File system internals

Tanenbaum, Chapter 4

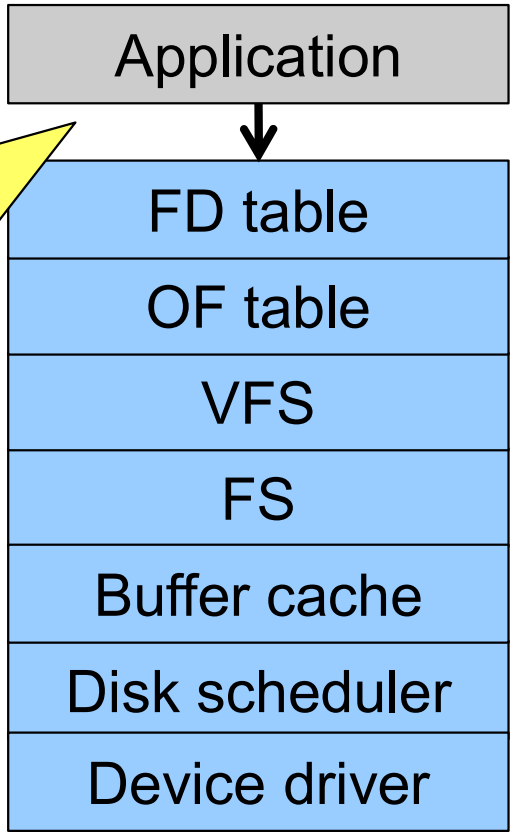
COMP3231

Operating Systems

UNIX storage stack

Syscall interface:

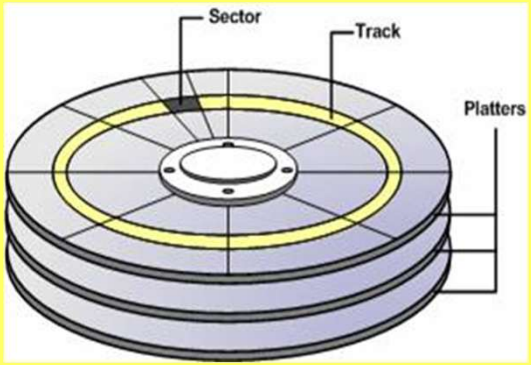
```
creat
open
read
write
...
```



Operating System

UNIX storage stack

Hard disk platters:
tracks
sectors



Application

FD table

OF table

VFS

FS

Buffer cache

Disk scheduler

Device driver

UNIX storage stack

Application

FD table

OF table

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Buffer cache

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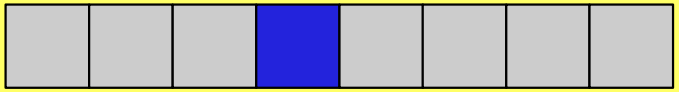
Device driver

Disk controller:

Hides disk geometry, bad sectors

Exposes linear sequence of blocks



0 N

the disk controller only exposes number 0 to N,
it hides disk geometry, bad sectors etc
if you want to update a byte on the block, you have to read the whole block it, update the byte, and write the whole block back

UNIX storage stack

Application

FD table

OF table

VFS

FS

Buffer cache

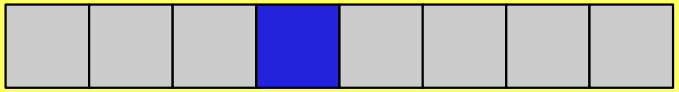
Disk scheduler

Device driver

Device driver:

Hides device-specific protocol

Exposes block-device Interface (linear sequence of blocks)



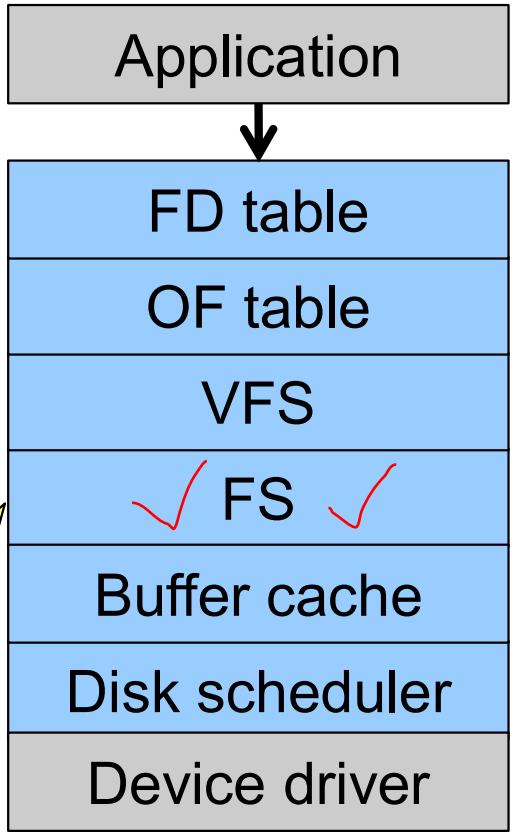
0 N

UNIX storage stack

File system:

Hides physical location of data on the disk

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



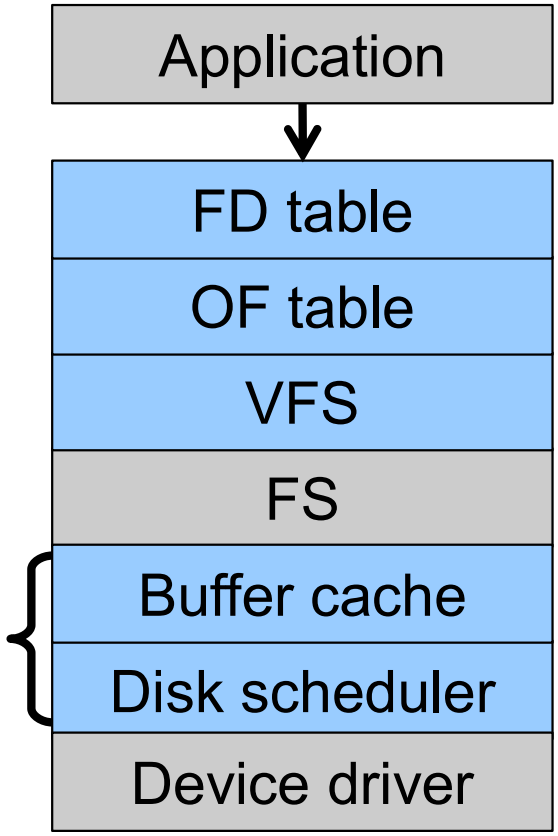
above the FS layer, we dealing with directory, files, unstructured string of bytes
below the FS layer, we dealing with the request of the blocks on the disk of the drive

