CISC 3320
C29b File System Implementation

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Acknowledgement

- These slides are a revision of the slides provided by the authors of the textbook via the publisher of the textbook

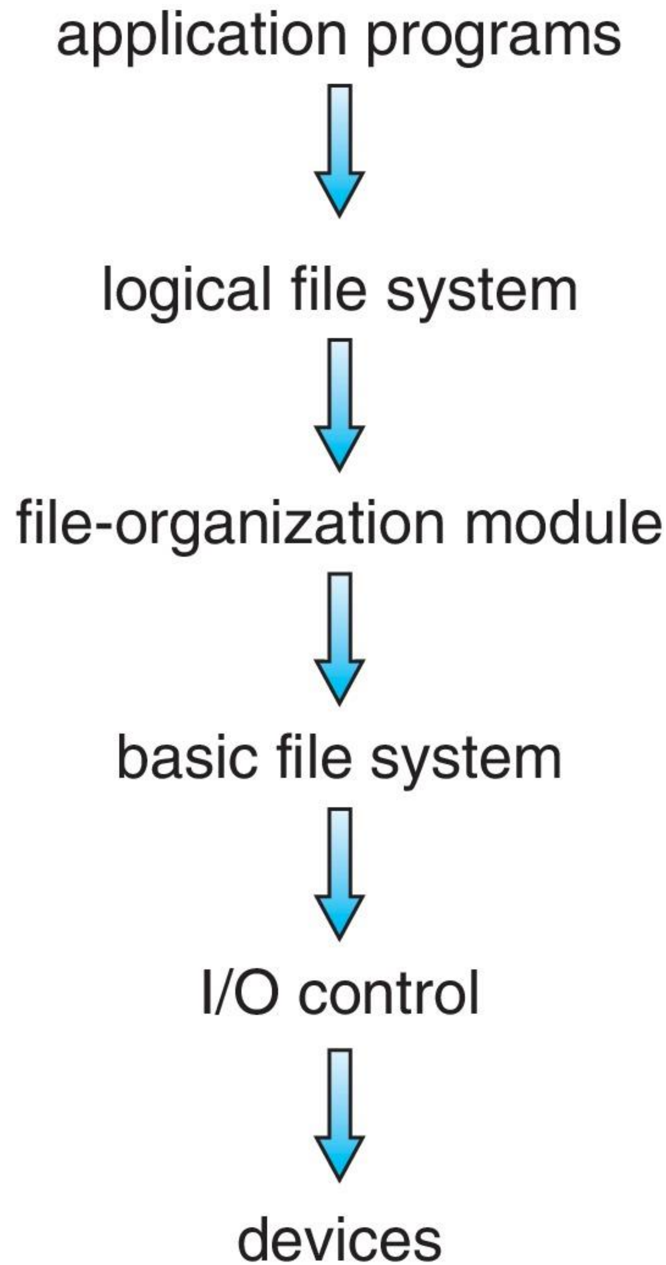
Outline

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

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

File-System Layers



File System Layers: Device Drivers

- **Device drivers** manage I/O devices at the I/O control layer
  - Outputs low-level hardware specific commands to hardware controller
  - Example:
    - Given commands like "read drive1, cylinder 72, track 2, sector 10, into memory location 1060" (CHS addressing) or "read drive1, block 1442, into memory location 1060" (LBA)

File System Layers: Basic File System

- **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 System Layers: File Organization Module

- **File organization module** understands files, logical address, and physical blocks
  - Translates logical block # to physical block #
  - Manages free space, disk allocation

File System Layers: Logical File System

- **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

File System Layers: Benefits and Overhead

- Layering useful for reducing complexity and redundancy
  - Duplication of code is minimized.
    - The I/O control and sometimes the basic file-system code can be used by multiple file systems.
    - Each file system can then have its own logical file-system and file-organization modules.
- But layering adds overhead and can decrease performance

File Systems: Examples

- Many file systems, sometimes many within an operating system
    - Each with its own format, e.g.,
        - 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

Questions?

- File system structure and layering

File-System Operations

- On-disk and in-memory structures
  - We have system calls at the API level, but how do we implement their functions?
- **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-System Operations: Control Blocks

- **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

File-System Operations: Directory Structures

- Directory structure organizes the files
  - Names and File Control Block (e.g., inode) numbers, master file table

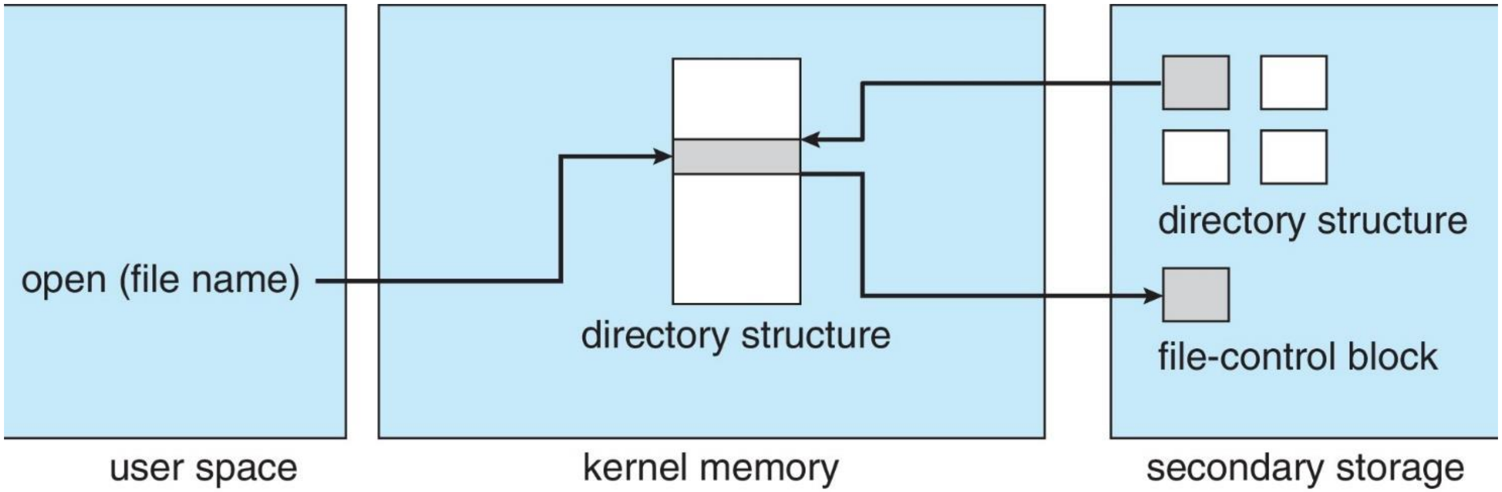
File-System Operations: Per-File File Control Block

