CSMC 412

Operating Systems

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Set 18

File System Implementation

File System

- Structure
- Naming
- Directory structure
- Operations
- …

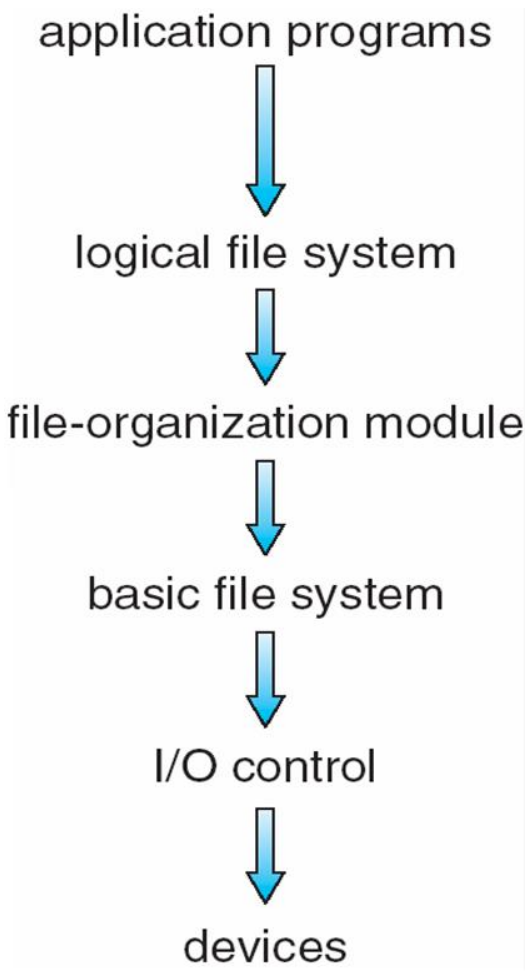
File system Implementation

- Defines
  - How files and directories are stored
  - How disk space is managed
  - How to make everything work efficiently and reliably

File-System Structure

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

Layered File System



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 to carry out the operations called for
- **Basic file system** given command like "retrieve block 123" translates to device driver commands
- 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.
- Translates file name into file number, file handle, location by maintaining file control blocks (**inodes** in UNIX)
  - Logical layers can be implemented by any coding method according to OS designer

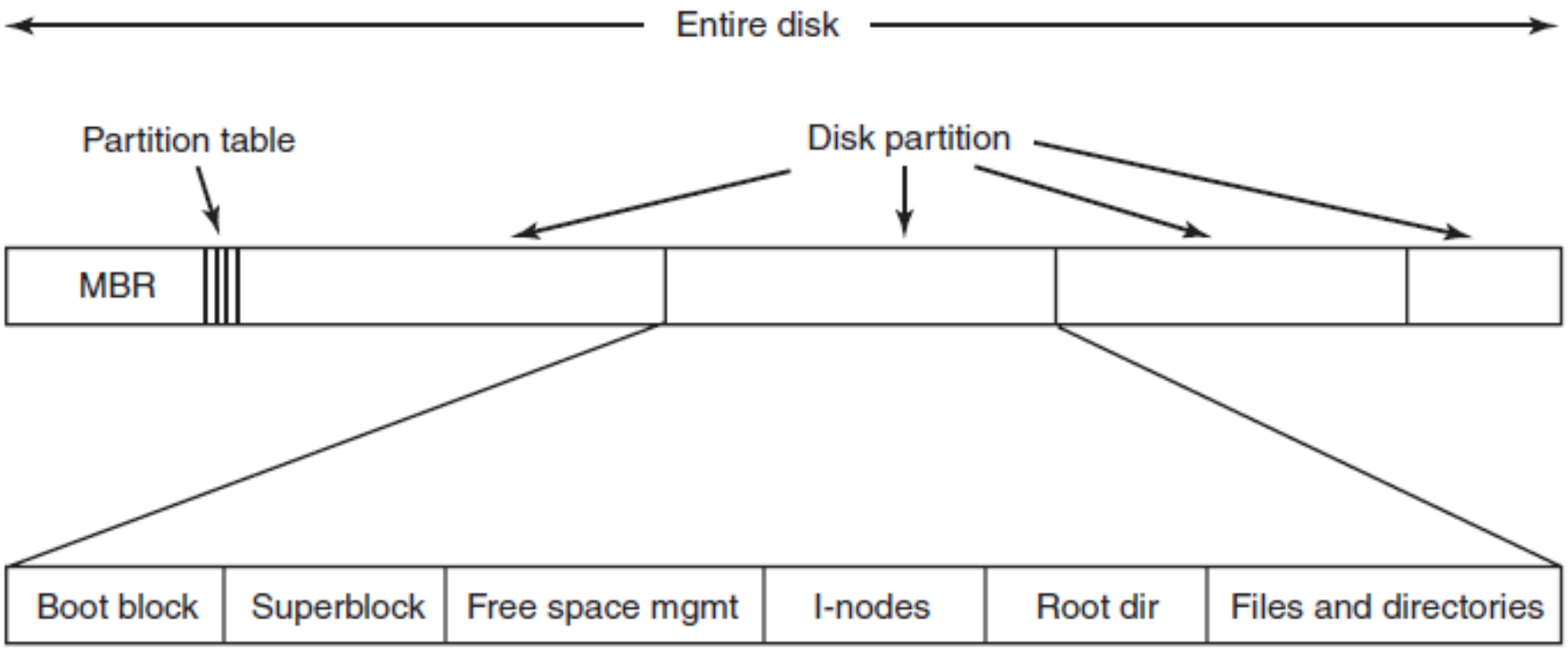
File System Layers (Cont.)

- 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 40 types, with **extended file system** ext2 and ext3 leading; plus distributed file systems, etc.)
  - New ones still arriving – ZFS, GoogleFS, Oracle ASM, FUSE

File-System Implementation

- 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 System Layout



File System Layout

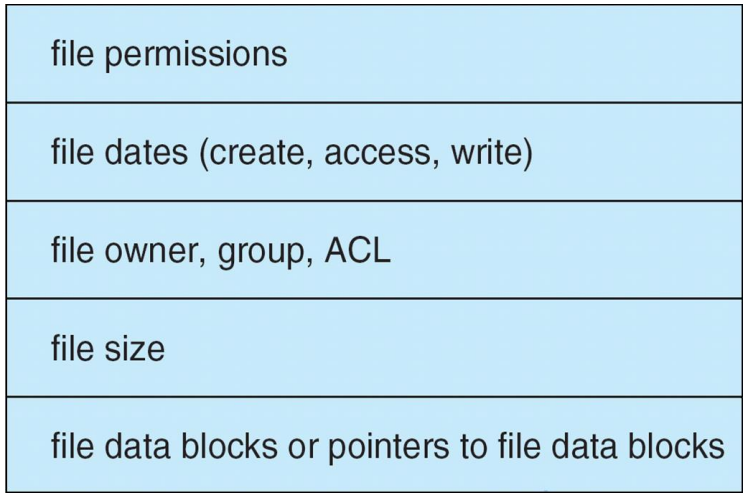
- MBR: Master Boot Record
- Partition table:
  - present at the end of MBR
  - Gives the starting and ending address of each partition
- Boot Block: When a computer is booted,
  - BIOS reads and executes MBR
  - Locates active partition
  - Reads the first block – Boot Block – and executes it.
    - Program in the boot block loads the operating system contained in that partition
  - Every partition contains a boot block even though it may not have a bootable OS

File System Layout (Cont.)

