1 File System Implementation

1.1 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 4096 bytes; usually, they are 512 bytes.
- A file system poses two quite different design problems.
    1. The first problem is defining how the file system should look to the user. This task involves defining a file and its attributes, the operations allowed on a file, and the directory structure for organizing files.
    2. 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 Fig 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.

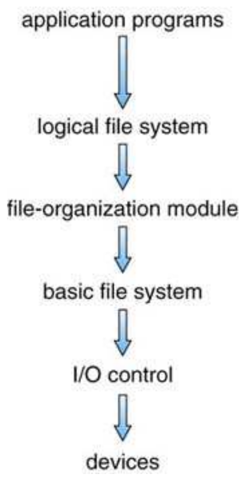


Figure 1: Layered file system.

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

- The **basic file system** needs only to issue generic commands to the appropriate device driver to read and write physical blocks on the disk.

- 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. 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).

- 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.

- Many file systems are in use today; ISO 9660, UNIX file system (UFS), FAT, FAT32, NTFS, ext2, ext3, ext4. There are also distributed file systems in which a file system on a server is mounted by one or more clients.

1.2 File-System Implementation

1.2.1 Overview

- The file system must keep track of
  - which blocks belong to which files.
  - in what order the blocks form the file.
  - which blocks are free for allocation.
- On disk, the file system may contain information about how to boot an OS stored there, the total number of blocks, the number and location of free blocks, the directory structure, and individual files.
- Often the file system will contain some of the items shown in Fig. 2.

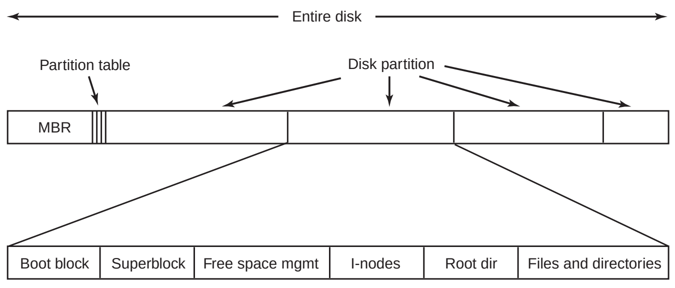


Figure 2: A possible file system layout.

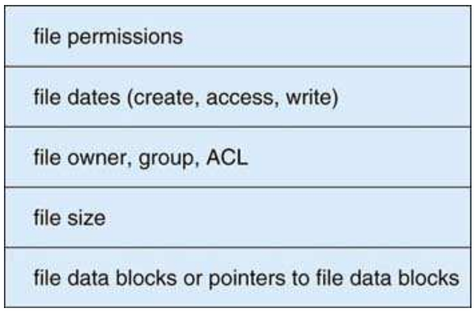
  - Sector 0 of the disk is called the MBR (Master Boot Record) and is used to boot the computer. The end of the MBR contains the partition table. This table gives the starting and ending addresses of each partition.

  - One of the partitions in the table is marked as active. When the computer is booted, the BIOS reads in and executes the MBR. The first thing the MBR program does is locate the active partition, read in its first block, called the *boot block*.
  - A **boot control block** (per volume) can contain information needed by the system to boot an OS from that volume. 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, freeblock 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**.
  - Next might come information about free blocks in the file system, for example in the form of a bitmap or a list of pointers.
  - 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**.
  - After that might come the root directory, which contains the top of the file system tree.
  - Finally, the remainder of the disk typically contains all the other directories and files.

- 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.

- To create a new file,
  - an application program calls the logical file system.
  - To create a new file, it allocates a new FCB.
  - 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 Fig. 3.



file permissions
file dates (create, access, write)
file owner, group, ACL
file size
file data blocks or pointers to file data blocks

Figure 3: A typical file-control block.

- Some OSs, including UNIX, treat a directory exactly the same as a file-one with a type field indicating that it is a directory.
- 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.
- The operating structures of a file-system implementation are summarized in Fig. 4.

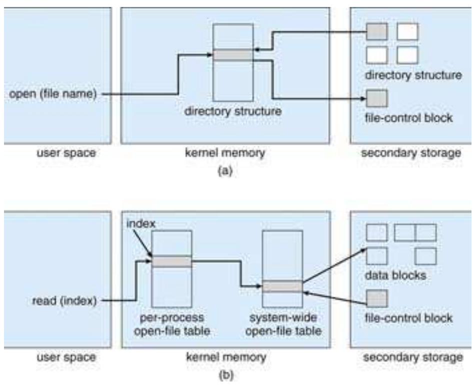


Figure 4: In-memory file-system structures. (a) File open. (b) File read.

