LS-05:
FILE SYSTEM IMPLEMENTATION

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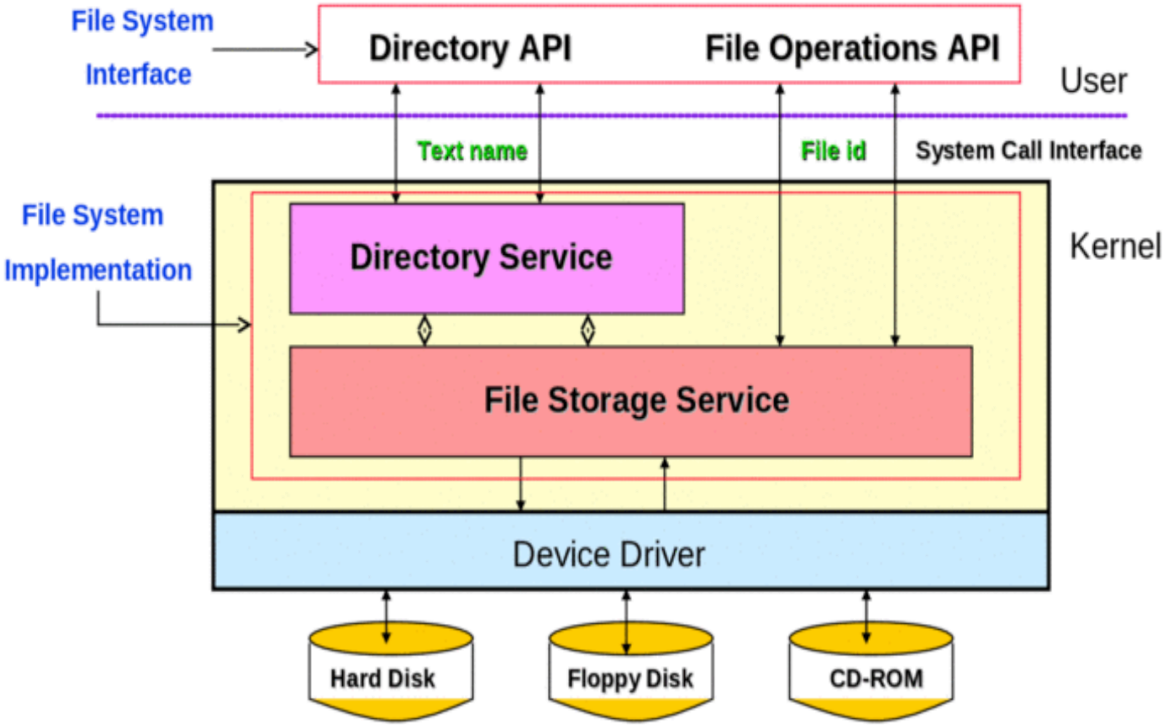
- File-System Structure
- File-System Implementation
- Directory Implementation
- Allocation Methods
- Free-Space Management
- Efficiency and Performance
- Recovery

Objectives

- To describe the details of implementing local file systems and directory structures
- To describe the implementation of remote file systems
- To discuss block allocation and free-block algorithms and trade-offs

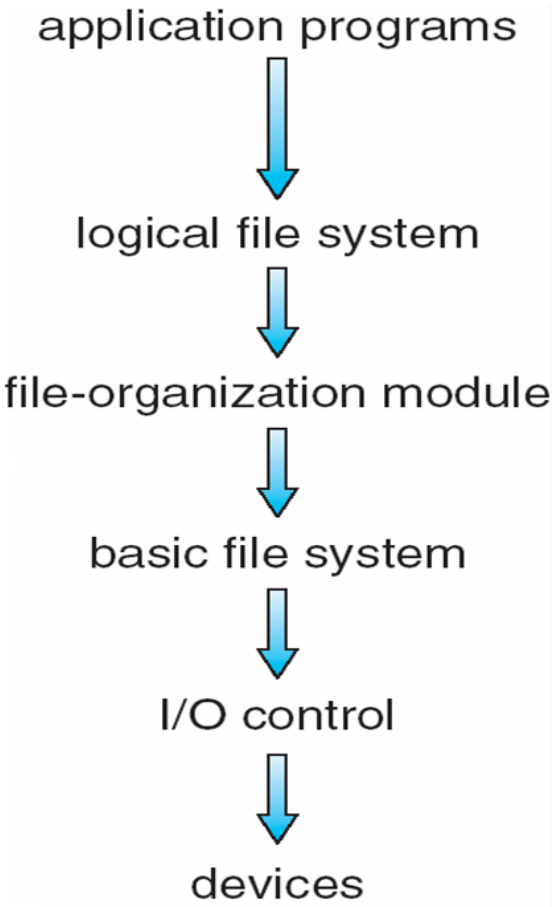
- **File System Framework**



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** – 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

