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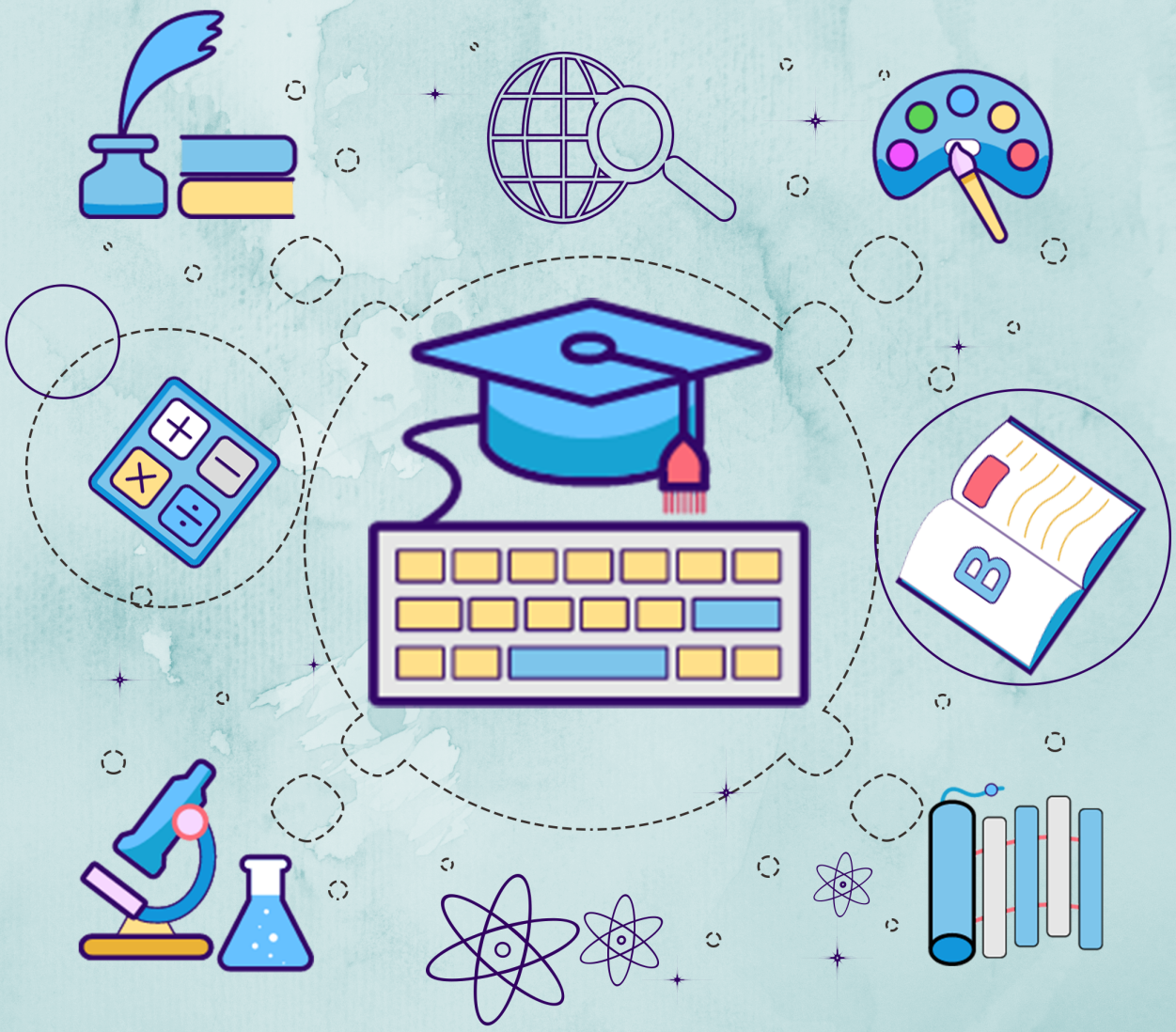

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MODULE 5
FILE SYSTEMS

Storage Management: *Overview of mass storage structure - disks and tapes. Disk Structure – Accessing disks. Disk Scheduling and Management. Swap Space.*
File System Interface: *File Concepts – Attributes – operations – types – structure – access mthods. File System Mounting. Protection. File System Implementation. Directory Implementation – allocation methods. Free Space Management.*
Protection **-** *Goals, Principles, Domain. Access Matrix.*

STORAGE MANAGEMENT

1. *Overview of Mass-Storage Structure*

- **Magnetic Disks**

Magnetic disks provide the bulk of secondary storage for modern computer systems. Conceptually, disks are relatively simple (Figure 12.1). Each disk platter has a flat circular shape, like a CD. Common platter diameters range from 1.8 to 5.25 inches. The two surfaces of a platter are covered with a magnetic material. We store information by recording it magnetically on the platters. A read-write head "flies" just above each surface of every platter. The heads are attached to a **disk arm** that moves all the heads as a unit. The surface of a platter is logically divided into circular **tracks,** which are subdivided into **sectors.** The set of tracks that are at one arm position makes up a **cylinder.** There may be thousands of concentric cylinders in a disk drive, and each track may contain hundreds of sectors. The storage capacity of common disk drives is measured in gigabytes.

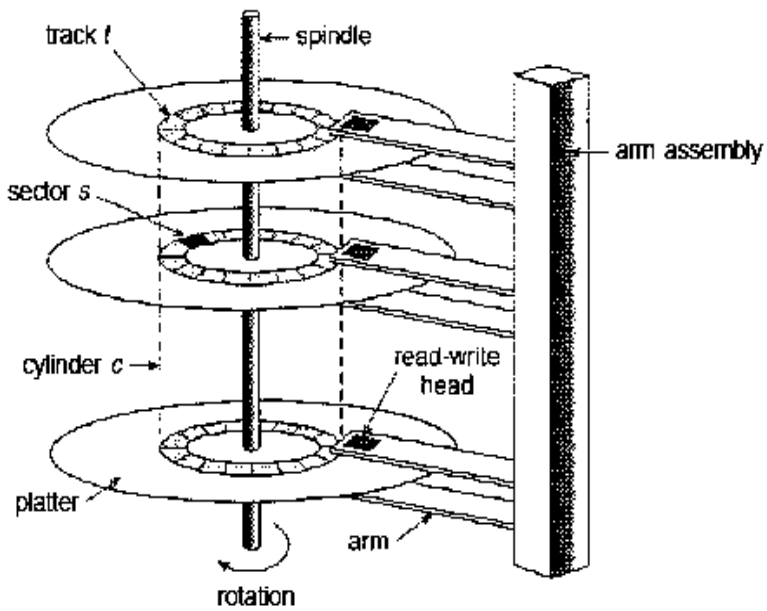

Figure 12.1 Moving-head disk mechanism.

When the disk is in use, a drive motor spins it at high speed. Most drives rotate 60 to 200 times per second. Disk speed has two parts. The **transfer rate** is the rate at which data flow between the drive and the computer. The **positioning time,** sometimes called the **random-access time,** consists of the time to move the disk arm to the desired cylinder, called the **seek time,** and the time for the desired sector to rotate to the disk head, called the **rotational**

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latency. Typical disks can transfer several megabytes of data per second, and they have seek times and rotational latencies of several milliseconds. Because the disk head flies on an extremely thin cushion of air (measured in microns), there is a danger that the head will make contact with the disk surface. Although the disk platters are coated with a thin protective layer, sometimes the head will damage the magnetic surface. This accident is called a **head crash.** A head crash normally cannot be repaired; the entire disk must be replaced. A disk can be **removable,** allowing different disks to be mounted as needed. Removable magnetic disks generally consist of one platter, held in a plastic case to prevent damage while not in the disk drive.

Floppy disks are inexpensive removable magnetic disks that have a soft plastic case containing a flexible platter. The head of a floppy-disk drive generally sits directly on the disk surface, so the drive is designed to rotate more slowly than a hard-disk drive to reduce the wear on the disk surface. The storage capacity of a floppy disk is typically only 1.44 MB or so. Removable disks are available that work much like normal hard disks and have capacities measured in gigabytes.

A disk drive is attached to a computer by a set of wires called an I/O **bus.** Several kinds of buses are available, including **enhanced integrated drive electronics (EIDE), advanced technology attachment (ATA), serial ATA** (SATA), **universal serial bus (USB), fiber channel (FC),** and **SCSI** buses. The data transfers on a bus are carried out by special electronic processors called **controllers.** The **host controller** is the controller at the computer end of the bus. A **disk controller** is built into each disk drive. To perform a disk I/O operation, the computer places a command into the host controller, typically using memory-mapped I/O ports. The host controller then sends the command via messages to the disk controller, and the disk controller operates the disk-drive hardware to carry out the command. Disk controllers usually have a built-in cache. Data transfer at the disk drive happens between the cache and the disk surface, and data transfer to the host, at fast electronic speeds, occurs between the cache and the host controller.

- **Magnetic Tapes**

Magnetic tape was used as an early secondary-storage medium. Although it is relatively permanent and can hold large quantities of data, its access time is slow compared with that of main memory and magnetic disk. In addition, random access to magnetic tape is about a thousand times slower than random access to magnetic disk, so tapes are not very useful for secondary storage. Tapes are used mainly for backup, for storage of infrequently used information, and as a medium for transferring information from one system to another.

A tape is kept in a spool and is wound or rewound past a read-write head. Moving to the correct spot on a tape can take minutes, but once positioned, tape drives can write data at speeds comparable to disk drives. Tape capacities vary greatly, depending on the particular kind of tape drive. Typically, they store from 20 GB to 200 GB. Some have built-in

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compressions that can more than double the effective storage. Tapes and their drivers are usually categorized by width, including 4, 8, and 19 millimeters and 1/4 and 1/2 inch. Some are named according to technology, such as LTO-2 and SDLT.

2. ***Disk Structure***

Modern disk drives are addressed as large one-dimensional arrays of **logical blocks,** where the logical block is the smallest unit of transfer. The size of a logical block is usually 512 bytes, although some disks can be **low-level formatted** to have a different logical block size, such as 1,024 bytes. The one-dimensional array of logical blocks is mapped onto the sectors of the disk sequentially. Sector 0 is the first sector of the first track on the outermost cylinder. The mapping proceeds in order through that track, then through the rest of the tracks in that cylinder, and then through the rest of the cylinders from outermost to innermost. By using this mapping, we can—at least in theory—convert a logical block number into an old-style disk address that consists of a cylinder number, a track number within that cylinder, and a sector number within that track. In practice, it is difficult to perform, this translation, for two reasons. First, most disks have some defective sectors, but the mapping hides this by substituting spare sectors from elsewhere on the disk.

