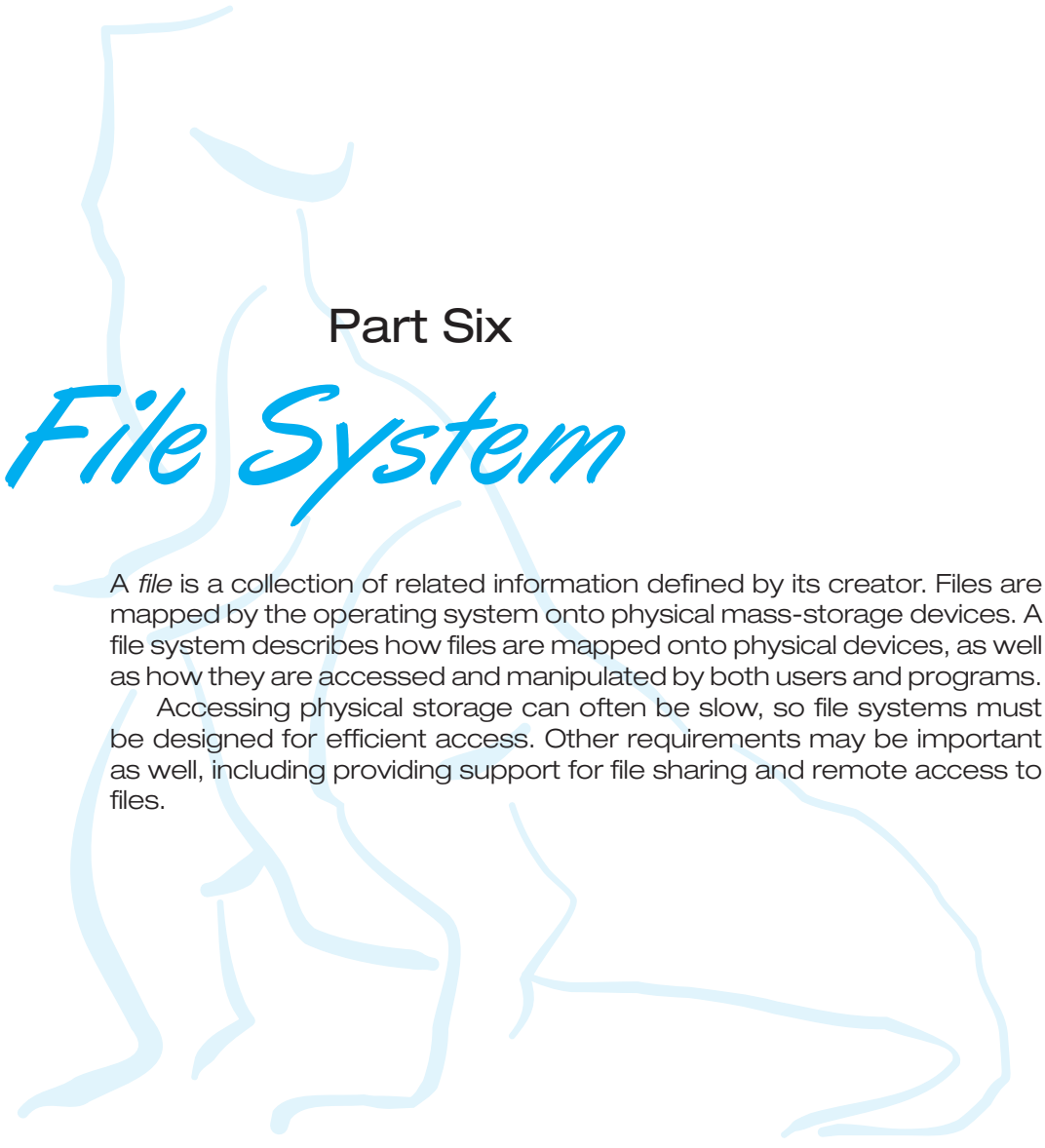

Part Six

File System

A *file* is a collection of related information defined by its creator. Files are mapped by the operating system onto physical mass-storage devices. A file system describes how files are mapped onto physical devices, as well as how they are accessed and manipulated by both users and programs.

Accessing physical storage can often be slow, so file systems must be designed for efficient access. Other requirements may be important as well, including providing support for file sharing and remote access to files.

File-System Interface

For most users, the file system is the most visible aspect of a general-purpose operating system. It provides the mechanism for on-line storage of and access to both data and programs of the operating system and all the users of the computer system. The file system consists of two distinct parts: a collection of files, each storing related data, and a directory structure, which organizes and provides information about all the files in the system. Most file systems live on storage devices, which we described in Chapter 11 and will continue to discuss in the next chapter. In this chapter, we consider the various aspects of files and the major directory structures. We also discuss the semantics of sharing files among multiple processes, users, and computers. Finally, we discuss ways to handle file protection, necessary when we have multiple users and want to control who may access files and how files may be accessed.

CHAPTER OBJECTIVES

- Explain the function of file systems.
- Describe the interfaces to file systems.
- Discuss file-system design tradeoffs, including access methods, file sharing, file locking, and directory structures.
- Explore file-system protection.

13.1 File Concept

Computers can store information on various storage media, such as NVM devices, HDDs, magnetic tapes, and optical disks. So that the computer system will be convenient to use, the operating system provides a uniform logical view of stored information. The operating system abstracts from the physical properties of its storage devices to define a logical storage unit, the **fil** . Files are mapped by the operating system onto physical devices. These storage devices are usually nonvolatile, so the contents are persistent between system reboots.

A file is a named collection of related information that is recorded on secondary storage. From a user's perspective, a file is the smallest allotment of logical secondary storage; that is, data cannot be written to secondary storage unless they are within a file. Commonly, files represent programs (both source and object forms) and data. Data files may be numeric, alphabetic, alphanumeric, or binary. Files may be free form, such as text files, or may be formatted rigidly. In general, a file is a sequence of bits, bytes, lines, or records, the meaning of which is defined by the file's creator and user. The concept of a file is thus extremely general.

Because files are **the** method users and applications use to store and retrieve data, and because they are so general purpose, their use has stretched beyond its original confines. For example, UNIX, Linux, and some other operating systems provide a `proc` file system that uses file-system interfaces to provide access to system information (such as process details).

The information in a file is defined by its creator. Many different types of information may be stored in a file—source or executable programs, numeric or text data, photos, music, video, and so on. A file has a certain defined structure, which depends on its type. A **text fil** is a sequence of characters organized into lines (and possibly pages). A **source fil** is a sequence of functions, each of which is further organized as declarations followed by executable statements. An **executable fil** is a series of code sections that the loader can bring into memory and execute.

13.1.1 File Attributes

A file is named, for the convenience of its human users, and is referred to by its name. A name is usually a string of characters, such as `example.c`. Some systems differentiate between uppercase and lowercase characters in names, whereas other systems do not. When a file is named, it becomes independent of the process, the user, and even the system that created it. For instance, one user might create the file `example.c`, and another user might edit that file by specifying its name. The file's owner might write the file to a USB drive, send it as an e-mail attachment, or copy it across a network, and it could still be called `example.c` on the destination system. Unless there is a sharing and synchonization method, that second copy is now independent of the first and can be changed separately.

A file's attributes vary from one operating system to another but typically consist of these:

- **Name**. The symbolic file name is the only information kept in human-readable form.
- **Identifie** . This unique tag, usually a number, identifies the file within the file system; it is the non-human-readable name for the file.
- **Type**. This information is needed for systems that support different types of files.
- **Location**. This information is a pointer to a device and to the location of the file on that device.

- **Size**. The current size of the file (in bytes, words, or blocks) and possibly the maximum allowed size are included in this attribute.
- **Protection**. Access-control information determines who can do reading, writing, executing, and so on.
- **Timestamps and user identificatio** . This information may be kept for creation, last modification, and last use. These data can be useful for protection, security, and usage monitoring.

Some newer file systems also support **extended file attributes**, including character encoding of the file and security features such as a file checksum. Figure 13.1 illustrates a **fil info window** on macOS that displays a file's attributes.

The information about all files is kept in the directory structure, which resides on the same device as the files themselves. Typically, a directory entry consists of the file's name and its unique identifier. The identifier in turn locates the other file attributes. It may take more than a kilobyte to record this information for each file. In a system with many files, the size of the directory itself may be megabytes or gigabytes. Because directories must match the volatility of the files, like files, they must be stored on the device and are usually brought into memory piecemeal, as needed.

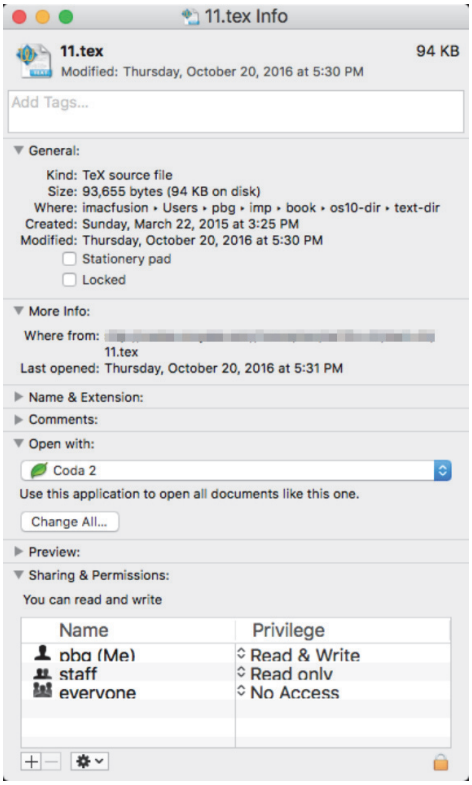

Figure 13.1 A file info window on macOS.

13.1.2 File Operations

A file is an abstract data type. To define a file properly, we need to consider the operations that can be performed on files. The operating system can provide system calls to create, write, read, reposition, delete, and truncate files. Let's examine what the operating system must do to perform each of these seven basic file operations. It should then be easy to see how other similar operations, such as renaming a file, can be implemented.

- **Creating a fil** . Two steps are necessary to create a file. First, space in the file system must be found for the file. We discuss how to allocate space for the file in Chapter 14. Second, an entry for the new file must be made in a directory.
- **Opening a fil** . Rather than have all file operations specify a file name, causing the operating system to evaluate the name, check access permissions, and so on, all operations except create and delete require a file `open()` first. If successful, the open call returns a file handle that is used as an argument in the other calls.
- **Writing a fil** . To write a file, we make a system call specifying both the open file handle and the information to be written to the file. The system must keep a **write pointer** to the location in the file where the next write is to take place if it is sequential. The write pointer must be updated whenever a write occurs.
- **Reading a fil** . To read from a file, we use a system call that specifies the file handle and where (in memory) the next block of the file should be put. Again, the system needs to keep a **read pointer** to the location in the file where the next read is to take place, if sequential. Once the read has taken place, the read pointer is updated. Because a process is usually either reading from or writing to a file, the current operation location can be kept as a per-process **current-file-positio pointer**. Both the read and write operations use this same pointer, saving space and reducing system complexity.
- **Repositioning within a file**. The current-file-position pointer of the open file is repositioned to a given value. Repositioning within a file need not involve any actual I/O. This file operation is also known as a file **seek**.
- **Deleting a fil** . To delete a file, we search the directory for the named file. Having found the associated directory entry, we release all file space, so that it can be reused by other files, and erase or mark as free the directory entry. Note that some systems allow **hard links**—multiple names (directory entries) for the same file. In this case the actual file contents is not deleted until the last link is deleted.
- **Truncating a fil** . The user may want to erase the contents of a file but keep its attributes. Rather than forcing the user to delete the file and then recreate it, this function allows all attributes to remain unchanged—except for file length. The file can then be reset to length zero, and its file space can be released.

These seven basic operations comprise the minimal set of required file operations. Other common operations include appending new information to the end of an existing file and renaming an existing file. These primitive operations can then be combined to perform other file operations. For instance, we can create a copy of a file by creating a new file and then reading from the old and writing to the new. We also want to have operations that allow a user to get and set the various attributes of a file. For example, we may want to have operations that allow a user to determine the status of a file, such as the file's length, and to set file attributes, such as the file's owner.

As mentioned, most of the file operations mentioned involve searching the directory for the entry associated with the named file. To avoid this constant searching, many systems require that an `open()` system call be made before a file is first used. The operating system keeps a table, called the **open-fil table**, containing information about all open files. When a file operation is requested, the file is specified via an index into this table, so no searching is required. When the file is no longer being actively used, it is closed by the process, and the operating system removes its entry from the open-file table, potentially releasing locks. `create()` and `delete()` are system calls that work with closed rather than open files.

Some systems implicitly open a file when the first reference to it is made. The file is automatically closed when the job or program that opened the file terminates. Most systems, however, require that the programmer open a file explicitly with the `open()` system call before that file can be used. The `open()` operation takes a file name and searches the directory, copying the directory entry into the open-file table. The `open()` call can also accept access-mode information—create, read-only, read–write, append-only, and so on. This mode is checked against the file's permissions. If the request mode is allowed, the file is opened for the process. The `open()` system call typically returns a pointer to the entry in the open-file table. This pointer, not the actual file name, is used in all I/O operations, avoiding any further searching and simplifying the system-call interface.

The implementation of the `open()` and `close()` operations is more complicated in an environment where several processes may open the file simultaneously. This may occur in a system where several different applications open the same file at the same time. Typically, the operating system uses two levels of internal tables: a per-process table and a system-wide table. The per-process table tracks all files that a process has open. Stored in this table is information regarding the process's use of the file. For instance, the current file pointer for each file is found here. Access rights to the file and accounting information can also be included.

Each entry in the per-process table in turn points to a system-wide open-file table. The system-wide table contains process-independent information, such as the location of the file on disk, access dates, and file size. Once a file has been opened by one process, the system-wide table includes an entry for the file. When another process executes an `open()` call, a new entry is simply added to the process's open-file table pointing to the appropriate entry in the system-wide table. Typically, the open-file table also has an **open count** associated with each file to indicate how many processes have the file open. Each `close()` decreases this open count, and when the open count reaches zero, the file is no longer in use, and the file's entry is removed from the open-file table.

FILE LOCKING IN JAVA

In the Java API, acquiring a lock requires first obtaining the `FileChannel` for the file to be locked. The `lock()` method of the `FileChannel` is used to acquire the lock. The API of the `lock()` method is

```
FileLock lock(long begin, long end, boolean shared)
```

where `begin` and `end` are the beginning and ending positions of the region being locked. Setting `shared` to `true` is for shared locks; setting `shared` to `false` acquires the lock exclusively. The lock is released by invoking the `release()` of the `FileLock` returned by the `lock()` operation.

The program in Figure 13.2 illustrates file locking in Java. This program acquires two locks on the file `file.txt`. The lock for the first half of the file is an exclusive lock; the lock for the second half is a shared lock.

In summary, several pieces of information are associated with an open file.

- **File pointer**. On systems that do not include a file offset as part of the `read()` and `write()` system calls, the system must track the last read–write location as a current-file-position pointer. This pointer is unique to each process operating on the file and therefore must be kept separate from the on-disk file attributes.
- **File-open count**. As files are closed, the operating system must reuse its open-file table entries, or it could run out of space in the table. Multiple processes may have opened a file, and the system must wait for the last file to close before removing the open-file table entry. The file-open count tracks the number of opens and closes and reaches zero on the last close. The system can then remove the entry.
- **Location of the fil** . Most file operations require the system to read or write data within the file. The information needed to locate the file (wherever it is located, be it on mass storage, on a file server across the network, or on a RAM drive) is kept in memory so that the system does not have to read it from the directory structure for each operation.
- **Access rights**. Each process opens a file in an access mode. This information is stored on the per-process table so the operating system can allow or deny subsequent I/O requests.

Some operating systems provide facilities for locking an open file (or sections of a file). File locks allow one process to lock a file and prevent other processes from gaining access to it. File locks are useful for files that are shared by several processes—for example, a system log file that can be accessed and modified by a number of processes in the system.

File locks provide functionality similar to reader–writer locks, covered in Section 7.1.2. A **shared lock** is akin to a reader lock in that several processes can acquire the lock concurrently. An **exclusive lock** behaves like a writer lock; only one process at a time can acquire such a lock. It is important to note that not

```
import java.io.*;
import java.nio.channels.*;

public class LockingExample {
  public static final boolean EXCLUSIVE = false;
  public static final boolean SHARED = true;

  public static void main(String args[]) throws IOException {
    FileLock sharedLock = null;
    FileLock exclusiveLock = null;

    try {
      RandomAccessFile raf = new RandomAccessFile("file.txt","rw");

      // get the channel for the file
      FileChannel ch = raf.getChannel();

      // this locks the first half of the file - exclusive
      exclusiveLock = ch.lock(0, raf.length()/2, EXCLUSIVE);

      /** Now modify the data . . . */

      // release the lock
      exclusiveLock.release();

      // this locks the second half of the file - shared
      sharedLock = ch.lock(raf.length()/2+1,raf.length(),SHARED);

      /** Now read the data . . . */

      // release the lock
      sharedLock.release();
    } catch (java.io.IOException ioe) {
      System.err.println(ioe);
    }
    finally {
      if (exclusiveLock != null)
            exclusiveLock.release();
      if (sharedLock != null)
            sharedLock.release();
    }
  }
}
```

Figure 13.2 File-locking example in Java.

all operating systems provide both types of locks: some systems provide only exclusive file locking.

Furthermore, operating systems may provide either **mandatory** or **advisory** file-locking mechanisms. With mandatory locking, once a process acquires an exclusive lock, the operating system will prevent any other process from

accessing the locked file. For example, assume a process acquires an exclusive lock on the file `system.log`. If we attempt to open `system.log` from another process—for example, a text editor—the operating system will prevent access until the exclusive lock is released. Alternatively, if the lock is advisory, then the operating system will not prevent the text editor from acquiring access to `system.log`. Rather, the text editor must be written so that it manually acquires the lock before accessing the file. In other words, if the locking scheme is mandatory, the operating system ensures locking integrity. For advisory locking, it is up to software developers to ensure that locks are appropriately acquired and released. As a general rule, Windows operating systems adopt mandatory locking, and UNIX systems employ advisory locks.

The use of file locks requires the same precautions as ordinary process synchronization. For example, programmers developing on systems with mandatory locking must be careful to hold exclusive file locks only while they are accessing the file. Otherwise, they will prevent other processes from accessing the file as well. Furthermore, some measures must be taken to ensure that two or more processes do not become involved in a deadlock while trying to acquire file locks.

13.1.3 File Types

When we design a file system—indeed, an entire operating system—we always consider whether the operating system should recognize and support file types. If an operating system recognizes the type of a file, it can then operate on the file in reasonable ways. For example, a common mistake occurs when a user tries to output the binary-object form of a program. This attempt normally produces garbage; however, the attempt can succeed if the operating system has been told that the file is a binary-object program.

A common technique for implementing file types is to include the type as part of the file name. The name is split into two parts—a name and an extension, usually separated by a period (Figure 13.3). In this way, the user and the operating system can tell from the name alone what the type of a file is. Most operating systems allow users to specify a file name as a sequence of characters followed by a period and terminated by an extension made up of additional characters. Examples include `resume.docx`, `server.c`, and `ReaderThread.cpp`.

The system uses the extension to indicate the type of the file and the type of operations that can be done on that file. Only a file with a `.com`, `.exe`, or `.sh` extension can be executed, for instance. The `.com` and `.exe` files are two forms of binary executable files, whereas the `.sh` file is a **shell script** containing, in ASCII format, commands to the operating system. Application programs also use extensions to indicate file types in which they are interested. For example, Java compilers expect source files to have a `.java` extension, and the Microsoft Word word processor expects its files to end with a `.doc` or `.docx` extension. These extensions are not always required, so a user may specify a file without the extension (to save typing), and the application will look for a file with the given name and the extension it expects. Because these extensions are not supported by the operating system, they can be considered "hints" to the applications that operate on them.