- Volume Control Block – per volume
    - Number of blocks in the volume
    - Size of blocks
    - Free blocks count
    - Free-block pointers
    - Free-FCB count
    - FCB pointer
  - In UFS it is called a Superblcok
  - In NTFS it is stored in Master File Table
- Directory Structure – per file system
  - Used to organize files
  - In UFS - File names and associated inode numbers

File-System Layout (Cont.)

- Per-file **File Control Block (FCB)** contains many details about the file
  - In UFS it includes inode number, permissions, size, dates
  - In NTFS stores into master file table
    - using relational DB structures
    - One row per file



Operations

- Open
  - Call passes the file name to the logical file system
  - Open system call searches the system-wide open-file table
    - To check if the file is in use by another process
      - Create a per-process open-file table entry, pointing to the system-wide open-file table entry
    - Else
      - Search the directory structure
      - Copy FCB into a system-wide open-file table entry in the memory
      - Make an entry in per-process open-file table with a pointer to the system-wide table entry
      - Per-process open-file table also stores information such as the current location in the file
  - Returns a pointer to the per-process entry
    - File descriptor in UFS
    - File handle in Windows

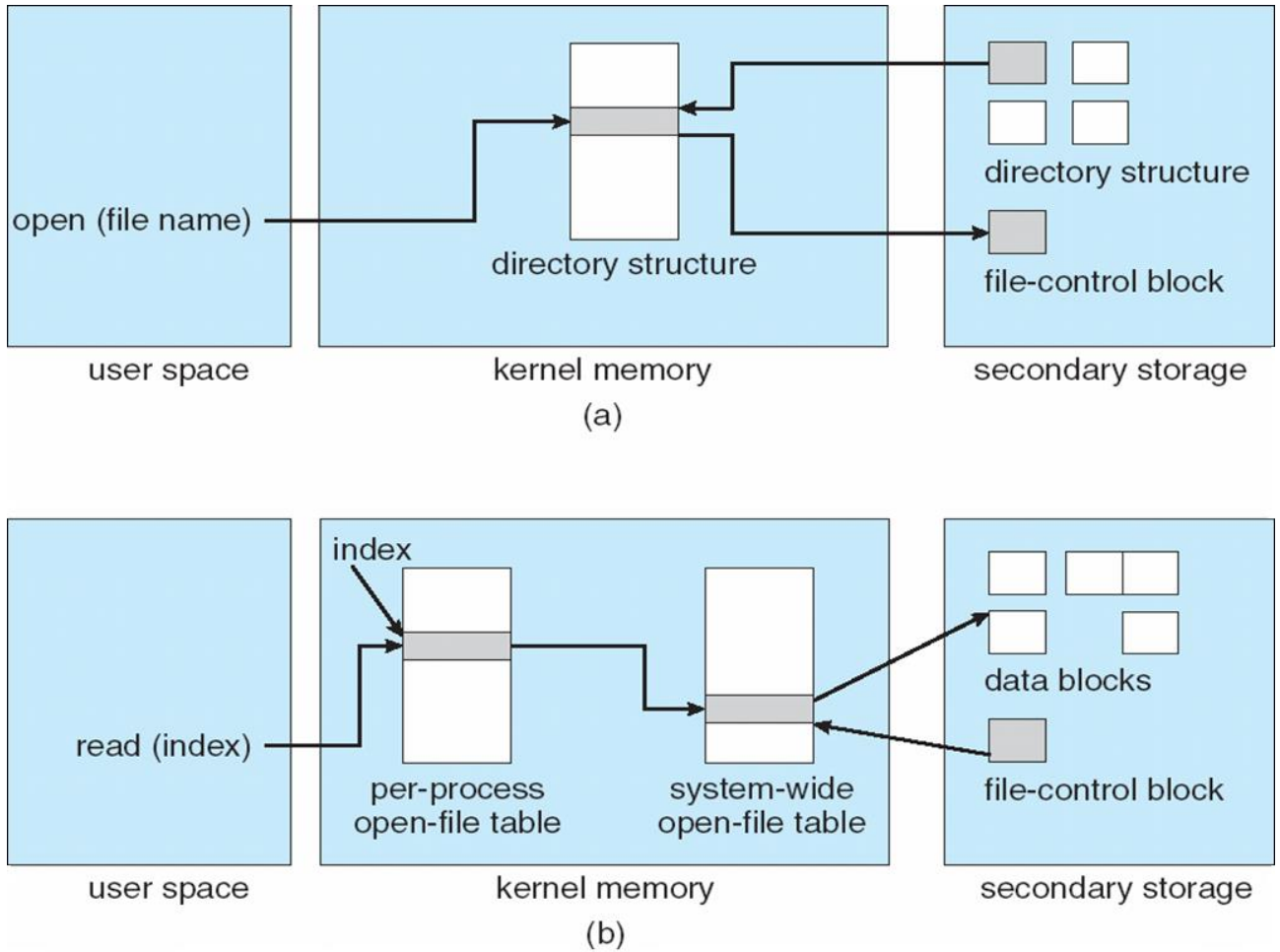
Operations

- Close
  - Remove per-process table entry
  - Decrement system-wide entry's open count
    - When count goes to zero
      - Any updated meta data copied to disk-based directory structure
      - System-wide entry is removed

In-Memory File System Structures

- Mount table storing file system mounts, mount points, file system types
- The following figure illustrates the necessary file system structures provided by the operating systems
- opening a file
- reading a file
- Plus 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

