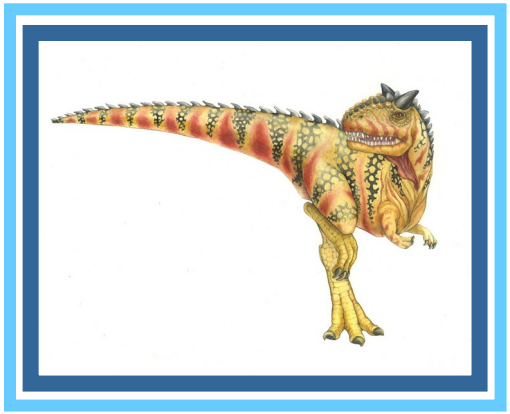
Chapter 11: File System Implementation

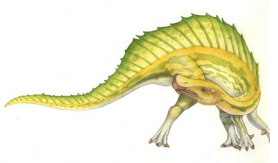


Outline

- File-System Structure
- File-System Operations
- Directory Implementation
- Allocation Methods
- Free-Space Management
- Efficiency and Performance
- Recovery
- Example: WAFL File System

Objectives

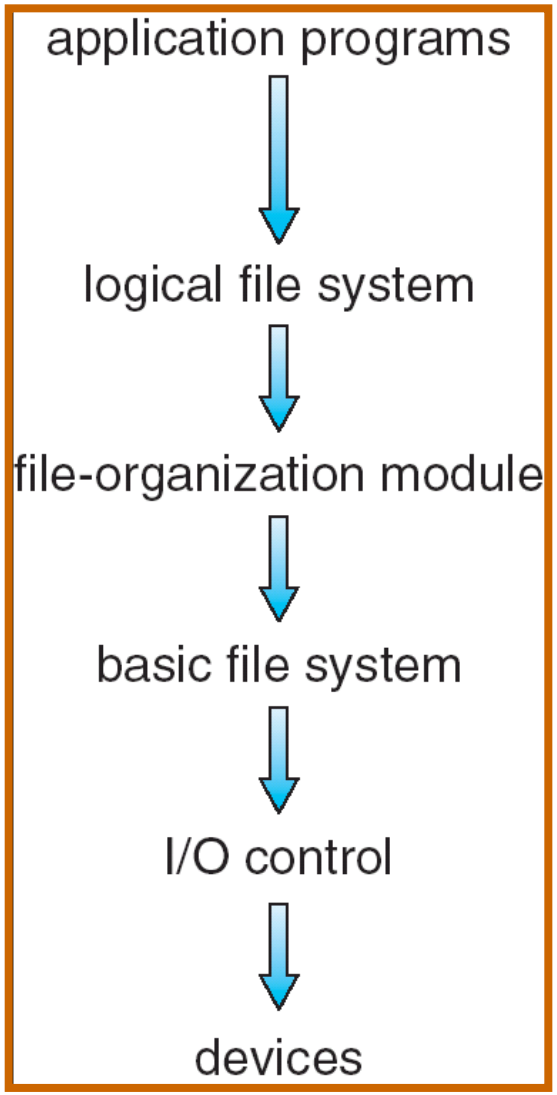
- Describe the details of implementing local file systems and directory structures
- Discuss block allocation and free-block algorithms and trade-offs
- Explore file system efficiency and performance issues
- Look at recovery from file system failures
- Describe the WAFL file system as a concrete example



File-System Structure

- File structure
  - Logical storage unit
  - Collection of related information
- **File system** resides on secondary storage (disks)
  - Provided user interface to storage, mapping logical to physical
  - Provides efficient and convenient access to disk by allowing data to be stored, located retrieved easily
- Disk provides in-place rewrite and random access
  - I/O transfers performed in **blocks** of **sectors** (usually 512 bytes)
- **File control block** (**FCB**) – storage structure consisting of information about a file
- **Device driver** controls the physical device
- File system organized into layers

Layered File System

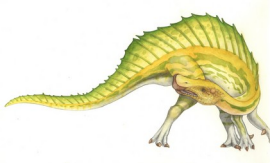


Metadata for files, directory structure,
FCB – File Control Block, which
Stores ownership, permission, location, …, etc.

Knows files, logical blocks and physical blocks

Issue Generic Commands

Device Drivers : Translator for hardware



File System Layers

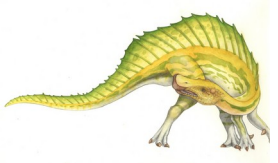
- **Device drivers** manage I/O devices at the I/O control layer
  - Given commands like
    - read drive1, cylinder 72, track 2, sector 10, into memory location 1060
  - Outputs low-level hardware specific commands to hardware controller
- **Basic file system** given command like “retrieve block 123” translates to device driver
- Also manages memory buffers and caches (allocation, freeing, replacement)
  - Buffers hold data in transit
  - Caches hold frequently used data
- **File organization module** understands files, logical address, and physical blocks
- Translates logical block # to physical block #
- Manages free space, disk allocation

File System Layers (Cont.)

- **Logical file system** manages metadata information
  - Translates file name into file number, file handle, location by maintaining file control blocks (**inodes** in UNIX)
  - Directory management
  - Protection
- Layering useful for reducing complexity and redundancy, but adds overhead and can decrease performance
- Logical layers can be implemented by any coding method according to OS designer
- Many file systems, sometimes many within an operating system
  - Each with its own format:
  - CD-ROM is ISO 9660;
  - Unix has **UFS**, FFS;
  - Windows has FAT, FAT32, NTFS as well as floppy, CD, DVD Blu-ray,
  - Linux has more than 130 types, with **extended file system** ext3 and ext4 leading; plus distributed file systems, etc.
  - New ones still arriving – ZFS, GoogleFS, Oracle ASM, FUSE

File-System Operations

- We have system calls at the API level, but how do we implement their functions?
  - On-disk and in-memory structures
- **Boot control block** contains info needed by system to boot OS from that volume
  - Needed if volume contains OS, usually first block of volume
- **Volume control block** (**superblock, master file table**) contains volume details
  - Total # of blocks, # of free blocks, block size, free block pointers or array
- Directory structure organizes the files
  - Names and inode numbers, master file table



