File system internals

Tanenbaum, Chapter 4

COMP3231

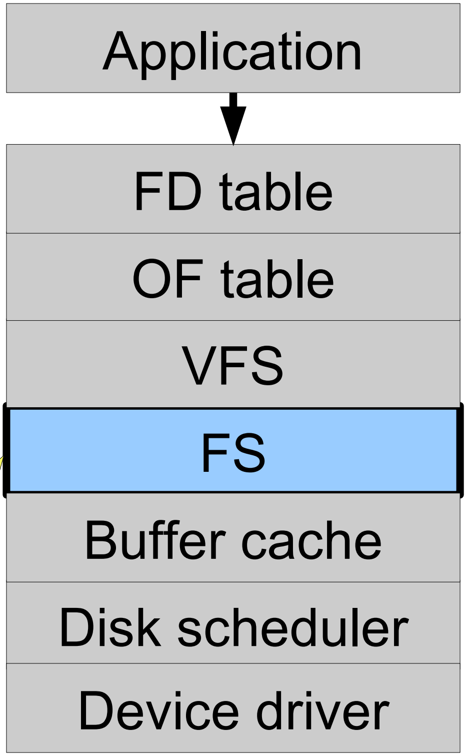
Operating Systems

THE UNIVERSITY OF
NEW SOUTH WALES

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?

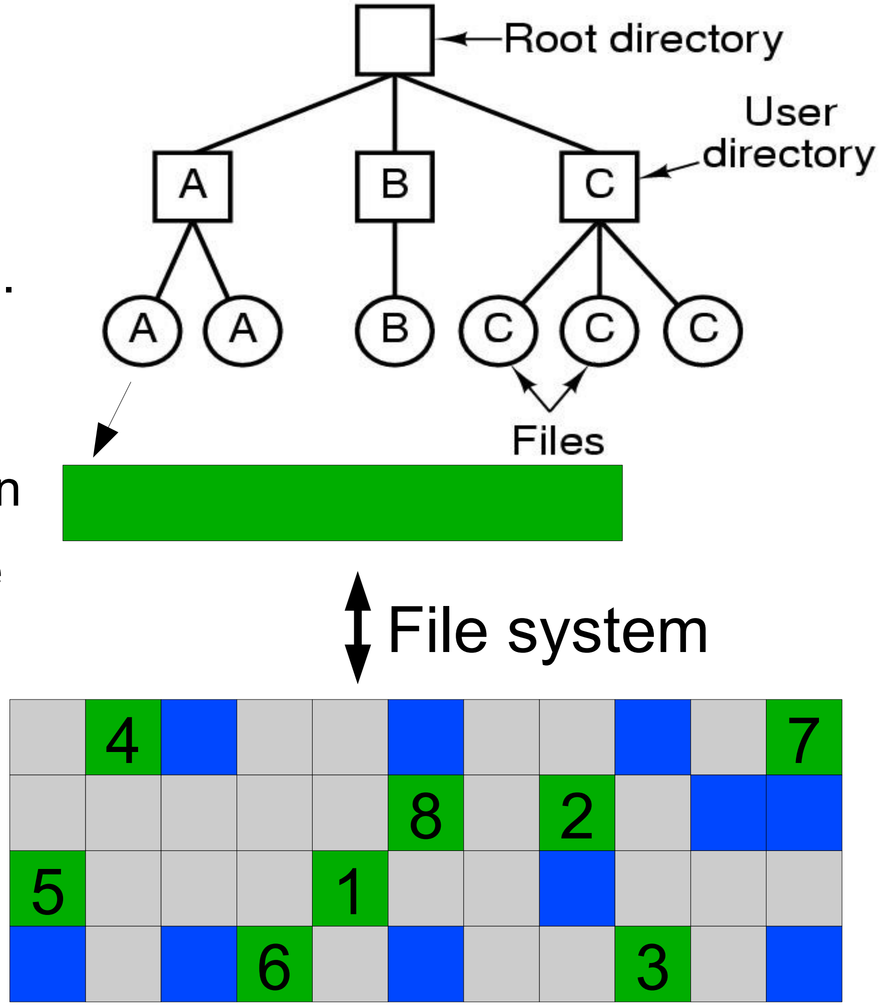
- Different physical nature of storage devices
  - Ext3 is optimised for magnetic disks
  - JFFS2 is optimised for flash memory devices
  - ISO9660 is optimised for CDROM
- Different storage capacities
  - FAT16 does not support drives >2GB
  - FAT32 becomes inefficient on drives >32GB
  - Btrfs is designed 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