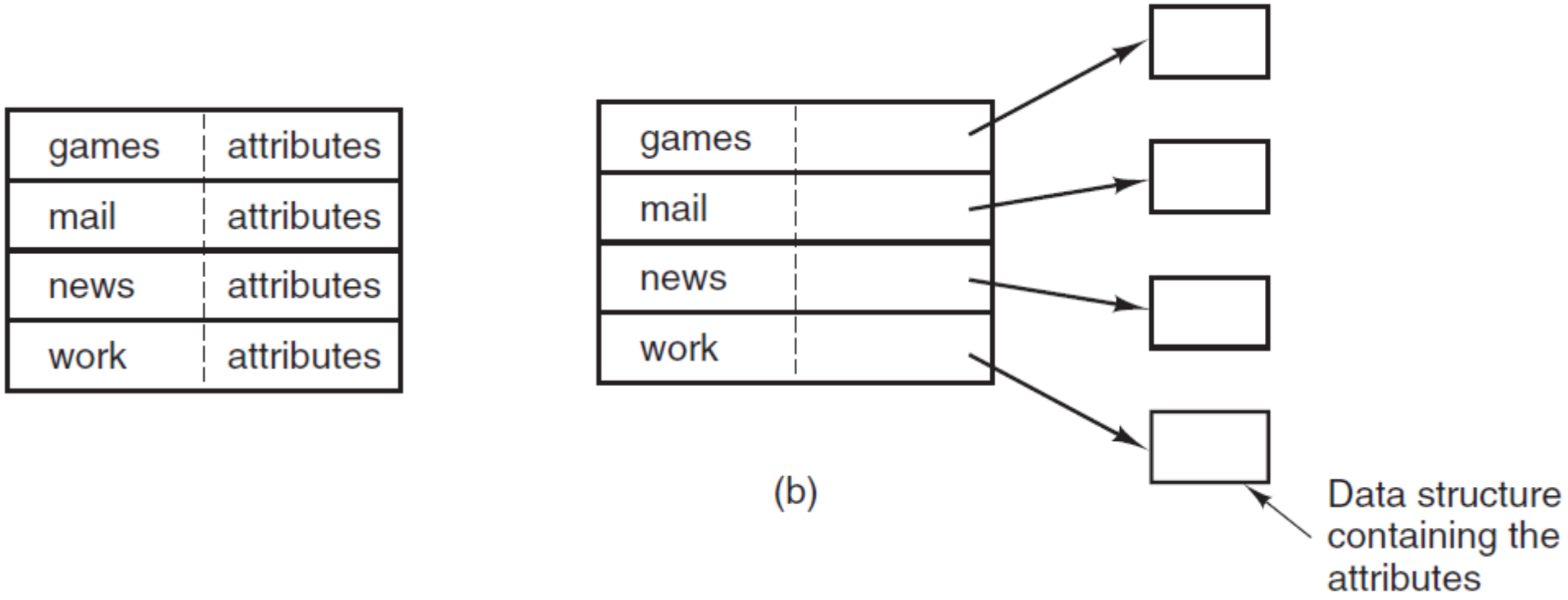
In-Memory File System Structures



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

Directory Implementation

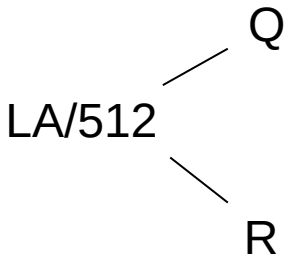


Allocation Methods - Contiguous

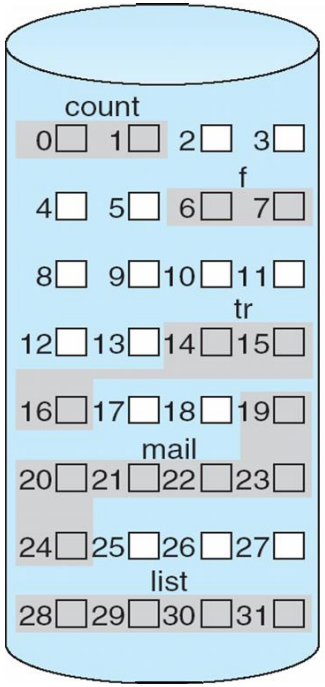
- An allocation method refers to how disk blocks are allocated for files:
- **Contiguous allocation** – each file occupies set of contiguous blocks
  - Best performance in most cases
  - Simple – only starting location (block #) and length (number of blocks) are required
  - Problems include
    - finding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

Contiguous Allocation

- 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

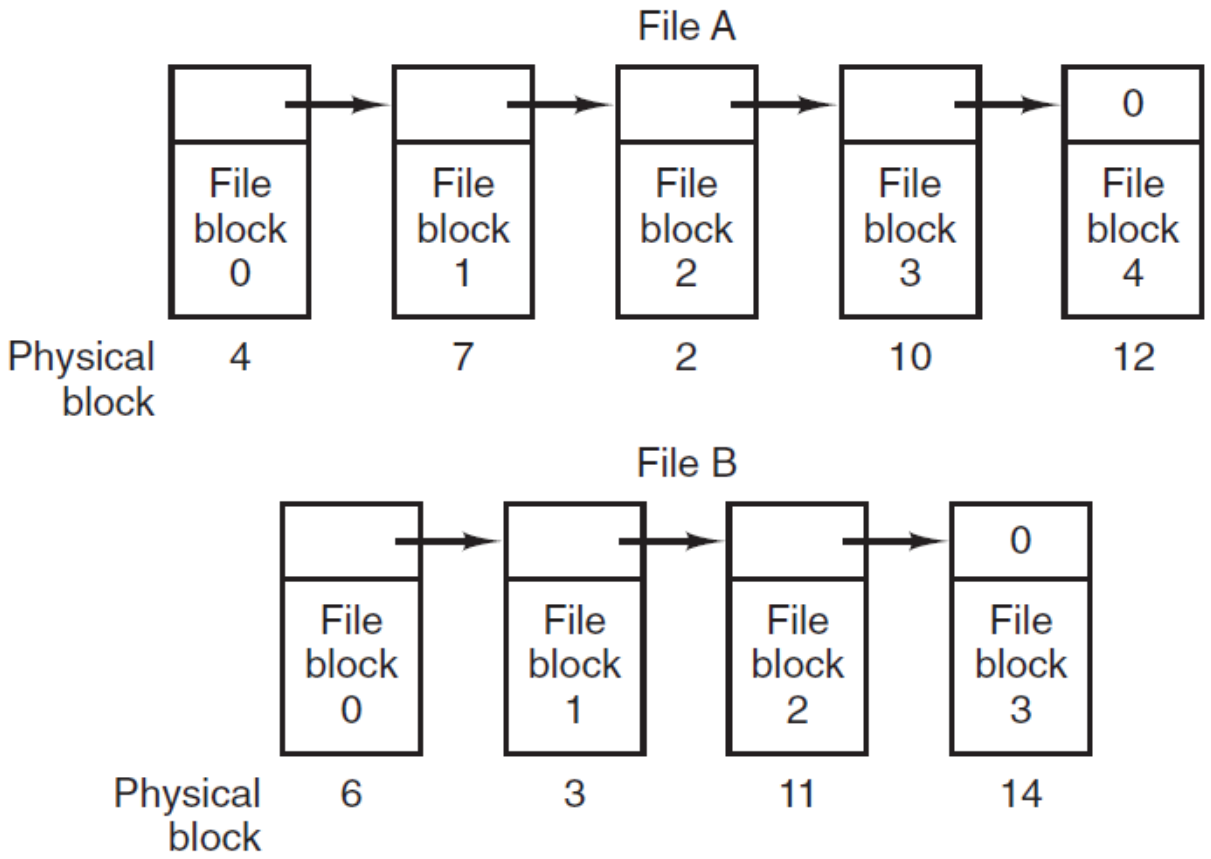
- Many newer file systems (i.e., Veritas File System) use a modified contiguous allocation scheme
- Extent-based file systems allocate disk blocks in extents
  - Allocate in contiguous chunk of space
- An **extent** is a contiguous block of disks sectors

