

Section 10: File Systems

CS 162

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1 Vocabulary

- **Simple File System** - The disk is treated as a big array. At the beginning of the disk is the Table of Content (TOC) field, followed by data field. Files are stored in data field contiguously, but there can be unused space between files. In the TOC field, there are limited chunks of file description entries, with each entry describing the name, start location and size of a file.

Pros and Cons

The main advantage of this implementation is simplicity. Whenever there is a new file created, a continuous space on disk is allocated for that file, which makes I/O (read and write) operations much faster.

However, this implementation also has many disadvantages. First of all, it has external fragmentation problem. Because only continuous space can be utilized, it may come to the situation that there is enough free space in sum, but none of the continuous space is large enough to hold the whole file. Second, once a file is created, it cannot be easily extended because the space after this file may already be occupied by another file. Third, there is no hierarchy of directories and no notion of file type.

- **External Fragmentation** - External fragmentation is the phenomenon in which free storage becomes divided into many small pieces over time. It occurs when an application allocates and deallocates regions of storage of varying sizes, and the allocation algorithm responds by leaving the allocated and deallocated regions interspersed. The result is that although free storage is available, it is effectively unusable because it is divided into pieces that are too small to satisfy the demands of the application.
- **Internal Fragmentation** - Internal fragmentation is the space wasted inside of allocated memory blocks because of the restriction on the minimum allowed size of allocated blocks.
- **FAT** - In FAT, the disk space is still viewed as an array. The very first field of the disk is the boot sector, which contains essential information to boot the computer. A super block, which is fixed sized and contains the metadata of the file system, sits just after the boot sector. It is immediately followed by a **file allocation table** (FAT). The last section of the disk space is the data section, consisting of small blocks with size of 4 KiB.

In FAT, a file is viewed as a linked list of data blocks. Instead of having a “next block pointer” in each data block to make up the linked list, FAT stores these pointers in the entries of the file allocation table, so that the data blocks can contain 100% data. There is a 1-to-1 correspondence between FAT entries and data blocks. Each FAT entry stores a data block index. Their meaning is interpreted as:

If $N > 0$, N is the index of next block

If $N = 0$, it means that this is the end of a file

If $N = -1$, it means this block is free

Thus, a file can be stored in a non-continuous pattern in FAT. The maximum internal fragmentation equals to 4095 bytes (4K bytes - 1 byte).

Directory in the FAT is a file that contains directory entries. The format of directory entries look as follows:

Name — Attributes — Index of 1st block — Size

Pros and Cons

Now we have a review of the pros and cons about FAT. Readers will find most of the following features have been already talked about above. So we only give a very simple list of these features.

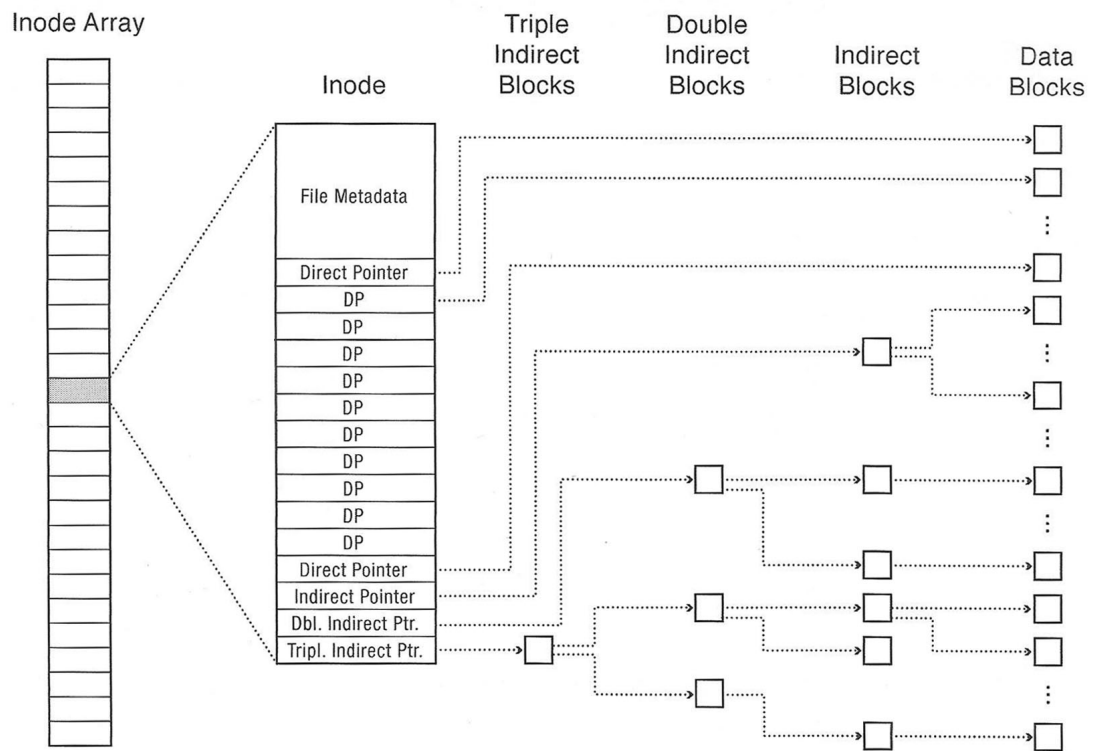
Pros: no external fragmentation, can grow file size, has hierarchy of directories