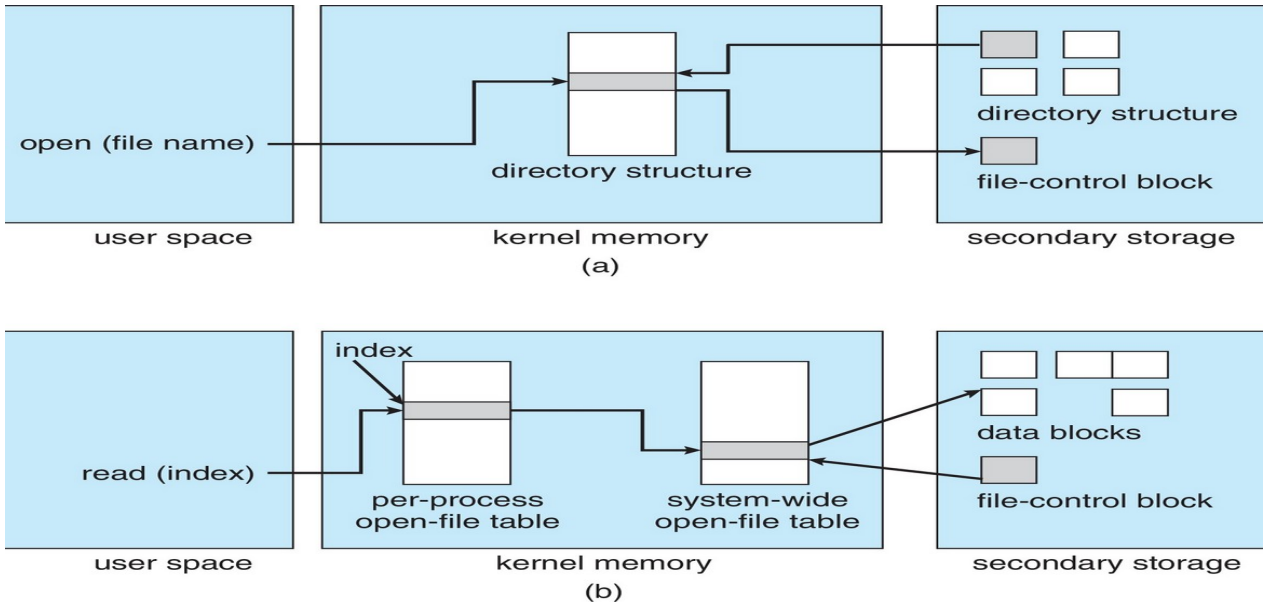
File Control Block (FCB)

- OS maintains **FCB** per file, which contains many details about the file
  - Typically, inode number, permissions, size, dates
  - Example

file permissions
file dates (create, access, write)
file owner, group, ACL
file size
file data blocks or pointers to file data blocks

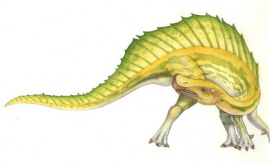
In-Memory File System Structures

- **Mount table** storing file system mounts, mount points, file system types
- **System-wide open-file table** contains a copy of the FCB of each file and other info
- **Per-process open-file table** contains pointers to appropriate entries in system-wide open-file table as well as other info



Directory Implementation

- **Linear list** of file names with pointer to the data blocks
  - Simple to program
  - Time-consuming to execute
    - Linear search time
    - Could keep ordered alphabetically via linked list or use B+ tree
- **Hash Table** – linear list with hash data structure
  - Decreases directory search time
  - **Collisions** – situations where two file names hash to the same location
  - Only good if entries are fixed size, or use chained-overflow method

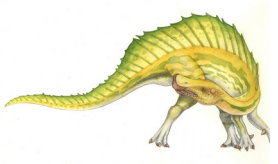


Allocation Methods

- An allocation method refers to how disk blocks are allocated for files.
- The main problem is how to allocate space to files so that disk space is utilized effectively and files can be accessed quickly.
- Three major methods:
  - Contiguous allocation
  - Linked allocation
  - Indexed allocation

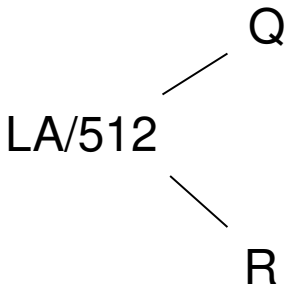
Contiguous Allocation Method

- An allocation method refers to how disk blocks are allocated for files:
- Each file occupies set of contiguous blocks
  - Best performance in most cases
  - Simple – only starting location (block #) and length (number of blocks) are required
  - Problems include:
    - Finding space on the disk for a file,
    - Knowing file size,
    - External fragmentation, need for **compaction off-line** (**downtime**) or **on-line**

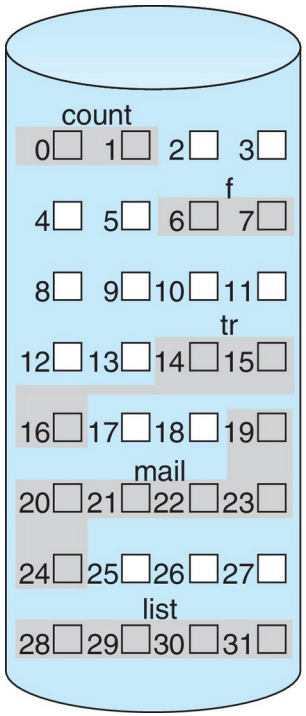


Contiguous Allocation (Cont.)

