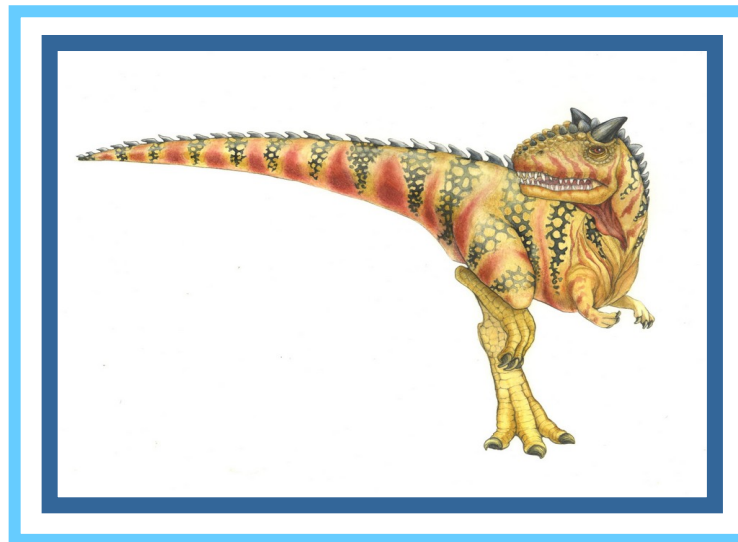
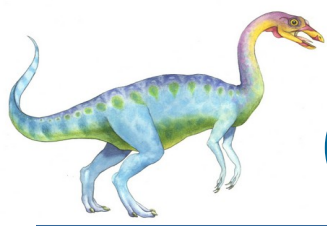


# Chapter 11: File System Implementation

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# Chapter 11: File System Implementation

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





# Objectives

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- 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

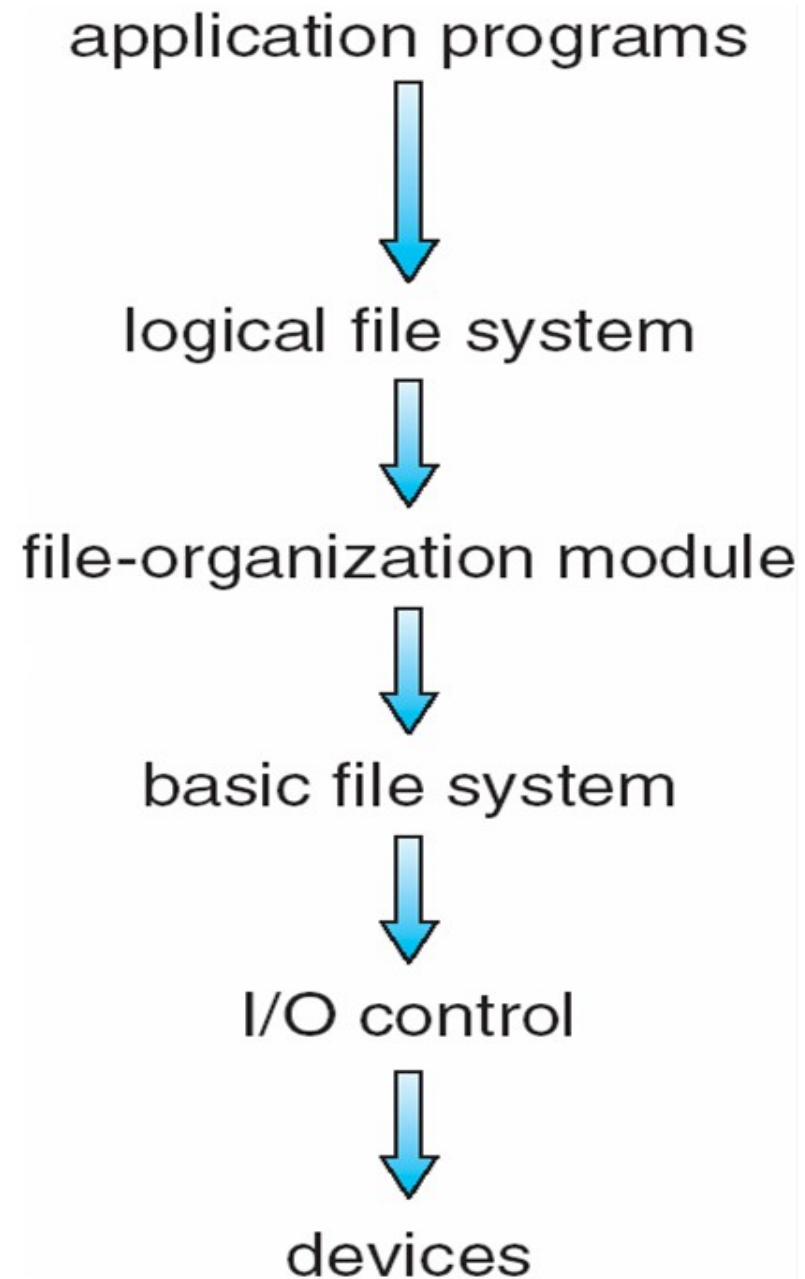
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- File structure
  - Logical storage unit
  - Collection of related information
- **File system** resides on secondary storage (disks)
  - Provided user interface to storage, mapping logical to physical
  - Provides efficient and convenient access 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