UNIX storage stack

Optimisations:

Keep recently accessed disk blocks in memory

Schedule disk accesses from multiple processes for performance and fairness



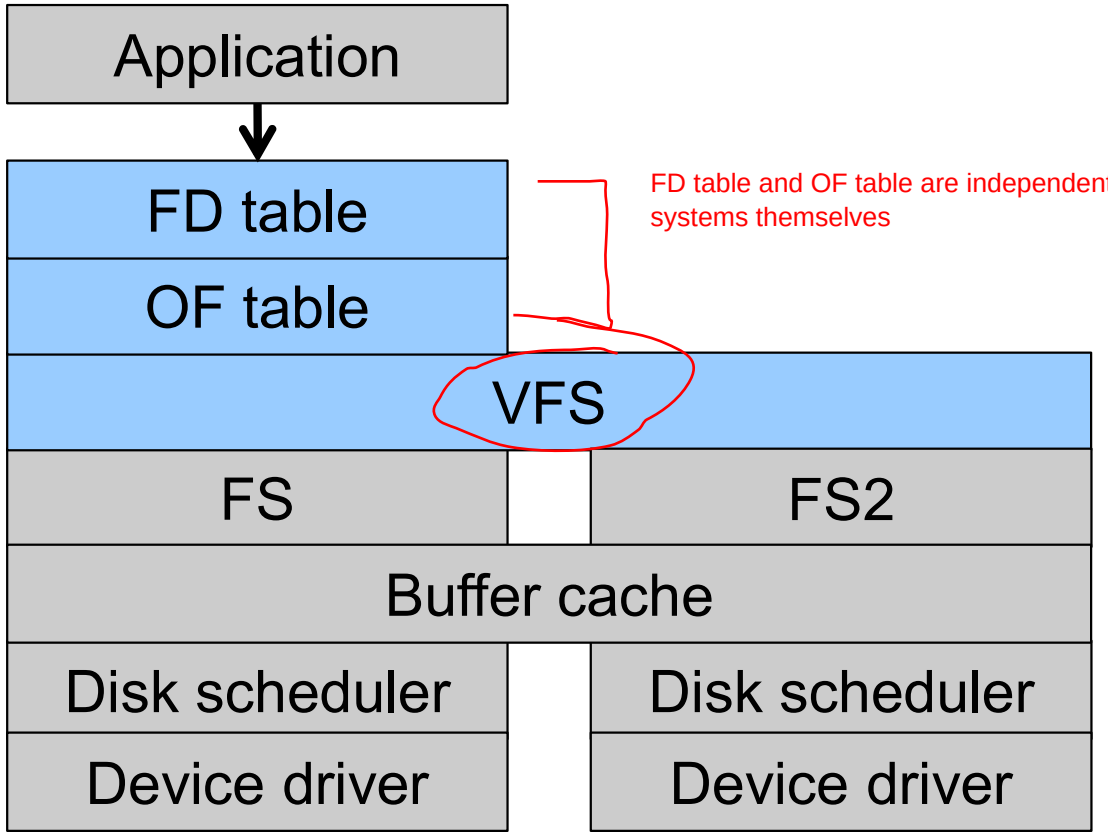
the buffer cache provides better performance and low latency without talking to the harddrive

UNIX storage stack

Virtual FS:

Unified interface to multiple FSs

real file systems are under virtual file system



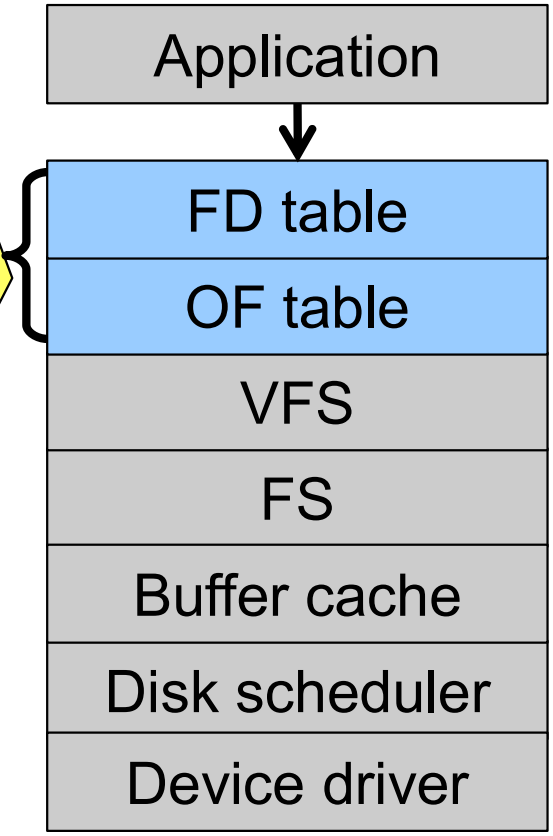
FD table and OF table are independent of the file systems themselves

UNIX storage stack

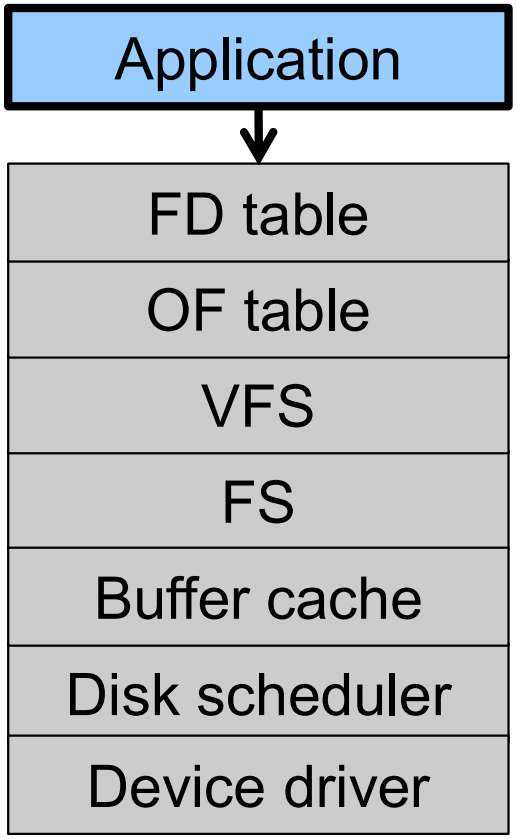
File descriptor and Open file tables:

