTP response, header, and body template, indicating that the
   method was not understood.  */

static char* bad_method_response_template =
  "HTTP/1.0 501 Method Not Implemented\n"
  "Content-type: text/html\n"
  "\n"
  "<html>\n"
  " <body>\n"
  "  <h1>Method Not Implemented</h1>\n"
  "  <p>The method %s is not implemented by this server.</p>\n"
  " </body>\n"
  "</html>\n";

/* Handler for SIGCHLD, to clean up child processes that have
   terminated.  */

static void clean_up_child_process (int signal_number)
{
  int status;
  wait (&status);
}

/* Process an HTTP "GET" request for PAGE, and send the results to the
   file descriptor CONNECTION_FD.  */

static void handle_get (int connection_fd, const char* page)
{
  struct server_module* module = NULL;

  /* Make sure the requested page begins with a slash and does not
     contain any additional slashes -- we don't support any
     subdirectories.  */
  if (*page == '/' && strchr (page + 1, '/') == NULL) {
    char module_file_name[64];

    /* The page name looks OK.  Construct the module name by appending
       ".so" to the page name.  */
    snprintf (module_file_name, sizeof (module_file_name),
              "%s.so", page + 1);
    /* Try to open the module.  */
    module = module_open (module_file_name);
  }

  if (module == NULL) {
    /* Either the requested page was malformed, or we couldn't open a
       module with the indicated name.  Either way, return the HTTP
       response 404, Not Found.  */
```

continues

Listing 11.4 **Continued**

```
    char response[1024];

    /* Generate the response message.  */
    snprintf (response, sizeof (response), not_found_response_template, page);
    /* Send it to the client.  */
    write (connection_fd, response, strlen (response));
  }
  else {
    /* The requested module was loaded successfully.  */

    /* Send the HTTP response indicating success, and the HTTP header
       for an HTML page.  */
    write (connection_fd, ok_response, strlen (ok_response));
    /* Invoke the module, which will generate HTML output and send it
       to the client file descriptor.  */
    (*module->generate_function) (connection_fd);
    /* We're done with the module.  */
    module_close (module);
  }
}

/* Handle a client connection on the file descriptor CONNECTION_FD.  */

static void handle_connection (int connection_fd)
{
  char buffer[256];
  ssize_t bytes_read;

  /* Read some data from the client.  */
  bytes_read = read (connection_fd, buffer, sizeof (buffer) - 1);
  if (bytes_read > 0) {
    char method[sizeof (buffer)];
    char url[sizeof (buffer)];
    char protocol[sizeof (buffer)];

    /* Some data was read successfully.  NUL-terminate the buffer so
       we can use string operations on it.  */
    buffer[bytes_read] = '\0';
    /* The first line the client sends is the HTTP request, which is
       composed of a method, the requested page, and the protocol
       version.  */
    sscanf (buffer, "%s %s %s", method, url, protocol);
    /* The client may send various header information following the
       request.  For this HTTP implementation, we don't care about it.
       However, we need to read any data the client tries to send.  Keep
       on reading data until we get to the end of the header, which is
       delimited by a blank line.  HTTP specifies CR/LF as the line
       delimiter.  */
    while (strstr (buffer, "\r\n\r\n") == NULL)
```

```
      bytes_read = read (connection_fd, buffer, sizeof (buffer));
    /* Make sure the last read didn't fail.  If it did, there's a
       problem with the connection, so give up.  */
    if (bytes_read == -1) {
      close (connection_fd);
      return;
    }
    /* Check the protocol field.  We understand HTTP versions 1.0 and
       1.1.  */
    if (strcmp (protocol, "HTTP/1.0") && strcmp (protocol, "HTTP/1.1")) {
      /* We don't understand this protocol.  Report a bad response.  */
      write (connection_fd, bad_request_response,
             sizeof (bad_request_response));
    }
    else if (strcmp (method, "GET")) {
      /* This server only implements the GET method.  The client
         specified some other method, so report the failure.  */
      char response[1024];

      snprintf (response, sizeof (response),
                bad_method_response_template, method);
      write (connection_fd, response, strlen (response));
    }
    else
      /* A valid request.  Process it.  */
      handle_get (connection_fd, url);
  }
  else if (bytes_read == 0)
    /* The client closed the connection before sending any data.
       Nothing to do.  */
    ;
  else
    /* The call to read failed.  */
    system_error ("read");
}


void server_run (struct in_addr local_address, uint16_t port)
{
  struct sockaddr_in socket_address;
  int rval;
  struct sigaction sigchld_action;
  int server_socket;

  /* Install a handler for SIGCHLD that cleans up child processes that
     have terminated.  */
  memset (&sigchld_action, 0, sizeof (sigchld_action));
  sigchld_action.sa_handler = &clean_up_child_process;
  sigaction (SIGCHLD, &sigchld_action, NULL);
```

continues

Listing 11.4 **Continued**

```
/* Create a TCP socket.  */
server_socket = socket (PF_INET, SOCK_STREAM, 0);
if (server_socket == -1)
  system_error ("socket");
/* Construct a socket address structure for the local address on
   which we want to listen for connections.  */
memset (&socket_address, 0, sizeof (socket_address));
socket_address.sin_family = AF_INET;
socket_address.sin_port = port;
socket_address.sin_addr = local_address;
/* Bind the socket to that address.  */
rval = bind (server_socket, &socket_address, sizeof (socket_address));
if (rval != 0)
  system_error ("bind");
/*  Instruct the socket to accept connections.  */
rval = listen (server_socket, 10);
if (rval != 0)
  system_error ("listen");

if (verbose) {
  /* In verbose mode, display the local address and port number
     we're listening on.  */
  socklen_t address_length;

  /* Find the socket's local address.  */
  address_length = sizeof (socket_address);
  rval = getsockname (server_socket, &socket_address, &address_length);
  assert (rval == 0);
  /* Print a message.  The port number needs to be converted from
     network byte order (big endian) to host byte order.  */
  printf ("server listening on %s:%d\n",
          inet_ntoa (socket_address.sin_addr),
          (int) ntohs (socket_address.sin_port));
}

/* Loop forever, handling connections.  */
while (1) {
  struct sockaddr_in remote_address;
  socklen_t address_length;
  int connection;
  pid_t child_pid;

  /* Accept a connection.  This call blocks until a connection is
     ready.  */
  address_length = sizeof (remote_address);
  connection = accept (server_socket, &remote_address, &address_length);
  if (connection == -1) {
    /* The call to accept failed.  */
    if (errno == EINTR)
```

```
      /* The call was interrupted by a signal.  Try again.  */
      continue;
    else
      /* Something else went wrong.  */
      system_error ("accept");
  }

  /* We have a connection.  Print a message if we're running in
     verbose mode.  */
  if (verbose) {
    socklen_t address_length;

    /* Get the remote address of the connection.  */
    address_length = sizeof (socket_address);
    rval = getpeername (connection, &socket_address, &address_length);
    assert (rval == 0);
    /* Print a message.  */
    printf ("connection accepted from %s\n",
            inet_ntoa (socket_address.sin_addr));
  }

  /* Fork a child process to handle the connection.  */
  child_pid = fork ();
  if (child_pid == 0) {
    /* This is the child process.  It shouldn't use stdin or stdout,
       so close them.  */
    close (STDIN_FILENO);
    close (STDOUT_FILENO);
    /* Also this child process shouldn't do anything with the
       listening socket.  */
    close (server_socket);
    /* Handle a request from the connection.  We have our own copy
       of the connected socket descriptor.  */
    handle_connection (connection);
    /* All done; close the connection socket, and end the child
       process.  */
    close (connection);
    exit (0);
  }
  else if (child_pid > 0) {
    /* This is the parent process.  The child process handles the
       connection, so we don't need our copy of the connected socket
       descriptor.  Close it.  Then continue with the loop and
       accept another connection.  */
    close (connection);
  }
  else
    /* Call to fork failed.  */
    system_error ("fork");
 }
}
```

These are the functions in `server.c`:

- `server_run` is the main entry point for running the server. This function starts the server and begins accepting connections, and does not return unless a serious error occurs. The server uses a TCP stream server socket (see Section 5.5.3, "Servers," in Chapter 5, "Interprocess Communication").

  The first argument to `server_run` specifies the local address at which connections are accepted. A GNU/Linux computer may have multiple network addresses, and each address may be bound to a different network interface.[2] To restrict the server to accept connections from a particular interface, specify the corresponding network address. Specify the local address `INADDR_ANY` to accept connections for any local address.

  The second argument to `server_run` is the port number on which to accept connections. If the port number is already in use, or if it corresponds to a privileged port and the server is not being run with superuser privilege, the server fails. The special value 0 instructs Linux to select an unused port automatically. See the `inet` man page for more information about Internet-domain addresses and port numbers.

  The server handles each client connection in a child process created with `fork` (see Section 3.2.2, "Using `fork` and `exec`," in Chapter 3, "Processes"). The main (parent) process continues accepting new connections while existing ones are being serviced. The child process invokes `handle_connection` and then closes the connection socket and exits.

- `handle_connection` processes a single client connection, using the socket file descriptor passed as its argument. This function reads data from the socket and attempts to interpret this as an HTTP page request.

  The server processes only HTTP version 1.0 and version 1.1 requests. When faced with a different protocol or version, it responds by sending the HTTP result code 400 and the message `bad_request_response`. The server understands only the HTTP GET method. If the client requests any other method, the server responds by sending the HTTP result code 501 and the message `bad_method_response_template`.

- If the client sends a well-formed GET request, `handle_connection` calls `handle_get` to service it. This function attempts to load a server module with a name generated from the requested page. For example, if the client requests the page named information, it attempts to load a server module named `information.so`. If the module can't be loaded, `handle_get` sends the client the HTTP result code 404 and the message `not_found_response_template`.

2. Your computer might be configured to include such interfaces as `eth0`, an Ethernet card; `lo`, the local (loopback) network; or `ppp0`, a dial-up network connection.

If the client sends a page request that corresponds to a server module, `handle_get` sends a result code 200 header to the client, which indicates that the request was processed successfully and invokes the module's `module_generate` function. This function generates the HTML source for a Web page and sends it to the Web client.

- `server_run` installs `clean_up_child_process` as the signal handler for `SIGCHLD`. This function simply cleans up terminated child processes (see Section 3.4.4, "Cleaning Up Children Asynchronously," in Chapter 3).

11.2.4 The Main Program

`main.c` (see Listing 11.5) provides the `main` function for the server program. Its responsibility is to parse command-line options, detect and report command-line errors, and configure and run the server.

Listing 11.5 **(*main.c*) Main Server Program and Command-Line Parsing**

```
#include <assert.h>
#include <getopt.h>
#include <netdb.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <sys/stat.h>
#include <unistd.h>

#include "server.h"

/* Description of long options for getopt_long.  */

static const struct option long_options[] = {
  { "address",          1, NULL, 'a' },
  { "help",             0, NULL, 'h' },
  { "module-dir",       1, NULL, 'm' },
  { "port",             1, NULL, 'p' },
  { "verbose",          0, NULL, 'v' },
};

/* Description of short options for getopt_long.  */

static const char* const short_options = "a:hm:p:v";

/* Usage summary text.  */

static const char* const usage_template =
  "Usage: %s [ options ]\n"
  "  -a, --address ADDR        Bind to local address (by default, bind\n"
  "                              to all local addresses).\n"
```

continues

Listing 11.5 **Continued**

```
    "  -h, --help                Print this information.\n"
    "  -m, --module-dir DIR      Load modules from specified directory\n"
    "                              (by default, use executable directory).\n"
    "  -p, --port PORT           Bind to specified port.\n"
    "  -v, --verbose             Print verbose messages.\n";

/* Print usage information and exit.  If IS_ERROR is nonzero, write to
   stderr and use an error exit code.  Otherwise, write to stdout and
   use a non-error termination code.  Does not return.  */

static void print_usage (int is_error)
{
  fprintf (is_error ? stderr : stdout, usage_template, program_name);
  exit (is_error ? 1 : 0);
}

int main (int argc, char* const argv[])
{
  struct in_addr local_address;
  uint16_t port;
  int next_option;

  /* Store the program name, which we'll use in error messages.  */
  program_name = argv[0];

  /* Set defaults for options.  Bind the server to all local addresses,
     and assign an unused port automatically.  */
  local_address.s_addr = INADDR_ANY;
  port = 0;
  /* Don't print verbose messages.  */
  verbose = 0;
  /* Load modules from the directory containing this executable.  */
  module_dir = get_self_executable_directory ();
  assert (module_dir != NULL);

  /* Parse options.  */
  do {
    next_option =
      getopt_long (argc, argv, short_options, long_options, NULL);
    switch (next_option) {
    case 'a':
      /* User specified -a or --address.  */
      {
        struct hostent* local_host_name;

        /* Look up the hostname the user specified.  */
        local_host_name = gethostbyname (optarg);
        if (local_host_name == NULL || local_host_name->h_length == 0)
```

```
      /* Could not resolve the name.  */
      error (optarg, "invalid host name");
    else
      /* Hostname is OK, so use it.  */
      local_address.s_addr =
        *((int*) (local_host_name->h_addr_list[0]));
  }
  break;

case 'h':
  /* User specified -h or --help.  */
  print_usage (0);

case 'm':
  /* User specified -m or --module-dir.  */
  {
    struct stat dir_info;

    /* Check that it exists.  */
    if (access (optarg, F_OK) != 0)
      error (optarg, "module directory does not exist");
    /* Check that it is accessible.  */
    if (access (optarg, R_OK | X_OK) != 0)
      error (optarg, "module directory is not accessible");
    /* Make sure that it is a directory.  */
    if (stat (optarg, &dir_info) != 0 || !S_ISDIR (dir_info.st_mode))
      error (optarg, "not a directory");
    /* It looks OK, so use it.  */
    module_dir = strdup (optarg);
  }
  break;

case 'p':
  /* User specified -p or --port.  */
  {
    long value;
    char* end;

    value = strtol (optarg, &end, 10);
    if (*end != '\0')
      /* The user specified nondigits in the port number.  */
      print_usage (1);
    /* The port number needs to be converted to network (big endian)
       byte order.  */
    port = (uint16_t) htons (value);
  }
  break;

case 'v':
  /* User specified -v or --verbose.  */
  verbose = 1;
  break;
```

continues

Listing 11.5 **Continued**

```
      case '?':
        /* User specified an unrecognized option.  */
        print_usage (1);

      case -1:
        /* Done with options.  */
        break;

      default:
        abort ();
      }
    } while (next_option != -1);

    /* This program takes no additional arguments.  Issue an error if the
       user specified any.  */
    if (optind != argc)
      print_usage (1);

    /* Print the module directory, if we're running verbose.  */
    if (verbose)
      printf ("modules will be loaded from %s\n", module_dir);

    /* Run the server.  */
    server_run (local_address, port);

    return 0;
  }
```

`main.c` contains these functions:

- `main` invokes `getopt_long` (see Section 2.1.3, "Using `getopt_long`," in Chapter 2) to parse command-line options. It provides both long and short option forms, the former in the `long_options` array and the latter in the `short_options` string.

  The default value for the server port is 0 and for a local address is `INADDR_ANY`. These can be overridden by the `--port` (`-p`) and `--address` (`-a`) options, respectively. If the user specifies an address, `main` calls the library function `gethostbyname` to convert it to a numerical Internet address.[3]

  The default value for the directory from which to load server modules is the directory containing the server executable, as determined by `get_self_executable_directory`. The user may override this with the `--module-dir` (`-m`) option; `main` makes sure that the specified directory is accessible.

  By default, verbose messages are not printed. The user may enable them by specifying the `--verbose` (`-v`) option.

3. `gethostbyname` performs name resolution using DNS, if necessary.

- If the user specifies the `--help` (`-h`) option or specifies invalid options, `main` invokes `print_usage`, which prints a usage summary and exits.

11.3 Modules

We provide four modules to demonstrate the kind of functionality you could implement using this server implementation. Implementing your own server module is as simple as defining a `module_generate` function to return the appropriate HTML text.

11.3.1 Show Wall-Clock Time

The `time.so` module (see Listing 11.6) generates a simple page containing the server's local wall-clock time. This module's `module_generate` calls `gettimeofday` to obtain the current time (see Section 8.7, "`gettimeofday`: Wall-Clock Time," in Chapter 8, "Linux System Calls") and uses `localtime` and `strftime` to generate a text representation of it. This representation is embedded in the HTML template `page_template`.

Listing 11.6 **(*time.c*) Server Module to Show Wall-Clock Time**

```
#include <assert.h>
#include <stdio.h>
#include <sys/time.h>
#include <time.h>

#include "server.h"

/* A template for the HTML page this module generates.  */

static char* page_template =
  "<html>\n"
  " <head>\n"
  "  <meta http-equiv=\"refresh\" content=\"5\">\n"
  " </head>\n"
  " <body>\n"
  "  <p>The current time is %s.</p>\n"
  " </body>\n"
  "</html>\n";

void module_generate (int fd)
{
  struct timeval tv;
  struct tm* ptm;
  char time_string[40];
  FILE* fp;

  /* Obtain the time of day, and convert it to a tm struct.  */
  gettimeofday (&tv, NULL);
  ptm = localtime (&tv.tv_sec);
```

continues

Listing 11.6 **Continued**

```
  /* Format the date and time, down to a single second.  */
  strftime (time_string, sizeof (time_string), "%H:%M:%S", ptm);