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

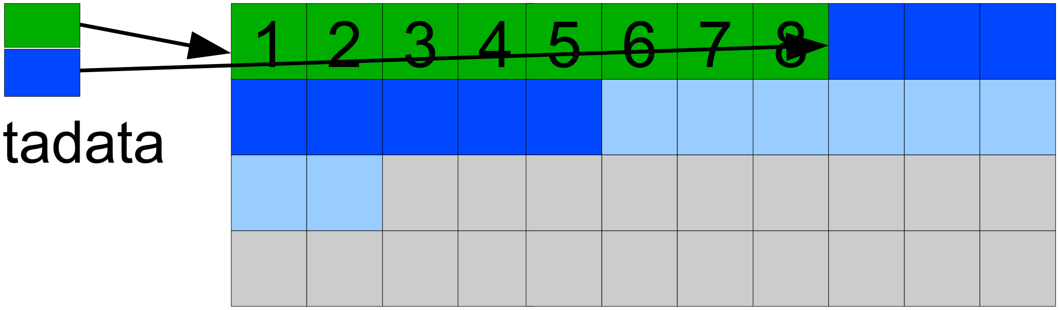
- The FS must map symbolic file names into block addresses
- The FS must keep track of
  - which blocks belong to which files.
  - in what order the blocks form the file
  - which blocks are free for allocation
- Given a logical region of a file, the FS must track the corresponding block(s) on disk.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



Allocation strategies

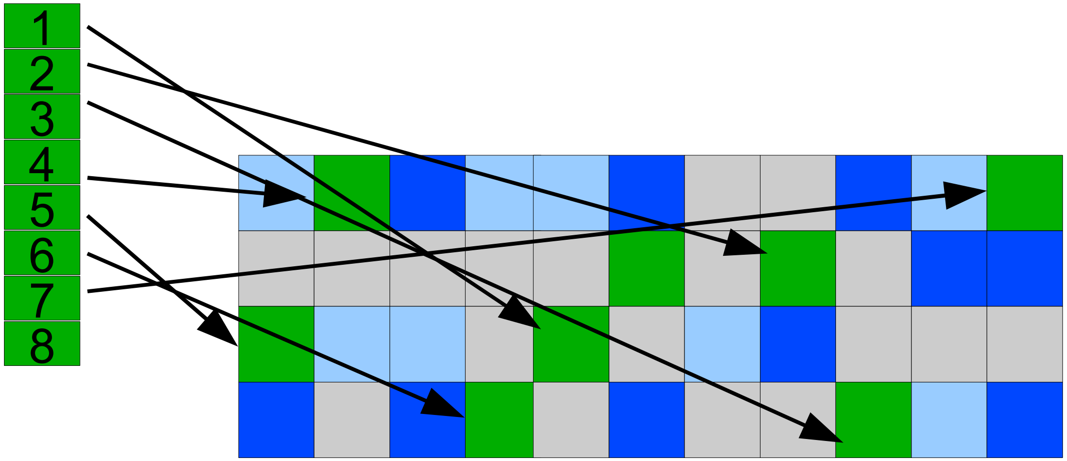
- Contiguous allocation
  - ✓ Easy bookkeeping (need to keep track of the starting block and length of the file)
  - ✓ Increases performance for sequential operations
  - ✗ Need the maximum size for the file at the time of creation
  - ✗ As files are deleted, free space becomes divided into many small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