1.2.2 Partitions and Mounting

- The layout of a disk can have many variations, depending on the OS. A disk can be sliced into multiple partitions, or a volume can span multiple partitions on multiple disks (RAID).
- Each partition can be either "raw", containing no file system (UNIX swap space can use a raw partition), or "cooked", containing a file system.
- Multiple OSs can be installed. How does the system know which one to boot?
  - A boot loader that understands multiple file systems and multiple OSs can occupy the boot space.
  - Once loaded, it can boot one of the OSs available on the disk.
- The **root partition**, which contains the OS kernel and sometimes other system files, is mounted at boot time.
- Other volumes can be automatically mounted at boot or manually mounted later, depending on the OS.
- As part of a successful mount operation, the OS verifies that the device contains a valid file system. If the format is invalid, the partition must have its consistency checked and possibly corrected, either with or without user intervention.
- Finally, the OS notes in its in-memory mount table structure that a file system is mounted, along with the type of the file system.
- Microsoft Windows-based systems mount each volume in a separate name space, denoted by a letter and a colon (F:).
- On UNIX, file systems can be mounted at any directory. Mounting is implemented by setting a flag in the in-memory copy of the inode for that directory. The flag indicates that the directory is a mount point.
- The mount table entry contains a pointer to the superblock of the file system on that device.

1.2.3 Virtual File Systems

- How does an OS allow multiple types of file systems to be integrated into a directory structure?
- An obvious but suboptimal method of implementing multiple types of file systems is to write directory and file routines for each type.
- Instead, most OSs, including UNIX, use object-oriented techniques to simplify, organize, and modularize the implementation.
- The use of these methods allows very dissimilar file-system types to be implemented within the same structure, including network file systems, such as NFS.
- The file-system implementation consists of three major layers, as depicted schematically in Fig. 5.

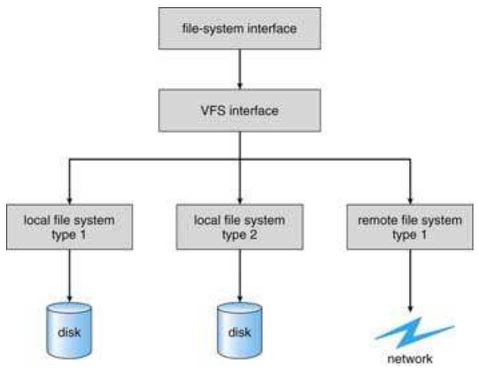


Figure 5: Schematic view of a virtual file system.

1 The first layer is the file-system interface, based on the *open*(), *read*(), *write*(), and *close*() calls and on file descriptors.

2 The second layer is called the virtual file system (VFS) layer; it serves two important functions:

   – It separates file-system-generic operations from their implementation by defining a clean VFS interface. Several implementations for the VFS interface may coexist on the same machine, allowing transparent access to different types of file systems mounted loca1ly.

  - The VFS provides a mechanism for uniquely representing a file throughout a network. The VFS is based on a file-representation structure, called a *vnode*, that contains a numerical designator for a network-wide unique file.

- The VFS distinguishes local files from remote ones, and local files are further distinguished according to their file-system types.

1.3 Directory Implementation

The selection of directory-allocation and directory-management algorithms significantly affects the efficiency performance, and reliability of the file system.

1.3.1 Linear List

- The simplest method of implementing a directory is to use a linear list of file names with pointers to the data blocks.

- This method is simple to program but time-consuming to execute.

  - To create a new file, we must first search the directory to be sure that no existing file has the same name. Then, we add a new entry at the end of the directory.
  - To delete a file, we search the directory for the named file, then release the space allocated to it.

- 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 OSs implement a software cache to store the most recently used directory information.

- 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.

1.3.2 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.

1.4 Allocation Methods

- The direct-access nature of disks allows us flexibility in the implementation of files.
- 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**.

1.4.1 Contiguous Allocation

- **Contiguous allocation** requires that each file occupy a set of contiguous blocks on the disk (see Fig. 6).