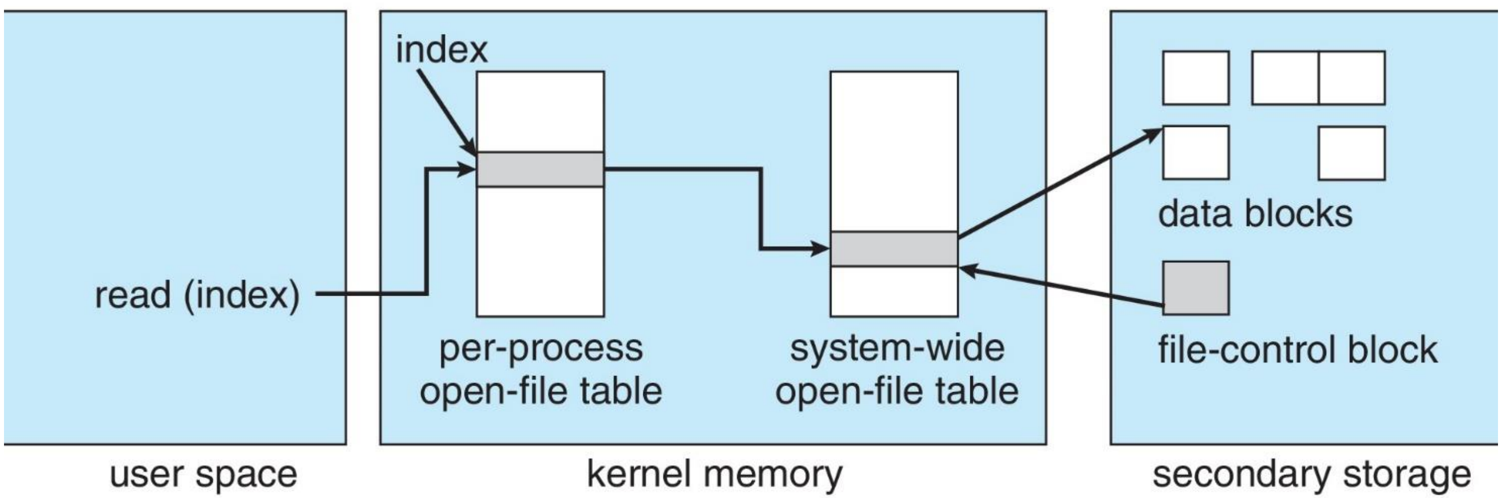
- Per-file **File Control Block** (**FCB**) contains many details about the file
  - typically inode number, permissions, size, dates
  - NFTS stores into in master file table using relational DB structures

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
  - Examples: (a) opening file;(b) reading a file
  - buffers hold data blocks from secondary storage
  - Open returns a file handle for subsequent use
  - Data from read eventually copied to specified user process memory address


open (file name)
directory structure
directory structure
file-control block
user space
kernel memory
secondary storage
(a)


index
read (index)
per-process
open-file table
system-wide
open-file table
data blocks
file-control block
user space
kernel memory
secondary storage
(b)

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

Questions?

- File system operations and supporting data structures
  - On-disk structures
  - In-memory structures
- Directory implementation

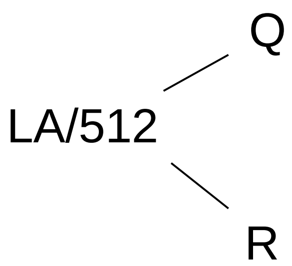
Allocation Methods

- Continuous allocation
- Linked allocation
- Indexed allocation
- Combined scheme

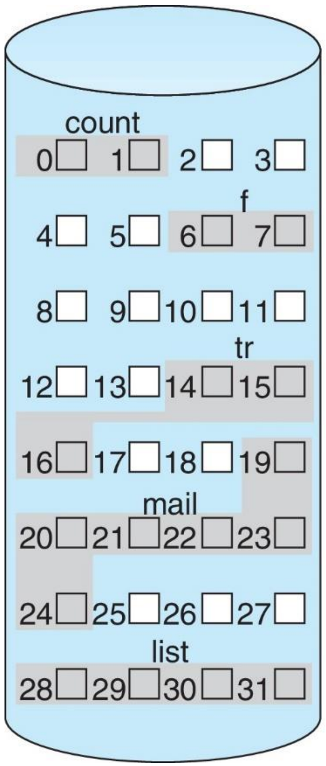
Allocation Methods: Contiguous

- An allocation method refers to how disk blocks are allocated for files:
- **Contiguous allocation** – 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 for file, knowing file size, external fragmentation, need for **compaction off-line** (**downtime**) or **on-line**

- Mapping from logical to physical



Block to be accessed = Q + starting address
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

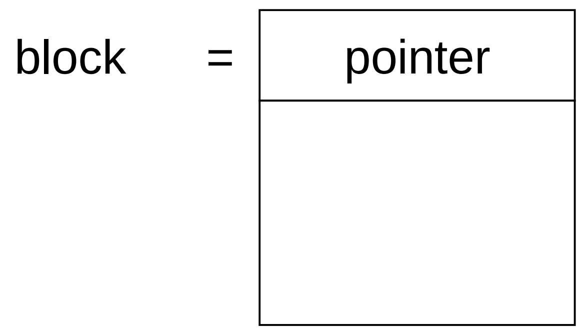
- A modified contiguous allocation scheme used in many newer file systems (e.g., Veritas File System)
- Extent-based file systems allocate disk blocks in extents
- An **extent** is a contiguous block of disks
  - Extents are allocated for file allocation
  - A file consists of one or more extents