  - Extents are allocated for file allocation

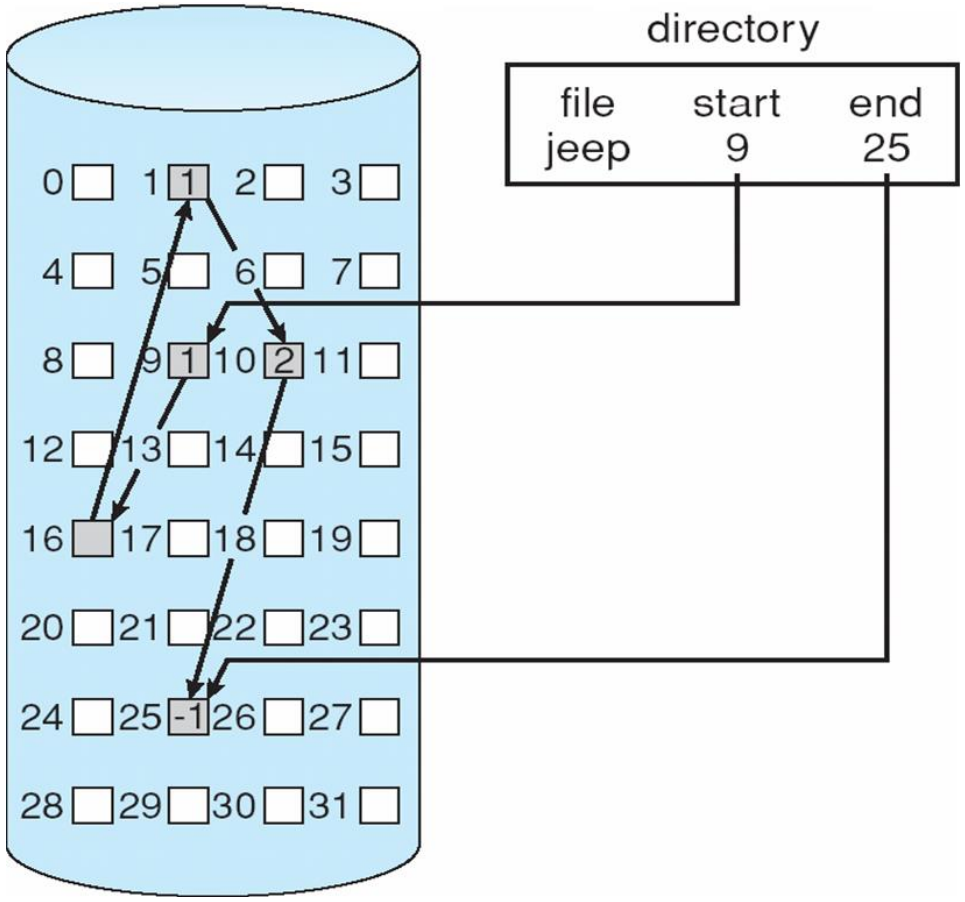
Allocation Methods - Linked

- **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 required
  - 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



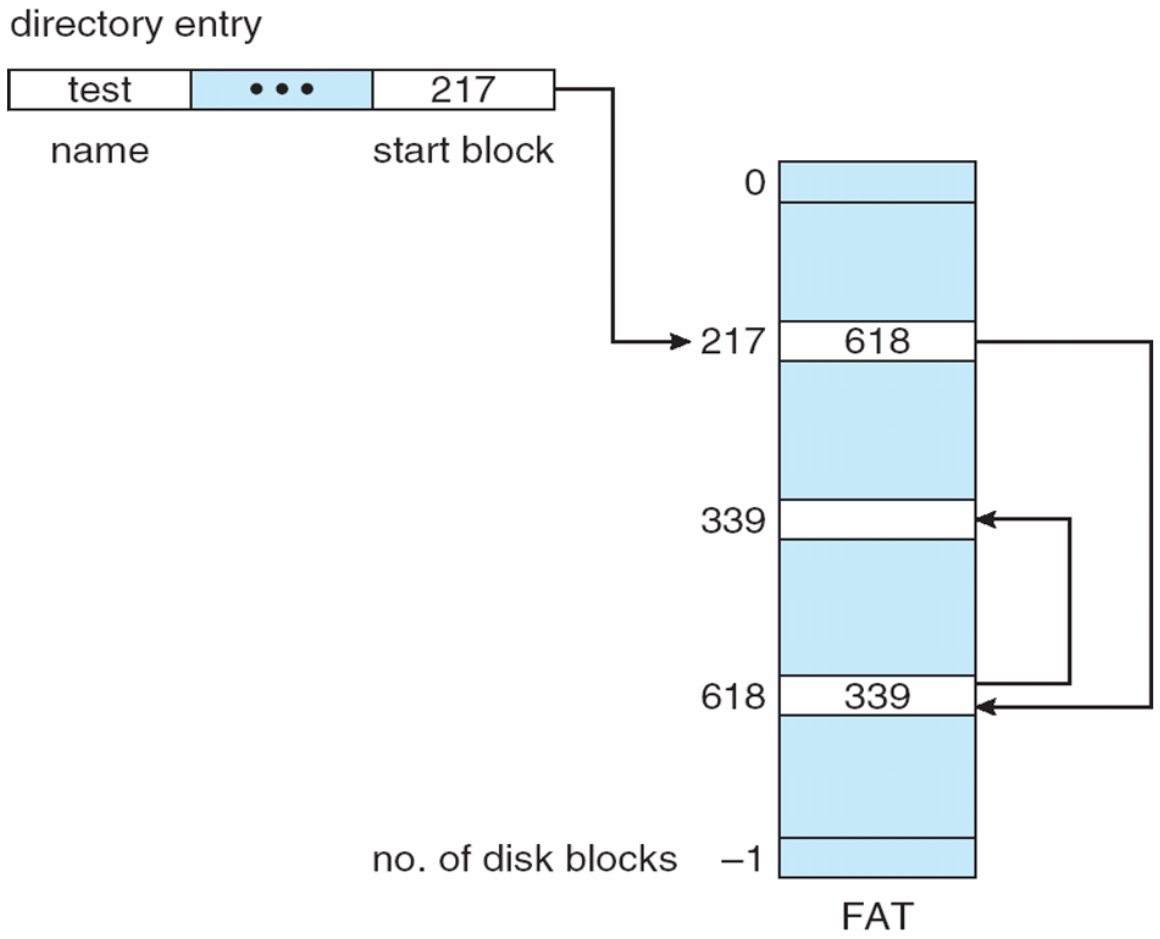
Linked Allocation



Allocation Methods – Linked (Cont.)