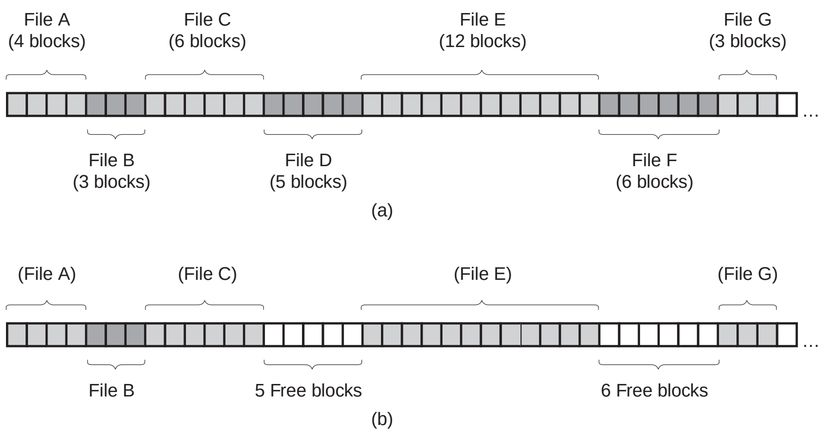


Figure 6: (a) Contiguous allocation of disk space for seven files. (b) The state of the disk after files D and F have been removed.

- Disk addresses define a linear ordering on the disk. With this ordering,
  - 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.
- 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 $b, b+1, b+2, \ldots b+n-1$..
- The directory entry for each file indicates the address of the starting block and the length of the area allocated for this file (see Fig. 7).

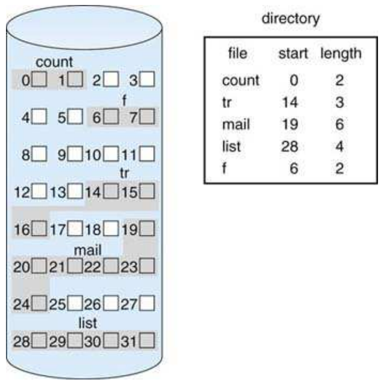


Figure 7: Contiguous allocation of disk space.

- Contiguous allocation is widely used on CD-ROMs. Here all the file sizes are known in advance and will never change during subsequent use of the CD-ROM file system.
- 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.

- 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.

- Compacting all free space into one contiguous space, solves 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.

- 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**.

- Two possibilities then exist.

- First, the user program can be terminated with an appropriate error message. The user must then allocate more space and run the program again. These repeated runs may be costly. To prevent them, the user will normally overestimate the amount of space needed, resulting in considerable wasted space.
- The other possibility is to find a larger hole, copy the contents of the file to the new space, and release the previous space.
- Even if the total amount of space needed for a file is known in advance, preallocation may be inefficient. The file therefore has a lager amount of internal fragmentation.

1.4.2 Linked Allocation

- The second method for storing files is to keep each one as a linked list of disk blocks, as shown in Fig. 8.

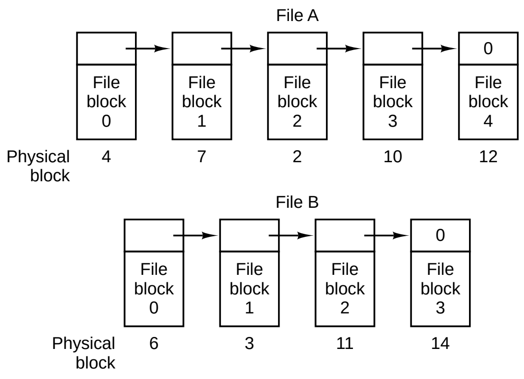


Figure 8: Storing a file as a linked list of disk blocks.

- **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 (see Fig. 9).

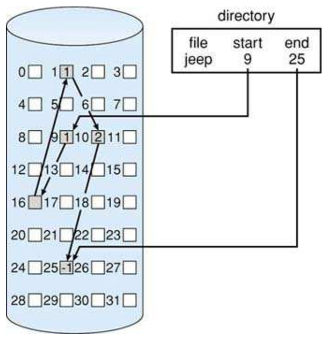


Figure 9: Linked allocation of disk space.