- Mapping from logical to physical (block size =512 bytes)



- Block to be accessed = starting address + Q
- Displacement into block = R



directory

file	start	length
count	0	2
tr	14	3
mail	19	6
list	28	4
f	6	2

Extent-Based Systems

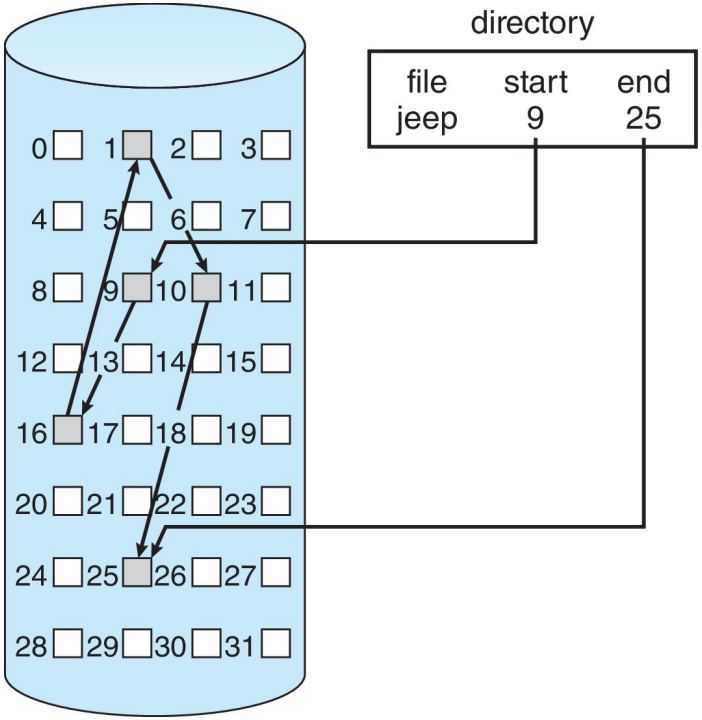
- Many newer file systems (i.e., Veritas File System) use a modified contiguous allocation scheme
- Extent-based file systems allocate disk blocks in extents
- An **extent** is a contiguous block of disks
  - Extents are allocated for file allocation
  - A file consists of one or more extents

Linked Allocation

- Each file is a linked list of blocks
- File ends at nil pointer
- No external fragmentation
- Each block contains pointer to next block
- No compaction, external fragmentation
- Free space management system called when new block needed
- Improve efficiency by clustering blocks into groups but increases internal fragmentation
- Reliability can be a problem
- Locating a block can take many I/Os and disk seeks

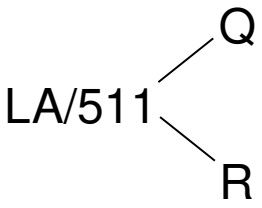
Linked Allocation Example

- Each file is a linked list of disk blocks: blocks may be scattered anywhere on the disk
- Scheme

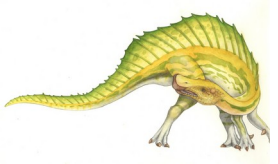


Linked Allocation (Cont.)

- Mapping

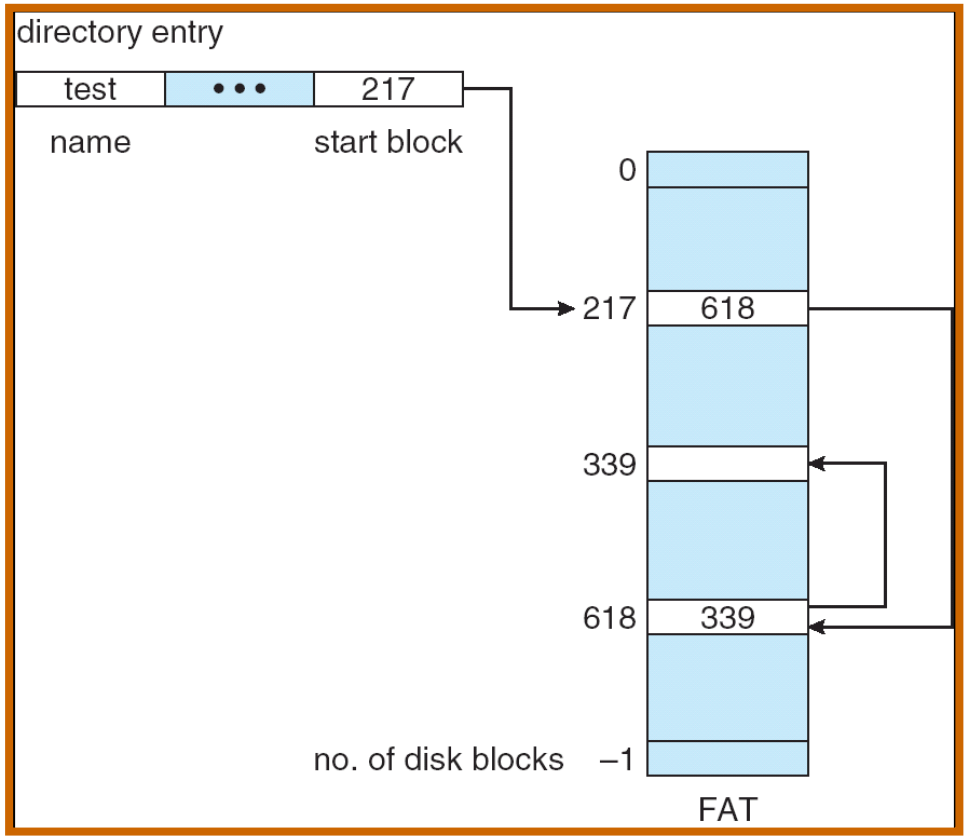


- Block to be accessed is the Q^{th} block in the linked chain of blocks representing the file.
- Displacement into block = R + 1



File-Allocation Table

- Beginning of volume has table, indexed by block number
- Much like a linked list, but faster on disk and cacheable
- New block allocation simple



MS File Allocation Table (FAT)