Consider, too, the macOS operating system. In this system, each file has a type, such as `.app` (for application). Each file also has a creator attribute

file type	usual extension	function
executable	exe, com, bin or none	ready-to-run machine-language program
object	obj, o	compiled, machine language, not linked
source code	c, cc, java, perl, asm	source code in various languages
batch	bat, sh	commands to the command interpreter
markup	xml, html, tex	textual data, documents
word processor	xml, rtf, docx	various word-processor formats
library	lib, a, so, dll	libraries of routines for programmers
print or view	gif, pdf, jpg	ASCII or binary file in a format for printing or viewing
archive	rar, zip, tar	related files grouped into one file, sometimes compressed, for archiving or storage
multimedia	mpeg, mov, mp3, mp4, avi	binary file containing audio or A/V information

Figure 13.3 Common file types.

containing the name of the program that created it. This attribute is set by the operating system during the `create()` call, so its use is enforced and supported by the system. For instance, a file produced by a word processor has the word processor's name as its creator. When the user opens that file, by double-clicking the mouse on the icon representing the file, the word processor is invoked automatically, and the file is loaded, ready to be edited.

The UNIX system uses a **magic number** stored at the beginning of some binary files to indicate the type of data in the file (for example, the format of an image file). Likewise, it uses a text magic number at the start of text files to indicate the type of file (which shell language a script is written in) and so on. (For more details on magic numbers and other computer jargon, see http://www.catb.org/esr/jargon/.) Not all files have magic numbers, so system features cannot be based solely on this information. UNIX does not record the name of the creating program, either. UNIX does allow file-name-extension hints, but these extensions are neither enforced nor depended on by the operating system; they are meant mostly to aid users in determining what type of contents the file contains. Extensions can be used or ignored by a given application, but that is up to the application's programmer.

13.1.4 File Structure

File types also can be used to indicate the internal structure of the file. Source and object files have structures that match the expectations of the programs that read them. Further, certain files must conform to a required structure that

is understood by the operating system. For example, the operating system requires that an executable file have a specific structure so that it can determine where in memory to load the file and what the location of the first instruction is. Some operating systems extend this idea into a set of system-supported file structures, with sets of special operations for manipulating files with those structures.

This point brings us to one of the disadvantages of having the operating system support multiple file structures: it makes the operating system large and cumbersome. If the operating system defines five different file structures, it needs to contain the code to support these file structures. In addition, it may be necessary to define every file as one of the file types supported by the operating system. When new applications require information structured in ways not supported by the operating system, severe problems may result.

For example, assume that a system supports two types of files: text files (composed of ASCII characters separated by a carriage return and line feed) and executable binary files. Now, if we (as users) want to define an encrypted file to protect the contents from being read by unauthorized people, we may find neither file type to be appropriate. The encrypted file is not ASCII text lines but rather is (apparently) random bits. Although it may appear to be a binary file, it is not executable. As a result, we may have to circumvent or misuse the operating system's file-type mechanism or abandon our encryption scheme.

Some operating systems impose (and support) a minimal number of file structures. This approach has been adopted in UNIX, Windows, and others. UNIX considers each file to be a sequence of 8-bit bytes; no interpretation of these bits is made by the operating system. This scheme provides maximum flexibility but little support. Each application program must include its own code to interpret an input file as to the appropriate structure. However, all operating systems must support at least one structure—that of an executable file—so that the system is able to load and run programs.

13.1.5 Internal File Structure

Internally, locating an offset within a file can be complicated for the operating system. Disk systems typically have a well-defined block size determined by the size of a sector. All disk I/O is performed in units of one block (physical record), and all blocks are the same size. It is unlikely that the physical record size will exactly match the length of the desired logical record. Logical records may even vary in length. Packing a number of logical records into physical blocks is a common solution to this problem.

For example, the UNIX operating system defines all files to be simply streams of bytes. Each byte is individually addressable by its offset from the beginning (or end) of the file. In this case, the logical record size is 1 byte. The file system automatically packs and unpacks bytes into physical disk blocks—say, 512 bytes per block—as necessary.

The logical record size, physical block size, and packing technique determine how many logical records are in each physical block. The packing can be done either by the user's application program or by the operating system. In either case, the file may be considered a sequence of blocks. All the basic I/O functions operate in terms of blocks. The conversion from logical records to physical blocks is a relatively simple software problem.

Because disk space is always allocated in blocks, some portion of the last block of each file is generally wasted. If each block were 512 bytes, for example, then a file of 1,949 bytes would be allocated four blocks (2,048 bytes); the last 99 bytes would be wasted. The waste incurred to keep everything in units of blocks (instead of bytes) is internal fragmentation. All file systems suffer from internal fragmentation; the larger the block size, the greater the internal fragmentation.

13.2 Access Methods

Files store information. When it is used, this information must be accessed and read into computer memory. The information in the file can be accessed in several ways. Some systems provide only one access method for files. Others (such as mainframe operating systems) support many access methods, and choosing the right one for a particular application is a major design problem.

13.2.1 Sequential Access

The simplest access method is **sequential access**. Information in the file is processed in order, one record after the other. This mode of access is by far the most common; for example, editors and compilers usually access files in this fashion.

Reads and writes make up the bulk of the operations on a file. A read operation—`read_next()`—reads the next portion of the file and automatically advances a file pointer, which tracks the I/O location. Similarly, the write operation—`write_next()`—appends to the end of the file and advances to the end of the newly written material (the new end of file). Such a file can be reset to the beginning, and on some systems, a program may be able to skip forward or backward n records for some integer n—perhaps only for $n = 1$. Sequential access, which is depicted in Figure 13.4, is based on a tape model of a file and works as well on sequential-access devices as it does on random-access ones.

13.2.2 Direct Access

Another method is **direct access** (or **relative access**). Here, a file is made up of fixed-length **logical records** that allow programs to read and write records rapidly in no particular order. The direct-access method is based on a disk model of a file, since disks allow random access to any file block. For direct access, the file is viewed as a numbered sequence of blocks or records. Thus,

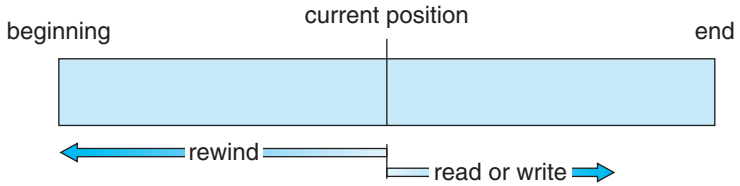

Figure 13.4 Sequential-access file.

we may read block 14, then read block 53, and then write block 7. There are no restrictions on the order of reading or writing for a direct-access file.

Direct-access files are of great use for immediate access to large amounts of information. Databases are often of this type. When a query concerning a particular subject arrives, we compute which block contains the answer and then read that block directly to provide the desired information.

As a simple example, on an airline-reservation system, we might store all the information about a particular flight (for example, flight 713) in the block identified by the flight number. Thus, the number of available seats for flight 713 is stored in block 713 of the reservation file. To store information about a larger set, such as people, we might compute a hash function on the people's names or search a small in-memory index to determine a block to read and search.

For the direct-access method, the file operations must be modified to include the block number as a parameter. Thus, we have `read(n)`, where *n* is the block number, rather than `read_next()`, and `write(n)` rather than `write_next()`. An alternative approach is to retain `read_next()` and `write_next()` and to add an operation `position_file(n)` where *n* is the block number. Then, to effect a `read(n)`, we would `position_file(n)` and then `read_next()`.

The block number provided by the user to the operating system is normally a **relative block number**. A relative block number is an index relative to the beginning of the file. Thus, the first relative block of the file is 0, the next is 1, and so on, even though the absolute disk address may be 14703 for the first block and 3192 for the second. The use of relative block numbers allows the operating system to decide where the file should be placed (called the **allocation problem**, as we discuss in Chapter 14) and helps to prevent the user from accessing portions of the file system that may not be part of her file. Some systems start their relative block numbers at 0; others start at 1.

How, then, does the system satisfy a request for record N in a file? Assuming we have a logical record length L, the request for record N is turned into an I/O request for L bytes starting at location $L * (N)$ within the file (assuming the first record is $N = 0$). Since logical records are of a fixed size, it is also easy to read, write, or delete a record.

Not all operating systems support both sequential and direct access for files. Some systems allow only sequential file access; others allow only direct access. Some systems require that a file be defined as sequential or direct when it is created. Such a file can be accessed only in a manner consistent with its declaration. We can easily simulate sequential access on a direct-access file by simply keeping a variable *cp* that defines our current position, as shown in Figure 13.5. Simulating a direct-access file on a sequential-access file, however, is extremely inefficient and clumsy.

13.2.3 Other Access Methods

Other access methods can be built on top of a direct-access method. These methods generally involve the construction of an index for the file. The **index**, like an index in the back of a book, contains pointers to the various blocks. To find a record in the file, we first search the index and then use the pointer to access the file directly and to find the desired record.

sequential access	implementation for direct access
reset	cp = 0;
read_next	read cp; cp = cp + 1;
write_next	write cp; cp = cp + 1;

Figure 13.5 Simulation of sequential access on a direct-access file.

For example, a retail-price file might list the universal product codes (UPCs) for items, with the associated prices. Each record consists of a 10-digit UPC and a 6-digit price, for a 16-byte record. If our disk has 1,024 bytes per block, we can store 64 records per block. A file of 120,000 records would occupy about 2,000 blocks (2 million bytes). By keeping the file sorted by UPC, we can define an index consisting of the first UPC in each block. This index would have 2,000 entries of 10 digits each, or 20,000 bytes, and thus could be kept in memory. To find the price of a particular item, we can make a binary search of the index. From this search, we learn exactly which block contains the desired record and access that block. This structure allows us to search a large file doing little I/O.

With large files, the index file itself may become too large to be kept in memory. One solution is to create an index for the index file. The primary index file contains pointers to secondary index files, which point to the actual data items.

For example, IBM's indexed sequential-access method (ISAM) uses a small master index that points to disk blocks of a secondary index. The secondary index blocks point to the actual file blocks. The file is kept sorted on a defined key. To find a particular item, we first make a binary search of the master index, which provides the block number of the secondary index. This block is read in, and again a binary search is used to find the block containing the desired record. Finally, this block is searched sequentially. In this way, any record can be located from its key by at most two direct-access reads. Figure 13.6 shows a similar situation as implemented by OpenVMS index and relative files.

13.3 Directory Structure

The directory can be viewed as a symbol table that translates file names into their file control blocks. If we take such a view, we see that the directory itself can be organized in many ways. The organization must allow us to insert entries, to delete entries, to search for a named entry, and to list all the entries in the directory. In this section, we examine several schemes for defining the logical structure of the directory system.

When considering a particular directory structure, we need to keep in mind the operations that are to be performed on a directory:

- **Search for a fil** . We need to be able to search a directory structure to find the entry for a particular file. Since files have symbolic names, and similar

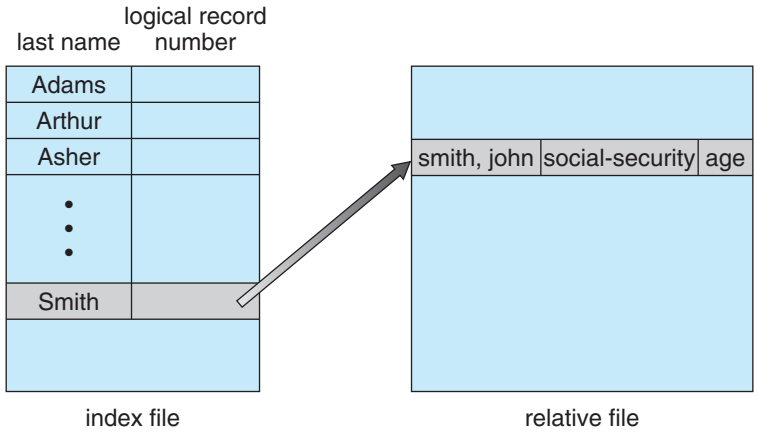

Figure 13.6 Example of index and relative files.

names may indicate a relationship among files, we may want to be able to find all files whose names match a particular pattern.

- **Create a fil** . New files need to be created and added to the directory.
- **Delete a file**. When a file is no longer needed, we want to be able to remove it from the directory. Note a delete leaves a hole in the directory structure and the file system may have a method to defragement the directory structure.
- **List a directory**. We need to be able to list the files in a directory and the contents of the directory entry for each file in the list.
- **Rename a file**. Because the name of a file represents its contents to its users, we must be able to change the name when the contents or use of the file changes. Renaming a file may also allow its position within the directory structure to be changed.
- **Traverse the file system**. We may wish to access every directory and every file within a directory structure. For reliability, it is a good idea to save the contents and structure of the entire file system at regular intervals. Often, we do this by copying all files to magnetic tape, other secondary storage, or across a network to another system or the cloud. This technique provides a backup copy in case of system failure. In addition, if a file is no longer in use, the file can be copied the backup target and the disk space of that file released for reuse by another file.

In the following sections, we describe the most common schemes for defining the logical structure of a directory.

13.3.1 Single-Level Directory

The simplest directory structure is the single-level directory. All files are contained in the same directory, which is easy to support and understand (Figure 13.7).

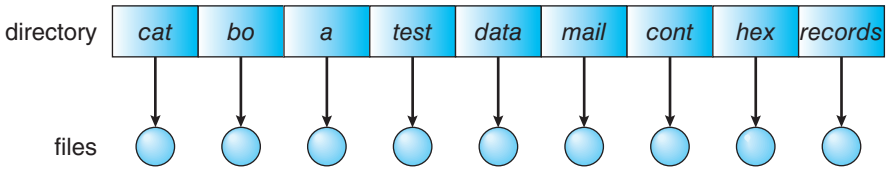

Figure 13.7 Single-level directory.

A single-level directory has significant limitations, however, when the number of files increases or when the system has more than one user. Since all files are in the same directory, they must have unique names. If two users call their data file `test.txt`, then the unique-name rule is violated. For example, in one programming class, 23 students called the program for their second assignment `prog2.c`; another 11 called it `assign2.c`. Fortunately, most file systems support file names of up to 255 characters, so it is relatively easy to select unique file names.

Even a single user on a single-level directory may find it difficult to remember the names of all the files as the number of files increases. It is not uncommon for a user to have hundreds of files on one computer system and an equal number of additional files on another system. Keeping track of so many files is a daunting task.

13.3.2 Two-Level Directory

As we have seen, a single-level directory often leads to confusion of file names among different users. The standard solution is to create a separate directory for each user.

In the two-level directory structure, each user has his own **user fil directory** (**UFD**). The UFDs have similar structures, but each lists only the files of a single user. When a user job starts or a user logs in, the system's **master fil directory** (**MFD**) is searched. The MFD is indexed by user name or account number, and each entry points to the UFD for that user (Figure 13.8).

When a user refers to a particular file, only his own UFD is searched. Thus, different users may have files with the same name, as long as all the file names within each UFD are unique. To create a file for a user, the operating system searches only that user's UFD to ascertain whether another file of that name

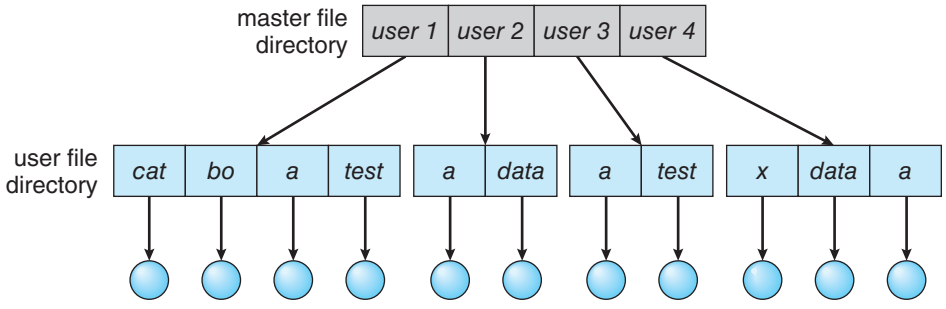

Figure 13.8 Two-level directory structure.

exists. To delete a file, the operating system confines its search to the local UFD; thus, it cannot accidentally delete another user's file that has the same name.

The user directories themselves must be created and deleted as necessary. A special system program is run with the appropriate user name and account information. The program creates a new UFD and adds an entry for it to the MFD. The execution of this program might be restricted to system administrators. The allocation of disk space for user directories can be handled with the techniques discussed in Chapter 14 for files themselves.

Although the two-level directory structure solves the name-collision problem, it still has disadvantages. This structure effectively isolates one user from another. Isolation is an advantage when the users are completely independent but is a disadvantage when the users want to cooperate on some task and to access one another's files. Some systems simply do not allow local user files to be accessed by other users.

If access is to be permitted, one user must have the ability to name a file in another user's directory. To name a particular file uniquely in a two-level directory, we must give both the user name and the file name. A two-level directory can be thought of as a tree, or an inverted tree, of height 2. The root of the tree is the MFD. Its direct descendants are the UFDs. The descendants of the UFDs are the files themselves. The files are the leaves of the tree. Specifying a user name and a file name defines a path in the tree from the root (the MFD) to a leaf (the specified file). Thus, a user name and a file name define a **path name**. Every file in the system has a path name. To name a file uniquely, a user must know the path name of the file desired.

For example, if user A wishes to access her own test file named `test.txt`, she can simply refer to `test.txt`. To access the file named `test.txt` of user B (with directory-entry name `userb`), however, she might have to refer to `/userb/test.txt`. Every system has its own syntax for naming files in directories other than the user's own.

Additional syntax is needed to specify the volume of a file. For instance, in Windows a volume is specified by a letter followed by a colon. Thus, a file specification might be `C:\userb\test`. Some systems go even further and separate the volume, directory name, and file name parts of the specification. In OpenVMS, for instance, the file `login.com` might be specified as: `u:[sst.crissmeyer]login.com;1`, where `u` is the name of the volume, `sst` is the name of the directory, `crissmeyer` is the name of the subdirectory, and `1` is the version number. Other systems—such as UNIX and Linux—simply treat the volume name as part of the directory name. The first name given is that of the volume, and the rest is the directory and file. For instance, `/u/pgalvin/test` might specify volume `u`, directory `pgalvin`, and file `test`.

A special instance of this situation occurs with the system files. Programs provided as part of the system—loaders, assemblers, compilers, utility routines, libraries, and so on—are generally defined as files. When the appropriate commands are given to the operating system, these files are read by the loader and executed. Many command interpreters simply treat such a command as the name of a file to load and execute. In the directory system as we defined it above, this file name would be searched for in the current UFD. One solution would be to copy the system files into each UFD. However, copying all the system files would waste an enormous amount of space. (If the system files

require 5 MB, then supporting 12 users would require 5 × 12 = 60 MB just for copies of the system files.)

The standard solution is to complicate the search procedure slightly. A special user directory is defined to contain the system files (for example, user 0). Whenever a file name is given to be loaded, the operating system first searches the local UFD. If the file is found, it is used. If it is not found, the system automatically searches the special user directory that contains the system files. The sequence of directories searched when a file is named is called the **search path**. The search path can be extended to contain an unlimited list of directories to search when a command name is given. This method is the one most used in UNIX and Windows. Systems can also be designed so that each user has his own search path.

13.3.3 Tree-Structured Directories

Once we have seen how to view a two-level directory as a two-level tree, the natural generalization is to extend the directory structure to a tree of arbitrary height (Figure 13.9). This generalization allows users to create their own subdirectories and to organize their files accordingly. A tree is the most common directory structure. The tree has a root directory, and every file in the system has a unique path name.