  /* Create a stream corresponding to the client socket file
     descriptor.  */
  fp = fdopen (fd, "w");
  assert (fp != NULL);
  /* Generate the HTML output.  */
  fprintf (fp, page_template, time_string);
  /* All done; flush the stream.  */
  fflush (fp);
}
```

This module uses standard C library I/O routines for convenience. The `fdopen` call generates a stream pointer (`FILE*`) corresponding to the client socket file descriptor (see Section B.4, "Relation to Standard C Library I/O Functions," in Appendix B, "Low-Level I/O"). The module writes to it using `fprintf` and flushes it using `fflush` to prevent the loss of buffered data when the socket is closed.

The HTML page returned by the `time.so` module includes a `<meta>` element in the page header that instructs clients to reload the page every 5 seconds. This way the client displays the current time.

11.3.2 Show the GNU/Linux Distribution

The `issue.so` module (see Listing 11.7) displays information about the GNU/Linux distribution running on the server. This information is traditionally stored in the file `/etc/issue`. This module sends the contents of this file, wrapped in a `<pre>` element of an HTML page.

Listing 11.7 **(*issue.c*) Server Module to Display GNU/Linux Distribution Information**

```
#include <fcntl.h>
#include <string.h>
#include <sys/sendfile.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

#include "server.h"

/* HTML source for the start of the page we generate.  */

static char* page_start =
  "<html>\n"
  " <body>\n"
```

```
  "  <pre>\n";

/* HTML source for the end of the page we generate.  */

static char* page_end =
  "  </pre>\n"
  " </body>\n"
  "</html>\n";

/* HTML source for the page indicating there was a problem opening
   /proc/issue.  */

static char* error_page =
  "<html>\n"
  " <body>\n"
  "  <p>Error: Could not open /proc/issue.</p>\n"
  " </body>\n"
  "</html>\n";

/* HTML source indicating an error.  */

static char* error_message = "Error reading /proc/issue.";

void module_generate (int fd)
{
  int input_fd;
  struct stat file_info;
  int rval;

  /* Open /etc/issue.  */
  input_fd = open ("/etc/issue", O_RDONLY);
  if (input_fd == -1)
    system_error ("open");
  /* Obtain file information about it.  */
  rval = fstat (input_fd, &file_info);

  if (rval == -1)
    /* Either we couldn't open the file or we couldn't read from it.  */
    write (fd, error_page, strlen (error_page));
  else {
    int rval;
    off_t offset = 0;

    /* Write the start of the page.  */
    write (fd, page_start, strlen (page_start));
    /* Copy from /proc/issue to the client socket.  */
    rval = sendfile (fd, input_fd, &offset, file_info.st_size);
    if (rval == -1)
      /* Something went wrong sending the contents of /proc/issue.
         Write an error message.  */
      write (fd, error_message, strlen (error_message));
```

continues

Listing 11.7 **Continued**

```
    /* End the page.  */
    write (fd, page_end, strlen (page_end));
  }

  close (input_fd);
}
```

The module first tries to open `/etc/issue`. If that file can't be opened, the module sends an error page to the client. Otherwise, the module sends the start of the HTML page, contained in `page_start`. Then it sends the contents of `/etc/issue` using `sendfile` (see Section 8.12, "`sendfile`: Fast Data Transfers," in Chapter 8). Finally, it sends the end of the HTML page, contained in `page_end`.

You can easily adapt this module to send the contents of another file. If the file contains a complete HTML page, simply omit the code that sends the contents of `page_start` and `page_end`. You could also adapt the main server implementation to serve static files, in the manner of a traditional Web server. Using `sendfile` provides an extra degree of efficiency.

11.3.3 Show Free Disk Space

The `diskfree.so` module (see Listing 11.8) generates a page displaying information about free disk space on the file systems mounted on the server computer. This generated information is simply the output of invoking the `df -h` command. Like `issue.so`, this module wraps the output in a `<pre>` element of an HTML page.

Listing 11.8 **(*diskfree.c*) Server Module to Display Information About Free Disk Space**

```
#include <stdlib.h>
#include <string.h>
#include <sys/types.h>
#include <sys/wait.h>
#include <unistd.h>

#include "server.h"

/* HTML source for the start of the page we generate.  */

static char* page_start =
  "<html>\n"
  " <body>\n"
  "  <pre>\n";
```

```
/* HTML source for the end of the page we generate.  */

static char* page_end =
  "  </pre>\n"
  " </body>\n"
  "</html>\n";

void module_generate (int fd)
{
  pid_t child_pid;
  int rval;

  /* Write the start of the page.  */
  write (fd, page_start, strlen (page_start));
  /* Fork a child process.  */
  child_pid = fork ();
  if (child_pid == 0) {
    /* This is the child process.  */
    /* Set up an argument list for the invocation of df.  */
    char* argv[] = { "/bin/df", "-h", NULL };

    /* Duplicate stdout and stderr to send data to the client socket.  */
    rval = dup2 (fd, STDOUT_FILENO);
    if (rval == -1)
      system_error ("dup2");
    rval = dup2 (fd, STDERR_FILENO);
    if (rval == -1)
      system_error ("dup2");
    /* Run df to show the free space on mounted file systems.  */
    execv (argv[0], argv);
    /* A call to execv does not return unless an error occurred.  */
    system_error ("execv");
  }
  else if (child_pid > 0) {
    /* This is the parent process.  Wait for the child process to
       finish.  */
    rval = waitpid (child_pid, NULL, 0);
    if (rval == -1)
      system_error ("waitpid");
  }
  else
    /* The call to fork failed.  */
    system_error ("fork");
  /* Write the end of the page.  */
  write (fd, page_end, strlen (page_end));
}
```

While `issue.so` sends the contents of a file using `sendfile`, this module must invoke a command and redirect its output to the client. To do this, the module follows these steps:

1. First, the module creates a child process using `fork` (see Section 3.2.2, "Using `fork` and `exec`," in Chapter 3).
2. The child process copies the client socket file descriptor to file descriptors `STDOUT_FILENO` and `STDERR_FILENO`, which correspond to standard output and standard error (see Section 2.1.4, "Standard I/O," in Chapter 2). The file descriptors are copied using the `dup2` call (see Section 5.4.3, "Redirecting the Standard Input, Output, and Error Streams," in Chapter 5). All further output from the process to either of these streams is sent to the client socket.
3. The child process invokes the `df` command with the `-h` option by calling `execv` (see Section 3.2.2, "Using `fork` and `exec`," in Chapter 3).
4. The parent process waits for the child process to exit by calling `waitpid` (see Section 3.4.2, "The `wait` System Calls," in Chapter 3).

You could easily adapt this module to invoke a different command and redirect its output to the client.

11.3.4 Summarize Running Processes

The `processes.so` module (see Listing 11.9) is a more extensive server module implementation. It generates a page containing a table that summarizes the processes currently running on the server system. Each process is represented by a row in the table that lists the PID, the executable program name, the owning user and group names, and the resident set size.

Listing 11.9 **(*processes.c*) Server Module to Summarize Processes**

```
#include <assert.h>
#include <dirent.h>
#include <fcntl.h>
#include <grp.h>
#include <pwd.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <sys/uio.h>
#include <unistd.h>

#include "server.h"

/* Set *UID and *GID to the owning user ID and group ID, respectively,
   of process PID.  Return 0 on success, nonzero on failure.  */
```

```
static int get_uid_gid (pid_t pid, uid_t* uid, gid_t* gid)
{
  char dir_name[64];
  struct stat dir_info;
  int rval;

  /* Generate the name of the process's directory in /proc.  */
  snprintf (dir_name, sizeof (dir_name), "/proc/%d", (int) pid);
  /* Obtain information about the directory.  */
  rval = stat (dir_name, &dir_info);
  if (rval != 0)
    /* Couldn't find it; perhaps this process no longer exists.  */
    return 1;
  /* Make sure it's a directory; anything else is unexpected.  */
  assert (S_ISDIR (dir_info.st_mode));

  /* Extract the IDs we want.  */
  *uid = dir_info.st_uid;
  *gid = dir_info.st_gid;
  return 0;
}

/* Return the name of user UID.  The return value is a buffer that the
   caller must allocate with free.  UID must be a valid user ID.  */

static char* get_user_name (uid_t uid)
{
  struct passwd* entry;

  entry = getpwuid (uid);
  if (entry == NULL)
    system_error ("getpwuid");
  return xstrdup (entry->pw_name);
}

/* Return the name of group GID.  The return value is a buffer that the
   caller must allocate with free.  GID must be a valid group ID.  */

static char* get_group_name (gid_t gid)
{
  struct group* entry;

  entry = getgrgid (gid);
  if (entry == NULL)
    system_error ("getgrgid");
  return xstrdup (entry->gr_name);
}
```

continues

Listing 11.9 **Continued**

```
/* Return the name of the program running in process PID, or NULL on
   error.  The return value is a newly allocated buffer which the caller
   must deallocate with free.  */

static char* get_program_name (pid_t pid)
{
  char file_name[64];
  char status_info[256];
  int fd;
  int rval;
  char* open_paren;
  char* close_paren;
  char* result;

  /* Generate the name of the "stat" file in the process's /proc
     directory, and open it.  */
  snprintf (file_name, sizeof (file_name), "/proc/%d/stat", (int) pid);
  fd = open (file_name, O_RDONLY);
  if (fd == -1)
    /* Couldn't open the stat file for this process.  Perhaps the
       process no longer exists.  */
    return NULL;
  /* Read the contents.  */
  rval = read (fd, status_info, sizeof (status_info) - 1);
  close (fd);
  if (rval <= 0)
    /* Couldn't read, for some reason; bail.  */
    return NULL;
  /* NUL-terminate the file contents.  */
  status_info[rval] = '\0';

  /* The program name is the second element of the file contents and is
     surrounded by parentheses.  Find the positions of the parentheses
     in the file contents.  */
  open_paren = strchr (status_info, '(');
  close_paren = strchr (status_info, ')');
  if (open_paren == NULL
      || close_paren == NULL
      || close_paren < open_paren)
    /* Couldn't find them; bail.  */
    return NULL;
  /* Allocate memory for the result.  */
  result = (char*) xmalloc (close_paren - open_paren);
  /* Copy the program name into the result.  */
  strncpy (result, open_paren + 1, close_paren - open_paren - 1);
  /* strncpy doesn't NUL-terminate the result, so do it here.  */
  result[close_paren - open_paren - 1] = '\0';
  /* All done.  */
  return result;
}
```

```
/* Return the resident set size (RSS), in kilobytes, of process PID.
   Return -1 on failure.  */

static int get_rss (pid_t pid)
{
  char file_name[64];
  int fd;
  char mem_info[128];
  int rval;
  int rss;

  /* Generate the name of the process's "statm" entry in its /proc
     directory.  */
  snprintf (file_name, sizeof (file_name), "/proc/%d/statm", (int) pid);
  /* Open it.  */
  fd = open (file_name, O_RDONLY);
  if (fd == -1)
    /* Couldn't open it; perhaps this process no longer exists.  */
    return -1;
  /* Read the file's contents.  */
  rval = read (fd, mem_info, sizeof (mem_info) - 1);
  close (fd);
  if (rval <= 0)
    /* Couldn't read the contents; bail.  */
    return -1;
  /* NUL-terminate the contents.  */
  mem_info[rval] = '\0';
  /* Extract the RSS.  It's the second item.  */
  rval = sscanf (mem_info, "%*d %d", &rss);
  if (rval != 1)
    /* The contents of statm are formatted in a way we don't understand.  */
    return -1;

  /* The values in statm are in units of the system's page size.
     Convert the RSS to kilobytes.  */
  return rss * getpagesize () / 1024;
}

/* Generate an HTML table row for process PID.  The return value is a
   pointer to a buffer that the caller must deallocate with free, or
   NULL if an error occurs.  */

static char* format_process_info (pid_t pid)
{
  int rval;
  uid_t uid;
  gid_t gid;
  char* user_name;
  char* group_name;
  int rss;
  char* program_name;
```

continues

Listing 11.9 **Continued**

```
  size_t result_length;
  char* result;

  /* Obtain the process's user and group IDs.  */
  rval = get_uid_gid (pid, &uid, &gid);
  if (rval != 0)
    return NULL;
  /* Obtain the process's RSS.  */
  rss = get_rss (pid);
  if (rss == -1)
    return NULL;
  /* Obtain the process's program name.  */
  program_name = get_program_name (pid);
  if (program_name == NULL)
    return NULL;
  /* Convert user and group IDs to corresponding names.  */
  user_name = get_user_name (uid);
  group_name = get_group_name (gid);

  /* Compute the length of the string we'll need to hold the result, and
     allocate memory to hold it.  */
  result_length = strlen (program_name)
    + strlen (user_name) + strlen (group_name) + 128;
  result = (char*) xmalloc (result_length);
  /* Format the result.  */
  snprintf (result, result_length,
            "<tr><td align=\"right\">%d</td><td><tt>%s</tt></td><td>%s</td>"
            "<td>%s</td><td align=\"right\">%d</td></tr>\n",
            (int) pid, program_name, user_name, group_name, rss);
  /* Clean up.  */
  free (program_name);
  free (user_name);
  free (group_name);
  /* All done.  */
  return result;
}

/* HTML source for the start of the process listing page.  */

static char* page_start =
  "<html>\n"
  " <body>\n"
  "  <table cellpadding=\"4\" cellspacing=\"0\" border=\"1\">\n"
  "   <thead>\n"
  "    <tr>\n"
  "     <th>PID</th>\n"
  "     <th>Program</th>\n"
  "     <th>User</th>\n"
  "     <th>Group</th>\n"
```

```
  "     <th>RSS (KB)</th>\n"
  "    </tr>\n"
  "   </thead>\n"
  "   <tbody>\n";

/* HTML source for the end of the process listing page.  */

static char* page_end =
  "   </tbody>\n"
  "  </table>\n"
  " </body>\n"
  "</html>\n";

void module_generate (int fd)
{
  size_t i;
  DIR* proc_listing;

  /* Set up an iovec array.  We'll fill this with buffers that'll be
     part of our output, growing it dynamically as necessary.  */

  /* The number of elements in the array that we've used.  */
  size_t vec_length = 0;
  /* The allocated size of the array.  */
  size_t vec_size = 16;
  /* The array of iovcec elements.  */
  struct iovec* vec =
    (struct iovec*) xmalloc (vec_size * sizeof (struct iovec));

  /* The first buffer is the HTML source for the start of the page.  */
  vec[vec_length].iov_base = page_start;
  vec[vec_length].iov_len = strlen (page_start);
  ++vec_length;

  /* Start a directory listing for /proc.  */
  proc_listing = opendir ("/proc");
  if (proc_listing == NULL)
    system_error ("opendir");

  /* Loop over directory entries in /proc.  */
  while (1) {
    struct dirent* proc_entry;
    const char* name;
    pid_t pid;
    char* process_info;

    /* Get the next entry in /proc.  */
    proc_entry  = readdir (proc_listing);
    if (proc_entry == NULL)
      /* We've hit the end of the listing.  */
      break;
```

continues

Listing 11.9 **Continued**

```
    /* If this entry is not composed purely of digits, it's not a
       process directory, so skip it.  */
    name = proc_entry->d_name;
    if (strspn (name, "0123456789") != strlen (name))
      continue;
    /* The name of the entry is the process ID.  */
    pid = (pid_t) atoi (name);
    /* Generate HTML for a table row describing this process.  */
    process_info = format_process_info (pid);
    if (process_info == NULL)
      /* Something went wrong.  The process may have vanished while we
         were looking at it.  Use a placeholder row instead.  */
      process_info = "<tr><td colspan=\"5\">ERROR</td></tr>";

    /* Make sure the iovec array is long enough to hold this buffer
       (plus one more because we'll add an extra element when we're done
       listing processes).  If not, grow it to twice its current size.  */
    if (vec_length == vec_size - 1) {
      vec_size *= 2;
      vec = xrealloc (vec, vec_size * sizeof (struct iovec));
    }
    /* Store this buffer as the next element of the array.  */
    vec[vec_length].iov_base = process_info;
    vec[vec_length].iov_len = strlen (process_info);
    ++vec_length;
  }

  /* End the directory listing operation.  */
  closedir (proc_listing);

  /* Add one last buffer with HTML that ends the page.  */
  vec[vec_length].iov_base = page_end;
  vec[vec_length].iov_len = strlen (page_end);
  ++vec_length;

  /* Output the entire page to the client file descriptor all at once.  */
  writev (fd, vec, vec_length);