Allocation Methods - Linked

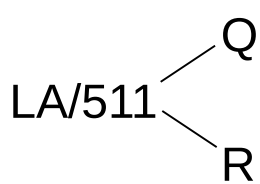
- **Linked allocation** – each file a linked list of blocks
  - File ends at nil pointer
  - No external fragmentation
  - Each block contains pointer to next block
  - No compaction, external fragmentation
  - Free space management system called when new block needed
  - Improve efficiency by clustering 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

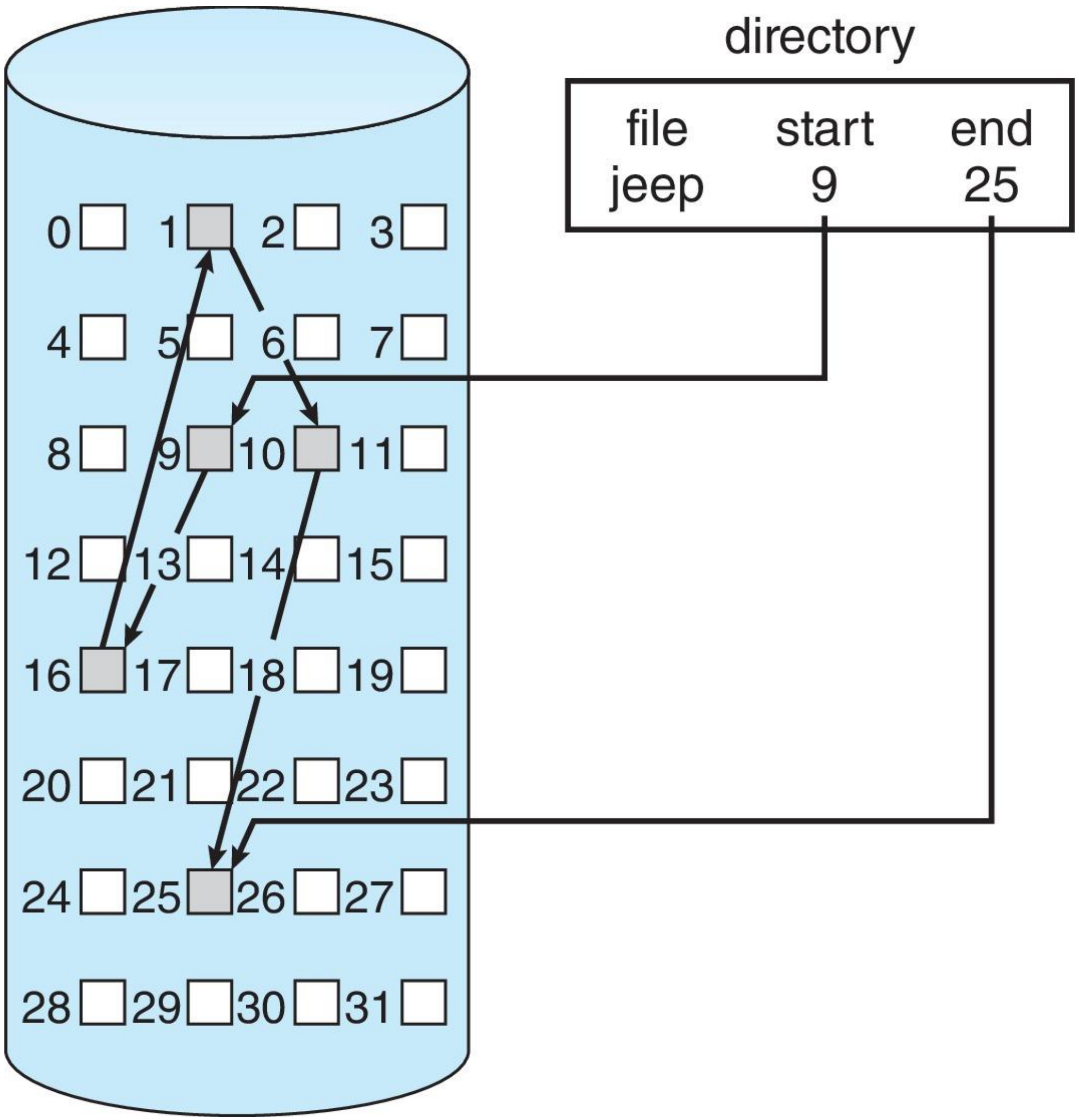
- Each file is a linked list of disk blocks: blocks may be scattered anywhere on the disk



