LUT University

LAND OF THE CURIOUS

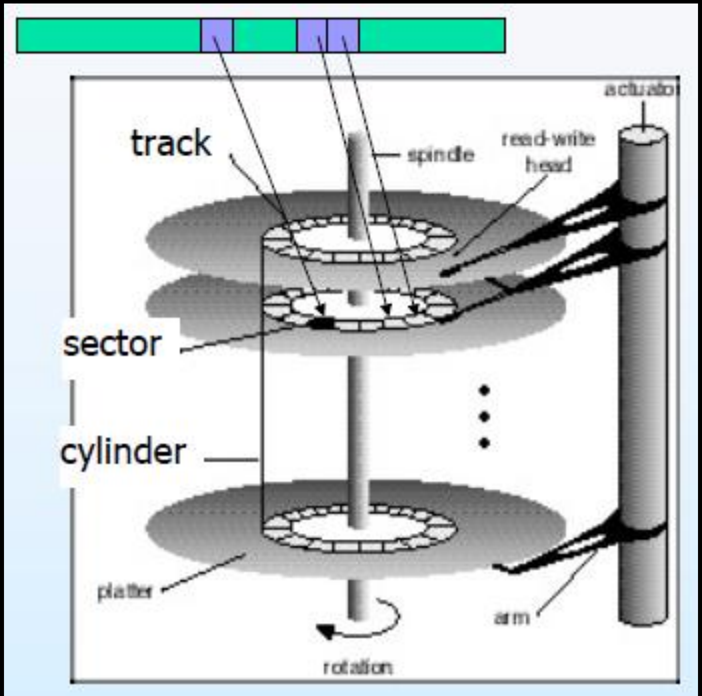
JANUARY 17, 2023

OPERATING SYSTEMS AND SYSTEMS PROGRAMMING (CT30A3370) 6 CREDITS

Venkata Marella

CHAPTER 11: FILE SYSTEM IMPLEMENTATION

- File-System Structure
- File-System Implementation
- Directory Implementation
- Allocation Methods
- Free-Space Management
- Efficiency and Performance
- Recovery
- Log-Structured File Systems
- NFS
- Example: WAFL File System



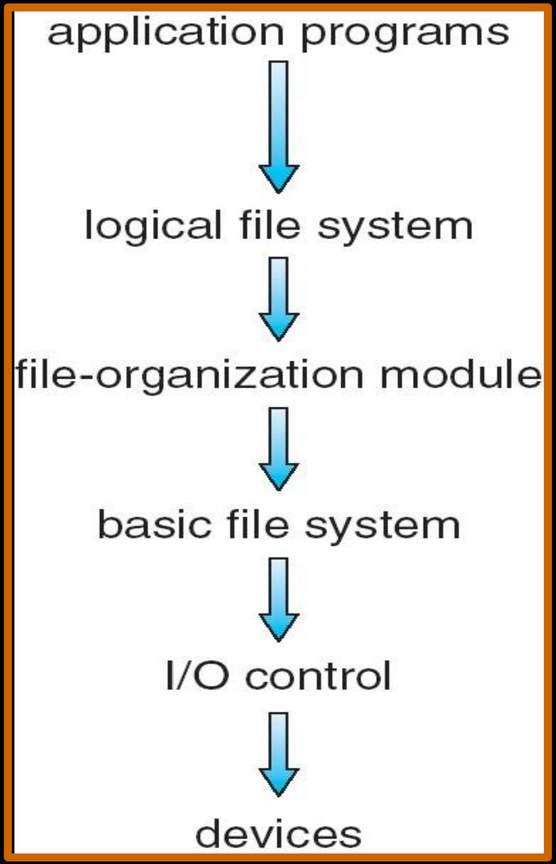
OBJECTIVES

- 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 STRUCTURE

- File structure
  - Logical storage unit
  - Collection of related information
- File system resides on secondary storage (disks)
- File system organized into layers
- **File control block** – storage structure consisting of information about a file

LAYERED FILE SYSTEM



Manages metadata of files, Protection and security

Translates logical block addr To physical addr. Free space mgmt

Commands to r/w physical blocks

A TYPICAL FILE CONTROL BLOCK

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

DATA STRUCTURES USED TO IMPLEMENT FS

- Disk structures
  - Boot control block
  - Volume control block
  - Directory structure per file system
  - Per-file FCB (inode in UFS, master file table entry in NTFS)
- In-memory structures
  - In-memory mount table about each mounted volume
  - Directory cache
  - System-wide open-file table
  - Per-process open-file table

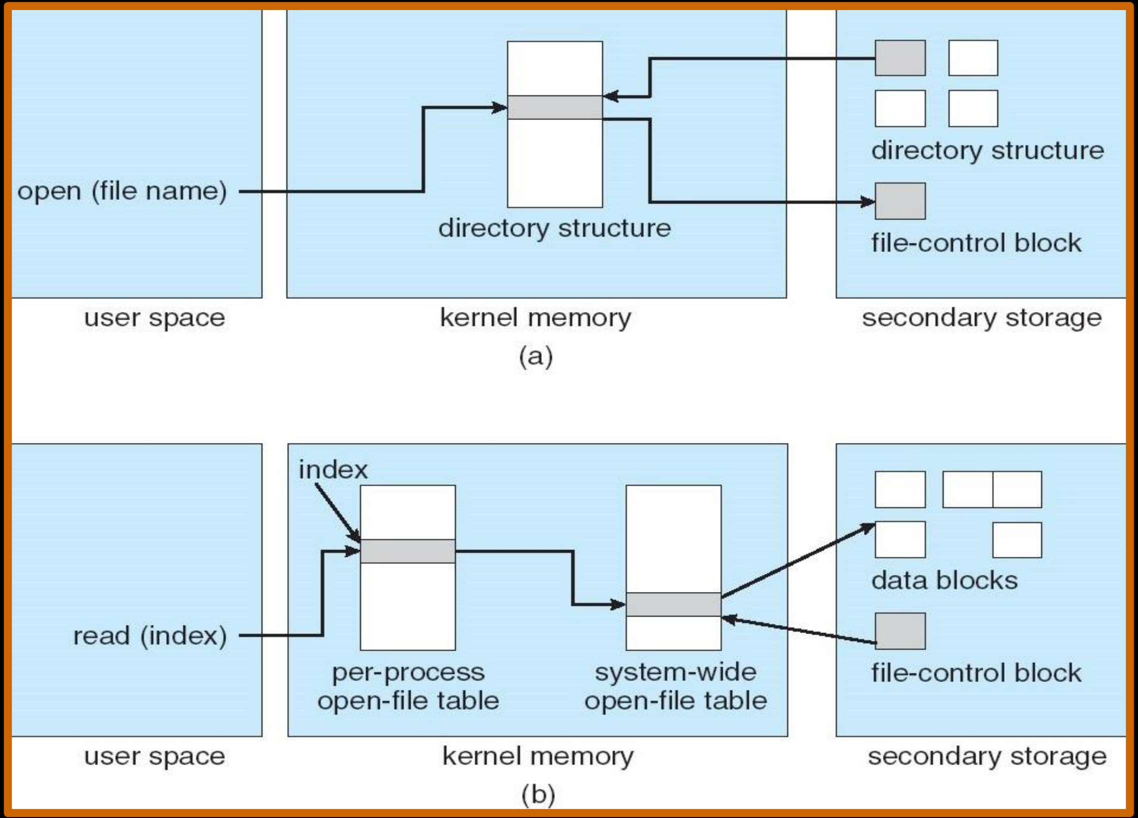
IN-MEMORY FILE SYSTEM STRUCTURES

- The following figure illustrates the necessary file system structures provided by the operating systems.

- Figure 12-3(a) refers to opening a file.

- Figure 12-3(b) refers to reading a file.