Second, the number of sectors per track is not a constant on some drives. On media that use **constant linear velocity** (CLV), the density of bits per track is uniform. The farther a track is from the center of the disk, the greater its length, so the more sectors it can hold. As we move from outer zones to inner zones, the number of sectors per track decreases. Tracks in the outermost zone typically hold 40 percent more sectors than do tracks in the innermost zone. The drive increases its rotation speed as the head moves from the outer to the inner tracks to keep the same rate of data moving under the head. This method is used in CD-ROM and DVD-ROM drives. Alternatively, the disk rotation speed can stay constant, and the density of bits decreases from inner tracks to outer tracks to keep the data rate constant. This method is used in hard disks and is known as **constant** angular **velocity (CAV).** The number of sectors per track has been increasing as disk technology improves, and the outer zone of a disk usually has several hundred sectors per track. Similarly, the number of cylinders per disk has been increasing; large disks have tens of thousands of cylinders.

- ***Disk scheduling***

Access time = Seek time + Rotational latency

Seek time: The seek time is the time for the disk arm to move the heads to the cylinder containing the desired sector.

Rotational latency: The rotational latency is the additional time for the disk to rotate the desired sector to the disk head.

The **disk bandwidth** is the total number of bytes transferred, divided by the total time between the first request for service and the completion of the last transfer. **We can improve**

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both the access time and the bandwidth by managing the order in which disk I/O requests are serviced.

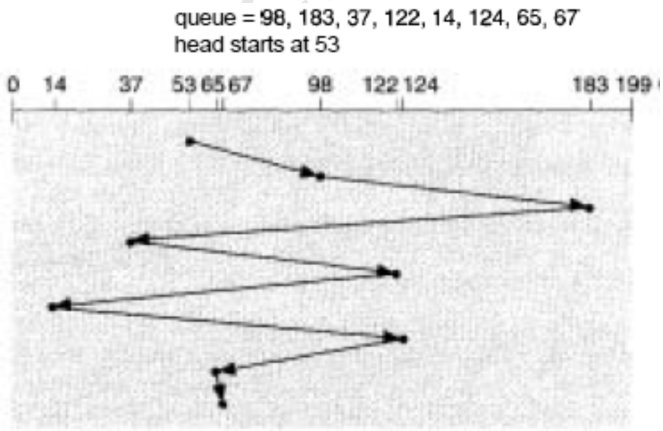
Whenever a process needs I/0 to or from the disk, it issues a system call to the operating system. The request specifies several pieces of information:

- Whether this operation is input or output
- What the disk address for the transfer is
- What the memory address for the transfer is
- What the number of sectors to be transferred is

If the desired disk drive and controller are available, the request can be serviced immediately. If the drive or controller is busy, any new requests for service will be placed in the **queue of pending requests** for that drive. For a multiprogramming system with many processes, the disk queue may often have several pending requests. Thus, when one request is completed, the operating system chooses which pending request to service next. Any one of several disk-scheduling algorithms can be used

- **FCFS Scheduling**

The simplest form of disk scheduling is, of course, the first-come, first-served (FCFS) algorithm. This algorithm is intrinsically fair, but it generally does not provide the fastest service. Consider, for example, a disk queue with requests for I/0 to blocks on cylinders 98, 183, 37, 122, 14, 124, 65, 67, in that order. If the disk head is initially at cylinder 53, it will first move from 53 to 98, then to 183, 37, 122, 14, 124, 65, and finally to 67, for a total head movement of 640 cylinders. This schedule is diagrammed in the Figure. The wild swing from 122 to 14 and then back to 124 illustrates the problem with this schedule. If the requests for cylinders 37 and 14 could be serviced together, before or after the requests for 122 and 124, the total head movement could be decreased substantially, and performance could be thereby improved.



- **SSTF Scheduling**

The **Shortest seek time first** algorithm selects the request with the least seek time from the current head position. Since seek time increases with the number of cylinders traversed by the head, **SSTF chooses the pending request closest to the current head position**.

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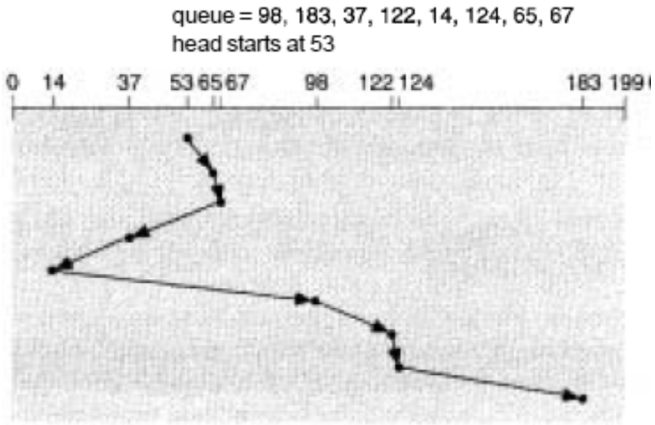
For our example request queue, the closest request to the initial head position (53) is at cylinder 65. Once we are at cylinder 65, the next closest request is at cylinder 67. From there, the request at cylinder 37 is closer than the one at 98, so 37 is served next. Continuing, we service the request at cylinder 14, then 98, 122, 124, and finally 183. This scheduling method results in a total head movement of only 236 cylinders-little more than one-third of the distance needed for FCFS scheduling of this request queue. Clearly, this algorithm gives a substantial improvement in performance.

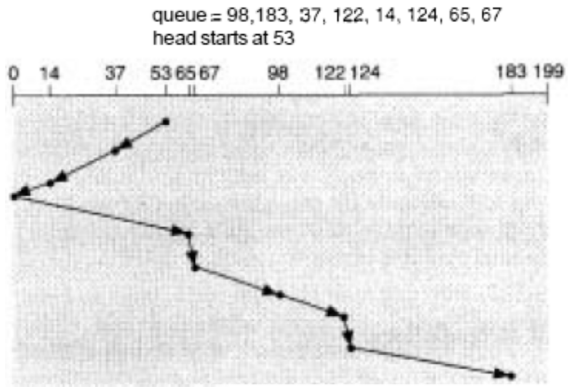


SSTF scheduling is essentially a form of shortest-job-first (SJF) scheduling; and like SJF scheduling, **it may cause starvation of some requests**. Remember that requests may arrive at any time. Suppose that we have two requests in the queue, for cylinders 14 and 186, and while the request from 14 is being serviced, a new request near 14 arrives. This new request will be serviced next, making the request at 186 wait. While this request is being serviced, another request close to 14 could arrive. In theory, a continual stream of requests near one another could cause the request for cylinder 186 to wait indefinitely.

- **SCAN Scheduling (Elevator algorithm)**

In the SCAN algorithm the disk arm starts at one end of the disk and moves toward the other end, servicing requests as it reaches each cylinder, until it gets to the other end of the disk. At the other end, the direction of head movement is reversed, and servicing continues. The head continuously scans back and forth across the disk. The SCAN algorithm is sometimes called the **elevator algorithm** since the disk arm behaves just like an elevator in a building, first servicing all the requests going up and then reversing to service requests the other way.

Let's return to our example to illustrate. Before applying SCAN to schedule the requests on cylinders 98, 183,37, 122, 14, 124, 65, and 67, we need to know the direction of head movement in addition to the head's current position. Assuming that the disk arm is moving toward 0 and that the initial head position is again 53, the head will next service 37 and then 14. At cylinder 0, the arm will reverse and will move toward the other end of the disk, servicing the requests at 65, 67, 98, 122, 124, and 183. If a request arrives in the queue just in front of the head, it will be serviced



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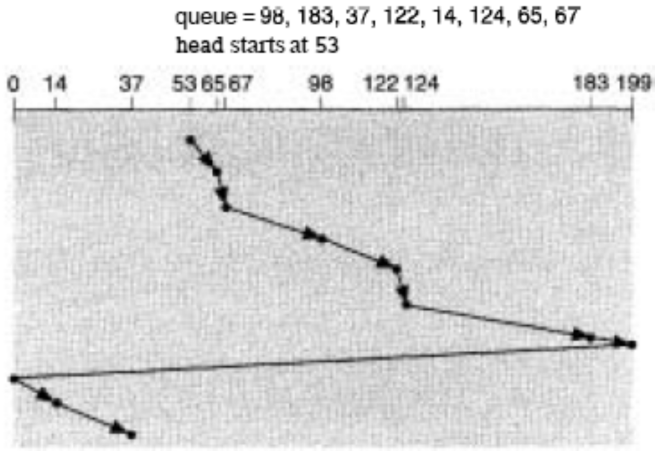
almost immediately; a request arriving just behind the head will have to wait until the arm moves to the end of the disk, reverses direction, and comes back.

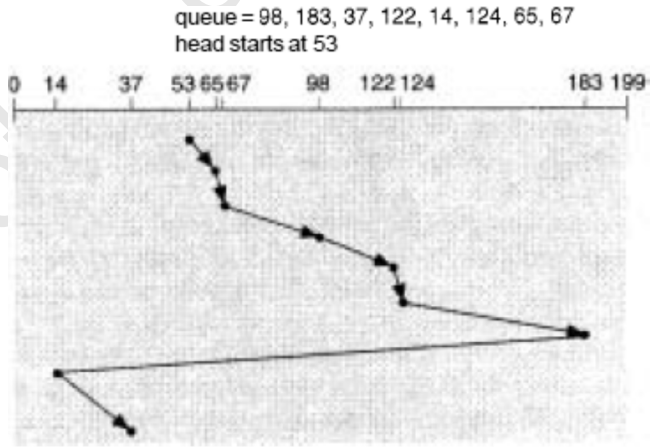
- **C-SCAN Scheduling**

Circular **SCAN (C-SCAN)** scheduling is a variant of SCAN designed to provide a more uniform wait time. Like SCAN, C-SCAN moves the head from one end of the disk to the other, servicing requests along the way. When the head reaches the other end, however, it immediately returns to the beginning of the disk, without servicing any requests on the return trip. The C-SCAN scheduling algorithm essentially treats the cylinders as a circular list that wraps around from the final cylinder to the first one.



- **LOOK Scheduling**

Both SCAN and C-SCAN move the disk arm across the full width of the disk. In practice, neither algorithm is implemented this way. More commonly, the arm goes only as far as the final request in each direction. Then, it reverses direction immediately, without going all the way to the end of the disk. These versions of SCAN and C-SCAN are called **LOOK** and **C-LOOK** scheduling, because they look for a request before continuing to move in a given direction.



- ***Disk Management***

The operating system is responsible for several other aspects of disk management, too.