Keep track of files opened by user-level processes

Matches syscall interface to VFS Interface



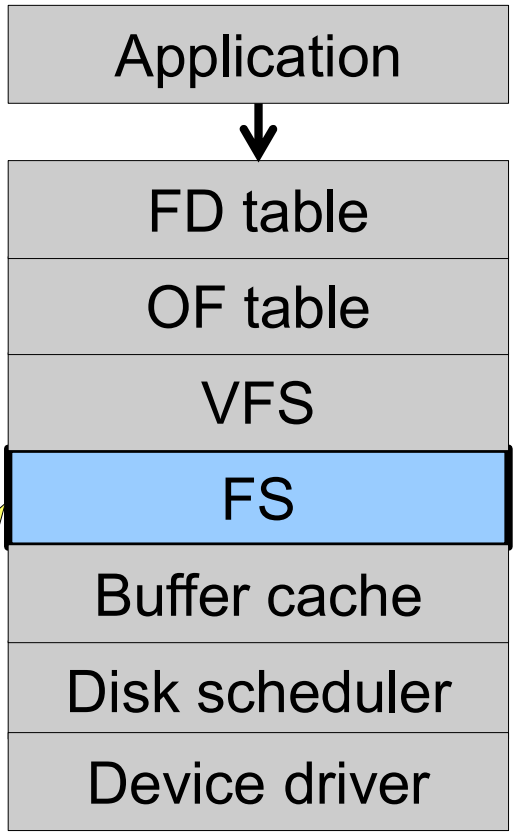
UNIX storage stack



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



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?

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

Outline

- File allocation methods
  - How files are stored in disk blocks, and what book keeping is required.
- Layout on disk
- Managing free space
- Directories
- Block size trade off

Assumptions

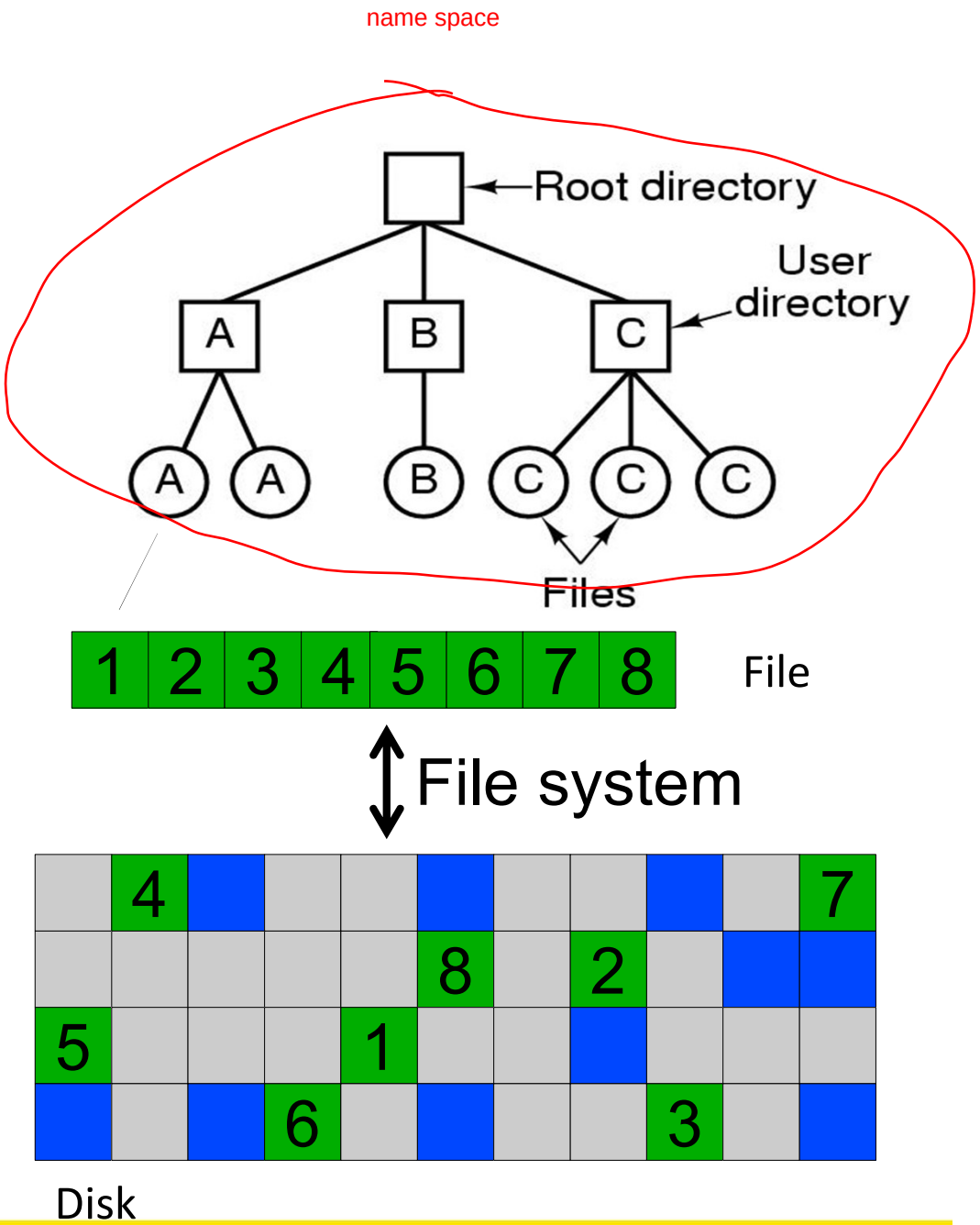
- In this lecture we focus on file systems for magnetic disks
  - Seek time
    - ~15ms worst case
  - Rotational delay
    - 8ms worst case for 7200rpm drive
  - For comparison, disk-to-buffer transfer speed of a modern drive is ~10µs per 4K block.
- Conclusion: keep blocks that are likely to be accessed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