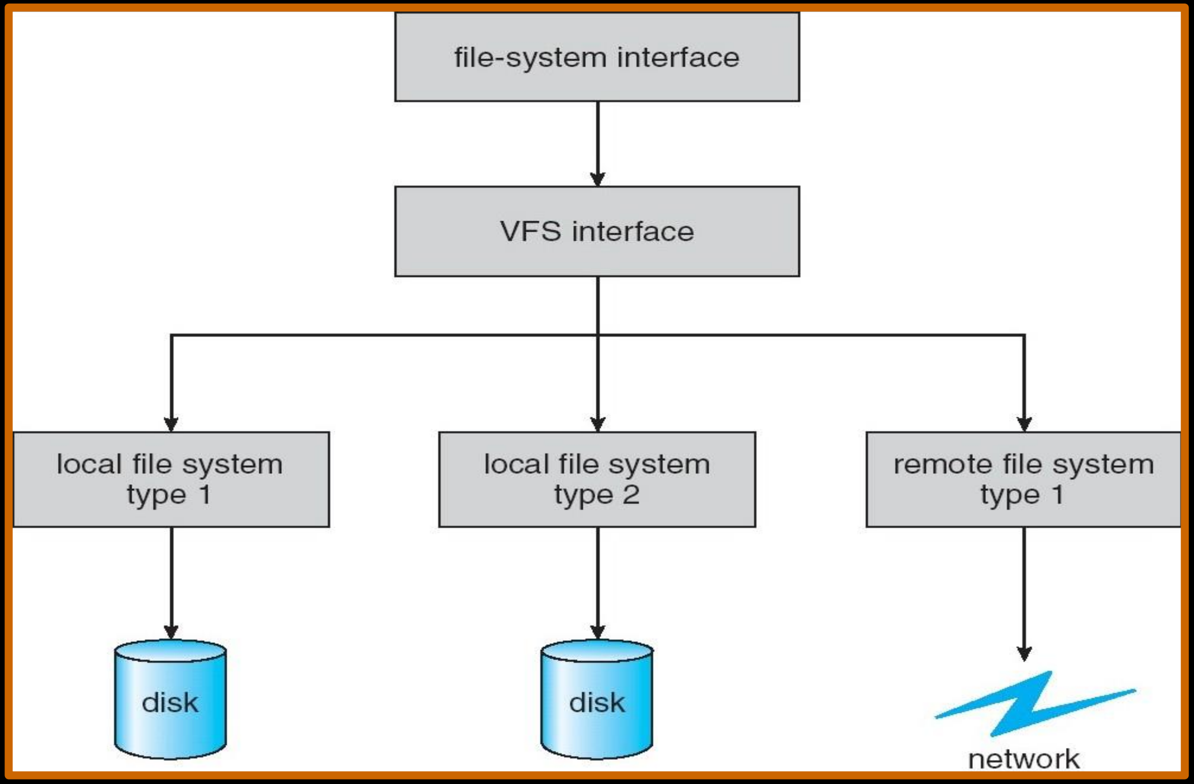
IN-MEMORY FILE SYSTEM STRUCTURE



VIRTUAL FILE SYSTEMS

- Virtual File Systems (VFS) 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.
- The API is to the VFS interface, rather than any specific type of file system.
- Defines a network-wide unique structure called vnode.

SCHEMATIC VIEW OF VIRTUAL FILE SYSTEM



DIRECTORY IMPLEMENTATION

- **Linear list** of file names with pointer to the data blocks.
  - simple to program
  - time-consuming to execute

tradeoff

- **Hash Table** – linear list with hash data structure.
  - decreases directory search time
  - **collisions** – situations where two file names hash to the same location
  - fixed size – can use chained-overflow hash table

ALLOCATION METHODS

- An allocation method refers to how disk blocks are allocated for files:
- **Contiguous allocation**
- **Linked allocation**
- **Indexed allocation**

CONTIGUOUS ALLOCATION

- Each file occupies a set of contiguous blocks on the disk
- Simple - only starting location (block #) and length (number of blocks) are required
- Random access supported
- Wasteful of space (dynamic storage-allocation problem)
- Files cannot grow

CONTIGUOUS ALLOCATION

- Mapping from logical to physical

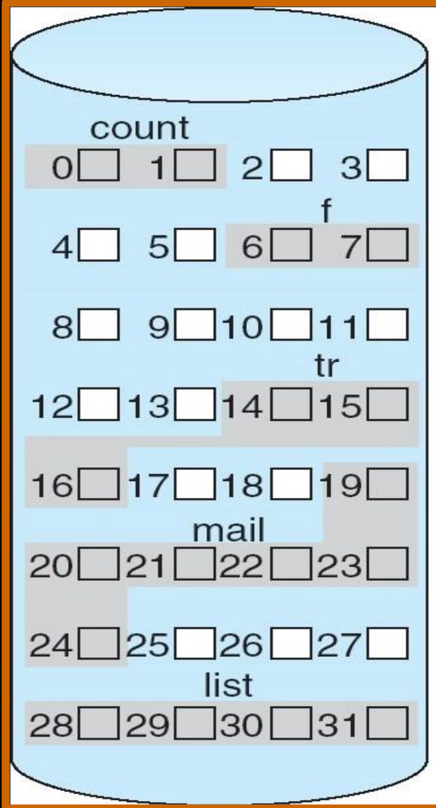
Q

LA/512

R

Block to be accessed = Q + start_address
Displacement into block = R

CONTIGUOUS ALLOCATION OF DISK SPACE

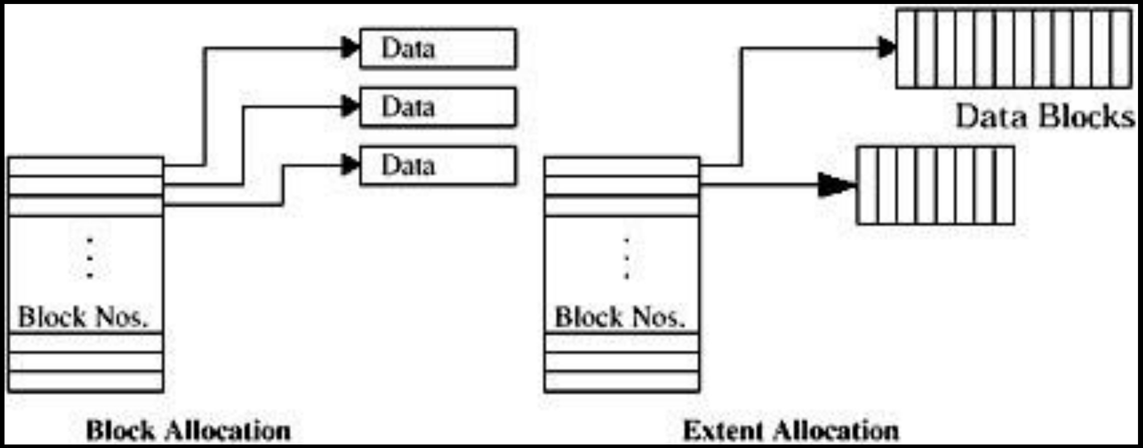


directory

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

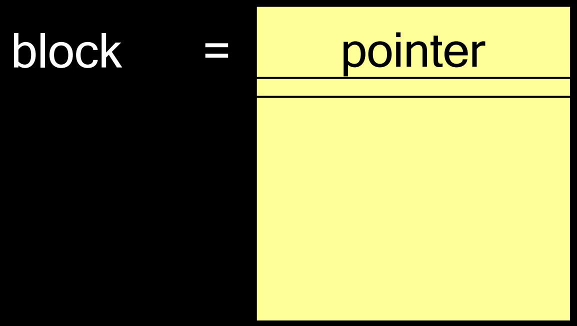
EXTENT-BASED SYSTEMS

- 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 disk blocks: blocks may be scattered anywhere on the disk.



LINKED ALLOCATION (CONT.)