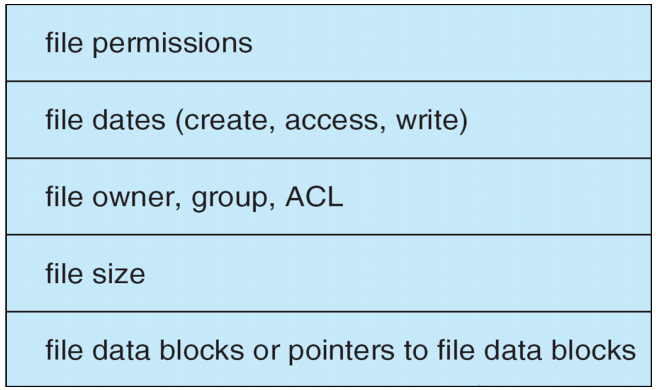
- **Device drivers** manage I/O devices at the I/O control layer
  - Given commands like "read drive1, cylinder 72, track 2, sector 10, into memory location 1060" outputs low-level hardware specific commands to hardware controller
  - **Basic file system** given command like "retrieve block 123" translates 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 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

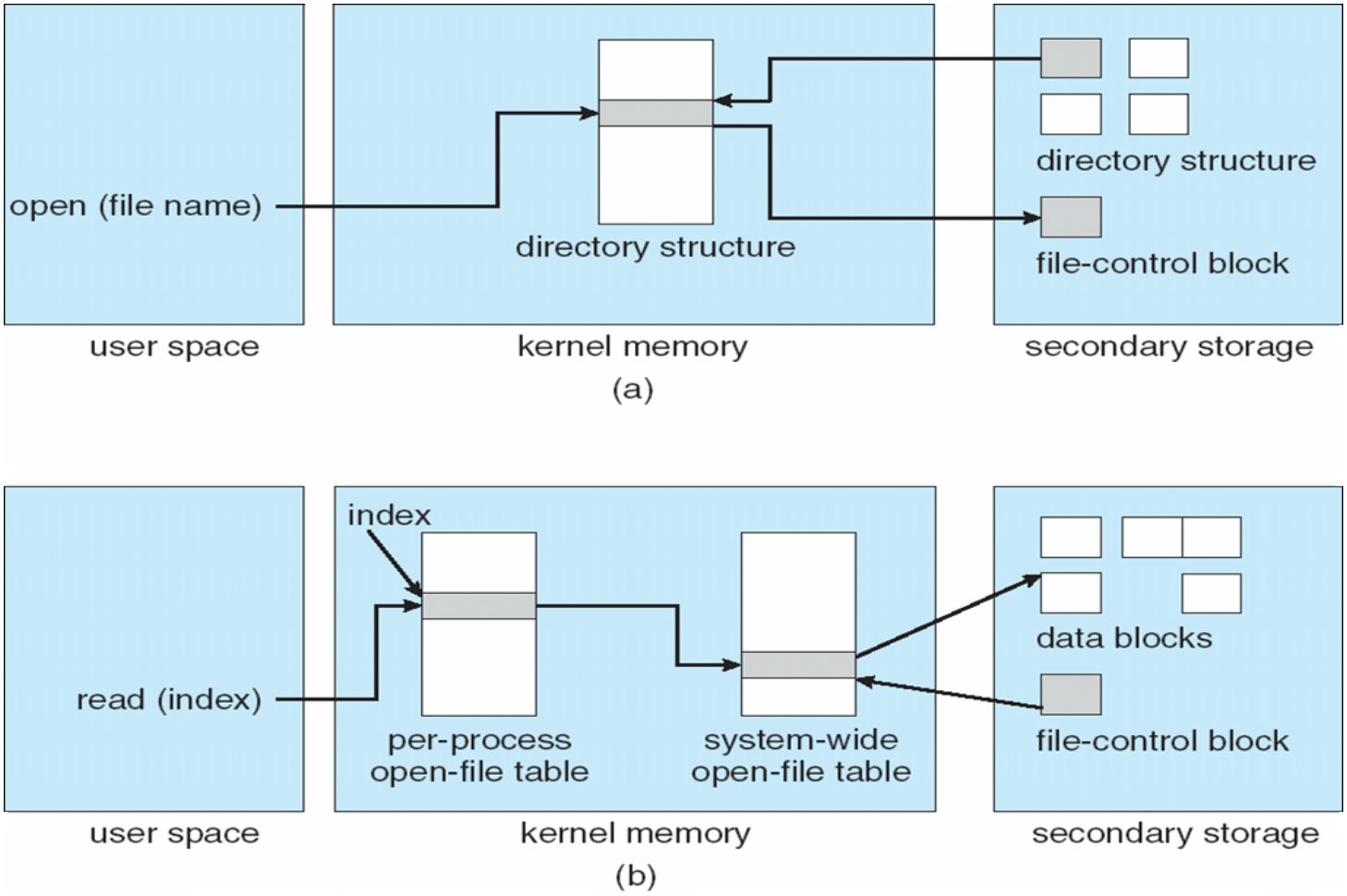
- We have system calls at the API level, but how do we implement their functions?
  - On-disk and in-memory structures
- **Boot control block** contains info needed by system to boot OS from that volume
  - Needed if volume contains OS, usually first block of volume
- **Volume control block** (**superblock, 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
- Per-file **File Control Block** (**FCB**) contains many details about the file
  - inode number, permissions, size, dates
  - NFTS stores into in master file table using relational DB structures