Seek time is the time taken for a hard disk controller to locate a specific piece of stored data
seek the head from inside to the outside of the rotating disk, or in reversed direction

everything is lined up

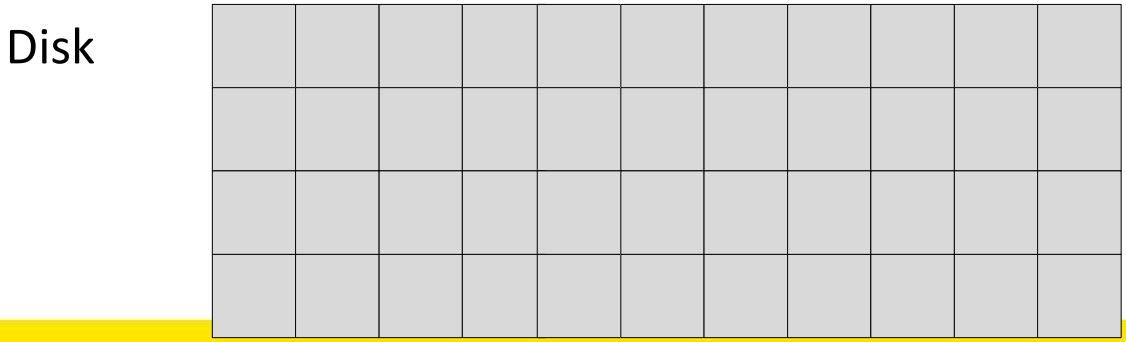
Implementing a file system

- 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



File Allocation Methods

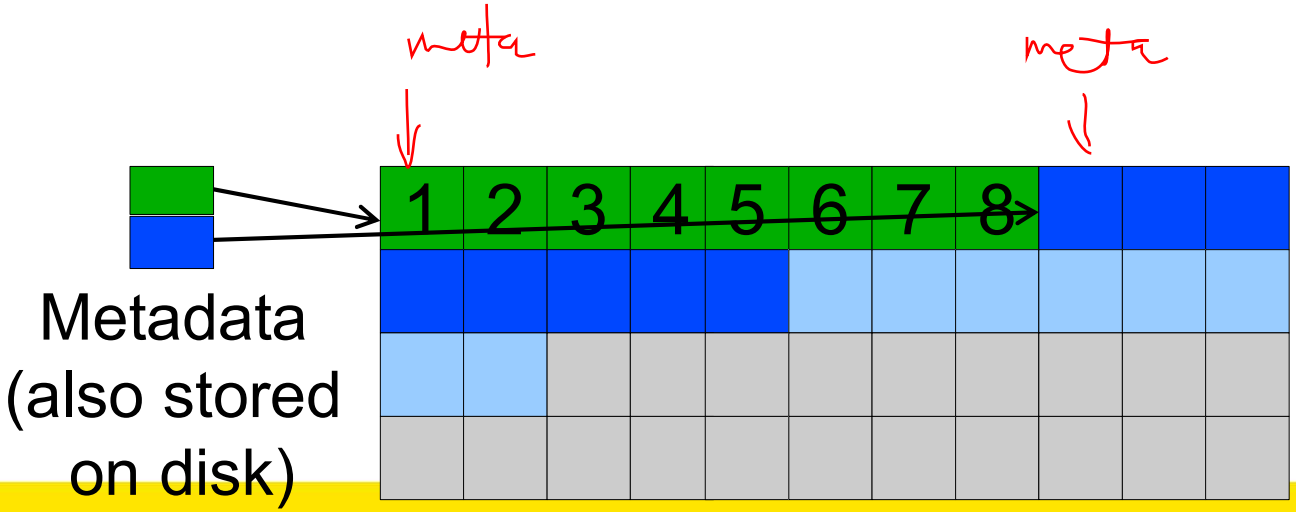
- A file is divided into “blocks”
  - the unit of transfer to storage
- Given the logical blocks of a file, what method is used to choose were to put the blocks on disk?



Contiguous Allocation

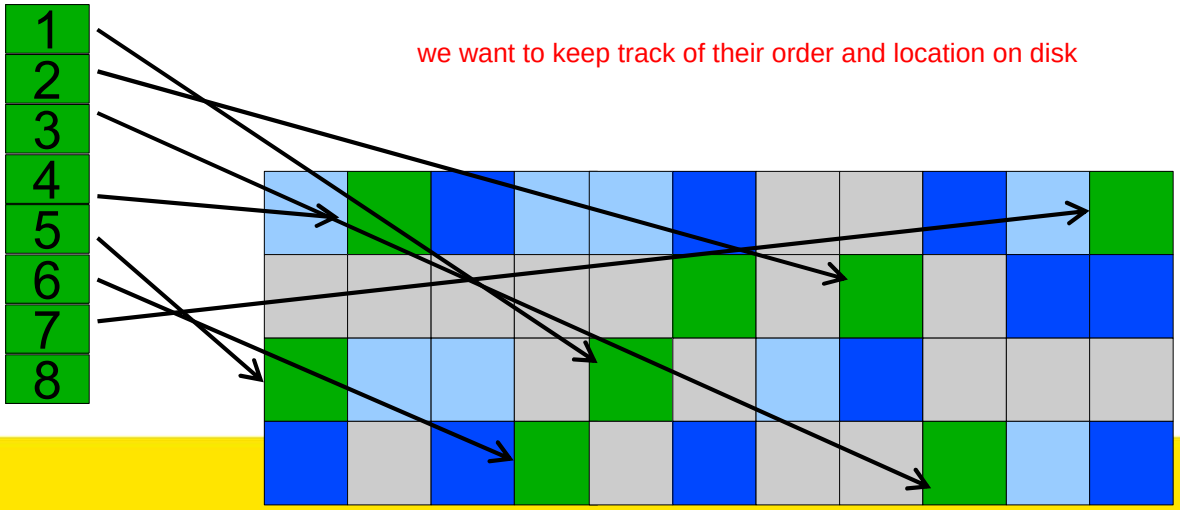
- ✓ Easy bookkeeping (need to keep track of the starting block and length of the file)
- ✓ Increases performance for sequential operations
- ✗ Need the maximum size for the file at the time of creation
- ✗ As files are deleted, free space becomes divided into many small chunks (external fragmentation)

Example: ISO 9660 (CDROM FS)

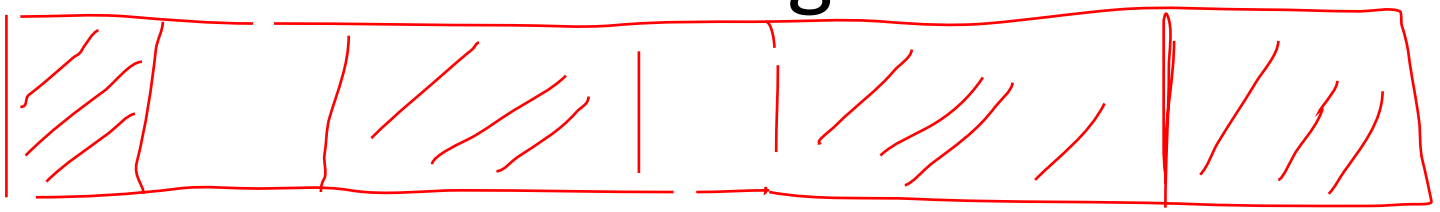


Dynamic Allocation Strategies

- – 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)