- **Disk Formatting**

A new magnetic disk is a blank slate: It is just a platter of a magnetic recording material. Before a disk can store data, it must be divided into sectors that the disk controller can read and write. This process is called low-level formatting, or physical formatting. Low-level formatting fills the disk with a special data structure for each sector. The data structure for a sector typically consists of a header, a data area (usually 512 bytes in size), and a trailer. The header and trailer contain information used by the disk controller, such as a sector number and an error-correcting code (ECC). When the controller writes a sector of data during normal

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I/O, the ECC is updated with a value calculated from all the bytes in the data area. When the sector is read, the ECC is recalculated and is compared with the stored value. If the stored and calculated numbers are different, this mismatch indicates that the data area of the sector has become corrupted and that the disk sector may be bad. The ECC is an *error-correcting* code because it contains enough information that, if only a few bits or data have been corrupted, the controller can identify which bits, have changed and can calculate what their correct values should be. It then reports a recoverable soft error. The controller automatically does the ECC processing whenever a sector is read or written.

Most hard disks are low-level-formatted at the factory as a part of the manufacturing process. This formatting enables the manufacturer to test the disk and to initialize the mapping from logical block numbers to defect-free sectors on the disk. For many hard disks, when the disk controller is instructed to low-level-format the disk, it can also be told how many bytes of data space to leave between the header and trailer of all sectors. It is usually possible to choose among a few sizes, such as 256, 512, and 1,024 bytes. Formatting a disk with a larger sector size means that fewer sectors can fit on each track; but it also means that fewer headers and trailers are written on each track and more space is available for user data. Some operating systems can handle only a sector size of 512 bytes.

To use a disk to hold files, the operating system still needs to record its own data structures on the disk. It does so in two steps. The first step is to **partition** the disk into one or more groups of cylinders. The operating system can treat each partition as though it were a separate disk. For instance, one partition can hold a copy of the operating system's executable code, while another holds user files. After partitioning, the second step is **logical formatting** (or creation of a file system). In this step, the operating system stores the initial file-system data structures onto the disk. These data structures may include maps of free and allocated space (a FAT or modes) and an initial empty directory. To increase efficiency, most file systems group blocks together into larger chunks, frequently called **clusters.**

Disk I/O is done via blocks, but file system I /O is done via clusters, effectively assuring that I/O has more sequential-access and fewer random-access characteristics. Some operating systems give special programs the ability to use a disk partition as a large sequential array of logical blocks, without any file-system data structures. This array is sometimes called the raw disk, and 1 /O to this array is termed raw I/O. For example, some database systems prefer raw I/O because it enables them to control the exact disk location where each database record is stored. Raw I/O bypasses all the file-system services, such as the buffer cache, file locking, prefetching, space allocation, file names, and directories.

- **Boot Block**

For a computer to start running—for instance, when it is powered up or rebooted—it must have an initial program to run. This initial *bootstrap* program tends to be simple. It initializes all aspects of the system, from CPU registers to device controllers and the contents of main

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memory, and then starts the operating system. To do its job, the bootstrap program finds the operating system kernel on disk, loads that kernel into memory, and jumps to an initial address to begin the operating-system execution.

For most computers, the bootstrap is stored in read-only memory (ROM). This location is convenient, because ROM needs no initialization and is at a fixed location that the processor can start executing when powered up or reset. And, since ROM is read only, it cannot be infected by a computer virus. The problem is that changing this bootstrap code requires changing the ROM, hardware chips. For this reason, most systems store a tiny bootstrap loader program in the boot ROM whose only job is to bring in a full bootstrap program from disk. The full bootstrap program can be changed easily: A new version is simply written onto the disk. The full bootstrap program is stored in "the boot blocks" at a fixed location on the disk. A disk that has a boot partition is called a **boot disk** or **system disk.** The code in the boot ROM instructs the disk controller to read the boot blocks into memory (no device drivers are loaded at this point) and then starts executing that code. The full bootstrap program is more sophisticated than the bootstrap loader in the boot ROM; it is able to load the entire operating system from a non-fixed location on disk and to start the operating system running. Even so, the full bootstrap code may be small.

- **Bad Blocks**

Because disks have moving parts and small tolerances (recall that the disk head flies just above the disk surface), they are prone to failure. Sometimes the failure is complete; in this case, the disk needs to be replaced and its contents restored from backup media to the new disk. More frequently, one or more sectors become defective. Most disks even come from the factory with bad blocks. Depending on the disk and controller in use, these blocks are handled in a variety of ways. On simple disks, such as some disks with IDE controllers, bad blocks are handled manually.

For instance, the MS-DOS format command performs logical formatting and, as a part of the process, scans the disk to find bad blocks. If format finds a bad block, it writes a special value into the corresponding FAT entry to tell the allocation routines not to use that block. If blocks go bad during normal operation, a special program (such as chkdsk) must be run manually to search for the bad blocks and to lock them away as before. Data that resided on the bad blocks usually are lost. More sophisticated disks, such as the SCSI disks used in high-end PCs and most workstations and servers, are smarter about bad-block recovery. The controller maintains a list of bad blocks on the disk. The list is initialized during the low-level formatting at the factory and is updated over the life of the disk. Low-level formatting also sets aside spare sectors not visible to the operating system. The controller can be told to replace each bad sector logically with one of the spare sectors. This scheme is known as **sector sparing** or **forwarding.**

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A typical bad-sector transaction might be as follows:

- The operating system tries to read logical block 87.
- The controller calculates the ECC and finds that the sector is bad. It reports this finding to the operating system.
- The next time the system is rebooted, a special, command is run to tell the SCSI controller to replace the bad sector with a spare.
- After that, whenever the system requests logical block 87, the request is translated into the replacement sector's address by the controller.

Such a redirection by the controller could invalidate any optimization by the operating system's disk-scheduling algorithm! For this reason, most disks are formatted to provide a few spare sectors in each, cylinder and a spare cylinder as well. When a bad block is remapped, the controller uses a spare sector from the same cylinder, if possible. As an alternative to sector sparing, some controllers can be instructed to replace a bad block by sector slipping.

Here is an example: Suppose that logical block 17 becomes defective and the first available spare follows sector 202. Then, sector slipping remaps all the sectors from 17 to 202, moving them all down one spot. That is, sector 202 is copied into the spare, then sector 201 into 202, and then 200 into 201, and so on, until sector 18 is copied into sector 19. Slipping the sectors in this way frees up the space of sector 18, so sector 17 can be mapped to it.

The replacement of a bad block generally is not totally automatic because the data in the bad block are usually lost. Several soft errors could trigger a process in which a copy of the block data is made and the block is spared or slipped. An unrecoverable hard error, however, results in lost data. Whatever file was using that block must be repaired (for instance, by restoration from a backup tape), and that requires manual intervention.

- ***Swap-Space Management***

Swapping is the process of moving entire processes between disk and main memory. Swapping in that setting occurs when the amount of physical memory reaches a critically low point and processes (which are usually selected because they are the least active) are moved from memory to swap space to free available memory. In practice, very few modern operating systems implement swapping in this fashion. Rather, systems now combine swapping with virtual memory techniques and swap pages, not necessarily entire processes. In fact, some systems now use the terms *swapping* and *paging* interchangeably, reflecting the merging of these two concepts.

Swap-space management is another low-level task of the operating system. Virtual memory uses disk space as an extension of main memory. Since disk access is much slower than memory access, using swap space significantly decreases system performance. The main goal for the design, and implementation of swap space is to provide the best throughput for

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the virtual memory system. Here we discuss how swap space is used, where swap space is located on disk, and how swap space is managed.

- **Swap-Space Use**

Swap space is used in various ways by different operating systems, depending on the memory-management algorithms in use. For instance, systems that implement swapping may use swap space to hold an entire process image, including the code and data segments. Paging systems may simply store pages that have been pushed out of main memory. The amount of swap space needed on a system can therefore vary depending on the amount of physical memory, the amount of virtual memory it is backing, and the way in which the virtual memory is used. It can range from a few megabytes of disk space to gigabytes.

Note that it may be safer to overestimate than to underestimate the amount of swap space required, because if a system runs out of swap space it may be forced to abort processes or may crash entirely. Overestimation wastes disk space that could otherwise be used for files, but it does no other harm. Some systems recommend the amount to be set aside for swap space.

Some operating systems—including Linux—allow the use of multiple swap spaces. These swap spaces are usually put on separate disks so the load placed on the I/O system by paging and swapping can be spread over the system's I/O devices.

- **Swap-Space Location**

A swap space can reside in one of two places: It can be carved out of the normal file system, or it can be in a separate disk partition. If the swap space is simply a large file within the file system, normal file-system routines can be used to create it, name it, and allocate its space. This approach, though easy to implement, is inefficient. Navigating the directory structure and the disk-allocation data structures takes time and (potentially) extra disk accesses.

External fragmentation can greatly increase swapping times by forcing multiple seeks during reading or writing of a process image. We can improve performance by caching the block location information in physical memory and by using special tools to allocate physically contiguous blocks for the swap file, but the cost of traversing the file-system data structures still remains.

Alternatively, swap space can be created in a separate raw partition, as no file system or directory structure is placed in this space. Rather, a separate swap-space storage manager is used to allocate and deallocate the blocks from the raw partition. This manager uses algorithms optimized for speed rather than for storage efficiency, because swap space is accessed much more frequently than file systems (when it is used).

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Internal fragmentation may increase, but this trade-off is acceptable because the life of data in the swap space generally is much shorter than that of files in the file system. Swap space is reinitialized at boot time so any fragmentation is short-lived. This approach creates a fixed amount of swap space during disk partitioning. Adding more swap space requires repartitioning the disk (which involves moving the other file-system, partitions or destroying them and restoring them from backup) or adding another swap space elsewhere.

FILE SYSTEM INTERFACE

1. File concepts

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

A file is a named collection of related information that is recorded on secondary storage. Commonly, files represent programs 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 information in a file is defined by its **creator**. Many different types of information may be stored in a file-source programs, object programs, executable programs, numeric data, text, payroll records, graphic images, sound recordings, and so on. A file has a certain defined **structure** which depends on its type.

A **text file** is a sequence of characters organized into lines (and possibly pages). A **source file** is a sequence of subroutines and functions, each of which is further organized as declarations followed by executable statements. An **object file** is a sequence of bytes organized in. to blocks understandable by the system's linker. An **executable file** is a series of code sections that the loader can bring into memory and execute.

- **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 bys pecifying its name. The file's owner might write the file to a floppy disk, send it in an e-mail, or copy it across a network, and it could still be called *example.c*on the

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destination system. 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.
- **Identifier:** 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.
- **Time, date, and user identification:** This information may be kept for creation, last modification, and last use. These data can be useful for protection, security, and usage monitoring.

The information about all files is kept in the directory structure, which also resides on secondary storage. Typically, a directory entry consists of the file's name and its unique identifier. The identifier in turn locates the other file attributes.

- **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.

