File system internals
Tanenbaum, Chapter 4

COMP3231
Operating Systems

1

UNIX storage stack

Syscall interface:
```
creat
open
read
write
...
```

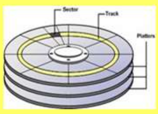
- Application
- FD table
- OF table
- VFS
- FS
- Buffer cache
- Disk scheduler
- Device driver

} Operating System

2

UNIX storage stack

Hard disk platters:
tracks
sectors



- Application
- FD table
- OF table
- VFS
- FS
- Buffer cache
- Disk scheduler
- Device driver

3

UNIX storage stack

Disk controller:

Hides disk geometry, bad sectors
Exposes linear sequence of blocks

0 N

- Application
- FD table
- OF table
- VFS
- FS
- Buffer cache
- Disk scheduler
- Device driver

4

UNIX storage stack

Device driver:

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

0 N

- Application
- FD table
- OF table
- VFS
- FS
- Buffer cache
- Disk scheduler
- Device driver

5

UNIX storage stack

File system:

Hides physical location of data on the disk

Exposes: directory hierarchy, symbolic file names, random-access files, protection

- Application
- FD table
- OF table
- VFS
- FS
- Buffer cache
- Disk scheduler
- Device driver

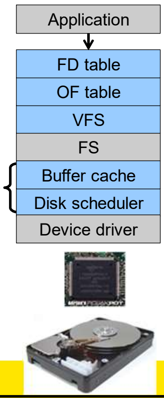
6

UNIX storage stack

Optimisations:

Keep recently accessed disk blocks in memory

Schedule disk accesses from multiple processes for performance and fairness

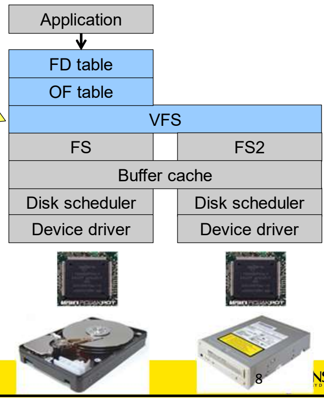


7

UNIX storage stack

Virtual FS:

Unified interface to multiple FSs



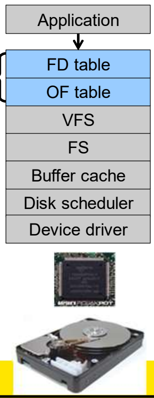
8

UNIX storage stack

File desctriptor and Open file tables:

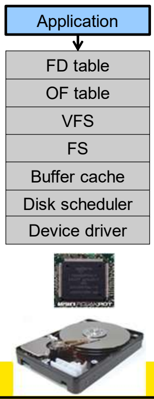
Keep track of files opened by user-level processes

Matches syscall interface to VFS Interface



9

UNIX storage stack

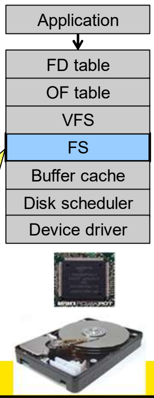


10

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



11

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?

12

Why are there so many?

- Different physical nature of storage devices
  - Ext3 is optimised for magnetic disks
  - JFFS2 is optimised for flash memory devices
  - ISO9660 is optimised for CDROM
- Different storage capacities
  - FAT16 does not support drives >2GB
  - FAT32 becomes inefficient on drives >32GB
  - ZFS, Btrfs is designed to scale to multi-TB disk arrays
- Different CPU and memory requirements
  - FAT16 is not suitable for modern PCs but is a good fit for many embedded devices
- Proprietary standards
  - NTFS may be a nice FS, but its specification is closed

13 UNSW

13

Assumptions

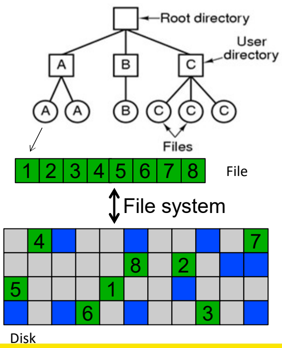
- In this lecture we focus on file systems for magnetic disks
  - Seek time
    - ~15ms worst case
  - Rotational delay
    - 8ms worst case for 7200rpm drive
  - For comparison, disk-to-buffer transfer speed of a modern drive is ~10µs per 4K block.
- Conclusion: keep blocks that are likely to be accessed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

14 UNSW

14

Implementing a file system

- The FS must map symbolic file names into a collection of 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

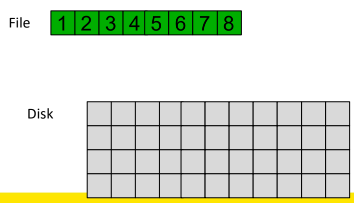


15 UNSW

15

File Allocation Methods

- A file is divided into “blocks”
  - the unit of transfer to storage
- Given the logical blocks of a file, what method is used to choose were to put the blocks on disk?



