File system internals

Tanenbaum, Chapter 4

COMP3231
Operating Systems

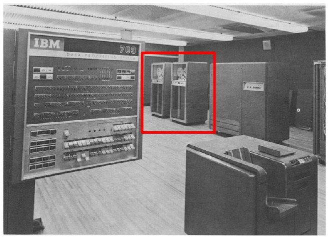
Summary of the FS abstraction

User's view	Under the hood
Hierarchical structure	Flat address space
Arbitrarily-sized files	Fixed-size blocks
Symbolic file names	Numeric block addresses
Contiguous address space inside a file	Fragmentation
Access control	No access control
(Some degree of) reliability	Data written to the disk survives OS crashes. RAID provides additional protection against disk crashes.

A brief history of file systems

- Early batch processing systems
  - No OS
  - I/O from/to punch cards
  - Tapes and drums for external storage, but no FS
  - Rudimentary library support for reading/writing tapes and drums

IBM 709 [1958]



A brief history of file systems

- The first file systems were single-level (everything in one directory)
- Files were stored in contiguous chunks
  - Maximal file size must be known in advance
- Now you can edit a program and save it in a named file on the tape!

PDP-8 with DECTape [1965]

A brief history of file systems

- Time-sharing OSs
  - Required full-fledged file systems
- MULTICS
  - Multilevel directory structure (keep files that belong to different users separately)
  - Access control lists
  - Symbolic links

Honeywell 6180 running MULTICS [1976]

A brief history of file systems

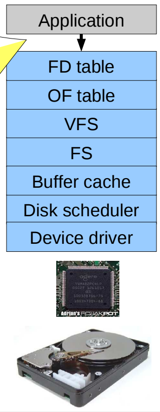
- UNIX
  - Based on ideas from MULTICS
  - Simpler access control model
  - Everything is a file!

PDP-7

Architecture of the OS storage stack

Syscall interface:

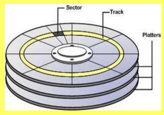
- `creat`
- `open`
- `read`
- `write`
- `...`

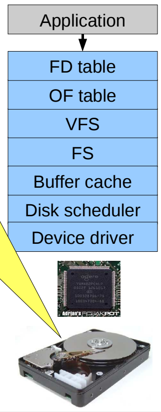


Architecture of the OS storage stack

Hard disk platters:

- tracks
- sectors

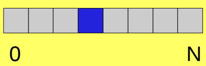


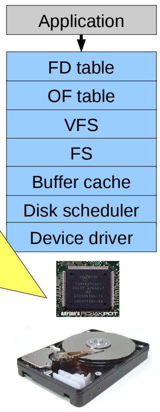


Architecture of the OS storage stack

Disk controller:

- Hides disk geometry, bad sectors
- Exposes linear sequence of blocks

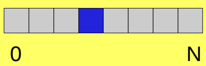


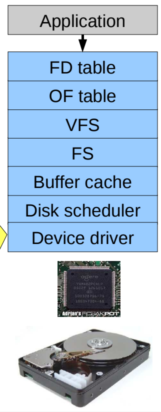


Architecture of the OS storage stack

Device driver:

- Hides device-specific protocol
- Exposes block-device Interface (linear sequence of blocks)

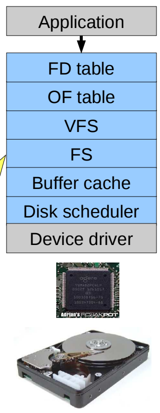




Architecture of the OS storage stack

File system:

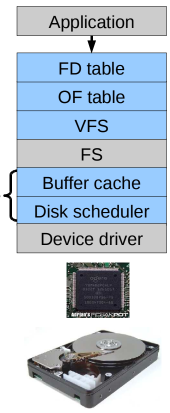
- Hides physical location of data on the disk
- Exposes: directory hierarchy, symbolic file names, random-access files, protection