- To create a new file, we simply create a new entry in the directory. The pointer is initialized to *nil* (the end-of-list pointer value) to signify an empty file. The size field is also set to O.
- 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. No space is lost to disk fragmentation (except for internal fragmentation in the last block).
- 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.
- The major problem is that it can be used effectively only for sequential-access files.
  - To find the i^{th} block of a file, we must start at the beginning of that file and follow the pointers until we get to the i^{th} block.
  - Each access to a pointer requires a 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.
- 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.
  - 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.
- 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 OS software or a disk hardware failure might result in picking up the wrong pointer.
- 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 OSs.
  - 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 O-valued table entry and replacing the previous end-of-file value with the address of the new block.

- An illustrative example is the FAT structure shown in Fig. 10 for a file consisting of disk blocks 217, 618, and 339.

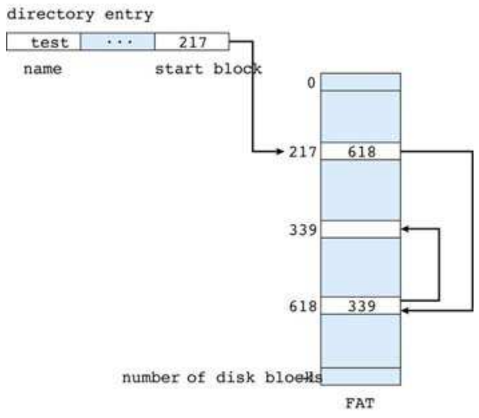


Figure 10: File allocation table.

- The FAT allocation scheme can result in a significant number of disk head seeks, unless the FAT is cached.

- The primary disadvantage of this method is that the entire table must be in memory all the time to make it work.
  - With a 20-GB disk and a 1-KB block size, the table needs 20 million entries.
  - Each entry has to be a minimum of 3 bytes. For speed in lookup, they should be 4 bytes.
  - Thus the table will take up 60 MB or 80 MB of main memory all the time.

1.4.3 Indexed Allocation

- Linked allocation solves the external-fragmentation and size-declaration problems of contiguous allocation.
- However, in the absence of a FAT, linked allocation cannot support efficient direct access, since the pointers to the blocks are scattered with the blocks themselves all over the disk and must be retrieved in order.
- A data structure called an **i-node** (index-node), which lists the attributes and disk addresses of the files blocks (see Fig. 11).

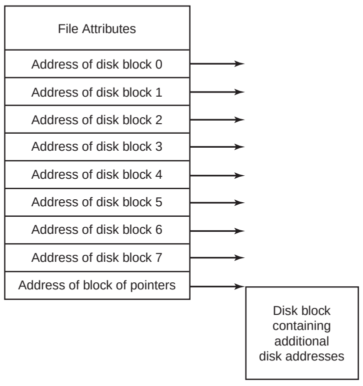


Figure 11: An example i-node.

- **Indexed allocation** solves this problem by bringing all the pointers together into one location: the index block.
- Each file has its own index block, which is an array of disk-block addresses.
- The i^{th} entry in the index block points to the i^{th} block of the file. The directory contains the address of the index block (see Fig. 12).
- To find and read the i^{th} block, we use the pointer in the i^{th} index-block entry. This scheme is similar to the paging scheme.
- Given the i-node, it is then possible to find all the blocks of the file. The big advantage of this scheme over linked files using an in-memory table is that the i-node need only be in memory when the corresponding file is open.

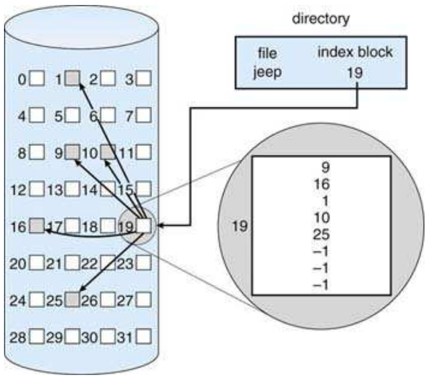


Figure 12: Indexed allocation of disk space.

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

- When a file is opened, the file system must take the file name supplied and locate its disk blocks. Let us consider how the path name */usr/ast/mbox* is looked up. The lookup process is illustrated in Fig. 13.