In-Memory File System Structures

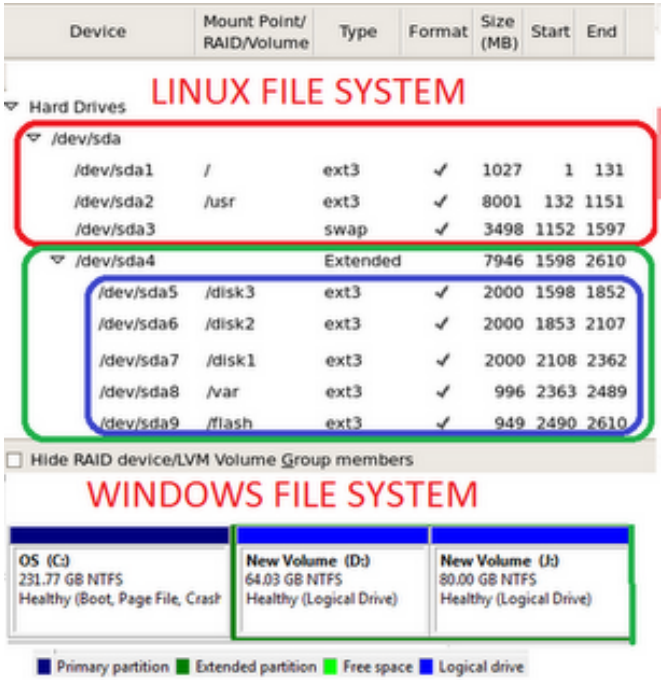
- Mount table storing file system mounts, mount points, file system types
- The following figure illustrates the necessary file system structures provided by the operating systems
- Figure (a) refers to opening a file
- Figure (b) refers to reading a file
- Plus buffers hold data blocks from secondary 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



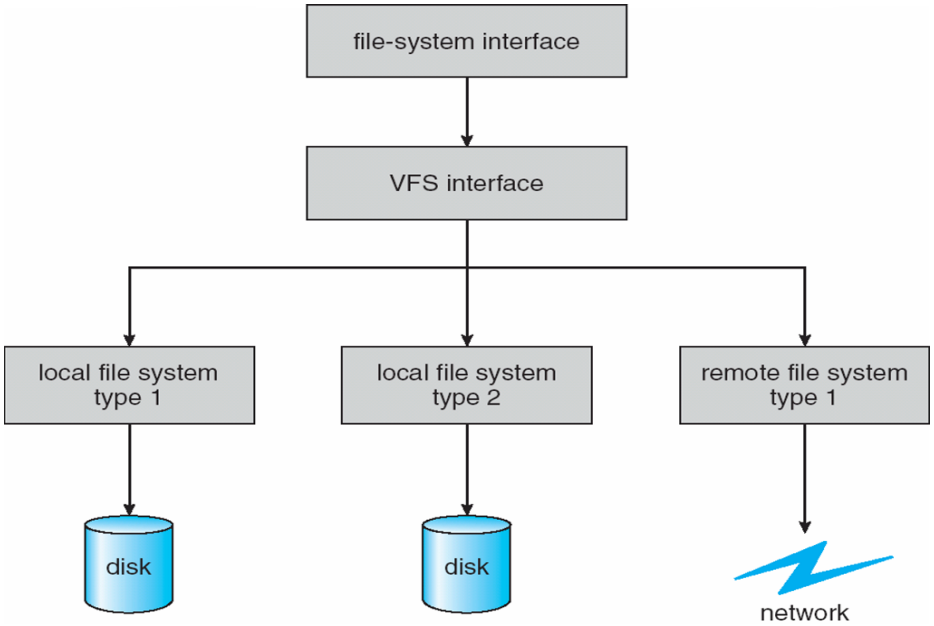
Partitions and Mounting

- Partition can be a volume containing a file system ("cooked") or **raw** – just a sequence of blocks with no file system
- Boot block can point to boot volume or boot loader set of blocks that contain enough code to know how to load the kernel from the file system
  - Or a boot management program for multi-os booting
- **Root partition** contains the OS, other partitions can hold other Oses, other file systems, or be raw
  - Mounted at boot time
  - Other partitions can mount automatically or manually
- At mount time, file system consistency checked
  - Is all metadata correct?
    - If not, fix it, try again
    - If yes, add to mount table, allow access



Virtual File Systems

- **Virtual File Systems** (**VFS**) on Unix provide an object-oriented way of implementing file systems
- VFS allows the same system call interface (the API) to be used for different types of file systems
  - Separates file-system generic operations from implementation details
  - Implementation can be one of many file systems types, or network file system
    - Implements **vnodes** which hold inodes or network file details
  - Then dispatches operation to appropriate file system implementation routines
- The API is to the VFS interface, rather than any specific type of file system



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Software layer in the kernel that provides the file system interface to user space programs.

Manages kernel level file abstractions in one format for all file systems (implement file system independent operations).

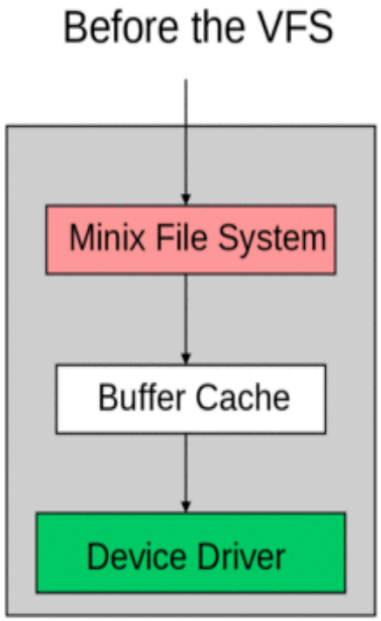
Receives file oriented system calls from user level.