# 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





# In-Memory File System Structures

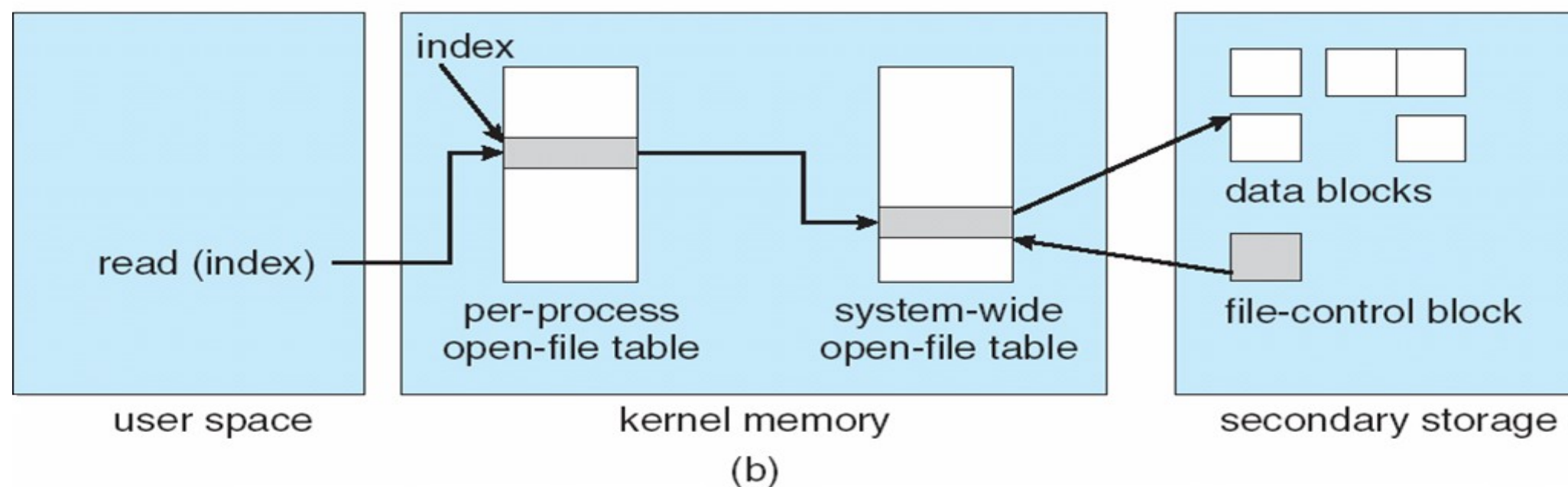
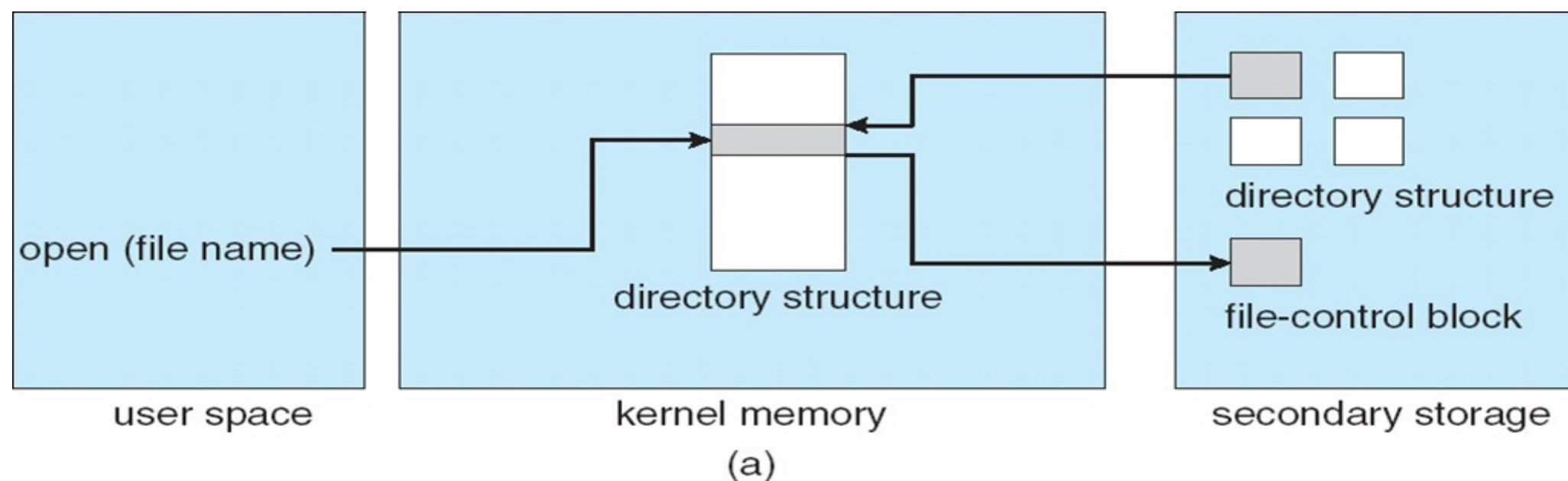
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- Mount table storing file system mounts, mount points, file system types
- The following figure illustrates the necessary file system structures provided by the operating systems
- Figure 11-3(a) refers to opening a file
- Figure 11-3(b) refers to 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