- Simple – need only starting address
- Free-space management system – no waste of space
- No random access, poor reliability
- Mapping

Q

LA/511

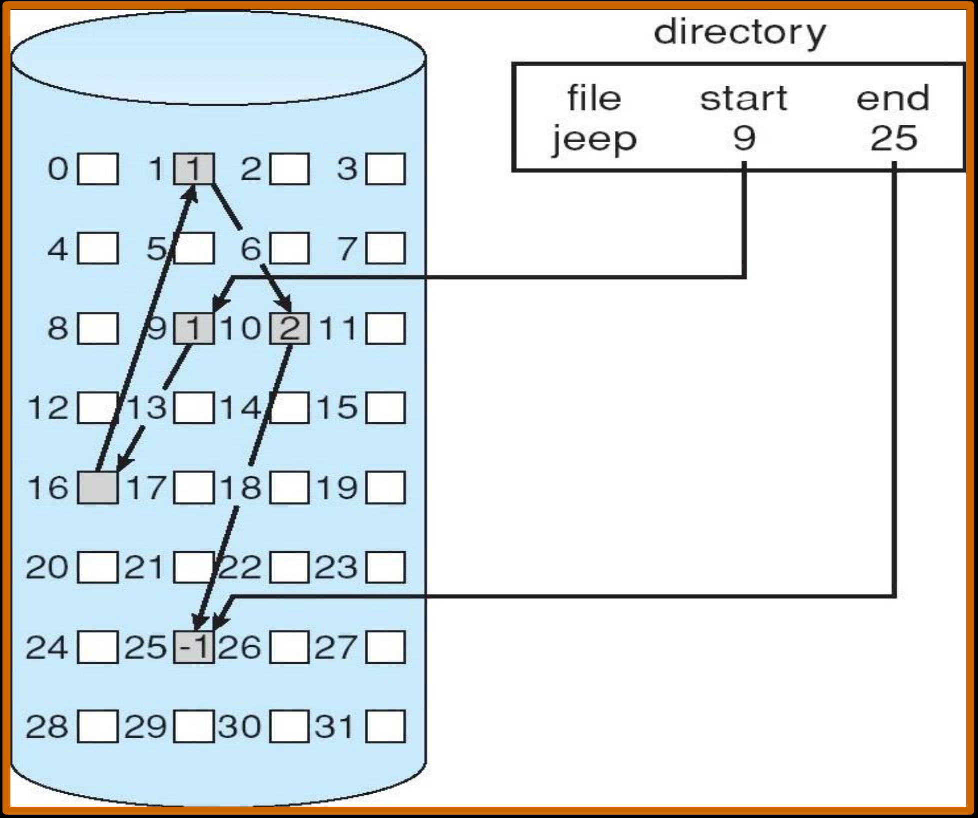
R

Block to be accessed is the Qth block in the linked chain of blocks representing the file.

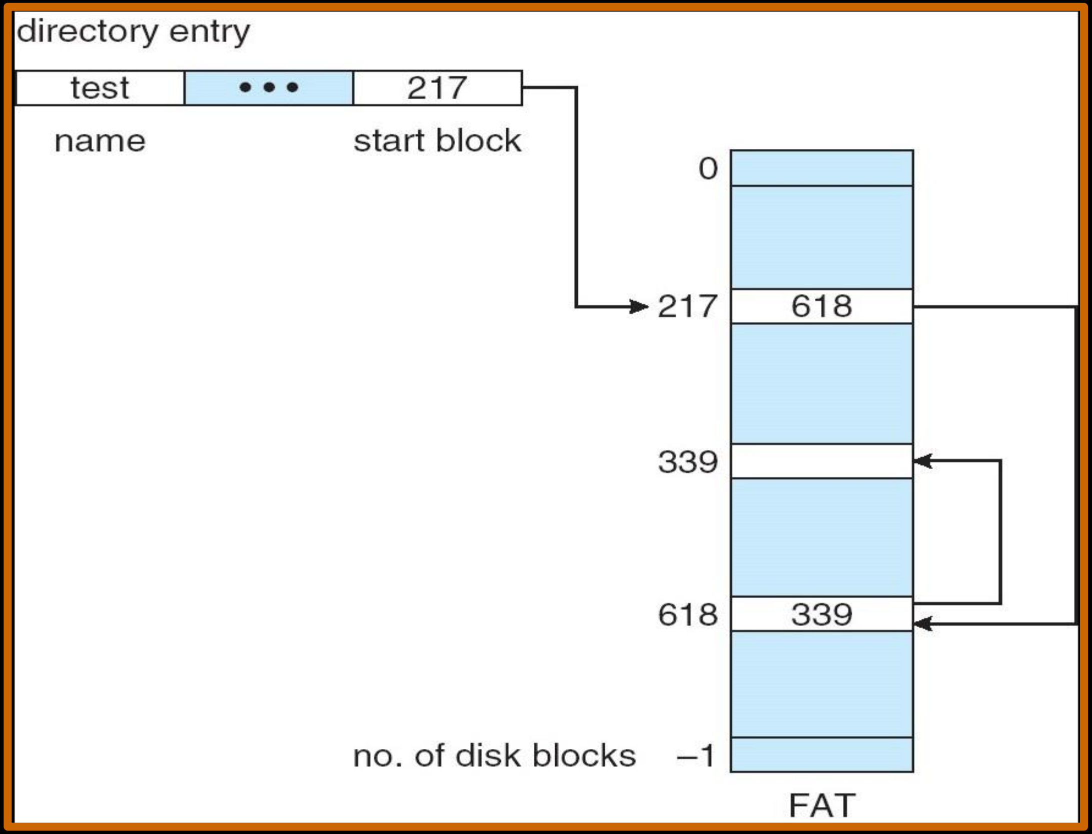
Displacement into block = R + 1

File-allocation table (FAT) – disk-space allocation used by MS-DOS and OS/2.