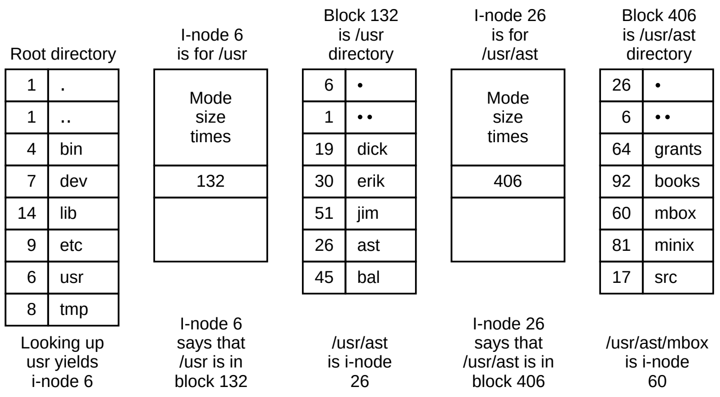

Root directory
1 .
1 ..
4 bin
7 dev
14 lib
9 etc
6 usr
8 tmp
Looking up usr yields i-node 6
I-node 6 is for /usr
Mode size times
132
I-node 6 says that /usr is in block 132
Block 132 is /usr directory
6 •
1 ••
19 dick
30 erik
51 jim
26 ast
45 bal
/usr/ast is i-node 26
I-node 26 is for /usr/ast
Mode size times
406
I-node 26 says that /usr/ast is in block 406
Block 406 is /usr/ast directory
26 •
6 ••
64 grants
92 books
60 mbox
81 minix
17 src
/usr/ast/mbox is i-node 60

Figure 13: The steps in looking up */usr/ast/mbox*.

- 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. 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.
- Mechanisms for this purpose include the followings.
- **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 OS 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 4096-byte blocks, we could store 1024 4-byte pointers in an index block.
  - Two levels of indexes allow 1048576 data blocks and a file size of up to 4 GB.

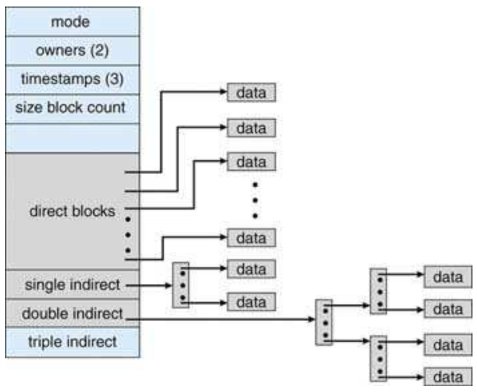
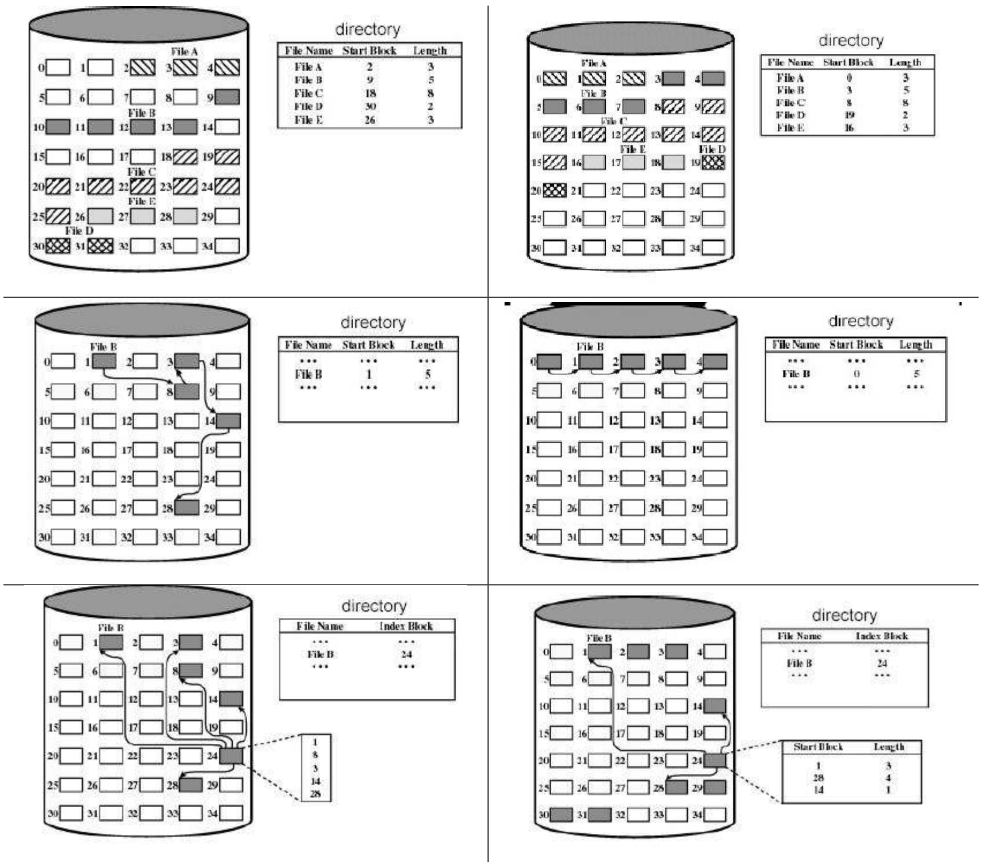