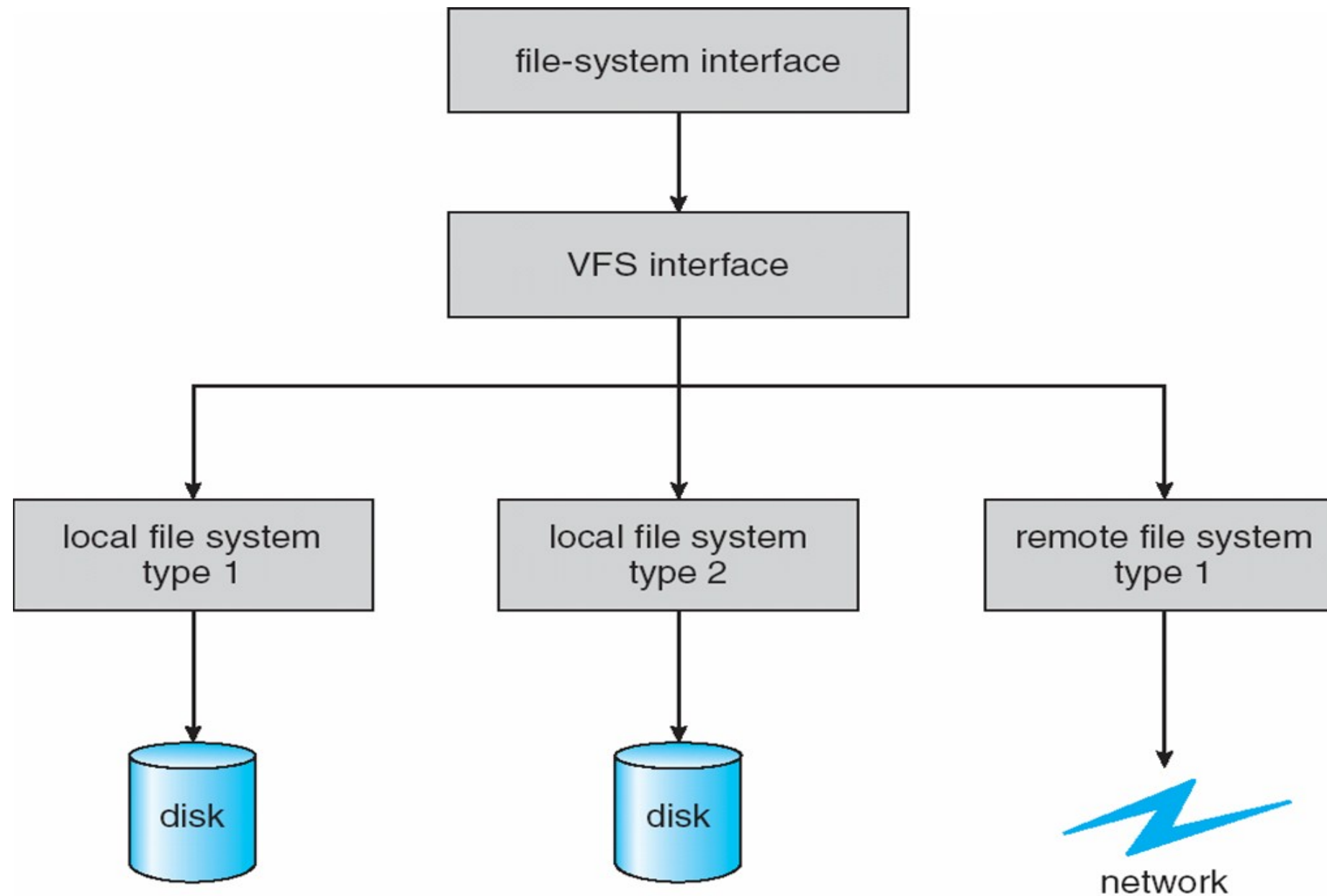
# Virtual File Systems

- 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





# Schematic View of Virtual File System





# 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







# 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

---

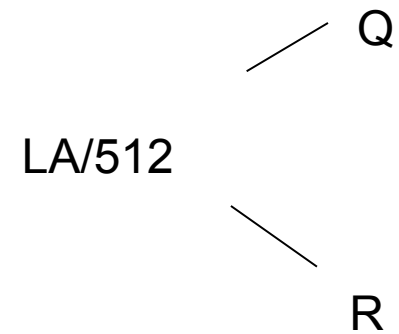
- An allocation method refers to how disk blocks are allocated for files:
- **Contiguous allocation** – each file occupies set of contiguous blocks
  - Best performance in most cases
  - Simple – only starting location (block #) and length (number of blocks) are required
  - Problems include finding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