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

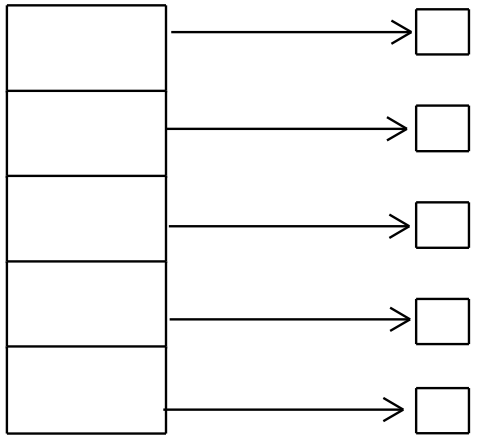
File-Allocation Table



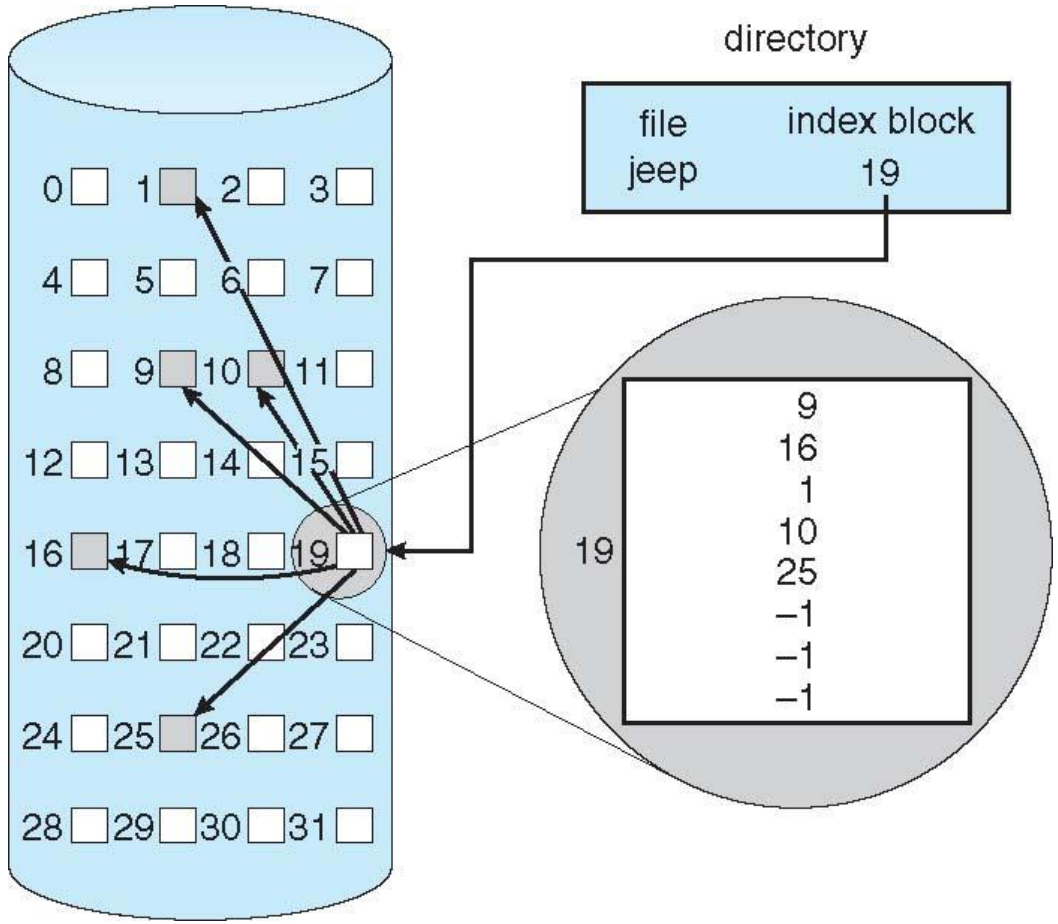
Allocation Methods - Indexed

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

- Logical view



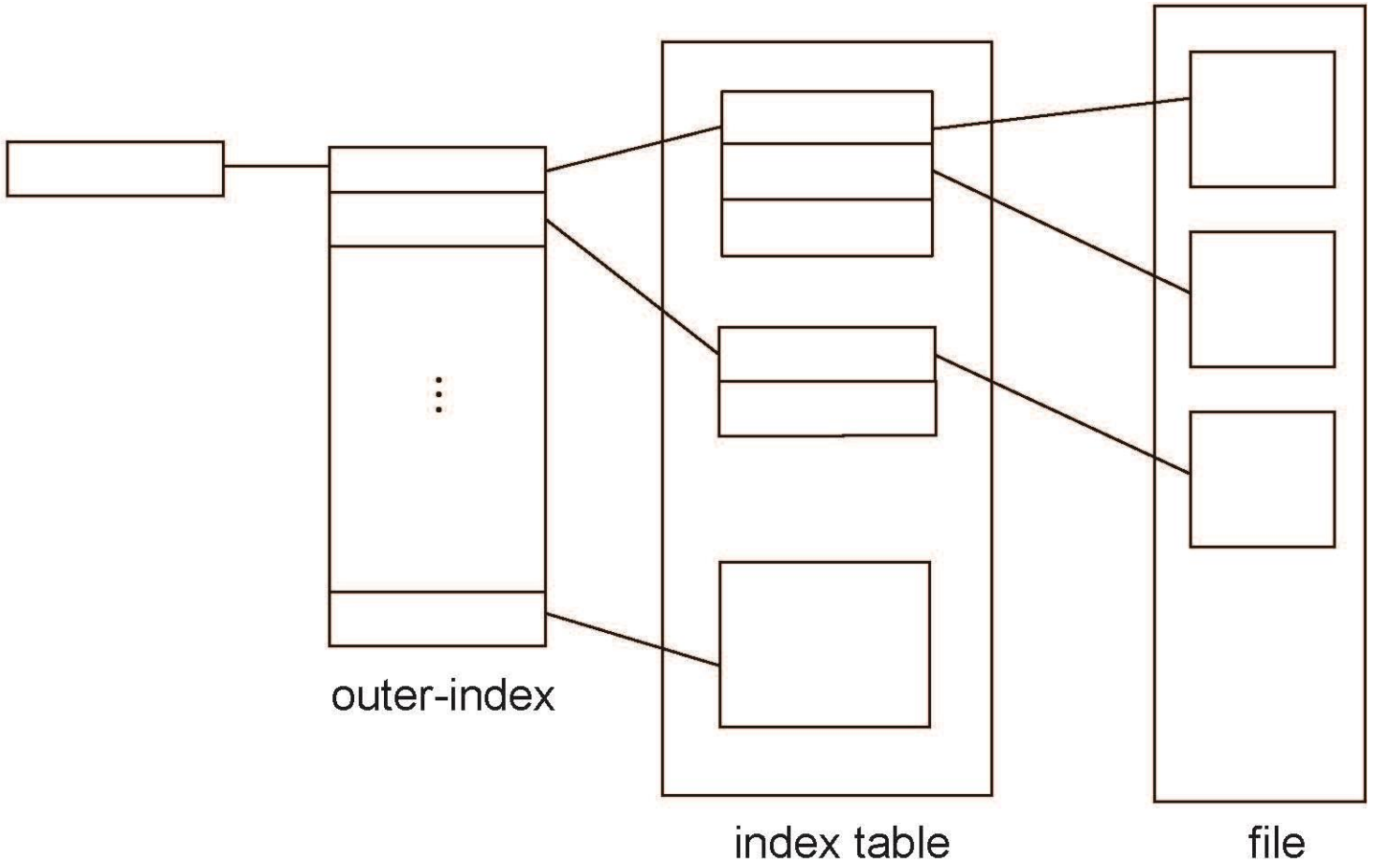
Example of Indexed Allocation



Indexed Allocation (Cont.)