- Example :Using FAT allocation method

  File1 consist of 7, 15, 4, 6

  File3 consist of 10, 11, 8, 12, 5

Directory	
File 1	7
File 2	2
File 3	10
File 4	57

4	6
5	null
6	null
7	15
8	12
9	free
10	11
11	8
12	5
14	13
15	4

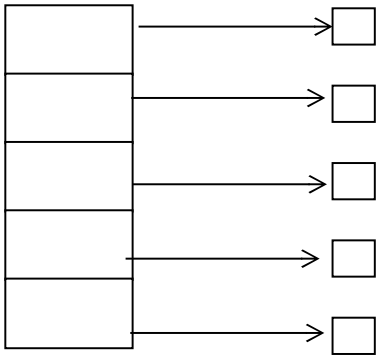
File Allocation Table (FAT)

Block No.	File Blocks
4	File1 Blk3
5	File3 Last
6	File1 Last
7	File1 Blk1
8	File3 Blk3
9	
10	File3 Blk1
11	File3 Blk2
12	File3 Blk4
13	
14	
15	File1 Blk2
16	
17	
…	

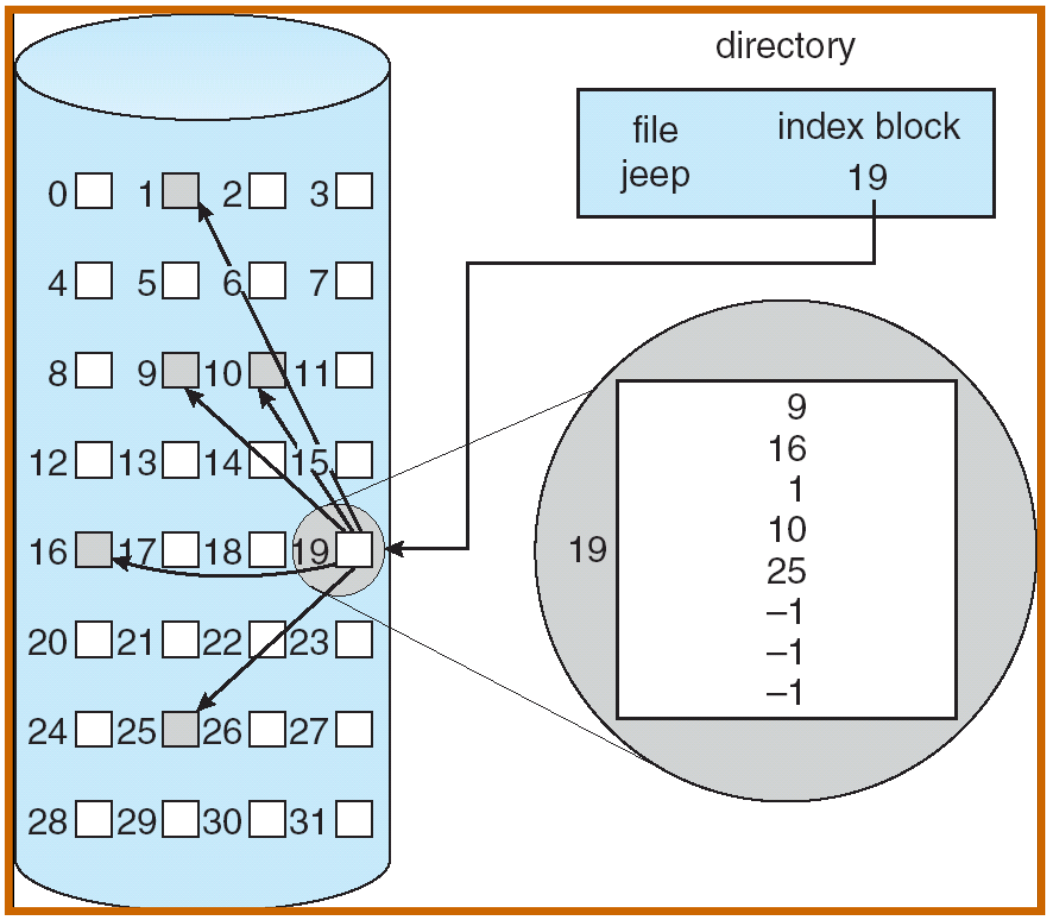
FAT16 – refers to 16 bit pointer used in FAT (Max. 65536 pointers for data blocks)

Indexed Allocation

- Brings all pointers together into the *index block.*
- Logical view.



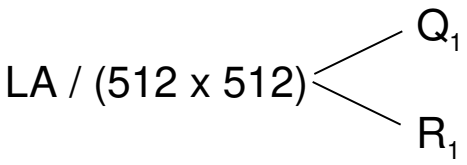
index table



Indexed Allocation (Cont.)

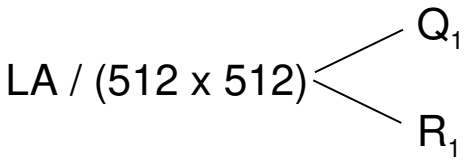
- Need index table
- Random access
- Dynamic access without external fragmentation, but have overhead of index block.
- Mapping from logical to physical in a file of maximum size of 256K words and block size of 512 words. We need only 1 block for index table.

Q = displacement into index table
R = displacement into block

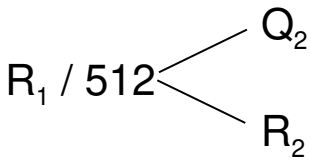


Indexed Allocation – Mapping (Cont.)

- Two-level index (maximum file size is 512^3)