- **Creating a file.** Two steps are necessary to create a file. First, space in the file system must be found for the file. Second, an entry for the new file must be made in the directory.
- **Writing a file.** To write a file, we make a system call specifying both the name of the file and the information to be written to the file. Given the name of the file, the system searches the directory to find the file's location. The system must keep a *write* pointer to the location in the file where the next write is to take place. The write pointer must be updated whenever a write occurs.
- **Reading a file.** To read from a file, we use a system call that specifies the name of the file and where (in memory) the next block of the file should be put. Again, the directory is searched for the associated entry, and the system needs to keep a *read* pointer to the location in the file where the next read is to take place. 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 . Both the read and write operations use this same pointer, saving space and reducing system complexity.

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- **Repositioning within a file.** The directory is searched for the appropriate entry, and the current-file-position pointer is repositioned to a given value. Repositioning within a file need not involve any actual I/0. This file operation is also known as a **file *seek***.
- **Deleting a file.** 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 the directory entry.
- **Truncating a file**. 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-but lets the file be reset to length zero and its file space released.

Other common operations include ***appending*** new information to the end of an existing file and ***renaming*** an existing file.

The operating system keeps a small table, called the **open-file 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. create and delete are system calls that work with closed rather than open files. 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.

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 use of the file by the process. 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.

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. Because multiple processes may have opened a file, the system must wait for the last file to close before removing the

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open-file table entry. The file-open counter tracks the number of opens and closes and reaches zero on the last close. The system can then remove the entry.

- **Disk location of the file**: Most file operations require the system to modify data within the file. The information needed to locate the file on disk is kept in memory so that the system does not have to read it from disk 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/0 requests.

- **File locks**

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.** A **shared lock** is similar 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.

Furthermore, operating systems may provide either **mandatory or advisory file-locking mechanisms**. If a lock is mandatory, then 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. This occurs even if the text editor is not written explicitly to acquire the lock.

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.

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, pas, asm, a	source code in various languages
batch	bat, sh	commands to the command interpreter
text	txt, doc	textual data, documents
word processor	wp, tex, rtf, doc	various word-processor formats
library	lib, a, so, dll	libraries of routines for programmers
print or view	ps, pdf, jpg	ASCII or binary file in a format for printing or viewing
archive	arc, zip, tar	related files grouped into one file, sometimes compressed, for archiving or storage
multimedia	mpeg, mov, rm, mp3, avi	binary file containing audio or A/V information

- **File Types**

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 character (Figure 5.1). In this way, the user and the operating system can tell from the name

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alone what the type of a file is. For example, most operating systems allow users to specify a file name as a sequence of characters followed by a period and terminated by an extension of additional characters. File name examples include *resume.doc, Server.java,* and *ReaderThread.* c.

- **File Structure**

File types also can be used to indicate the internal structure of the file. Certain files must conform to a required structure that is understood by the operating system.
Example: The Macintosh operating system expects files to contain two parts: a **resource fork** and a **data fork**. The resource fork contains information of interest to the user. For instance, it holds the labels of any buttons displayed by the program. The data fork contains program code or data-the traditional file contents.

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/0 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.

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.

- **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. Other systems, such as those of IBM, support many access methods, and choosing the right one for a particular application is a major design problem.

Sequential Access

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The simplest access method is sequential method. **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***-read 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 5.3, is based on a tape model of a file and works as well on sequential-access devices as it does on random-access ones.

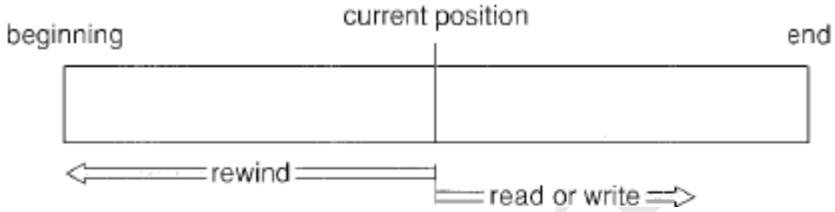

Fig 5.3: Sequential access file

Direct Access (Relative access)

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, 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.

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,* as with sequential access, and to add an operation *position file to n,* where *n* is the block number. Then, to effect a *read n,* we would *position to n* and then *read next.*

sequential access	implementation for direct access
reset	*cp* = 0;
read next	*read cp*; *cp* = *cp* + 1;
write next	*write cp*; *cp* = *cp* + 1;

Fig 5.4: Simulation of sequential access on a direct-access file

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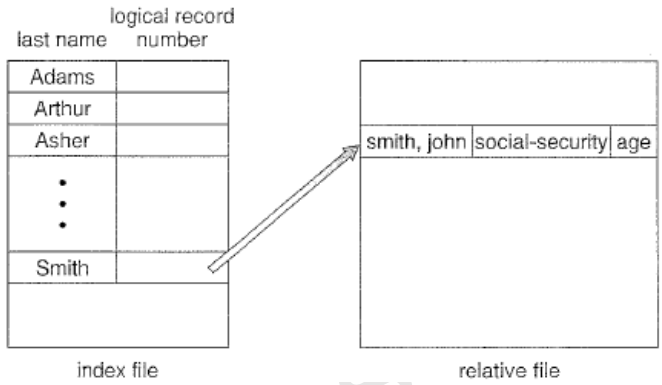
Other Access Methods

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.

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 would contain pointers to secondary index files, which would point to the actual data items.



2. **File-System Mounting**

Just as a file must be *opened* before it is used, a file system must be *mounted* before it can be available to processes on the system. More specifically, the directory structure can be built out of multiple volumes, which must be mounted to make them available within the file-system name space. The mount procedure is straightforward. The operating system is given the name of the device and the **mount point**—the location within the file structure where the file system is to be attached. Typically, a mount point is an empty directory. For instance, on a UNIX system, a file system containing a user's home directories might be mounted as */home;* then, to access the directory structure within that file system, we could precede the directory names with *ftiome,* as in */homc/jane.* Mounting that file system under */users* would result in the path name */users/jane,* which we could use to reach the same directory.

Next, the operating system verifies that the device contains a valid file system. It does so by asking the device driver to read the device directory and verifying that the directory has the expected format. Finally, the operating system notes in its directory structure that a file system is mounted at the specified mount point. This scheme enables the operating system to traverse its directory structure, switching among file systems as appropriate.

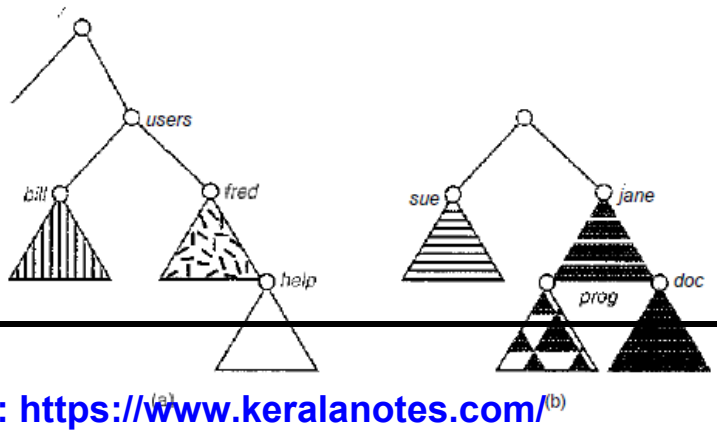


Figure 10.12 File system. (a) Existing system. (b) Unmounted volume.

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To illustrate file mounting, consider the file system depicted in Figure 10.12, where the triangles represent subtrees of directories that are of interest. Figure 10.12(a) shows an existing file system, while Figure 10.12(b) shows an unmounted volume residing on */device'/dsk.* At this point, only the files on the existing file system can be accessed. Figure 10.13 shows the effects of mounting the volume residing on */device/dsk* over */users.* If the volume is unmounted, the file system is restored to the situation depicted in Figure 10.12.

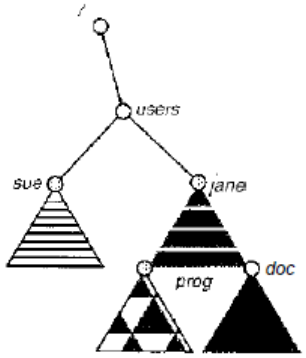

Figure 10.13 Mount point.

Consider the actions of the Macintosh operating system. Whenever the system encounters a disk for the first time (hard disks are found at boot time, and floppy disks are seen when they are inserted into the drive), the Macintosh operating system searches for a file system on the device. If it finds one, it automatically mounts the file system at the root level, adding a folder icon on the screen labeled with the name of the file system (as stored in the device directory). The user is then able to click on the icon and thus display the newly mounted file system.

The Microsoft Windows family of operating systems (95, 98, NT, small 2000, XP) maintains an extended two-level directory structure, with devices and volumes assigned drive letters. Volumes have a general graph directory structure associated with the drive letter. The path to a specific file takes the form of *drive-letter;\path\to\file.* The more recent versions of Windows allow a file system to he mounted anywhere in the directory tree, just as UNIX does.

Windows operating systems automatically discover all devices and mount all located file systems at boot time. In some systems, like UNIX, the mount commands are explicit. A system configuration file contains a list of devices and mount points for automatic mounting at boot time, but other mounts may be executed manually.

3. Protection

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

Protection can be provided in many ways. For a small single-user system, we might provide protection by physically removing the floppy disks and locking them in a desk drawer or file cabinet. In a multiuser system, however, other mechanisms are needed.

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- **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 tree its space for possible reuse.
• **List**. List the name and 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.

- **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.

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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 needs to 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.

• **Universe**. All other users in the system constitute the universe.

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.

4. File-System Structure

Disks provide the bulk of secondary storage on which a file system is maintained. They have two characteristics that make them a convenient medium for storing multiple files:

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 place.
2. A disk can access directly any given 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 only moving the read-write heads and waiting for the disk to rotate. Rather than transferring a byte at a time, to improve I/O efficiency, I/O transfers between memory and disk are performed in units of *blocks.* Each block has one or more sectors. Depending on the disk drive, sectors vary from 32 bytes to 4,096 bytes; usually, they are 512 bytes.

To provide efficient and convenient access to the disk, the operating system imposes one or more file systems to allow the 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

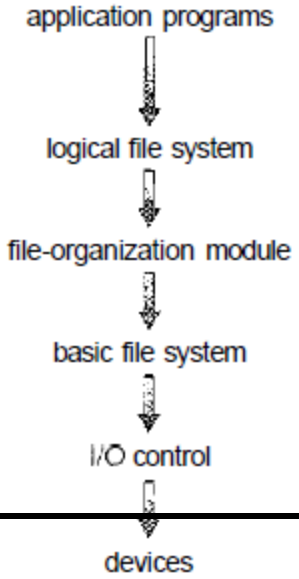

Figure 11.1 Layered file system.

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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 11.1 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 lowest level, the *I/O control,* 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 lowlevel, 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 **basic file system** needs only to issue generic commands to the appropriate device driver to read and write physical blocks on the disk. Each physical block is identified by its numeric disk address (for example, drive 1, cylinder 73, track 2, sector 10).