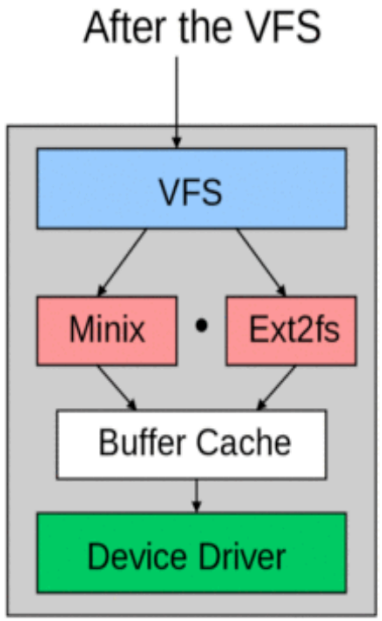
write, open, stat, link

VFS switch: Translate them into the internal ones to interface with a specific file system module (file system dependent part).

File system provides methods to VFS that the VFS switch can call: Many are optional.

Also receives requests from other parts of the kernel, mostly from memory management.





Virtual File System Implementation

- For example, Linux has four object types:
  - inode, file, superblock, dentry
- VFS defines set of operations on the objects that must be implemented
  - Every object has a pointer to a function table
    - Function table has addresses of routines to implement that function on that object
    - For example:
    - • `int open(. . .)` —Open a file
    - • `int close(. . .)` —Close an already-open file
    - • `ssize t read(. . .)` —Read from a file
    - • `ssize t write(. . .)` —Write to a file
    - • `int mmap(. . .)` —Memory-map a file

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 - Contiguous

- An allocation method refers to how disk blocks are allocated for files:

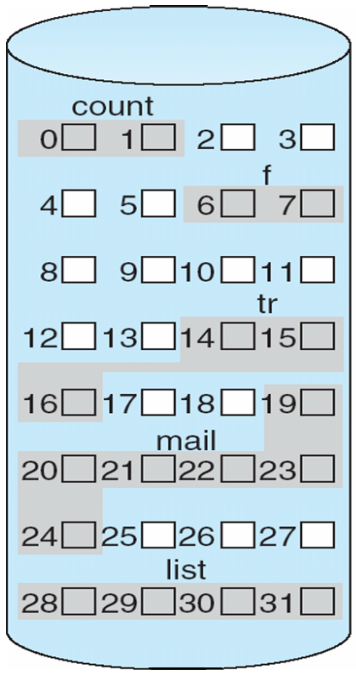
- **Contiguous allocation** – each file occupies set of contiguous blocks
  - Best performance in most cases
  - Simple – only starting location (block #) and length (number of blocks) are required
  - Problems include finding space for file, knowing file size, external fragmentation, need for **compaction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

File Allocation Methods

- The allocation methods define how the files are stored in the disk blocks.
- There are three main disk space or file allocation methods.
  - Contiguous Allocation
  - Linked Allocation
  - Indexed Allocation
- The main idea behind these methods is to provide:
  - Efficient disk space utilization.
  - Fast access to the file blocks.
- All the three methods have their own advantages and disadvantages as discussed below:

Contiguous Allocation

- In this scheme, each file occupies a contiguous set of blocks on the disk.
- The directory entry for a file with contiguous allocation contains
  - Address of starting block
  - Length of the allocated portion.
- *The file 'mail' in the following figure starts from the block 19 with length = 6 blocks. Therefore, it occupies 19, 20, 21, 22, 23, 24 blocks.*



directory

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

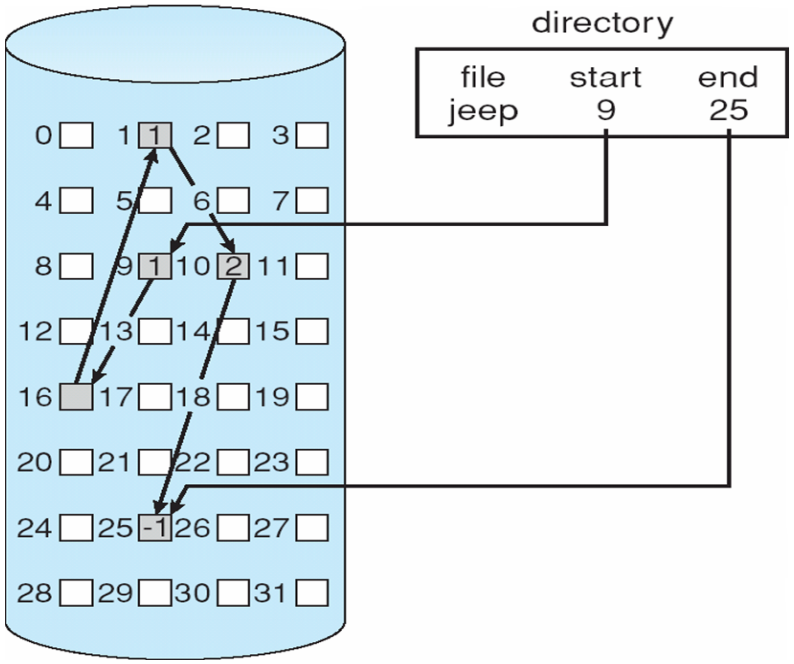
- **Advantages:**
  - Both the Sequential and Direct Accesses are supported by this. For direct access, the address of the k^{th} block of the file which starts at block b can easily be obtained as (b+k).
  - This is extremely fast since the number of seeks are minimal because of contiguous allocation of file blocks.
- **Disadvantages:**
  - This method suffers from both internal and external fragmentation. This makes it inefficient in terms of memory utilization.
  - Increasing file size is difficult because it depends on the availability of contiguous memory at a particular instance.