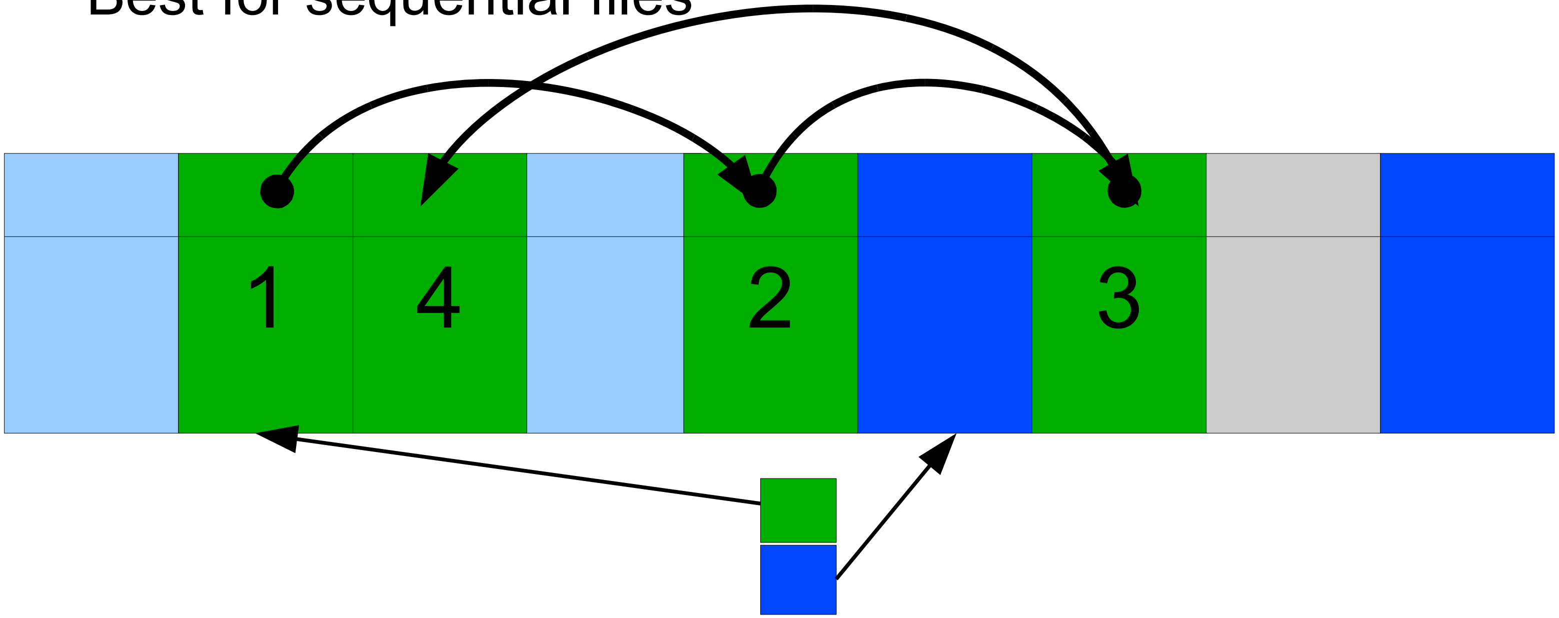


External and internal fragmentation

- 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

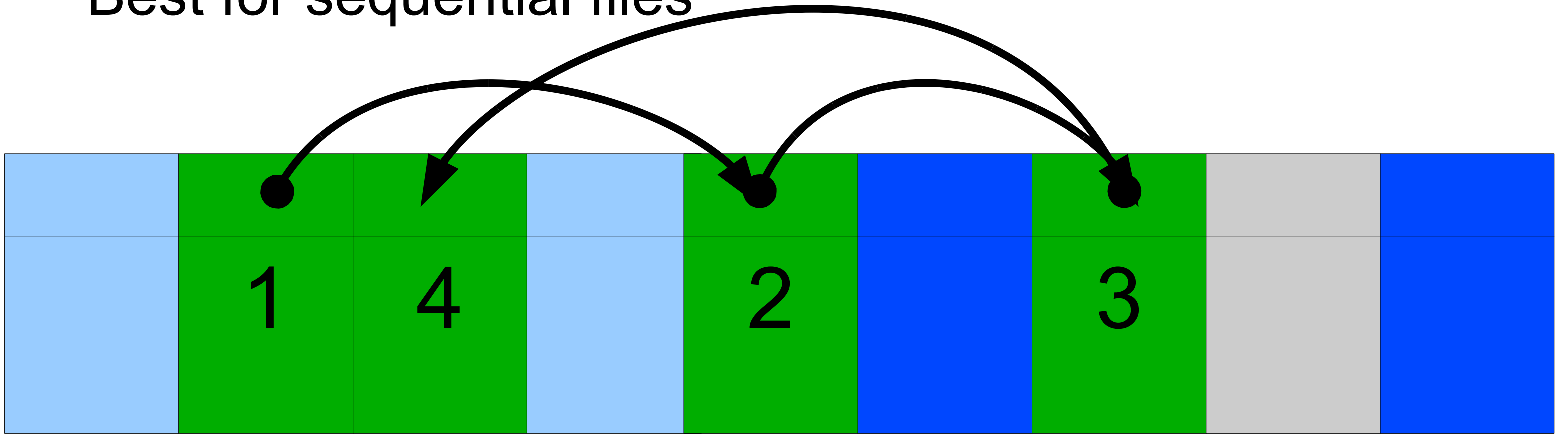
- Each block contains a pointer to the next block in the chain. Free blocks are also linked in a chain.
  - ✓ Only single metadata entry per file
  - ✓ Best for sequential files



Question: What are the downsides?