  /* Deallocate the buffers we created.  The first and last are static
     and should not be deallocated.  */
  for (i = 1; i < vec_length - 1; ++i)
    free (vec[i].iov_base);
  /* Deallocate the iovec array.  */
  free (vec);
}
```

Gathering process data and formatting it as an HTML table is broken down into several simpler operations:

- `get_uid_gid` extracts the IDs of the owning user and group of a process. To do this, the function invokes `stat` (see Section B.2, "`stat`," in Appendix B) on the process's subdirectory in `/proc` (see Section 7.2, "Process Entries," in Chapter 7). The user and group that own this directory are identical to the process's owning user and group.
- `get_user_name` returns the username corresponding to a UID. This function simply calls the C library function `getpwuid`, which consults the system's `/etc/passwd` file and returns a copy of the result. `get_group_name` returns the group name corresponding to a GID. It uses the `getgrgid` call.
- `get_program_name` returns the name of the program running in a specified process. This information is extracted from the `stat` entry in the process's directory under `/proc` (see Section 7.2, "Process Entries," in Chapter 7). We use this entry rather than examining the `exe` symbolic link (see Section 7.2.4, "Process Executable," in Chapter 7) or `cmdline` entry (see Section 7.2.2, "Process Argument List," in Chapter 7) because the latter two are inaccessible if the process running the server isn't owned by the same user as the process being examined. Also, reading from `stat` doesn't force Linux to page the process under examination back into memory, if it happens to be swapped out.
- `get_rss` returns the resident set size of a process. This information is available as the second element in the contents of the process's `statm` entry (see Section 7.2.6, "Process Memory Statistics," in Chapter 7) in its `/proc` subdirectory.
- `format_process_info` generates a string containing HTML elements for a single table row, representing a single process. After calling the functions listed previously to obtain this information, it allocates a buffer and generates HTML using `snprintf`.
- `module_generate` generates the entire HTML page, including the table. The output consists of one string containing the start of the page and the table (in `page_start`), one string for each table row (generated by `format_process_info`), and one string containing the end of the table and the page (in `page_end`).

  `module_generate` determines the PIDs of the processes running on the system by examining the contents of `/proc`. It obtains a listing of this directory using `opendir` and `readdir` (see Section B.6, "Reading Directory Contents," in Appendix B). It scans the contents, looking for entries whose names are composed entirely of digits; these are taken to be process entries.

  Potentially a large number of strings must be written to the client socket—one each for the page start and end, plus one for each process. If we were to write each string to the client socket file descriptor with a separate call to `write`, this would generate unnecessary network traffic because each string may be sent in a separate network packet.

To optimize packing of data into packets, we use a single call to `writev` instead (see Section B.3, "Vector Reads and Writes," in Appendix B). To do this, we must construct an array of `struct iovec` objects, `vec`. However, because we do not know the number of processes beforehand, we must start with a small array and expand it as new processes are added. The variable `vec_length` contains the number of elements of `vec` that are used, while `vec_size` contains the allocated size of `vec`. When `vec_length` is about to exceed `vec_size`, we expand `vec` to twice its size by calling `xrealloc`. When we're done with the vector write, we must deallocate all of the dynamically allocated strings pointed to by `vec`, and then `vec` itself.

11.4 Using the Server

If we were planning to distribute this program in source form, maintain it on an ongoing basis, or port it to other platforms, we probably would want to package it using GNU Automake and GNU Autoconf, or a similar configuration automation system. Such tools are outside the scope of this book; for more information about them, consult *GNU Autoconf, Automake, and Libtool* (by Vaughan, Elliston, Tromey, and Taylor, published by New Riders, 2000).

11.4.1 The *Makefile*

Instead of using Autoconf or a similar tool, we provide a simple `Makefile` compatible with GNU Make[4] so that it's easy to compile and link the server and its modules. The `Makefile` is shown in Listing 11.10. See the info page for GNU Make for details of the file's syntax.

Listing 11.10 **(*Makefile*) GNU Make Configuration File for Server Example**

```
### Configuration.  #####################################################

# Default C compiler options.
CFLAGS                = -Wall -g
# C source files for the server.
SOURCES               = server.c module.c common.c main.c
# Corresponding object files.
OBJECTS               = $(SOURCES:.c=.o)
# Server module shared library files.
MODULES               = diskfree.so issue.so processes.so time.so

### Rules.  ############################################################

# Phony targets don't correspond to files that are built; they're names
# for conceptual build targets.
.PHONY:         all clean
```

4. GNU Make comes installed on GNU/Linux systems.

```
# Default target: build everything.
all:            server $(MODULES)

# Clean up build products.
clean:
        rm -f $(OBJECTS) $(MODULES) server

# The main server program.  Link with -Wl,-export-dyanamic so
# dynamically loaded modules can bind symbols in the program.  Link in
# libdl, which contains calls for dynamic loading.
server:         $(OBJECTS)
        $(CC) $(CFLAGS) -Wl,-export-dynamic -o $@ $^ -ldl

# All object files in the server depend on server.h.  But use the
# default rule for building object files from source files.
$(OBJECTS):     server.h

# Rule for building module shared libraries from the corresponding
# source files.   Compile -fPIC and generate a shared object file.
$(MODULES): \
%.so:           %.c server.h
        $(CC) $(CFLAGS) -fPIC -shared -o $@ $<
```

The `Makefile` provides these targets:

- `all` (the default if you invoke `make` without arguments because it's the first target in the `Makefile`) includes the `server` executable and all the modules. The modules are listed in the variable `MODULES`.
- `clean` deletes any build products that are produced by the `Makefile`.
- `server` links the server executable. The source files listed in the variable `SOURCES` are compiled and linked in.
- The last rule is a generic pattern for compiling shared object files for server modules from the corresponding source files.

Note that source files for server modules are compiled with the `-fPIC` option because they are linked into shared libraries (see Section 2.3.2, "Shared Libraries," in Chapter 2).

Also observe that the `server` executable is linked with the `-Wl,-export-dynamic` compiler option. With this option, GCC passes the `-export-dynamic` option to the linker, which creates an executable file that also exports its external symbols as a shared library. This allows modules, which are dynamically loaded as shared libraries, to reference functions from `common.c` that are linked statically into the `server` executable.

11.4.2 Building the Server

Building the program is easy. From the directory containing the sources, simply invoke `make`:

```
% make
cc -Wall -g   -c -o server.o server.c
cc -Wall -g   -c -o module.o module.c
cc -Wall -g   -c -o common.o common.c
cc -Wall -g   -c -o main.o main.c
cc -Wall -g -Wl,-export-dynamic -o server server.o module.o common.o main.o -ldl
cc -Wall -g -fPIC -shared -o diskfree.so diskfree.c
cc -Wall -g -fPIC -shared -o issue.so issue.c
cc -Wall -g -fPIC -shared -o processes.so processes.c
cc -Wall -g -fPIC -shared -o time.so time.c
```

This builds the `server` program and the server module shared libraries.

```
% ls -l server *.so
-rwxr-xr-x    1 samuel   samuel      25769 Mar 11 01:15 diskfree.so
-rwxr-xr-x    1 samuel   samuel      31184 Mar 11 01:15 issue.so
-rwxr-xr-x    1 samuel   samuel      41579 Mar 11 01:15 processes.so
-rwxr-xr-x    1 samuel   samuel      71758 Mar 11 01:15 server
-rwxr-xr-x    1 samuel   samuel      13980 Mar 11 01:15 time.so
```

11.4.3 Running the Server

To run the server, simply invoke the `server` executable.

If you do not specify the server port number with the `--port` (`-p`) option, Linux will choose one for you; in this case, specify `--verbose` (`-v`) to make the server print out the port number in use.

If you do not specify an address with `--address` (`-a`), the server runs on all your computer's network addresses. If your computer is attached to a network, that means that others will be capable of accessing the server, provided that they know the correct port number to use and page to request. For security reasons, it's a good idea to specify the `localhost` address until you're confident that the server works correctly and is not releasing any information that you prefer to not make public. Binding to the `localhost` causes the server to bind to the local network device (designated "lo")—only programs running on the same computer can connect to it. If you specify a different address, it must be an address that corresponds to your computer:

```
% ./server --address localhost --port 4000
```

The server is now running. Open a browser window, and attempt to contact the server at this port number. Request a page whose name matches one of the modules. For instance, to invoke the `diskfree.so` module, use this URL:

```
http://localhost:4000/diskfree
```

Instead of `4000`, enter the port number you specified (or the port number that Linux chose for you). Press Ctrl+C to kill the server when you're done.

If you didn't specify `localhost` as the server address, you can also connect to the server with a Web browser running on another computer by using your computer's hostname in the URL—for example:

```
http://host.domain.com:4000/diskfree
```

If you specify the `--verbose` (`-v`) option, the server prints some information at startup and displays the numerical Internet address of each client that connects to it. If you connect via the `localhost` address, the client address will always be 127.0.0.1.

If you experiment with writing your own server modules, you may place them in a different directory than the one containing the `server` module. In this case, specify that directory with the `--module-dir` (`-m`) option. The server will look in this directory for server modules instead.

If you forget the syntax of the command-line options, invoke `server` with the `--help` (`-h`) option.

```
% ./server --help
Usage: ./server [ options ]
  -a, --address ADDR        Bind to local address (by default, bind
                              to all local addresses).
  -h, --help                Print this information.
  -m, --module-dir DIR      Load modules from specified directory
                              (by default, use executable directory).
  -p, --port PORT           Bind to specified port.
  -v, --verbose             Print verbose messages.
```

11.5 Finishing Up

If you were really planning on releasing this program for general use, you'd need to write documentation for it as well. Many people don't realize that writing good documentation is just as difficult and time-consuming—and just as important—as writing good software. However, software documentation is a subject for another book, so we'll leave you with a few references of where to learn more about documenting GNU/Linux software.

You'd probably want to write a man page for the `server` program, for instance. This is the first place many users will look for information about a program. Man pages are formatted using a classic UNIX formatting system `troff`. To view the man page for `troff`, which describes the format of troff files, invoke the following:

```
% man troff
```

To learn about how GNU/Linux locates man pages, consult the man page for the `man` command itself by invoking this:

```
% man man
```

You might also want to write info pages, using the GNU Info system, for the server and its modules. Naturally, documentation about the info system comes in info format; to view it, invoke this line:

```
% info info
```

Many GNU/Linux programs come with documentation in plain text or HTML formats as well.

Happy GNU/Linux programming!

III

Appendixes

A

Other Development Tools

Developing correct, fast C or C++ GNU/Linux programs requires more than just understanding the GNU/Linux operating system and its system calls. In this appendix, we discuss development tools to find runtime errors such as illegal use of dynamically allocated memory and to determine which parts of a program are taking most of the execution time. Analyzing a program's source code can reveal some of this information; by using these runtime tools and actually executing the program, you can find out much more.

A.1 Static Program Analysis

Some programming errors can be detected using static analysis tools that analyze the program's source code. If you invoke GCC with `-Wall` and `-pedantic`, the compiler issues warnings about risky or possibly erroneous programming constructions. By eliminating such constructions, you'll reduce the risk of program bugs, and you'll find it easier to compile your programs on different GNU/Linux variants and even on other operating systems.

Using various command options, you can cause GCC to issue warnings about many different types of questionable programming constructs. The `-Wall` option enables most of these checks. For example, the compiler will produce a warning about a comment that begins within another comment, about an incorrect return type specified for `main`, and about a non void function omitting a `return` statement. If you specify the `-pedantic` option, GCC emits warnings demanded by strict ANSI C and ISO C++ compliance. For example, use of the GNU `asm` extension causes a warning using this option. A few GNU extensions, such as using alternate keywords beginning with `__` (two underscores), will not trigger warning messages. Although the GCC info pages deprecate use of this option, we recommend that you use it anyway and avoid most GNU language extensions because GCC extensions tend to change through time and frequently interact poorly with code optimization.

Listing A.1 **(*hello.c*) Hello World Program**

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

Consider compiling the "Hello World" program shown in Listing A.1. Though GCC compiles the program without complaint, the source code does not obey ANSI C rules. If you enable warnings by compiling with the `-Wall -pedantic`, GCC reveals three questionable constructs.

```
% gcc -Wall -pedantic hello.c
hello.c:2: warning: return type defaults to 'int'
hello.c: In function 'main':
hello.c:3: warning: implicit declaration of function 'printf'
hello.c:4: warning: control reaches end of non-void function
```

These warnings indicate that the following problems occurred:

- The return type for `main` was not specified.
- The function `printf` is implicitly declared because `<stdio.h>` is not included.
- The function, implicitly declared to return an `int`, actually returns no value.

Analyzing a program's source code cannot find all programming mistakes and inefficiencies. In the next section, we present four tools to find mistakes in using dynamically allocated memory. In the subsequent section, we show how to analyze the program's execution time using the `gprof` profiler.

A.2 Finding Dynamic Memory Errors

When writing a program, you frequently can't know how much memory the program will need when it runs. For example, a line read from a file at runtime might have any finite length. C and C++ programs use `malloc`, `free`, and their variants to dynamically allocate memory while the program is running. The rules for dynamic memory use include these:

- The number of allocation calls (calls to `malloc`) must exactly match the number of deallocation calls (calls to `free`).
- Reads and writes to the allocated memory must occur within the memory, not outside its range.
- The allocated memory cannot be used before it is allocated or after it is deallocated.

Because dynamic memory allocation and deallocation occur at runtime, static program analysis rarely find violations. Instead, memory-checking tools run the program, collecting data to determine if any of these rules have been violated. The violations a tool may find include the following:

- Reading from memory before allocating it
- Writing to memory before allocating it
- Reading before the beginning of allocated memory
- Writing before the beginning of allocated memory
- Reading after the end of allocated memory
- Writing after the end of allocated memory
- Reading from memory after its deallocation
- Writing to memory after its deallocation
- Failing to deallocate allocated memory
- Deallocating the same memory twice
- Deallocating memory that is not allocated

It is also useful to warn about requesting an allocation with 0 bytes, which probably indicates programmer error.

Table A.1 indicates four different tools' diagnostic capabilities. Unfortunately, no single tool diagnoses all the memory use errors. Also, no tool claims to detect reading or writing before allocating memory, but doing so will probably cause a segmentation fault. Deallocating memory twice will probably also cause a segmentation fault. These tools diagnose only errors that actually occur while the program is running. If you run the program with inputs that cause no memory to be allocated, the tools will indicate no memory errors. To test a program thoroughly, you must run the program using different inputs to ensure that every possible path through the program occurs. Also, you may use only one tool at a time, so you'll have to repeat testing with several tools to get the best error checking.

Table A.1 **Capabilities of Dynamic Memory-Checking Tools (X Indicates Detection, and O Indicates Detection for Some Cases)**

Erroneous Behavior	*malloc* Checking	mtrace	ccmalloc	Electric Fence
Read before allocating memory				
Write before allocating memory				
Read before beginning of allocation				X
Write before beginning of allocation	O		O	X
Read after end of allocation				X
Write after end of allocation			X	X
Read after deallocation				X
Write after deallocation				X
Failure to deallocate memory		X	X	
Deallocating memory twice	X		X	
Deallocating nonallocated memory		X	X	
Zero-size memory allocation			X	X

In the sections that follow, we first describe how to use the more easily used `malloc` checking and `mtrace`, and then `ccmalloc` and Electric Fence.

A.2.1 A Program to Test Memory Allocation and Deallocation

We'll use the `malloc-use` program in Listing A.2 to illustrate memory allocation, deallocation, and use. To begin running it, specify the maximum number of allocated memory regions as its only command-line argument. For example, `malloc-use 12` creates an array `A` with 12 character pointers that do not point to anything. The program accepts five different commands:

- To allocate *b* bytes pointed to by array entry `A[i]`, enter `a i b`. The array index *i* can be any non-negative number smaller than the command-line argument. The number of bytes must be non-negative.
- To deallocate memory at array index *i*, enter `d i`.
- To read the *p*th character from the allocated memory at index *i* (as in `A[i][p]`), enter `r i p`. Here, *p* can have an integral value.
- To write a character to the *p*th position in the allocated memory at index *i*, enter `w i p`.
- When finished, enter `q`.

We'll present the program's code later, in Section A.2.7, and illustrate how to use it.

A.2.2 *malloc* Checking

The memory allocation functions provided by the GNU C library can detect writing before the beginning of an allocation and deallocating the same allocation twice. Defining the environment variable `MALLOC_CHECK_` to the value 2 causes a program to halt when such an error is detected. (Note the environment variable's ending underscore.) There is no need to recompile the program.

We illustrate diagnosing a write to memory to a position just before the beginning of an allocation.

```
% export MALLOC_CHECK_=2
% ./malloc-use 12
Please enter a command: a 0 10
Please enter a command: w 0 -1
Please enter a command: d 0
Aborted (core dumped)
```

`export` turns on `malloc` checking. Specifying the value 2 causes the program to halt as soon as an error is detected.

Using `malloc` checking is advantageous because the program need not be recompiled, but its capability to diagnose errors is limited. Basically, it checks that the allocator data structures have not been corrupted. Thus, it can detect double deallocation of the same allocation. Also, writing just before the beginning of a memory allocation can usually be detected because the allocator stores the size of each memory allocation just before the allocated region. Thus, writing just before the allocated memory will corrupt this number. Unfortunately, consistency checking can occur only when your program calls allocation routines, not when it accesses memory, so many illegal reads and writes can occur before an error is detected. In the previous example, the illegal write was detected only when the allocated memory was deallocated.

A.2.3 Finding Memory Leaks Using *mtrace*

The `mtrace` tool helps diagnose the most common error when using dynamic memory: failure to match allocations and deallocations. There are four steps to using `mtrace`, which is available with the GNU C library:

1. Modify the source code to include `<mcheck.h>` and to invoke `mtrace ()` as soon as the program starts, at the beginning of `main`. The call to `mtrace` turns on tracking of memory allocations and deallocations.
2. Specify the name of a file to store information about all memory allocations and deallocations:

   ```
   % export MALLOC_TRACE=memory.log
   ```

3. Run the program. All memory allocations and deallocations are stored in the logging file.

4. Using the `mtrace` command, analyze the memory allocations and deallocations to ensure that they match.

```
% mtrace my_program $MALLOC_TRACE
```

The messages produced by `mtrace` are relatively easy to understand. For example, for our `malloc-use` example, the output would look like this:

```
- 0000000000 Free 3 was never alloc'd malloc-use.c:39

Memory not freed:
-----------------
   Address     Size     Caller
0x08049d48      0xc  at malloc-use.c:30
```

These messages indicate an attempt on line 39 of `malloc-use.c` to free memory that was never allocated, and an allocation of memory on line 30 that was never freed.

`mtrace` diagnoses errors by having the executable record all memory allocations and deallocations in the file specified by the `MALLOC_TRACE` environment variable. The executable must terminate normally for the data to be written. The `mtrace` command analyzes this file and lists unmatched allocations and deallocations.

A.2.4 Using *ccmalloc*

The `ccmalloc` library diagnoses dynamic memory errors by replacing `malloc` and `free` with code tracing their use. If the program terminates gracefully, it produces a report of memory leaks and other errors. The `ccmalloc` library was written by Armin Bierce.

You'll probably have to download and install the `ccmalloc` library yourself. Download it from `http://www.inf.ethz.ch/personal/biere/projects/ccmalloc/`, unpack the code, and run `configure`. Run `make` and `make install`, copy the `ccmalloc.cfg` file to the directory where you'll run the program you want to check, and rename the copy to `.ccmalloc`. Now you are ready to use the tool.

The program's object files must be linked with `ccmalloc`'s library and the dynamic linking library. Append `-lccmalloc -ldl` to your link command, for instance.