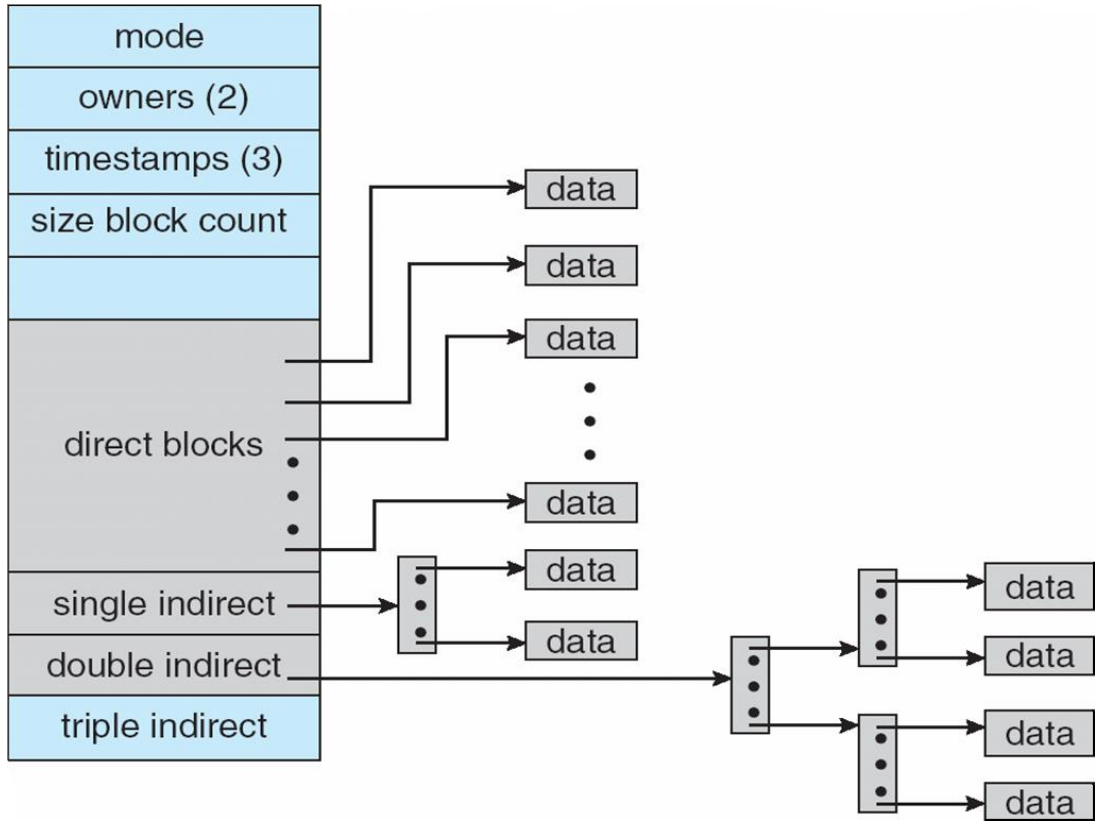
- Need index table
- Random access
- Dynamic access without external fragmentation, but have overhead of index block
- Mapping from logical to physical in a file of maximum size of 256K bytes and block size of 512 bytes. We need only 1 block for index table

Indexed Allocation – Mapping (Cont.)