A directory (or subdirectory) contains a set of files or subdirectories. In many implementations, a directory is simply another file, but it is treated in a special way. All directories have the same internal format. One bit in each directory entry defines the entry as a file (0) or as a subdirectory (1). Special

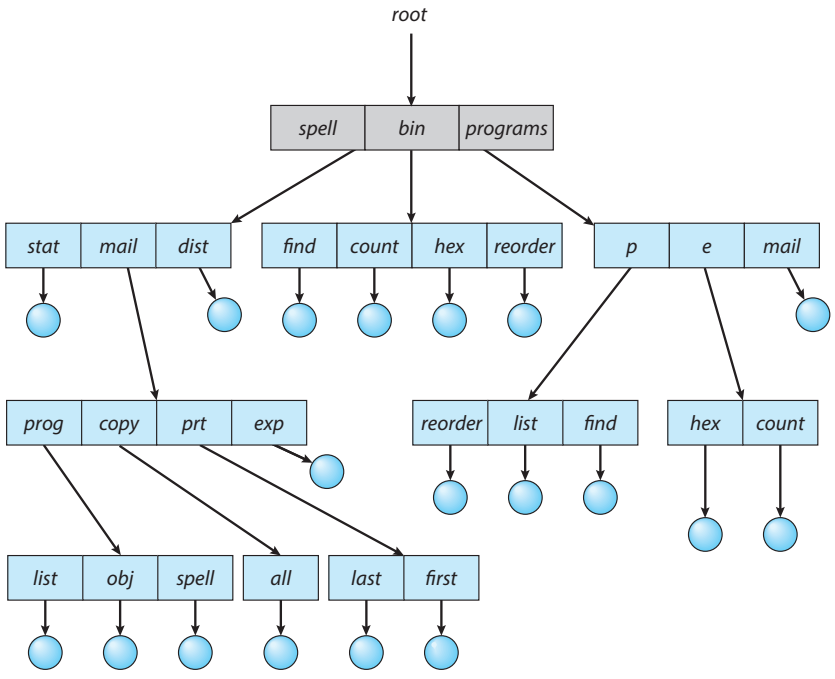

Figure 13.9 Tree-structured directory structure.

system calls are used to create and delete directories. In this case the operating system (or the file system code) implements another file format, that of a directory.

In normal use, each process has a current directory. The **current directory** should contain most of the files that are of current interest to the process. When reference is made to a file, the current directory is searched. If a file is needed that is not in the current directory, then the user usually must either specify a path name or change the current directory to be the directory holding that file. To change directories, a system call could be provided that takes a directory name as a parameter and uses it to redefine the current directory. Thus, the user can change her current directory whenever she wants. Other systems leave it to the application (say, a shell) to track and operate on a current directory, as each process could have different current directories.

The initial current directory of a user's login shell is designated when the user job starts or the user logs in. The operating system searches the accounting file (or some other predefined location) to find an entry for this user (for accounting purposes). In the accounting file is a pointer to (or the name of) the user's initial directory. This pointer is copied to a local variable for this user that specifies the user's initial current directory. From that shell, other processes can be spawned. The current directory of any subprocess is usually the current directory of the parent when it was spawned.

Path names can be of two types: absolute and relative. In UNIX and Linux, an **absolute path name** begins at the root (which is designated by an initial "/") and follows a path down to the specified file, giving the directory names on the path. A **relative path name** defines a path from the current directory. For example, in the tree-structured file system of Figure 13.9, if the current directory is `/spell/mail`, then the relative path name `prt/first` refers to the same file as does the absolute path name `/spell/mail/prt/first`.

Allowing a user to define her own subdirectories permits her to impose a structure on her files. This structure might result in separate directories for files associated with different topics (for example, a subdirectory was created to hold the text of this book) or different forms of information. For example, the directory `programs` may contain source programs; the directory `bin` may store all the binaries. (As a side note, executable files were known in many systems as "binaries" which led to them being stored in the `bin` directory.)

An interesting policy decision in a tree-structured directory concerns how to handle the deletion of a directory. If a directory is empty, its entry in the directory that contains it can simply be deleted. However, suppose the directory to be deleted is not empty but contains several files or subdirectories. One of two approaches can be taken. Some systems will not delete a directory unless it is empty. Thus, to delete a directory, the user must first delete all the files in that directory. If any subdirectories exist, this procedure must be applied recursively to them, so that they can be deleted also. This approach can result in a substantial amount of work. An alternative approach, such as that taken by the UNIX `rm` command, is to provide an option: when a request is made to delete a directory, all that directory's files and subdirectories are also to be deleted. Either approach is fairly easy to implement; the choice is one of policy. The latter policy is more convenient, but it is also more dangerous, because an entire directory structure can be removed with one command. If that command

is issued in error, a large number of files and directories will need to be restored (assuming a backup exists).

With a tree-structured directory system, users can be allowed to access, in addition to their files, the files of other users. For example, user B can access a file of user A by specifying its path name. User B can specify either an absolute or a relative path name. Alternatively, user B can change her current directory to be user A's directory and access the file by its file name.

13.3.4 Acyclic-Graph Directories

Consider two programmers who are working on a joint project. The files associated with that project can be stored in a subdirectory, separating them from other projects and files of the two programmers. But since both programmers are equally responsible for the project, both want the subdirectory to be in their own directories. In this situation, the common subdirectory should be ***shared.*** A shared directory or file exists in the file system in two (or more) places at once.

A tree structure prohibits the sharing of files or directories. An **acyclic graph**—that is, a graph with no cycles—allows directories to share subdirectories and files (Figure 13.10). The same file or subdirectory may be in two different directories. The acyclic graph is a natural generalization of the tree-structured directory scheme.

It is important to note that a shared file (or directory) is not the same as two copies of the file. With two copies, each programmer can view the copy rather than the original, but if one programmer changes the file, the changes will not appear in the other's copy. With a shared file, only one actual file exists, so any changes made by one person are immediately visible to the other. Sharing is

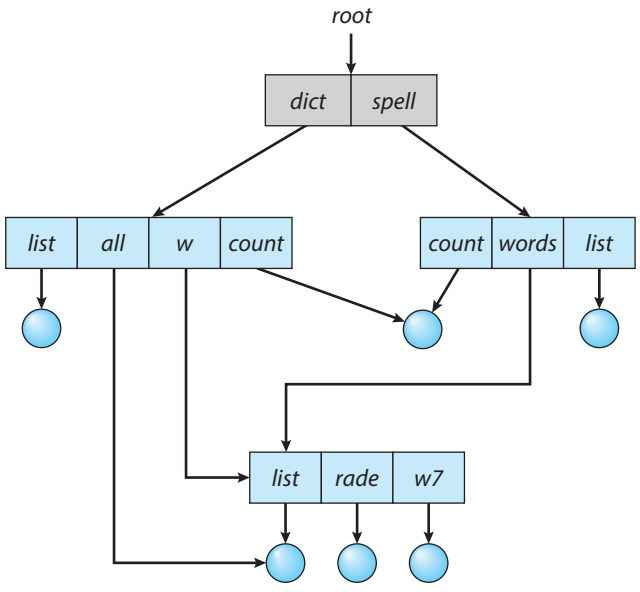

Figure 13.10 Acyclic-graph directory structure.

particularly important for subdirectories; a new file created by one person will automatically appear in all the shared subdirectories.

When people are working as a team, all the files they want to share can be put into one directory. The home directory of each team member could contain this directory of shared files as a subdirectory. Even in the case of a single user, the user's file organization may require that some file be placed in different subdirectories. For example, a program written for a particular project should be both in the directory of all programs and in the directory for that project.

Shared files and subdirectories can be implemented in several ways. A common way, exemplified by UNIX systems, is to create a new directory entry called a link. A **link** is effectively a pointer to another file or subdirectory. For example, a link may be implemented as an absolute or a relative path name. When a reference to a file is made, we search the directory. If the directory entry is marked as a link, then the name of the real file is included in the link information. We **resolve** the link by using that path name to locate the real file. Links are easily identified by their format in the directory entry (or by having a special type on systems that support types) and are effectively indirect pointers. The operating system ignores these links when traversing directory trees to preserve the acyclic structure of the system.

Another common approach to implementing shared files is simply to duplicate all information about them in both sharing directories. Thus, both entries are identical and equal. Consider the difference between this approach and the creation of a link. The link is clearly different from the original directory entry; thus, the two are not equal. Duplicate directory entries, however, make the original and the copy indistinguishable. A major problem with duplicate directory entries is maintaining consistency when a file is modified.

An acyclic-graph directory structure is more flexible than a simple tree structure, but it is also more complex. Several problems must be considered carefully. A file may now have multiple absolute path names. Consequently, distinct file names may refer to the same file. This situation is similar to the aliasing problem for programming languages. If we are trying to traverse the entire file system—to find a file, to accumulate statistics on all files, or to copy all files to backup storage—this problem becomes significant, since we do not want to traverse shared structures more than once.

Another problem involves deletion. When can the space allocated to a shared file be deallocated and reused? One possibility is to remove the file whenever anyone deletes it, but this action may leave dangling pointers to the now-nonexistent file. Worse, if the remaining file pointers contain actual disk addresses, and the space is subsequently reused for other files, these dangling pointers may point into the middle of other files.

In a system where sharing is implemented by symbolic links, this situation is somewhat easier to handle. The deletion of a link need not affect the original file; only the link is removed. If the file entry itself is deleted, the space for the file is deallocated, leaving the links dangling. We can search for these links and remove them as well, but unless a list of the associated links is kept with each file, this search can be expensive. Alternatively, we can leave the links until an attempt is made to use them. At that time, we can determine that the file of the name given by the link does not exist and can fail to resolve the link name; the access is treated just as with any other illegal file name. (In this case, the system designer should consider carefully what to do when a file is

deleted and another file of the same name is created, before a symbolic link to the original file is used.) In the case of UNIX, symbolic links are left when a file is deleted, and it is up to the user to realize that the original file is gone or has been replaced. Microsoft Windows uses the same approach.

Another approach to deletion is to preserve the file until all references to it are deleted. To implement this approach, we must have some mechanism for determining that the last reference to the file has been deleted. We could keep a list of all references to a file (directory entries or symbolic links). When a link or a copy of the directory entry is established, a new entry is added to the file-reference list. When a link or directory entry is deleted, we remove its entry on the list. The file is deleted when its file-reference list is empty.

The trouble with this approach is the variable and potentially large size of the file-reference list. However, we really do not need to keep the entire list—we need to keep only a count of the number of references. Adding a new link or directory entry increments the reference count. Deleting a link or entry decrements the count. When the count is 0, the file can be deleted; there are no remaining references to it. The UNIX operating system uses this approach for nonsymbolic links (or **hard links**), keeping a reference count in the file information block (or inode; see Section C.7.2). By effectively prohibiting multiple references to directories, we maintain an acyclic-graph structure.

To avoid problems such as the ones just discussed, some systems simply do not allow shared directories or links.

13.3.5 General Graph Directory

A serious problem with using an acyclic-graph structure is ensuring that there are no cycles. If we start with a two-level directory and allow users to create subdirectories, a tree-structured directory results. It should be fairly easy to see that simply adding new files and subdirectories to an existing tree-structured directory preserves the tree-structured nature. However, when we add links, the tree structure is destroyed, resulting in a simple graph structure (Figure 13.11).

The primary advantage of an acyclic graph is the relative simplicity of the algorithms to traverse the graph and to determine when there are no more references to a file. We want to avoid traversing shared sections of an acyclic graph twice, mainly for performance reasons. If we have just searched a major shared subdirectory for a particular file without finding it, we want to avoid searching that subdirectory again; the second search would be a waste of time.

If cycles are allowed to exist in the directory, we likewise want to avoid searching any component twice, for reasons of correctness as well as performance. A poorly designed algorithm might result in an infinite loop continually searching through the cycle and never terminating. One solution is to limit arbitrarily the number of directories that will be accessed during a search.

A similar problem exists when we are trying to determine when a file can be deleted. With acyclic-graph directory structures, a value of 0 in the reference count means that there are no more references to the file or directory, and the file can be deleted. However, when cycles exist, the reference count may not be 0 even when it is no longer possible to refer to a directory or file. This anomaly results from the possibility of self-referencing (or a cycle) in the directory structure. In this case, we generally need to use a **garbage collection**

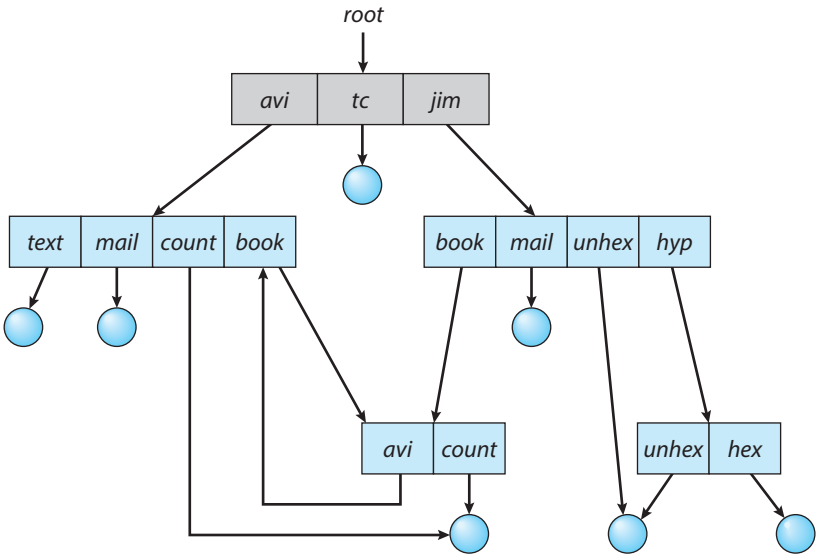

Figure 13.11 General graph directory.

scheme to determine when the last reference has been deleted and the disk space can be reallocated. Garbage collection involves traversing the entire file system, marking everything that can be accessed. Then, a second pass collects everything that is not marked onto a list of free space. (A similar marking procedure can be used to ensure that a traversal or search will cover everything in the file system once and only once.) Garbage collection for a disk-based file system, however, is extremely time consuming and is thus seldom attempted.

Garbage collection is necessary only because of possible cycles in the graph. Thus, an acyclic-graph structure is much easier to work with. The difficulty is to avoid cycles as new links are added to the structure. How do we know when a new link will complete a cycle? There are algorithms to detect cycles in graphs; however, they are computationally expensive, especially when the graph is on disk storage. A simpler algorithm in the special case of directories and links is to bypass links during directory traversal. Cycles are avoided, and no extra overhead is incurred.

13.4 Protection

When information is stored in a computer system, we want to keep it safe from physical damage (the issue of reliability) and improper access (the issue of protection).

Reliability is generally provided by duplicate copies of files. Many computers have systems programs that automatically (or through computer-operator intervention) copy disk files to tape at regular intervals (once per day or week or month) to maintain a copy should a file system be accidentally destroyed. File systems can be damaged by hardware problems (such as errors in reading or writing), power surges or failures, head crashes, dirt, temperature extremes,

and vandalism. Files may be deleted accidentally. Bugs in the file-system software can also cause file contents to be lost. Reliability was covered in more detail in Chapter 11.

Protection can be provided in many ways. For a laptop system running a modern operating system, we might provide protection by requiring a user name and password authentication to access it, encrypting the secondary storage so even someone opening the laptop and removing the drive would have a difficult time accessing its data, and firewalling network access so that when it is in use it is difficult to break in via its network connection. In multiuser system, even valid access of the system needs more advanced mechanisms to allow only valid access of the data.

13.4.1 Types of Access

The need to protect files is a direct result of the ability to access files. Systems that do not permit access to the files of other users do not need protection. Thus, we could provide complete protection by prohibiting access. Alternatively, we could provide free access with no protection. Both approaches are too extreme for general use. What is needed is controlled access.

Protection mechanisms provide controlled access by limiting the types of file access that can be made. Access is permitted or denied depending on several factors, one of which is the type of access requested. Several different types of operations may be controlled:

- **Read**. Read from the file.
- **Write**. Write or rewrite the file.
- **Execute**. Load the file into memory and execute it.
- **Append**. Write new information at the end of the file.
- **Delete**. Delete the file and free its space for possible reuse.
- **List**. List the name and attributes of the file.
- **Attribute change**. Changing the attributes of the file.

Other operations, such as renaming, copying, and editing the file, may also be controlled. For many systems, however, these higher-level functions may be implemented by a system program that makes lower-level system calls. Protection is provided at only the lower level. For instance, copying a file may be implemented simply by a sequence of read requests. In this case, a user with read access can also cause the file to be copied, printed, and so on.

Many protection mechanisms have been proposed. Each has advantages and disadvantages and must be appropriate for its intended application. A small computer system that is used by only a few members of a research group, for example, may not need the same types of protection as a large corporate computer that is used for research, finance, and personnel operations. We discuss some approaches to protection in the following sections and present a more complete treatment in Chapter 17.

13.4.2 Access Control

The most common approach to the protection problem is to make access dependent on the identity of the user. Different users may need different types of access to a file or directory. The most general scheme to implement identity-dependent access is to associate with each file and directory an **access-control list** (ACL) specifying user names and the types of access allowed for each user. When a user requests access to a particular file, the operating system checks the access list associated with that file. If that user is listed for the requested access, the access is allowed. Otherwise, a protection violation occurs, and the user job is denied access to the file.

This approach has the advantage of enabling complex access methodologies. The main problem with access lists is their length. If we want to allow everyone to read a file, we must list all users with read access. This technique has two undesirable consequences:

- Constructing such a list may be a tedious and unrewarding task, especially if we do not know in advance the list of users in the system.
- The directory entry, previously of fixed size, now must be of variable size, resulting in more complicated space management.

These problems can be resolved by use of a condensed version of the access list.

To condense the length of the access-control list, many systems recognize three classifications of users in connection with each file:

- **Owner**. The user who created the file is the owner.
- **Group**. A set of users who are sharing the file and need similar access is a group, or work group.
- **Other**. All other users in the system.

The most common recent approach is to combine access-control lists with the more general (and easier to implement) owner, group, and universe access-control scheme just described. For example, Solaris uses the three categories of access by default but allows access-control lists to be added to specific files and directories when more fine-grained access control is desired.

To illustrate, consider a person, Sara, who is writing a new book. She has hired three graduate students (Jim, Dawn, and Jill) to help with the project. The text of the book is kept in a file named `book.tex`. The protection associated with this file is as follows:

- Sara should be able to invoke all operations on the file.
- Jim, Dawn, and Jill should be able only to read and write the file; they should not be allowed to delete the file.
- All other users should be able to read, but not write, the file. (Sara is interested in letting as many people as possible read the text so that she can obtain feedback.)

PERMISSIONS IN A UNIX SYSTEM

In the UNIX system, directory protection and file protection are handled similarly. Associated with each file and directory are three fields—owner, group, and universe—each consisting of the three bits `rwx`, where `r` controls **r**ead access, `w` controls **w**rite access, and `x` controls e**x**ecution. Thus, a user can list the content of a subdirectory only if the `r` bit is set in the appropriate field. Similarly, a user can change his current directory to another current directory (say, `foo`) only if the `x` bit associated with the `foo` subdirectory is set in the appropriate field.

A sample directory listing from a UNIX environment is shown in below:

```
-rw-rw-r--   1 pbg   staff     31200  Sep 3 08:30   intro.ps
drwx------   5 pbg   staff       512  Jul 8 09.33   private/
drwxrwxr-x   2 pbg   staff       512  Jul 8 09:35   doc/
drwxrwx---   2 jwg   student     512  Aug 3 14:13   student-proj/
-rw-r--r--   1 pbg   staff      9423  Feb 24 2017   program.c
-rwxr-xr-x   1 pbg   staff     20471  Feb 24 2017   program
drwx--x--x   4 tag   faculty     512  Jul 31 10:31  lib/
drwx------   3 pbg   staff      1024  Aug 29 06:52  mail/
drwxrwxrwx   3 pbg   staff       512  Jul 8 09:35   test/
```

The first field describes the protection of the file or directory. A `d` as the first character indicates a subdirectory. Also shown are the number of links to the file, the owner's name, the group's name, the size of the file in bytes, the date of last modification, and finally the file's name (with optional extension).

To achieve such protection, we must create a new group—say, `text`—with members Jim, Dawn, and Jill. The name of the group, `text`, must then be associated with the file `book.tex`, and the access rights must be set in accordance with the policy we have outlined.

Now consider a visitor to whom Sara would like to grant temporary access to Chapter 1. The visitor cannot be added to the `text` group because that would give him access to all chapters. Because a file can be in only one group, Sara cannot add another group to Chapter 1. With the addition of access-control-list functionality, though, the visitor can be added to the access control list of Chapter 1.

For this scheme to work properly, permissions and access lists must be controlled tightly. This control can be accomplished in several ways. For example, in the UNIX system, groups can be created and modified only by the manager of the facility (or by any superuser). Thus, control is achieved through human interaction. Access lists are discussed further in Section 17.6.2.