LINKED ALLOCATION

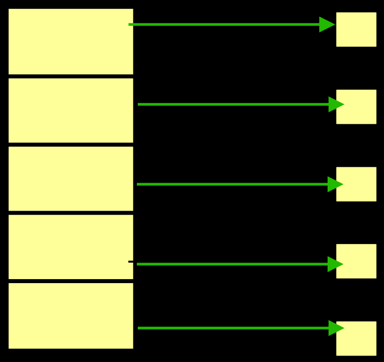


FILE-ALLOCATION TABLE



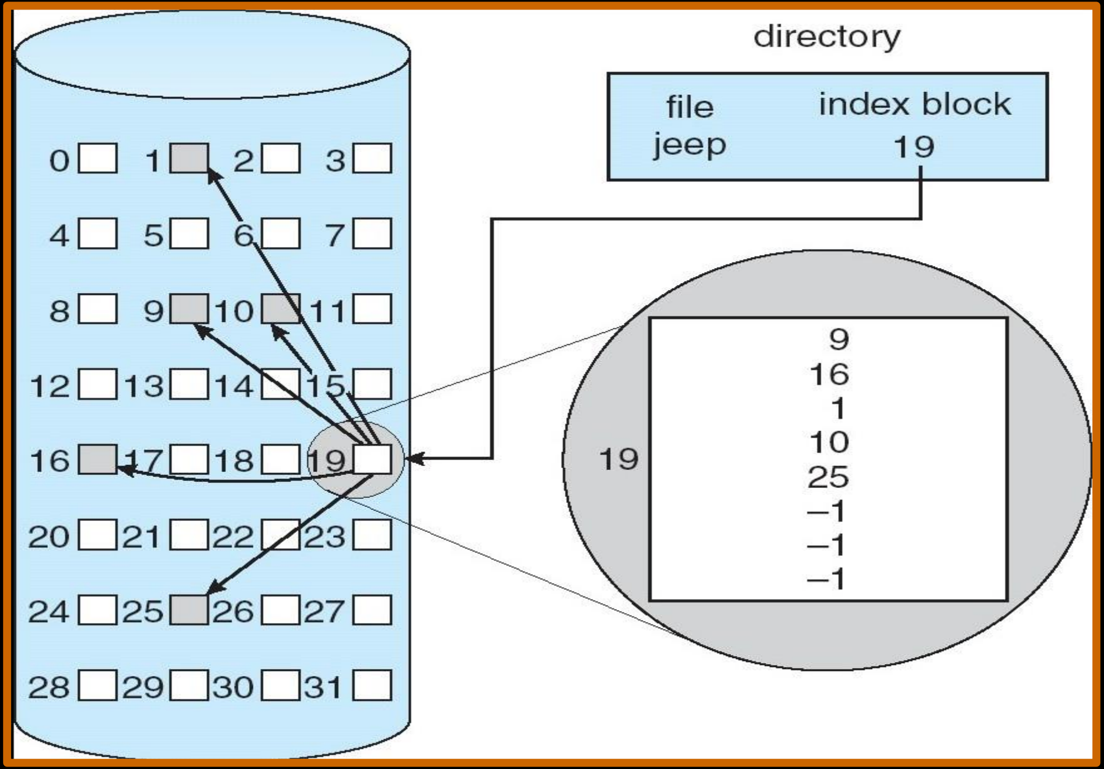
INDEXED ALLOCATION

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

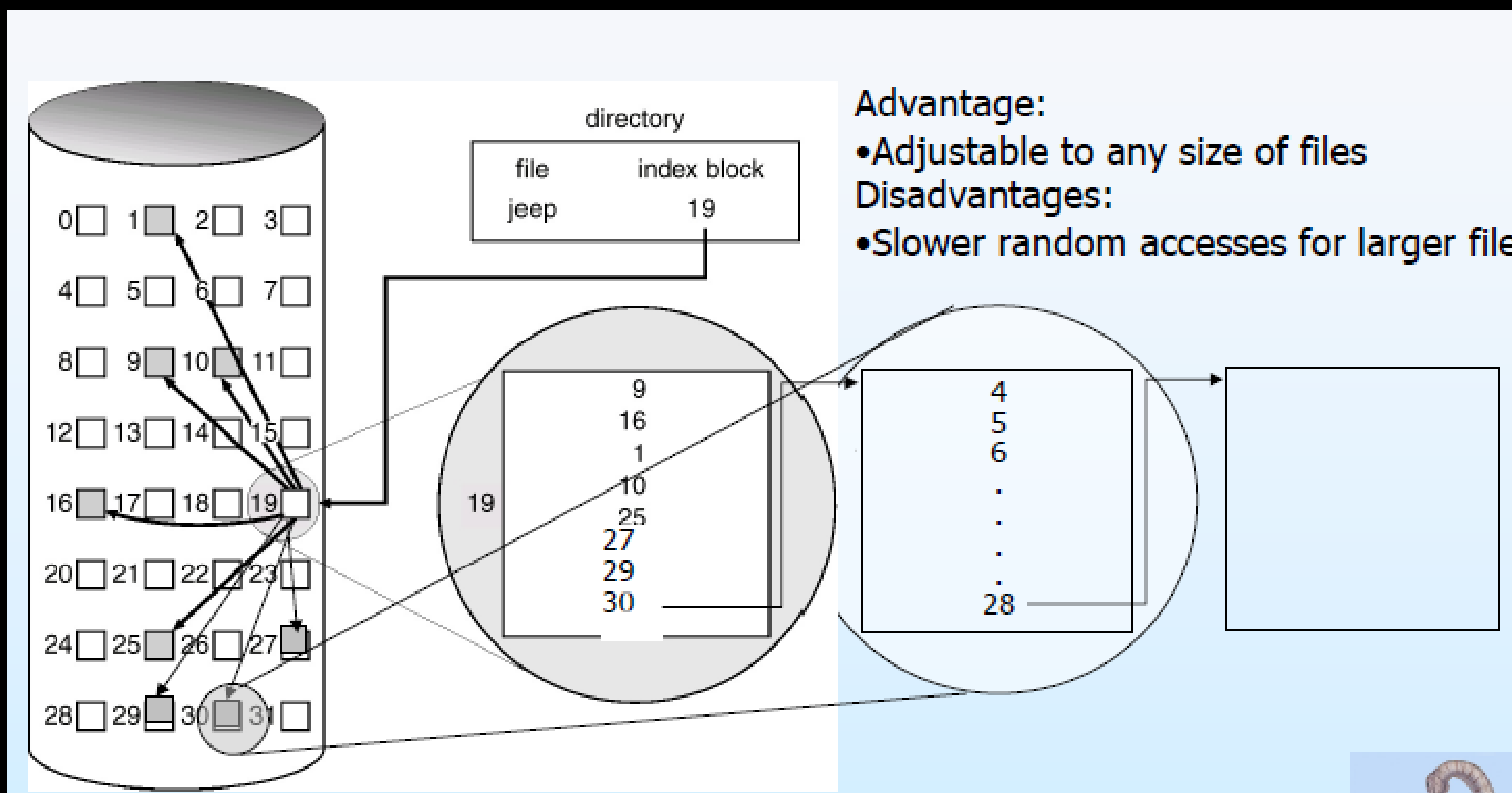


index table

EXAMPLE OF INDEXED ALLOCATION



EXAMPLE OF INDEXED ALLOCATION (CONT.)



INDEXED ALLOCATION (CONT.)

- Need index table (analogous to page table)
- Random access
- Dynamic access without external fragmentation, but have overhead of index block.
- When mapping from logical to physical in a file of maximum size of 256K words and block size of 512 words (512=2^9, 2^9 * 2^9 = 2^18, 2^18 /1024 = 256). We need only 1 block for index table.

Q

LA/512

R

Q = displacement into index table
R = displacement into block

INDEXED ALLOCATION – MAPPING (CONT.)

- When mapping from logical to physical in a file of unbounded length (block size of 512 words). - more pointers are needed
- 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:

INDEXED ALLOCATION – MAPPING (CONT.)

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

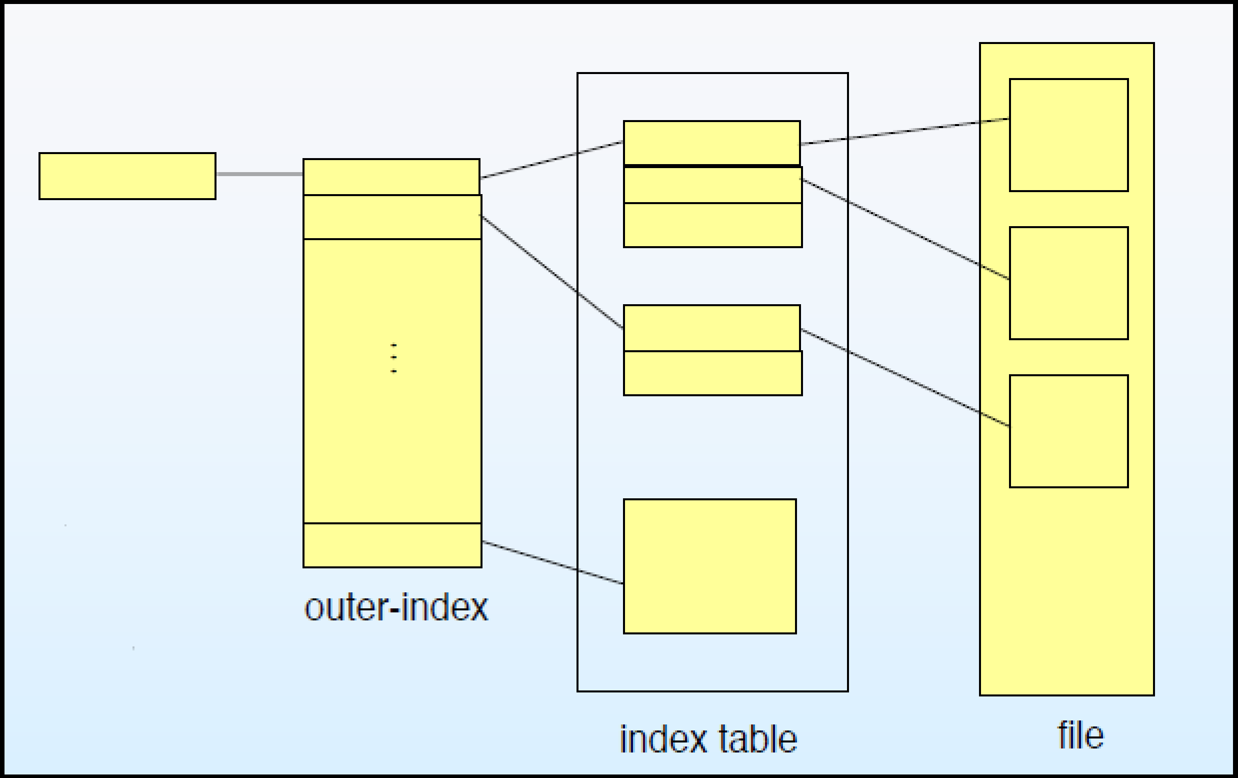
$$LA / (512 \times 512) \rightarrow Q_1, R_1$$