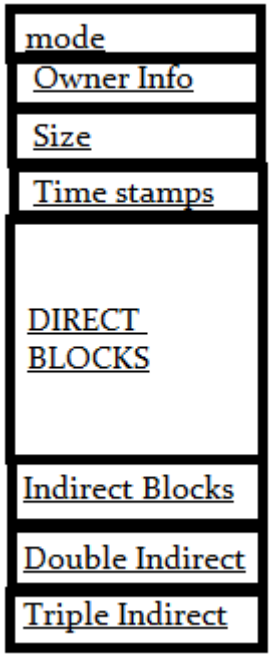
Combined Scheme: UNIX UFS

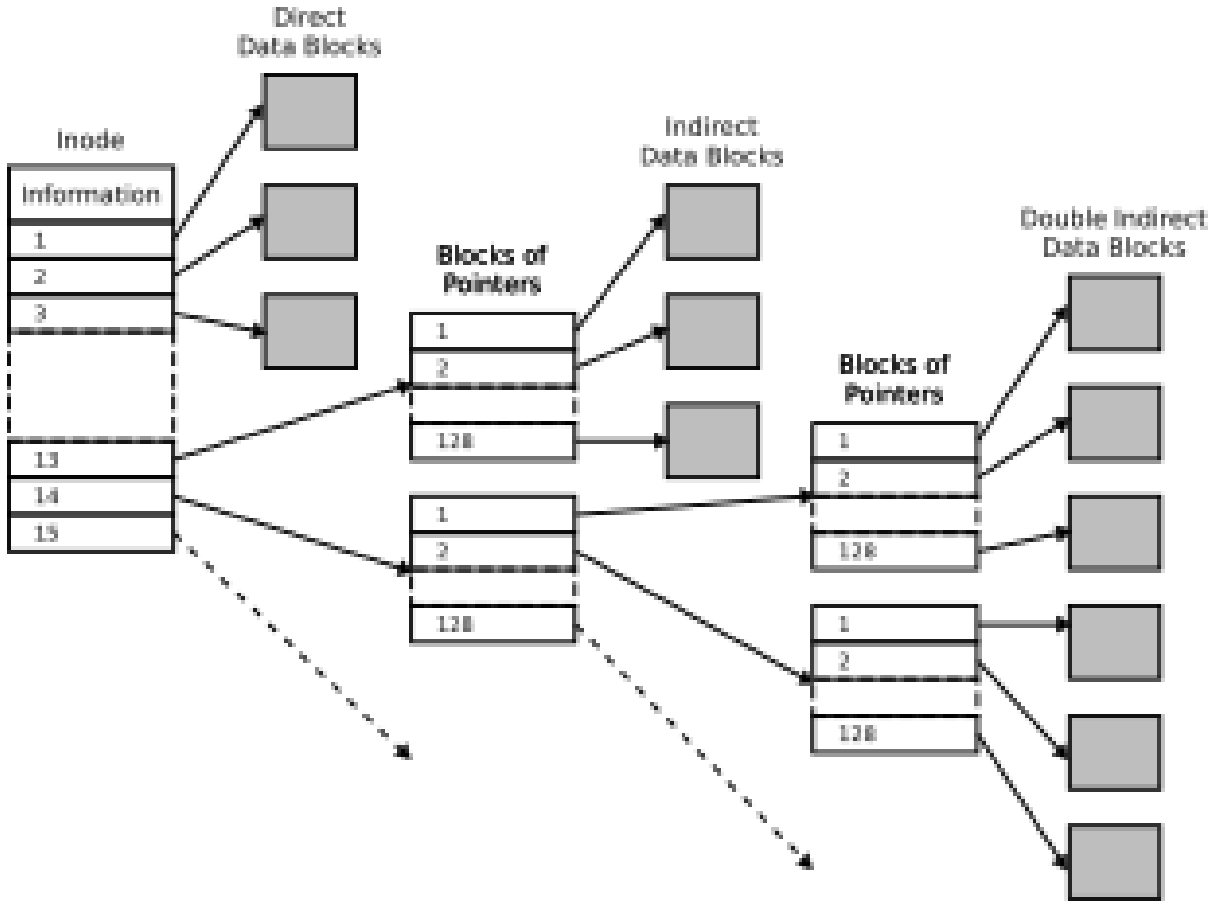
4K bytes per block, 32-bit addresses



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

Inode Structure





Performance

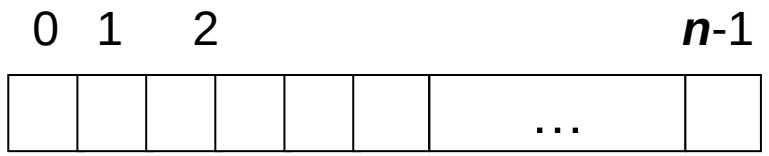
- Best method depends on file access type
  - Contiguous great for sequential and random
- Linked good for sequential, not random
- Declare access type at creation -> select either contiguous or linked
- Indexed more complex
  - Single block access could require 2 index block reads then data block read
  - Clustering can help improve throughput, reduce CPU overhead

Performance (Cont.)

- Adding instructions to the execution path to save one disk I/O is reasonable
  - Intel Core i9 – 9900K (2019) at 4.7Ghz = 412,090 MIPS
    - http://en.wikipedia.org/wiki/Instructions_per_second
  - Typical disk drive at 250 I/Os per second
    - 412,090 MIPS / 250 = 1,648 million instructions during one disk I/O
  - Fast SSD drives provide 60,000 IOPS
    - 412,090 MIPS / 60,000 = 6.86 millions instructions during one disk I/O

Free-Space Management

- File system maintains **free-space list** to track available blocks/clusters
  - (Using term "block" for simplicity)
- **Bit vector** or **bit map** (***n*** blocks)



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

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

Free-Space Management (Cont.)

- Bit map requires extra space
  - Example:

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

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

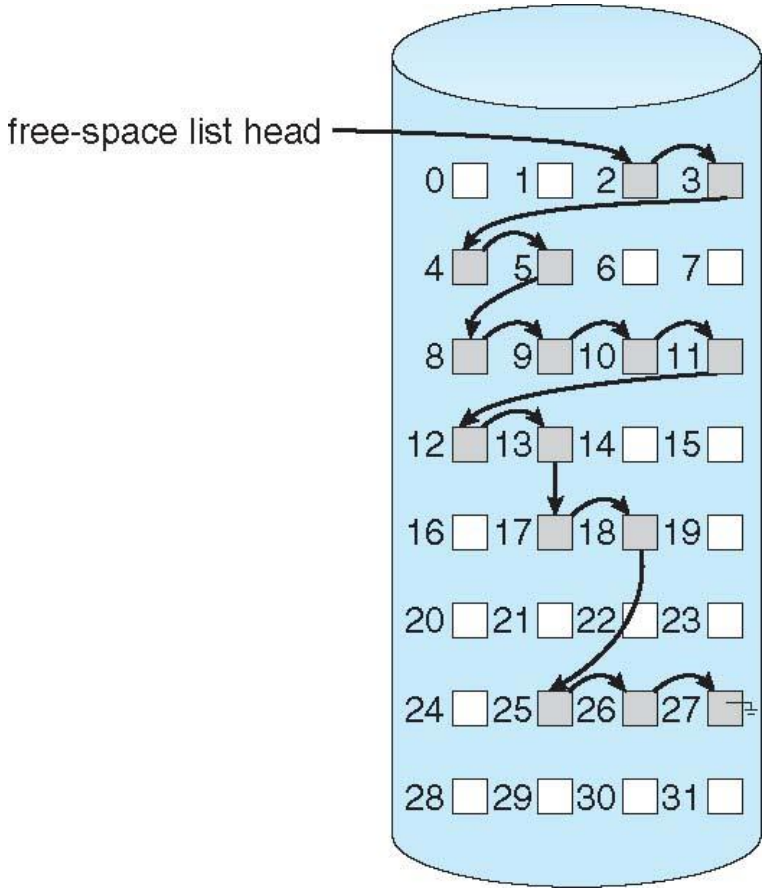
    $\boldsymbol{n}$ = $2^{40}/2^{12}$ = 2^{28} bits (or 32MB)

    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)



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, 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