Figure 14: The UNIX inode.

- **Combined scheme**. Another alternative, used in the UFS (UNIX File System), 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 OSs. A 32-bit file pointer: 2^{32} bytes, or 4 GB.
  - Many UNIX implementations, including Solaris and IBM's AIX, now support up to 64-bit file pointers (terabytes).
  - A UNIX inode is shown in Fig. 14.

- 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.

Summary of the allocation methods is given in Fig. 15.



directory

File Name	Start Block	Length
File A	2	3
File B	9	5
File C	18	8
File D	30	2
File E	26	3

directory

File Name	Start Block	Length
File A	0	3
File B	3	5
File C	8	8
File D	19	2
File E	16	3

directory

File Name	Start Block	Length
•••	•••	•••
File B	1	5
•••	•••	•••

directory

File Name	Start Block	Length
•••	•••	•••
File B	0	5
•••	•••	•••

directory

File Name	Index Block
•••	•••
File B	24
•••	•••

1
8
3
14
28

directory

File Name	Index Block
•••	•••
File B	24
•••	•••

Start Block	Length
1	3
28	4
14	1

Figure 15: (a) Contiguous allocation (b) Contiguous allocation with compaction (c) Storing a file as a linked list of disk blocks (d) Storing a file as a linked list of disk blocks with defragmentation (e) Indexed allocation with block partitions (f) Indexed allocation with variable–length partitions.

1.5 Free-Space Management

- Since disk space is limited, we need to reuse the space from deleted files for new files, if possible.
- To keep track of free disk space, the system maintains a free-space list. The free-space list records all free disk blocks.
- To create a file, we search the free-space list for the required amount of space and allocate that space to the new file.
- When a file is deleted, its disk space is added to the free-space list.

1.5.1 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 O.
- 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.
- 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 83 KB per disk ($1.3 * 1020 * 1024 * 1024/512/8/1.024 = 332.8\ KB$).

- A 40-GB disk with 1-KB blocks requires over 5 MB to store its bit map ($40 * 1020 * 1024 * 1024/1024/8/1.024 = 5.12\ MB$).
- A 500-GB disk with a 1-KB block and a 32-bit (4 bytes) disk block number, we need 488 million bits for the map, which requires just under 60000 1-KB blocks to store ($(500x10^9/1KB)/1024/8$).

1.5.2 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 earlier example (Section 1.5.1);
  - 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 (see Fig. 16).

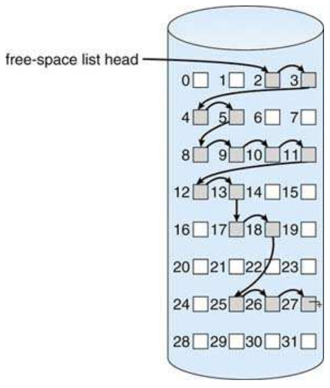


Figure 16: Linked free-space list on disk.

- 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 OS 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.
- Keeping it in main memory;
  - With a 1-KB block and a 32-bit (4 bytes) disk block number, each block on the free list holds the numbers of 255 free blocks. (1KB/32-bit=256; one slot is needed for the pointer to the next block. The number of blocks that could be addressed:$2^{32} \simeq 4.3x10^9$).
  - A 500-GB disk, which has about 488 million ($500x10^9/1KB$) disk blocks . To store all these addresses at 255 per block requires about 1.9 million blocks ($500x10^9/1KB/255$). Generally, free blocks are used to hold the free list, so the storage is essentially free.
  - It is not surprising that the bitmap requires less space (60000 blocks), since it uses 1 bit per block, versus 32 bits in the linked list model. Only if the disk is nearly full (i.e., has few free blocks) will the linked list scheme require fewer blocks than the bitmap.