The file-organization module knows about files and their logical blocks, as well as physical blocks. By knowing the type of file allocation used and the location of the file, the file-organization module can translate logical block addresses to physical block addresses for the basic file system to transfer. Each file's logical blocks are numbered from 0 (or 1) through *N.* Since the physical blocks containing the data usually do not match the logical numbers, a translation is needed to locate each block. 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) contains information about the file, including ownership, permissions, and location of the file contents. The logical file system is also responsible for protection and security.

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.

5. **<u>File-System implementation</u>**

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Operating systems implement open() and close () systems calls for processes to request access to file contents.

- **Overview**

Several on-disk 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 disk, 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.

- 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 (or partition) details, such as the number of blocks in the partition, size of the blocks, free block count and free-block pointers, and free FCB count and FCB pointers. In UFS, this is called a **superblock;** in NTFS, it is stored in. the **master file 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, including file permissions, ownership, size, and location of the data blocks. In UFS, this is called the inode. 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 and discarded at dismount. The structures may include the ones described below:

- 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-file table** contains a copy of the FCB of each open file, as well as other information.

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- The **per-process open-file table** contains a pointer to the appropriate entry in the system-wide open-file table, as well as other information.

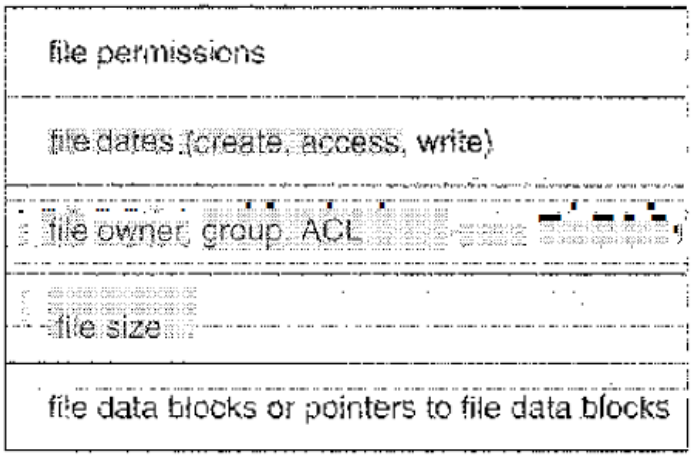

Figure 11.2 A typical file-control block.

To create a new file, an application program 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 disk. A typical FCB is shown in Figure 11.2.

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 operating systems, including Windows NT, 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 disk-block numbers, which are passed on to the basic file system and I/O control system.

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 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.

When a file is opened, 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 can 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.

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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.** Consequently, as long as the file is not closed, all file operations are done on the open-file table.

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 is copied back to the disk-based directory structure, and the system-wide open-file table entry is removed. Some systems complicate this scheme further by using the file system as an interface to other system aspects, such as networking.

The operating structures of a file-system implementation are summarized in Figure 11.3.

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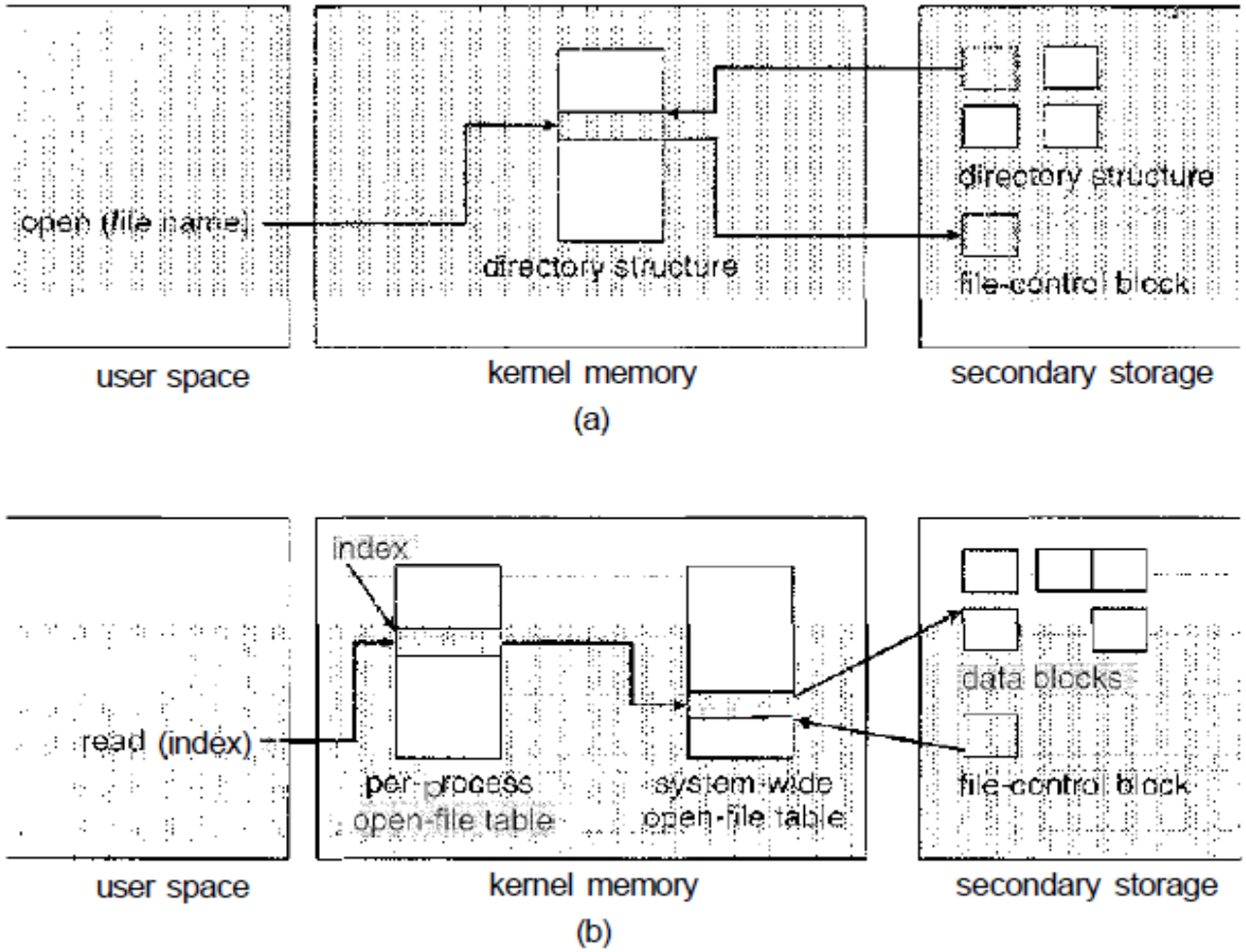
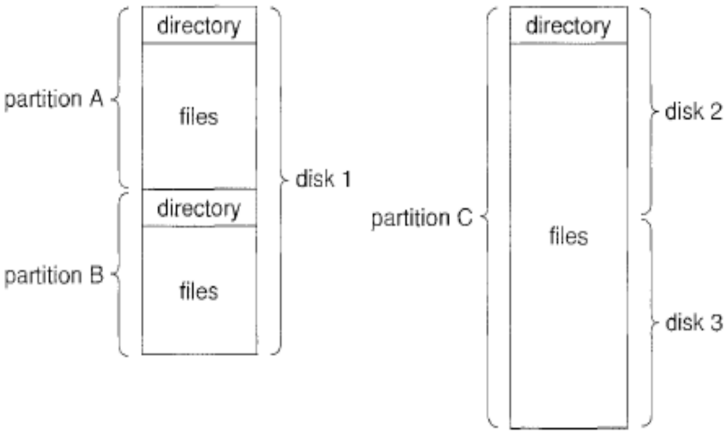


Figure 11.3 In-memory file-system structures. (a) File open. (b) File read.

6. **Directory Implementation**

- **Directory Structure**

A storage device can be used in its entirety for a file system. It can also be subdivided for finer-grained control. For example, a disk can be **partitioned** into quarters, and each quarter can hold a file system. Partitioning is useful for limiting the sizes of individual file systems, putting multiple file-system types on the same device, or leaving part of the device available for other uses, such as swap space or unformatted (raw) disk space.



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Partitions are also known as **slices** or **minidisk.** A file system can be created on each of these parts of the disk. Any entity containing a file system is generally known as a **volume**. The volume may be a subset of a device, a whole device, or multiple devices linked together into a RAID set. Each volume can be thought of as a virtual disk. Volumes can also store multiple operating systems, allowing a system to boot and run more than one operating system.

Each volume that contains a file system must also contain information about the files in the system. This information is kept in entries in a **device directory** or **volume table of contents**. The device directory (or **directory**) records information -such as name, location, size, and type-for all files on that volume. Figure 5.6 shows a typical file-system organization.

- **Directory Overview**

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 file**: 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 names may indicate a relationship between files, we may want to be able to find all files whose names match a particular pattern.
- **Create a file:** 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.
- **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. 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 *to* tape 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.

- **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 5.7).

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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,* then the unique-name rule is violated. 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**.

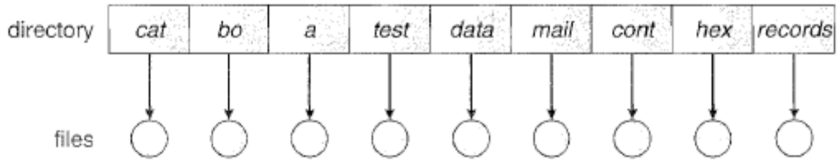

Fig 5.7: Single-level directory

- **<u>Two-Level Directory</u>**

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 file 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 file 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 5.8).

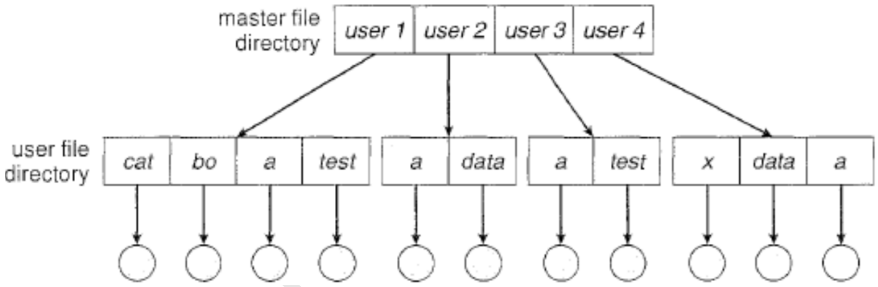

Fig 5.8 Two-level directory structure

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 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.

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.