Linked list allocation

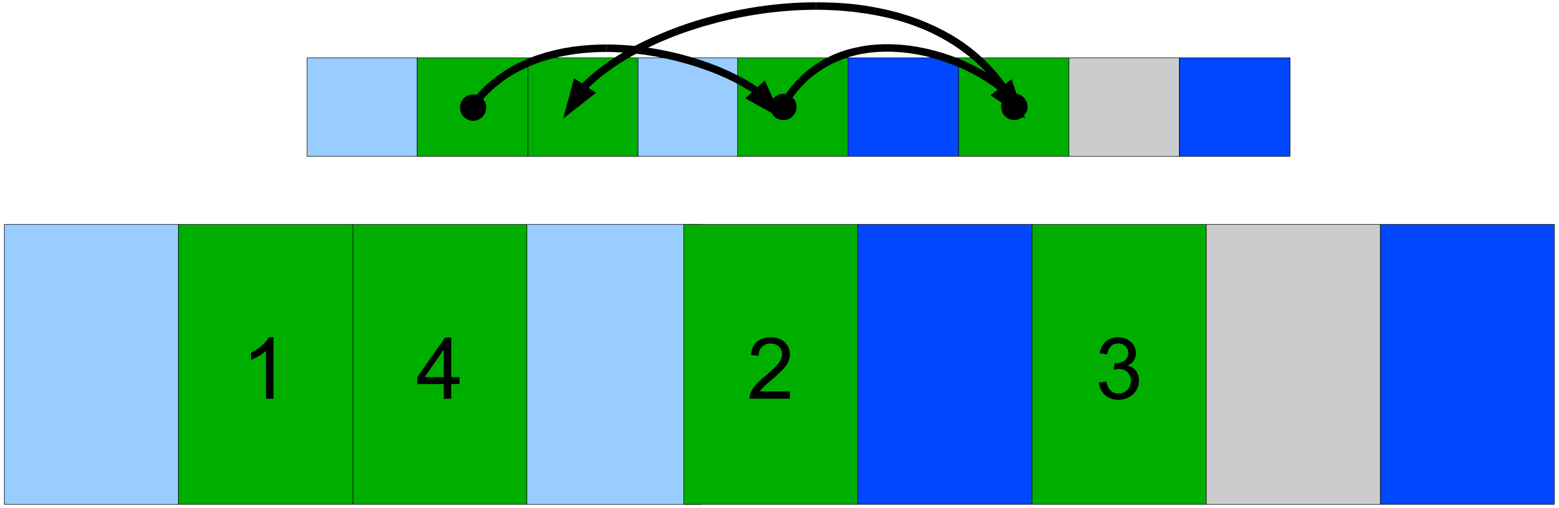
- Each block contains a pointer to the next block in the chain. Free blocks are also linked in a chain.
  - ✓ Only single metadata entry per file
  - ✓ Best for sequential files



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

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)