# Contiguous Allocation

- Mapping from logical to physical

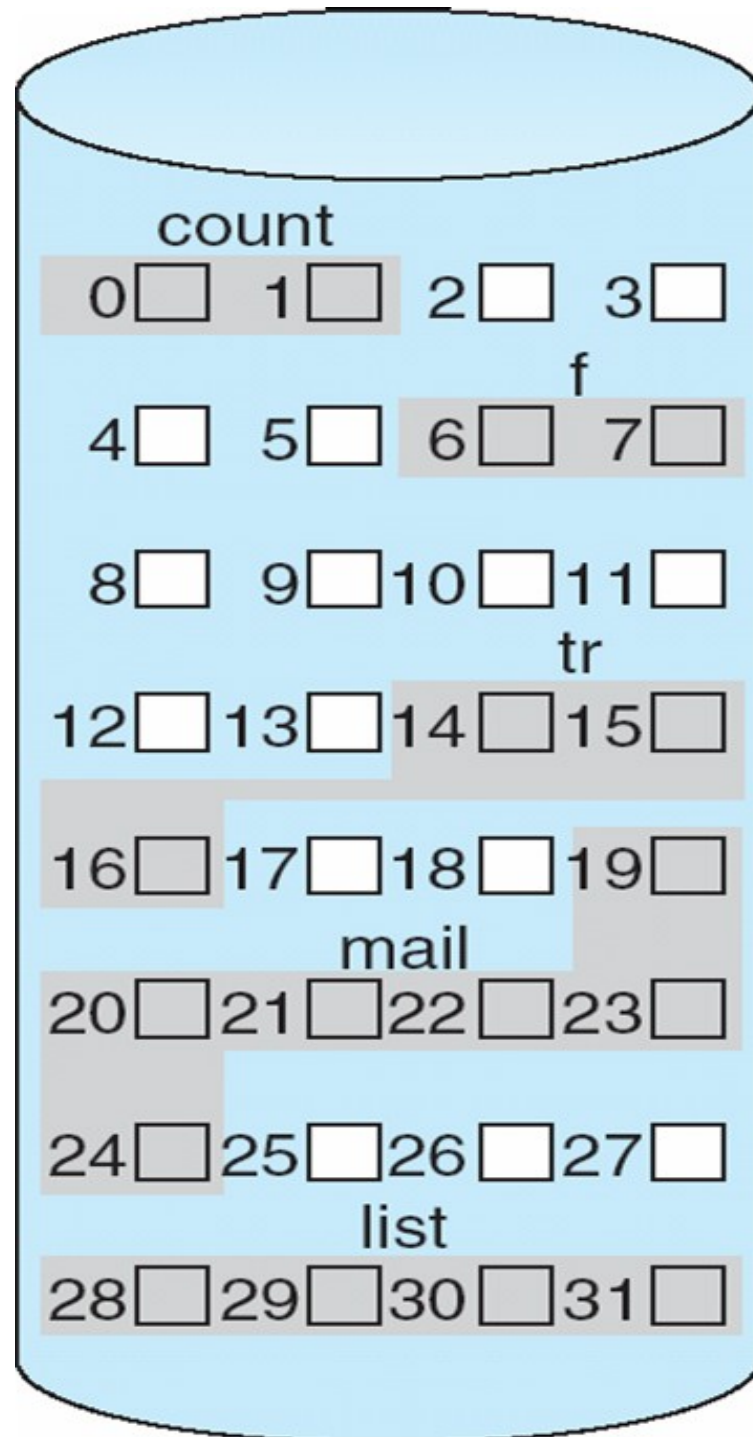


Block to be accessed =  $Q + \text{starting address}$   
Displacement into block =  $R$





# 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





# Allocation Methods - Linked

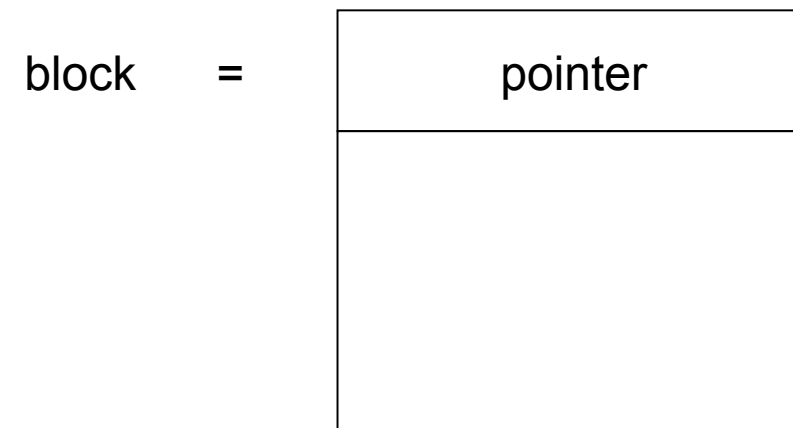
- **Linked allocation** – each file a linked list of blocks
  - File ends at nil pointer
  - No external fragmentation
  - Each block contains pointer to next block
  - No compaction, external fragmentation
  - Free space management system called when new block needed
  - Improve efficiency by clustering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





# Linked Allocation

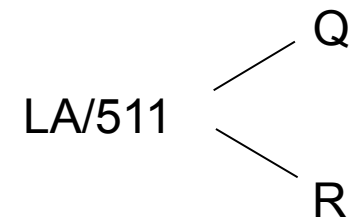
- Each file is a linked list of disk blocks: blocks may be scattered anywhere on the disk