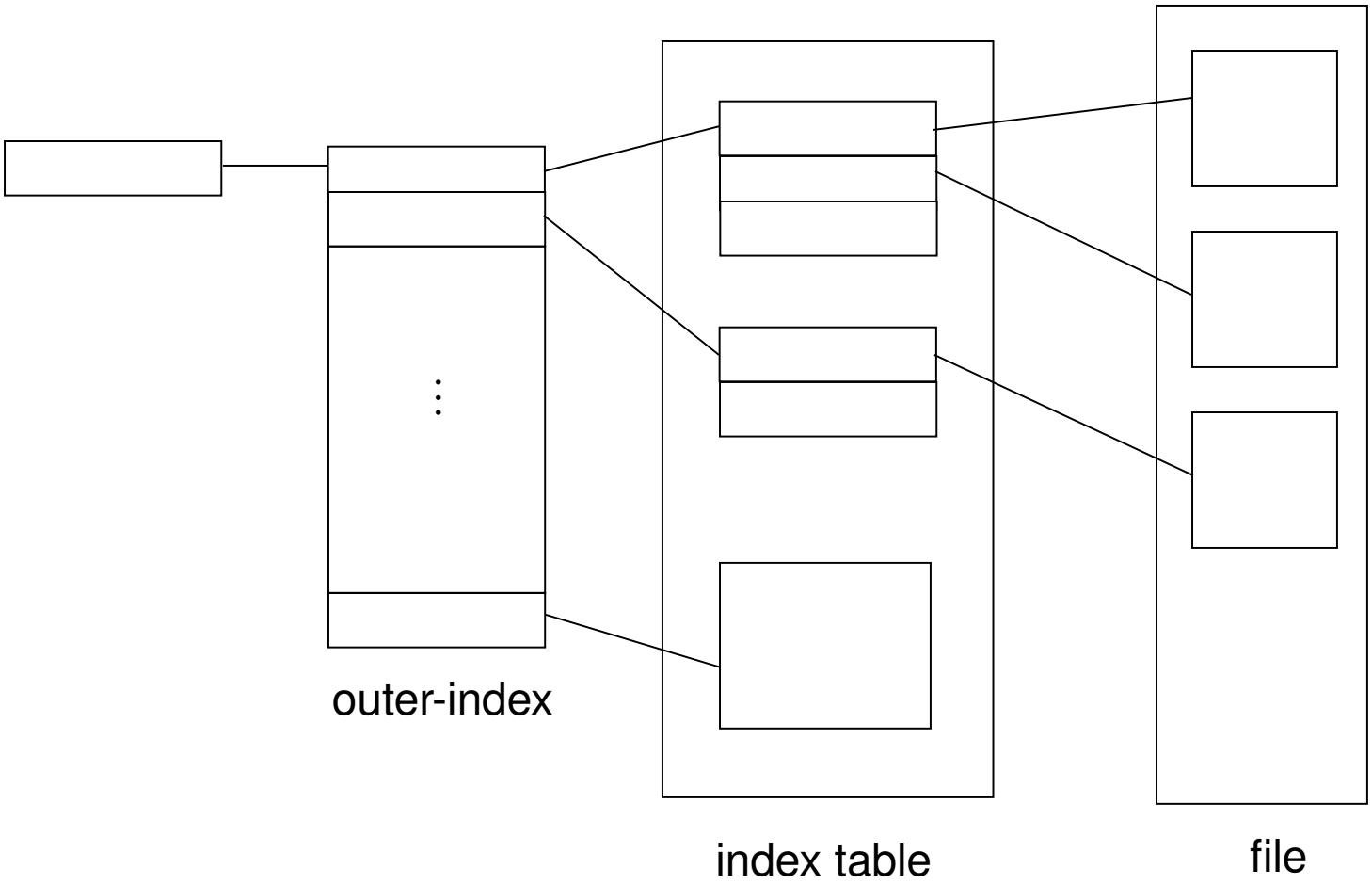


Q_1 = displacement into outer-index
R_1 is used as follows:



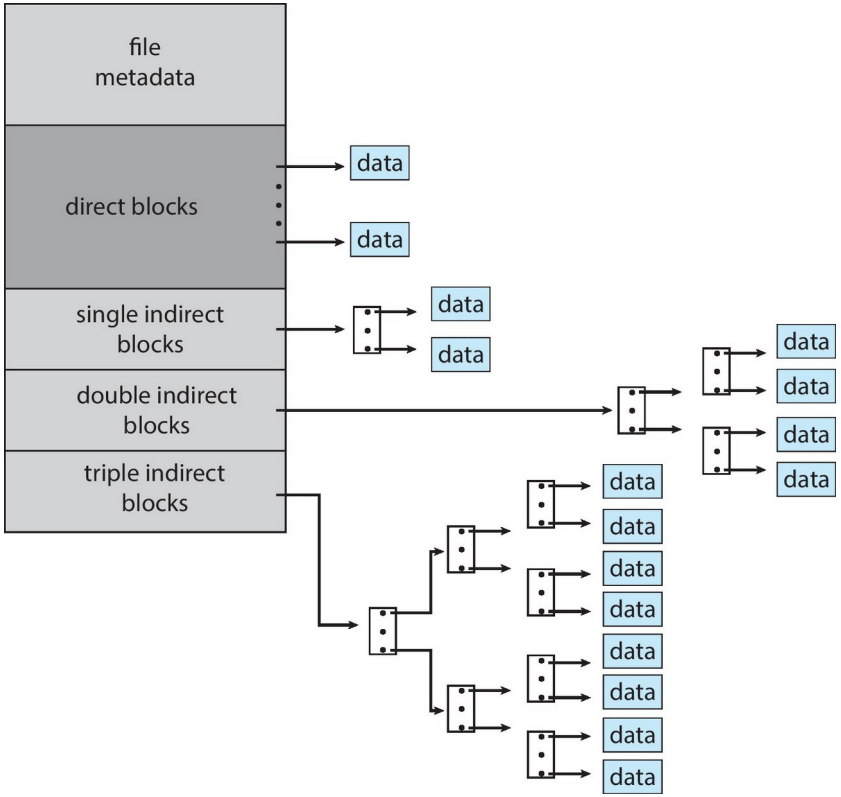
Q_2 = displacement into block of index table
R_2 displacement into block of file:

Indexed Allocation – Mapping (Cont.)