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

Allocation Methods - Linked

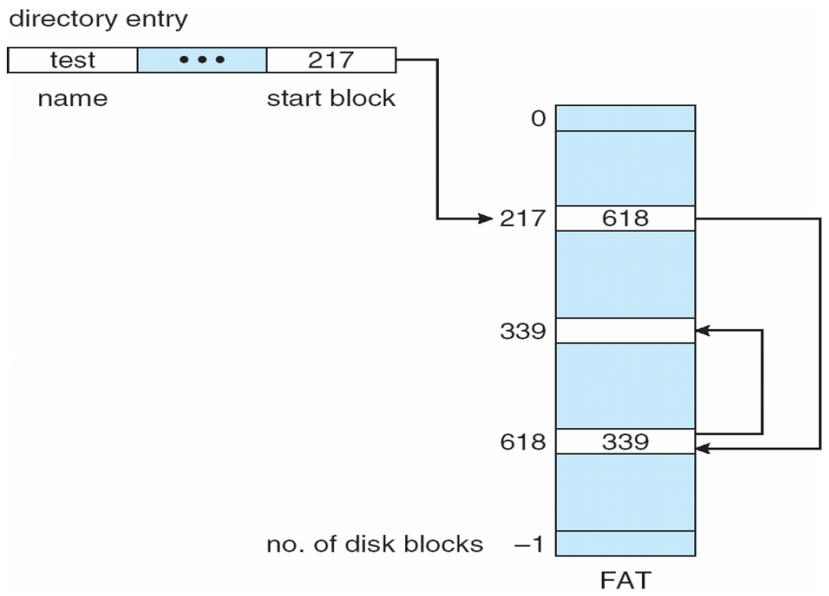
- In this scheme, each file is a linked list of disk blocks which **need not be** contiguous.
  - Each block contains a pointer to the next block occupied by the file.
  - File ends at nil pointer
- The directory entry contains a pointer to the starting and the ending file block.
- *The file 'jeep' in following image shows how the blocks are randomly distributed. The last block (25) contains -1 indicating a null pointer and does not point to any other block.*



- **Advantages:**
  - File size can be increased easily since the system does not have to look for a contiguous chunk of memory.
- **Disadvantages:**
  - Because the file blocks are distributed randomly on the disk, a large number of seeks are needed to access every block individually. This makes linked allocation slower.
  - It does not support random or direct access. We can not directly access the blocks of a file. A block k of a file can be accessed by traversing k blocks sequentially (sequential access) from the starting block of the file via block pointers.
  - Pointers required in the linked allocation incur some extra overhead.
  - Reliability can be a problem

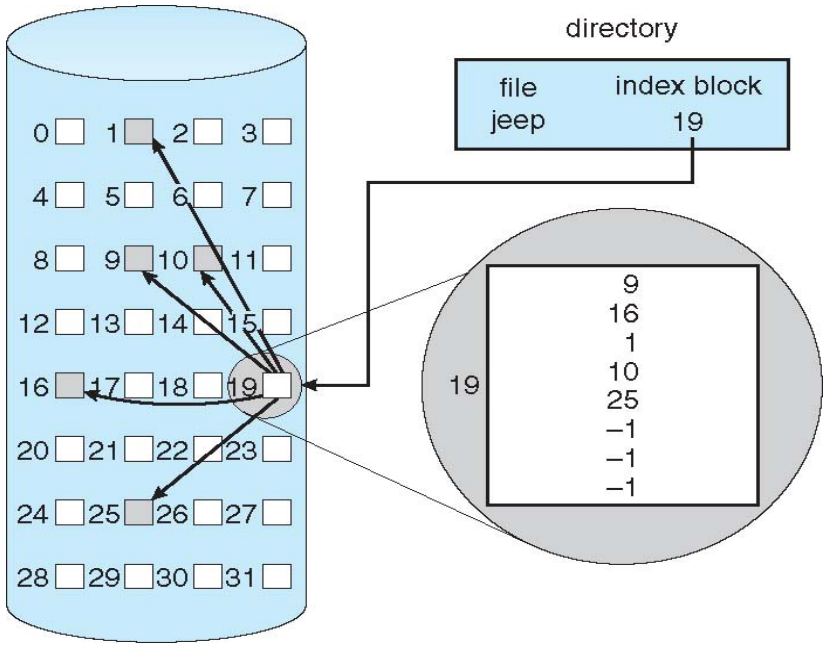
Linked Allocation: File-Allocation Table

- 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



Indexed Allocation

- In this scheme, a special block known as the **Index block** contains the pointers to all the blocks occupied by a file.
- Each file has its own index block. The i^{th} entry in the index block contains the disk address of the i^{th} file block.
- The directory entry contains the address of the index block as shown in the image:



- **Advantages:**
  - This supports direct access to the blocks occupied by the file and therefore provides fast access to the file blocks.
  - 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
  - It overcomes the problem of external fragmentation.
- **Disadvantages:**
  - The pointer overhead for indexed allocation is greater than linked allocation.
  - For very small files, say files that expand only 2-3 blocks, the indexed allocation would keep one entire block (index block) for the pointers which is inefficient in terms of memory utilization. However, in linked allocation we lose the space of only 1 pointer per block.