Cons: no pre-allocation, disk space allocation is not contiguous (accordingly read and write operations will slow), assume File Allocation Table fits in RAM. Otherwise lseek and extending a file would take intolerably long time due to frequent memory operation.

- **Unix File System (Fast File System)** - The Unix File System is a file system used by many Unix and Unix-like operating systems. Many modern operating systems use file systems that are based off of the Unix File System.
- **inode** - An inode is the data structure that describes the metadata of a file or directory. Each inode contains several metadata fields, including the owner, file size, modification time, file mode, and reference count. Each inode also contains several data block pointers, which help the file system locate the file's data blocks.

Each inode typically has 12 direct block pointers, 1 singly indirect block pointer, 1 doubly indirect block pointer, and 1 triply indirect block pointer. Every direct block pointer directly points to a data block. The singly indirect block pointer points to a block of pointers, each of which points to a data block. The doubly indirect block pointer contains another level of indirection, and the triply indirect block pointer contains yet another level of indirection.

- **Queueing Theory** Here are some useful symbols: (both the symbols used in lecture and in the book are listed)
 - μ is the average service rate (jobs per second)
 - T_{ser} or S is the average service time, so $T_{ser} = \frac{1}{\mu}$
 - λ is the average arrival rate (jobs per second)
 - U or u or ρ is the utilization (fraction from 0 to 1), so $U = \frac{\lambda}{\mu} = \lambda S$
 - T_q or W is the average queueing time (aka waiting time) which is how much time a task needs to wait before getting serviced (it does not include the time needed to actually perform the task)
 - L_q or Q is the average length of the queue, and it's equal to λT_q (this is Little's law)



2 File Allocation Table

What does it mean to format a FAT file system? Approximately how many bytes of data need to be written in order to format a 2GiB flash drive (with 4KiB blocks and a FAT entry size of 4 bytes) using the FAT file system?

Your friend (who has never taken an Operating Systems class) wants to format their external hard drive with the FAT32 file system. The external hard drive will be used to share home videos with your friend's family. Give one reason why FAT32 might be the right choice. Then, give one reason why your friend should consider other options.

Explain how an operating system reads a file like "D:\My Files\Video.mp4" from a FAT volume (from a software point of view).

Compare bitmap-based allocation of blocks on disk with a free block list.

3 Inode-Based File System

1. What are the advantages of an inode-based file system design compared to FAT?

2. What is the difference between a hard link and a soft link?

3. Why do we have direct blocks? Why not just have indirect blocks?

4. Consider a file system with 2048 byte blocks and 32-bit disk and file block pointers. Each file has 12 direct pointers, a singly-indirect pointer, a doubly-indirect pointer, and a triply-indirect pointer.

- (a) How large of a disk can this file system support?

- (b) What is the maximum file size?

5. Rather than writing updated files to disk immediately, many UNIX systems use a delayed *write-behind policy* in which dirty disk blocks are flushed to disk once every x seconds. List two advantages and one disadvantage of such a scheme.

6. List the set of disk blocks that must be read into memory in order to read the file `/home/cs162/test.txt` in its entirety from a UNIX BSD 4.2 file system (10 direct pointers, a singly-indirect pointer, a doubly-indirect pointer, and a triply-indirect pointer). Assume the file is 15,234 bytes long and that disk blocks are 1024 bytes long. Assume that the directories in question all fit into a single disk block each. Note that this is not always true in reality.