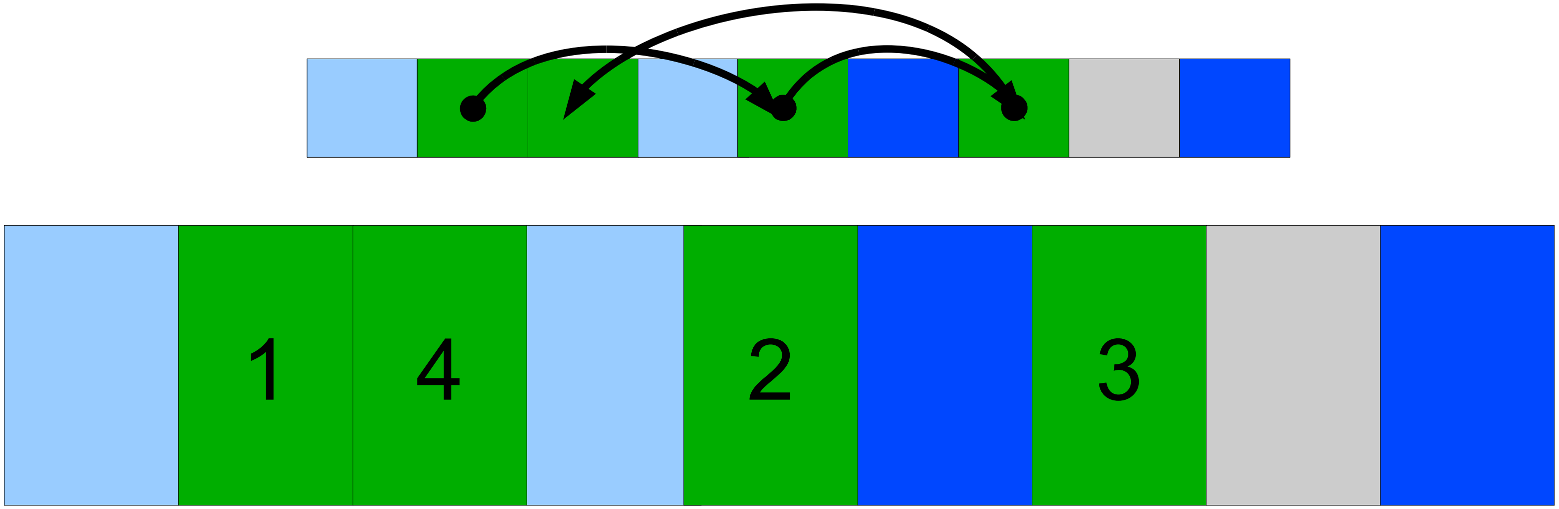


Question: any issues with this design?

File allocation table

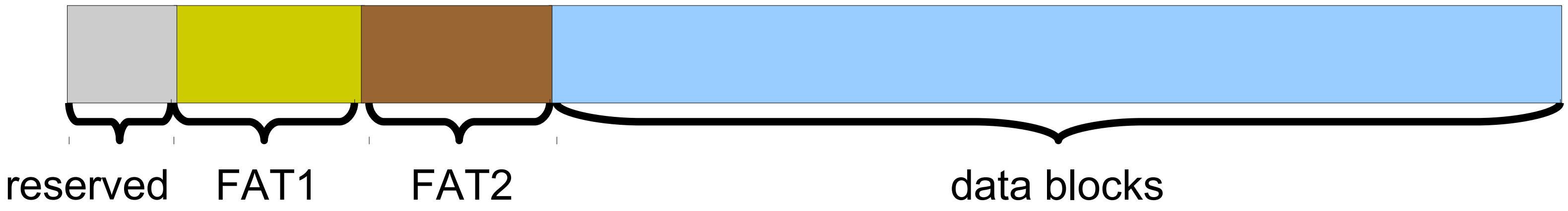
- Issues
  - Requires a lot of memory for large disks
    - 200GB = 200*10^6 * 1K-blocks ==>