Combined Scheme : UNIX UFS

- 4K bytes per block, 32-bit addresses



- More index blocks than can be addressed with 32-bit file pointer

Performance

- Best method depends on file access type
  - Contiguous great for sequential and random
- Linked good for sequential, not random
- Declare access type at creation
  - Select either contiguous or linked
- Indexed more complex
  - Single block access could require 2 index block reads then data block read
  - Clustering can help improve throughput, reduce CPU overhead
- For NVM, no disk head so different algorithms and optimizations needed
  - Using old algorithm uses many CPU cycles trying to avoid non-existent head movement
  - Goal is to reduce CPU cycles and overall path needed for I/O

Free-Space Management

- File system maintains **free-space list** to track available blocks
- **Bit vector** or **bit map** (***n*** blocks)

- Bit map requires extra space
  - Example:

    block size = 4KB = 2^{12} bytes

    disk size = 2^{40} bytes (1 terabyte)

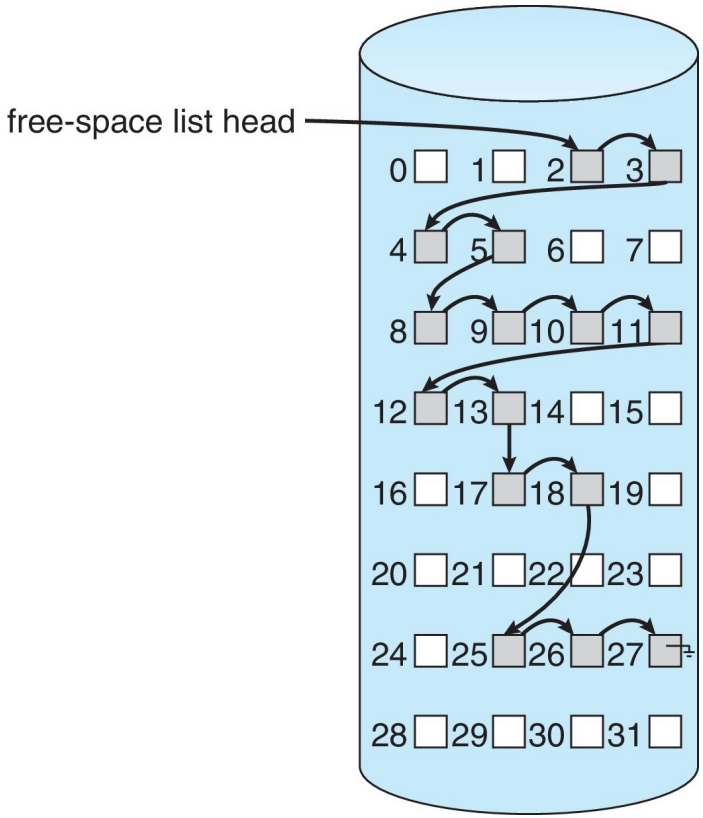
    n = $2^{40}/2^{12} = 2^{28}$ bits (or 32MB)

    if clusters of 4 blocks -> 8MB of memory

- Easy to get contiguous files

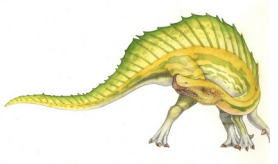
Linked Free Space List on Disk

- Linked list (free list)
  - Cannot get contiguous space easily
  - No waste. Linked Free Space List on Disk of space
  - No need to traverse the entire list (if # free blocks recorded)



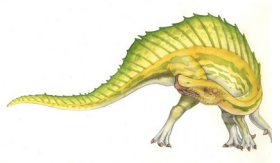
Free-Space Management (Cont.)

- Grouping
  - Modify linked list to store address of next *n-1* free blocks in first free block, plus a pointer to next block that contains free-block-pointers (like this one)
- Counting
  - Because space is frequently contiguously used and freed, with contiguous-allocation allocation, extents, or clustering
    - Keep address of first free block and count of following free blocks
    - Free space list then has entries containing addresses and counts



Free-Space Management (Cont.)

- Space Maps
  - Used in **ZFS**
  - Consider meta-data I/O on very large file systems
    - Full data structures like bit maps cannot fit in memory ➔ thousands of I/Os
  - Divides device space into **metaslab** units and manages metaslabs
    - Given volume can contain hundreds of metaslabs
  - Each metaslab has associated space map
    - Uses counting algorithm
  - But records to log file rather than file system
    - Log of all block activity, in time order, in counting format
  - Metaslab activity ➔ load space map into memory in balanced-tree structure, indexed by offset
    - Replay log into that structure
    - Combine contiguous free blocks into single entry

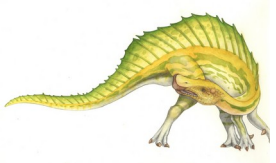


TRIMing Unused Blocks

- HDDS overwrite in place so need only free list
- Blocks not treated specially when freed
  - Keeps its data but without any file pointers to it, until overwritten
- Storage devices not allowing overwrite (like NVM) suffer badly with same algorithm
  - Must be erased before written, erases made in large chunks (blocks, composed of pages) and are slow
  - TRIM is a newer mechanism for the file system to inform the NVM storage device that a page is free
    - Can be garbage collected or if block is free, now block can be erased