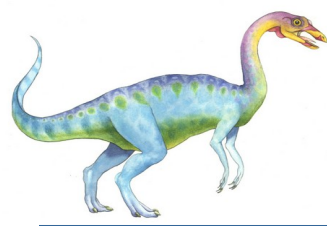
# Linked Allocation

## ■ Mapping

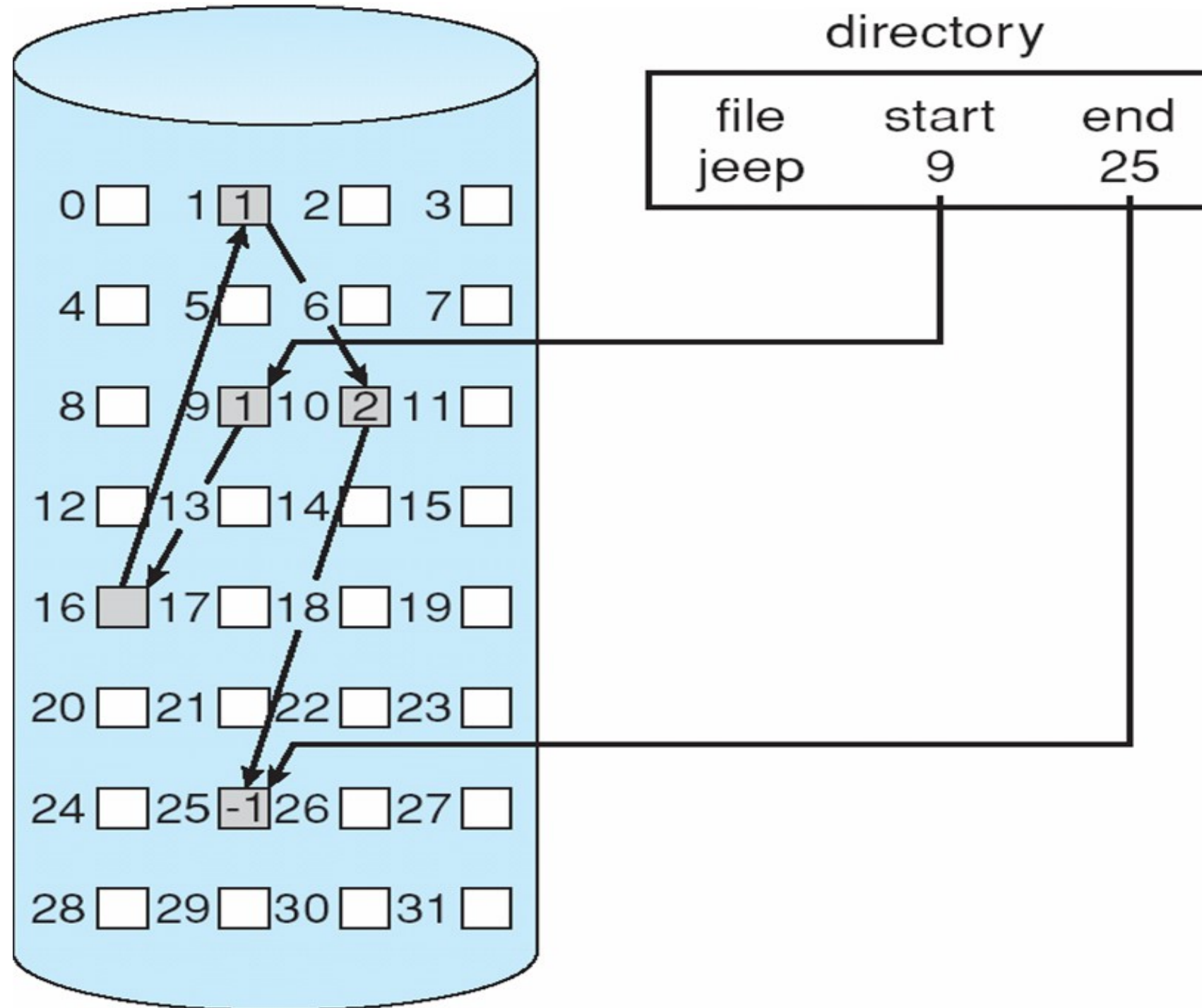


Block to be accessed is the Qth block in the linked chain of blocks representing the file.  
Displacement into block =  $R + 1$

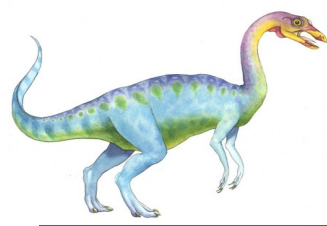




# Linked Allocation

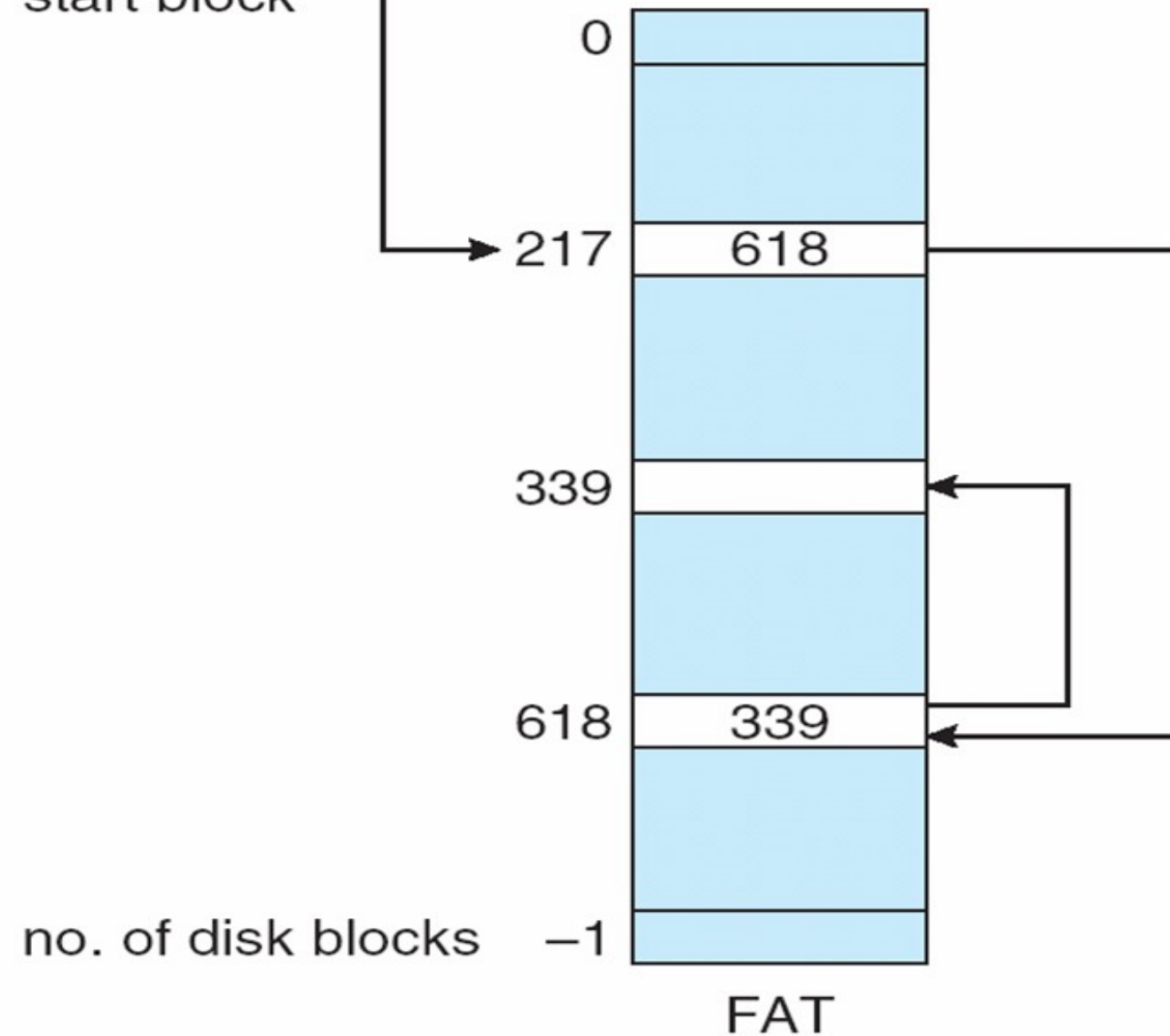
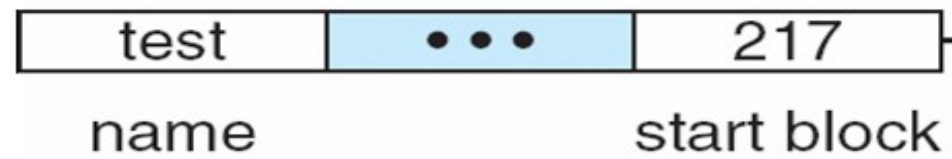