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

$$R_1 / 512 \rightarrow Q_2, R_2$$

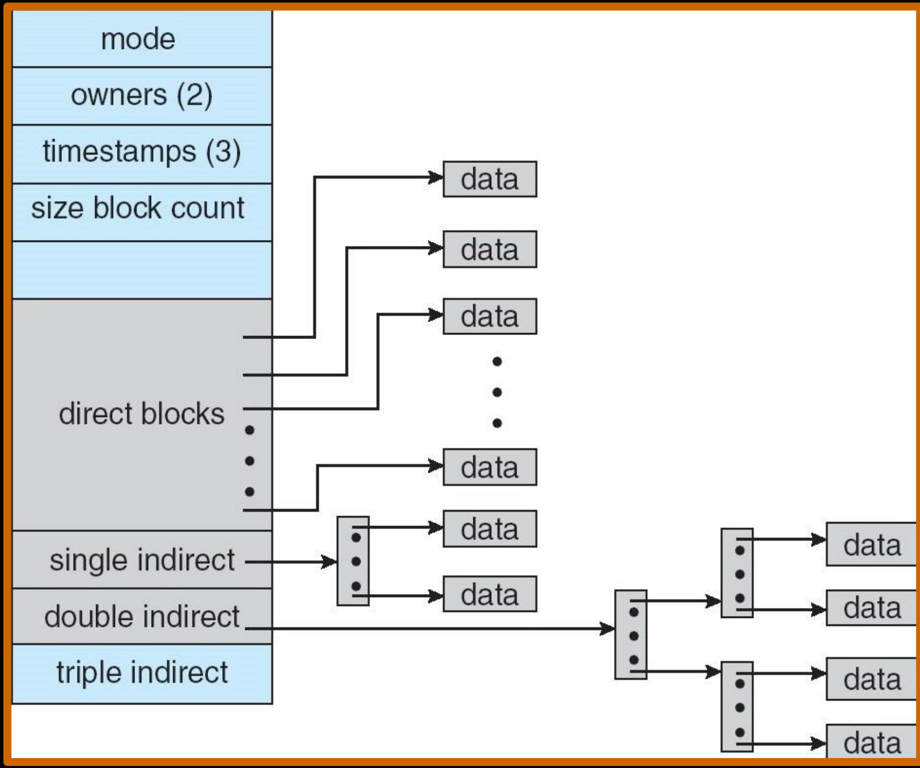
Q_2 = displacement into block of index table
R_2 displacement into block of file:

INDEXED ALLOCATION – MAPPING (CONT.)



COMBINED SCHEME: UNIX (4K BYTES PER BLOCK)

- Inode
  - File information
  - The first 12 pointers point directly to data blocks
  - The 13th pointer points to an index block
  - The 14th pointer points to a block containing the addresses of index blocks
  - The 15th pointer points to a triple index block.



FILE SYSTEM

- Consider a UNIX filesystem with the following components:
  - Disk blocks are 4096 bytes. Sectors are 512 bytes long.
  - All metadata pointers are 32-bits long.
  - An inode has 12 direct block pointers, one indirect block pointer and one double-indirect block pointer.
  - The total inode size is 256 bytes.
  - Both indirect and double indirect blocks take up an entire disk block.

FREE-SPACE MANAGEMENT (CONT.)

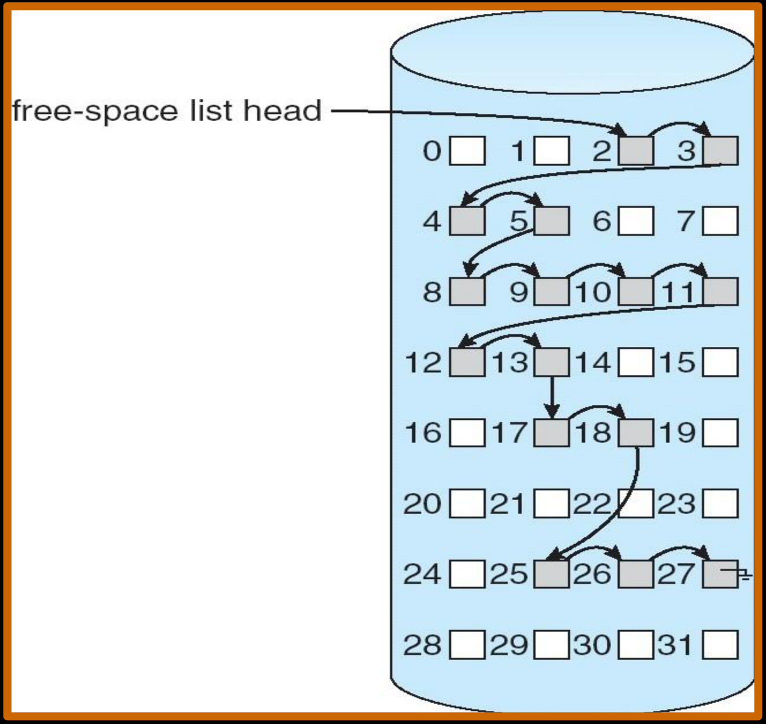
- Bit map requires extra space
  - Example:

    block size $= 2^{12}$ bytes

    disk size $= 2^{30}$ bytes (1 gigabyte)

    $n = 2^{30}/2^{12} = 2^{18}$ bits (or 32K bytes)
- Easy to get contiguous files
- Linked list (free list) – see figure
  - Cannot get contiguous space easily
  - But basically can work (FAT)
  - No waste of space
- Grouping – a modification of the Linked List
  - Addresses of the n free blocks are stored in the first block.
  - The first n-1 blocks are actually free. The last block contains addresses of another n free blocks
- Counting - Address of the first free block and number n contiguous blocks

LINKED FREE SPACE LIST ON DISK



FREE-SPACE MANAGEMENT (CONT.)

- Need to protect:
  - Pointer to free list
  - Bit map
    - Must be kept on disk
    - The copy in memory and disk may differ
    - Cannot allow for block[*i*] to have a situation where bit[*i*] = 1 in memory and bit[*i*] = 0 on disk
  - Solution:
    - Set bit[*i*] = 1 in disk
    - deallocate block[*i*]
    - Set bit[*i*] = 1 in memory

EFFICIENCY AND PERFORMANCE

- Efficiency dependent on:
  - disk allocation and directory algorithms
  - types of data kept in file's directory entry (for example "last write date" is recorded in directory)

  Generally, every data item has to be considered for its effect.
- Performance
  - **disk cache** – separate section of main memory for frequently used blocks
  - **free-behind and read-ahead** – techniques to optimize sequential access
  - improve PC performance by dedicating section of memory as virtual disk, or **RAM disk**

PAGE CACHE

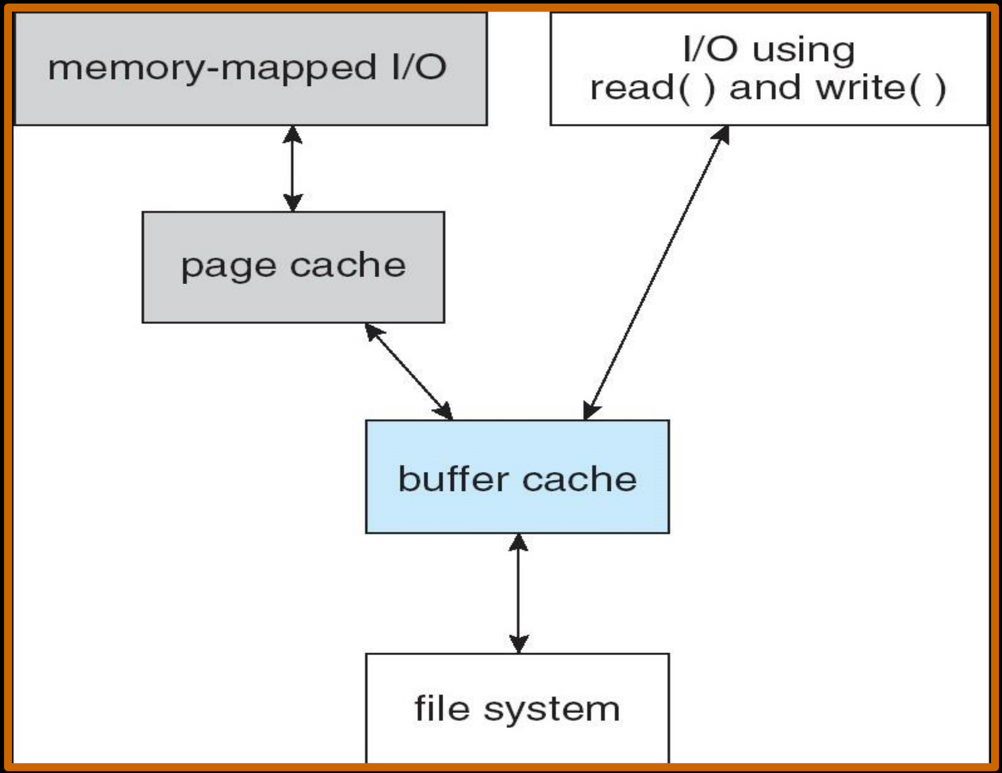
- A **page cache** caches pages rather than disk blocks using virtual memory techniques