```
% gcc -g -Wall -pedantic malloc-use.o -o ccmalloc-use -lccmalloc -ldl
```

Execute the program to produce a report. For example, running our `malloc-use` program to allocate but not deallocate memory produces the following report:

```
% ./ccmalloc-use 12
file-name=a.out does not contain valid symbols
trying to find executable in current directory ...
using symbols from 'ccmalloc-use'
(to speed up this search specify 'file ccmalloc-use'
 in the startup file '.ccmalloc')
Please enter a command: a 0 12
Please enter a command: q
```

```
.--------------.
|ccmalloc report|
=======================================================
| total # of|   allocated | deallocated |     garbage |
+-----------+-------------+-------------+-------------+
|      bytes|          60 |          48 |          12 |
+-----------+-------------+-------------+-------------+
|allocations|           2 |           1 |           1 |
+-------------------------------------------------------+
| number of checks: 1                                   |
| number of counts: 3                                   |
| retrieving function names for addresses ... done.     |
| reading file info from gdb ... done.                  |
| sorting by number of not reclaimed bytes ... done.    |
| number of call chains: 1                              |
| number of ignored call chains: 0                      |
| number of reported call chains: 1                     |
| number of internal call chains: 1                     |
| number of library call chains: 0                      |
=======================================================
|
*100.0% = 12 Bytes of garbage allocated in 1 allocation
|       |
|       |       0x400389cb in <???>
|       |
|       |       0x08049198 in <main>
|       |                   at malloc-use.c:89
|       |
|       |       0x08048fdc in <allocate>
|       |                   at malloc-use.c:30
|       |
|       '-----> 0x08049647 in <malloc>
|                           at src/wrapper.c:284
|
'-------------------------------------------------------
```

The last few lines indicate the chain of function calls that allocated memory that was not deallocated.

To use `ccmalloc` to diagnose writes before the beginning or after the end of the allocated region, you'll have to modify the `.ccmalloc` file in the current directory. This file is read when the program starts execution.

A.2.5 Electric Fence

Written by Bruce Perens, Electric Fence halts executing programs on the exact line where a write or a read outside an allocation occurs. This is the only tool that discovers illegal reads. It is included in most GNU/Linux distributions, but the source code can be found at `http://www.perens.com/FreeSoftware/`.

As with `ccmalloc`, your program's object files must be linked with Electric Fence's library by appending `-lefence` to the linking command, for instance:

```
% gcc -g -Wall -pedantic malloc-use.o -o emalloc-use -lefence
```

As the program runs, allocated memory uses are checked for correctness. A violation causes a segmentation fault:

```
% ./emalloc-use 12
  Electric Fence 2.0.5 Copyright (C) 1987-1998 Bruce Perens.
Please enter a command: a 0 12
Please enter a command: r 0 12
Segmentation fault
```

Using a debugger, you can determine the context of the illegal action.

By default, Electric Fence diagnoses only accesses beyond the ends of allocations. To find accesses before the beginning of allocations *instead of* accesses beyond the end of allocations, use this code:

```
% export EF_PROTECT_BELOW=1
```

To find accesses to deallocated memory, set `EF_PROTECT_FREE` to 1. More capabilities are described in the `libefence` manual page.

Electric Fence diagnoses illegal memory accesses by storing each allocation on at least two memory pages. It places the allocation at the end of the first page; any access beyond the end of the allocation, on the second page, causes a segmentation fault. If you set `EF_PROTECT_BELOW` to 1, it places the allocation at the beginning of the second page instead. Because it allocates two memory pages per call to `malloc`, Electric Fence can use an enormous amount of memory. Use this library for debugging only.

A.2.6 Choosing Among the Different Memory-Debugging Tools

We have discussed four separate, incompatible tools to diagnose erroneous use of dynamic memory. How does a GNU/Linux programmer ensure that dynamic memory is correctly used? No tool guarantees diagnosing all errors, but using any of them does increase the probability of finding errors. To ease finding dynamically allocated memory errors, separately develop and test the code that deals with dynamic memory. This reduces the amount of code that you must search for errors. If you are using C++, write a class that handles all dynamic memory use. If you are using C, minimize the number of functions using allocation and deallocation. When testing this code, be sure to use only one tool at a one time because they are incompatible. When testing a program, be sure to vary how the program executes, to test the most commonly executed portions of the code.

Which of the four tools should you use? Because failing to match allocations and deallocations is the most common dynamic memory error, use `mtrace` during initial development. The program is available on all GNU/Linux systems and has been well tested. After ensuring that the number of allocations and deallocations match, use

Electric Fence to find illegal memory accesses. This will eliminate almost all memory errors. When using Electric Fence, you will need to be careful to not perform too many allocations and deallocations because each allocation requires at least two pages of memory. Using these two tools will reveal most memory errors.

A.2.7 Source Code for the Dynamic Memory Program

Listing A.2 shows the source code for a program illustrating dynamic memory allocation, deallocation, and use. See Section A.2.1, "A Program to Test Memory Allocation and Deallocation," for a description of how to use it.

Listing A.2 **(*malloc-use.c*) Dynamic Memory Allocation Checking Example**

```
/* Use C's dynamic memory allocation functions.  */

/* Invoke the program using one command-line argument specifying the
   size of an array.  This array consists of pointers to (possibly)
   allocated arrays.

   When the programming is running, select among the following
   commands:

   o allocate memory:   a <index> <memory-size>
   o deallocate memory: d <index>
   o read from memory:  r <index> <position-within-allocation>
   o write to memory:   w <index> <position-within-allocation>
   o quit:              q

   The user is responsible for obeying (or disobeying) the rules on dynamic
   memory use.  */

#ifdef MTRACE
#include <mcheck.h>
#endif /* MTRACE */
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

/* Allocate memory with the specified size, returning nonzero upon
   success.  */

void allocate (char** array, size_t size)
{
  *array = malloc (size);
}

/* Deallocate memory.  */

void deallocate (char** array)
```

continues

Listing A.2 **Continued**

```
{
  free ((void*) *array);
}

/* Read from a position in memory.  */

void read_from_memory (char* array, int position)
{
  char character = array[position];
}

/* Write to a position in memory.  */

void write_to_memory (char* array, int position)
{
  array[position] = 'a';
}

int main (int argc, char* argv[])
{
  char** array;
  unsigned array_size;
  char command[32];
  unsigned array_index;
  char command_letter;
  int size_or_position;
  int error = 0;

#ifdef MTRACE
  mtrace ();
#endif /* MTRACE */

  if (argc != 2) {
    fprintf (stderr, "%s: array-size\n", argv[0]);
    return 1;
  }

  array_size = strtoul (argv[1], 0, 0);
  array = (char **) calloc (array_size, sizeof (char *));
  assert (array != 0);

  /* Follow the user's commands.  */
  while (!error) {
    printf ("Please enter a command: ");
    command_letter = getchar ();
    assert (command_letter != EOF);
    switch (command_letter) {

    case 'a':
      fgets (command, sizeof (command), stdin);
      if (sscanf (command, "%u %i", &array_index, &size_or_position) == 2
          && array_index < array_size)
```

```
          allocate (&(array[array_index]), size_or_position);
        else
          error = 1;
        break;

      case 'd':
        fgets (command, sizeof (command), stdin);
        if (sscanf (command, "%u", &array_index) == 1
            && array_index < array_size)
          deallocate (&(array[array_index]));
        else
          error = 1;
        break;

      case 'r':
        fgets (command, sizeof (command), stdin);
        if (sscanf (command, "%u %i", &array_index, &size_or_position) == 2
            && array_index < array_size)
          read_from_memory (array[array_index], size_or_position);
        else
          error = 1;
        break;

      case 'w':
        fgets (command, sizeof (command), stdin);
        if (sscanf (command, "%u %i", &array_index, &size_or_position) == 2
            && array_index < array_size)
          write_to_memory (array[array_index], size_or_position);
        else
          error = 1;
        break;

      case 'q':
        free ((void *) array);
        return 0;

      default:
        error = 1;
      }
    }

    free ((void *) array);
    return 1;
  }
```

A.3 Profiling

Now that your program is (hopefully) correct, we turn to speeding its execution. Using the profiler `gprof`, you can determine which functions require the most execution time. This can help you determine which parts of the program to optimize or rewrite to execute more quickly. It can also help you find errors. For example, you may find that a particular function is called many more times than you expect.

In this section, we describe how to use `gprof`. Rewriting code to run more quickly requires creativity and careful choice of algorithms.

Obtaining profiling information requires three steps:

1. Compile and link your program to enable profiling.
2. Execute your program to generate profiling data.
3. Use `gprof` to analyze and display the profiling data.

Before we illustrate these steps, we introduce a large enough program to make profiling interesting.

A.3.1 A Simple Calculator

To illustrate profiling, we'll use a simple calculator program. To ensure that the calculator takes a nontrivial amount of time, we'll use unary numbers for calculations, something we would definitely not want to do in a real-world program. Code for this program appears at the end of this chapter.

A *unary number* is represented by as many symbols as its value. For example, the number 1 is represented by "x," 2 by "xx," and 3 by "xxx." Instead of using x's, our program represents a non-negative number using a linked list with as many elements as the number's value. The `number.c` file contains routines to create the number 0, add 1 to a number, subtract 1 from a number, and add, subtract, and multiply numbers. Another function converts a string holding a non-negative decimal number to a unary number, and a function converts from a unary number to an `int`. Addition is implemented using repeated addition of 1s, while subtraction uses repeated removal of 1s. Multiplication is defined using repeated addition. The unary predicates `even` and `odd` each return the unary number for 1 if and only if its one operand is even or odd, respectively; otherwise they return the unary number for 0. The two predicates are mutually recursive. For example, a number is even if it is zero, or if one less than the number is odd.

The calculator accepts one-line postfix expressions[1] and prints each expression's value—for example:

```
% ./calculator
Please enter a postfix expression:
2 3 +
5
Please enter a postfix expression:
2 3 + 4 -
1
```

1. In *postfix* notation, a binary operator is placed after its operands instead of between them. So, for example, to multiply 6 and 8, you would use 6 8 ×. To multiply 6 and 8 and then add 5 to the result, you would use 6 8 × 5 +.

The calculator, defined in `calculator.c`, reads each expression, storing intermediate values on a stack of unary numbers, defined in `stack.c`. The stack stores its unary numbers in a linked list.

A.3.2 Collecting Profiling Information

The first step in profiling a program is to annotate its executable to collect profiling information. To do so, use the `-pg` compiler flag when both compiling the object files and linking. For example, consider this code:

```
% gcc -pg -c -o calculator.o calculator.c
% gcc -pg -c -o stack.o stack.c
% gcc -pg -c -o number.o number.c
% gcc -pg calculator.o stack.o number.o -o calculator
```

This enables collecting information about function calls and timing information. To collect line-by-line use information, also specify the debugging flag `-g`. To count basic block executions, such as the number of `do`-loop iterations, use `-a`.

The second step is to run the program. While it is running, profiling data is collected into a file named `gmon.out`, only for those portions of the code that are exercised. You must vary the program's input or commands to exercise the code sections that you want to profile. The program must terminate normally for the profiling file to be written.

A.3.3 Displaying Profiling Data

Given the name of an executable, `gprof` analyzes the `gmon.out` file to display information about how much time each function required. For example, consider the "flat" profiling data for computing $1787 \times 13 - 1918$ using our calculator program, which is produced by executing `gprof ./calculator`:

```
Flat profile:

Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ms/call  ms/call  name
 26.07      1.76     1.76 20795463     0.00     0.00  decrement_number
 24.44      3.41     1.65     1787     0.92     1.72  add
 19.85      4.75     1.34 62413059     0.00     0.00  zerop
 15.11      5.77     1.02     1792     0.57     2.05  destroy_number
 14.37      6.74     0.97 20795463     0.00     0.00  add_one
  0.15      6.75     0.01     1788     0.01     0.01  copy_number
  0.00      6.75     0.00     1792     0.00     0.00  make_zero
  0.00      6.75     0.00       11     0.00     0.00  empty_stack
```

Computing the function `decrement_number` and all the functions it calls required 26.07% of the program's total execution time. It was called 20,795,463 times. Each individual execution required 0.0 seconds—namely, a time too small to measure. The `add` function was invoked 1,787 times, presumably to compute the product. Each call

required 0.92 seconds. The `copy_number` function was invoked only 1,788 times, while it and the functions it calls required only 0.15% of the total execution time. Sometimes the `mcount` and `profil` functions used by profiling appear in the data.

In addition to the *flat profile data*, which indicates the total time spent within each function, `gprof` produces *call graph data* showing the time spent in each function and its children within the context of a function call chain:

```
index % time    self  children    called     name
                                                <spontaneous>
[1]    100.0    0.00    6.75                 main [1]
                0.00    6.75       2/2           apply_binary_function [2]
                0.00    0.00       1/1792        destroy_number [4]
                0.00    0.00       1/1           number_to_unsigned_int [10]
                0.00    0.00       3/3           string_to_number [12]
                0.00    0.00       3/5           push_stack [16]
                0.00    0.00       1/1           create_stack [18]
                0.00    0.00       1/11          empty_stack [14]
                0.00    0.00       1/5           pop_stack [15]
                0.00    0.00       1/1           clear_stack [17]
-----------------------------------------------
                0.00    6.75       2/2           main [1]
[2]    100.0    0.00    6.75       2         apply_binary_function [2]
                0.00    6.74       1/1           product [3]
                0.00    0.01       4/1792        destroy_number [4]
                0.00    0.00       1/1           subtract [11]
                0.00    0.00       4/11          empty_stack [14]
                0.00    0.00       4/5           pop_stack [15]
                0.00    0.00       2/5           push_stack [16]
-----------------------------------------------
                0.00    6.74       1/1           apply_binary_function [2]
[3]     99.8    0.00    6.74       1         product [3]
                1.02    2.65    1787/1792        destroy_number [4]
                1.65    1.43    1787/1787        add [5]
                0.00    0.00    1788/62413059     zerop [7]
                0.00    0.00       1/1792        make_zero [13]
```

The first frame shows that executing `main` and its children required 100% of the program's 6.75 seconds. It called `apply_binary_function` twice, which was called a total of two times throughout the entire program. Its caller was `<spontaneous>`; this indicates that the profiler was not capable of determining who called `main`. This first frame also shows that `string_to_number` called `push_stack` three times but was called five times throughout the program. The third frame shows that executing `product` and the functions it calls required 99.8% of the program's total execution time. It was invoked once by `apply_binary_function`.

The call graph data displays the total time spent executing a function and its children. If the function call graph is a tree, this number is easy to compute, but recursively defined functions must be treated specially. For example, the `even` function calls `odd`, which calls `even`. Each largest such call cycle is given its own number and is dis-

played individually in the call graph data. Consider this profiling data from determining whether $1787 \times 13 \times 3$ is even:

```
-----------------------------------------------
                0.00    0.02       1/1           main [1]
[9]      0.1    0.00    0.02       1         apply_unary_function [9]
                0.01    0.00       1/1           even <cycle 1> [13]
                0.00    0.00       1/1806        destroy_number [5]
                0.00    0.00       1/13          empty_stack [17]
                0.00    0.00       1/6           pop_stack [18]
                0.00    0.00       1/6           push_stack [19]
-----------------------------------------------
[10]     0.1    0.01    0.00       1+69693   <cycle 1 as a whole> [10]
                0.00    0.00   34847             even <cycle 1> [13]
-----------------------------------------------
                               34847             even <cycle 1> [13]
[11]     0.1    0.01    0.00   34847         odd <cycle 1> [11]
                0.00    0.00   34847/186997954     zerop [7]
                0.00    0.00       1/1806        make_zero [16]
                               34846             even <cycle 1> [13]
```

The `1+69693` in the `[10]` frame indicates that cycle 1 was called once, while the functions in the cycle were called 69,693 times. The cycle called the `even` function. The next entry shows that `odd` was called 34,847 times by `even`.

In this section, we have briefly discussed only some of `gprof`'s features. Its info pages contain information about other useful features:

- Use the `-s` option to sum the execution results from several different runs.
- Use the `-c` option to identify children that could have been called but were not.
- Use the `-l` option to display line-by-line profiling information.
- Use the `-A` option to display source code annotated with percentage execution numbers.

The info pages also provide more information about the interpretation of the analyzed data.

A.3.4 How *gprof* Collects Data

When a profiled executable runs, every time a function is called its count is also incremented. Also, `gprof` periodically interrupts the executable to determine the currently executing function. These samples determine function execution times. Because Linux's clock ticks are 0.01 seconds apart, these interruptions occur, at most, every 0.01 seconds. Thus, profiles for quickly executing programs or for quickly executing infrequently called functions may be inaccurate. To avoid these inaccuracies, run the executable for longer periods of time, or sum together profile data from several executions. Read about the `-s` option to sum profiling data in `gprof`'s info pages.

A.3.5 Source Code for the Calculator Program

Listing A.3 presents a program that calculates the value of postfix expressions.

Listing A.3 **(*calculator.c*) Main Calculator Program**

```
/* Calculate using unary numbers.  */

/* Enter one-line expressions using reverse postfix notation, e.g.,
     602 7 5 - 3 * +
   Nonnegative numbers are entered using decimal notation.  The
   operators "+", "-", and "*" are supported.  The unary operators
   "even" and "odd" return the number 1 if its one operand is even
   or odd, respectively.  Spaces must separate all words.  Negative
   numbers are not supported.  */