With the more limited protection classification, only three fields are needed to define protection. Often, each field is a collection of bits, and each bit either allows or prevents the access associated with it. For example, the UNIX system defines three fields of three bits each—`rwx`, where `r` controls read access, `w` controls write access, and `x` controls execution. A separate field is kept for the

file owner, for the file's group, and for all other users. In this scheme, nine bits per file are needed to record protection information. Thus, for our example, the protection fields for the file `book.tex` are as follows: for the owner Sara, all bits are set; for the group `text`, the `r` and `w` bits are set; and for the universe, only the `r` bit is set.

One difficulty in combining approaches comes in the user interface. Users must be able to tell when the optional ACL permissions are set on a file. In the Solaris example, a "+" is appended to the regular permissions, as in:

```
19 -rw-r--r--+ 1 jim staff 130 May 25 22:13 file1
```

A separate set of commands, `setfacl` and `getfacl`, is used to manage the ACLs.

Windows users typically manage access-control lists via the GUI. Figure 13.12 shows a file-permission window on Windows 7 NTFS file system. In this example, user "guest" is specifically denied access to the file `ListPanel.java`.

Another difficulty is assigning precedence when permission and ACLs conflict. For example, if Walter is in a file's group, which has read permission, but the file has an ACL granting Walter read and write permission, should a write by Walter be granted or denied? Solaris and other operating systems give ACLs precedence (as they are more fine-grained and are not assigned by default). This follows the general rule that specificity should have priority.

13.4.3 Other Protection Approaches

Another approach to the protection problem is to associate a password with each file. Just as access to the computer system is often controlled by a password, access to each file can be controlled in the same way. If the passwords are chosen randomly and changed often, this scheme may be effective in limiting access to a file. The use of passwords has a few disadvantages, however. First, the number of passwords that a user needs to remember may become large, making the scheme impractical. Second, if only one password is used for all the files, then once it is discovered, all files are accessible; protection is on an all-or-none basis. Some systems allow a user to associate a password with a subdirectory, rather than with an individual file, to address this problem. More commonly encryption of a partition or individual files provides strong protection, but password management is key.

In a multilevel directory structure, we need to protect not only individual files but also collections of files in subdirectories; that is, we need to provide a mechanism for directory protection. The directory operations that must be protected are somewhat different from the file operations. We want to control the creation and deletion of files in a directory. In addition, we probably want to control whether a user can determine the existence of a file in a directory. Sometimes, knowledge of the existence and name of a file is significant in itself. Thus, listing the contents of a directory must be a protected operation. Similarly, if a path name refers to a file in a directory, the user must be allowed access to both the directory and the file. In systems where files may have numerous path names (such as acyclic and general graphs), a given user may have different access rights to a particular file, depending on the path name used.

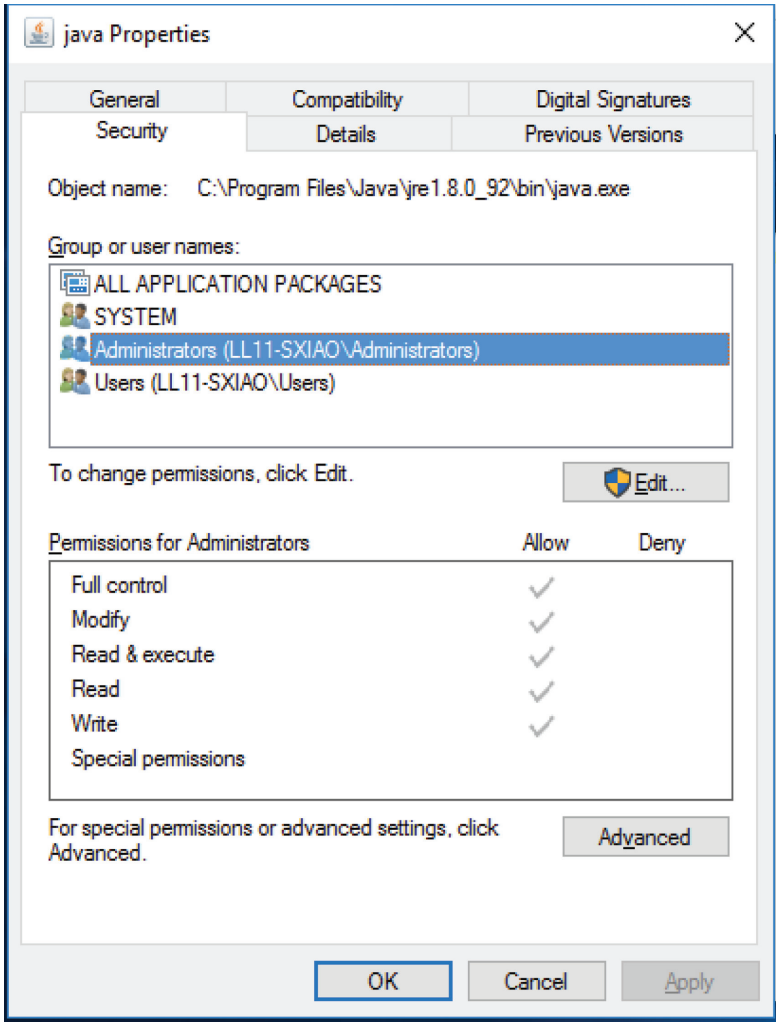

Figure 13.12 Windows 10 access-control list management.

13.5 Memory-Mapped Files

There is one other method of accessing files, and it is very commonly used. Consider a sequential read of a file on disk using the standard system calls `open()`, `read()`, and `write()`. Each file access requires a system call and disk access. Alternatively, we can use the virtual memory techniques discussed in Chapter 10 to treat file I/O as routine memory accesses. This approach, known as **memory mapping** a file, allows a part of the virtual address space to be logically associated with the file. As we shall see, this can lead to significant performance increases.

13.5.1 Basic Mechanism

Memory mapping a file is accomplished by mapping a disk block to a page (or pages) in memory. Initial access to the file proceeds through ordinary demand

paging, resulting in a page fault. However, a page-sized portion of the file is read from the file system into a physical page (some systems may opt to read in more than a page-sized chunk of memory at a time). Subsequent reads and writes to the file are handled as routine memory accesses. Manipulating files through memory rather than incurring the overhead of using the `read()` and `write()` system calls simplifies and speeds up file access and usage.

Note that writes to the file mapped in memory are not necessarily immediate (synchronous) writes to the file on secondary storage. Generally, systems update the file based on changes to the memory image only when the file is closed. Under memory pressure, systems will have any intermediate changes to swap space to not lose them when freeing memory for other uses. When the file is closed, all the memory-mapped data are written back to the file on secondary storage and removed from the virtual memory of the process.

Some operating systems provide memory mapping only through a specific system call and use the standard system calls to perform all other file I/O. However, some systems choose to memory-map a file regardless of whether the file was specified as memory-mapped. Let's take Solaris as an example. If a file is specified as memory-mapped (using the `mmap()` system call), Solaris maps the file into the address space of the process. If a file is opened and accessed using ordinary system calls, such as `open()`, `read()`, and `write()`, Solaris still memory-maps the file; however, the file is mapped to the kernel address space. Regardless of how the file is opened, then, Solaris treats all file I/O as memory-mapped, allowing file access to take place via the efficient memory subsystem and avoiding system call overhead caused by each traditional `read()` and `write()`.

Multiple processes may be allowed to map the same file concurrently, to allow sharing of data. Writes by any of the processes modify the data in virtual memory and can be seen by all others that map the same section of the file. Given our earlier discussions of virtual memory, it should be clear how the sharing of memory-mapped sections of memory is implemented: the virtual memory map of each sharing process points to the same page of physical memory—the page that holds a copy of the disk block. This memory sharing is illustrated in Figure 13.13. The memory-mapping system calls can also support copy-on-write functionality, allowing processes to share a file in read-only mode but to have their own copies of any data they modify. So that access to the shared data is coordinated, the processes involved might use one of the mechanisms for achieving mutual exclusion described in Chapter 6.

Quite often, shared memory is in fact implemented by memory mapping files. Under this scenario, processes can communicate using shared memory by having the communicating processes memory-map the same file into their virtual address spaces. The memory-mapped file serves as the region of shared memory between the communicating processes (Figure 13.14). We have already seen this in Section 3.5, where a POSIX shared-memory object is created and each communicating process memory-maps the object into its address space. In the following section, we discuss support in the Windows API for shared memory using memory-mapped files.

13.5.2 Shared Memory in the Windows API

The general outline for creating a region of shared memory using memory-mapped files in the Windows API involves first creating a **file mapping** for the

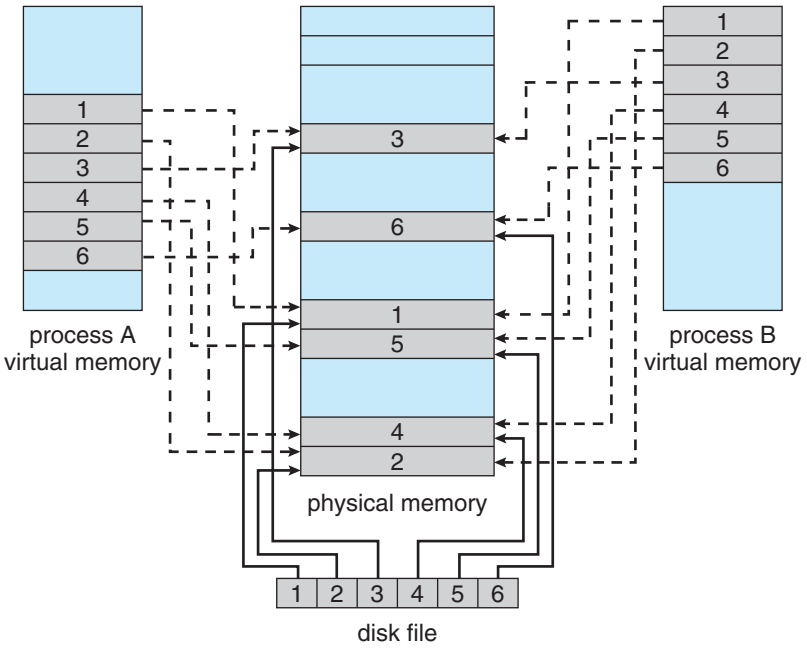

Figure 13.13 Memory-mapped files.

file to be mapped and then establishing a **view** of the mapped file in a process's virtual address space. A second process can then open and create a view of the mapped file in its virtual address space. The mapped file represents the shared-memory object that will enable communication to take place between the processes.

We next illustrate these steps in more detail. In this example, a producer process first creates a shared-memory object using the memory-mapping features available in the Windows API. The producer then writes a message to shared memory. After that, a consumer process opens a mapping to the shared-memory object and reads the message written by the consumer.

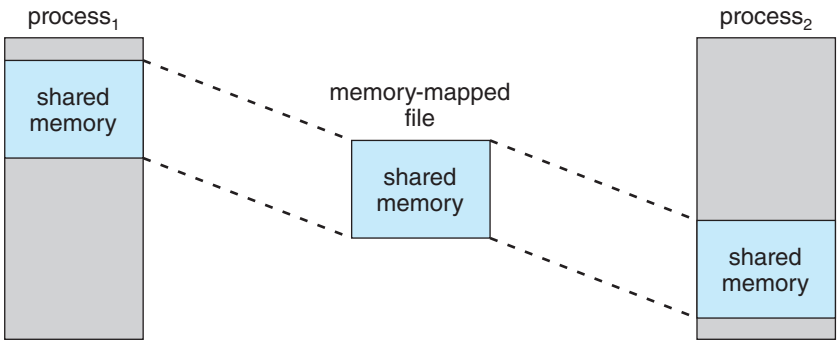

Figure 13.14 Shared memory using memory-mapped I/O.

To establish a memory-mapped file, a process first opens the file to be mapped with the `CreateFile()` function, which returns a `HANDLE` to the opened file. The process then creates a mapping of this file `HANDLE` using the `CreateFileMapping()` function. Once the file mapping is done, the process establishes a view of the mapped file in its virtual address space with the `MapViewOfFile()` function. The view of the mapped file represents the portion of the file being mapped in the virtual address space of the process—the entire file or only a portion of it may be mapped. This sequence in the program

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

int main(int argc, char *argv[])
{
   HANDLE hFile, hMapFile;
   LPVOID lpMapAddress;

   hFile = CreateFile("temp.txt", /* file name */
      GENERIC_READ | GENERIC_WRITE, /* read/write access */
      0, /* no sharing of the file */
      NULL, /* default security */
      OPEN_ALWAYS, /* open new or existing file */
      FILE_ATTRIBUTE_NORMAL, /* routine file attributes */
      NULL); /* no file template */

   hMapFile = CreateFileMapping(hFile, /* file handle */
      NULL, /* default security */
      PAGE_READWRITE, /* read/write access to mapped pages */
      0, /* map entire file */
      0,
      TEXT("SharedObject")); /* named shared memory object */

   lpMapAddress = MapViewOfFile(hMapFile, /* mapped object handle */
      FILE_MAP_ALL_ACCESS, /* read/write access */
      0, /* mapped view of entire file */
      0,
      0);

   /* write to shared memory */
   sprintf(lpMapAddress,"Shared memory message");

   UnmapViewOfFile(lpMapAddress);
   CloseHandle(hFile);
   CloseHandle(hMapFile);
}
```

Figure 13.15 Producer writing to shared memory using the Windows API.

is shown in Figure 13.15. (We eliminate much of the error checking for code brevity.)

The call to `CreateFileMapping()` creates a **named shared-memory object** called `SharedObject`. The consumer process will communicate using this shared-memory segment by creating a mapping to the same named object. The producer then creates a view of the memory-mapped file in its virtual address space. By passing the last three parameters the value 0, it indicates that the mapped view is the entire file. It could instead have passed values specifying an offset and size, thus creating a view containing only a subsection of the file. (It is important to note that the entire mapping may not be loaded into memory when the mapping is established. Rather, the mapped file may be demand-paged, thus bringing pages into memory only as they are accessed.) The `MapViewOfFile()` function returns a pointer to the shared-memory object; any accesses to this memory location are thus accesses to the memory-mapped file. In this instance, the producer process writes the message "`Shared memory message`" to shared memory.

A program illustrating how the consumer process establishes a view of the named shared-memory object is shown in Figure 13.16. This program is

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

int main(int argc, char *argv[])
{
   HANDLE hMapFile;
   LPVOID lpMapAddress;

   hMapFile = OpenFileMapping(FILE_MAP_ALL_ACCESS, /* R/W access */
      FALSE, /* no inheritance */
      TEXT("SharedObject")); /* name of mapped file object */

   lpMapAddress = MapViewOfFile(hMapFile, /* mapped object handle */
      FILE_MAP_ALL_ACCESS, /* read/write access */
      0, /* mapped view of entire file */
      0,
      0);

   /* read from shared memory */
   printf("Read message %s", lpMapAddress);

   UnmapViewOfFile(lpMapAddress);
   CloseHandle(hMapFile);
}
```

Figure 13.16 Consumer reading from shared memory using the Windows API.

somewhat simpler than the one shown in Figure 13.15, as all that is necessary is for the process to create a mapping to the existing named shared-memory object. The consumer process must also create a view of the mapped file, just as the producer process did in the program in Figure 13.15. The consumer then reads from shared memory the message "`Shared memory message`" that was written by the producer process.

Finally, both processes remove the view of the mapped file with a call to `UnmapViewOfFile()`. We provide a programming exercise at the end of this chapter using shared memory with memory mapping in the Windows API.

13.6 Summary

- A file is an abstract data type defined and implemented by the operating system. It is a sequence of logical records. A logical record may be a byte, a line (of fixed or variable length), or a more complex data item. The operating system may specifically support various record types or may leave that support to the application program.
- A major task for the operating system is to map the logical file concept onto physical storage devices such as hard disk or NVM device. Since the physical record size of the device may not be the same as the logical record size, it may be necessary to order logical records into physical records. Again, this task may be supported by the operating system or left for the application program.
- Within a file system, it is useful to create directories to allow files to be organized. A single-level directory in a multiuser system causes naming problems, since each file must have a unique name. A two-level directory solves this problem by creating a separate directory for each user's files. The directory lists the files by name and includes the file's location on the disk, length, type, owner, time of creation, time of last use, and so on.
- The natural generalization of a two-level directory is a tree-structured directory. A tree-structured directory allows a user to create subdirectories to organize files. Acyclic-graph directory structures enable users to share subdirectories and files but complicate searching and deletion. A general graph structure allows complete flexibility in the sharing of files and directories but sometimes requires garbage collection to recover unused disk space.
- Remote file systems present challenges in reliability, performance, and security. Distributed information systems maintain user, host, and access information so that clients and servers can share state information to manage use and access.
- Since files are the main information-storage mechanism in most computer systems, file protection is needed on multiuser systems. Access to files can be controlled separately for each type of access—read, write, execute, append, delete, list directory, and so on. File protection can be provided by access lists, passwords, or other techniques.

Practice Exercises

13.1 Some systems automatically delete all user files when a user logs off or a job terminates, unless the user explicitly requests that they be kept. Other systems keep all files unless the user explicitly deletes them. Discuss the relative merits of each approach.

13.2 Why do some systems keep track of the type of a file, while still others leave it to the user and others simply do not implement multiple file types? Which system is "better"?

13.3 Similarly, some systems support many types of structures for a file's data, while others simply support a stream of bytes. What are the advantages and disadvantages of each approach?

13.4 Could you simulate a multilevel directory structure with a single-level directory structure in which arbitrarily long names can be used? If your answer is yes, explain how you can do so, and contrast this scheme with the multilevel directory scheme. If your answer is no, explain what prevents your simulation's success. How would your answer change if file names were limited to seven characters?

13.5 Explain the purpose of the `open()` and `close()` operations.

13.6 In some systems, a subdirectory can be read and written by an authorized user, just as ordinary files can be.

a. Describe the protection problems that could arise.

b. Suggest a scheme for dealing with each of these protection problems.

13.7 Consider a system that supports 5,000 users. Suppose that you want to allow 4,990 of these users to be able to access one file.

a. How would you specify this protection scheme in UNIX?

b. Can you suggest another protection scheme that can be used more effectively for this purpose than the scheme provided by UNIX?

13.8 Researchers have suggested that, instead of having an access-control list associated with each file (specifying which users can access the file, and how), we should have a **user control list** associated with each user (specifying which files a user can access, and how). Discuss the relative merits of these two schemes.

Further Reading

A multilevel directory structure was first implemented on the MULTICS system ([Organick (1972)]). Most operating systems now implement multilevel directory structures. These include Linux ([Love (2010)]), macOS ([Singh (2007)]), Solaris ([McDougall and Mauro (2007)]), and all versions of Windows ([Russinovich et al. (2017)]).

A general discussion of Solaris file systems is found in the Sun *System Administration Guide: Devices and File Systems* (http://docs.sun.com/app/docs/doc/817-5093).

The network file system (NFS), designed by Sun Microsystems, allows directory structures to be spread across networked computer systems. NFS Version 4 is described in RFC3505 (http://www.ietf.org/rfc/rfc3530.txt).

A great source of the meanings of computer jargon is http://www.catb.org/esr/jargon/.

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[Singh (2007)] A. Singh, *Mac OS X Internals: A Systems Approach*, Addison-Wesley (2007).

Chapter 13 Exercises

13.9 Consider a file system in which a file can be deleted and its disk space reclaimed while links to that file still exist. What problems may occur if a new file is created in the same storage area or with the same absolute path name? How can these problems be avoided?

13.10 The open-file table is used to maintain information about files that are currently open. Should the operating system maintain a separate table for each user or maintain just one table that contains references to files that are currently being accessed by all users? If the same file is being accessed by two different programs or users, should there be separate entries in the open-file table? Explain.

13.11 What are the advantages and disadvantages of providing mandatory locks instead of advisory locks whose use is left to users' discretion?

13.12 Provide examples of applications that typically access files according to the following methods:

- Sequential
- Random

13.13 Some systems automatically open a file when it is referenced for the first time and close the file when the job terminates. Discuss the advantages and disadvantages of this scheme compared with the more traditional one, where the user has to open and close the file explicitly.

13.14 If the operating system knew that a certain application was going to access file data in a sequential manner, how could it exploit this information to improve performance?