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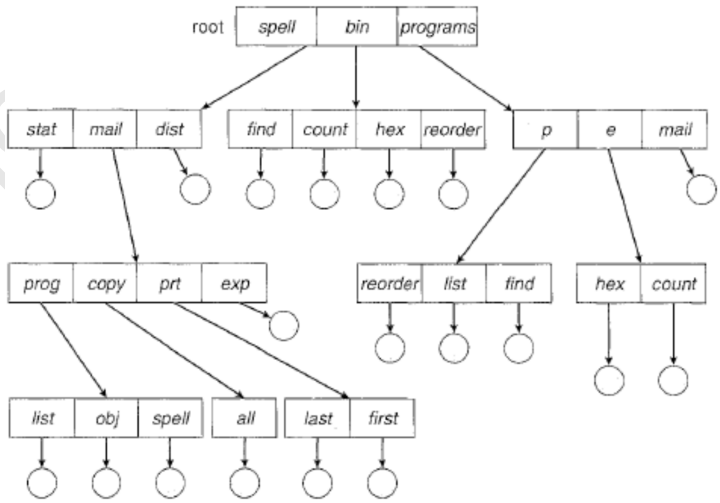
If access is to be permitted, one user must have the ability to name a file in another user's directory. To name a particular file uniquely in a two-level directory, we must give both the user name and the file name. A two-level directory can be thought of as a tree, or an inverted tree, of height 2. 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,* she can simply refer to *test.* To access the file named *test* of user B (with directory-entry name *userb),* however, she might have to refer to */userb/test.*

- **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 5.9). 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. 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 system calls are used to create and delete directories.

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 is provided that takes a directory name as a parameter and uses it to redefine the current directory.

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

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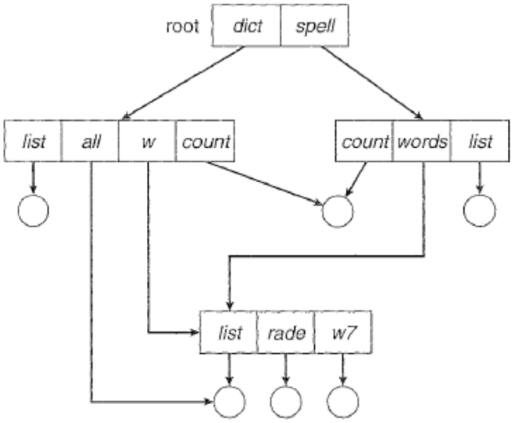
specifying its path names. User B can specify either an absolute or a relative path name. Alternatively, user B can change her current directory to be user *A's* directory and access the file by its file names. Path names can be of two types: ***absolute*** and ***relative***. An absolute path name begins at the root 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 5.9 if the current directory is *root/spell/mail,* then the relative path name *prt/first* refers to the same file as does the absolute path name *root/spell/mail/prt/fjirst.*

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, such as MS-DOS, 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.**

- **<u>Acyclic-Graph Directories</u>**



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. 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 a shared file, only *one* actual file exists**, so any changes made by one person are immediately visible to the other. Sharing is particularly important for subdirectories; a new file created by one person will automatically appear in all the shared subdirectories.

Shared files and subdirectories can be implemented in several ways. A common way, exemplified by many of the UNIX systems, is to create a new directory entry called a **link.** A link is effectively a pointer to another file or subdirectory. 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

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the copy indistinguishable. A major problem with duplicate directory entries is maintaining consistency when a file is modified.

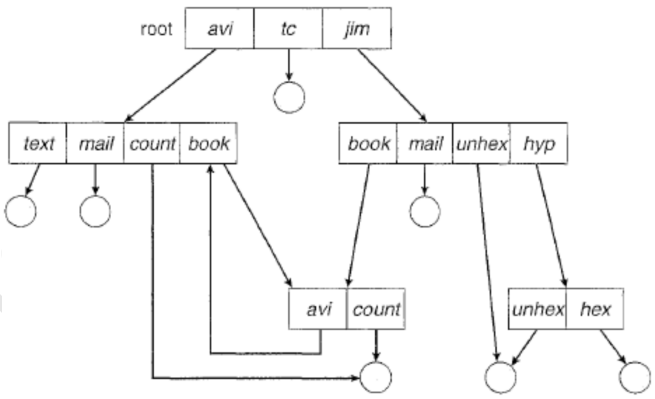
Problems:

- An acyclic-graph directory structure is more flexible than is a simple tree structure, but it is also more complex. A file may now have multiple absolute path names. Consequently, distinct file names may refer to the same file.
- When the space allocated to a shared file is deallocated whenever anyone deletes it, this action may leave dangling pointers to the now-nonexistent file.

Another approach to deletion is to preserve the file until all references to it are deleted. 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.

- **General Graph Directory**

A serious problem with using an acyclic-graph structure is ensuring that there are no cycles. 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.



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 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.

7. **Directory implementation**

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- **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, or with 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 disk. 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 B-tree, might help here. An advantage of the sorted list is that a sorted directory listing can be produced without a separate sort step.

- **Hash Table**

Another data structure used for a file directory is a hash table. With this method, 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.

8. **Allocation Methods**

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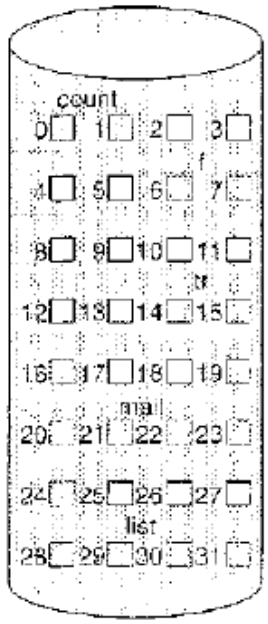
The direct-access nature of disks allows us flexibility in the implementation of files, in almost every case, many files are stored on the same disk. The main problem is how to allocate space to these files so that disk space is utilized effectively and files can be accessed quickly. Three major methods of allocating disk space are in wide use: contiguous, linked, and indexed. Each method has advantages and disadvantages. More commonly, a system vises one method for all files within a file system type.

- **Contiguous Allocation**

Contiguous allocation requires that each file occupy a set of contiguous blocks on the disk. Disk addresses define a linear ordering on the disk. With this ordering, assuming that only one job is accessing the disk, 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, the number of disk seeks required for accessing contiguously allocated files is minimal, as is seek time when a seek is finally needed. The IBM VM/CMS operating system uses contiguous allocation because it provides such good performance. Contiguous allocation of a file is defined by the disk address and length (in block units) of the first block. If the file is *n* blocks long and starts at location *b,* then it occupies blocks *b, b* + 1, *b* + *2,* ..., *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 11.5).

Accessing a file that has been allocated contiguously is easy. For sequential access, the file system remembers the disk 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.



directory

file	start	length
count	0	2
tr	14	3
mail	19	6
list	28	4
f	6	2

Figure 11.5 Contiguous allocation of disk space.

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. 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 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

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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 disk 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, no one 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. Some older PC systems used contiguous allocation on floppy disks. To prevent loss of significant amounts of disk space to external fragmentation, the user had to run a repacking routine that copied the entire file system onto another floppy disk or onto a tape. The original floppy disk was then freed completely, creating one large contiguous free space. The routine then copied the files back onto the floppy disk 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. The time cost is particularly severe for large hard disks that use contiguous allocation, where compacting all the space 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 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. However, the user need never be informed explicitly about what is happening; 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, pre-allocation may be inefficient. A file that will grow slowly over a long period (months or years) must be allocated

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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, some operating systems use a modified contiguous-allocation scheme. Here, a contiguous chunk of space is allocated initially; and 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.

- **Linked Allocation**

Linked allocation solves all problems of contiguous allocation. With linked allocation, each file is a linked list of disk blocks; the disk blocks may be scattered anywhere on the disk. 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 11.6). 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 disk 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 disk block of the file. This pointer is initialized to *nil* (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 that 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 ith block of a file, we must start at the beginning of that file and follow the pointers until we get to the ith block. Each access to a pointer requires a disk read, and some require a disk 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.

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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 disk only in cluster units. Pointers then use a much smaller percentage of the file's disk space. This method allows the logical-to-physical block mapping to remain simple but improves disk 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. 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 disk, and consider what would happen if a pointer were lost or damaged. A bug in the operating-system software or a disk 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-allocation table** (FAT). This simple but efficient method of disk-space allocation is used by the MS-DOS and OS/2 operating systems. A section of disk at the beginning of each volume is set aside to contain the table. The table has one entry for each disk 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 the last block, which has a special end-of-file value as the table entry. Unused blocks are indicated by a 0 table value. 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 11.7 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.

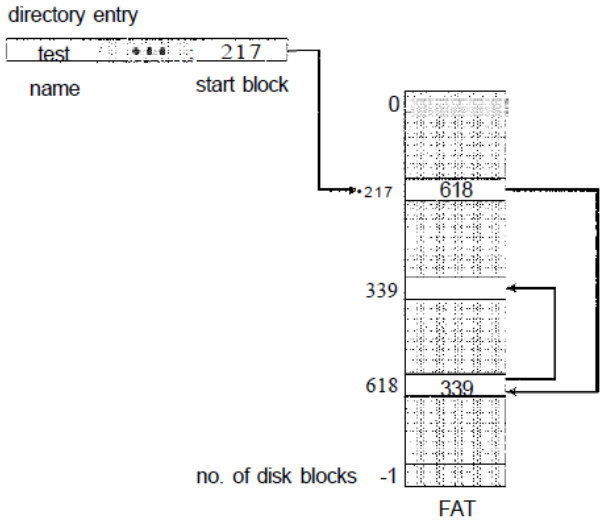

Figure 11.7 File-allocation table.

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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.

- **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.**

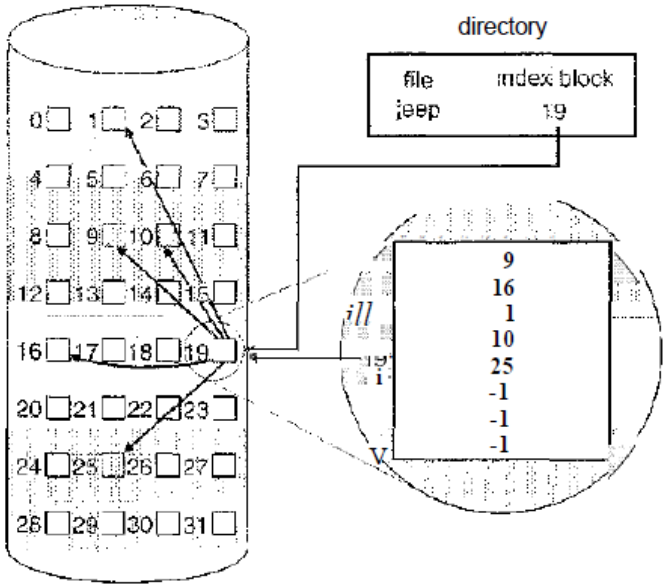

Figure 11.8 Indexed allocation of disk space.