Indexed Allocation: Mapping

For files that are very large, single index block may not be able to hold all the pointers. Following mechanisms can be used to resolve this:

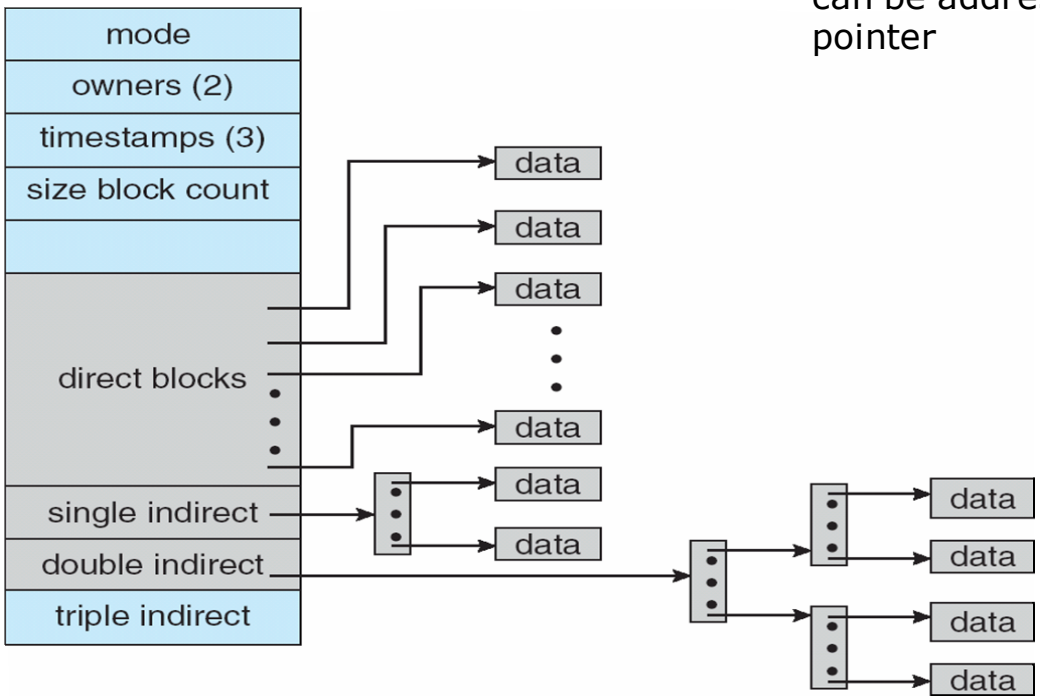
- **Linked scheme:** This scheme links two or more index blocks together for holding the pointers. Every index block would then contain a pointer or the address to the next index block (no limit on size).

- **Multilevel index:** In this policy, a first level index block is used to point to the second level index blocks which inturn points to the disk blocks occupied by the file. This can be extended to 3 or more levels depending on the maximum file size. 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).

- **Combined Scheme:** In this scheme, a special block called the **Inode (information Node)** contains all the information about the file such as the name, size, authority, etc and the remaining space of Inode is used to store the Disk Block addresses which contain the actual file *as shown in the image below.* The first few of these pointers in Inode point to the **direct blocks** i.e the pointers contain the addresses of the disk blocks that contain data of the file. The next few pointers point to indirect blocks. Indirect blocks may be single indirect, double indirect or triple indirect. **Single Indirect block** is the disk block that does not contain the file data but the disk address of the blocks that contain the file data. Similarly, **double indirect blocks** do not contain the file data but the disk address of the blocks that contain the address of the blocks containing the file data.

Combined Scheme: UNIX UFS (4K bytes per block, 32-bit addresses)

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

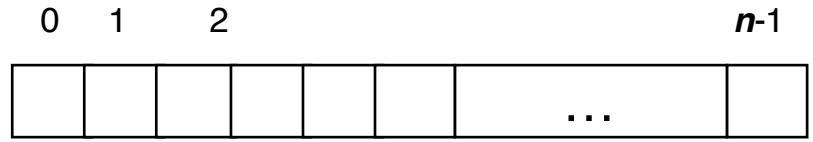


Performance

- Best method depends on file access type
  - Contiguous great for sequential and random
  - Linked good for sequential, not random
  - Indexed more complex
    - Single block access could require 2 index block reads then data block read
    - Clustering can help improve throughput, reduce CPU overhead
- CPU instructions speed vs to save one disk I/O
  - Intel Core i7 Extreme Edition 990x (2011) at 3.46Ghz = 150000 MIPS
    - http://en.wikipedia.org/wiki/Instructions_per_second
  - Typical disk drive at 250 IOPS
    - 150000 MIPS / 250 = 600 million instructions during one disk I/O
  - Fast SSD drives provide 60000 IOPS
    - 150000 MIPS / 60000 = 2.5 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)



bit[*i*] = { 1 ⇒ block[*i*] free ; 0 ⇒ block[*i*] occupied }

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)