13.15 Give an example of an application that could benefit from operating-system support for random access to indexed files.

13.16 Some systems provide file sharing by maintaining a single copy of a file. Other systems maintain several copies, one for each of the users sharing the file. Discuss the relative merits of each approach.

CHAPTER 14

File-System Implementation

As we saw in Chapter 13, the file system provides the mechanism for on-line storage and access to file contents, including data and programs. File systems usually reside permanently on secondary storage, which is designed to hold a large amount of data. This chapter is primarily concerned with issues surrounding file storage and access on the most common secondary-storage media, hard disk drives and nonvolatile memory devices. We explore ways to structure file use, to allocate storage space, to recover freed space, to track the locations of data, and to interface other parts of the operating system to secondary storage. Performance issues are considered throughout the chapter.

A given general-purpose operating system provides several file systems. Additionally, many operating systems allow administrators or users to add file systems. Why so many? File systems vary in many respects, including features, performance, reliability, and design goals, and different file systems may serve different purposes. For example, a temporary file system is used for fast storage and retrieval of nonpersistent files, while the default secondary storage file system (such as Linux ext4) sacrifices performance for reliability and features. As we've seen throughout this study of operating systems, there are plenty of choices and variations, making thorough coverage a challenge. In this chapter, we concentrate on the common denominators.

CHAPTER OBJECTIVES

- Describe the details of implementing local file systems and directory structures.
- Discuss block allocation and free-block algorithms and trade-offs.
- Explore file system efficiency and performance issues.
- Look at recovery from file system failures.
- Describe the WAFL file system as a concrete example.

14.1 File-System Structure

Disks provide most of the secondary storage on which file systems are maintained. Two characteristics make them convenient for this purpose:

1. A disk can be rewritten in place; it is possible to read a block from the disk, modify the block, and write it back into the same block.
2. A disk can access directly any block of information it contains. Thus, it is simple to access any file either sequentially or randomly, and switching from one file to another requires the drive moving the read–write heads and waiting for the media to rotate.

Nonvolatile memory (NVM) devices are increasingly used for file storage and thus as a location for file systems. They differ from hard disks in that they cannot be rewritten in place and they have different performance characteristics. We discuss disk and NVM-device structure in detail in Chapter 11.

To improve I/O efficiency, I/O transfers between memory and mass storage are performed in units of **blocks**. Each block on a hard disk drive has one or more sectors. Depending on the disk drive, sector size is usually 512 bytes or 4,096 bytes. NVM devices usually have blocks of 4,096 bytes, and the transfer methods used are similar to those used by disk drives.

File systems provide efficient and convenient access to the storage device by allowing data to be stored, located, and retrieved easily. A file system poses two quite different design problems. The first problem is defining how the file system should look to the user. This task involves defining a file and its attributes, the operations allowed on a file, and the directory structure for organizing files. The second problem is creating algorithms and data structures to map the logical file system onto the physical secondary-storage devices.

The file system itself is generally composed of many different levels. The structure shown in Figure 14.1 is an example of a layered design. Each level in the design uses the features of lower levels to create new features for use by higher levels.

The **I/O control** level consists of device drivers and interrupt handlers to transfer information between the main memory and the disk system. A device driver can be thought of as a translator. Its input consists of high-level commands, such as "retrieve block 123." Its output consists of low-level, hardware-specific instructions that are used by the hardware controller, which interfaces the I/O device to the rest of the system. The device driver usually writes specific bit patterns to special locations in the I/O controller's memory to tell the controller which device location to act on and what actions to take. The details of device drivers and the I/O infrastructure are covered in Chapter 12.

The **basic file system** (called the "block I/O subsystem" in Linux) needs only to issue generic commands to the appropriate device driver to read and write blocks on the storage device. It issues commands to the drive based on logical block addresses. It is also concerned with I/O request scheduling. This layer also manages the memory buffers and caches that hold various file-system, directory, and data blocks. A block in the buffer is allocated before the transfer of a mass storage block can occur. When the buffer is full, the buffer manager must find more buffer memory or free up buffer space to allow a

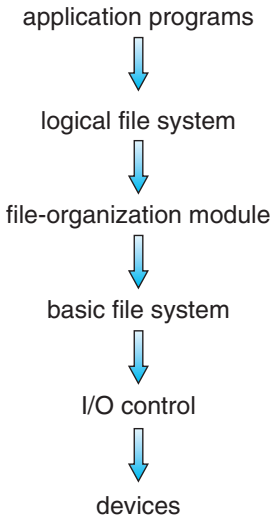


Figure 14.1 Layered file system.

requested I/O to complete. Caches are used to hold frequently used file-system metadata to improve performance, so managing their contents is critical for optimum system performance.

The **file-organizatio module** knows about files and their logical blocks. Each file's logical blocks are numbered from 0 (or 1) through *N*. The file-organization module also includes the free-space manager, which tracks unallocated blocks and provides these blocks to the file-organization module when requested.

Finally, the **logical file system** manages metadata information. Metadata includes all of the file-system structure except the actual data (or contents of the files). The logical file system manages the directory structure to provide the file-organization module with the information the latter needs, given a symbolic file name. It maintains file structure via file-control blocks. A **file control block** (**FCB**) (an **inode** in UNIX file systems) contains information about the file, including ownership, permissions, and location of the file contents. The logical file system is also responsible for protection, as discussed in Chapters 13 and 17.

When a layered structure is used for file-system implementation, duplication of code is minimized. The I/O control and sometimes the basic file-system code can be used by multiple file systems. Each file system can then have its own logical file-system and file-organization modules. Unfortunately, layering can introduce more operating-system overhead, which may result in decreased performance. The use of layering, including the decision about how many layers to use and what each layer should do, is a major challenge in designing new systems.

Many file systems are in use today, and most operating systems support more than one. For example, most CD-ROMs are written in the ISO 9660 format, a standard format agreed on by CD-ROM manufacturers. In addition to removable-media file systems, each operating system has one or more disk-based file systems. UNIX uses the **UNIX fil system** (**UFS**), which is based on the

Berkeley Fast File System (FFS). Windows supports disk file-system formats of FAT, FAT32, and NTFS (or Windows NT File System), as well as CD-ROM and DVD file-system formats. Although Linux supports over 130 different file systems, the standard Linux file system is known as the **extended file system**, with the most common versions being ext3 and ext4. There are also distributed file systems in which a file system on a server is mounted by one or more client computers across a network.

File-system research continues to be an active area of operating-system design and implementation. Google created its own file system to meet the company's specific storage and retrieval needs, which include high-performance access from many clients across a very large number of disks. Another interesting project is the FUSE file system, which provides flexibility in file-system development and use by implementing and executing file systems as user-level rather than kernel-level code. Using FUSE, a user can add a new file system to a variety of operating systems and can use that file system to manage her files.

14.2 File-System Operations

As was described in Section 13.1.2, operating systems implement `open()` and `close()` systems calls for processes to request access to file contents. In this section, we delve into the structures and operations used to implement file-system operations.

14.2.1 Overview

Several on-storage and in-memory structures are used to implement a file system. These structures vary depending on the operating system and the file system, but some general principles apply.

On storage, the file system may contain information about how to boot an operating system stored there, the total number of blocks, the number and location of free blocks, the directory structure, and individual files. Many of these structures are detailed throughout the remainder of this chapter. Here, we describe them briefly:

- A **boot control block** (per volume) can contain information needed by the system to boot an operating system from that volume. If the disk does not contain an operating system, this block can be empty. It is typically the first block of a volume. In UFS, it is called the **boot block**. In NTFS, it is the **partition boot sector**.
- A **volume control block** (per volume) contains volume details, such as the number of blocks in the volume, the size of the blocks, a free-block count and free-block pointers, and a free-FCB count and FCB pointers. In UFS, this is called a **superblock**. In NTFS, it is stored in the **master fil table**.
- A directory structure (per file system) is used to organize the files. In UFS, this includes file names and associated inode numbers. In NTFS, it is stored in the master file table.

- A per-file FCB contains many details about the file. It has a unique identifier number to allow association with a directory entry. In NTFS, this information is actually stored within the master file table, which uses a relational database structure, with a row per file.

The in-memory information is used for both file-system management and performance improvement via caching. The data are loaded at mount time, updated during file-system operations, and discarded at dismount. Several types of structures may be included.

- An in-memory **mount table** contains information about each mounted volume.
- An in-memory directory-structure cache holds the directory information of recently accessed directories. (For directories at which volumes are mounted, it can contain a pointer to the volume table.)
- The **system-wide open-fil table** contains a copy of the FCB of each open file, as well as other information.
- The **per-process open-fil table** contains pointers to the appropriate entries in the system-wide open-file table, as well as other information, for all files the process has open.
- Buffers hold file-system blocks when they are being read from or written to a file system.

To create a new file, a process calls the logical file system. The logical file system knows the format of the directory structures. To create a new file, it allocates a new FCB. (Alternatively, if the file-system implementation creates all FCBs at file-system creation time, an FCB is allocated from the set of free FCBs.) The system then reads the appropriate directory into memory, updates it with the new file name and FCB, and writes it back to the file system. A typical FCB is shown in Figure 14.2.

Some operating systems, including UNIX, treat a directory exactly the same as a file—one with a "type" field indicating that it is a directory. Other oper-

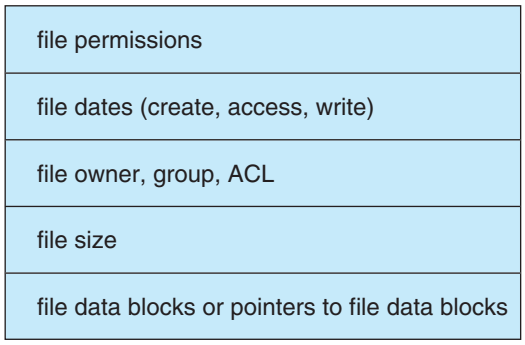


Figure 14.2 A typical file-control block.

ating systems, including Windows, implement separate system calls for files and directories and treat directories as entities separate from files. Whatever the larger structural issues, the logical file system can call the file-organization module to map the directory I/O into storage block locations, which are passed on to the basic file system and I/O control system.

14.2.2 Usage

Now that a file has been created, it can be used for I/O. First, though, it must be opened. The `open()` call passes a file name to the logical file system. The `open()` system call first searches the system-wide open-file table to see if the file is already in use by another process. If it is, a per-process open-file table entry is created pointing to the existing system-wide open-file table. This algorithm can save substantial overhead. If the file is not already open, the directory structure is searched for the given file name. Parts of the directory structure are usually cached in memory to speed directory operations. Once the file is found, the FCB is copied into a system-wide open-file table in memory. This table not only stores the FCB but also tracks the number of processes that have the file open.

Next, an entry is made in the per-process open-file table, with a pointer to the entry in the system-wide open-file table and some other fields. These other fields may include a pointer to the current location in the file (for the next `read()` or `write()` operation) and the access mode in which the file is open. The `open()` call returns a pointer to the appropriate entry in the per-process file-system table. All file operations are then performed via this pointer. The file name may not be part of the open-file table, as the system has no use for it once the appropriate FCB is located on disk. It could be cached, though, to save time on subsequent opens of the same file. The name given to the entry varies. UNIX systems refer to it as a **file descriptor**; Windows refers to it as a **file handle**.

When a process closes the file, the per-process table entry is removed, and the system-wide entry's open count is decremented. When all users that have opened the file close it, any updated metadata are copied back to the disk-based directory structure, and the system-wide open-file table entry is removed.

The caching aspects of file-system structures should not be overlooked. Most systems keep all information about an open file, except for its actual data blocks, in memory. The BSD UNIX system is typical in its use of caches wherever disk I/O can be saved. Its average cache hit rate of 85 percent shows that these techniques are well worth implementing. The BSD UNIX system is described fully in Appendix C.

The operating structures of a file-system implementation are summarized in Figure 14.3.

14.3 Directory Implementation

The selection of directory-allocation and directory-management algorithms significantly affects the efficiency, performance, and reliability of the file system. In this section, we discuss the trade-offs involved in choosing one of these algorithms.

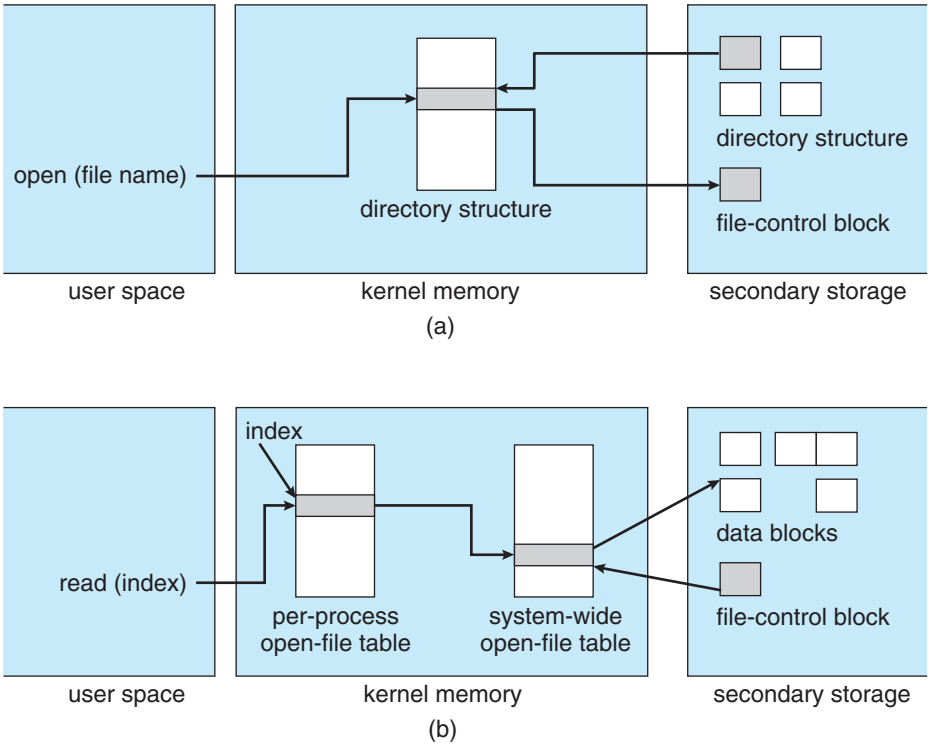


Figure 14.3 In-memory file-system structures. (a) File open. (b) File read.

14.3.1 Linear List

The simplest method of implementing a directory is to use a linear list of file names with pointers to the data blocks. This method is simple to program but time-consuming to execute. To create a new file, we must first search the directory to be sure that no existing file has the same name. Then, we add a new entry at the end of the directory. To delete a file, we search the directory for the named file and then release the space allocated to it. To reuse the directory entry, we can do one of several things. We can mark the entry as unused (by assigning it a special name, such as an all-blank name, assigning it an invalid inode number (such as 0), or by including a used–unused bit in each entry), or we can attach it to a list of free directory entries. A third alternative is to copy the last entry in the directory into the freed location and to decrease the length of the directory. A linked list can also be used to decrease the time required to delete a file.

The real disadvantage of a linear list of directory entries is that finding a file requires a linear search. Directory information is used frequently, and users will notice if access to it is slow. In fact, many operating systems implement a software cache to store the most recently used directory information. A cache hit avoids the need to constantly reread the information from secondary storage. A sorted list allows a binary search and decreases the average search time. However, the requirement that the list be kept sorted may complicate creating and deleting files, since we may have to move substantial amounts of

directory information to maintain a sorted directory. A more sophisticated tree data structure, such as a balanced tree, might help here. An advantage of the sorted list is that a sorted directory listing can be produced without a separate sort step.

14.3.2 Hash Table

Another data structure used for a file directory is a hash table. Here, a linear list stores the directory entries, but a hash data structure is also used. The hash table takes a value computed from the file name and returns a pointer to the file name in the linear list. Therefore, it can greatly decrease the directory search time. Insertion and deletion are also fairly straightforward, although some provision must be made for collisions—situations in which two file names hash to the same location.

The major difficulties with a hash table are its generally fixed size and the dependence of the hash function on that size. For example, assume that we make a linear-probing hash table that holds 64 entries. The hash function converts file names into integers from 0 to 63 (for instance, by using the remainder of a division by 64). If we later try to create a 65th file, we must enlarge the directory hash table—say, to 128 entries. As a result, we need a new hash function that must map file names to the range 0 to 127, and we must reorganize the existing directory entries to reflect their new hash-function values.

Alternatively, we can use a chained-overflow hash table. Each hash entry can be a linked list instead of an individual value, and we can resolve collisions by adding the new entry to the linked list. Lookups may be somewhat slowed, because searching for a name might require stepping through a linked list of colliding table entries. Still, this method is likely to be much faster than a linear search through the entire directory.

14.4 Allocation Methods

The direct-access nature of secondary storage gives us flexibility in the implementation of files. In almost every case, many files are stored on the same device. The main problem is how to allocate space to these files so that storage space is utilized effectively and files can be accessed quickly. Three major methods of allocating secondary storage space are in wide use: contiguous, linked, and indexed. Each method has advantages and disadvantages. Although some systems support all three, it is more common for a system to use one method for all files within a file-system type.

14.4.1 Contiguous Allocation

Contiguous allocation requires that each file occupy a set of contiguous blocks on the device. Device addresses define a linear ordering on the device. With this ordering, assuming that only one job is accessing the device, accessing block $b + 1$ after block b normally requires no head movement. When head movement is needed (from the last sector of one cylinder to the first sector of the next cylinder), the head need only move from one track to the next. Thus, for HDDs, the number of disk seeks required for accessing contiguously allocated files is

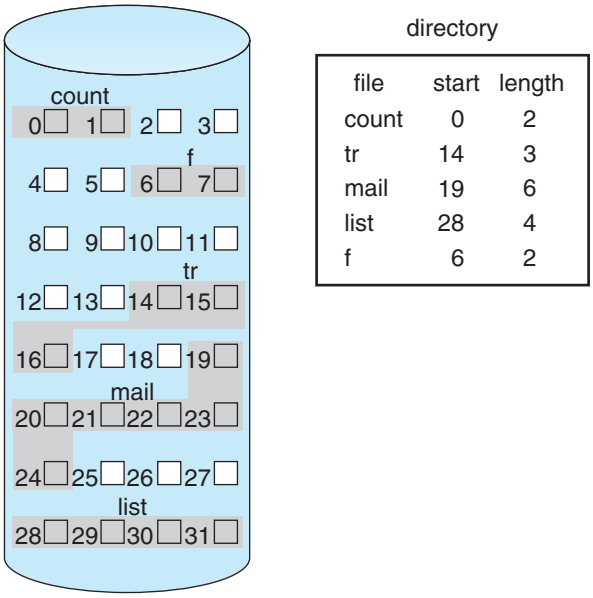


Figure 14.4 Contiguous allocation of disk space.

minimal (assuming blocks with close logical addresses are close physically), as is seek time when a seek is finally needed.

Contiguous allocation of a file is defined by the address of the first block and length (in block units) of the file. If the file is n blocks long and starts at location b, then it occupies blocks $b, b + 1, b + 2, \ldots, b + n - 1$. The directory entry for each file indicates the address of the starting block and the length of the area allocated for this file (Figure 14.4). Contiguous allocation is easy to implement but has limitations, and is therefore not used in modern file systems.

Accessing a file that has been allocated contiguously is easy. For sequential access, the file system remembers the address of the last block referenced and, when necessary, reads the next block. For direct access to block i of a file that starts at block b, we can immediately access block $b + i$. Thus, both sequential and direct access can be supported by contiguous allocation.

Contiguous allocation has some problems, however. One difficulty is finding space for a new file. The system chosen to manage free space determines how this task is accomplished; these management systems are discussed in Section 14.5. Any management system can be used, but some are slower than others.

The contiguous-allocation problem can be seen as a particular application of the general **dynamic storage-allocation** problem discussed in Section 9.2, which involves how to satisfy a request of size n from a list of free holes. First fit and best fit are the most common strategies used to select a free hole from the set of available holes. Simulations have shown that both first fit and best fit are more efficient than worst fit in terms of both time and storage utilization. Neither first fit nor best fit is clearly best in terms of storage utilization, but first fit is generally faster.