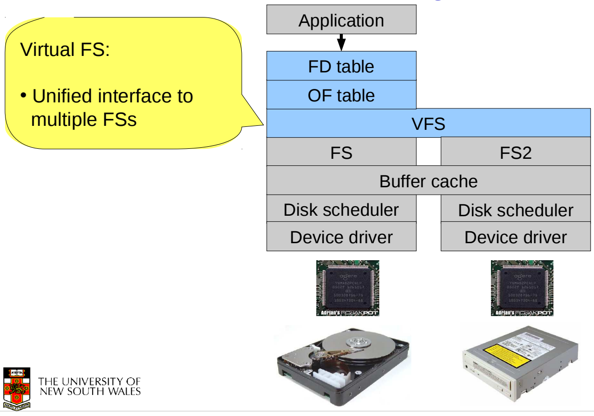
Architecture of the OS storage stack

Optimisations:

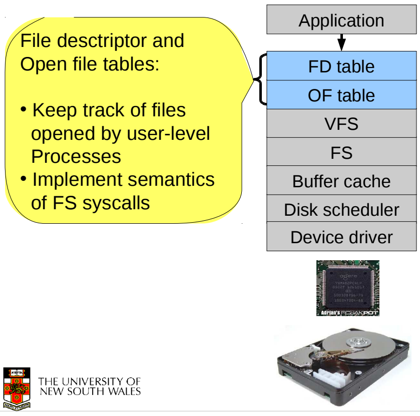
- Keep recently accessed disk blocks in memory
- Schedule disk accesses from multiple processes for performance and fairness



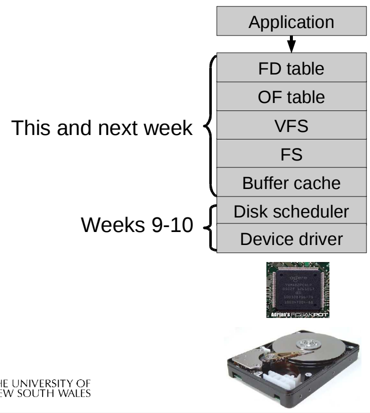
Architecture of the OS storage stack



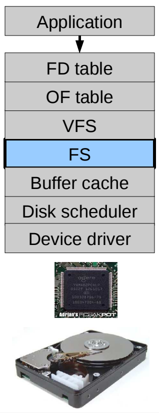
Architecture of the OS storage stack



Architecture of the OS storage stack



Architecture of the OS storage stack



Some popular file systems

- FAT16
- FAT32
- NTFS
- Ext2
- Ext3
- Ext4
- ReiserFS
- XFS
- ISO9660
- HFS+
- UFS2
- ZFS
- JFS
- OCFS
- Btrfs
- JFFS2
- ExFAT
- UBIFS

Question: why are there so many?

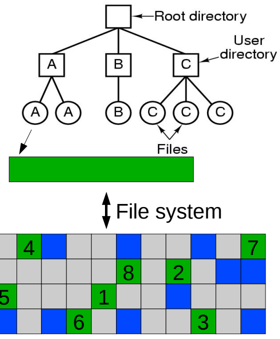
Question 1

Assumptions

- In this lecture we focus on file systems for magnetic disks
  - Rotational delay
    - 8ms worst case for 7200rpm drive
  - Seek time
    - ~15ms worst case
  - For comparison, disk-to-buffer transfer speed of a modern drive is ~10µs per 4K block.
- Conclusion: keep blocks that are likely to be accessed together close to each other

Implementing a file system

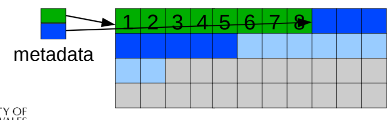
- The FS must map symbolic file names into block addresses
- The FS must keep track of
  - which blocks belong to which files.
  - in what order the blocks form the file
  - which blocks are free for allocation
- Given a logical region of a file, the FS must track the corresponding block(s) on disk.
  - Stored in file system metadata