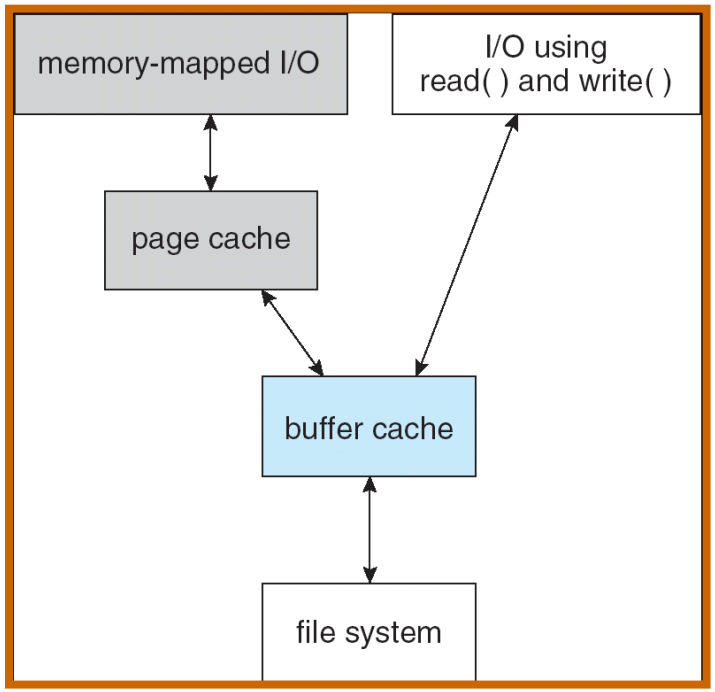
Efficiency and Performance

- Efficiency dependent on:
  - Disk allocation and directory algorithms
  - Types of data kept in file's directory entry
  - Pre-allocation or as-needed allocation of metadata structures
  - Fixed-size or varying-size data structures
- Performance
  - Keeping data and metadata close together
  - **Buffer cache** – separate section of main memory for frequently used blocks
  - **Synchronous** writes sometimes requested by apps or needed by OS
    - No buffering / caching – writes must hit disk before acknowledgement
    - **Asynchronous** writes more common, buffer-able, faster
  - **Free-behind** and **read-ahead** – techniques to optimize sequential access
  - Reads frequently slower than writes



Page Cache

- A **page cache** caches pages rather than disk blocks using virtual memory techniques
- Memory-mapped I/O uses a page cache
- Routine I/O through the file system uses the buffer (disk) cache
- This leads to the following figure

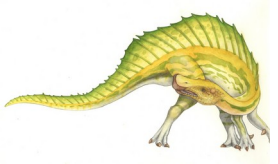


Recovery

- **Consistency checking** – compares data in directory structure with data blocks on disk, and tries to fix inconsistencies
  - Can be slow and sometimes fails
- Use system programs to **back up** data from disk to another storage device (magnetic tape, other magnetic disk, optical)
- Recover lost file or disk by **restoring** data from backup

Log Structured File Systems

- **Log structured** (or **journaling**) file systems record each metadata update to the file system as a **transaction**
- All transactions are written to a log
  - A transaction is considered committed once it is written to the log (sequentially)
  - Sometimes to a separate device or section of disk
  - However, the file system may not yet be updated
- The transactions in the log are asynchronously written to the file system structures
  - When the file system structures are modified, the transaction is removed from the log
- If the file system crashes, all remaining transactions in the log must still be performed
- Faster recovery from crash, removes chance of inconsistency of metadata

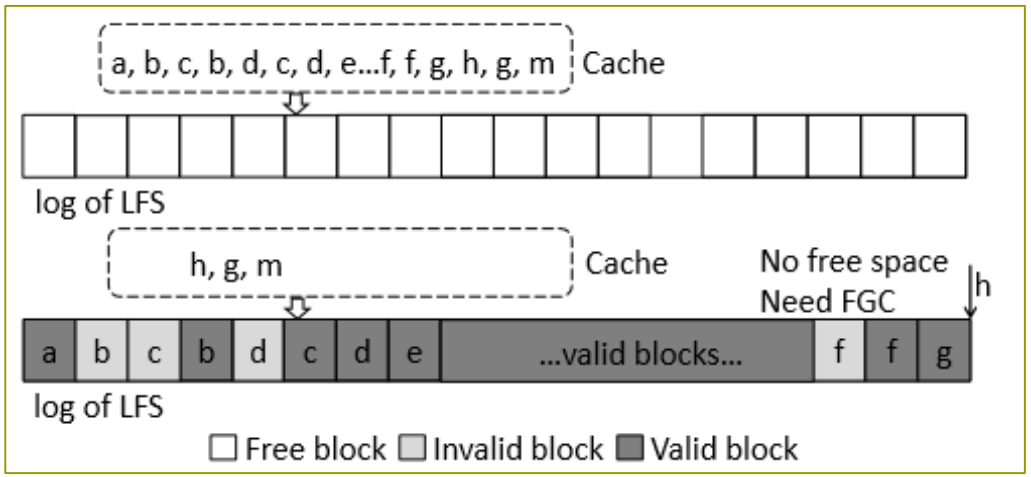


Example: Flash Friendly File System (F2FS)

- Used on Mobile devices– log-structured file system

Mobile devices employing F2FS	Announced time
Huawei P20	2018
Huawei P10	2017
Huawei Mate9	2016
Huawei P9	2016
Huawei Honor 8/V8	2016
Oneplus 3T	2016
Moto Z family	2016/2017/2018
Moto E LTE	2015
Google Nexus9	2014
Moto X family	2013/2014/2015
Moto G family	2013/2014
Motorola Droid family	2013
Moto MSM8960 JBBL devices	2012