All these algorithms suffer from the problem of **external fragmentation**. As files are allocated and deleted, the free storage space is broken into little pieces.

External fragmentation exists whenever free space is broken into chunks. It becomes a problem when the largest contiguous chunk is insufficient for a request; storage is fragmented into a number of holes, none of which is large enough to store the data. Depending on the total amount of disk storage and the average file size, external fragmentation may be a minor or a major problem.

One strategy for preventing loss of significant amounts of storage space to external fragmentation is to copy an entire file system onto another device. The original device is then freed completely, creating one large contiguous free space. We then copy the files back onto the original device by allocating contiguous space from this one large hole. This scheme effectively **compacts** all free space into one contiguous space, solving the fragmentation problem. The cost of this compaction is time, however, and the cost can be particularly high for large storage devices. Compacting these devices may take hours and may be necessary on a weekly basis. Some systems require that this function be done **off-line**, with the file system unmounted. During this **down time**, normal system operation generally cannot be permitted, so such compaction is avoided at all costs on production machines. Most modern systems that need defragmentation can perform it **on-line** during normal system operations, but the performance penalty can be substantial.

Another problem with contiguous allocation is determining how much space is needed for a file. When the file is created, the total amount of space it will need must be found and allocated. How does the creator (program or person) know the size of the file to be created? In some cases, this determination may be fairly simple (copying an existing file, for example). In general, however, the size of an output file may be difficult to estimate.

If we allocate too little space to a file, we may find that the file cannot be extended. Especially with a best-fit allocation strategy, the space on both sides of the file may be in use. Hence, we cannot make the file larger in place. Two possibilities then exist. First, the user program can be terminated, with an appropriate error message. The user must then allocate more space and run the program again. These repeated runs may be costly. To prevent them, the user will normally overestimate the amount of space needed, resulting in considerable wasted space. The other possibility is to find a larger hole, copy the contents of the file to the new space, and release the previous space. This series of actions can be repeated as long as space exists, although it can be time consuming. The user need never be informed explicitly about what is happening, however; the system continues despite the problem, although more and more slowly.

Even if the total amount of space needed for a file is known in advance, preallocation may be inefficient. A file that will grow slowly over a long period (months or years) must be allocated enough space for its final size, even though much of that space will be unused for a long time. The file therefore has a large amount of internal fragmentation.

To minimize these drawbacks, an operating system can use a modified contiguous-allocation scheme. Here, a contiguous chunk of space is allocated initially. Then, if that amount proves not to be large enough, another chunk of contiguous space, known as an **extent**, is added. The location of a file's blocks is then recorded as a location and a block count, plus a link to the first block of the next extent. On some systems, the owner of the file can set the extent size, but this setting results in inefficiencies if the owner is incorrect. Internal

fragmentation can still be a problem if the extents are too large, and external fragmentation can become a problem as extents of varying sizes are allocated and deallocated. The commercial Symantec Veritas file system uses extents to optimize performance. Veritas is a high-performance replacement for the standard UNIX UFS.

14.4.2 Linked Allocation

Linked allocation solves all problems of contiguous allocation. With linked allocation, each file is a linked list of storage blocks; the blocks may be scattered anywhere on the device. The directory contains a pointer to the first and last blocks of the file. For example, a file of five blocks might start at block 9 and continue at block 16, then block 1, then block 10, and finally block 25 (Figure 14.5). Each block contains a pointer to the next block. These pointers are not made available to the user. Thus, if each block is 512 bytes in size, and a block address (the pointer) requires 4 bytes, then the user sees blocks of 508 bytes.

To create a new file, we simply create a new entry in the directory. With linked allocation, each directory entry has a pointer to the first block of the file. This pointer is initialized to `null` (the end-of-list pointer value) to signify an empty file. The size field is also set to 0. A write to the file causes the free-space management system to find a free block, and this new block is written to and is linked to the end of the file. To read a file, we simply read blocks by following the pointers from block to block. There is no external fragmentation with linked allocation, and any free block on the free-space list can be used to satisfy a request. The size of a file need not be declared when the file is created. A file can continue to grow as long as free blocks are available. Consequently, it is never necessary to compact disk space.

Linked allocation does have disadvantages, however. The major problem is that it can be used effectively only for sequential-access files. To find the *i*th

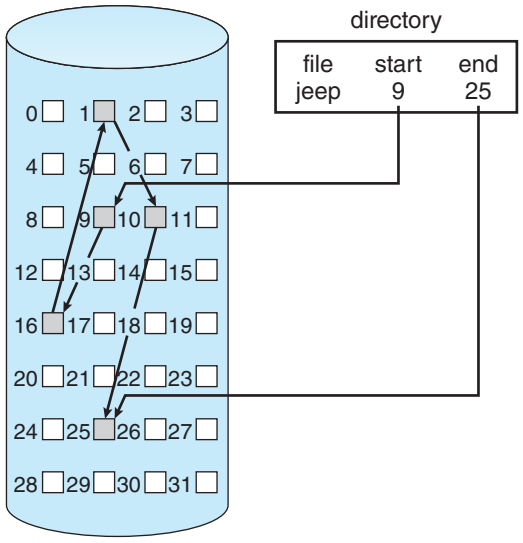


Figure 14.5 Linked allocation of disk space.

block of a file, we must start at the beginning of that file and follow the pointers until we get to the *i*th block. Each access to a pointer requires a storage device read, and some require an HDD seek. Consequently, it is inefficient to support a direct-access capability for linked-allocation files.

Another disadvantage is the space required for the pointers. If a pointer requires 4 bytes out of a 512-byte block, then 0.78 percent of the disk is being used for pointers, rather than for information. Each file requires slightly more space than it would otherwise.

The usual solution to this problem is to collect blocks into multiples, called **clusters**, and to allocate clusters rather than blocks. For instance, the file system may define a cluster as four blocks and operate on the secondary storage device only in cluster units. Pointers then use a much smaller percentage of the file's space. This method allows the logical-to-physical block mapping to remain simple but improves HDD throughput (because fewer disk-head seeks are required) and decreases the space needed for block allocation and free-list management. The cost of this approach is an increase in internal fragmentation, because more space is wasted when a cluster is partially full than when a block is partially full. Also random I/O performance suffers because a request for a small amount of data transfers a large amount of data. Clusters can be used to improve the disk-access time for many other algorithms as well, so they are used in most file systems.

Yet another problem of linked allocation is reliability. Recall that the files are linked together by pointers scattered all over the device, and consider what would happen if a pointer was lost or damaged. A bug in the operating-system software or a hardware failure might result in picking up the wrong pointer. This error could in turn result in linking into the free-space list or into another file. One partial solution is to use doubly linked lists, and another is to store the file name and relative block number in each block. However, these schemes require even more overhead for each file.

An important variation on linked allocation is the use of a **file-allocatio table** (**FAT**). This simple but efficient method of disk-space allocation was used by the MS-DOS operating system. A section of storage at the beginning of each volume is set aside to contain the table. The table has one entry for each block and is indexed by block number. The FAT is used in much the same way as a linked list. The directory entry contains the block number of the first block of the file. The table entry indexed by that block number contains the block number of the next block in the file. This chain continues until it reaches the last block, which has a special end-of-file value as the table entry. An unused block is indicated by a table value of 0. Allocating a new block to a file is a simple matter of finding the first 0-valued table entry and replacing the previous end-of-file value with the address of the new block. The 0 is then replaced with the end-of-file value. An illustrative example is the FAT structure shown in Figure 14.6 for a file consisting of disk blocks 217, 618, and 339.

The FAT allocation scheme can result in a significant number of disk head seeks, unless the FAT is cached. The disk head must move to the start of the volume to read the FAT and find the location of the block in question, then move to the location of the block itself. In the worst case, both moves occur for each of the blocks. A benefit is that random-access time is improved, because the disk head can find the location of any block by reading the information in the FAT.

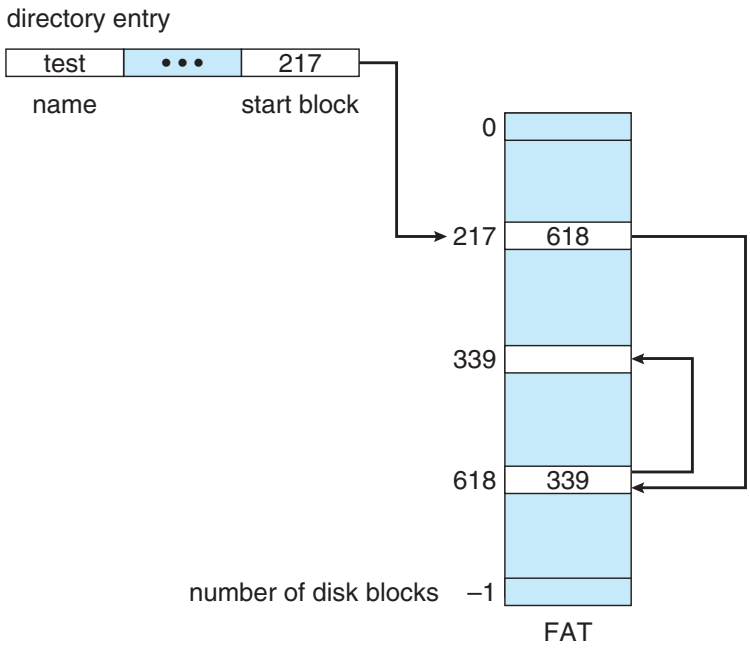


Figure 14.6 File-allocation table.

14.4.3 Indexed Allocation

Linked allocation solves the external-fragmentation and size-declaration problems of contiguous allocation. However, in the absence of a FAT, linked allocation cannot support efficient direct access, since the pointers to the blocks are scattered with the blocks themselves all over the disk and must be retrieved in order. **Indexed allocation** solves this problem by bringing all the pointers together into one location: the **index block**.

Each file has its own index block, which is an array of storage-block addresses. The *i*th entry in the index block points to the *i*th block of the file. The directory contains the address of the index block (Figure 14.7). To find and read the *i*th block, we use the pointer in the *i*th index-block entry. This scheme is similar to the paging scheme described in Section 9.3.

When the file is created, all pointers in the index block are set to `null`. When the *i*th block is first written, a block is obtained from the free-space manager, and its address is put in the *i*th index-block entry.

Indexed allocation supports direct access, without suffering from external fragmentation, because any free block on the storage device can satisfy a request for more space. Indexed allocation does suffer from wasted space, however. The pointer overhead of the index block is generally greater than the pointer overhead of linked allocation. Consider a common case in which we have a file of only one or two blocks. With linked allocation, we lose the space of only one pointer per block. With indexed allocation, an entire index block must be allocated, even if only one or two pointers will be non-`null`.

This point raises the question of how large the index block should be. Every file must have an index block, so we want the index block to be as small as

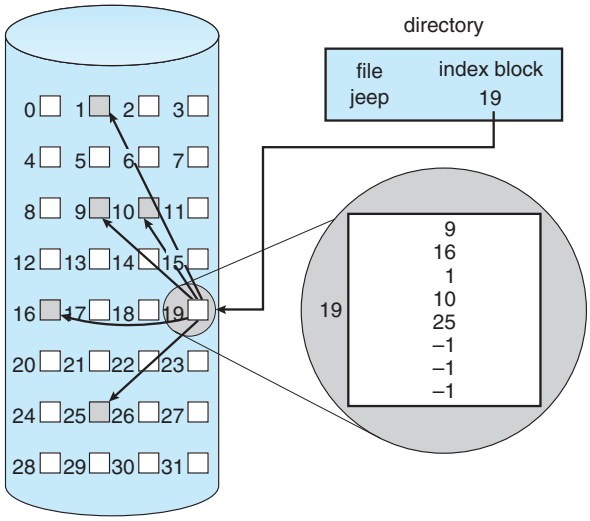


Figure 14.7 Indexed allocation of disk space.

possible. If the index block is too small, however, it will not be able to hold enough pointers for a large file, and a mechanism will have to be available to deal with this issue. Mechanisms for this purpose include the following:

- **Linked scheme**. An index block is normally one storage block. Thus, it can be read and written directly by itself. To allow for large files, we can link together several index blocks. For example, an index block might contain a small header giving the name of the file and a set of the first 100 disk-block addresses. The next address (the last word in the index block) is `null` (for a small file) or is a pointer to another index block (for a large file).
- **Multilevel index**. A variant of linked representation uses a first-level index block to point to a set of second-level index blocks, which in turn point to the file blocks. To access a block, the operating system uses the first-level index to find a second-level index block and then uses that block to find the desired data block. This approach could be continued to a third or fourth level, depending on the desired maximum file size. With 4,096-byte blocks, we could store 1,024 four-byte pointers in an index block. Two levels of indexes allow 1,048,576 data blocks and a file size of up to 4 GB.
- **Combined scheme**. Another alternative, used in UNIX-based file systems, is to keep the first, say, 15 pointers of the index block in the file's inode. The first 12 of these pointers point to **direct blocks**; that is, they contain addresses of blocks that contain data of the file. Thus, the data for small files (of no more than 12 blocks) do not need a separate index block. If the block size is 4 KB, then up to 48 KB of data can be accessed directly. The next three pointers point to **indirect blocks**. The first points to a **single indirect block**, which is an index block containing not data but the addresses of blocks that do contain data. The second points to a **double indirect block**, which contains the address of a block that contains the addresses of blocks that contain pointers to the actual data blocks. The last pointer contains the address of a **triple indirect block**. (A UNIX inode is shown in Figure 14.8.)

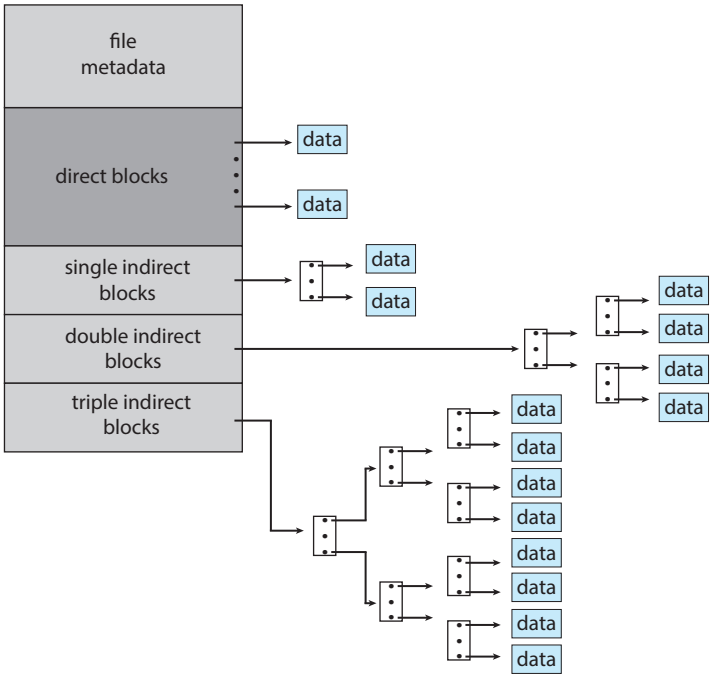


Figure 14.8 The UNIX inode.

Under this method, the number of blocks that can be allocated to a file exceeds the amount of space addressable by the 4-byte file pointers used by many operating systems. A 32-bit file pointer reaches only 2^{32} bytes, or 4 GB. Many UNIX and Linux implementations now support 64-bit file pointers, which allows files and file systems to be several exbibytes in size. The ZFS file system supports 128-bit file pointers.

Indexed-allocation schemes suffer from some of the same performance problems as does linked allocation. Specifically, the index blocks can be cached in memory, but the data blocks may be spread all over a volume.

14.4.4 Performance

The allocation methods that we have discussed vary in their storage efficiency and data-block access times. Both are important criteria in selecting the proper method or methods for an operating system to implement.

Before selecting an allocation method, we need to determine how the systems will be used. A system with mostly sequential access should not use the same method as a system with mostly random access.

For any type of access, contiguous allocation requires only one access to get a block. Since we can easily keep the initial address of the file in memory, we can calculate immediately the address of the *i*th block (or the next block) and read it directly.

For linked allocation, we can also keep the address of the next block in memory and read it directly. This method is fine for sequential access; for direct access, however, an access to the *i*th block might require *i* block reads. This

problem indicates why linked allocation should not be used for an application requiring direct access.

As a result, some systems support direct-access files by using contiguous allocation and sequential-access files by using linked allocation. For these systems, the type of access to be made must be declared when the file is created. A file created for sequential access will be linked and cannot be used for direct access. A file created for direct access will be contiguous and can support both direct access and sequential access, but its maximum length must be declared when it is created. In this case, the operating system must have appropriate data structures and algorithms to support both allocation methods. Files can be converted from one type to another by the creation of a new file of the desired type, into which the contents of the old file are copied. The old file may then be deleted and the new file renamed.

Indexed allocation is more complex. If the index block is already in memory, then the access can be made directly. However, keeping the index block in memory requires considerable space. If this memory space is not available, then we may have to read first the index block and then the desired data block. For a two-level index, two index-block reads might be necessary. For an extremely large file, accessing a block near the end of the file would require reading in all the index blocks before the needed data block finally could be read. Thus, the performance of indexed allocation depends on the index structure, on the size of the file, and on the position of the block desired.

Some systems combine contiguous allocation with indexed allocation by using contiguous allocation for small files (up to three or four blocks) and automatically switching to an indexed allocation if the file grows large. Since most files are small, and contiguous allocation is efficient for small files, average performance can be quite good.

Many other optimizations are in use. Given the disparity between CPU speed and disk speed, it is not unreasonable to add thousands of extra instructions to the operating system to save just a few disk-head movements. Furthermore, this disparity is increasing over time, to the point where hundreds of thousands of instructions could reasonably be used to optimize head movements.

For NVM devices, there are no disk head seeks, so different algorithms and optimizations are needed. Using an old algorithm that spends many CPU cycles trying to avoid a nonexistent head movement would be very inefficient. Existing file systems are being modified and new ones being created to attain maximum performance from NVM storage devices. These developments aim to reduce the instruction count and overall path between the storage device and application access to the data.

14.5 Free-Space Management

Since storage space is limited, we need to reuse the space from deleted files for new files, if possible. (Write-once optical disks allow only one write to any given sector, and thus reuse is not physically possible.) To keep track of free disk space, the system maintains a **free-space list**. The free-space list records all free device blocks—those not allocated to some file or directory. To create a file, we search the free-space list for the required amount of space and allocate

that space to the new file. This space is then removed from the free-space list. When a file is deleted, its space is added to the free-space list. The free-space list, despite its name, is not necessarily implemented as a list, as we discuss next.

14.5.1 Bit Vector

Frequently, the free-space list is implemented as a **bitmap** or **bit vector**. Each block is represented by 1 bit. If the block is free, the bit is 1; if the block is allocated, the bit is 0.

For example, consider a disk where blocks 2, 3, 4, 5, 8, 9, 10, 11, 12, 13, 17, 18, 25, 26, and 27 are free and the rest of the blocks are allocated. The free-space bitmap would be

001111001111110001100000011100000 ...

The main advantage of this approach is its relative simplicity and its efficiency in finding the first free block or n consecutive free blocks on the disk. Indeed, many computers supply bit-manipulation instructions that can be used effectively for that purpose. One technique for finding the first free block on a system that uses a bit vector to allocate space is to sequentially check each word in the bitmap to see whether that value is not 0, since a 0-valued word contains only 0 bits and represents a set of allocated blocks. The first non-0 word is scanned for the first 1 bit, which is the location of the first free block. The calculation of the block number is

(number of bits per word) × (number of 0-value words) + offset of first 1 bit.

Again, we see hardware features driving software functionality. Unfortunately, bit vectors are inefficient unless the entire vector is kept in main memory (and is written to the device containing the file system occasionally for recovery needs). Keeping it in main memory is possible for smaller devices but not necessarily for larger ones. A 1.3-GB disk with 512-byte blocks would need a bitmap of over 332 KB to track its free blocks, although clustering the blocks in groups of four reduces this number to around 83 KB per disk. A 1-TB disk with 4-KB blocks would require 32 MB (2^{40} / 2^{12} = 2^{28} bits = 2^{25} bytes = 2^{5} MB) to store its bitmap. Given that disk size constantly increases, the problem with bit vectors will continue to escalate as well.