Allocation strategies

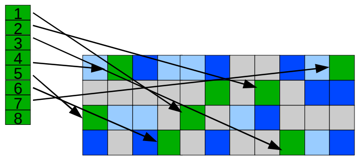
- Contiguous allocation
  - ✓ Easy bookkeeping (need to keep track of the starting block and length of the file)
  - ✓ Increases performance for sequential operations
  - ✗ Need the maximum size for the file at the time of creation
  - ✗ As files are deleted, free space becomes divided into many small chunks (external fragmentation)

Example: ISO 9660 (CDROM FS)



Allocation strategies

- Dynamic allocation
  - Disk space allocated in portions as needed
  - Allocation occurs in fixed-size blocks
  - ✓ No external fragmentation
  - ✓ Does not require pre-allocating disk space
  - ✗ Partially filled blocks (internal fragmentation)
  - ✗ File blocks are scattered across the disk
  - ✗ Complex metadata management (maintain the list of blocks for each file)

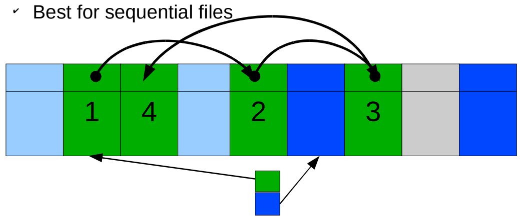


External and internal fragmentation

- External fragmentation
  - The space wasted external to the allocated memory regions
  - Memory space exists to satisfy a request but it is unusable as it is not contiguous
- Internal fragmentation
  - The space wasted internal to the allocated memory regions
  - Allocated memory may be slightly larger than requested memory; this size difference is wasted memory internal to a partition

Linked list allocation

- Each block contains a pointer to the next block in the chain. Free blocks are also linked in a chain.
  - ✓ Only single metadata entry per file
  - ✓ Best for sequential files

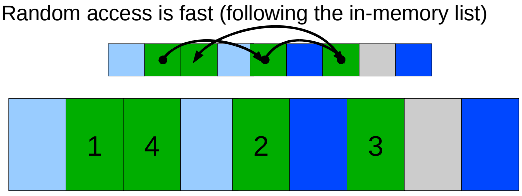


Question: What are the downsides?

Question 2

File allocation table

- Keep a map of the entire FS in a separate table
  - A table entry contains the number of the next block of the file
  - The last block in a file and empty blocks are marked using reserved values
- The table is stored on the disk and is replicated in memory
- Random access is fast (following the in-memory list)



Question: any issues with this design?

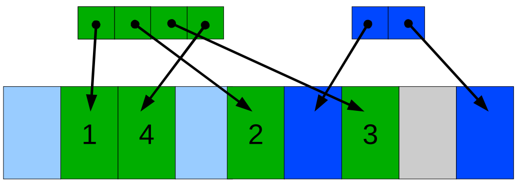
Question 3

File allocation table

- Examples
  - FAT12, FAT16, FAT32

inode-based FS structure

- Idea: separate table (index-node or i-node) for each file.
  - Only keep table for open files in memory
  - Fast random access
- The most popular FS structure today

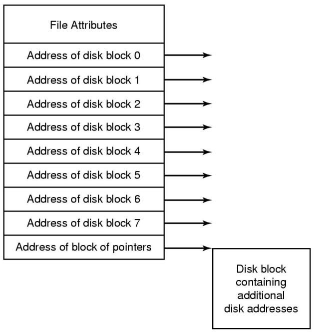


i-node implementation issues

- i-nodes occupy one or several disk areas

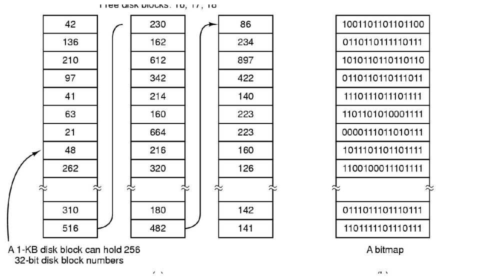
- i-nodes are allocated dynamically, hence free-space management is required for i-nodes
  - Use fixed-size i-nodes to simplify dynamic allocation
  - Reserve the last i-node entry for a pointer to an extension i-node