- 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

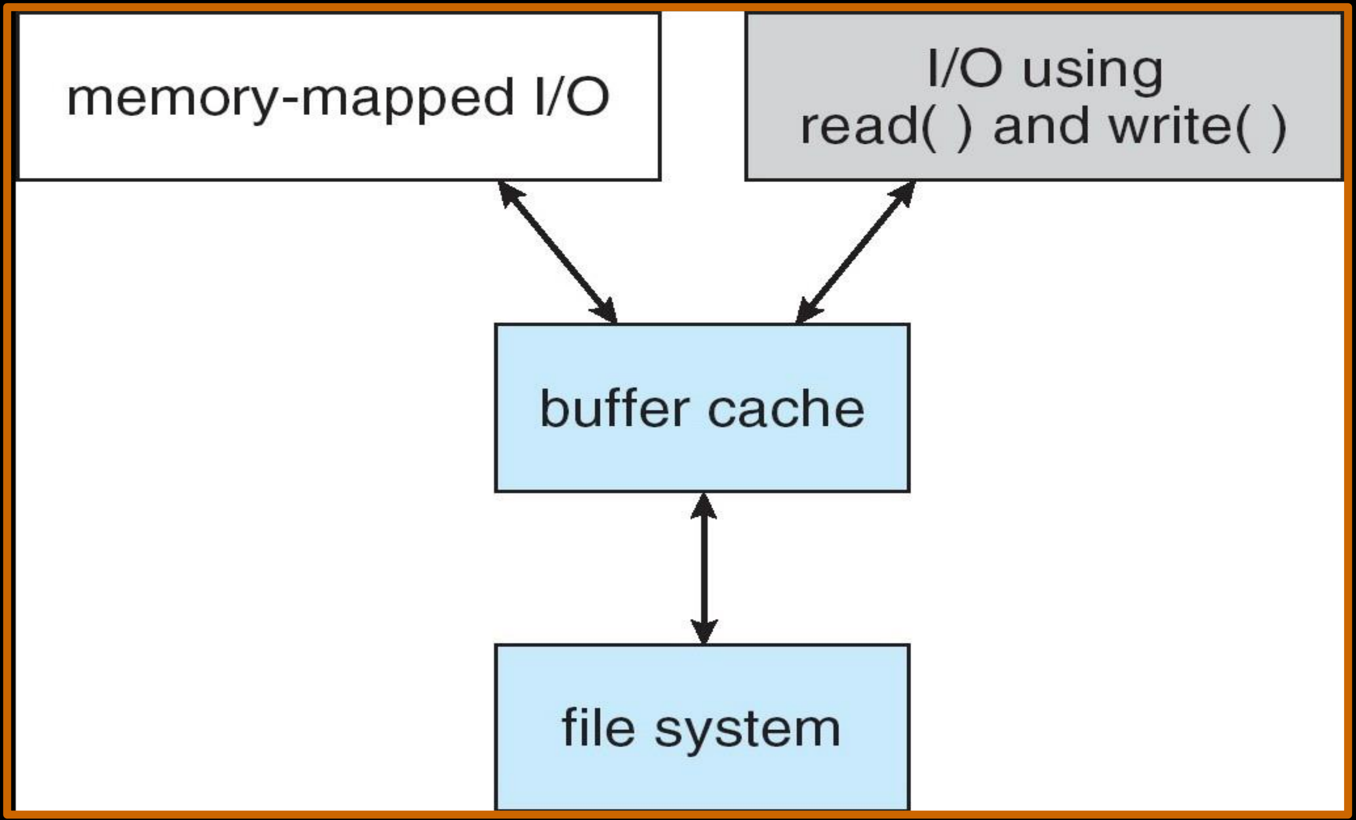
I/O WITHOUT A UNIFIED BUFFER CACHE



UNIFIED BUFFER CACHE

- A unified buffer cache uses the same page cache to cache both memory-mapped pages and ordinary file system I/O
- Avoids double caching

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

- Use system programs to **back up** data from disk to another storage device (floppy disk, magnetic tape, other magnetic disk, optical)

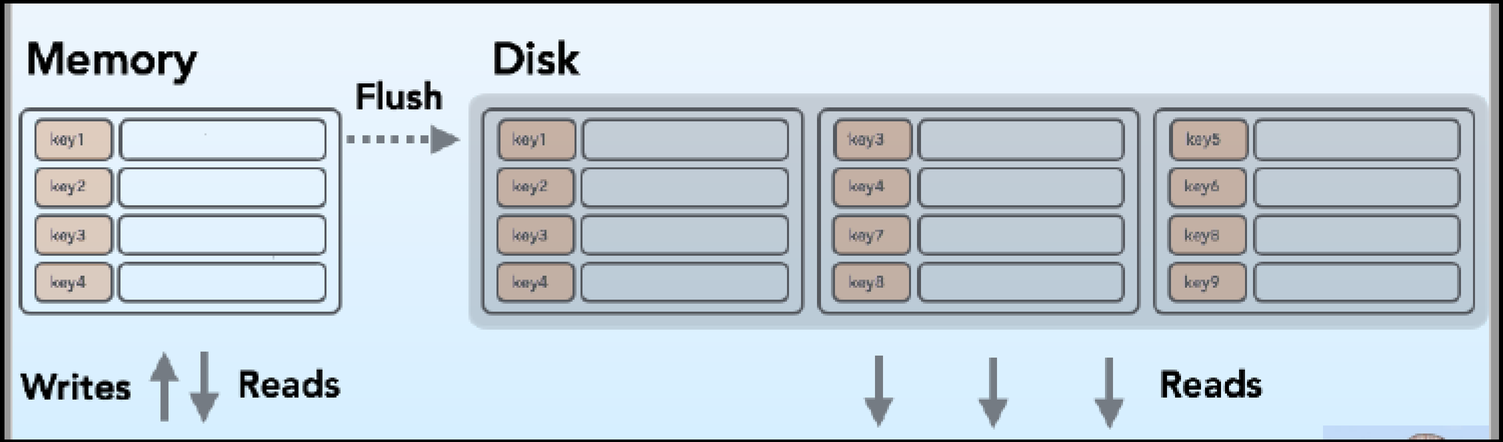
- Recover lost file or disk by **restoring** data from backup. **Full backup** and N **incremental backups** for convenience.