#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <ctype.h>
#include "definitions.h"


/* Apply the binary function with operands obtained from the stack,
   pushing the answer on the stack.  Return nonzero upon success.  */

int apply_binary_function (number (*function) (number, number),
                           Stack* stack)
{
  number operand1, operand2;
  if (empty_stack (*stack))
    return 0;
  operand2 = pop_stack (stack);
  if (empty_stack (*stack))
    return 0;
  operand1 = pop_stack (stack);
  push_stack (stack, (*function) (operand1, operand2));
  destroy_number (operand1);
  destroy_number (operand2);
  return 1;
}

/* Apply the unary function with an operand obtained from the stack,
   pushing the answer on the stack.  Return nonzero upon success.  */

int apply_unary_function (number (*function) (number),
                          Stack* stack)
{
  number operand;
  if (empty_stack (*stack))
    return 0;
```

```
  operand = pop_stack (stack);
  push_stack (stack, (*function) (operand));
  destroy_number (operand);
  return 1;
}

int main ()
{
  char command_line[1000];
  char* command_to_parse;
  char* token;
  Stack number_stack = create_stack ();

  while (1) {
    printf ("Please enter a postfix expression:\n");
    command_to_parse = fgets (command_line, sizeof (command_line), stdin);
    if (command_to_parse == NULL)
      return 0;

    token = strtok (command_to_parse, " \t\n");
    command_to_parse = 0;
    while (token != 0) {
      if (isdigit (token[0]))
        push_stack (&number_stack, string_to_number (token));
      else if (((strcmp (token, "+") == 0) &&
                !apply_binary_function (&add, &number_stack)) ||
               ((strcmp (token, "-") == 0) &&
                !apply_binary_function (&subtract, &number_stack)) ||
               ((strcmp (token, "*") == 0) &&
                !apply_binary_function (&product, &number_stack)) ||
               ((strcmp (token, "even") == 0) &&
                !apply_unary_function (&even, &number_stack)) ||
               ((strcmp (token, "odd") == 0) &&
                !apply_unary_function (&odd, &number_stack)))
        return 1;
      token = strtok (command_to_parse, " \t\n");
    }
    if (empty_stack (number_stack))
      return 1;
    else {
      number answer = pop_stack (&number_stack);
      printf ("%u\n", number_to_unsigned_int (answer));
      destroy_number (answer);
      clear_stack (&number_stack);
    }
  }

  return 0;
}
```

The functions in Listing A.4 implement unary numbers using empty linked lists.

Listing A.4 **(*number.c*) Unary Number Implementation**

```
/* Operate on unary numbers.  */

#include <assert.h>
#include <stdlib.h>
#include <limits.h>
#include "definitions.h"

/* Create a number representing zero.  */

number make_zero ()
{
  return 0;
}

/* Return nonzero if the number represents zero.  */

int zerop (number n)
{
  return n == 0;
}

/* Decrease a positive number by 1.  */

number decrement_number (number n)
{
  number answer;
  assert (!zerop (n));
  answer = n->one_less_;
  free (n);
  return answer;
}

/* Add 1 to a number.  */

number add_one (number n)
{
  number answer = malloc (sizeof (struct LinkedListNumber));
  answer->one_less_ = n;
  return answer;
}

/* Destroying a number.  */

void destroy_number (number n)
{
  while (!zerop (n))
    n = decrement_number (n);
```

```
}

/* Copy a number.  This function is needed only because of memory
   allocation.  */

number copy_number (number n)
{
  number answer = make_zero ();
  while (!zerop (n)) {
    answer = add_one (answer);
    n = n->one_less_;
  }
  return answer;
}

/* Add two numbers.  */

number add (number n1, number n2)
{
  number answer = copy_number (n2);
  number addend = n1;
  while (!zerop (addend)) {
    answer = add_one (answer);
    addend = addend->one_less_;
  }
  return answer;
}

/* Subtract a number from another.  */

number subtract (number n1, number n2)
{
  number answer = copy_number (n1);
  number subtrahend = n2;
  while (!zerop (subtrahend)) {
    assert (!zerop (answer));
    answer = decrement_number (answer);
    subtrahend = subtrahend->one_less_;
  }
  return answer;
}

/* Return the product of two numbers.  */

number product (number n1, number n2)
{
  number answer = make_zero ();
  number multiplicand = n1;
  while (!zerop (multiplicand)) {
    number answer2 = add (answer, n2);
    destroy_number (answer);
```

continues

Listing A.4 **Continued**

```
    answer = answer2;
    multiplicand = multiplicand->one_less_;
  }
  return answer;
}

/* Return nonzero if number is even.  */

number even (number n)
{
  if (zerop (n))
    return add_one (make_zero ());
  else
    return odd (n->one_less_);
}

/* Return nonzero if number is odd.  */

number odd (number n)
{
  if (zerop (n))
    return make_zero ();
  else
    return even (n->one_less_);
}

/* Convert a string representing a decimal integer into a "number".  */

number string_to_number (char * char_number)
{
  number answer = make_zero ();
  int num = strtoul (char_number, (char **) 0, 0);
  while (num != 0) {
    answer = add_one (answer);
    --num;
  }
  return answer;
}

/* Convert a "number" into an "unsigned int".  */

unsigned number_to_unsigned_int (number n)
{
  unsigned answer = 0;
  while (!zerop (n)) {
    n = n->one_less_;
    ++answer;
  }
  return answer;
}
```

The functions in Listing A.5 implement a stack of unary numbers using a linked list.

Listing A.5 **(*stack.c*) Unary Number Stack**

```
/* Provide a stack of "number"s.  */

#include <assert.h>
#include <stdlib.h>
#include "definitions.h"

/* Create an empty stack.  */

Stack create_stack ()
{
  return 0;
}

/* Return nonzero if the stack is empty.  */

int empty_stack (Stack stack)
{
  return stack == 0;
}

/* Remove the number at the top of a nonempty stack.  If the stack is
   empty, abort.  */

number pop_stack (Stack* stack)
{
  number answer;
  Stack rest_of_stack;

  assert (!empty_stack (*stack));
  answer = (*stack)->element_;
  rest_of_stack = (*stack)->next_;
  free (*stack);
  *stack = rest_of_stack;
  return answer;
}

/* Add a number to the beginning of a stack.  */

void push_stack (Stack* stack, number n)
{
  Stack new_stack = malloc (sizeof (struct StackElement));
  new_stack->element_ = n;
  new_stack->next_ = *stack;
  *stack = new_stack;
}

/* Remove all the stack's elements.  */
```

continues

Listing A.5 **Continued**

```
void clear_stack (Stack* stack)
{
  while (!empty_stack (*stack)) {
    number top = pop_stack (stack);
    destroy_number (top);
  }
}
```

Listing A.6 contains declarations for stacks and numbers.

Listing A.6 **(*definitions.h*) Header File for number.c and stack.c**

```
#ifndef DEFINITIONS_H
#define DEFINITIONS_H 1

/* Implement a number using a linked list.  */
struct LinkedListNumber
{
  struct LinkedListNumber*
                one_less_;
};
typedef struct LinkedListNumber* number;

/* Implement a stack of numbers as a linked list.  Use 0 to represent
   an empty stack.  */
struct StackElement
{
  number        element_;
  struct        StackElement* next_;
};
typedef struct StackElement* Stack;

/* Operate on the stack of numbers.  */
Stack create_stack ();
int empty_stack (Stack stack);
number pop_stack (Stack* stack);
void push_stack (Stack* stack, number n);
void clear_stack (Stack* stack);

/* Operations on numbers.  */
number make_zero ();
void destroy_number (number n);
number add (number n1, number n2);
number subtract (number n1, number n2);
number product (number n1, number n2);
number even (number n);
number odd (number n);
number string_to_number (char* char_number);
unsigned number_to_unsigned_int (number n);

#endif /* DEFINITIONS_H */
```

B

Low-Level I/O

C programmers on GNU/Linux have two sets of input/output functions at their disposal. The standard C library provides I/O functions: `printf`, `fopen`, and so on.[1] The Linux kernel itself provides another set of I/O operations that operate at a lower level than the C library functions.

Because this book is for people who already know the C language, we'll assume that you have encountered and know how to use the C library I/O functions.

Often there are good reasons to use Linux's low-level I/O functions. Many of these are kernel system calls[2] and provide the most direct access to underlying system capabilities that is available to application programs. In fact, the standard C library I/O routines are implemented on top of the Linux low-level I/O system calls. Using the latter is usually the most efficient way to perform input and output operations—and is sometimes more convenient, too.

1. The C++ standard library provides *iostreams* with similar functionality. The standard C library is also available in the C++ language.

2. See Chapter 8, "Linux System Calls," for an explanation of the difference between a system call and an ordinary function call.

Throughout this book, we assume that you're familiar with the calls described in this appendix. You may already be familiar with them because they're nearly the same as those provided on other UNIX and UNIX-like operating systems (and on the Win32 platform as well). If you're not familiar with them, however, read on; you'll find the rest of the book much easier to understand if you familiarize yourself with this material first.

B.1 Reading and Writing Data

The first I/O function you likely encountered when you first learned the C language was `printf`. This formats a text string and then prints it to standard output. The generalized version, `fprintf`, can print the text to a stream other than standard output. A stream is represented by a `FILE*` pointer. You obtain a `FILE*` pointer by opening a file with `fopen`. When you're done, you can close it with `fclose`. In addition to `fprintf`, you can use such functions as `fputc`, `fputs`, and `fwrite` to write data to the stream, or `fscanf`, `fgetc`, `fgets`, and `fread` to read data.

With the Linux low-level I/O operations, you use a handle called a *file descriptor* instead of a `FILE*` pointer. A file descriptor is an integer value that refers to a particular instance of an open file in a single process. It can be open for reading, for writing, or for both reading and writing. A file descriptor doesn't have to refer to an open file; it can represent a connection with another system component that is capable of sending or receiving data. For example, a connection to a hardware device is represented by a file descriptor (see Chapter 6, "Devices"), as is an open socket (see Chapter 5, "Interprocess Communication," Section 5.5, "Sockets") or one end of a pipe (see Section 5.4, "Pipes").

Include the header files `<fcntl.h>`, `<sys/types.h>`, `<sys/stat.h>`, and `<unistd.h>` if you use any of the low-level I/O functions described here.

B.1.1 Opening a File

To open a file and produce a file descriptor that can access that file, use the `open` call. It takes as arguments the path name of the file to open, as a character string, and flags specifying how to open it. You can use `open` to create a new file; if you do, pass a third argument that specifies the access permissions to set for the new file.

If the second argument is `O_RDONLY`, the file is opened for reading only; an error will result if you subsequently try to write to the resulting file descriptor. Similarly, `O_WRONLY` causes the file descriptor to be write-only. Specifying `O_RDWR` produces a file descriptor that can be used both for reading and for writing. Note that not all files may be opened in all three modes. For instance, the permissions on a file might forbid a particular process from opening it for reading or for writing; a file on a read-only device such as a CD-ROM drive may not be opened for writing.

You can specify additional options by using the bitwise or of this value with one or more flags. These are the most commonly used values:

- Specify `O_TRUNC` to truncate the opened file, if it previously existed. Data written to the file descriptor will replace previous contents of the file.
- Specify `O_APPEND` to append to an existing file. Data written to the file descriptor will be added to the end of the file.
- Specify `O_CREAT` to create a new file. If the filename that you provide to `open` does not exist, a new file will be created, provided that the directory containing it exists and that the process has permission to create files in that directory. If the file already exists, it is opened instead.
- Specify `O_EXCL` with `O_CREAT` to force creation of a new file. If the file already exists, the `open` call will fail.

If you call `open` with `O_CREAT`, provide an additional third argument specifying the permissions for the new file. See Chapter 10, "Security," Section 10.3, "File System Permissions," for a description of permission bits and how to use them.

For example, the program in Listing B.1 creates a new file with the filename specified on the command line. It uses the `O_EXCL` flag with `open`, so if the file already exists, an error occurs. The new file is given read and write permissions for the owner and owning group, and read permissions only for others. (If your umask is set to a nonzero value, the actual permissions may be more restrictive.)

Umasks

When you create a new file with `open`, some permission bits that you specify may be turned off. This is because your umask is set to a nonzero value. A process's umask specifies bits that are masked out of all newly created files' permissions. The actual permissions used are the bitwise and of the permissions you specify to `open` and the bitwise complement of the umask.

To change your umask from the shell, use the `umask` command, and specify the numerical value of the mask, in octal notation. To change the umask for a running process, use the `umask` call, passing it the desired mask value to use for subsequent `open` calls.

For example, calling this line

```
umask (S_IRWXO | S_IWGRP);
```

in a program, or invoking this command

```
% umask 027
```

specifies that write permissions for group members and read, write, and execute permissions for others will always be masked out of a new file's permissions.

Listing B.1 **(*create-file.c*) Create a New File**

```
#include <fcntl.h>
#include <stdio.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

int main (int argc, char* argv[])
{
  /* The path at which to create the new file.  */
  char* path = argv[1];
  /* The permissions for the new file.  */
  mode_t mode = S_IRUSR | S_IWUSR | S_IRGRP | S_IWGRP | S_IROTH;

  /* Create the file.  */
  int fd = open (path, O_WRONLY | O_EXCL | O_CREAT, mode);
  if (fd == -1) {
    /* An error occurred.  Print an error message and bail.  */
    perror ("open");
    return 1;
  }

  return 0;
}
```

Here's the program in action:

```
% ./create-file testfile
% ls -l testfile
-rw-rw-r--    1 samuel   users           0 Feb  1 22:47 testfile
% ./create-file testfile
open: File exists
```

Note that the length of the new file is 0 because the program didn't write any data to it.

B.1.2 Closing File Descriptors

When you're done with a file descriptor, close it with `close`. In some cases, such as the program in Listing B.1, it's not necessary to call `close` explicitly because Linux closes all open file descriptors when a process terminates (that is, when the program ends). Of course, once you close a file descriptor, you should no longer use it.

Closing a file descriptor may cause Linux to take a particular action, depending on the nature of the file descriptor. For example, when you close a file descriptor for a network socket, Linux closes the network connection between the two computers communicating through the socket.

Linux limits the number of open file descriptors that a process may have open at a time. Open file descriptors use kernel resources, so it's good to close file descriptors when you're done with them. A typical limit is 1,024 file descriptors per process. You can adjust this limit with the `setrlimit` system call; see Section 8.5, "`getrlimit` and `setrlimit`: Resource Limits," for more information.

B.1.3 Writing Data

Write data to a file descriptor using the `write` call. Provide the file descriptor, a pointer to a buffer of data, and the number of bytes to write. The file descriptor must be open for writing. The data written to the file need not be a character string; `write` copies arbitrary bytes from the buffer to the file descriptor.

The program in Listing B.2 appends the current time to the file specified on the command line. If the file doesn't exist, it is created. This program also uses the `time`, `localtime`, and `asctime` functions to obtain and format the current time; see their respective man pages for more information.

Listing B.2 **(*timestamp.c*) Append a Timestamp to a File**

```
#include <fcntl.h>
#include <stdio.h>
#include <string.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <time.h>
#include <unistd.h>

/* Return a character string representing the current date and time.  */

char* get_timestamp ()
{
  time_t now = time (NULL);
  return asctime (localtime (&now));
}

int main (int argc, char* argv[])
{
  /* The file to which to append the timestamp.  */
  char* filename = argv[1];
  /* Get the current timestamp.  */
  char* timestamp = get_timestamp ();
  /* Open the file for writing.  If it exists, append to it;
     otherwise, create a new file.  */
  int fd = open (filename, O_WRONLY | O_CREAT | O_APPEND, 0666);
  /* Compute the length of the timestamp string.  */
  size_t length = strlen (timestamp);
  /* Write the timestamp to the file.  */
  write (fd, timestamp, length);
  /* All done.  */
  close (fd);
  return 0;
}
```

Here's how the `timestamp` program works:

```
% ./timestamp tsfile
% cat tsfile
Thu Feb  1 23:25:20 2001
% ./timestamp tsfile
% cat tsfile
Thu Feb  1 23:25:20 2001
Thu Feb  1 23:25:47 2001
```

Note that the first time we invoke `timestamp`, it creates the file `tsfile`, while the second time it appends to it.

The `write` call returns the number of bytes that were actually written, or -1 if an error occurred. For certain kinds of file descriptors, the number of bytes actually written may be less than the number of bytes requested. In this case, it's up to you to call `write` again to write the rest of the data. The function in Listing B.3 demonstrates how you might do this. Note that for some applications, you may have to check for special conditions in the middle of the writing operation. For example, if you're writing to a network socket, you'll have to augment this function to detect whether the network connection was closed in the middle of the write operation, and if it has, to react appropriately.

Listing B.3 **(*write-all.c*) Write All of a Buffer of Data**