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

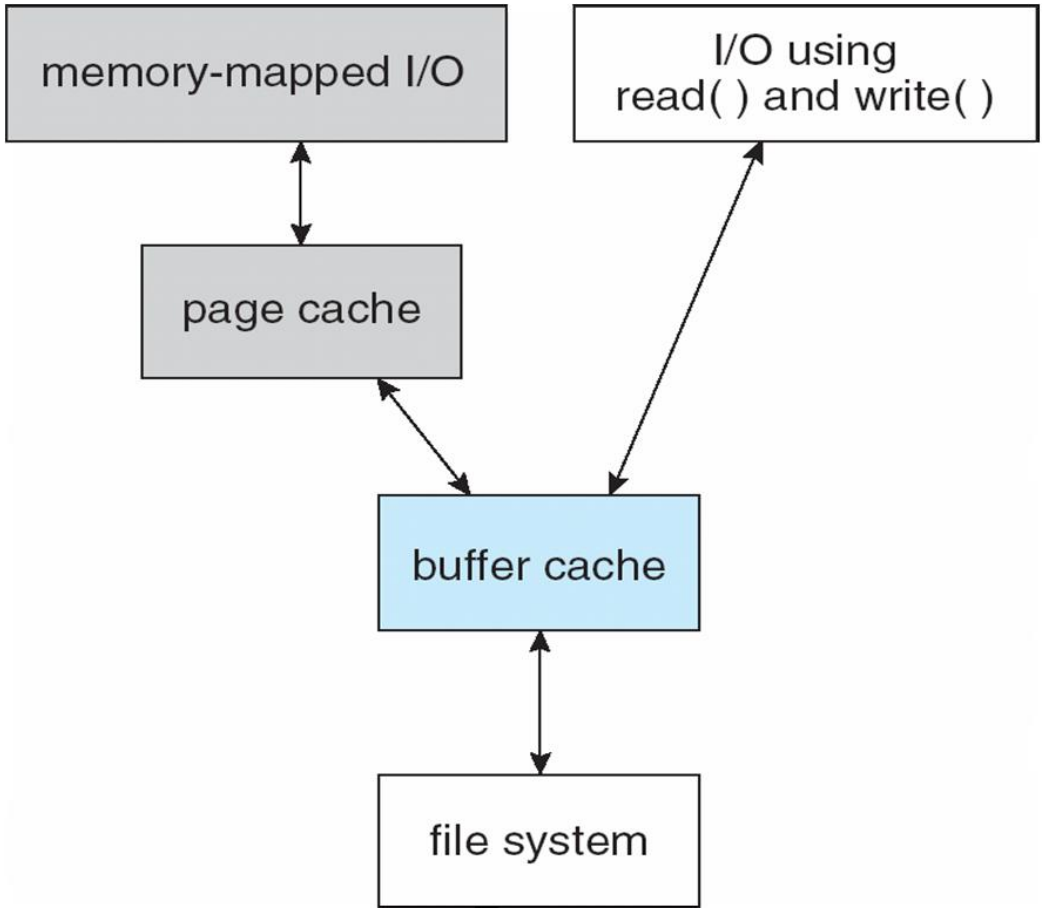
Efficiency and Performance (Cont.)

- 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
- This leads to the following figure

I/O Without a Unified Buffer Cache

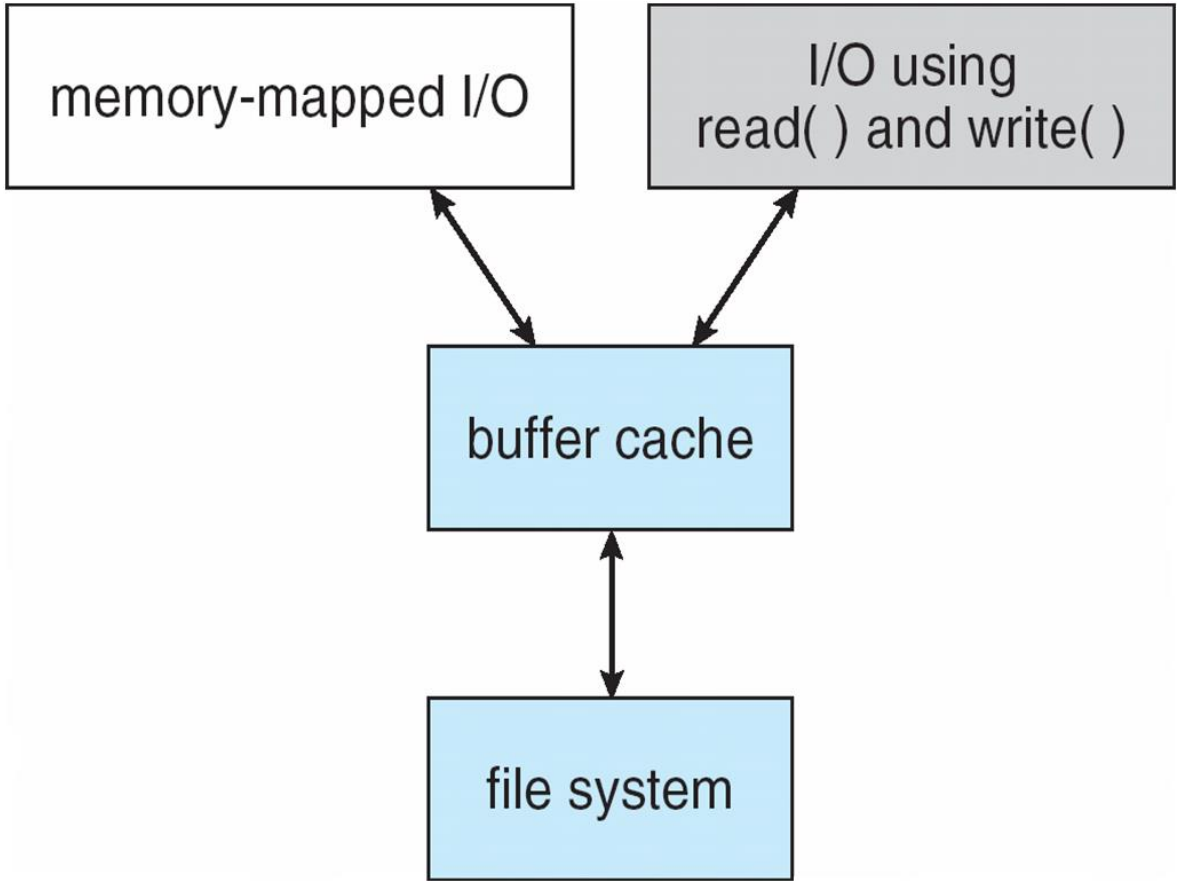


Unified Buffer Cache

- 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



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