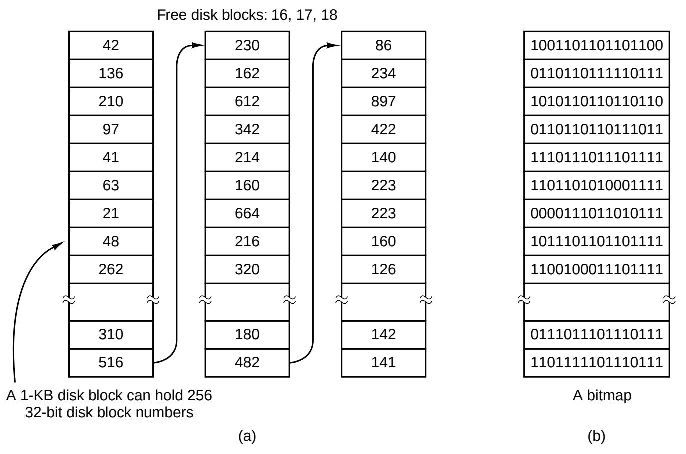


Figure 17: (a) Storing the free list on a linked list. (b) A bitmap.

1.5.3 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.

1.5.4 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.

1.6 Log-Structured File Systems

- CPUs keep getting faster, disks are becoming much bigger and cheaper (but not much faster), and memories are growing exponentially in size.
- The one parameter that is not improving and bounds is *disk seek time*. A performance bottleneck is arising in many file systems.
- The idea that drove the LFS (the Log-structured File System) design is that as CPUs get faster and RAM memories get larger, disk caches are also increasing rapidly. Consequently, it is now possible to satisfy a very substantial fraction of all read requests directly from the file system cache, with no disk access needed.
- Most disk accesses will be writes. In most file systems, writes are done in very small chunks. Small writes are highly inefficient, since a 50-μsec disk write is often preceded by a 10-msec seek and a 4-msec rotational delay. With these parameters, disk efficiency drops to a fraction of 1 percent.

- While the writes can be delayed, doing so exposes the file system to serious consistency problems if a crash occurs before the writes are done.
- From this reasoning, the LFS designers decided to re-implement the UNIX file system in such a way as to achieve the full bandwidth of the disk. The basic idea is to structure the entire disk as a *log*.
- The logging algorithms have been also applied successfully to the problem of consistency checking.
- The resulting implementations are known as **log-based transaction-oriented** (or **journaling**) file systems.
- Such file systems are actually in use (NTFS, ext3, ReiserFS).
- Recall that a system crash can cause inconsistencies among on-disk file system data structures, such as directory structures, free-block pointers, and free FCB pointers.
- A typical operation, such as file create, can involve many structural changes within the file system on the disk.
  - Directory structures are modified,
  - FCBs are allocated,
  - Data blocks are allocated,
  - The free counts for all of these blocks are decreased.
- These changes can be interrupted by a crash, and inconsistencies among the structures can result.
- For example, the free FCB count might indicate that an FCB had been allocated, but the directory structure might not point to the FCB.
- The consistency check may not be able to recover the structures, resulting in loss of files and even entire directories.
- The solution to this problem is to apply log-based recovery techniques to file-system metadata updates.
- Both NTFS and the Veritas (improved UFS) file system use this method, and it is an optional addition to UFS on Solaris 7 and beyond.

- Fundamentally, all metadata changes are written sequentially to a log. Each set of operations for performing a specific task is a **transaction**.
  - Once the changes are written to this log, they are considered to be committed, and the system call can return to the user process, allowing it to continue execution.
  - Meanwhile, these log entries are replayed across the actual file system structures.
  - As the changes are made, a pointer is updated to indicate which actions have completed and which are still incomplete.
  - When an entire committed transaction is completed, it is removed from the log file, which is actually a **circular buffer**.
- The log may be in a separate section of the file system or even on a separate disk.
- If the system crashes, the log file will contain zero or more transactions.
  - Any transactions it contains were not completed to the file system, even though they were committed by the OS, so they must now be completed.
  - The transactions can be executed from the pointer until the work is complete so that the file-system structures remain consistent.
- The only problem occurs when a transaction was aborted -that is, was not committed before the system crashed.
  - Any changes from such a transaction that were applied to the file system must be undone, again preserving the consistency of the file system.
  - This recovery is all that is needed after a crash, eliminating any problems with consistency checking.