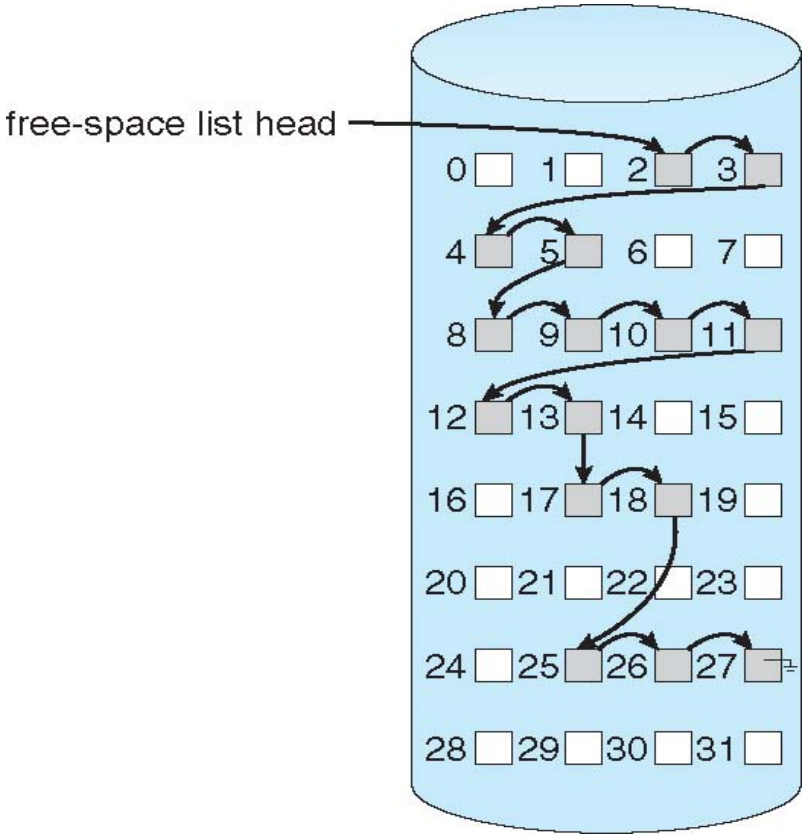
    $n = 2^{40}/2^{12} = 2^{28}$ bits (or 32MB)

    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 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 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

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

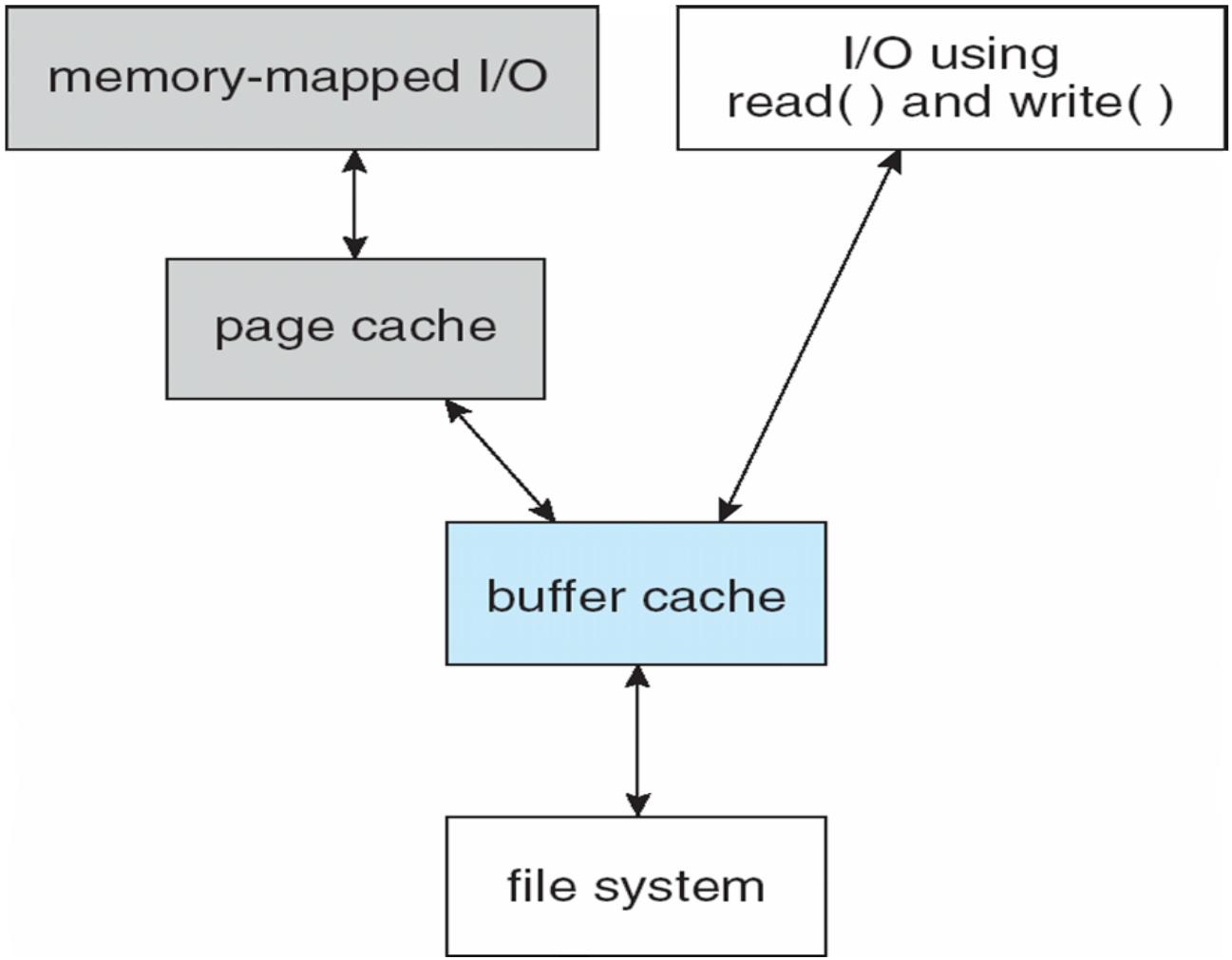
Efficiency and Performance (Cont.)