- Mapping



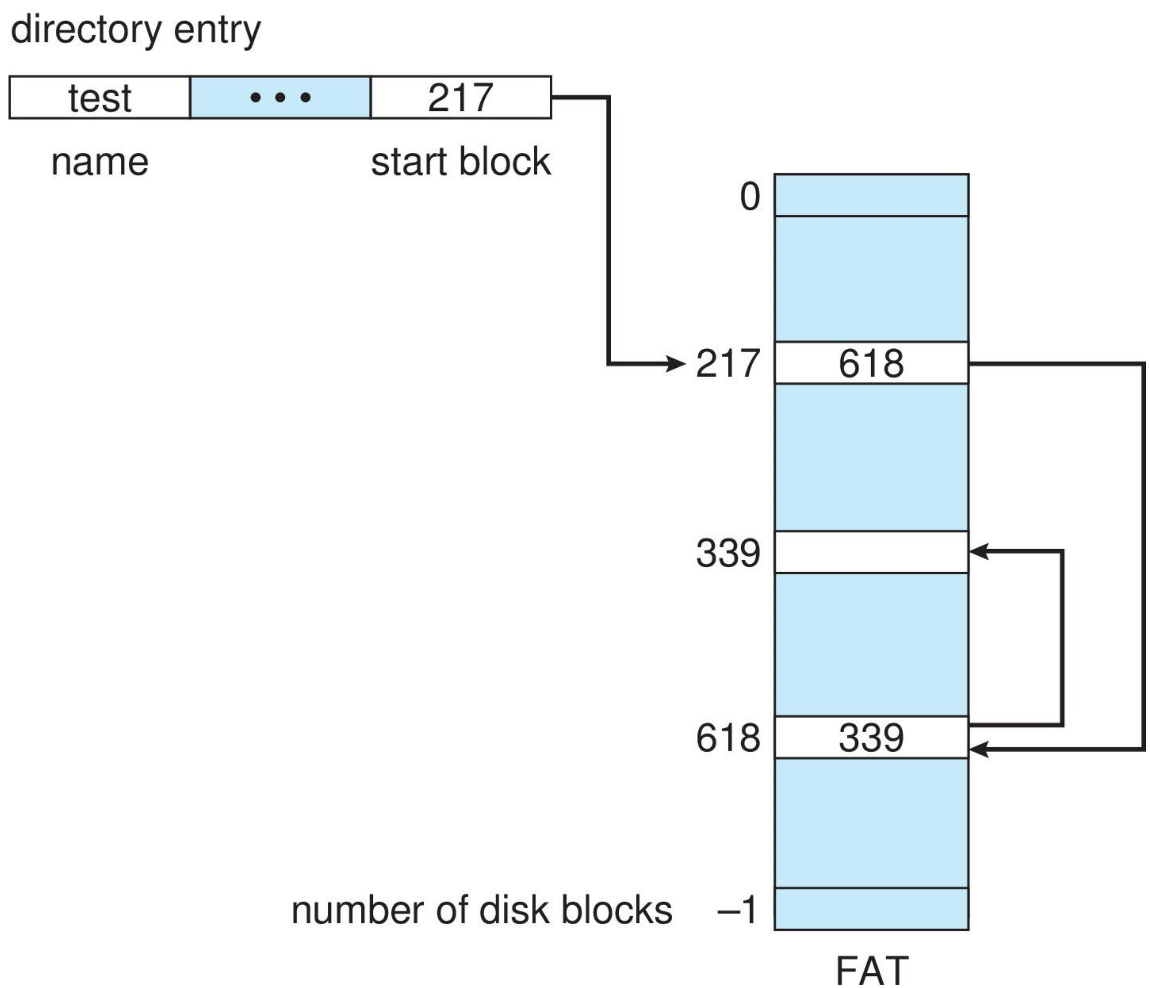
- Block to be accessed is the Qth block in the linked chain of blocks representing the file.
  - Displacement into block = R + 1


directory
file start end
jeep 9 25
0 1 2 3
4 5 6 7
8 9 10 11
12 13 14 15
16 17 18 19
20 21 22 23
24 25 26 27
28 29 30 31

FAT Variation

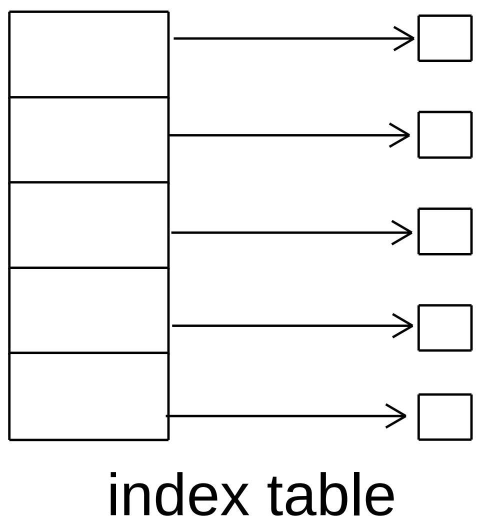
- FAT (File Allocation Table) variation
  - Much like a linked list, but faster on disk and cacheable
  - Beginning of volume has table, indexed by block number
  - New block allocation simple