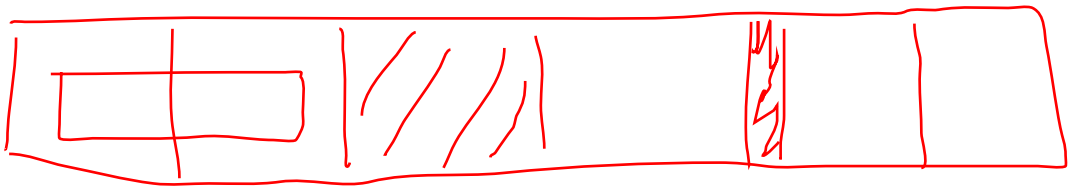
External and internal fragmentation



- External fragmentation

if I want to add a new memory of this new size, we have the space in total, but we don't have continuous free space

  - 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

fixed size allocation

  - The space wasted internal to the allocated memory regions

we have to round up to some unit sizes

  - Allocated memory may be slightly larger than requested memory; this size difference is wasted memory internal to a partition

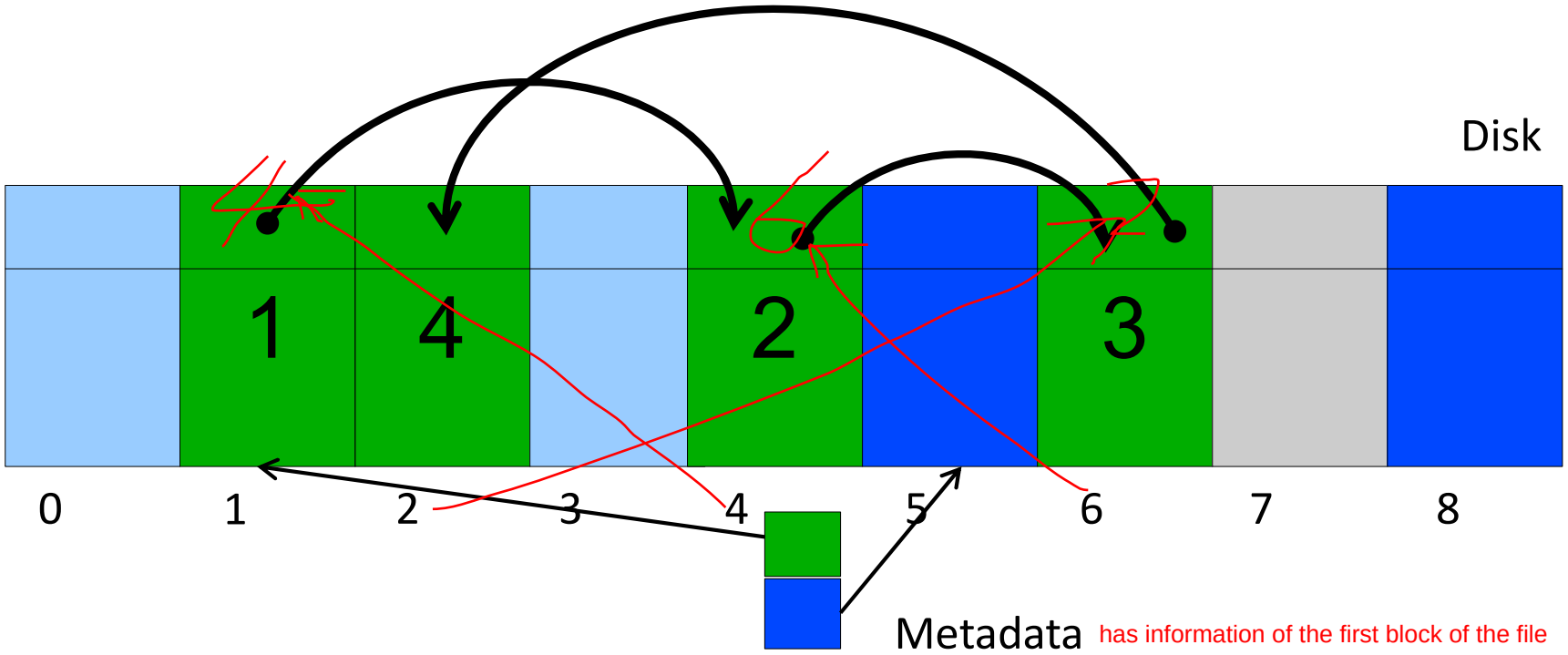
a malloc suffer from external fragmentation

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 sequentially accessed files

record its successor

read from start to finish

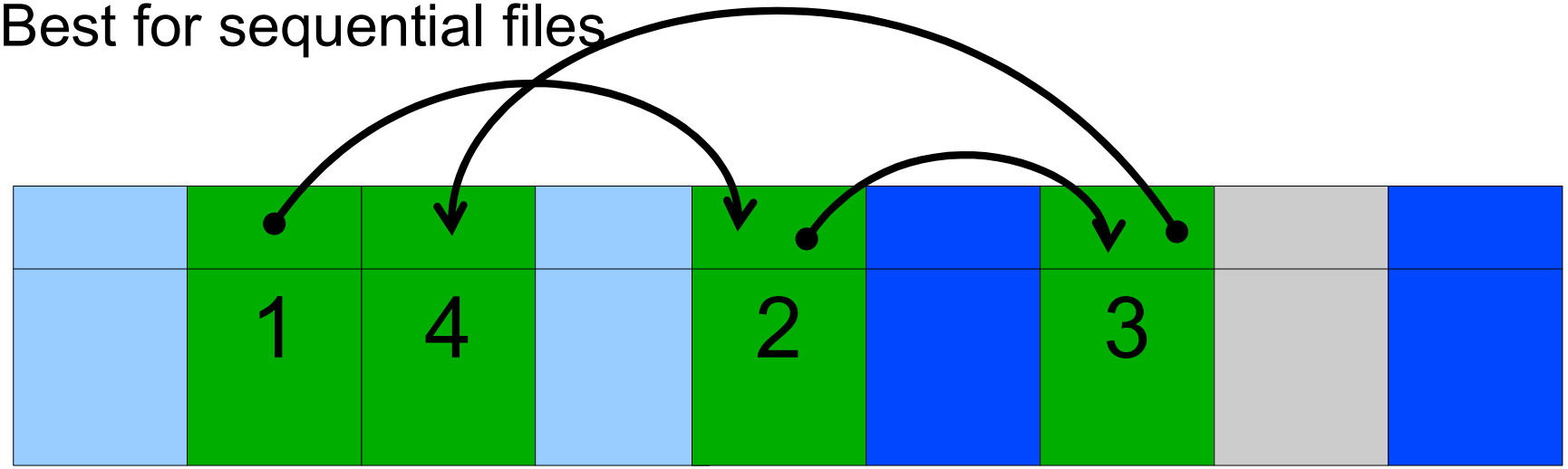


Question: What are the downsides?