- 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

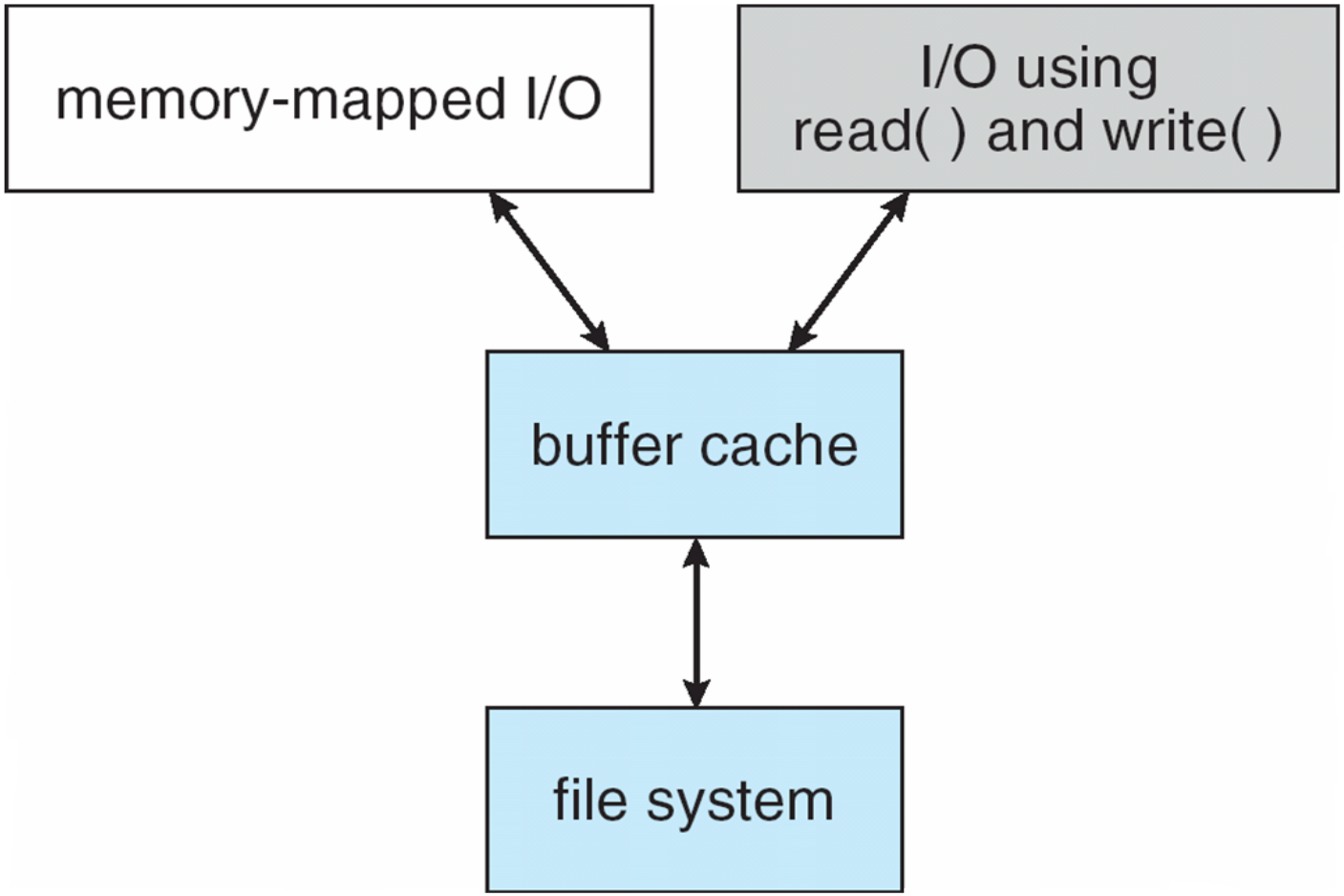
I/O Without a Unified Buffer Cache



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

END