      200*10^6 FAT entries = 800MB
  - Free block lookup is slow



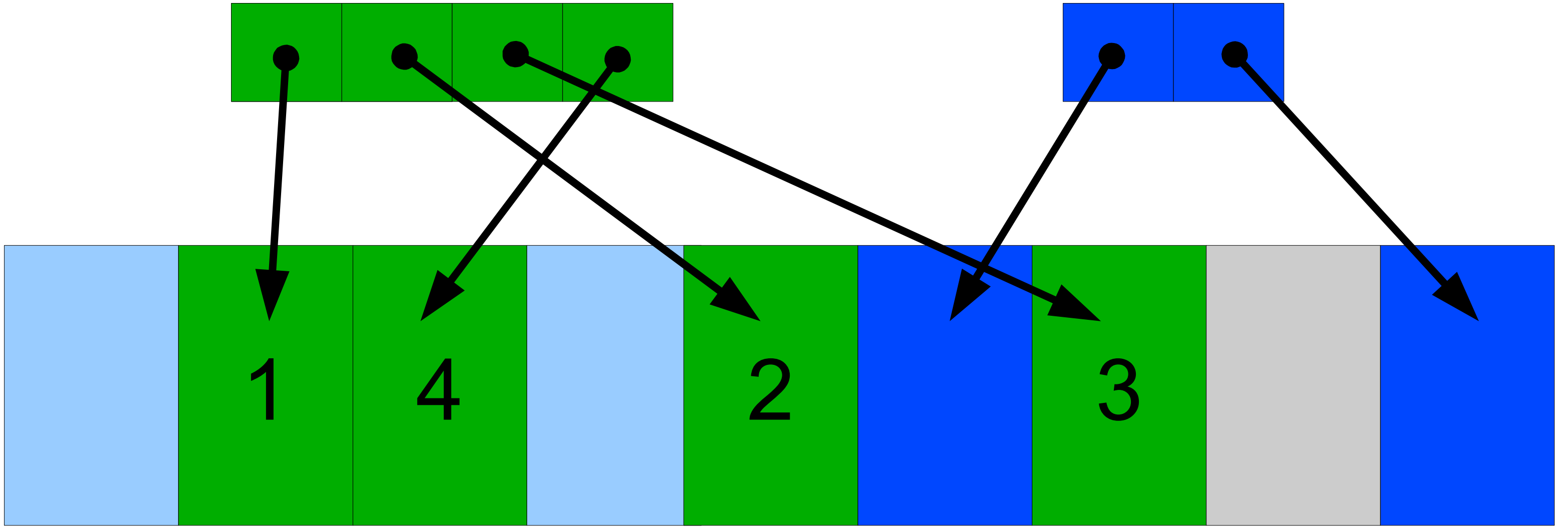
File allocation table

- Examples
  - FAT12, FAT16, FAT32



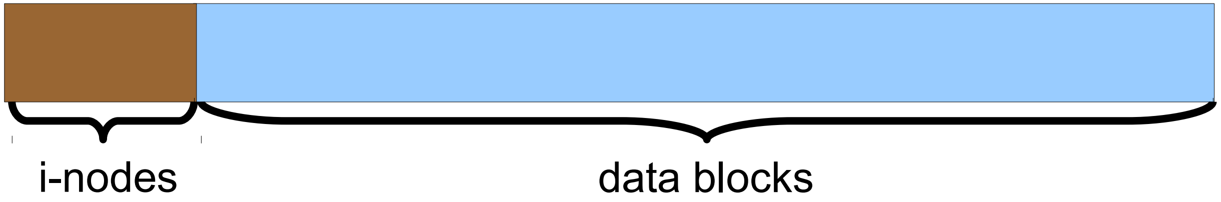
inode-based FS structure

- 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



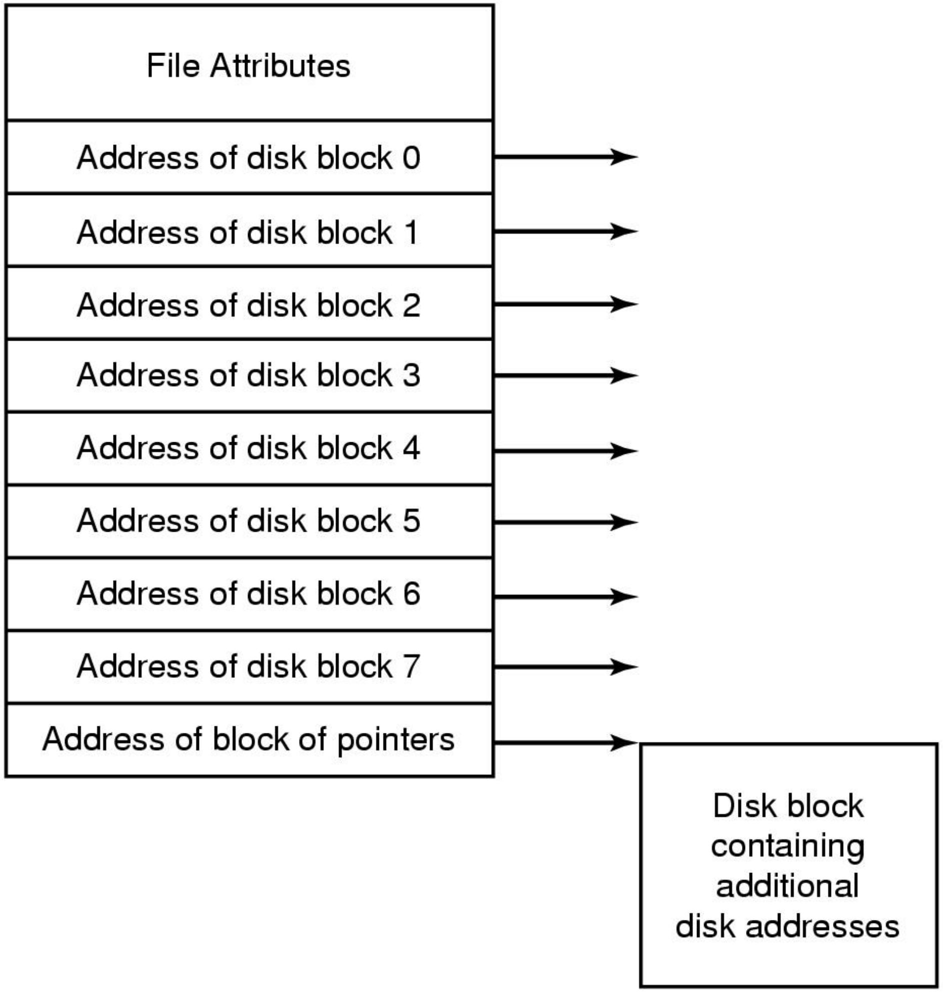
i-node implementation issues

- 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



File Attributes

Address of disk block 0

Address of disk block 1

Address of disk block 2

Address of disk block 3

Address of disk block 4

Address of disk block 5