Each file has its own index block, which is an array of disk-block addresses. The ith entry in the index block points to the ith block of the file. The directory contains the address of the index block (Figure 11.8). To find and read the ith block, we use the pointer in the ith index-block entry.

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

Indexed allocation supports direct access, without suffering from external fragmentation, because any free block on the disk 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-nil.*

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 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.

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Mechanisms for this purpose include the following:
* **Linked scheme.** An index block is normally one disk 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 *nil* (for a small file) or is a pointer to another index block (for a large file).

• **Multilevel index.** A variant of the linked representation is to use 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 4-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, vised in the UFS, 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.** 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 232 bytes, or 4 GB.

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.

- **<u>Performance</u>**

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.

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For any type of access, contiguous allocation requires only one access to get a disk block. Since we can easily keep the initial address of the file in memory, we can calculate immediately the disk address of the ;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 ;th block might require / disk 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 by 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.

9. Free-Space Management

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

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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 disk space is added to the free-space list.

- **Bit Vector**

Frequently, the free-space list is implemented as a bit **map** 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 bit map 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 disk space is to sequentially check each word in the bit map to see whether that value is not 0, since a 0-valued word has all 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) x (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 disk occasionally for recovery needs). Keeping it in main memory is possible for smaller disks but not necessarily for larger ones. A 1.3-GB disk with 512-byte blocks would need a bit map of over 332 KB to track its free blocks, although clustering the blocks in groups of four reduces this number to over 33 KB per disk. A 40-GB disk with 1-KB blocks requires over 5 MB to store its bit map.

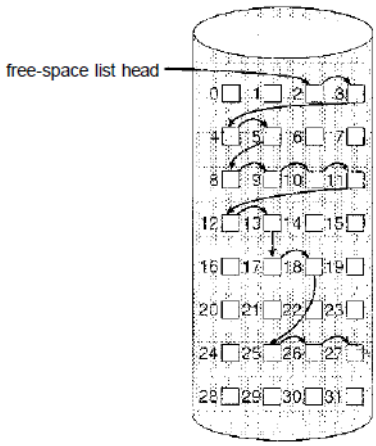

Figure 11.10 Linked free-space list on disk.

- **Linked List**

Another approach to free-space management is to link together all the free disk blocks, keeping a pointer to the first free block in a special location on the disk and caching it in memory. This first block contains a pointer to the next free disk block, and so on. In our example above, 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 11.10). However; this scheme is not efficient; to traverse the list, we must read each block, which requires substantial I/O time. Fortunately, traversing the free list is not a frequent action. Usually, 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.

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The FAT method incorporates free-block accounting into the allocation data structure. No separate method is needed.

- **Grouping**

A modification of the free-list approach is to store 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.

- **Counting**

Another approach is to take 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 disk 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 disk address and a count. Although each entry requires more space than would a simple disk address, the overall list will be shorter, as long as the count is generally greater than 1.

The processes in an operating system must be protected from one another's activities. To provide such protection, we can use various mechanisms to ensure that only processes that have gained proper authorization from the operating system can operate on the files, memory segments, CPU, and other resources of a system.

Protection refers to a mechanism for controlling the access of programs, processes, or users to the resources defined by a computer system. This mechanism must provide a means for specifying the controls to be imposed, together with a means of enforcement. We distinguish between protection and security, which is a measure of confidence that the integrity of a system and its data will be preserved.

PROTECTION

1. Goals of Protection

As computer systems have become more sophisticated and pervasive in their applications, the need to protect their integrity has also grown. Protection was originally conceived as an adjunct to multiprogramming operating systems,, so that untrustworthy users might safely share a common logical name space, such as a directory of files, or share a common physical name space, such as memory. Modern protection concepts have evolved to increase the reliability of any complex system that makes use of shared resources.

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We need to provide protection for several reasons. The most obvious is the need to prevent mischievous, intentional violation of an access restriction by a user. Of more general importance, however, is the need to ensure that each program component active in a system uses system resources only in ways consistent with stated policies. This requirement is an absolute one for a reliable system.

Protection can improve reliability by detecting latent errors at the interfaces between component subsystems. Early detection of interface errors can often prevent contamination of a healthy subsystem by a malfunctioning subsystem. An unprotected resource cannot defend against use (or misuse) by an unauthorized or incompetent user. A protection-oriented system provicies means to distinguish between authorized and unauthorized usage.

The role of protection in a computer system is to provide a mechanism for the enforcement of the policies governing resource use. These policies can be established in a variety of ways. Some are fixed in the design of the system, while others are formulated by the management of a system. Still others are defined by the individual users to protect their own files and programs. A protection system must have the flexibility to enforce a variety of policies.

Policies for resource use may vary by application, and they may change over time. For these reasons, protection is no longer the concern solely of the designer of an operating system. The application programmer needs to use protection mechanisms as well, to guard resources created and supported by an application subsystem against misuse.

Here, we describe the protection mechanisms the operating system should provide, so that application designers can use them in designing their own protection software. Note that *mechanisms* are distinct *horn policies.* Mechanisms determine *how* something will be done; policies decide *what* will be done. The separation of policy and mechanism is important for flexibility. Policies are likely to change from place to place or time to time. In the worst case, every change in policy would require a change in the underlying mechanism. Using general mechanisms enables us to avoid such a situation.

2. Principles of Protection

Frequently, a guiding principle can be used throughout a project, such as the design of an operating system. Following this principle simplifies design decisions and keeps the system consistent and easy to understand. A key, time-tested guiding principle for protection is the principle of least privilege. It dictates that programs, users, and even systems be given just enough privileges to perform their tasks.

Consider the analogy of a security guard with a passkey. If this key allows the guard into just the public areas that she guards, then misuse of the key will result in minimal damage. If,

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however, the passkey allows access to all areas, then damage from its being lost, stolen, misused, copied, or otherwise compromised will be much greater.

An operating system following the principle of least privilege implements its features, programs, system calls, and data structures so that failure or compromise of a component does the minimum damage and allows the minimum damage to be done. The overflow of a buffer in a system daemon might cause the daemon to fail, for example, but should not allow the execution of code from the process's stack that would enable a remote user to gain today).

Such an operating system also provides system calls and services that allow applications to be written with fine-grained access controls. It provides mechanisms to enable privileges when they are needed and to disable them when they are not needed. Also beneficial is the creation of audit trails for all privileged function access. The audit trail allows the programmer, systems administrator, or law-enforcement officer to trace all protection and security activities on the system.

Managing users with the principle of least privilege entails creating a separate account for each user, with just the privileges that the user needs. An operator who needs to mount tapes and backup files on the system has access to just those commands and files needed to accomplish the job. Some systems implement role-based access control (RBAC) to provide this functionality. Computers implemented in a computing facility under the principle of least privilege can be limited to running specific services, accessing specific remote hosts via specific services, and doing so during specific times. Typically, these restrictions are implemented through enabling or disabling each service and through access control lists.

The principle of least privilege can help produce a more secure computing environment. Unfortunately, it frequently does not. For example, Windows 2000 has a complex protection scheme at its core and yet has many security holes. By comparison, Solaris is considered relatively secure, even though it is a variant of UNIX, which historically was designed with little protection in mind. One reason for the difference may be that Windows 2000 has more lines of code and more services than Solaris and thus has more to secure and protect. Another reason could be that the protection scheme in Windows 2000 is incomplete or protects the wrong aspects of the operating system, leaving other areas vulnerable.

3. Domain of Protection

A computer system is a collection of processes and objects. By *objects,* we mean both **hardware objects** (such as the CPU, memory segments, printers, disks, and tape drives) and **software objects** (such as files, programs, and semaphores). Each object has a unique name that differentiates it from all other objects in the system, and each can be accessed only through well-defined and meaningful operations. Objects are essentially abstract data types.

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The operations that are possible may depend on the object. For example, a CPU can only be executed on. Memory segments can be read and written, whereas a CD-ROM or DVD-ROM can only be read. Tape drives can be read, written, and rewound. Data files can be created, opened, read, written, closed, and deleted; program files can be read, written, executed, and deleted.

A process should be allowed to access only those resources for which it has authorization. Furthermore, at any time, a process should be able to access only those resources that it currently requires to complete its task. This second requirement, commonly referred to as the *need-to-know* principle, is useful in limiting the amount of damage a faulty process can cause in the system. For example, when process *p* invokes procedure *A(),* the procedure should be allowed to access only its own variables and the formal parameters passed to it; it should not be able to access all the variables of process *p.* Similarly, consider the case where process *p* invokes a compiler to compile a particular file. The compiler should not be able to access files arbitrarily but should have access only to a well-defined subset of files (such as the source file, listing file, and so on) related to the file to be compiled. Conversely, the compiler may have private files used for accounting or optimization purposes that process *p* should not be able to access.

- **Domain Structure**

To facilitate this scheme, a process operates within a protection domain, which specifies the resources that the process may access. Each domain defines a set of objects and the types of operations that may be invoked on each object. The ability to execute an operation on an object is an **access right.** A domain is a collection of access rights, each of which is an ordered pair *<object-iiame, rights-set>.* For example, if domain D has the access right *<file F,* {read,write} >, then a process executing in domain D can both read and write file *F;* it cannot, however, perform any other operation on that object.

Domains do not need to be disjoint; they may share access rights. For example, in Figure 14.1, we have three domains: *Dir D2,* and D3. The access right < *O4,* (print}> is shared by D2 and *D3,* implying that a process executing in either of these two domains can print object O4. Note that a process must be executing in domain *D1* to read and write object *O1,* while only processes in domain D3 may execute object *O3.*

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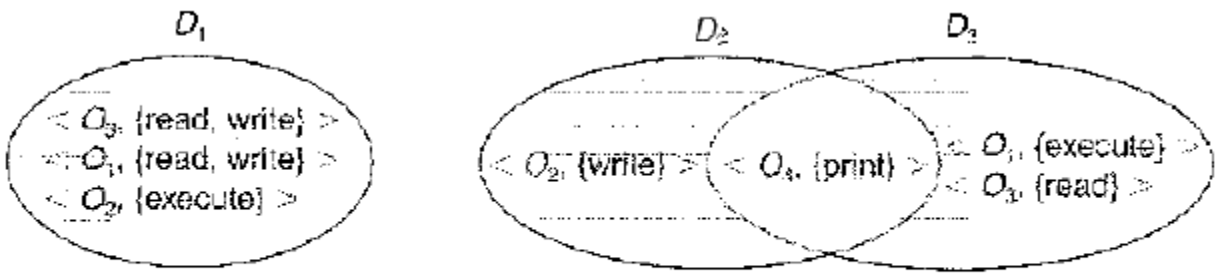

Figure 14.1 System with three protection domains.

The association between a process and a domain may be either **static,** if the set of resources available to the process is fixed throughout the process's lifetime, or **dynamic.** As might be expected, establishing dynamic protection domains is more complicated than establishing static protection domains. If the association between processes and domains is fixed, and we want to adhere to the need-to-know principle, then a mechanism must be available to change the content of a domain.