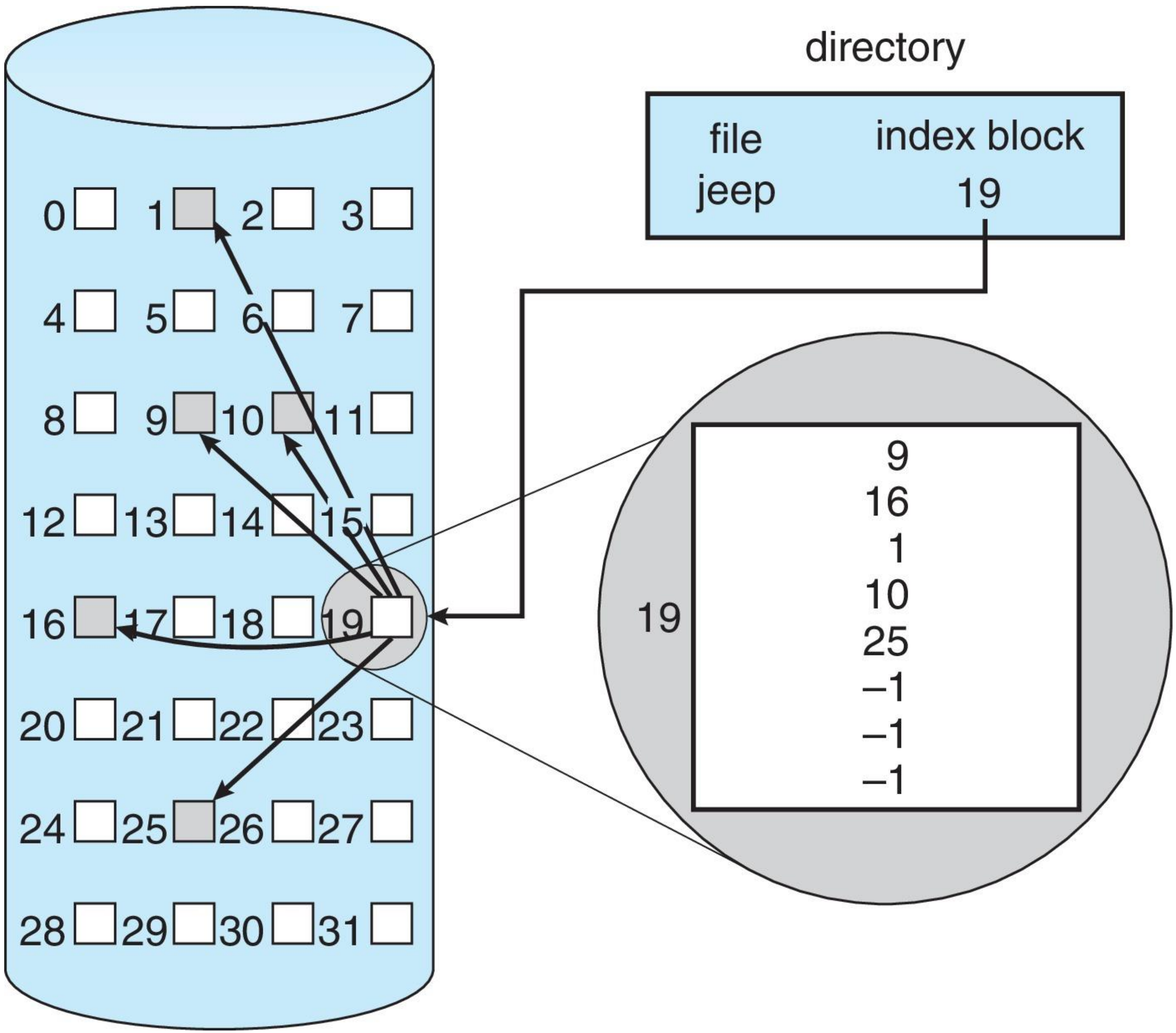
File-Allocation Table



Allocation Methods - Indexed

- **Indexed allocation**
  - Each file has its own **index block**(s) of pointers to its data blocks
  - Logical view




directory
file
index block
jeep
19
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
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22
23
24
25
26
27
28
29
30
31
19
9
16
1
10
25
–1
–1
–1

Indexed Allocation

LA/512 → Q, R

Q = displacement into index table
R = displacement into block

- 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 bytes and block size of 512 bytes. We need only 1 block for index table

Mapping in Indexed Allocation

- Mapping from logical to physical in a file of unbounded length (block size of 512 words)
- Linked scheme – Link blocks of index table (no limit on size)

$$LA / (512 \times 511) \begin{cases} Q_1 \\ R_1 \end{cases}$$

Q_1 = block of index table
R_1 is used as follows:

$$R_1 / 512 \begin{cases} Q_2 \\ R_2 \end{cases}$$

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

- Two-level index (4K blocks could store 1,024 four-byte pointers in outer index → 1,048,567 data blocks and file size of up to 4GB)

Q_1

$LA / (512 \text{ x } 512)$

R_1

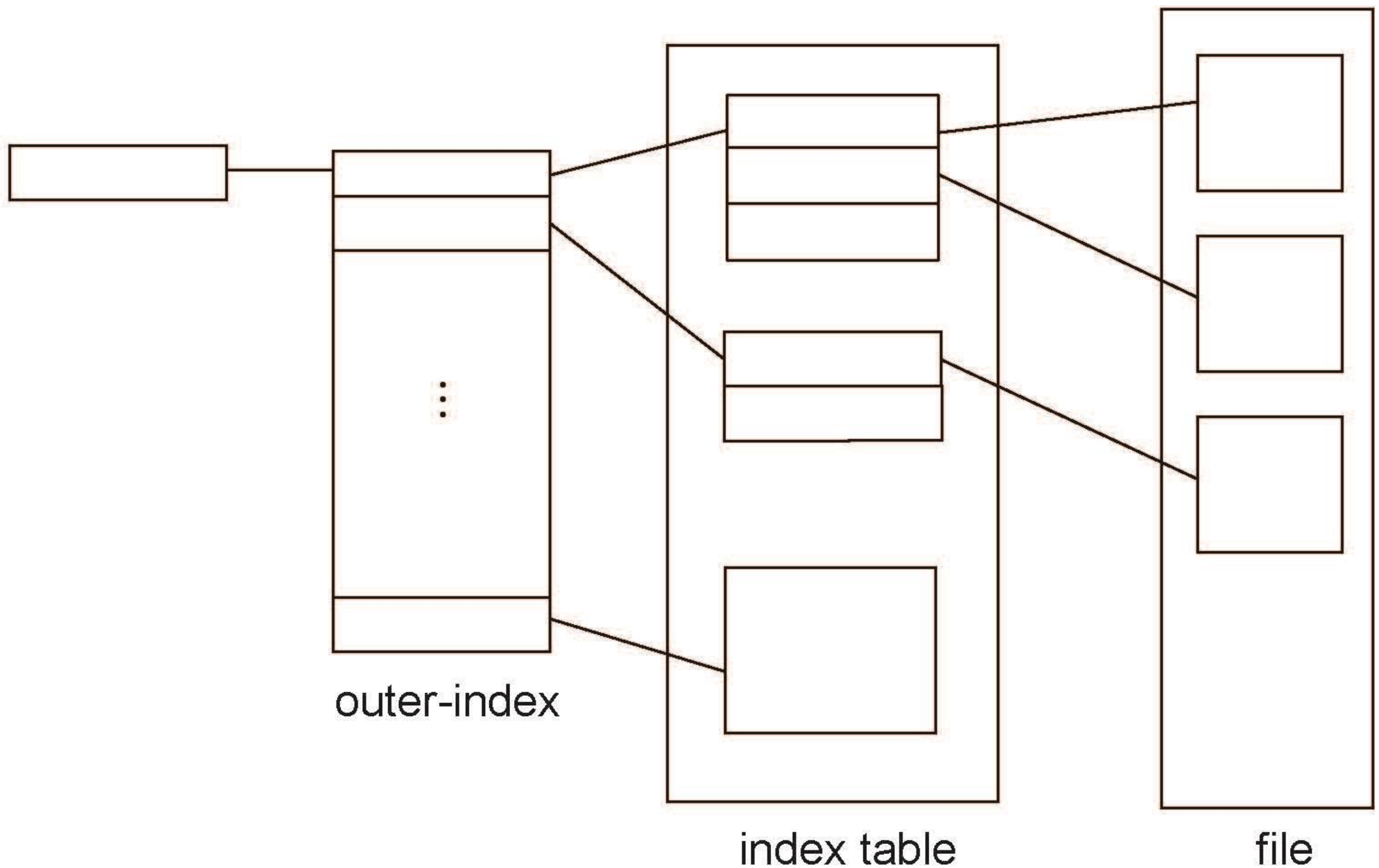
Q_1 = displacement into outer-index
R_1 is used as follows:

Q_2

$R_1 / 512$

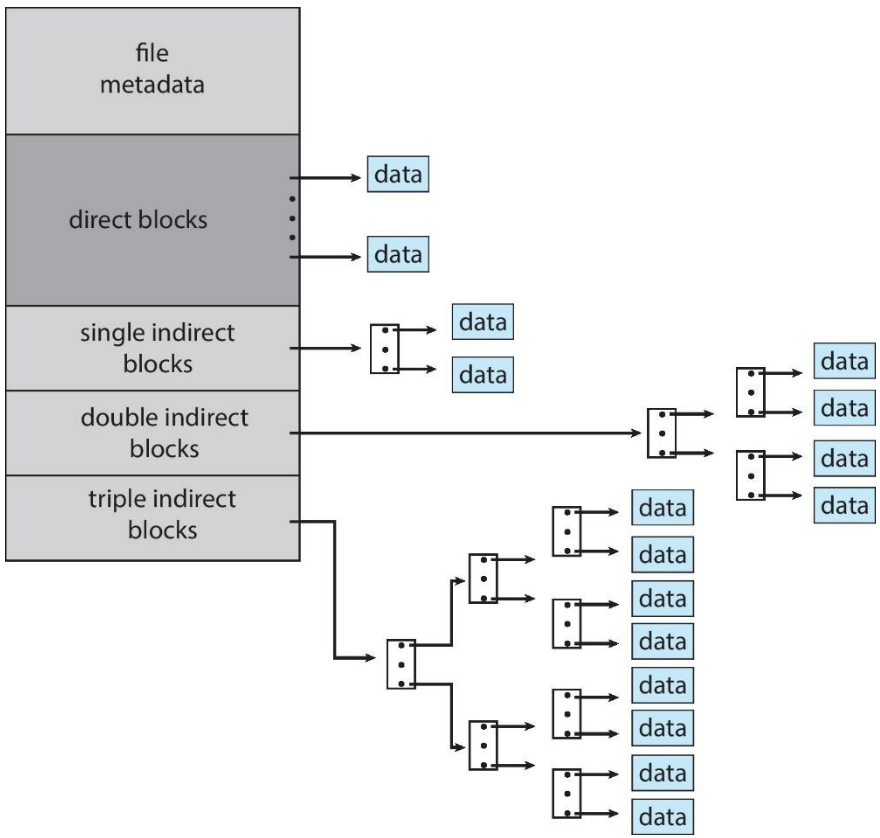
R_2

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


outer-index
index table
file

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
  - With NVM goal is to reduce CPU cycles and overall path needed for I/O

Performance

- Adding instructions to the execution path to save one disk I/O is reasonable
  - Intel Core i7 Extreme Edition 990x (2011) at 3.46Ghz = 159,000 MIPS
    - http://en.wikipedia.org/wiki/Instructions_per_second
  - Typical disk drive at 250 I/Os per second
    - 159,000 MIPS / 250 = 630 million instructions during one disk I/O
  - Fast SSD drives provide 60,000 IOPS
    - 159,000 MIPS / 60,000 = 2.65 millions instructions during one disk I/O

Questions?

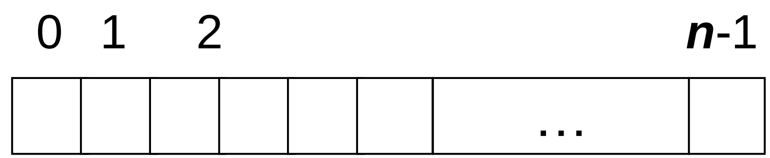
- Continuous allocation
- Linked allocation
- Indexed allocation
- Combined scheme

Free-Space Management

- File system maintains free-space list to track available blocks/clusters
  - (Using term “block” for simplicity)

Bit Vector/Map

- (n blocks)



$$\text{bit}[\boldsymbol{i}] = \begin{cases} 1 \Rightarrow \text{block}[\boldsymbol{i}] \text{ free} \\ 0 \Rightarrow \text{block}[\boldsymbol{i}] \text{ occupied} \end{cases}$$

Block number calculation

(number of bits per word) *
(number of 0-value words) +
offset of first 1 bit

CPUs have instructions to return offset within word of first "1" bit

- Bit map requires extra space
  - Example:

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

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

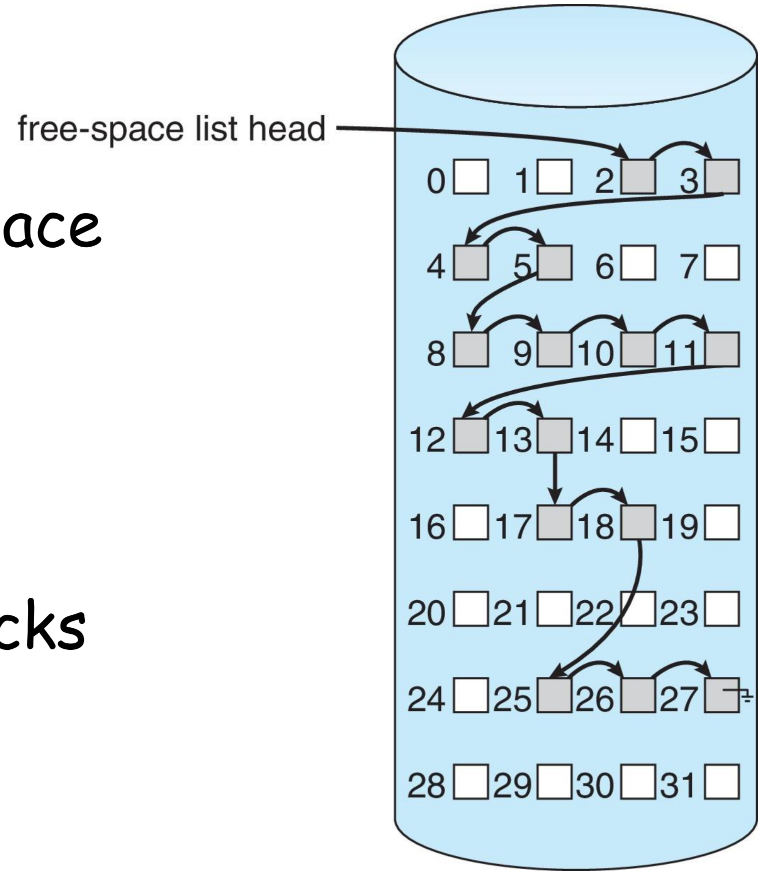
$\boldsymbol{n} = 2^{40}/2^{12} = 2^{28}$ bits (or 32MB)