Linked list allocation

linked list allocation has really bad performance in reading random access

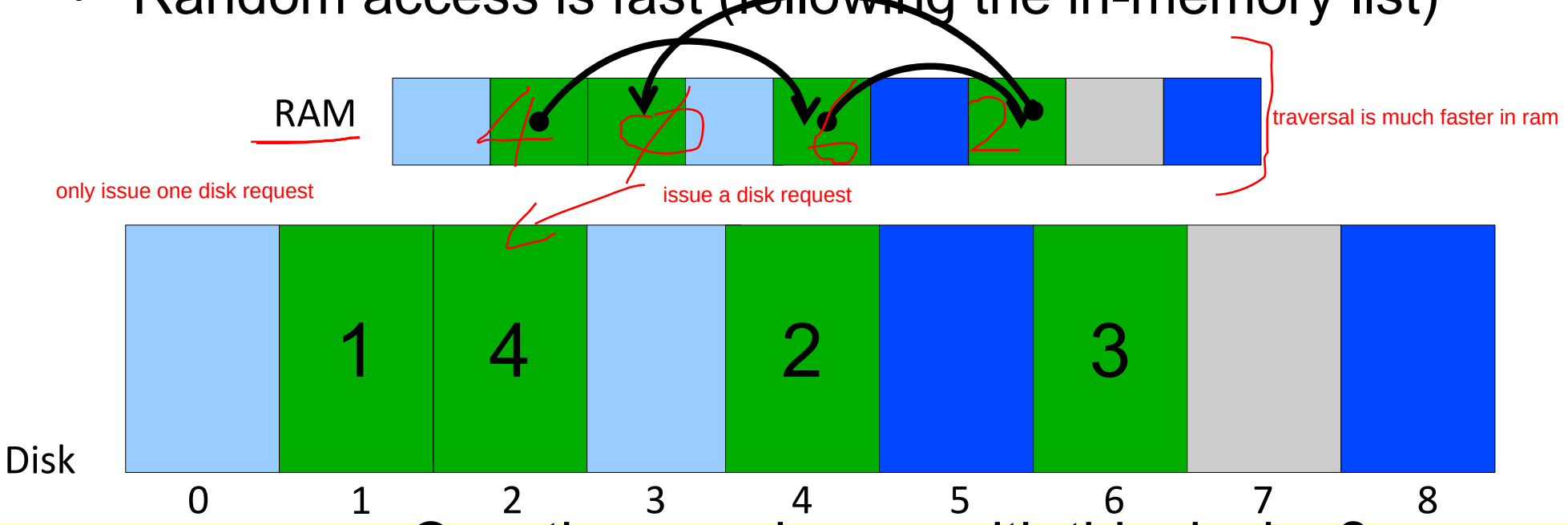
- Each block contains a pointer to the next block in the chain. Free blocks are also linked in a chain.
  - ✓ Only single metadata entry per file
  - ✓ Best for sequential files



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

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)

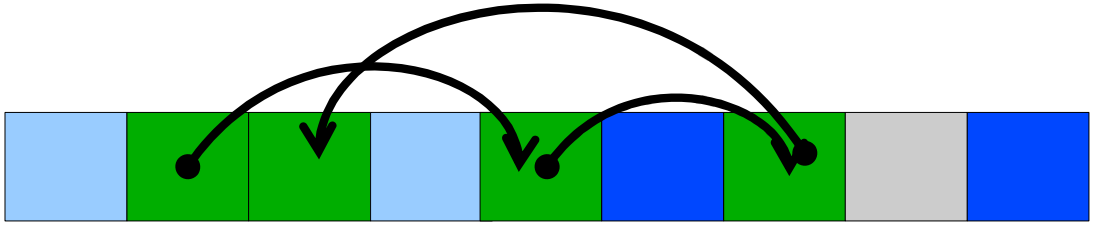


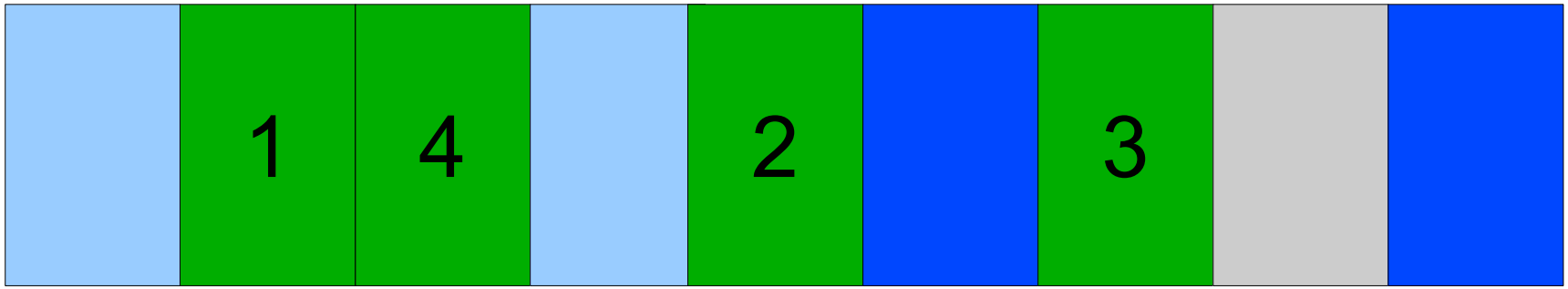
Question: any issues with this design?