# File-Allocation Table

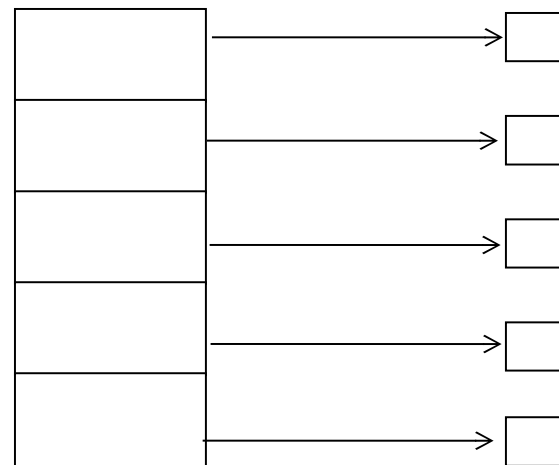
directory entry





# Allocation Methods - Indexed

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

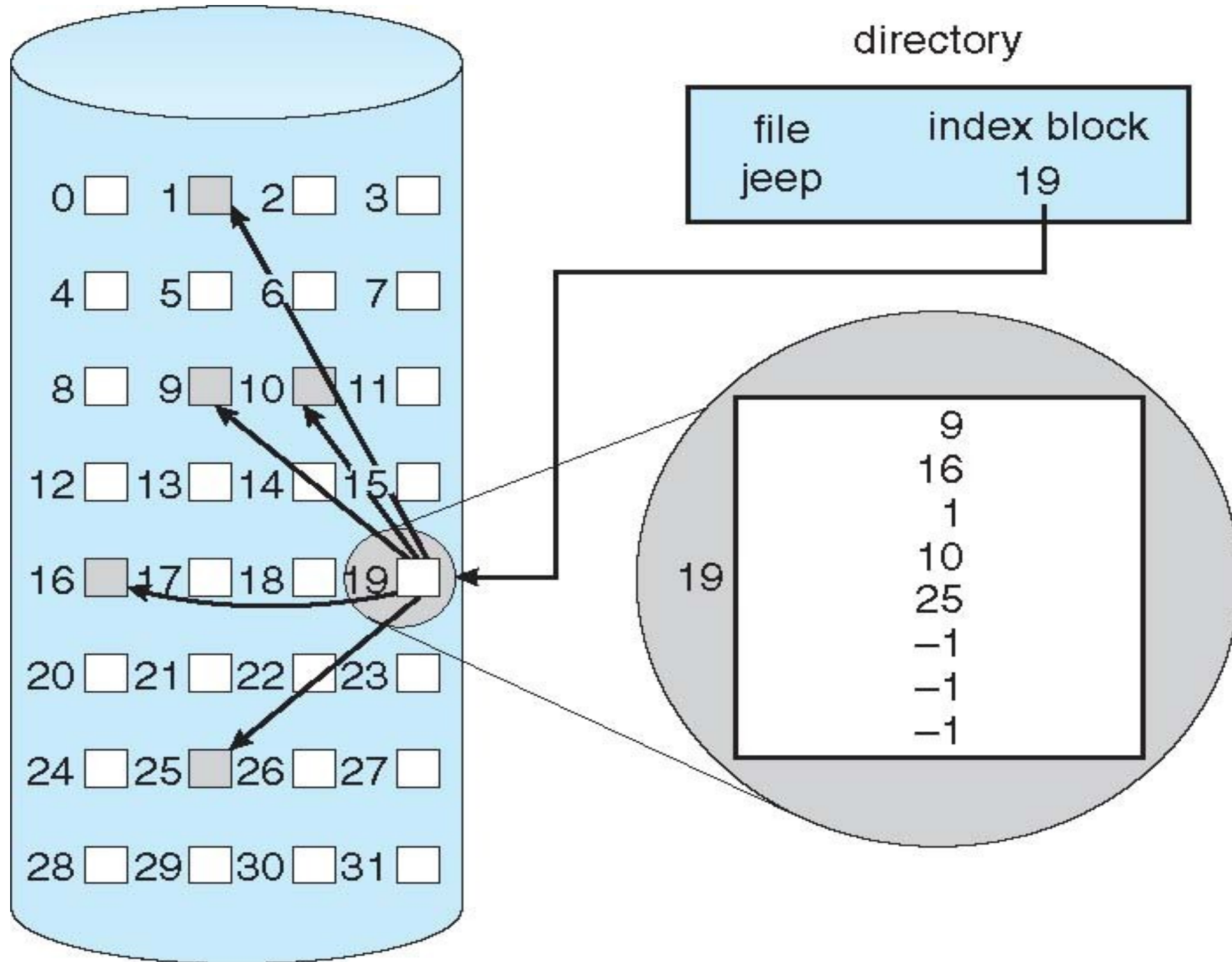


index table





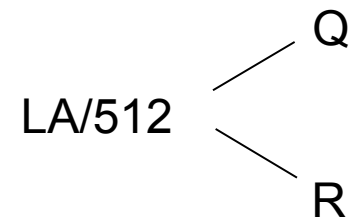
# Example of Indexed Allocation





# 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



Q = displacement into index table  
R = displacement into block