```
/* Write all of COUNT bytes from BUFFER to file descriptor FD.
   Returns -1 on error, or the number of bytes written.  */

ssize_t write_all (int fd, const void* buffer, size_t count)
{
  size_t left_to_write = count;
  while (left_to_write > 0) {
    size_t written = write (fd, buffer, count);
    if (written == -1)
      /* An error occurred; bail.  */
      return -1;
    else
      /* Keep count of how much more we need to write.  */
      left_to_write -= written;
  }
  /* We should have written no more than COUNT bytes!  */
  assert (left_to_write == 0);
  /* The number of bytes written is exactly COUNT.  */
  return count;
}
```

B.1.4 Reading Data

The corresponding call for reading data is `read`. Like `write`, it takes a file descriptor, a pointer to a buffer, and a count. The count specifies how many bytes are read from the file descriptor into the buffer. The call to `read` returns -1 on error or the number of bytes actually read. This may be smaller than the number of bytes requested, for example, if there aren't enough bytes left in the file.

> **Reading DOS/Windows Text Files**
>
> After reading this book, we're positive that you'll choose to write all your programs for GNU/Linux. However, your programs may occasionally need to read text files generated by DOS or Windows programs. It's important to anticipate an important difference in how text files are structured between these two platforms.
>
> In GNU/Linux text files, each line is separated from the next with a newline character. A newline is represented by the character constant `'\n'`, which has ASCII code 10. On Windows, however, lines are separated by a two-character combination: a carriage return character (the character `'\r'`, which has ASCII code 13), followed by a newline character.
>
> Some GNU/Linux text editors display `^M` at the end of each line when showing a Windows text file—this is the carriage return character. Emacs displays Windows text files properly but indicates them by showing `(DOS)` in the mode line at the bottom of the buffer. Some Windows editors, such as Notepad, display all the text in a GNU/Linux text file on a single line because they expect a carriage return at the end of each line. Other programs for both GNU/Linux and Windows that process text files may report mysterious errors when given as input a text file in the wrong format.
>
> If your program reads text files generated by Windows programs, you'll probably want to replace the sequence `'\r\n'` with a single newline. Similarly, if your program writes text files that must be read by Windows programs, replace lone newline characters with `'\r\n'` combinations. You must do this whether you use the low-level I/O calls presented in this appendix or the standard C library I/O functions.

Listing B.4 provides a simple demonstration of `read`. The program prints a hexadecimal dump of the contents of the file specified on the command line. Each line displays the offset in the file and the next 16 bytes.

Listing B.4 **(*hexdump.c*) Print a Hexadecimal Dump of a File**

```
#include <fcntl.h>
#include <stdio.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

int main (int argc, char* argv[])
{
  unsigned char buffer[16];
  size_t offset = 0;
  size_t bytes_read;
```

continues

Listing B.4 **Continued**

```
  int i;

  /* Open the file for reading.  */
  int fd = open (argv[1], O_RDONLY);

  /* Read from the file, one chunk at a time.  Continue until read
     "comes up short", that is, reads less than we asked for.
     This indicates that we've hit the end of the file.  */
  do {
    /* Read the next line's worth of bytes.  */
    bytes_read = read (fd, buffer, sizeof (buffer));
    /* Print the offset in the file, followed by the bytes themselves.  */
    printf ("0x%06x : ", offset);
    for (i = 0; i < bytes_read; ++i)
      printf ("%02x ", buffer[i]);
    printf ("\n");
    /* Keep count of our position in the file.  */
    offset += bytes_read;
  }
  while (bytes_read == sizeof (buffer));

  /* All done.  */
  close (fd);
  return 0;
}
```

Here's `hexdump` in action. It's shown printing out a dump of its own executable file:

```
% ./hexdump hexdump
0x000000 : 7f 45 4c 46 01 01 01 00 00 00 00 00 00 00 00 00
0x000010 : 02 00 03 00 01 00 00 00 c0 83 04 08 34 00 00 00
0x000020 : e8 23 00 00 00 00 00 00 34 00 20 00 06 00 28 00
0x000030 : 1d 00 1a 00 06 00 00 00 34 00 00 00 34 80 04 08
...
```

Your output may be different, depending on the compiler you used to compile `hexdump` and the compilation flags you specified.

B.1.5 Moving Around a File

A file descriptor remembers its position in a file. As you read from or write to the file descriptor, its position advances corresponding to the number of bytes you read or write. Sometimes, however, you'll need to move around a file without reading or writing data. For instance, you might want to write over the middle of a file without modifying the beginning, or you might want to jump back to the beginning of a file and reread it without reopening it.

The `lseek` call enables you to reposition a file descriptor in a file. Pass it the file descriptor and two additional arguments specifying the new position.

- If the third argument is `SEEK_SET`, `lseek` interprets the second argument as a position, in bytes, from the start of the file.
- If the third argument is `SEEK_CUR`, `lseek` interprets the second argument as an offset, which may be positive or negative, from the current position.
- If the third argument is `SEEK_END`, `lseek` interprets the second argument as an offset from the end of the file. A positive value indicates a position beyond the end of the file.

The call to `lseek` returns the new position, as an offset from the beginning of the file. The type of the offset is `off_t`. If an error occurs, `lseek` returns -1. You can't use `lseek` with some types of file descriptors, such as socket file descriptors.

If you want to find the position of a file descriptor in a file without changing it, specify a 0 offset from the current position—for example:

```
off_t position = lseek (file_descriptor, 0, SEEK_CUR);
```

Linux enables you to use `lseek` to position a file descriptor beyond the end of the file. Normally, if a file descriptor is positioned at the end of a file and you write to the file descriptor, Linux automatically expands the file to make room for the new data. If you position a file descriptor beyond the end of a file and then write to it, Linux first expands the file to accommodate the "gap" that you created with the `lseek` operation and then writes to the end of it. This gap, however, does not actually occupy space on the disk; instead, Linux just makes a note of how long it is. If you later try to read from the file, it appears to your program that the gap is filled with 0 bytes.

Using this behavior of `lseek`, it's possible to create extremely large files that occupy almost no disk space. The program `lseek-huge` in Listing B.5 does this. It takes as command-line arguments a filename and a target file size, in megabytes. The program opens a new file, advances past the end of the file using `lseek`, and then writes a single 0 byte before closing the file.

Listing B.5 **(*lseek-huge.c*) Create Large Files with *lseek***

```
#include <fcntl.h>
#include <stdlib.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

int main (int argc, char* argv[])
{
  int zero = 0;
  const int megabyte = 1024 * 1024;

  char* filename = argv[1];
```

continues

Listing B.5 **Continued**

```
  size_t length = (size_t) atoi (argv[2]) * megabyte;

  /* Open a new file.  */
  int fd = open (filename, O_WRONLY | O_CREAT | O_EXCL, 0666);
  /* Jump to 1 byte short of where we want the file to end.  */
  lseek (fd, length - 1, SEEK_SET);
  /* Write a single 0 byte.  */
  write (fd, &zero, 1);
  /* All done.  */
  close (fd);

  return 0;
}
```

Using `lseek-huge`, we'll make a 1GB (1024MB) file. Note the free space on the drive before and after the operation.

```
% df -h .
Filesystem            Size  Used Avail Use% Mounted on
/dev/hda5             2.9G  2.1G  655M  76% /
% ./lseek-huge bigfile 1024
% ls -l bigfile
-rw-r-----    1 samuel   samuel   1073741824 Feb  5 16:29 bigfile
% df -h .
Filesystem            Size  Used Avail Use% Mounted on
/dev/hda5             2.9G  2.1G  655M  76% /
```

No appreciable disk space is consumed, despite the enormous size of `bigfile`. Still, if we open `bigfile` and read from it, it appears to be filled with 1GB worth of 0s. For instance, we can examine its contents with the `hexdump` program of Listing B.4.

```
% ./hexdump bigfile | head -10
0x000000 : 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x000010 : 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x000020 : 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x000030 : 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x000040 : 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x000050 : 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
...
```

If you run this yourself, you'll probably want to kill it with Ctrl+C, rather than watching it print out 2^{30} 0 bytes.

Note that these magic gaps in files are a special feature of the `ext2` file system that's typically used for GNU/Linux disks. If you try to use `lseek-huge` to create a file on some other type of file system, such as the `fat` or `vfat` file systems used to mount DOS and Windows partitions, you'll find that the resulting file does actually occupy the full amount of disk space.

Linux does not permit you to rewind before the start of a file with `lseek`.

B.2 *stat*

Using `open` and `read`, you can extract the contents of a file. But how about other information? For instance, invoking `ls -l` displays, for the files in the current directory, such information as the file size, the last modification time, permissions, and the owner.

The `stat` call obtains this information about a file. Call `stat` with the path to the file you're interested in and a pointer to a variable of type `struct stat`. If the call to `stat` is successful, it returns 0 and fills in the fields of the structure with information about that file; otherwise, it returns -1.

These are the most useful fields in `struct stat`:

- `st_mode` contains the file's access permissions. File permissions are explained in Section 10.3, "File System Permissions."
- In addition to the access permissions, the `st_mode` field encodes the type of the file in higher-order bits. See the text immediately following this bulleted list for instructions on decoding this information.
- `st_uid` and `st_gid` contain the IDs of the user and group, respectively, to which the file belongs. User and group IDs are described in Section 10.1, "Users and Groups."
- `st_size` contains the file size, in bytes.
- `st_atime` contains the time when this file was last accessed (read or written).
- `st_mtime` contains the time when this file was last modified.

These macros check the value of the `st_mode` field value to figure out what kind of file you've invoked `stat` on. A macro evaluates to true if the file is of that type.

`S_ISBLK (`*`mode`*`)`	block device
`S_ISCHR (`*`mode`*`)`	character device
`S_ISDIR (`*`mode`*`)`	directory
`S_ISFIFO (`*`mode`*`)`	fifo (named pipe)
`S_ISLNK (`*`mode`*`)`	symbolic link
`S_ISREG (`*`mode`*`)`	regular file
`S_ISSOCK (`*`mode`*`)`	socket

The `st_dev` field contains the major and minor device number of the hardware device on which this file resides. Device numbers are discussed in Chapter 6. The major device number is shifted left 8 bits; the minor device number occupies the least significant 8 bits. The `st_ino` field contains the *inode number* of this file. This locates the file in the file system.

If you call `stat` on a symbolic link, `stat` follows the link and you can obtain the information about the file that the link points to, not about the symbolic link itself. This implies that `S_ISLNK` will never be true for the result of `stat`. Use the `lstat` function if you don't want to follow symbolic links; this function obtains information about the link itself rather than the link's target. If you call `lstat` on a file that isn't a symbolic link, it is equivalent to `stat`. Calling `stat` on a broken link (a link that points to a nonexistent or inaccessible target) results in an error, while calling `lstat` on such a link does not.

If you already have a file open for reading or writing, call `fstat` instead of `stat`. This takes a file descriptor as its first argument instead of a path.

Listing B.6 presents a function that allocates a buffer large enough to hold the contents of a file and then reads the file into the buffer. The function uses `fstat` to determine the size of the buffer that it needs to allocate and also to check that the file is indeed a regular file.

Listing B.6 **(*read-file.c*) Read a File into a Buffer**

```
#include <fcntl.h>
#include <stdio.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

/* Read the contents of FILENAME into a newly allocated buffer.  The
   size of the buffer is stored in *LENGTH.  Returns the buffer, which
   the caller must free.  If FILENAME doesn't correspond to a regular
   file, returns NULL.  */

char* read_file (const char* filename, size_t* length)
{
  int fd;
  struct stat file_info;
  char* buffer;

  /* Open the file.  */
  fd = open (filename, O_RDONLY);

  /* Get information about the file.  */
  fstat (fd, &file_info);
  *length = file_info.st_size;
  /* Make sure the file is an ordinary file.  */
  if (!S_ISREG (file_info.st_mode)) {
    /* It's not, so give up.  */
    close (fd);
    return NULL;
  }
```

```
  /* Allocate a buffer large enough to hold the file's contents.  */
  buffer = (char*) malloc (*length);
  /* Read the file into the buffer.  */
  read (fd, buffer, *length);

  /* Finish up.  */
  close (fd);
  return buffer;
}
```

B.3 Vector Reads and Writes

The `write` call takes as arguments a pointer to the start of a buffer of data and the length of that buffer. It writes a contiguous region of memory to the file descriptor. However, a program often will need to write several items of data, each residing at a different part of memory. To use `write`, the program either will have to copy the items into a single memory region, which obviously makes inefficient use of CPU cycles and memory, or will have to make multiple calls to `write`.

For some applications, multiple calls to `write` are inefficient or undesirable. For example, when writing to a network socket, two calls to `write` may cause two packets to be sent across the network, whereas the same data could be sent in a single packet if a single call to `write` were possible.

The `writev` call enables you to write multiple discontiguous regions of memory to a file descriptor in a single operation. This is called a *vector write*. The cost of using `writev` is that you must set up a data structure specifying the start and length of each region of memory. This data structure is an array of `struct iovec` elements. Each element specifies one region of memory to write; the fields `iov_base` and `iov_len` specify the address of the start of the region and the length of the region, respectively. If you know ahead of time how many regions you'll need, you can simply declare a `struct iovec` array variable; if the number of regions can vary, you must allocate the array dynamically.

Call `writev` passing a file descriptor to write to, the `struct iovec` array, and the number of elements in the array. The return value is the total number of bytes written.

The program in Listing B.7 writes its command-line arguments to a file using a single `writev` call. The first argument is the name of the file; the second and subsequent arguments are written to the file of that name, one on each line. The program allocates an array of `struct iovec` elements that is twice as long as the number of arguments it is writing—for each argument it writes the text of the argument itself as well as a new line character. Because we don't know the number of arguments in advance, the array is allocated using `malloc`.

Listing B.7 (*write-args.c*) **Write the Argument List to a File with writev**

```
#include <fcntl.h>
#include <stdlib.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <sys/uio.h>
#include <unistd.h>

int main (int argc, char* argv[])
{
  int fd;
  struct iovec* vec;
  struct iovec* vec_next;
  int i;
  /* We'll need a "buffer" containing a newline character.  Use an
     ordinary char variable for this.  */
  char newline = '\n';
  /* The first command-line argument is the output filename.  */
  char* filename = argv[1];
  /* Skip past the first two elements of the argument list.  Element
     0 is the name of this program, and element 1 is the output
     filename.  */
  argc -= 2;
  argv += 2;

  /* Allocate an array of iovec elements.  We'll need two for each
     element of the argument list, one for the text itself, and one for
     a newline.  */
  vec = (struct iovec*) malloc (2 * argc * sizeof (struct iovec));

  /* Loop over the argument list, building the iovec entries.  */
  vec_next = vec;
  for (i = 0; i < argc; ++i) {
    /* The first element is the text of the argument itself.  */
    vec_next->iov_base = argv[i];
    vec_next->iov_len = strlen (argv[i]);
    ++vec_next;
    /* The second element is a single newline character.  It's okay for
       multiple elements of the struct iovec array to point to the
       same region of memory.  */
    vec_next->iov_base = &newline;
    vec_next->iov_len = 1;
    ++vec_next;
  }

  /* Write the arguments to a file.  */
  fd = open (filename, O_WRONLY | O_CREAT);
  writev (fd, vec, 2 * argc);
```

```
  close (fd);

  free (vec);
  return 0;
}
```

Here's an example of running `write-args`.

```
% ./write-args outputfile "first arg" "second arg" "third arg"
% cat outputfile
first arg
second arg
third arg
```

Linux provides a corresponding function `readv` that reads in a single operation into multiple discontiguous regions of memory. Similar to `writev`, an array of `struct iovec` elements specifies the memory regions into which the data will be read from the file descriptor.

B.4 Relation to Standard C Library I/O Functions

We mentioned earlier that the standard C library I/O functions are implemented on top of these low-level I/O functions. Sometimes, though, it's handy to use standard library functions with file descriptors, or to use low-level I/O functions on a standard library `FILE*` stream. GNU/Linux enables you to do both.

If you've opened a file using `fopen`, you can obtain the underlying file descriptor using the `fileno` function. This takes a `FILE*` argument and returns the file descriptor. For example, to open a file with the standard library `fopen` call but write to it with `writev`, you could use this code:

```
FILE* stream = fopen (filename, "w");
int file_descriptor = fileno (stream);
writev (file_descriptor, vector, vector_length);
```

Note that `stream` and `file_descriptor` correspond to the same opened file. If you call this line, you may no longer write to `file_descriptor`:

```
fclose (stream);
```

Similarly, if you call this line, you may no longer write to `stream`:

```
close (file_descriptor);
```

To go the other way, from a file descriptor to a stream, use the `fdopen` function. This constructs a `FILE*` stream pointer corresponding to a file descriptor. The `fdopen` function takes a file descriptor argument and a string argument specifying the mode in

which to create the stream. The syntax of the mode argument is the same as that of the second argument to `fopen`, and it must be compatible with the file descriptor. For example, specify a mode of `r` for a read file descriptor or `w` for a write file descriptor. As with `fileno`, the stream and file descriptor refer to the same open file, so if you close one, you may not subsequently use the other.

B.5 Other File Operations

A few other operations on files and directories come in handy:

- `getcwd` obtains the current working directory. It takes two arguments, a `char` buffer and the length of the buffer. It copies the path of the current working directory into the buffer.
- `chdir` changes the current working directory to the path provided as its argument.
- `mkdir` creates a new directory. Its first argument is the path of the new directory. Its second argument is the access permissions to use for the new file. The interpretation of the permissions are the same as that of the third argument to `open` and are modified by the process's umask.
- `rmdir` deletes a directory. Its argument is the directory's path.
- `unlink` deletes a file. Its argument is the path to the file. This call can also be used to delete other file system objects, such as named pipes (see Section 5.4.5, "FIFOs") or devices (see Chapter 6).

  Actually, `unlink` doesn't necessarily delete the file's contents. As its name implies, it unlinks the file from the directory containing it. The file is no longer listed in that directory, but if any process holds an open file descriptor to the file, the file's contents are not removed from the disk. Only when no process has an open file descriptor are the file's contents deleted. So, if one process opens a file for reading or writing and then a second process unlinks the file and creates a new file with the same name, the first process sees the old contents of the file rather than the new contents (unless it closes the file and reopens it).
- `rename` renames or moves a file. Its two arguments are the old path and the new path for the file. If the paths are in different directories, `rename` moves the file, as long as both are on the same file system. You can use `rename` to move directories or other file system objects as well.

B.6 Reading Directory Contents

GNU/Linux provides functions for reading the contents of directories. Although these aren't directly related to the low-level I/O functions described in this appendix, we present them here anyway because they're often useful in application programs.

To read the contents of a directory, follow these steps:

1. Call `opendir`, passing the path of the directory that you want to examine. The call to `opendir` returns a `DIR*` handle, which you'll use to access the directory contents. If an error occurs, the call returns NULL.
2. Call `readdir` repeatedly, passing the `DIR*` handle that you obtained from `opendir`. Each time you call `readdir`, it returns a pointer to a `struct dirent` instance corresponding to the next directory entry. When you reach the end of the directory's contents, `readdir` returns NULL.

   The `struct dirent` that you get back from `readdir` has a field `d_name`, which contains the name of the directory entry.
3. Call `closedir`, passing the `DIR*` handle, to end the directory listing operation.

Include `<sys/types.h>` and `<dirent.h>` if you use these functions in your program.

Note that if you need the contents of the directory arranged in a particular order, you'll have to sort them yourself.

The program in Listing B.8 prints out the contents of a directory. The directory may be specified on the command line, but if it is not specified, the program uses the current working directory. For each entry in the directory, it displays the type of the entry and its path. The `get_file_type` function uses `lstat` to determine the type of a file system entry.

Listing B.8 **(*listdir.c*) Print a Directory Listing**