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





File allocation table disk layout

- Examples
  - FAT12, FAT16, FAT32

32 bit

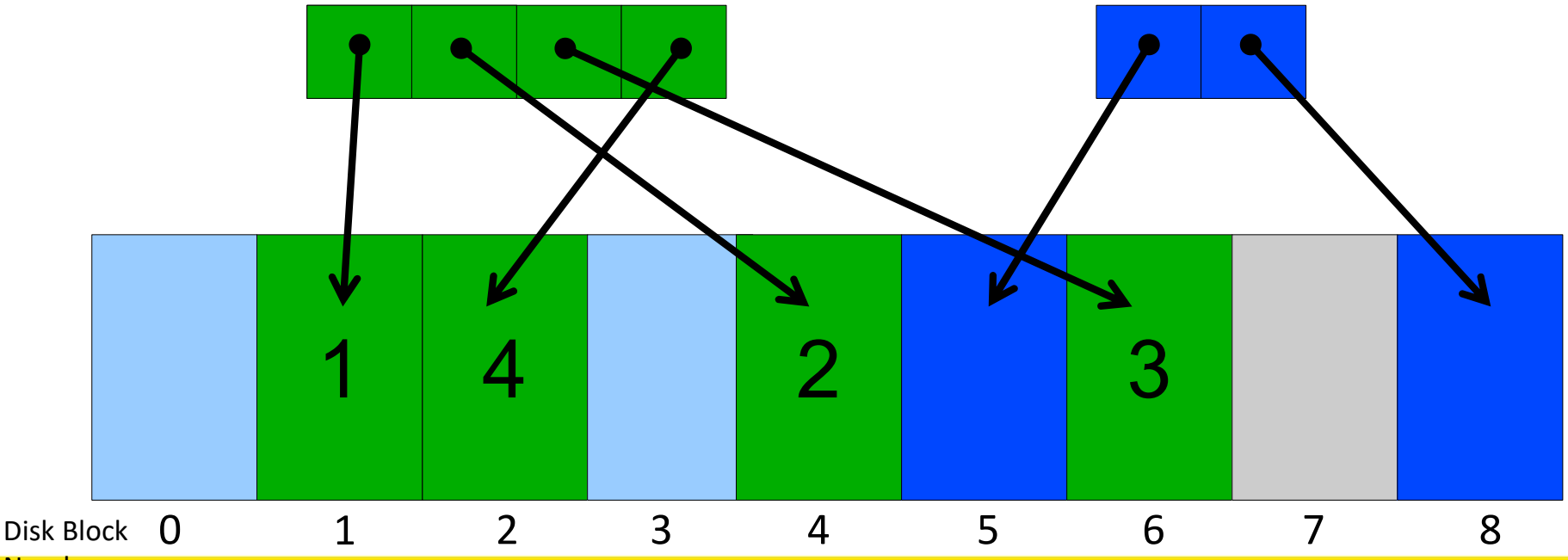
unsigned

12 bit block number 4096

Two copies of FAT for redundancy

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



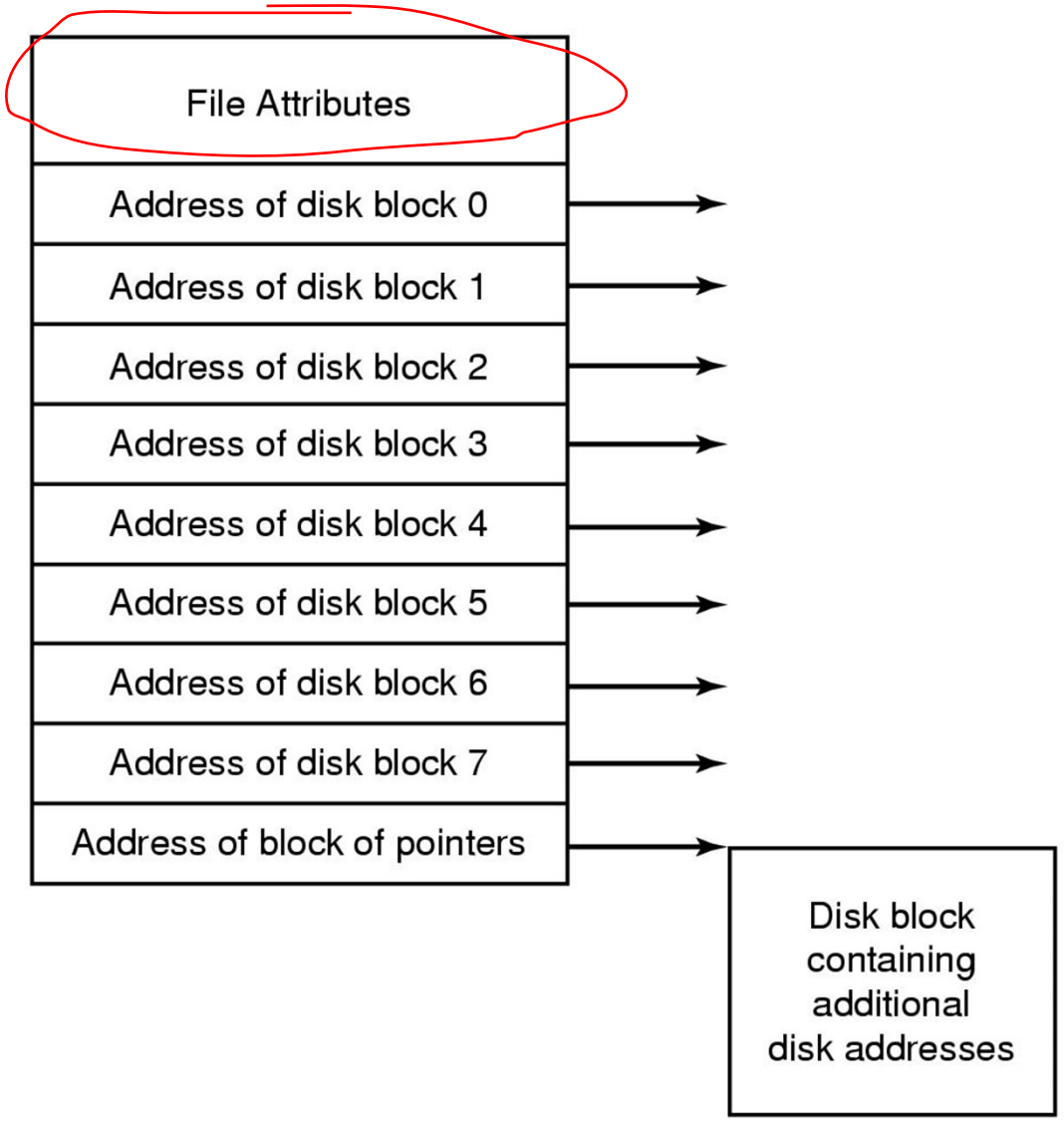
i-node implementation issues

- 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.