LOG STRUCTURED FILE SYSTEMS

- **Log structured** (or journaling) file systems record each 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
  - However, the file system may not yet be updated
- The transactions in the log are asynchronously written to the file system
  - When the file system is modified, the transaction is removed from the log
- If the file system crashes, all remaining transactions in the log must still be performed

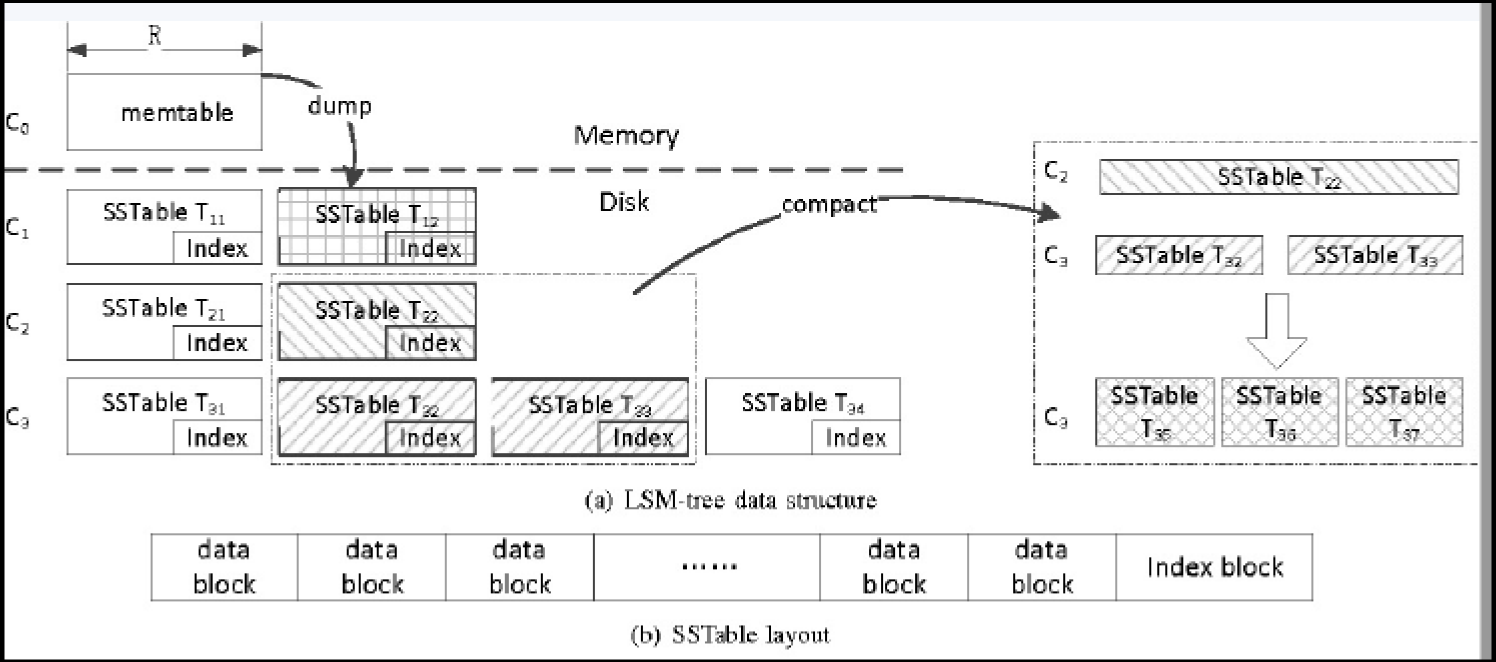
LOG STRUCTURED MERGE (LSM) TREE

- Writes are initially done to an in-memory structure called memtable, where the keys are kept sorted (random access of RAM is not expensive). Once the table “fills up”, it’s persisted in disk as an immutable (read-only) file



LOG STRUCTURED MERGE TREE

» If tables are full, a compaction algorithm is invoked.

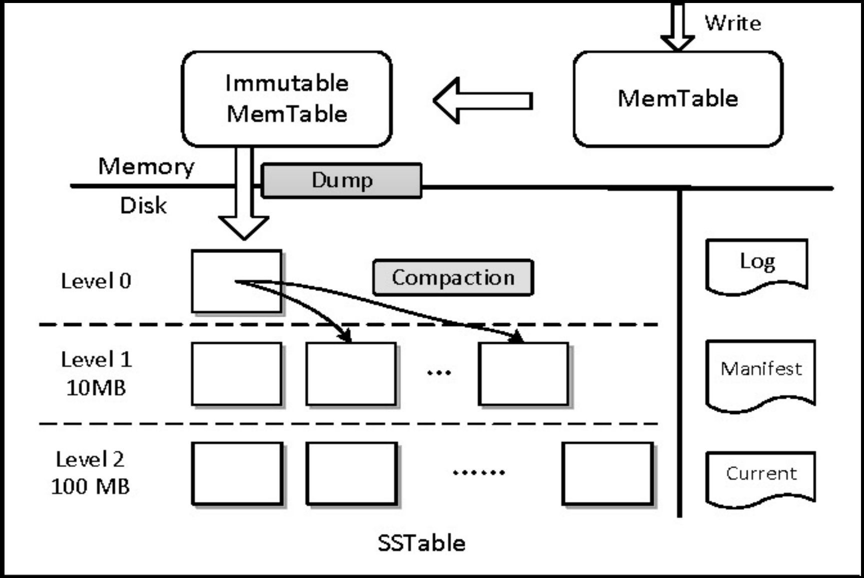


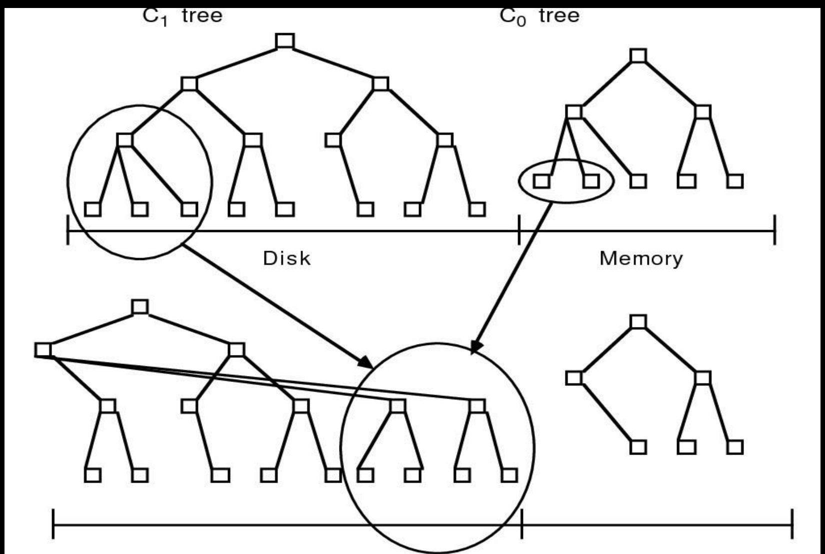
(a) LSM-tree data structure

(b) SSTable layout

LOG STRUCTURED MERGE TREE

- Layer by Layer Compaction
- Each level is k times larger than the previous one. In LevelDB [4], level L has a (10^L) MB size limit (that is, 10MB for level 1, 100MB for level 2, etc).





e 2.2. Conceptual picture of rolling merge steps, with result writt

THE SUN NETWORK FILE SYSTEM (NFS)

- An implementation and a specification of a software system for accessing remote files across LANs (or WANs)

- The implementation is part of the Solaris and SunOS operating systems running on Sun workstations using an unreliable datagram protocol (UDP/IP protocol and Ethernet)

NFS (CONT.)

- Interconnected workstations viewed as a set of independent machines with independent file systems, which allows sharing among these file systems in a transparent manner
  - A remote directory is mounted over a local file system directory
    - The mounted directory looks like an integral subtree of the local file system, replacing the subtree descending from the local directory
  - Specification of the remote directory for the mount operation is nontransparent; the host name of the remote directory has to be provided
    - Files in the remote directory can then be accessed in a transparent manner
  - Subject to access-rights accreditation, potentially any file system (or directory within a file system), can be mounted remotely on top of any local directory