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 of space
  - No need to traverse the entire list (if # free blocks recorded)



Grouping and Counting

- 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

Space Maps

- Used in **ZFS**
- Consider meta-data I/O on very large file systems
  - Full data structures like bit maps couldn't 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

- 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

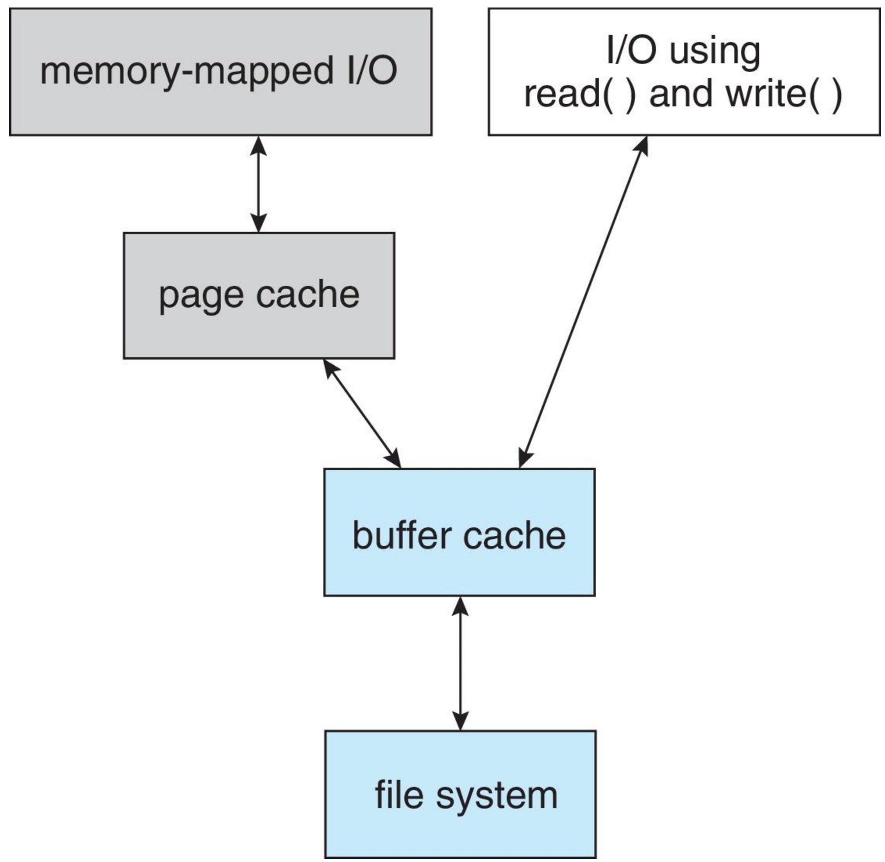
Performance

- 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 and addresses
- Memory-mapped I/O uses a page cache
- Routine I/O through the file system uses the buffer (disk) cache