Address of disk block 6

Address of disk block 7

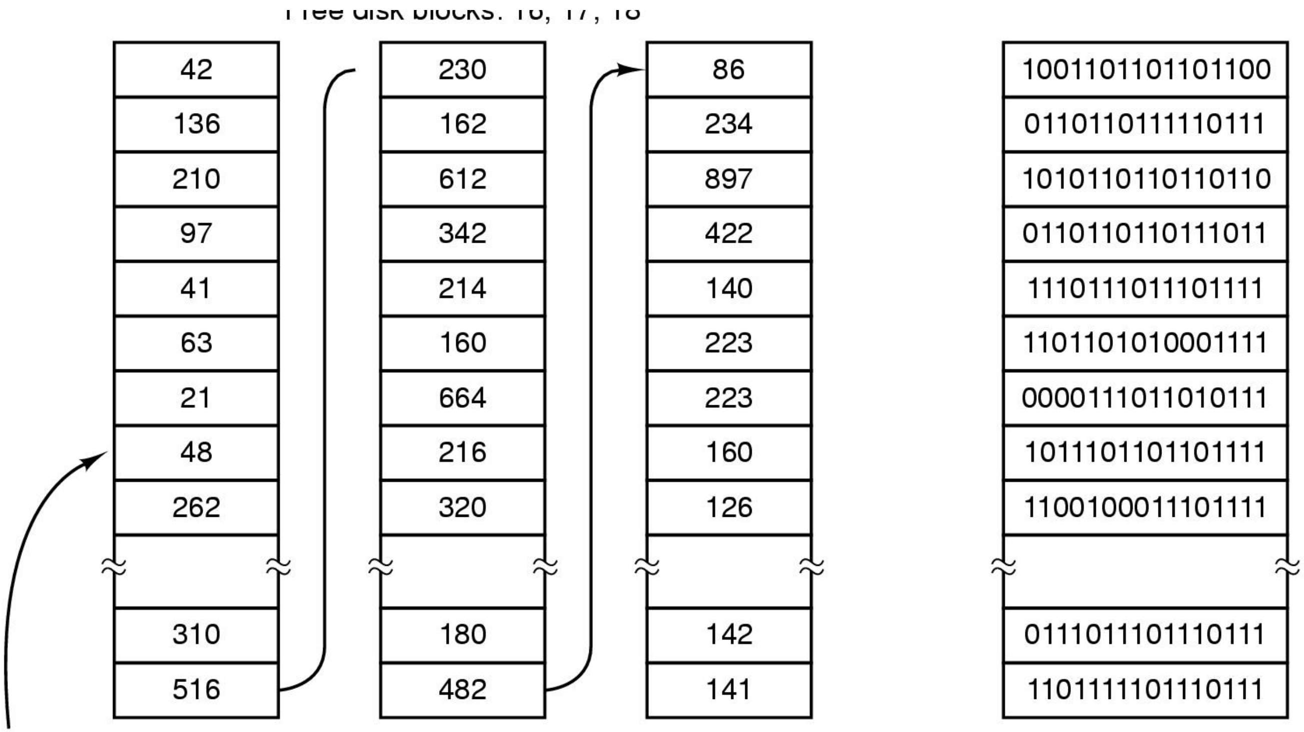
Address of block of pointers

Disk block containing additional disk addresses

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 disk blocks: 16, 17, 18



42	230	86	1001101101101100
136	162	234	0110110111110111
210	612	897	1010110110110110
97	342	422	0110110110111011
41	214	140	1110111011101111
63	160	223	1101101010001111
21	664	223	0000111011010111
48	216	160	1011101101101111
262	320	126	1100100011101111
≈	≈	≈	≈
310	180	142	0111011101110111
516	482	141	1101111101110111