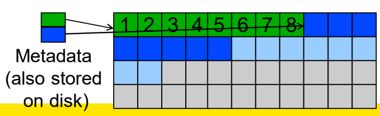
16 UNSW

16

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)

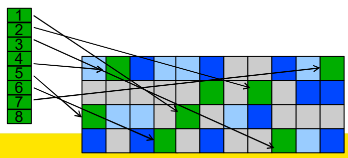


17 UNSW

17

Dynamic Allocation Strategies

- 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 collection of blocks for each file)



18 UNSW

18

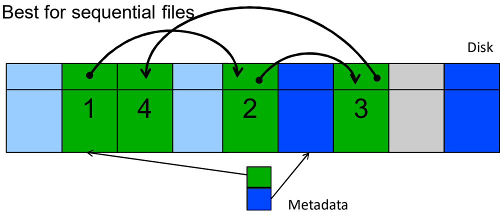
External and internal fragmentation

- 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

19

Dynamic allocation: 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

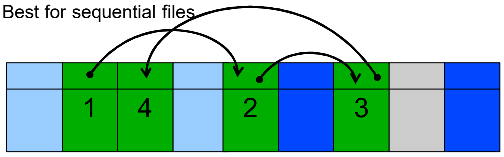


Question: What are the downsides?

20

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

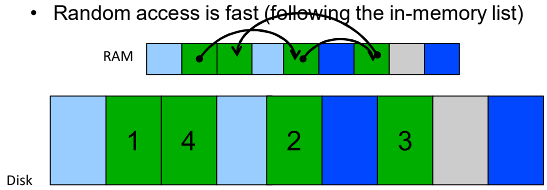


  - ✗ Poor for random access
  - ✗ Blocks end up scattered across the disk due to free list eventually being randomised

21

Dynamic Allocation: File Allocation Table (FAT)

- 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)

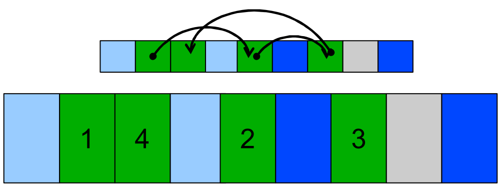


Question: any issues with this design?

22

File allocation table

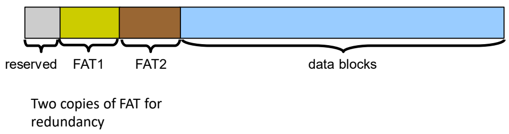
- Issues
  - Requires a lot of memory for large disks
    - 200GB = 200*10^6 * 1K-blocks ==> 200*10^6 FAT entries = 800MB
  - Free block lookup is slow
    - searches for a free entry in table



23

File allocation table disk layout

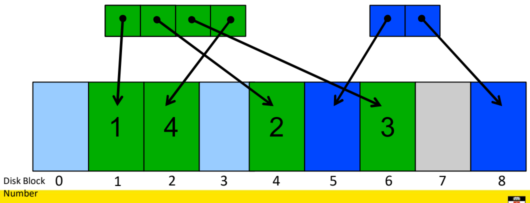
- Examples
  - FAT12, FAT16, FAT32



24

Dynamical Allocation: 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

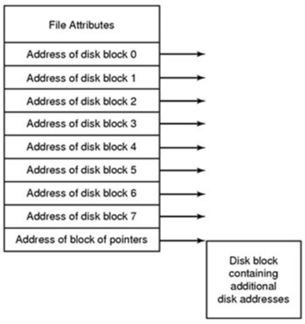


i-node implementation issues

- i-nodes occupy one or several disk areas

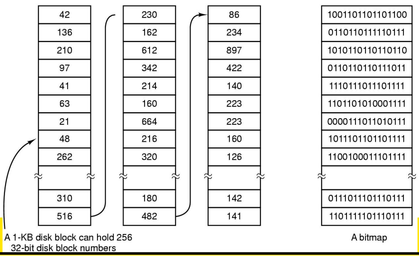
- i-nodes are allocated dynamically, hence free-space management is required for i-nodes
  - Use fixed-size i-nodes to simplify dynamic allocation
  - Reserve the last i-node entry for a pointer (a block number) to an extension i-node.

i-node implementation issues



i-node implementation issues

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



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

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
  - Optimisations possible, e.g. 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

31

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

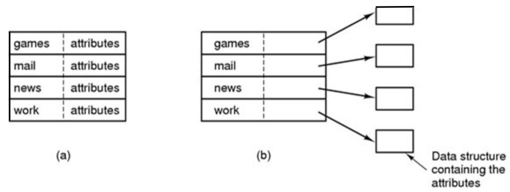
32

Searching Directory Listings

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

33

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

34

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 (less internal fragmentation)
- 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

35