- Allocation: append-only logging, out-of-place update, and GC

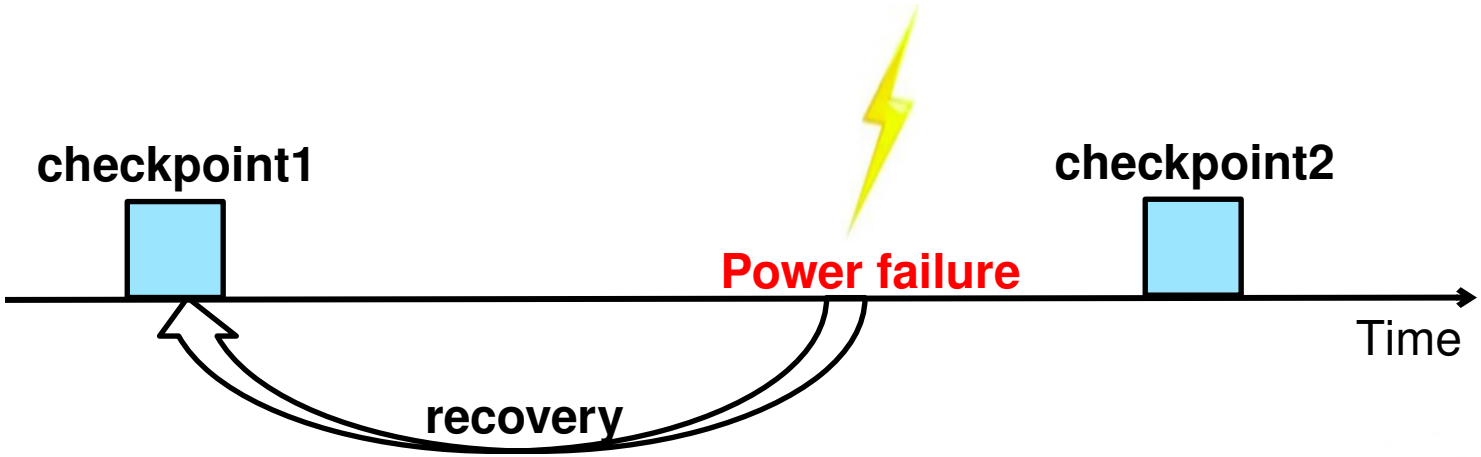


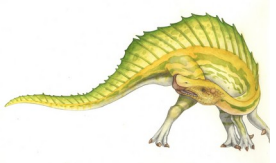
Checkpoint in F2FS

- Checkpoint companies with recovery to guarantee the consistency

Trigger Condition	Description
f2fs_gc	Foreground FGC calls checkpoint.
f2fs_sync_fs	Syncing files calls checkpoint.
recovery_fsync_data	Recovery data.
f2fs_put_super	Shutting down calls checkpoint.
f2fs_ioc_checkpoint	User calls checkpoint.
f2fs_trim_fs	Trim operations call checkpoint.
Periodically checkpoint	Default interval is 60s.

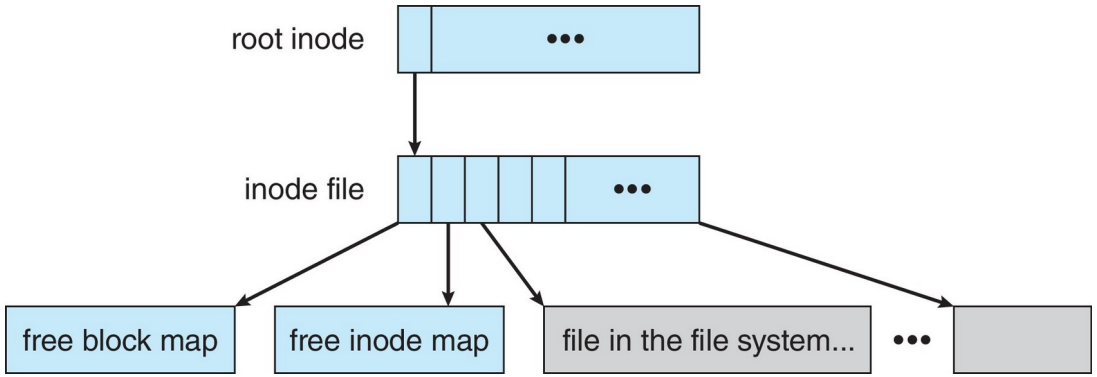
- Flush metadata, dirty data and checkpoint package



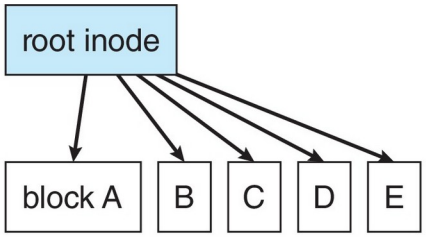


Example: WAFL File System

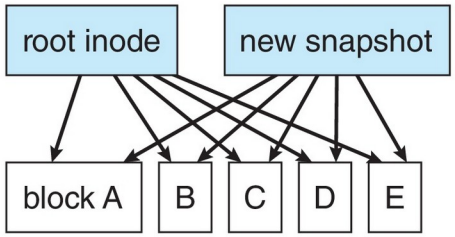
- Used on Network Appliance “Filers” – distributed file system appliances
- “Write-anywhere file layout”
- Serves up NFS, CIFS, http, ftp
- Random I/O optimized, write optimized
  - NVRAM for write caching
- Similar to Berkeley Fast File System, with extensive modifications



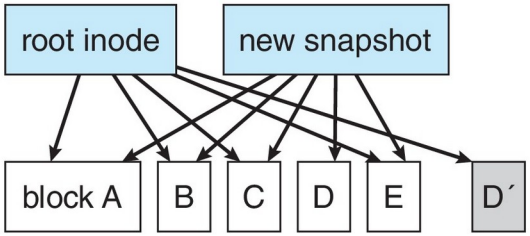
Snapshots in WAFL



(a) Before a snapshot.



(b) After a snapshot, before any blocks change.



(c) After block D has changed to D´.

The Apple File System

In 2017, Apple, Inc., released a new file system to replace its 30-year-old HFS+ file system. HFS+ had been stretched to add many new features, but as usual, this process added complexity, along with lines of code, and made adding more features more difficult. Starting from scratch on a blank page allows a design to start with current technologies and methodologies and provide the exact set of features needed.

Apple File System (**APFS**) is a good example of such a design. Its goal is to run on all current Apple devices, from the Apple Watch through the iPhone to the Mac computers. Creating a file system that works in watchOS, I/Os, tvOS, and macOS is certainly a challenge. APFS is feature-rich, including 64-bit pointers, clones for files and directories, snapshots, space sharing, fast directory sizing, atomic safe-save primitives, copy-on-write design, encryption (single- and multi-key), and I/O coalescing. It understands NVM as well as HDD storage.

Most of these features we've discussed, but there are a few new concepts worth exploring. **Space sharing** is a ZFS-like feature in which storage is available as one or more large free spaces (**containers**) from which file systems can draw allocations (allowing APFS-formatted volumes to grow and shrink). **Fast directory sizing** provides quick used-space calculation and updating. **Atomic safe-save** is a primitive (available via API, not via file-system commands) that performs renames of files, bundles of files, and directories as single atomic operations. I/O coalescing is an optimization for NVM devices in which several small writes are gathered together into a large write to optimize write performance.

Apple chose not to implement RAID as part of the new APFS, instead depending on the existing Apple RAID volume mechanism for software RAID. APFS is also compatible with HFS+, allowing easy conversion for existing deployments.