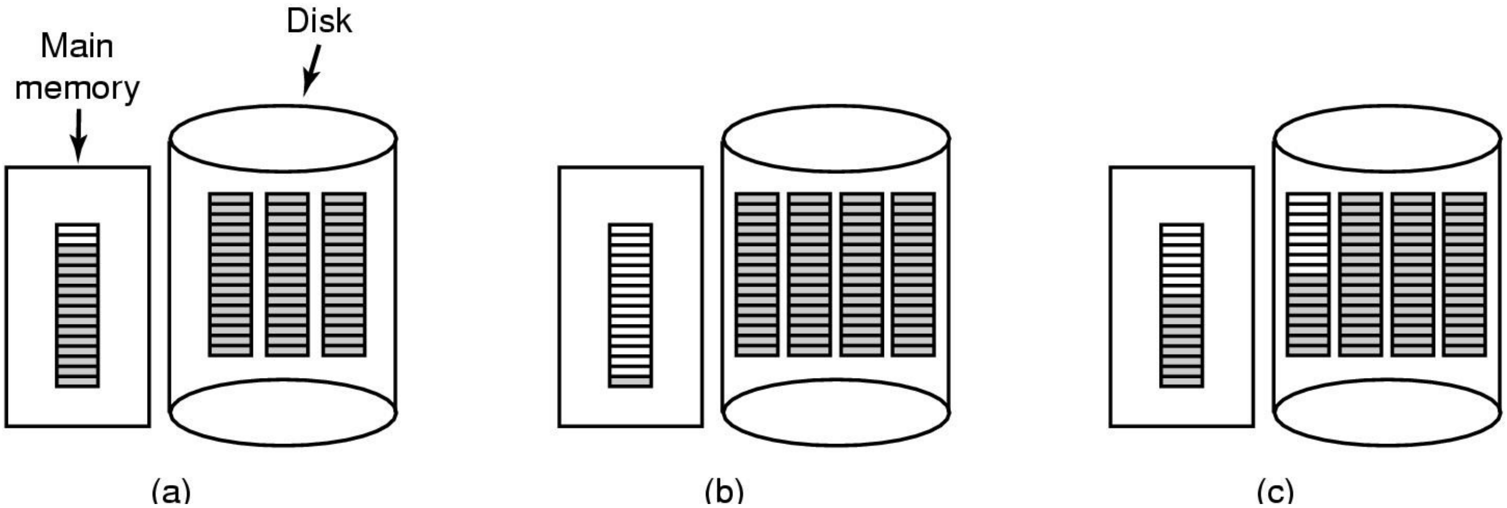
A 1-KB disk block can hold 256
32-bit disk block numbers

A bitmap

Free block list

- List of all unallocated blocks
- Background jobs can re-order list for better contiguity
- 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

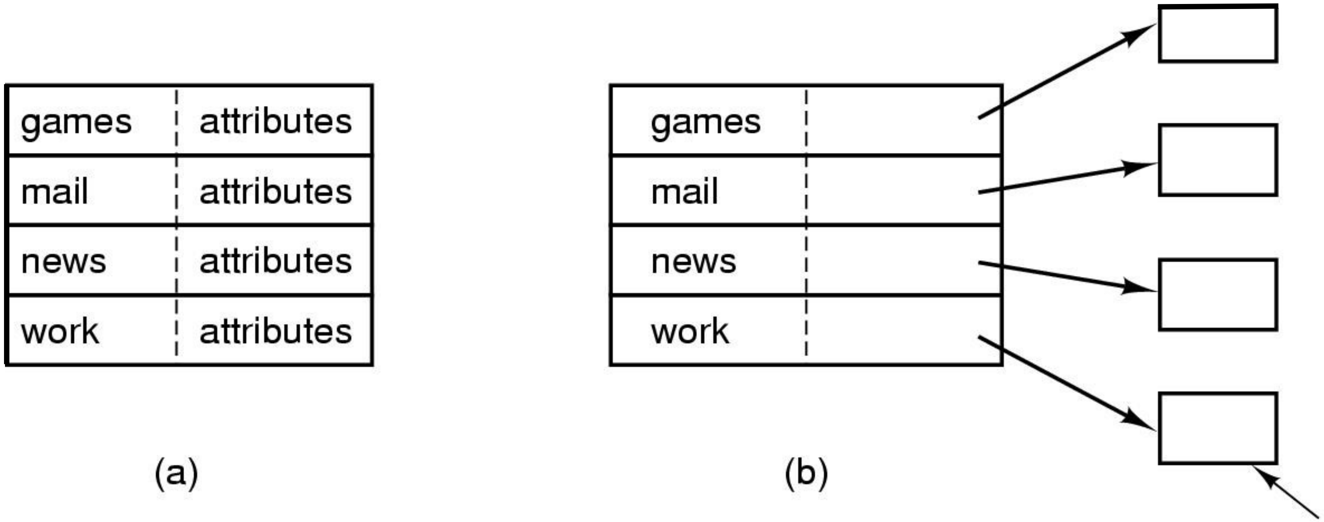
Fixed-size vs variable-size directory entries

- 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



Data structure containing the 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