# Indexed Allocation – Mapping (Cont.)

- 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:





# Indexed Allocation – Mapping (Cont.)

- 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)

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

$Q_1$  = displacement into outer-index

$R_1$  is used as follows:

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

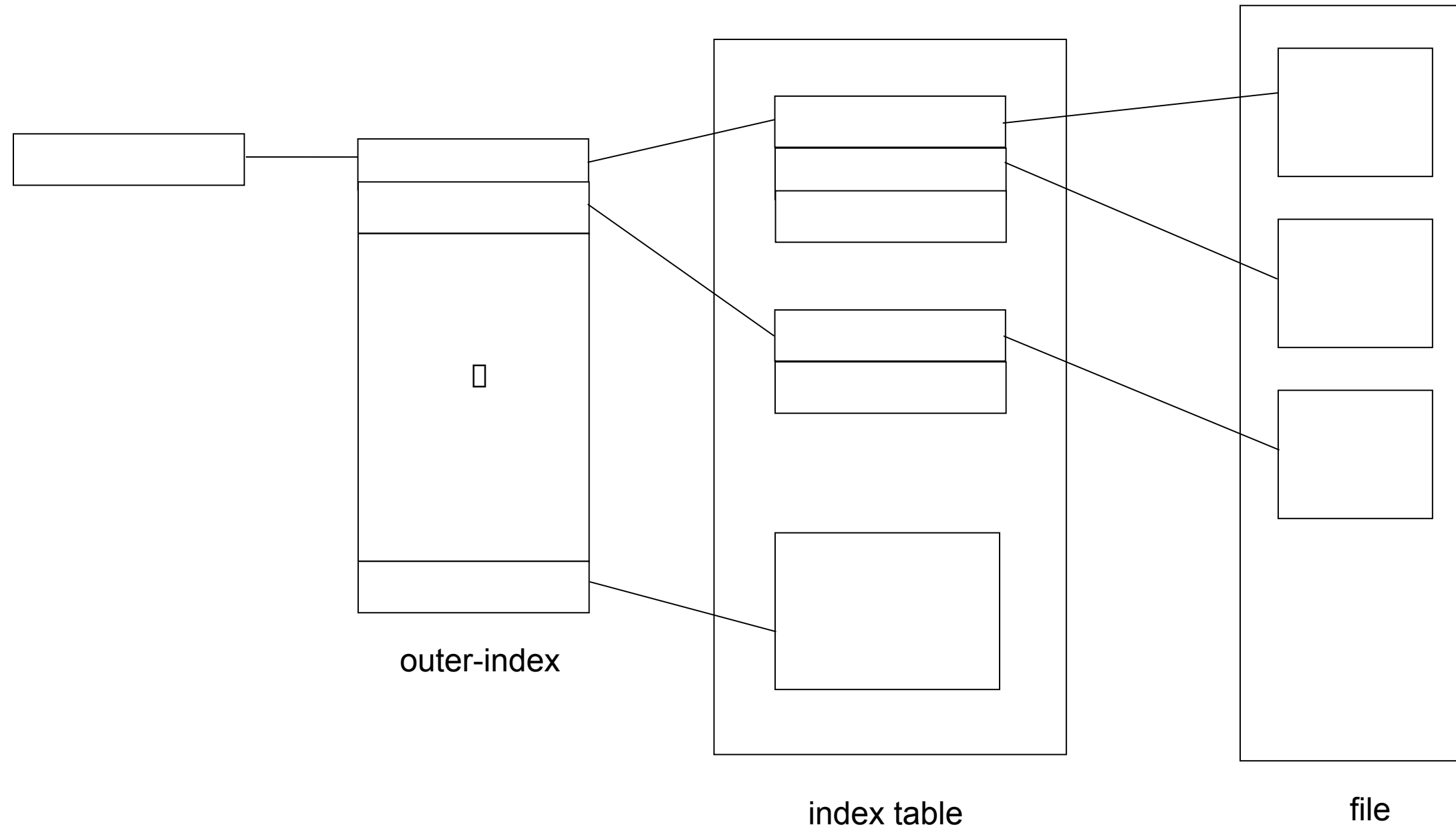
$Q_2$  = displacement into block of index table