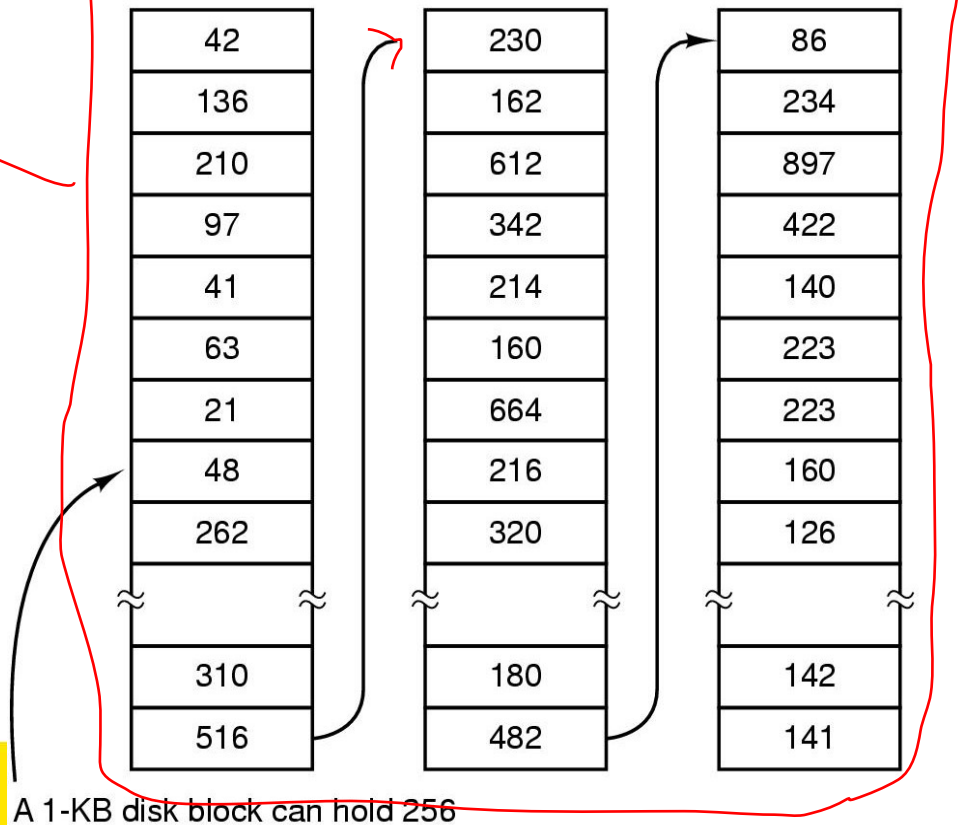
load the table based on inode

i-node implementation issues

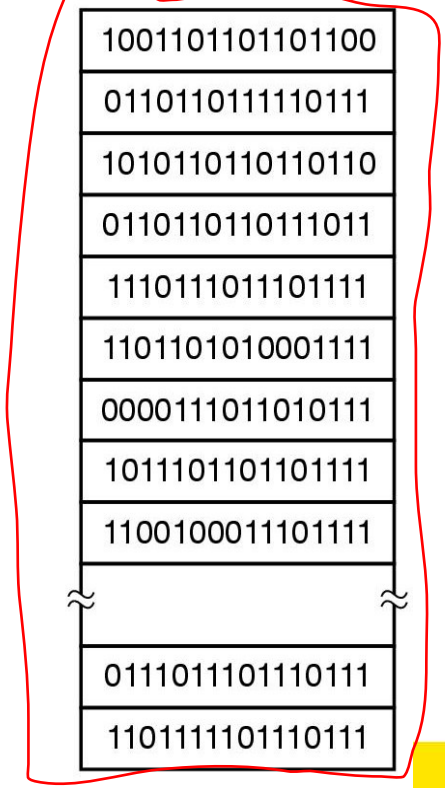


i-node implementation issues

- 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



A 1-KB disk block can hold 256 32-bit disk block numbers



A bitmap

Free block list

- List of all unallocated blocks
- Background jobs can re-order list for better contiguity to improve performance
- Store in free blocks themselves
  - Does not reduce disk capacity
- Only one block of pointers need be kept in the main memory when one is used up just grab the next one

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

if they are series of 0s, they are next to each other

- 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

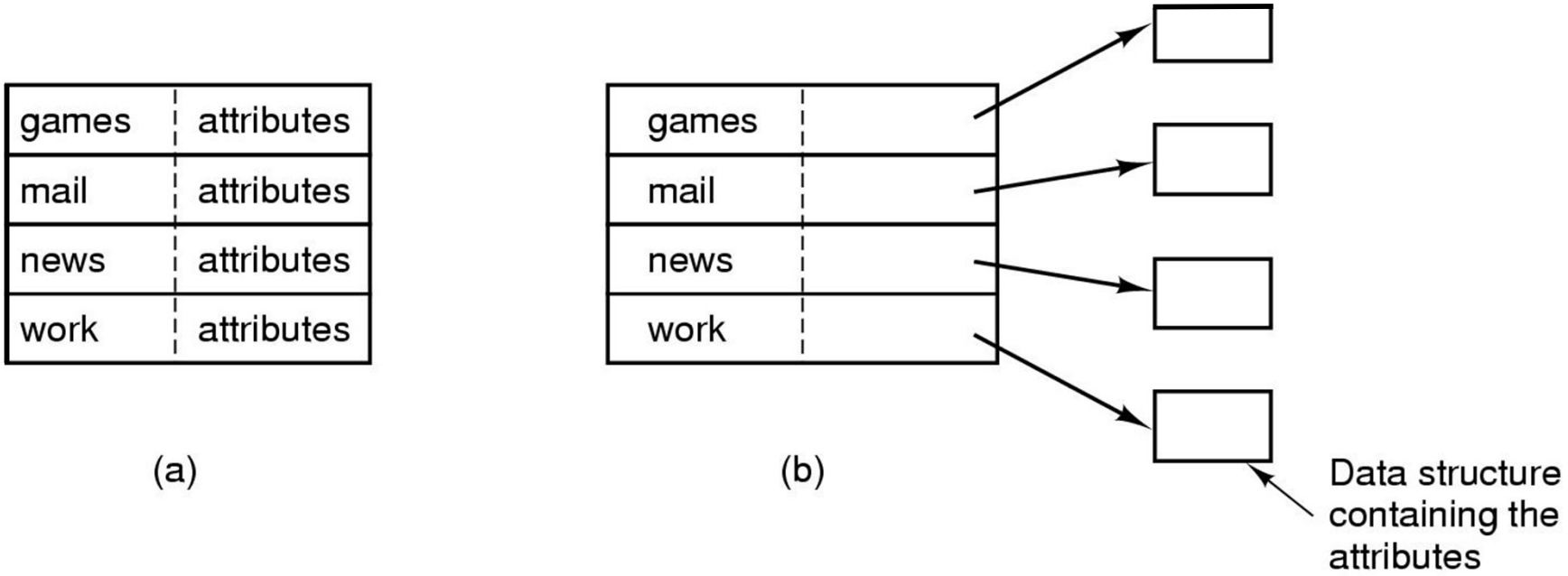
Fixed-size vs variable-size directory entries

- 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

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)

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 (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