14.5.2 Linked List

Another approach to free-space management is to link together all the free blocks, keeping a pointer to the first free block in a special location in the file system and caching it in memory. This first block contains a pointer to the next free block, and so on. Recall our earlier example (Section 14.5.1), in which blocks 2, 3, 4, 5, 8, 9, 10, 11, 12, 13, 17, 18, 25, 26, and 27 were free and the rest of the blocks were allocated. In this situation, we would keep a pointer to block 2 as the first free block. Block 2 would contain a pointer to block 3, which would point to block 4, which would point to block 5, which would point to block 8, and so on (Figure 14.9). This scheme is not efficient; to traverse the list, we must read each block, which requires substantial I/O time on HDDs. Fortunately, however, traversing the free list is not a frequent action. Usually,

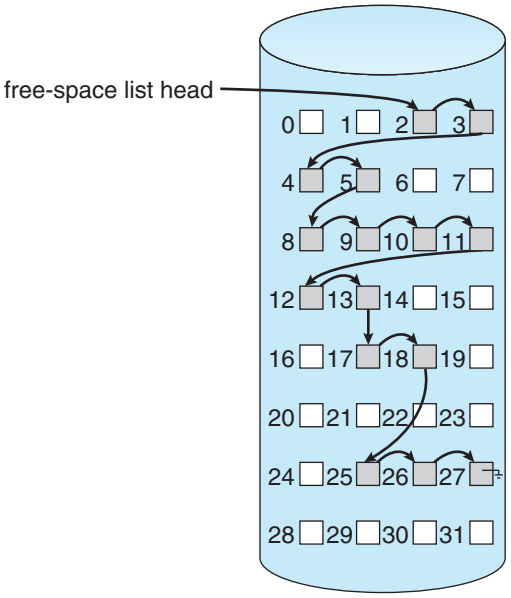


Figure 14.9 Linked free-space list on disk.

the operating system simply needs a free block so that it can allocate that block to a file, so the first block in the free list is used. The FAT method incorporates free-block accounting into the allocation data structure. No separate method is needed.

14.5.3 Grouping

A modification of the free-list approach stores the addresses of n free blocks in the first free block. The first $n-1$ of these blocks are actually free. The last block contains the addresses of another n free blocks, and so on. The addresses of a large number of free blocks can now be found quickly, unlike the situation when the standard linked-list approach is used.

14.5.4 Counting

Another approach takes advantage of the fact that, generally, several contiguous blocks may be allocated or freed simultaneously, particularly when space is allocated with the contiguous-allocation algorithm or through clustering. Thus, rather than keeping a list of n free block addresses, we can keep the address of the first free block and the number (n) of free contiguous blocks that follow the first block. Each entry in the free-space list then consists of a device address and a count. Although each entry requires more space than would a simple disk address, the overall list is shorter, as long as the count is generally greater than 1. Note that this method of tracking free space is similar to the extent method of allocating blocks. These entries can be stored in a balanced tree, rather than a linked list, for efficient lookup, insertion, and deletion.

14.5.5 Space Maps

Oracle's **ZFS** file system (found in Solaris and some other operating systems) was designed to encompass huge numbers of files, directories, and even file systems (in ZFS, we can create file-system hierarchies). On these scales, metadata I/O can have a large performance impact. Consider, for example, that if the free-space list is implemented as a bitmap, bitmaps must be modified both when blocks are allocated and when they are freed. Freeing 1 GB of data on a 1-TB disk could cause thousands of blocks of bitmaps to be updated, because those data blocks could be scattered over the entire disk. Clearly, the data structures for such a system could be large and inefficient.

In its management of free space, ZFS uses a combination of techniques to control the size of data structures and minimize the I/O needed to manage those structures. First, ZFS creates **metaslabs** to divide the space on the device into chunks of manageable size. A given volume may contain hundreds of metaslabs. Each metaslab has an associated space map. ZFS uses the counting algorithm to store information about free blocks. Rather than write counting structures to disk, it uses log-structured file-system techniques to record them. The space map is a log of all block activity (allocating and freeing), in time order, in counting format. When ZFS decides to allocate or free space from a metaslab, it loads the associated space map into memory in a balanced-tree structure (for very efficient operation), indexed by offset, and replays the log into that structure. The in-memory space map is then an accurate representation of the allocated and free space in the metaslab. ZFS also condenses the map as much as possible by combining contiguous free blocks into a single entry. Finally, the free-space list is updated on disk as part of the transaction-oriented operations of ZFS. During the collection and sorting phase, block requests can still occur, and ZFS satisfies these requests from the log. In essence, the log plus the balanced tree ***is*** the free list.

14.5.6 TRIMing Unused Blocks

HDDs and other storage media that allow blocks to be overwritten for updates need only the free list for managing free space. Blocks do not need to be treated specially when freed. A freed block typically keeps its data (but without any file pointers to the block) until the data are overwritten when the block is next allocated.

Storage devices that do not allow overwrite, such as NVM flash-based storage devices, suffer badly when these same algorithms are applied. Recall from Section 11.1.2 that such devices must be erased before they can again be written to, and that those erases must be made in large chunks (blocks, composed of pages) and take a relatively long time compared with reads or writes.

A new mechanism is needed to allow the file system to inform the storage device that a page is free and can be considered for erasure (once the block containing the page is entirely free). That mechanism varies based on the storage controller. For ATA-attached drives, it is TRIM, while for NVMe-based storage, it is the `unallocate` command. Whatever the specific controller command, this mechanism keeps storage space available for writing. Without such a capability, the storage device gets full and needs garbage collection and block erasure, leading to decreases in storage I/O write performance (known as "a write cliff").

With the TRIM mechanism and similar capabilities, the garbage collection and erase steps can occur before the device is nearly full, allowing the device to provide more consistent performance.

14.6 Efficiency and Performance

Now that we have discussed various block-allocation and directory-management options, we can further consider their effect on performance and efficient storage use. Disks tend to represent a major bottleneck in system performance, since they are the slowest main computer component. Even NVM devices are slow compared with CPU and main memory, so their performance must be optimized as well. In this section, we discuss a variety of techniques used to improve the efficiency and performance of secondary storage.

14.6.1 Efficiency

The efficient use of storage device space depends heavily on the allocation and directory algorithms in use. For instance, UNIX inodes are preallocated on a volume. Even an empty disk has a percentage of its space lost to inodes. However, by preallocating the inodes and spreading them across the volume, we improve the file system's performance. This improved performance results from the UNIX allocation and free-space algorithms, which try to keep a file's data blocks near that file's inode block to reduce seek time.

As another example, let's reconsider the clustering scheme discussed in Section 14.4, which improves file-seek and file-transfer performance at the cost of internal fragmentation. To reduce this fragmentation, BSD UNIX varies the cluster size as a file grows. Large clusters are used where they can be filled, and small clusters are used for small files and the last cluster of a file. This system is described in Appendix C.

The types of data normally kept in a file's directory (or inode) entry also require consideration. Commonly, a "last write date" is recorded to supply information to the user and to determine whether the file needs to be backed up. Some systems also keep a "last access date," so that a user can determine when the file was last read. The result of keeping this information is that, whenever the file is read, a field in the directory structure must be written to. That means the block must be read into memory, a section changed, and the block written back out to the device, because operations on secondary storage occur only in block (or cluster) chunks. So any time a file is opened for reading, its FCB must be read and written as well. This requirement can be inefficient for frequently accessed files, so we must weigh its benefit against its performance cost when designing a file system. Generally, every data item associated with a file needs to be considered for its effect on efficiency and performance.

Consider, for instance, how efficiency is affected by the size of the pointers used to access data. Most systems use either 32-bit or 64-bit pointers throughout the operating system. Using 32-bit pointers limits the size of a file to 2^{32}, or 4 GB. Using 64-bit pointers allows very large file sizes, but 64-bit pointers require more space to store. As a result, the allocation and free-space-management methods (linked lists, indexes, and so on) use more storage space.

One of the difficulties in choosing a pointer size—or, indeed, any fixed allocation size within an operating system—is planning for the effects of changing technology. Consider that the IBM PC XT had a 10-MB hard drive and an MS-DOS FAT file system that could support only 32 MB. (Each FAT entry was 12 bits, pointing to an 8-KB cluster.) As disk capacities increased, larger disks had to be split into 32-MB partitions, because the file system could not track blocks beyond 32 MB. As hard disks with capacities of over 100 MB became common, the disk data structures and algorithms in MS-DOS had to be modified to allow larger file systems. (Each FAT entry was expanded to 16 bits and later to 32 bits.) The initial file-system decisions were made for efficiency reasons; however, with the advent of MS-DOS Version 4, millions of computer users were inconvenienced when they had to switch to the new, larger file system. Solaris's ZFS file system uses 128-bit pointers, which theoretically should never need to be extended. (The minimum mass of a device capable of storing 2^{128} bytes using atomic-level storage would be about 272 trillion kilograms.)

As another example, consider the evolution of the Solaris operating system. Originally, many data structures were of fixed length, allocated at system startup. These structures included the process table and the open-file table. When the process table became full, no more processes could be created. When the file table became full, no more files could be opened. The system would fail to provide services to users. Table sizes could be increased only by recompiling the kernel and rebooting the system. With later releases of Solaris, (as with modern Linux kernels) almost all kernel structures were allocated dynamically, eliminating these artificial limits on system performance. Of course, the algorithms that manipulate these tables are more complicated, and the operating system is a little slower because it must dynamically allocate and deallocate table entries; but that price is the usual one for more general functionality.

14.6.2 Performance

Even after the basic file-system algorithms have been selected, we can still improve performance in several ways. As was discussed in Chapter 12, storage device controllers include local memory to form an on-board cache that is large enough to store entire tracks or blocks at a time. On an HDD, once a seek is performed, the track is read into the disk cache starting at the sector under the disk head (reducing latency time). The disk controller then transfers any sector requests to the operating system. Once blocks make it from the disk controller into main memory, the operating system may cache the blocks there.

Some systems maintain a separate section of main memory for a **buffer cache**, where blocks are kept under the assumption that they will be used again shortly. Other systems cache file data using a **page cache**. The page cache uses virtual memory techniques to cache file data as pages rather than as file-system-oriented blocks. Caching file data using virtual addresses is far more efficient than caching through physical disk blocks, as accesses interface with virtual memory rather than the file system. Several systems—including Solaris, Linux, and Windows—use page caching to cache both process pages and file data. This is known as **unifie virtual memory**.

Some versions of UNIX and Linux provide a **unifie buffer cache**. To illustrate the benefits of the unified buffer cache, consider the two alternatives

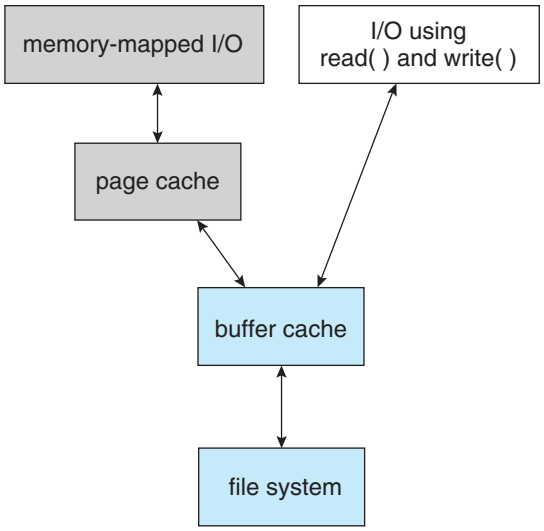


Figure 14.10 I/O without a unified buffer cache.

for opening and accessing a file. One approach is to use memory mapping (Section 13.5); the second is to use the standard system calls `read()` and `write()`. Without a unified buffer cache, we have a situation similar to Figure 14.10. Here, the `read()` and `write()` system calls go through the buffer cache. The memory-mapping call, however, requires using two caches—the page cache and the buffer cache. A memory mapping proceeds by reading in disk blocks from the file system and storing them in the buffer cache. Because the virtual memory system does not interface with the buffer cache, the contents of the file in the buffer cache must be copied into the page cache. This situation, known as **double caching**, requires caching file-system data twice. Not only does this waste memory but it also wastes significant CPU and I/O cycles due to the extra data movement within system memory. In addition, inconsistencies between the two caches can result in corrupt files. In contrast, when a unified buffer cache is provided, both memory mapping and the `read()` and `write()` system calls use the same page cache. This has the benefit of avoiding double caching, and it allows the virtual memory system to manage file-system data. The unified buffer cache is shown in Figure 14.11.

Regardless of whether we are caching storage blocks or pages (or both), least recently used (LRU) (Section 10.4.4) seems a reasonable general-purpose algorithm for block or page replacement. However, the evolution of the Solaris page-caching algorithms reveals the difficulty in choosing an algorithm. Solaris allows processes and the page cache to share unused memory. Versions earlier than Solaris 2.5.1 made no distinction between allocating pages to a process and allocating them to the page cache. As a result, a system performing many I/O operations used most of the available memory for caching pages. Because of the high rates of I/O, the page scanner (Section 10.10.3) reclaimed pages from processes—rather than from the page cache—when free memory ran low. Solaris 2.6 and Solaris 7 optionally implemented priority paging, in which the page scanner gave priority to process pages over the page cache. Solaris 8 applied a fixed limit to process pages and the file-system page cache, prevent-

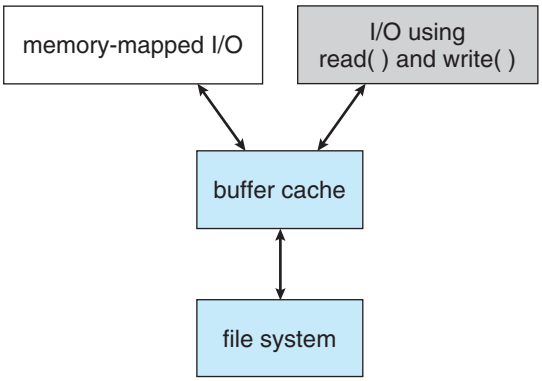


Figure 14.11 I/O using a unified buffer cache.

ing either from forcing the other out of memory. Solaris 9 and 10 again changed the algorithms to maximize memory use and minimize thrashing.

Another issue that can affect the performance of I/O is whether writes to the file system occur synchronously or asynchronously. **Synchronous writes** occur in the order in which the storage subsystem receives them, and the writes are not buffered. Thus, the calling routine must wait for the data to reach the drive before it can proceed. In an **asynchronous write**, the data are stored in the cache, and control returns to the caller. Most writes are asynchronous. However, metadata writes, among others, can be synchronous. Operating systems frequently include a flag in the `open` system call to allow a process to request that writes be performed synchronously. For example, databases use this feature for atomic transactions, to assure that data reach stable storage in the required order.

Some systems optimize their page cache by using different replacement algorithms, depending on the access type of the file. A file being read or written sequentially should not have its pages replaced in LRU order, because the most recently used page will be used last, or perhaps never again. Instead, sequential access can be optimized by techniques known as free-behind and read-ahead. **Free-behind** removes a page from the buffer as soon as the next page is requested. The previous pages are not likely to be used again and waste buffer space. With **read-ahead**, a requested page and several subsequent pages are read and cached. These pages are likely to be requested after the current page is processed. Retrieving these data from the disk in one transfer and caching them saves a considerable amount of time. One might think that a track cache on the controller would eliminate the need for read-ahead on a multiprogrammed system. However, because of the high latency and overhead involved in making many small transfers from the track cache to main memory, performing a read-ahead remains beneficial.

The page cache, the file system, and the device drivers have some interesting interactions. When small amounts of data are written to a file, the pages are buffered in the cache, and the storage device driver sorts its output queue according to device address. These two actions allow a disk driver to minimize disk-head seeks. Unless synchronous writes are required, a process writing to disk simply writes into the cache, and the system asynchronously writes the

data to disk when convenient. The user process sees very fast writes. When data are read from a disk file, the block I/O system does some read-ahead; however, writes are much more nearly asynchronous than are reads. Thus, output to the disk through the file system is often faster than is input for small transfers, counter to intuition. No matter how much buffering and caching is available, large, continuous I/O can overrun the capacity and end up bottlenecked on the device's performance. Consider writing a large movie file to a HDD. If the file is larger than the page cache (or the part of the page cache available to the process) then the page cache will fill and all I/O will occur at drive speed. Current HDDs read faster than they write, so in this instance the performance aspects are reversed from smaller I/O performance.

14.7 Recovery

Files and directories are kept both in main memory and on the storage volume, and care must be taken to ensure that a system failure does not result in loss of data or in data inconsistency. A system crash can cause inconsistencies among on-storage file-system data structures, such as directory structures, free-block pointers, and free FCB pointers. Many file systems apply changes to these structures in place. A typical operation, such as creating a file, can involve many structural changes within the file system on the disk. Directory structures are modified, FCBs are allocated, data blocks are allocated, and the free counts for all of these blocks are decreased. These changes can be interrupted by a crash, and inconsistencies among the structures can result. For example, the free FCB count might indicate that an FCB had been allocated, but the directory structure might not point to the FCB. Compounding this problem is the caching that operating systems do to optimize I/O performance. Some changes may go directly to storage, while others may be cached. If the cached changes do not reach the storage device before a crash occurs, more corruption is possible.

In addition to crashes, bugs in file-system implementation, device controllers, and even user applications can corrupt a file system. File systems have varying methods to deal with corruption, depending on the file-system data structures and algorithms. We deal with these issues next.

14.7.1 Consistency Checking

Whatever the cause of corruption, a file system must first detect the problems and then correct them. For detection, a scan of all the metadata on each file system can confirm or deny the consistency of the system. Unfortunately, this scan can take minutes or hours and should occur every time the system boots. Alternatively, a file system can record its state within the file-system metadata. At the start of any metadata change, a status bit is set to indicate that the metadata is in flux. If all updates to the metadata complete successfully, the file system can clear that bit. If, however, the status bit remains set, a consistency checker is run.

The **consistency checker**—a systems program such as `fsck` in UNIX—compares the data in the directory structure and other metadata with the state on storage and tries to fix any inconsistencies it finds. The allocation and free-space-management algorithms dictate what types of problems the

checker can find and how successful it will be in fixing them. For instance, if linked allocation is used and there is a link from any block to its next block, then the entire file can be reconstructed from the data blocks, and the directory structure can be recreated. In contrast, the loss of a directory entry on an indexed allocation system can be disastrous, because the data blocks have no knowledge of one another. For this reason, some UNIX file systems cache directory entries for reads, but any write that results in space allocation, or other metadata changes, is done synchronously, before the corresponding data blocks are written. Of course, problems can still occur if a synchronous write is interrupted by a crash. Some NVM storage devices contain a battery or supercapacitor to provide enough power, even during a power loss, to write data from device buffers to the storage media so the data are not lost. But even those precautions do not protect against corruption due to a crash.

14.7.2 Log-Structured File Systems

Computer scientists often find that algorithms and technologies originally used in one area are equally useful in other areas. Such is the case with the database log-based recovery algorithms. These logging algorithms have been applied successfully to the problem of consistency checking. The resulting implementations are known as **log-based transaction-oriented** (or **journaling**) file systems.

Note that with the consistency-checking approach discussed in the preceding section, we essentially allow structures to break and repair them on recovery. However, there are several problems with this approach. One is that the inconsistency may be irreparable. The consistency check may not be able to recover the structures, resulting in loss of files and even entire directories. Consistency checking can require human intervention to resolve conflicts, and that is inconvenient if no human is available. The system can remain unavailable until the human tells it how to proceed. Consistency checking also takes system and clock time. To check terabytes of data, hours of clock time may be required.

The solution to this problem is to apply log-based recovery techniques to file-system metadata updates. Both NTFS and the Veritas file system use this method, and it is included in recent versions of UFS on Solaris. In fact, it is now common on many file systems including ext3, ext4, and ZFS.