The reason stems from the fact that a process may execute in two different phases and may, for example, need read access in one phase and write access in another. If a domain is static, we must define the domain to include both read and write access. However, this arrangement provides more rights than are needed in each of the two phases, since we have read access in the phase where we need only write access, and vice versa. Thus, the need-to-know principle is violated.

We must allow the contents of a domain to be modified so that it always reflects the minimum necessary access rights. If the association is dynamic, a mechanism is available to allow domain switching, enabling the process to switch from one domain to another. We may also want to allow the content of a domain to be changed. If we cannot change the content of a domain, we can provide the same effect by creating a new domain with the changed content and switching to that new domain when we want to change the domain content.

A domain can be realized in a variety of ways:

- Each *user* may be a domain. In this case, the set of objects that can be accessed depends on the identity of the user. Domain switching occurs when the user is changed—generally when one user logs out and another user logs in.
- Each *process* may be a domain. In this case, the set of objects that can be accessed depends on the identity of the process. Domain switching occurs when one process sends a message to another process and then waits for a response.

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- Each *procedure* may be a domain. In this case, the set of objects that can be accessed corresponds to the local variables defined within the procedure. Domain switching occurs when a procedure call is made.

4. Access Matrix

Our model of protection can be viewed abstractly as a matrix, called an **access matrix.** The rows of the access matrix represent domains, and the columns represent objects. Each entry in the matrix consists of a set of access rights. Because the column defines objects explicitly, we can omit the object name from the access right. The entry access(i,j) defines the set of operations that a process executing in domain *Dj* can invoke on object *Oj.*

To illustrate these concepts, we consider the access matrix shown in Figure 14.3. There are four domains and four objects—three files (F1, F2, F3) and one laser printer. A process executing in domain *D1* can read files F1 and F3. A process executing in domain D4 has the same privileges as one executing in domain *D1;* but in addition, it can also write onto files F1 and F3. Note that the laser printer can be accessed only by a process executing in domain *Do-* The access-matrix scheme provides us with the mechanism for specifying a variety of policies. The mechanism consists of implementing the access matrix and ensuring that the semantic properties we have outlined indeed, hold. More specifically, we must ensure that a process executing in domain *D,* can access only those objects specified in row \, and then only as allowed by the access-matrix entries.

domain \ object	F_1	F_2	F_3	printer
D_1	read		read	
D_2				print
D_3		read	execute	
D_4	read write		read write	

Figure 14.3 Access matrix.

The access matrix can implement policy decisions concerning protection. The policy decisions involve which rights should be included in the (i,j)th entry. We must also decide the domain in which each process executes. This last policy is usually decided by the operating system.

The users normally decide the contents of the access-matrix entries. When a user creates a new object Oj, the column Oj is added to the access matrix with the appropriate initialization entries, as dictated by the creator. The user may decide to enter some rights in some entries in column / and other rights in other entries, as needed.

The access matrix provides an appropriate mechanism for defining and implementing strict control for both the static and dynamic association between processes and domains. When we switch a process from one domain to another, we are executing an operation (switch) on

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an object (the domain). We can control domain switching by including domains among the objects of the access matrix. Similarly, when we change the content of the access matrix, we are performing an operation on an object: the access matrix. Again, we can control these changes by including the access matrix itself as an object. Actually, since each entry in the access matrix may be modified individually, we must consider each entry in the access matrix as an object to be protected.

Processes should be able to switch from one domain to another. Domain switching from domain Di to domain *Di* is allowed if and only if the access right switch e access(i,j). Thus, in Figure 14.4, a process executing in domain D2 can switch to domain D3 or to domain D4. A process in domain D4 can switch to D3, and one in domain *D1* can switch to domain D2.

Allowing controlled change in the contents of the access-matrix entries requires three additional operations: copy, owner, and control. We examine these operations next. The ability to copy an access right from one domain (or row) of the access matrix to another is denoted by an asterisk (*) appended to the access right.

domain \ object	F_1	F_2	F_3	laser printer	D_1	D_2	D_3	D_4
D_1	read		read			switch		
D_2				print			switch	switch
D_3		read	execute					
D_4	read write		read write		switch			

Figure 14.4 Access matrix of Figure 14.3 with domains as objects.

The *copy* right allows the copying of the access right only within the column (that is, for the object) for which the right is defined. For example, in Figure 14.5(a), a process executing in domain *D2* can copy the read operation into any entry associated with file F2. Hence, the access matrix of Figure 14.5(a) can be modified to the access matrix shown in Figure 14.5(b).

domain \ object	F_1	F_2	F_3
D_1	execute		write*
D_2	execute	read*	execute
D_3	execute		

(a)

domain \ object	F_1	F_2	F_3
D_1	execute		write*
D_2	execute	read*	execute
D_3	execute	read	

(b)

This scheme has two variants:

1. A right is copied from access(i,j) to access(k,j); it is then removed from

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Figure 14.5 Access matrix with copy rights.

access(i,j). This action is a *transfer* of a right, rather than a copy.

2. Propagation of the *copy* right may be limited. That is, when the right *R** is copied from access(i,j) to access(k,j), only the right *R* (not *R"*) is created. A process executing in domain *Dk* cannot further copy the right *R.*

A system may select only one of these three *copy* rights, or it may provide all three by identifying them as separate rights: *copy, transfer,* and *limited copy.*

We also need a mechanism to allow addition of new rights and removal of some rights. The *owner* right controls these operations. If access(i,j) includes the *owner* right, then a process executing in domain D, can add and remove any right in any entry in column j. For example, in Figure 14.6(a), domain D1 is the owner of F1, and thus can add and delete any valid right in column F1,. Similarly, domain *D2* is the owner of *F2* and F3 and thus can add and remove any valid right within these two columns. Thus, the access matrix of Figure 14.6(a) can be modified to the access matrix shown in Figure 14.6(b).

domain \ object	F_1	F_2	F_3
D_1	owner execute		write
D_2		read* owner	read* owner write
D_3	execute		

(a)

domain \ object	F_1	F_2	F_3
D_1	owner execute		fill!'
D_2		owner read* write*	read* owner write
D_3		write	write

(b)

Figure 14.6 Access matrix with *owner* rights.

The *copy* and *owner* rights allow a process to change the entries in a column. A mechanism is also needed to change the entries in a row. The *control* right is applicable only to domain objects. If access(i,j) includes the

domain \ object	F_1	F_2	F_3	laser printer	D_1	D_2	D_3	D_4
D_1	read		read			switch		
D_2				print			switch	switch control
D_3		read	execute					
D_4	write		write		switch			

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Figure 14.7 Modified access matrix of Figure 14.4.

control right, then a process executing in domain *D.* can remove any access right from row j. For example, suppose that, in Figure 14.4, we include the *control* right in access(D2, D4). Then, a process executing in domain DT could modify domain D4, as shown in Figure 14.7.

- **Implementation of Access Matrix**

How can the access matrix be implemented effectively? In general, the matrix will be sparse; that is, most of the entries will be empty. Although data structure techniques are available for representing sparse matrices, they are not particularly useful for this application, because of the way in which the protection facility is used. Here, we first describe several methods of implementing the access matrix and then compare the methods.

- **Global Table**

The simplest implementation of the access matrix is a global table consisting of a set of ordered triples *<domain, object, rights-set>.* Whenever an operation *M* is executed on an object O, within domain *Di,* the global table is searched for a triple *<Di,* Oj, *Rk>,* with *M* € Rk. If this triple is found, the operation is allowed to continue; otherwise, an exception (or error) condition is raised. This implementation suffers from several drawbacks. The table is usually large and thus cannot be kept in main memory, so additional I/O is needed. Virtual memory techniques are often used for managing this table. In addition, it is difficult to take advantage of special groupings of objects or domains. For example, if everyone can read a particular object, it must have a separate entry in every domain.

- **Access Lists for Objects**

Each column in the access matrix can be implemented as an access list for one object. Obviously, the empty entries can be discarded. The resulting list for each object consists of ordered pairs *<domain, rights-set>,* which define all domains with a nonempty set of access rights for that object.

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This approach can be extended easily to define a list plus a *default* set of access rights. When an operation *M* on an object Oj is attempted in domain *Di,* we search the access list for object Oj., looking for an entry <*Di,* Ri > with M € Kj. If the entry is found, we allow the operation; if it is not, we check the default set. If M is in the default set, we allow the access. Otherwise, access is denied, and an exception condition occurs. For efficiency, we may check the default set first and then search the access list.

- **Capability Lists for Domains**

Rather than associating the columns of the access matrix with the objects as access lists, we can associate each row with its domain. A capability list for a domain is a list of objects together with the operations allowed on those objects. An object is often represented by its physical, name or address, called a capability. To execute operation M on object *Oj,* the process executes the operation *M,* specifying the capability (or pointer) for object Oj as a parameter. Simple possession of the capability means that access is allowed.

The capability list is associated with a domain, but it is never directly accessible to a process executing in that domain. Rather, the capability list is itself a protected object, maintained by the operating system and accessed by the user only indirectly.

Capability-based protection relies on the fact that the capabilities are never allowed to migrate into any address space directly accessible by a user process (where they could be modified). If all capabilities are secure, the object they protect is also secure against unauthorized access.
Capabilities were originally proposed as a kind of secure pointer, to meet the need for resource protection that was foreseen as multiprogrammed computer systems came of age. The idea of an inherently protected pointer provides a foundation for protection that can be extended up to the applications level. To provide inherent protection, we must distinguish capabilities from other kinds of objects and they must be interpreted by an abstract machine on which higher-level programs run. Capabilities are usually distinguished from other data in one of two ways:

- Each object has a tag to denote its type either as a capability or as accessible data. The tags themselves must not be directly accessible by an application program. Hardware or firmware support may be used to enforce this restriction. Although only 1 bit is necessary to distinguish between capabilities and other objects, more bits are often used. This extension allows all objects to be tagged with their types by the hardware. Thus, the hardware can distinguish integers, floating-point numbers, pointers, Booleans, characters, instructions, capabilities, and uninitialized values by their tags.

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- Alternatively, the address space associated with a program can be split into two parts. One part is accessible to the program and contains the program's normal data and instructions. The other part, containing the capability list, is accessible only by the operating system. A segmented memory space is useful to support this approach.

- **A Lock-Key Mechanism**

The lock-key scheme is a compromise between access lists and capability lists. Each object has a list of unique bit patterns, called locks. Similarly, each domain has a list of unique bit patterns, called keys. A process executing in a domain can access an object only if that domain has a key that matches one of the locks of the object. As with capability lists, the list of keys for a domain must be managed by the operating system on behalf of the domain. Users are not allowed to examine or modify the list of keys (or locks) directly.

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