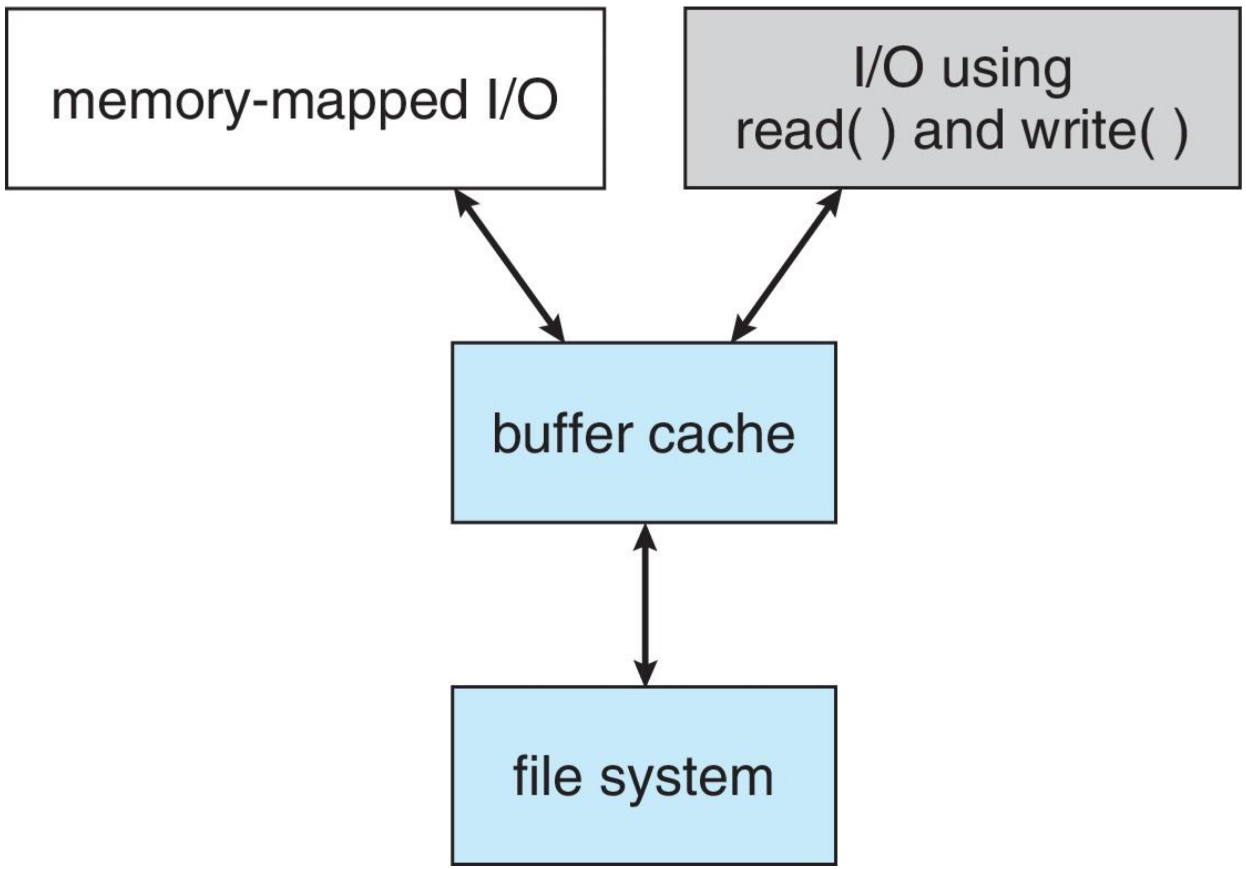
I/O Without a Unified Buffer Cache



Unified Buffer Cache

- A **unified buffer cache** uses the same page cache to cache both memory-mapped pages and ordinary file system I/O to avoid **double caching**
- But which caches get priority, and what replacement algorithms to use?

I/O Using a Unified Buffer Cache



Questions?

- Efficiency
- Performance
- Cache

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

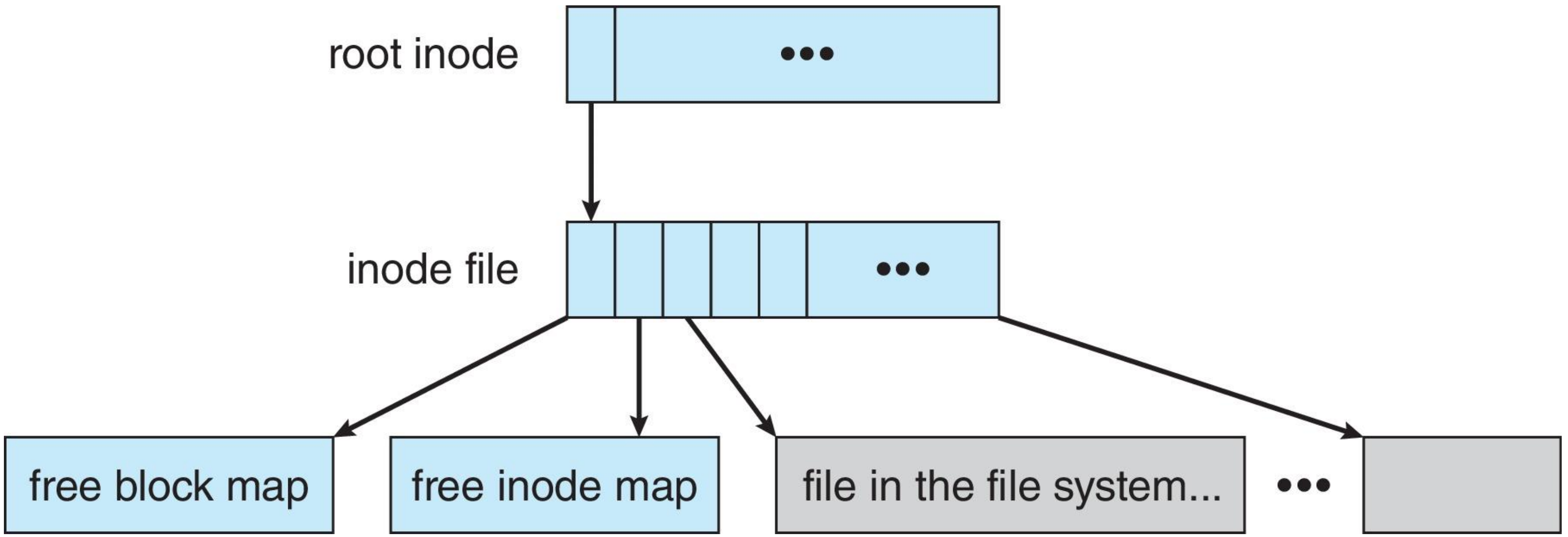
Log Structured File Systems

- **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

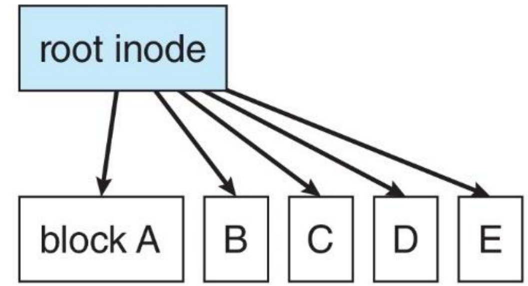
Example: WAFL File System

- 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

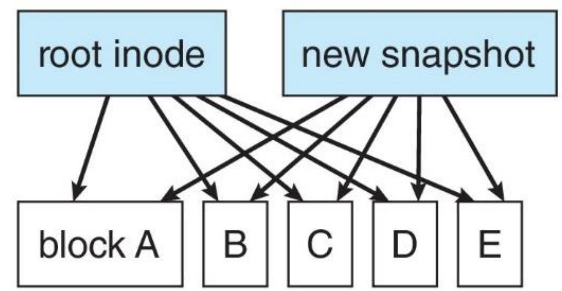
The WAFL File Layout



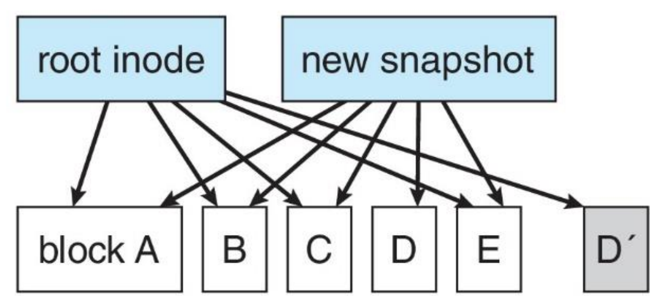
Snapshots in WAFL



(a) Before a snapshot.



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



(c) After block D has changed to D´.

Questions?

- Recovery
- Log structured file systems
- WAFL