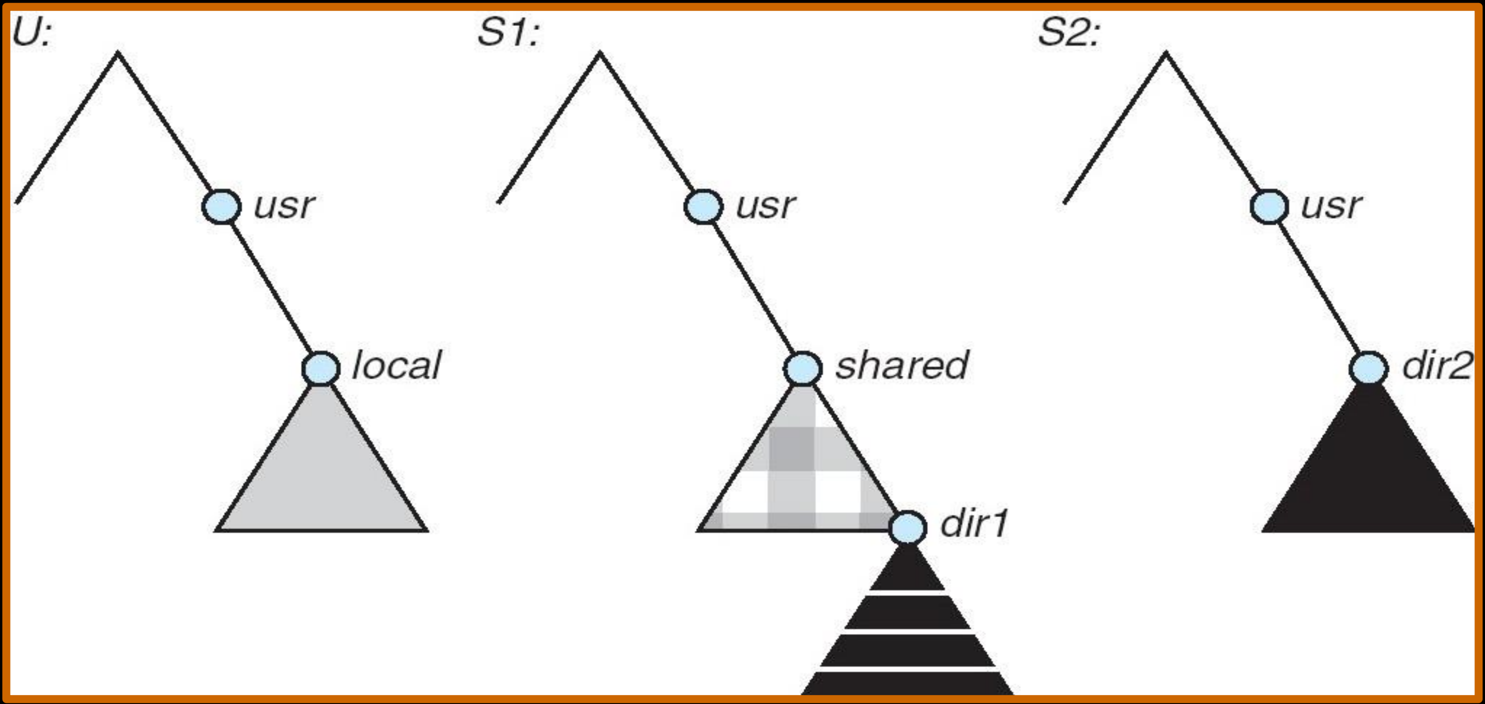
NFS (CONT.)

- NFS is designed to operate in a heterogeneous environment of different machines, operating systems, and network architectures; the NFS specifications independent of these media
- This independence is achieved through the use of RPC primitives built on top of an External Data Representation (XDR) protocol used between two implementation-independent interfaces
- The NFS specification distinguishes between the services provided by a mount mechanism and the actual remote-file-access services

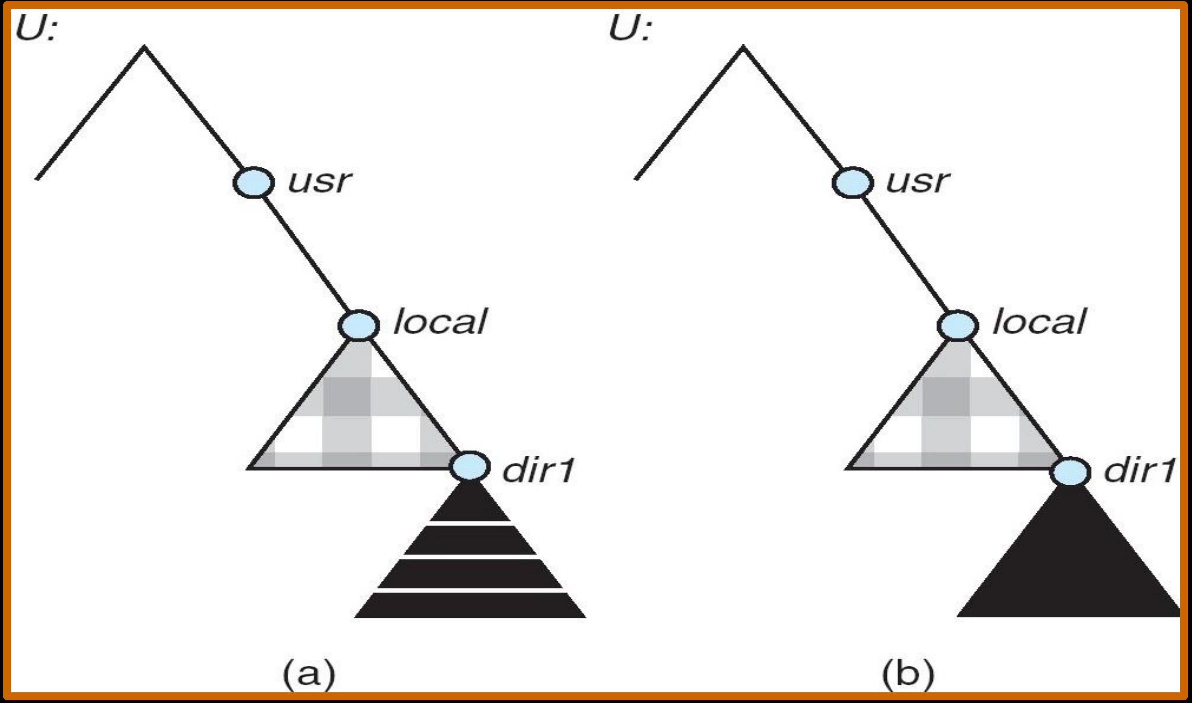
Mount protocol

NFS protocol

THREE INDEPENDENT FILE SYSTEMS



MOUNTING IN NFS



Mounts

Cascading mounts are allowed

Mount S1:/usr/shared
Over U:/usr/local

Then mount S2:/usr/dir2
Over U:/usr/local/dir1

NFS MOUNT PROTOCOL

- Establishes initial logical connection between server and client
- Mount operation includes name of remote directory to be mounted and name of server machine storing it
  - Mount request is mapped to corresponding RPC and forwarded to mount server running on server machine
  - Export list - specifies local file systems that server exports for mounting, along with names of machines that are permitted to mount them
- Following a mount request that conforms to its export list, the server returns a file handle—a key for further accesses
- File handle - a file-system identifier, and an inode number to identify the mounted directory within the exported file system
- The mount operation changes only the user's view and does not affect the server side

NFS PROTOCOL

- Provides a set of remote procedure calls for remote file operations. The procedures support the following operations:
  - searching for a file within a directory
  - reading a set of directory entries
  - manipulating links and directories
  - accessing file attributes
  - reading and writing files
- NFS servers are **stateless**; each request has to provide a full set of arguments (unique file id, absolute offset inside file)

  (NFS V4 is just coming available – very different, stateful)
- Modified data must be committed to the server's disk before results are returned to the client (lose advantages of caching)
- The NFS protocol does not provide concurrency-control mechanisms

THREE MAJOR LAYERS OF NFS ARCHITECTURE

- UNIX file-system interface (based on the **open, read, write**, and **close** calls, and **file descriptors**)
- *Virtual File System* (VFS) layer – distinguishes local files from remote ones, and local files are further distinguished according to their file-system types
  - The VFS activates file-system-specific operations to handle local requests according to their file-system types
  - Calls the NFS protocol procedures for remote requests
- NFS service layer – bottom layer of the architecture
  - Implements the NFS protocol

NFS PATH-NAME TRANSLATION

- Performed by breaking the path into component names and performing a separate NFS lookup call for every pair of component name and directory vnode

- To make lookup faster, a directory name lookup cache on the client’s side holds the vnodes for remote directory names

NFS REMOTE OPERATIONS

- Nearly one-to-one correspondence between regular UNIX system calls and the NFS protocol RPCs (except opening and closing files)
- NFS adheres to the remote-service paradigm, but employs buffering and caching techniques for the sake of performance
- File-blocks cache – when a file is opened, the kernel checks with the remote server whether to fetch or revalidate the cached attributes
  - Cached file blocks are used only if the corresponding cached attributes are up to date
- File-attribute cache – the attribute cache is updated whenever new attributes arrive from the server
- Clients do not free delayed-write blocks until the server confirms that the data have been written to disk

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 (flash memory) for write caching
- Similar to Berkeley Fast File System, with extensive modifications


LUT
University