i-node implementation issues



i-node implementation issues

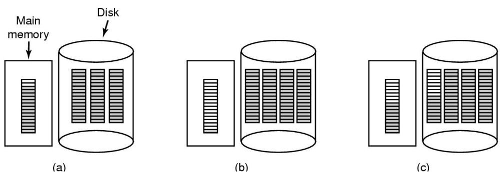
- Free-space management
  - Approach 1: linked list of free blocks
  - Approach 2: keep bitmaps of free blocks and free i-nodes



Free block list

- List of all unallocated blocks
- Background jobs can re-order list for better contiguity
- Store in free blocks themselves
  - Does not reduce disk capacity
- Only one block of pointers need be kept in the main memory

Free block list



(a) Almost-full block of pointers to free disk blocks in RAM
- three blocks of pointers on disk

(b) Result of freeing a 3-block file

(c) Alternative strategy for handling 3 free blocks
- shaded entries are pointers to free disk blocks

Bit tables

- Individual bits in a bit vector flags used/free blocks
- 16GB disk with 512-byte blocks --> 4MB table
- May be too large to hold in main memory
- Expensive to search
  - But may use a two level table
- Concentrating (de)allocations in a portion of the bitmap has desirable effect of concentrating access
- Simple to find contiguous free space

Implementing directories

- Directories are stored like normal files
  - directory entries are contained inside data blocks
- The FS assigns special meaning to the content of these files
  - a directory file is a list of directory entries
  - a directory entry contains file name, attributes, and the file i-node number
    - maps human-oriented file name to a system-oriented name

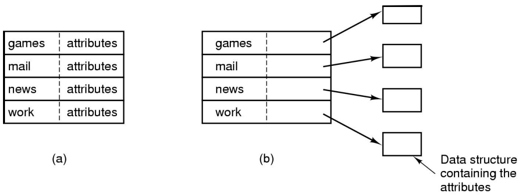
Fixed-size vs variable-size directory entries

- Fixed-size directory entries
  - Either too small
    - Example: DOS 8+3 characters
  - Or waste too much space
    - Example: 255 characters per file name
- Variable-size directory entries
  - Freeing variable length entries can create external fragmentation in directory blocks
    - Can compact when block is in RAM

Directory listing

- Locating a file in a directory
  - Linear scan
    - Use a directory cache to speed-up search
  - Hash lookup
  - B-tree (100's of thousands entries)

Storing file attributes



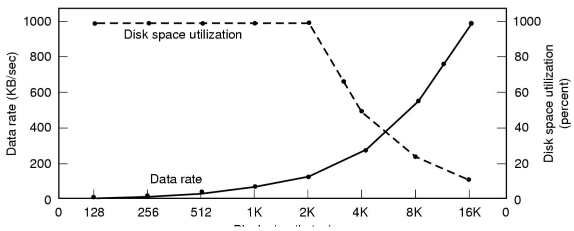
(a) disk addresses and attributes in directory entry
  – FAT

(b) directory in which each entry just refers to an i-node
  – UNIX

Trade-off in FS block size

- File systems deal with 2 types of blocks
  - Disk blocks or sectors (usually 512 bytes)
  - File system blocks 512 * 2^N bytes
  - What is the optimal N?
- Larger blocks require less FS metadata
- Smaller blocks waste less disk space
- Sequential Access
  - The larger the block size, the fewer I/O operations required
- Random Access
  - The larger the block size, the more unrelated data loaded.
  - Spatial locality of access improves the situation
- Choosing an appropriate block size is a compromise

Example block-size trade-off



- Dark line (left hand scale) gives data rate of a disk
- Dotted line (righ-hand scale) gived disk space efficiency
  - All files 2KB (an approximate median size)