```
#include <assert.h>
#include <dirent.h>
#include <stdio.h>
#include <string.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

/* Return a string that describes the type of the file system entry PATH.  */

const char* get_file_type (const char* path)
{
  struct stat st;
  lstat (path, &st);
  if (S_ISLNK (st.st_mode))
    return "symbolic link";
  else if (S_ISDIR (st.st_mode))
    return "directory";
  else if (S_ISCHR (st.st_mode))
    return "character device";
  else if (S_ISBLK (st.st_mode))
    return "block device";
```

continues

Listing B.8 **Continued**

```
  else if (S_ISFIFO (st.st_mode))
    return "fifo";
  else if (S_ISSOCK (st.st_mode))
    return "socket";
  else if (S_ISREG (st.st_mode))
    return "regular file";
  else
    /* Unexpected.  Each entry should be one of the types above.  */
    assert (0);
}

int main (int argc, char* argv[])
{
  char* dir_path;
  DIR* dir;
  struct dirent* entry;
  char entry_path[PATH_MAX + 1];
  size_t path_len;

  if (argc >= 2)
    /* If a directory was specified on the command line, use it.  */
    dir_path = argv[1];
  else
    /* Otherwise, use the current directory.  */
    dir_path = ".";
  /* Copy the directory path into entry_path.  */
  strncpy (entry_path, dir_path, sizeof (entry_path));
  path_len = strlen (dir_path);
  /* If the directory path doesn't end with a slash, append a slash.  */
  if (entry_path[path_len - 1] != '/') {
    entry_path[path_len] = '/';
    entry_path[path_len + 1] = '\0';
    ++path_len;
  }

  /* Start the listing operation of the directory specified on the
     command line.  */
  dir = opendir (dir_path);
  /* Loop over all directory entries.  */
  while ((entry = readdir (dir)) != NULL) {
    const char* type;
    /* Build the path to the directory entry by appending the entry
       name to the path name.  */
    strncpy (entry_path + path_len, entry->d_name,
             sizeof (entry_path) - path_len);
    /* Determine the type of the entry.  */
    type = get_file_type (entry_path);
    /* Print the type and path of the entry.  */
    printf ("%-18s: %s\n", type, entry_path);
  }
```

```
  /* All done.  */
  closedir (dir);
  return 0;
}
```

Here are the first few lines of output from listing the `/dev` directory. (Your output might differ somewhat.)

```
% ./listdir /dev
directory         : /dev/.
directory         : /dev/..
socket            : /dev/log
character device  : /dev/null
regular file      : /dev/MAKEDEV
fifo              : /dev/initctl
character device  : /dev/agpgart
...
```

To verify this, you can use the `ls` command on the same directory. Specify the `-U` flag to instruct `ls` not to sort the entries, and specify the `-a` flag to cause the current directory (`.`) and the parent directory (`..`) to be included.

```
% ls -lUa /dev
total 124
drwxr-xr-x    7 root     root        36864 Feb  1 15:14 .
drwxr-xr-x   22 root     root         4096 Oct 11 16:39 ..
srw-rw-rw-    1 root     root            0 Dec 18 01:31 log
crw-rw-rw-    1 root     root       1,   3 May  5  1998 null
-rwxr-xr-x    1 root     root        26689 Mar  2  2000 MAKEDEV
prw-------    1 root     root            0 Dec 11 18:37 initctl
crw-rw-r--    1 root     root      10, 175 Feb  3  2000 agpgart
...
```

The first character of each line in the output of `ls` indicates the type of the entry.

C

Table of Signals

TABLE C.1 LISTS SOME OF THE LINUX SIGNALS YOU'RE MOST LIKELY to encounter or use. Note that some signals have multiple interpretations, depending on where they occur.

The names of the signals listed here are defined as preprocessor macros. To use them in your program, include `<signal.h>`. The actual definitions are in `/usr/include/sys/signum.h`, which is included as part of `<signal.h>`.

For a full list of Linux signals, including a short description of each and the default behavior when the signal is delivered, consult the `signal` man page in Section 7 by invoking the following:

```
% man 7 signal
```

Table C.1 **Linux Signals**

Name	Description
`SIGHUP`	Linux sends a process this signal when it becomes disconnected from a terminal. Many Linux programs use `SIGHUP` for an unrelated purpose: to indicate to a running program that it should reread its configuration files.

continues

Table C.1 **Continued**

Name	Description
SIGINT	Linux sends a process this signal when the user tries to end it by pressing Ctrl+C.
SIGILL	A process gets this signal when it attempts to execute an illegal instruction. This could indicate that the program's stack is corrupted.
SIGABRT	The `abort` function causes the process to receive this signal.
SIGFPE	The process has executed an invalid floating-point math instruction. Depending on how the CPU is configured, an invalid floating-point operation may return a special non-number value such as `inf` (infinity) or `NaN` (not a number) instead of raising `SIGFPE`.
SIGKILL	This signal ends a process immediately and cannot be handled.
SIGUSR1	This signal is reserved for application use.
SIGUSR2	This signal is reserved for application use.
SIGSEGV	The program attempted an invalid memory access. The access may be to an address that is invalid in the process's virtual memory space, or the access may be forbidden by the target memory's permissions. Dereferencing a "wild pointer" can cause a `SIGSEGV`.
SIGPIPE	The program has attempted to access a broken data stream, such as a socket connection that has been closed by the other party.
SIGALRM	The `alarm` system call schedules the delivery of this signal at a later time. See Section 8.13, "`setitimer`: Setting Interval Timers," in Chapter 8, "Linux System Calls," for information about `setitimer`, a generalized version of `alarm`.
SIGTERM	This signal requests that a process terminate. This is the default signal sent by the `kill` command.
SIGCHLD	Linux sends a process this signal when a child process exits. See Section 3.4.4, "Cleaning Up Children Asynchronously," in Chapter 3, "Processes."
SIGXCPU	Linux sends a process this signal when it exceeds the limit of CPU time that it can consume. See Section 8.5, "`getrlimit` and `setrlimit`: Resource Limits," in Chapter 8 for information on CPU time limits.
SIGVTALRM	The `setitimer` schedules the delivery of this signal at a future time. See Section 8.13, "`setitimer`: Setting Interval Timers."

D

Online Resources

This appendix lists some places to visit on the Internet to learn more about programming for the GNU/Linux system.

D.1 General Information

- `http://www.advancedlinuxprogramming.com` is this book's home on the Internet. Here, you can download the full text of this book and program source code, find links to other online resources, and get more information about programming GNU/Linux. The same information can also be found at `http://www.newriders.com`.
- `http://www.linuxdoc.org` is the home of the Linux Documentation Project. This site is a repository for a wealth of documentation, FAQ lists, HOWTOs, and other documentation about GNU/Linux systems and software.

D.2 Information About GNU/Linux Software

- `http://www.gnu.org` is the home of the GNU Project. From this site, you can download a staggering array of sophisticated free software applications. Among them is the GNU C library, which is part of every GNU/Linux system and contains many of the functions described in this book. The GNU Project site also provides information about how you can contribute to the development of the GNU/Linux system by writing code or documentation, by using free software, and by spreading the free software message.
- `http://www.kernel.org` is the primary site for distribution of the Linux kernel source code. For the trickiest and most technically detailed questions about how Linux works, the source code is the best place to look. See also the `Documentation` directory for explanation of the kernel internals.
- `http://www.linuxhq.com` also distributes Linux kernel sources, patches, and related information.
- `http://gcc.gnu.org` is the home of the GNU Compiler Collection (GCC). GCC is the primary compiler used on GNU/Linux systems, and it includes compilers for C, C++, Objective C, Java, Chill, and Fortran.
- `http://www.gnome.org` and `http://www.kde.org` are the homes of the two most popular GNU/Linux windowing environments, Gnome and KDE. If you plan to write an application with a graphical user interface, you should familiarize yourself with either or both.

D.3 Other Sites

- `http://developer.intel.com` provides information about Intel processor architectures, including the x86 (IA32) architecture. If you are developing for x86 Linux and you use inline assembly instructions, the technical manuals available here will be very useful.
- `http://www.amd.com/devconn/` provides similar information about AMD's line of microprocessors and its special features.
- `http://freshmeat.net` is an index of open source software, generally for GNU/Linux. This site is one of the best places to stay abreast of the newest releases of GNU/Linux software, from core system components to more obscure, specialized applications.
- `http://www.linuxsecurity.com` contains information, techniques, and links to software related to GNU/Linux security. The site is of interest to users, system administrators, and developers.

E

Open Publication License Version 1.0

I. Requirements on Both Unmodified and Modified Versions

The Open Publication works may be reproduced and distributed in whole or in part, in any medium, physical or electronic, provided that the terms of this license are adhered to and that this license or an incorporation of it by reference (with any options elected by the author(s) and/or publisher) is displayed in the reproduction.

Proper form for an incorporation by reference is as follows:

> Copyright© <year> by <author's name or designee>. This material may be distributed only subject to the terms and conditions set forth in the Open Publication License, vX.Y or later (the latest version is presently available at `http://www.opencontent.org/openpub/`).

The reference must be immediately followed with any options elected by the author(s) or publisher of the document (see Section VI, "License Options").

Commercial redistribution of Open Publication-licensed material is permitted.

Any publication in standard (paper) book form shall require the citation of the original publisher and author. The publisher and author's names shall appear on all outer surfaces of the book. On all outer surfaces of the book, the original publisher's name shall be as large as the title of the work and cited as possessive with respect to the title.

II. Copyright

The copyright to each Open Publication is owned by its author(s) or designee.

III. Scope of License

The following license terms apply to all Open Publication works, unless otherwise explicitly stated in the document.

Mere aggregation of Open Publication works or a portion of an Open Publication work with other works or programs on the same media shall not cause this license to apply to those other works. The aggregate work shall contain a notice specifying the inclusion of the Open Publication material and appropriate copyright notice.

- **Severability.** If any part of this license is found to be unenforceable in any jurisdiction, the remaining portions of the license remain in force.
- **No warranty.** Open Publication works are licensed and provided "as is" without warranty of any kind, express or implied, including, but not limited to, the implied warranties of merchantability and fitness for a particular purpose or a warranty of noninfringement.

IV. Requirements on Modified Works

All modified versions of documents covered by this license, including translations, anthologies, compilations, and partial documents, must meet the following requirements:

1. The modified version must be labeled as such.
2. The person making the modifications must be identified, and the modifications must be dated.
3. Acknowledgement of the original author and publisher, if applicable, must be retained according to normal academic citation practices.
4. The location of the original unmodified document must be identified.
5. The original author's (or authors') name(s) may not be used to assert or imply endorsement of the resulting document without the original author's (or authors') permission.

V. Good-Practice Recommendations

In addition to the requirements of this license, it is requested from and strongly recommended of redistributors that:

1. If you are distributing Open Publication works on hard copy or CD-ROM, you provide email notification to the authors of your intent to redistribute at least 30 days before your manuscript or media freeze, to give the authors time to provide updated documents. This notification should describe modifications, if any, made to the document.

2. All substantive modifications (including deletions) be either clearly marked up in the document or else described in an attachment to the document.
3. Finally, although it is not mandatory under this license, it is considered good form to offer a free copy of any hard copy and CD-ROM expression of an Open Publication-licensed work to its author(s).

VI. License Options

The author(s) or publisher of an Open Publication-licensed document may elect certain options by appending language to the reference to or copy of the license. These options are considered part of the license instance and must be included with the license (or its incorporation by reference) in derived works.

A. To prohibit distribution of substantively modified versions without the explicit permission of the author(s). "Substantive modification" is defined as a change to the semantic content of the document and excludes mere changes in format or typographical corrections.

   To accomplish this, add the phrase "Distribution of substantively modified versions of this document is prohibited without the explicit permission of the copyright holder" to the license reference or copy.

B. To prohibit any publication of this work or derivative works in whole or in part in standard (paper) book form for commercial purposes is prohibited unless prior permission is obtained from the copyright holder.

   To accomplish this, add the phrase "Distribution of the work or derivative of the work in any standard (paper) book form is prohibited unless prior permission is obtained from the copyright holder" to the license reference or copy.

Open Publication Policy Appendix

(This is not considered part of the license.)

Open Publication works are available in source format via the Open Publication home page at `http://works.opencontent.org/`.

Open Publication authors who want to include their own license on Open Publication works may do so, as long as their terms are not more restrictive than the Open Publication license.

If you have questions about the Open Publication License, please contact David Wiley, or the Open Publication Authors' List at `opal@opencontent.org`, via email.

To subscribe to the Open Publication Authors' List, send email to `opal-request@opencontent.org` with the word "subscribe" in the body.

To post to the Open Publication Authors' List, send email to opal@opencontent.org, or simply reply to a previous post.

To unsubscribe from the Open Publication Authors' List, send email to opal-request@opencontent.org with the word "unsubscribe" in the body.

F

GNU General Public License[1]

Preamble

The licenses for most software are designed to take away your freedom to share and change it. By contrast, the GNU General Public License is intended to guarantee your freedom to share and change free software—to make sure the software is free for all its users. This General Public License applies to most of the Free Software Foundation's software and to any other program whose authors commit to using it. (Some other Free Software Foundation software is covered by the GNU Library General Public License instead.) You can apply it to your programs, too.

When we speak of free software, we are referring to freedom, not price. Our General Public Licenses are designed to make sure that you have the freedom to distribute copies of free software (and charge for this service if you wish), that you receive source code or can get it if you want it, that you can change the software or use pieces of it in new free programs; and that you know you can do these things.

1. This license can also be found online at `http://www.gnu.org/copyleft/gpl.html`.

To protect your rights, we need to make restrictions that forbid anyone to deny you these rights or to ask you to surrender the rights. These restrictions translate to certain responsibilities for you if you distribute copies of the software, or if you modify it.

For example, if you distribute copies of such a program, whether gratis or for a fee, you must give the recipients all the rights that you have. You must make sure that they, too, receive or can get the source code. And you must show them these terms so they know their rights.

We protect your rights with two steps: (1) copyright the software, and (2) offer you this license which gives you legal permission to copy, distribute and/or modify the software.

Also, for each author's protection and ours, we want to make certain that everyone understands that there is no warranty for this free software. If the software is modified by someone else and passed on, we want its recipients to know that what they have is not the original, so that any problems introduced by others will not reflect on the original authors' reputations.

Finally, any free program is threatened constantly by software patents. We wish to avoid the danger that redistributors of a free program will individually obtain patent licenses, in effect making the program proprietary. To prevent this, we have made it clear that any patent must be licensed for everyone's free use or not licensed at all.

The precise terms and conditions for copying, distribution and modification follow.

Terms and Conditions for Copying, Distribution and Modification

0. This License applies to any program or other work which contains a notice placed by the copyright holder saying it may be distributed under the terms of this General Public License. The "Program," below, refers to any such program or work, and a "work based on the Program" means either the Program or any derivative work under copyright law: that is to say, a work containing the Program or a portion of it, either verbatim or with modifications and/or translated into another language. (Hereinafter, translation is included without limitation in the term "modification.") Each licensee is addressed as "you."

   Activities other than copying, distribution and modification are not covered by this License; they are outside its scope. The act of running the Program is not restricted, and the output from the Program is covered only if its contents constitute a work based on the Program (independent of having been made by running the Program). Whether that is true depends on what the Program does.

1. You may copy and distribute verbatim copies of the Program's source code as you receive it, in any medium, provided that you conspicuously and appropriately publish on each copy an appropriate copyright notice and disclaimer of warranty; keep intact all the notices that refer to this License and to the absence

of any warranty; and give any other recipients of the Program a copy of this License along with the Program.

You may charge a fee for the physical act of transferring a copy, and you may at your option offer warranty protection in exchange for a fee.

2. You may modify your copy or copies of the Program or any portion of it, thus forming a work based on the Program, and copy and distribute such modifications or work under the terms of Section 1 above, provided that you also meet all of these conditions:
   - a) You must cause the modified files to carry prominent notices stating that you changed the files and the date of any change.
   - b) You must cause any work that you distribute or publish, that in whole or in part contains or is derived from the Program or any part thereof, to be licensed as a whole at no charge to all third parties under the terms of this License.
   - c) If the modified program normally reads commands interactively when run, you must cause it, when started running for such interactive use in the most ordinary way, to print or display an announcement including an appropriate copyright notice and a notice that there is no warranty (or else, saying that you provide a warranty) and that users may redistribute the program under these conditions, and telling the user how to view a copy of this License. (Exception: if the Program itself is interactive but does not normally print such an announcement, your work based on the Program is not required to print an announcement.)

   These requirements apply to the modified work as a whole. If identifiable sections of that work are not derived from the Program, and can be reasonably considered independent and separate works in themselves, then this License, and its terms, do not apply to those sections when you distribute them as separate works. But when you distribute the same sections as part of a whole which is a work based on the Program, the distribution of the whole must be on the terms of this License, whose permissions for other licensees extend to the entire whole, and thus to each and every part regardless of who wrote it.

   Thus, it is not the intent of this section to claim rights or contest your rights to work written entirely by you; rather, the intent is to exercise the right to control the distribution of derivative or collective works based on the Program.

   In addition, mere aggregation of another work not based on the Program with the Program (or with a work based on the Program) on a volume of a storage or distribution medium does not bring the other work under the scope of this License.

3. You may copy and distribute the Program (or a work based on it, under Section 2) in object code or executable form under the terms of Sections 1 and 2 above provided that you also do one of the following:
   - a) Accompany it with the complete corresponding machine-readable source code, which must be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange; or,
   - b) Accompany it with a written offer, valid for at least three years, to give any third party, for a charge no more than your cost of physically performing source distribution, a complete machine-readable copy of the corresponding source code, to be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange; or,
   - c) Accompany it with the information you received as to the offer to distribute corresponding source code. (This alternative is allowed only for noncommercial distribution and only if you received the program in object code or executable form with such an offer, in accord with Subsection b above.)

   The source code for a work means the preferred form of the work for making modifications to it. For an executable work, complete source code means all the source code for all modules it contains, plus any associated interface definition files, plus the scripts used to control compilation and installation of the executable. However, as a special exception, the source code distributed need not include anything that is normally distributed (in either source or binary form) with the major components (compiler, kernel, and so on) of the operating system on which the executable runs, unless that component itself accompanies the executable.

   If distribution of executable or object code is made by offering access to copy from a designated place, then offering equivalent access to copy the source code from the same place counts as distribution of the source code, even though third parties are not compelled to copy the source along with the object code.
4. You may not copy, modify, sublicense, or distribute the Program except as expressly provided under this License. Any attempt otherwise to copy, modify, sublicense or distribute the Program is void, and will automatically terminate your rights under this License. However, parties who have received copies, or rights, from you under this License will not have their licenses terminated so long as such parties remain in full compliance.
5. You are not required to accept this License, since you have not signed it. However, nothing else grants you permission to modify or distribute the Program or its derivative works. These actions are prohibited by law if you do not accept this License. Therefore, by modifying or distributing the Program (or any work based on the Program), you indicate your acceptance of this License to do so, and all its terms and conditions for copying, distributing or modifying the Program or works based on it.

6. Each time you redistribute the Program (or any work based on the Program), the recipient automatically receives a license from the original licensor to copy, distribute or modify the Program subject to these terms and conditions. You may not impose any further restrictions on the recipients' exercise of the rights granted herein. You are not responsible for enforcing compliance by third parties to this License.
7. If, as a consequence of a court judgment or allegation of patent infringement or for any other reason (not limited to patent issues), conditions are imposed on you (whether by court order, agreement or otherwise) that contradict the conditions of this License, they do not excuse you from the conditions of this License. If you cannot distribute so as to satisfy simultaneously your obligations under this License and any other pertinent obligations, then as a consequence you may not distribute the Program at all. For example, if a patent license would not permit royalty-free redistribution of the Program by all those who receive copies directly or indirectly through you, then the only way you could satisfy both it and this License would be to refrain entirely from distribution of the Program.

   If any portion of this section is held invalid or unenforceable under any particular circumstance, the balance of the section is intended to apply and the section as a whole is intended to apply in other circumstances.

   It is not the purpose of this section to induce you to infringe any patents or other property right claims or to contest validity of any such claims; this section has the sole purpose of protecting the integrity of the free software distribution system, which is implemented by public license practices. Many people have made generous contributions to the wide range of software distributed through that system in reliance on consistent application of that system; it is up to the author/donor to decide if he or she is willing to distribute software through any other system and a licensee cannot impose that choice.

   This section is intended to make thoroughly clear what is believed to be a consequence of the rest of this License.
8. If the distribution and/or use of the Program is restricted in certain countries either by patents or by copyrighted interfaces, the original copyright holder who places the Program under this License may add an explicit geographical distribution limitation excluding those countries, so that distribution is permitted only in or among countries not thus excluded. In such case, this License incorporates the limitation as if written in the body of this License.
9. The Free Software Foundation may publish revised and/or new versions of the General Public License from time to time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns.

Each version is given a distinguishing version number. If the Program specifies a version number of this License which applies to it and "any later version", you have the option of following the terms and conditions either of that version or of any later version published by the Free Software Foundation. If the Program does not specify a version number of this License, you may choose any version ever published by the Free Software Foundation.

10. If you wish to incorporate parts of the Program into other free programs whose distribution conditions are different, write to the author to ask for permission. For software which is copyrighted by the Free Software Foundation, write to the Free Software Foundation; we sometimes make exceptions for this. Our decision will be guided by the two goals of preserving the free status of all derivatives of our free software and of promoting the sharing and reuse of software generally.

No Warranty

11. BECAUSE THE PROGRAM IS LICENSED FREE OF CHARGE, THERE IS NO WARRANTY FOR THE PROGRAM, TO THE EXTENT PERMITTED BY APPLICABLE LAW. EXCEPT WHEN OTHERWISE STATED IN WRITING THE COPYRIGHT HOLDERS AND/OR OTHER PARTIES PROVIDE THE PROGRAM "AS IS" WITHOUT WARRANTY OF ANY KIND, EITHER EXPRESSED OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. THE ENTIRE RISK AS TO THE QUALITY AND PERFORMANCE OF THE PROGRAM IS WITH YOU. SHOULD THE PROGRAM PROVE DEFECTIVE, YOU ASSUME THE COST OF ALL NECESSARY SERVICING, REPAIR OR CORRECTION.
12. IN NO EVENT UNLESS REQUIRED BY APPLICABLE LAW OR AGREED TO IN WRITING WILL ANY COPYRIGHT HOLDER, OR ANY OTHER PARTY WHO MAY MODIFY AND/OR REDISTRIBUTE THE PROGRAM AS PERMITTED ABOVE, BE LIABLE TO YOU FOR DAMAGES, INCLUDING ANY GENERAL, SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES ARISING OUT OF THE USE OR INABILITY TO USE THE PROGRAM (INCLUDING BUT NOT LIMITED TO LOSS OF DATA OR DATA BEING RENDERED INACCURATE OR LOSSES SUSTAINED BY YOU OR THIRD PARTIES OR A FAILURE OF THE PROGRAM TO OPERATE WITH ANY OTHER PROGRAMS), EVEN IF SUCH HOLDER OR OTHER PARTY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

End of Terms and Conditions

How to Apply These Terms to Your New Programs

If you develop a new program, and you want it to be of the greatest possible use to the public, the best way to achieve this is to make it free software which everyone can redistribute and change under these terms.

To do so, attach the following notices to the program. It is safest to attach them to the start of each source file to most effectively convey the exclusion of warranty; and each file should have at least the "copyright" line and a pointer to where the full notice is found.

> one line to give the program's name and an idea of what it does.
>
> Copyright © yyyy name of author

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

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

You should have received a copy of the GNU General Public License along with this program; if not, write to the Free Software Foundation, Inc., 59 Temple Place–Suite 330, Boston, MA 02111-1307, USA.

Also add information on how to contact you by electronic and paper mail.

If the program is interactive, make it output a short notice like this when it starts in an interactive mode:

> Gnomovision version 69, Copyright © year name of author
>
> Gnomovision comes with ABSOLUTELY NO WARRANTY; for details type 'show w'. This is free software, and you are welcome to redistribute it under certain conditions; type 'show c' for details.

The hypothetical commands 'show w' and 'show c' should show the appropriate parts of the General Public License. Of course, the commands you use may be called something other than 'show w' and 'show c'; they could even be mouse-clicks or menu items—whatever suits your program.

You should also get your employer (if you work as a programmer) or your school, if any, to sign a "copyright disclaimer" for the program, if necessary. Here is a sample; alter the names:

> Yoyodyne, Inc., hereby disclaims all copyright interest in the program 'Gnomovision' (which makes passes at compilers) written by James Hacker.
>
> signature of Ty Coon, 1 April 1989
>
> Ty Coon, President of Vice

This General Public License does not permit incorporating your program into proprietary programs. If your program is a subroutine library, you may consider it more useful to permit linking proprietary applications with the library. If this is what you want to do, use the GNU Library General Public License instead of this License.

FSF & GNU inquiries & questions to gnu@gnu.org.

Comments on these web pages to webmasters@www.gnu.org, send other questions to gnu@gnu.org.

Copyright notice above.

Free Software Foundation, Inc., 59 Temple Place–Suite 330, Boston, MA 02111, USA

Updated: 31 Jul 2000 jonas

Index

Symbols

A

B

C

D

E

F

G

H

I

J-K

L

M

N

O

P

Q-R

S

T

U

V

W-Z

VOICES THAT MATTER

HOW TO CONTACT US

VISIT OUR WEB SITE

WWW.NEWRIDERS.COM

On our Web site, you'll find information about our other books, authors, tables of contents, and book errata. You will also find information about book registration and how to purchase our books, both domestically and internationally.

EMAIL US

Contact us at: **nrfeedback@newriders.com**

- If you have comments or questions about this book
- To report errors that you have found in this book
- If you have a book proposal to submit or are interested in writing for New Riders
- If you are an expert in a computer topic or technology and are interested in being a technical editor who reviews manuscripts for technical accuracy

Contact us at: **nreducation@newriders.com**

- If you are an instructor from an educational institution who wants to preview New Riders books for classroom use. Email should include your name, title, school, department, address, phone number, office days/hours, text in use, and enrollment, along with your request for desk/examination copies and/or additional information.

Contact us at: **nrmedia@newriders.com**

- If you are a member of the media who is interested in reviewing copies of New Riders books. Send your name, mailing address, and email address, along with the name of the publication or Web site you work for.

BULK PURCHASES/CORPORATE SALES

If you are interested in buying 10 or more copies of a title or want to set up an account for your company to purchase directly from the publisher at a substantial discount, contact us at 800-382-3419 or email your contact information to `corpsales@pearsontechgroup.com`. A sales representative will contact you with more information.

WRITE TO US

New Riders Publishing
201 W. 103rd St.
Indianapolis, IN 46290-1097

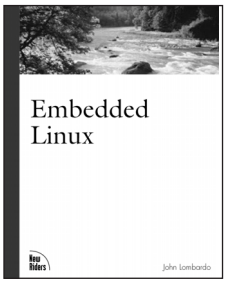
CALL/FAX US

Toll-free (800) 571-5840
If outside U.S. (317) 581-3500
Ask for New Riders
FAX: (317) 581-4663

New Riders

WWW.NEWRIDERS.COM

TOP SELLING BOOKS FROM NEW RIDERS

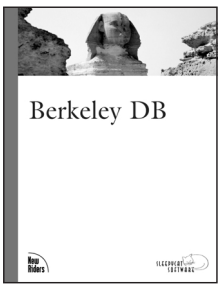


ISBN: 073570998X
Available Summer 2001
US $39.99

Embedded Linux

John Lombardo

Embedded Linux provides the reader the information needed to design, develop, and debug an embedded Linux appliance. It explores why Linux is a great choice for an embedded application and what to look for when choosing hardware.

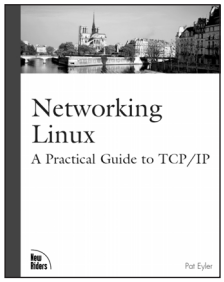


ISBN: 0735710643
Available Summer 2001
US $49.99

Berkeley DB

Sleepycat Software

This book is a tutorial on using the Berkeley DB, covering methods, architecture, data applications, memory, and configuring the APIs in Perl, Java, and Tcl, etc. The second part of the book is a reference section of the various Berkeley DB APIs.

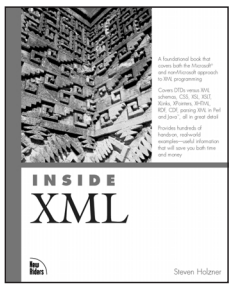


ISBN: 0735710317
400 pages
US $39.99

Networking Linux: A Practical Guide to TCP/IP

Pat Eyler

This book goes beyond the conceptual and shows the necessary know-how to Linux TCP/IP implementation step-by-step. It is ideal for programmers and networking administrators who are in need of a platform-specific guide in order to increase their knowledge and overall efficiency.

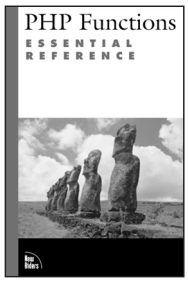


ISBN: 0735710201
1152 pages
US $49.99

Inside XML

Steven Holzner

Inside XML is a foundation book that covers both the Microsoft and non-Microsoft approach to XML programming. It covers in detail the hot aspects of XML, such as DTD's vs. XML Schemas, CSS, XSL, XSLT, Xlinks, Xpointers, XHTML, RDF, CDF, parsing XML in Perl and Java, and much more.



ISBN 073570970X
500 pages
US $39.99

PHP Functions Essential Reference

The *PHP Functions Essential Reference* is a simple, clear, and authoritative function reference that clarifies and expands upon PHP's existing documentation. It will help the reader write effective code that makes full use of the rich variety of functions available in PHP.

Solutions from experts you know and trust.

www.informit.com

OPERATING SYSTEMS

WEB DEVELOPMENT

PROGRAMMING

NETWORKING

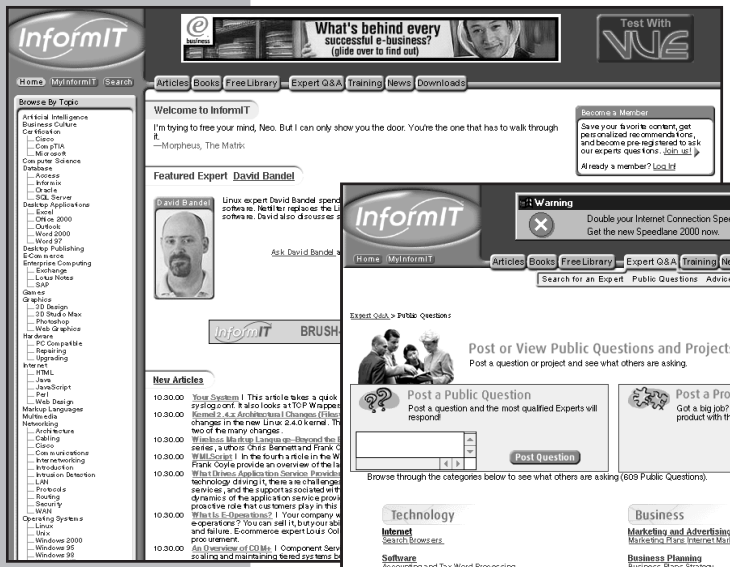
CERTIFICATION

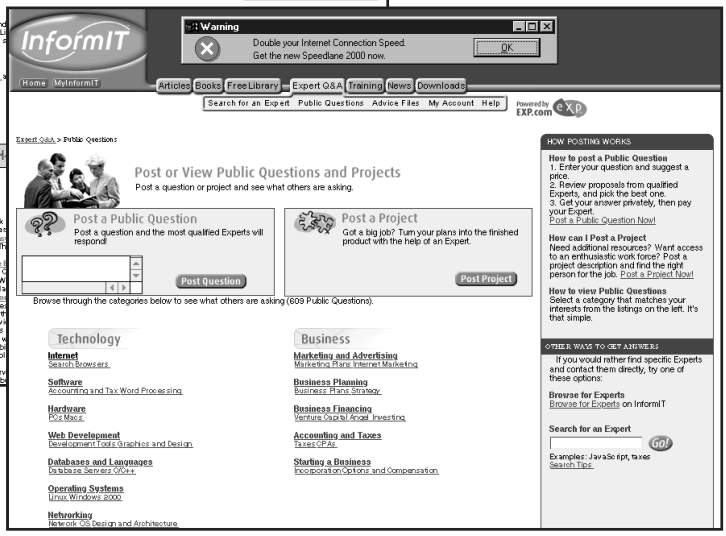
AND MORE...

Expert Access. Free Content.

New Riders has partnered with **InformIT.com** to bring technical information to your desktop. Drawing on New Riders authors and reviewers to provide additional information on topics you're interested in, **InformIT.com** has free, in-depth information you won't find anywhere else.

- **Master the skills you need, when you need them**
- **Call on resources from some of the best minds in the industry**
- **Get answers when you need them, using InformIT's comprehensive library or live experts online**
- **Go above and beyond what you find in New Riders books, extending your knowledge**





As an **InformIT** partner, **New Riders** has shared the wisdom and knowledge of our authors with you online. Visit **InformIT.com** to see what you're missing.

InformIT

www.informit.com ▪ www.newriders.com

New Riders

Colophon

The ruins of the Stabian Baths in Pompeii, captured by photographer Mel Curtis, are featured on the cover of this book. Said to be the largest and oldest of the baths, the Stabian baths also offered massages and poetry readings. Residents of Pompeii visited these public baths daily. The baths are named for their location on Stabian Street.

This book was written and edited in LaTeX, and then converted to Microsoft Word by New Riders and laid out in QuarkXPress. The font used for the body text is Bembo and MCPdigital. It was printed on 50# Husky Offset Smooth paper at R.R. Donnelley & Sons in Crawfordsville, Indiana. Prepress consisted of PostScript computer-to-plate technology (filmless process). The cover was printed at Moore Langen Printing in Terre Haute, Indiana, on Carolina, coated on one side.