4 Extending an inode

Consider the following `inode_disk` struct, which is used on a disk with a 512 byte block size.

```
/* Definition of block_sector_t */
typedef uint32_t block_sector_t;
/* Contents of on-disk inode. Must be exactly 512 bytes long. */
struct inode_disk
{
    off_t length;                /* File size in bytes. */
    block_sector_t direct[12];   /* 12 direct pointers */
    block_sector_t indirect;     /* a singly indirect pointer */
    uint32_t unused[114];       /* Not used. */
};
```

Why isn't the file name stored inside the `inode_disk` struct?

What is the maximum file size supported by this inode design?

How would you design the in-memory representation of the indirect block? (e.g. the disk sector that corresponds to an inode's `indirect` member)

Implement the following function, which changes the size of an inode. If the resize operation fails, the inode should be unchanged and the function should return `false`. Use the value 0 for unallocated block pointers. You do not need to write the inode itself back to disk. You can use these functions:

- “`block_sector_t block_allocate()`” – Allocates a disk block and returns the sector number. If the disk is full, then returns 0. For this question, assume unlimited disk space.
- “`void block_free(block_sector_t n)`” – Free a disk block.
- “`void block_read(block_sector_t n, uint8_t buffer[512])`” – Reads the contents of a disk sector into a buffer.
- “`void block_write(block_sector_t n, uint8_t buffer[512])`” – Writes the contents of a buffer into a disk sector.

1. Handle resizing the inode for direct pointers first

```
bool inode_resize(struct inode_disk *id, off_t size) {
    block_sector_t sector; // A variable that may be useful.
    for (int i = 0; i < 12; i++) { // Handle direct pointers
        if (size <= 512 * i && id->direct[i] != 0) { // Shrink inode
            -----
            -----
        }
        if (size > 512 * i && id->direct[i] == 0) { // Grow inode
            -----
        }
    }
}
```

2. Next, try to extend your implementation to the indirect pointers. Note we have to check if the indirect pointer page is even allocated yet, and do so if necessary. (we are still in `inode_resize`)

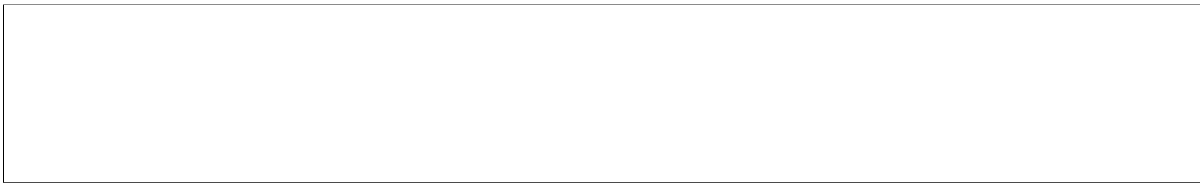
```
if (id->indirect == 0 && size <= 12 * 512) { // Check to handle indirects
    id->length = size;
    return true;
}
block_sector_t buffer[128];
memset(buffer, 0, 512);
if (id->indirect == 0) { // Allocate indirect page if does not exist
    -----
} else {
    -----
}
for (int i = 0; i < 128; i++) { // Handle indirect pointers
    if (size <= (12 + i) * 512 && buffer[i] != 0) { // Shrink inode
        -----
        -----
    }
    if (size > (12 + i) * 512 && buffer[i] == 0) { // Grow inode
        -----
    }
}
if (id->indirect != 0 && size <= 12 * 512) {
    -----
    -----
} else {
    -----
}
id->length = size;
return true;
}
```

5 Queueing Theory

Explain intuitively why response time is nonlinear with utilization. Draw a plot of utilization (x axis) vs response time (y axis) and label the endpoints on the x axis.



If 50 jobs arrive at a system every second and the average response time for any particular job is 100ms, how many jobs are in the system (either queued or being serviced) on average at a particular moment? Which law describes this relationship?



Is it better to have N queues, each of which is serviced at the rate of 1 job per second, or 1 queue that is serviced at the rate of N jobs per second? Give reasons to justify your answer.



What is the average queuing time for a work queue with 1 server, average arrival rate of λ , average service time S , and squared coefficient of variation of service time C ?

What does it mean if $C = 0$? What does it mean if $C = 1$?