Fundamentally, all metadata changes are written sequentially to a log. Each set of operations for performing a specific task is a **transaction**. Once the changes are written to this log, they are considered to be committed, and the system call can return to the user process, allowing it to continue execution. Meanwhile, these log entries are replayed across the actual file-system structures. As the changes are made, a pointer is updated to indicate which actions have completed and which are still incomplete. When an entire committed transaction is completed, and entry is made in the log indicating that. The log file is is actually a circular buffer. A **circular buffer** writes to the end of its space and then continues at the beginning, overwriting older values as it goes. We would not want the buffer to write over data that had not yet been saved, so that scenario is avoided. The log may be in a separate section of the file system or even on a separate storage device.

If the system crashes, the log file will contain zero or more transactions. Any transactions it contains were not completed to the file system, even though they were committed by the operating system, so they must now be completed. The transactions can be executed from the pointer until the work is complete so that the file-system structures remain consistent. The only problem occurs when a transaction was aborted—that is, was not committed before the system crashed. Any changes from such a transaction that were applied to the file system must be undone, again preserving the consistency of the file system. This recovery is all that is needed after a crash, eliminating any problems with consistency checking.

A side benefit of using logging on disk metadata updates is that those updates proceed much faster than when they are applied directly to the on-disk data structures. The reason is found in the performance advantage of sequential I/O over random I/O. The costly synchronous random metadata writes are turned into much less costly synchronous sequential writes to the log-structured file system's logging area. Those changes, in turn, are replayed asynchronously via random writes to the appropriate structures. The overall result is a significant gain in performance of metadata-oriented operations, such as file creation and deletion, on HDD storage.

14.7.3 Other Solutions

Another alternative to consistency checking is employed by Network Appliance's WAFL file system and the Solaris ZFS file system. These systems never overwrite blocks with new data. Rather, a transaction writes all data and metadata changes to new blocks. When the transaction is complete, the metadata structures that pointed to the old versions of these blocks are updated to point to the new blocks. The file system can then remove the old pointers and the old blocks and make them available for reuse. If the old pointers and blocks are kept, a **snapshot** is created; the snapshot is a view of the file system at a specific point in time (before any updates after that time were applied). This solution should require no consistency checking if the pointer update is done atomically. WAFL does have a consistency checker, however, so some failure scenarios can still cause metadata corruption. (See Section 14.8 for details of the WAFL file system.)

ZFS takes an even more innovative approach to disk consistency. Like WAFL, it never overwrites blocks. However, ZFS goes further and provides checksumming of all metadata and data blocks. This solution (when combined with RAID) assures that data are always correct. ZFS therefore has no consistency checker. (More details on ZFS are found in Section 11.8.6.)

14.7.4 Backup and Restore

Storage devices sometimes fail, and care must be taken to ensure that the data lost in such a failure are not lost forever. To this end, system programs can be used to **back up** data from one storage device to another, such as a magnetic tape or other secondary storage device. Recovery from the loss of an individual file, or of an entire device, may then be a matter of **restoring** the data from backup.

To minimize the copying needed, we can use information from each file's directory entry. For instance, if the backup program knows when the last

backup of a file was done, and the file's last write date in the directory indicates that the file has not changed since that date, then the file does not need to be copied again. A typical backup schedule may then be as follows:

- **Day 1**. Copy to a backup medium all files from the file system. This is called a **full backup**.
- **Day 2**. Copy to another medium all files changed since day 1. This is an **incremental backup**.
- **Day 3**. Copy to another medium all files changed since day 2.

. . .

- **Day** N. Copy to another medium all files changed since day $N-1$. Then go back to day 1.

The new cycle can have its backup written over the previous set or onto a new set of backup media.

Using this method, we can restore an entire file system by starting restores with the full backup and continuing through each of the incremental backups. Of course, the larger the value of N, the greater the number of media that must be read for a complete restore. An added advantage of this backup cycle is that we can restore any file accidentally deleted during the cycle by retrieving the deleted file from the backup of the previous day.

The length of the cycle is a compromise between the amount of backup needed and the number of days covered by a restore. To decrease the number of tapes that must be read to do a restore, an option is to perform a full backup and then each day back up all files that have changed since the full backup. In this way, a restore can be done via the most recent incremental backup and the full backup, with no other incremental backups needed. The trade-off is that more files will be modified each day, so each successive incremental backup involves more files and more backup media.

A user may notice that a particular file is missing or corrupted long after the damage was done. For this reason, we usually plan to take a full backup from time to time that will be saved "forever." It is a good idea to store these permanent backups far away from the regular backups to protect against hazard, such as a fire that destroys the computer and all the backups too. In the TV show "Mr. Robot," hackers not only attacked the primary sources of banks' data but also their backup sites. Having multiple backup sites might not be a bad idea if your data are important.

14.8 Example: The WAFL File System

Because secondary-storage I/O has such a huge impact on system performance, file-system design and implementation command quite a lot of attention from system designers. Some file systems are general purpose, in that they can provide reasonable performance and functionality for a wide variety of file sizes, file types, and I/O loads. Others are optimized for specific tasks in an attempt to provide better performance in those areas than general-purpose

file systems. The **write-anywhere file layout** (WAFL) from NetApp, Inc. is an example of this sort of optimization. WAFL is a powerful, elegant file system optimized for random writes.

WAFL is used exclusively on network file servers produced by NetApp and is meant for use as a distributed file system. It can provide files to clients via the NFS, CIFS, iSCSI, `ftp`, and `http` protocols, although it was designed just for NFS and CIFS. When many clients use these protocols to talk to a file server, the server may see a very large demand for random reads and an even larger demand for random writes. The NFS and CIFS protocols cache data from read operations, so writes are of the greatest concern to file-server creators.

WAFL is used on file servers that include an NVRAM cache for writes. The WAFL designers took advantage of running on a specific architecture to optimize the file system for random I/O, with a stable-storage cache in front. Ease of use is one of the guiding principles of WAFL. Its creators also designed it to include a new snapshot functionality that creates multiple read-only copies of the file system at different points in time, as we shall see.

The file system is similar to the Berkeley Fast File System, with many modifications. It is block-based and uses inodes to describe files. Each inode contains 16 pointers to blocks (or indirect blocks) belonging to the file described by the inode. Each file system has a root inode. All of the metadata lives in files. All inodes are in one file, the free-block map in another, and the free-inode map in a third, as shown in Figure 14.12. Because these are standard files, the data blocks are not limited in location and can be placed anywhere. If a file system is expanded by addition of disks, the lengths of the metadata files are automatically expanded by the file system.

Thus, a WAFL file system is a tree of blocks with the root inode as its base. To take a snapshot, WAFL creates a copy of the root inode. Any file or metadata updates after that go to new blocks rather than overwriting their existing blocks. The new root inode points to metadata and data changed as a result of these writes. Meanwhile, the snapshot (the old root inode) still points to the old blocks, which have not been updated. It therefore provides access to the file system just as it was at the instant the snapshot was made—and takes very little storage space to do so. In essence, the extra space occupied by a snapshot consists of just the blocks that have been modified since the snapshot was taken.

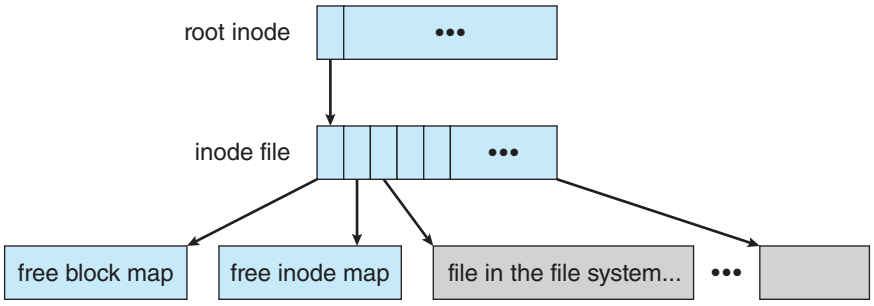
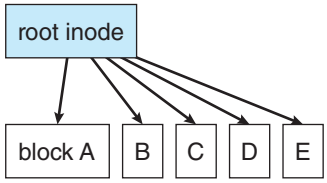


Figure 14.12 The WAFL file layout.

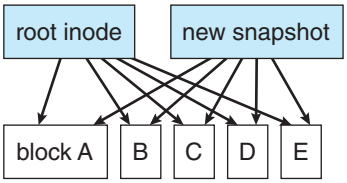
An important change from more standard file systems is that the free-block map has more than one bit per block. It is a bitmap with a bit set for each snapshot that is using the block. When all snapshots that have been using the block are deleted, the bitmap for that block is all zeros, and the block is free to be reused. Used blocks are never overwritten, so writes are very fast, because a write can occur at the free block nearest the current head location. There are many other performance optimizations in WAFL as well.

Many snapshots can exist simultaneously, so one can be taken each hour of the day and each day of the month, for example. A user with access to these snapshots can access files as they were at any of the times the snapshots were taken. The snapshot facility is also useful for backups, testing, versioning, and so on. WAFL's snapshot facility is very efficient in that it does not even require that copy-on-write copies of each data block be taken before the block is modified. Other file systems provide snapshots, but frequently with less efficiency. WAFL snapshots are depicted in Figure 14.13.

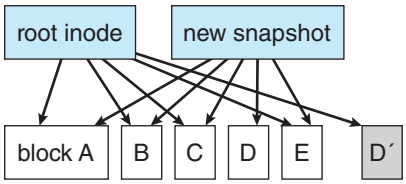
Newer versions of WAFL actually allow read–write snapshots, known as **clones**. Clones are also efficient, using the same techniques as shapshots. In this case, a read-only snapshot captures the state of the file system, and a clone refers back to that read-only snapshot. Any writes to the clone are stored in new blocks, and the clone's pointers are updated to refer to the new blocks. The original snapshot is unmodified, still giving a view into the file system as



(a) Before a snapshot.



(b) After a snapshot, before any blocks change.



(c) After block D has changed to D´.

Figure 14.13 Snapshots in WAFL.

THE APPLE FILE SYSTEM

In 2017, Apple, Inc., released a new file system to replace its 30-year-old HFS+ file system. HFS+ had been stretched to add many new features, but as usual, this process added complexity, along with lines of code, and made adding more features more difficult. Starting from scratch on a blank page allows a design to start with current technologies and methodologies and provide the exact set of features needed.

Apple File System (**APFS**) is a good example of such a design. Its goal is to run on all current Apple devices, from the Apple Watch through the iPhone to the Mac computers. Creating a file system that works in watchOS, I/Os, tvOS, and macOS is certainly a challenge. APFS is feature-rich, including 64-bit pointers, clones for files and directories, snapshots, space sharing, fast directory sizing, atomic safe-save primitives, copy-on-write design, encryption (single- and multi-key), and I/O coalescing. It understands NVM as well as HDD storage.

Most of these features we've discussed, but there are a few new concepts worth exploring. **Space sharing** is a ZFS-like feature in which storage is available as one or more large free spaces (**containers**) from which file systems can draw allocations (allowing APFS-formatted volumes to grow and shrink). **Fast directory sizing** provides quick used-space calculation and updating. **Atomic safe-save** is a primitive (available via API, not via file-system commands) that performs renames of files, bundles of files, and directories as single atomic operations. I/O coalescing is an optimization for NVM devices in which several small writes are gathered together into a large write to optimize write performance.

Apple chose not to implement RAID as part of the new APFS, instead depending on the existing Apple RAID volume mechanism for software RAID. APFS is also compatible with HFS+, allowing easy conversion for existing deployments.

it was before the clone was updated. Clones can also be promoted to replace the original file system; this involves throwing out all of the old pointers and any associated old blocks. Clones are useful for testing and upgrades, as the original version is left untouched and the clone deleted when the test is done or if the upgrade fails.

Another feature that naturally results from the WAFL file system implementation is **replication,** the duplication and synchronization of a set of data over a network to another system. First, a snapshot of a WAFL file system is duplicated to another system. When another snapshot is taken on the source system, it is relatively easy to update the remote system just by sending over all blocks contained in the new snapshot. These blocks are the ones that have changed between the times the two snapshots were taken. The remote system adds these blocks to the file system and updates its pointers, and the new system then is a duplicate of the source system as of the time of the second snapshot. Repeating this process maintains the remote system as a nearly up-to-date copy of the first system. Such replication is used for disaster recovery. Should the first system be destroyed, most of its data are available for use on the remote system.

Finally, note that the ZFS file system supports similarly efficient snapshots, clones, and replication, and those features are becoming more common in various file systems as time goes by.

14.9 Summary

- Most file systems reside on secondary storage, which is designed to hold a large amount of data permanently. The most common secondary-storage medium is the disk, but the use of NVM devices is increasing.
- Storage devices are segmented into partitions to control media use and to allow multiple, possibly varying, file systems on a single device. These file systems are mounted onto a logical file system architecture to make them available for use.
- File systems are often implemented in a layered or modular structure. The lower levels deal with the physical properties of storage devices and communicating with them. Upper levels deal with symbolic file names and logical properties of files.
- The various files within a file system can be allocated space on the storage device in three ways: through contiguous, linked, or indexed allocation. Contiguous allocation can suffer from external fragmentation. Direct access is very inefficient with linked allocation. Indexed allocation may require substantial overhead for its index block. These algorithms can be optimized in many ways. Contiguous space can be enlarged through extents to increase flexibility and to decrease external fragmentation. Indexed allocation can be done in clusters of multiple blocks to increase throughput and to reduce the number of index entries needed. Indexing in large clusters is similar to contiguous allocation with extents.
- Free-space allocation methods also influence the efficiency of disk-space use, the performance of the file system, and the reliability of secondary storage. The methods used include bit vectors and linked lists. Optimizations include grouping, counting, and the FAT, which places the linked list in one contiguous area.
- Directory-management routines must consider efficiency, performance, and reliability. A hash table is a commonly used method, as it is fast and efficient. Unfortunately, damage to the table or a system crash can result in inconsistency between the directory information and the disk's contents.
- A consistency checker can be used to repair damaged file-system structures. Operating-system backup tools allow data to be copied to magnetic tape or other storage devices, enabling the user to recover from data loss or even entire device loss due to hardware failure, operating system bug, or user error.
- Due to the fundamental role that file systems play in system operation, their performance and reliability are crucial. Techniques such as log structures and caching help improve performance, while log structures and RAID improve reliability. The WAFL file system is an example of optimization of performance to match a specific I/O load.

Practice Exercises

14.1 Consider a file currently consisting of 100 blocks. Assume that the file-control block (and the index block, in the case of indexed allocation) is already in memory. Calculate how many disk I/O operations are required for contiguous, linked, and indexed (single-level) allocation strategies, if, for one block, the following conditions hold. In the contiguous-allocation case, assume that there is no room to grow at the beginning but there is room to grow at the end. Also assume that the block information to be added is stored in memory.

a. The block is added at the beginning.

b. The block is added in the middle.

c. The block is added at the end.

d. The block is removed from the beginning.

e. The block is removed from the middle.

f. The block is removed from the end.

14.2 Why must the bit map for file allocation be kept on mass storage, rather than in main memory?

14.3 Consider a system that supports the strategies of contiguous, linked, and indexed allocation. What criteria should be used in deciding which strategy is best utilized for a particular file?

14.4 One problem with contiguous allocation is that the user must preallocate enough space for each file. If the file grows to be larger than the space allocated for it, special actions must be taken. One solution to this problem is to define a file structure consisting of an initial contiguous area of a specified size. If this area is filled, the operating system automatically defines an overflow area that is linked to the initial contiguous area. If the overflow area is filled, another overflow area is allocated. Compare this implementation of a file with the standard contiguous and linked implementations.

14.5 How do caches help improve performance? Why do systems not use more or larger caches if they are so useful?

14.6 Why is it advantageous to the user for an operating system to dynamically allocate its internal tables? What are the penalties to the operating system for doing so?

Further Reading

The internals of the BSD UNIX system are covered in full in [McKusick et al. (2015)]. Details concerning file systems for Linux can be found in [Love (2010)]. The Google file system is described in [Ghemawat et al. (2003)]. FUSE can be found at http://fuse.sourceforge.net.

Log-structured file organizations for enhancing both performance and consistency are discussed in [Rosenblum and Ousterhout (1991)], [Seltzer et al. (1993)], and [Seltzer et al. (1995)]. Log-structured designs for networked file systems are proposed in [Hartman and Ousterhout (1995)] and [Thekkath et al. (1997)].

The ZFS source code for space maps can be found at http://src.opensolaris.org/source/xref/onnv/onnv-gate/usr/src/uts/common/ fs/zfs/space_map.c.

ZFS documentation can be found at http://www.opensolaris.org/os/community/ZFS/docs.

The NTFS file system is explained in [Solomon (1998)], the Ext3 file system used in Linux is described in [Mauerer (2008)], and the WAFL file system is covered in [Hitz et al. (1995)].

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[Solomon (1998)] D. A. Solomon, *Inside Windows NT*, Second Edition, Microsoft Press (1998).

[Thekkath et al. (1997)] C. A. Thekkath, T. Mann, and E. K. Lee, "Frangipani: A Scalable Distributed File System", *Symposium on Operating Systems Principles* (1997), pages 224–237.

Chapter 14 Exercises

14.7 Consider a file system that uses a modified contiguous-allocation scheme with support for extents. A file is a collection of extents, with each extent corresponding to a contiguous set of blocks. A key issue in such systems is the degree of variability in the size of the extents. What are the advantages and disadvantages of the following schemes?

a. All extents are of the same size, and the size is predetermined.

b. Extents can be of any size and are allocated dynamically.

c. Extents can be of a few fixed sizes, and these sizes are predetermined.

14.8 Contrast the performance of the three techniques for allocating disk blocks (contiguous, linked, and indexed) for both sequential and random file access.

14.9 What are the advantages of the variant of linked allocation that uses a FAT to chain together the blocks of a file?

14.10 Consider a system where free space is kept in a free-space list.

a. Suppose that the pointer to the free-space list is lost. Can the system reconstruct the free-space list? Explain your answer.

b. Consider a file system similar to the one used by UNIX with indexed allocation. How many disk I/O operations might be required to read the contents of a small local file at `/a/b/c`? Assume that none of the disk blocks is currently being cached.

c. Suggest a scheme to ensure that the pointer is never lost as a result of memory failure.

14.11 Some file systems allow disk storage to be allocated at different levels of granularity. For instance, a file system could allocate 4 KB of disk space as a single 4-KB block or as eight 512-byte blocks. How could we take advantage of this flexibility to improve performance? What modifications would have to be made to the free-space management scheme in order to support this feature?

14.12 Discuss how performance optimizations for file systems might result in difficulties in maintaining the consistency of the systems in the event of computer crashes.

14.13 Discuss the advantages and disadvantages of supporting links to files that cross mount points (that is, the file link refers to a file that is stored in a different volume).

14.14 Consider a file system on a disk that has both logical and physical block sizes of 512 bytes. Assume that the information about each file is already in memory. For each of the three allocation strategies (contiguous, linked, and indexed), answer these questions:

a. How is the logical-to-physical address mapping accomplished in this system? (For the indexed allocation, assume that a file is always less than 512 blocks long.)

b. If we are currently at logical block 10 (the last block accessed was block 10) and want to access logical block 4, how many physical blocks must be read from the disk?

14.15 Consider a file system that uses inodes to represent files. Disk blocks are 8 KB in size, and a pointer to a disk block requires 4 bytes. This file system has 12 direct disk blocks, as well as single, double, and triple indirect disk blocks. What is the maximum size of a file that can be stored in this file system?

14.16 Fragmentation on a storage device can be eliminated through compaction. Typical disk devices do not have relocation or base registers (such as those used when memory is to be compacted), so how can we relocate files? Give three reasons why compacting and relocating files are often avoided.

14.17 Explain why logging metadata updates ensures recovery of a file system after a file-system crash.

14.18 Consider the following backup scheme:

- **Day 1**. Copy to a backup medium all files from the disk.
- **Day 2**. Copy to another medium all files changed since day 1.
- **Day 3**. Copy to another medium all files changed since day 1.

This differs from the schedule given in Section 14.7.4 by having all subsequent backups copy all files modified since the first full backup. What are the benefits of this system over the one in Section 14.7.4? What are the drawbacks? Are restore operations made easier or more difficult? Explain your answer.

14.19 Discuss the advantages and disadvantages of associating with remote file systems (stored on file servers) a set of failure semantics different from those associated with local file systems.

14.20 What are the implications of supporting UNIX consistency semantics for shared access to files stored on remote file systems?