$R_2$  displacement into block of file:





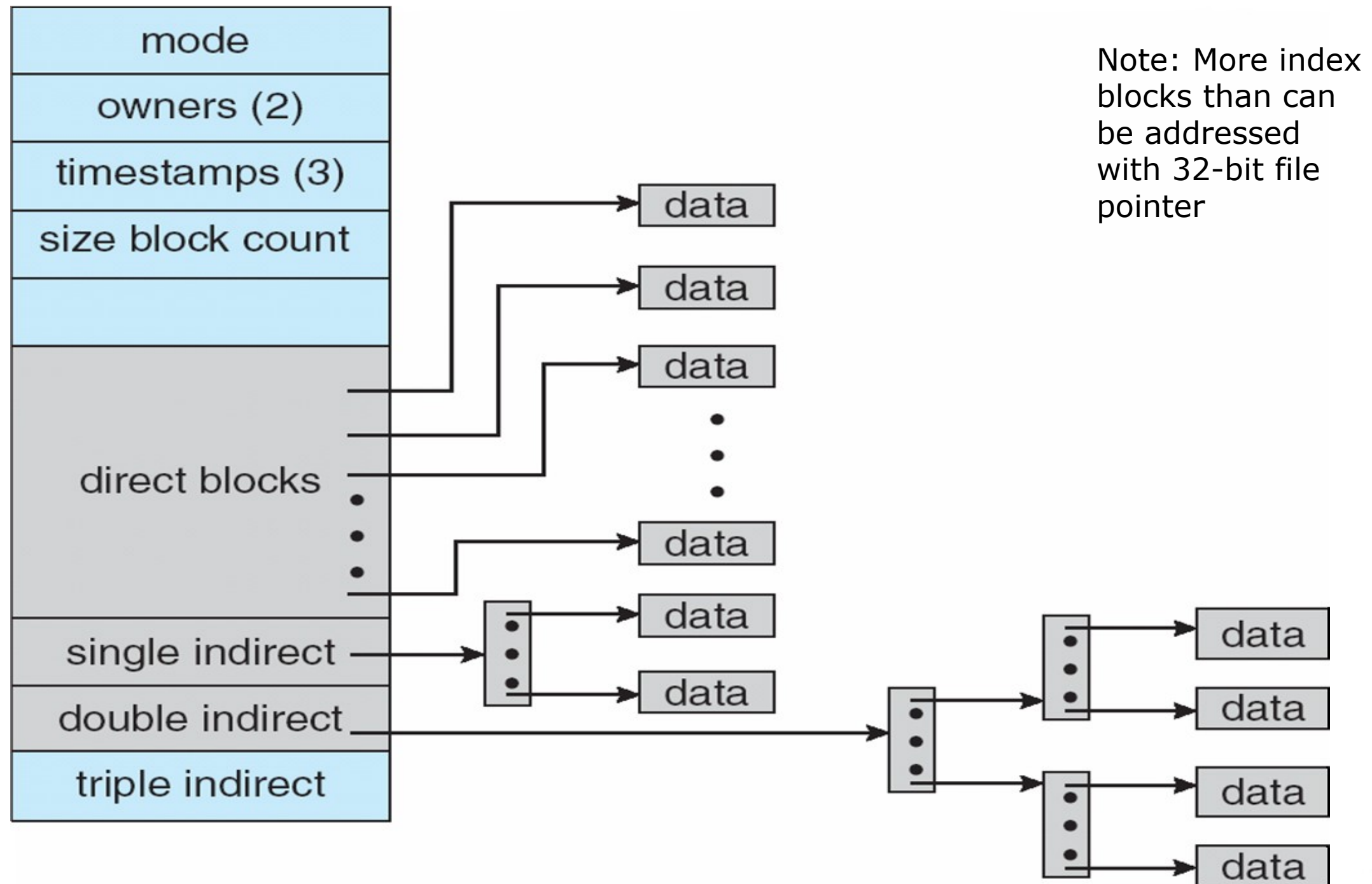
# Indexed Allocation – Mapping (Cont.)



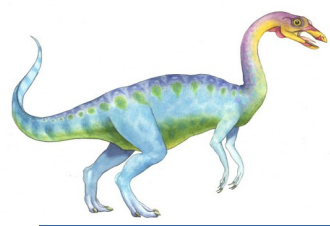




# Combined Scheme: UNIX UFS (4K bytes per block, 32-bit addresses)







# 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.)

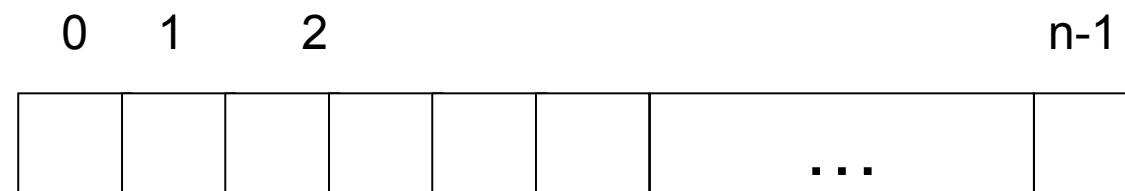
- Adding instructions to the execution path to save one disk I/O is reasonable
  - Intel Core i7 Extreme Edition 990x (2011) at 3.46Ghz = 159,000 MIPS
    - ▶ [http://en.wikipedia.org/wiki/Instructions\\_per\\_second](http://en.wikipedia.org/wiki/Instructions_per_second)
  - Typical disk drive at 250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





# 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  $\Rightarrow$  block[ $i$ ] free  
☐ 0  $\Rightarrow$  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.)

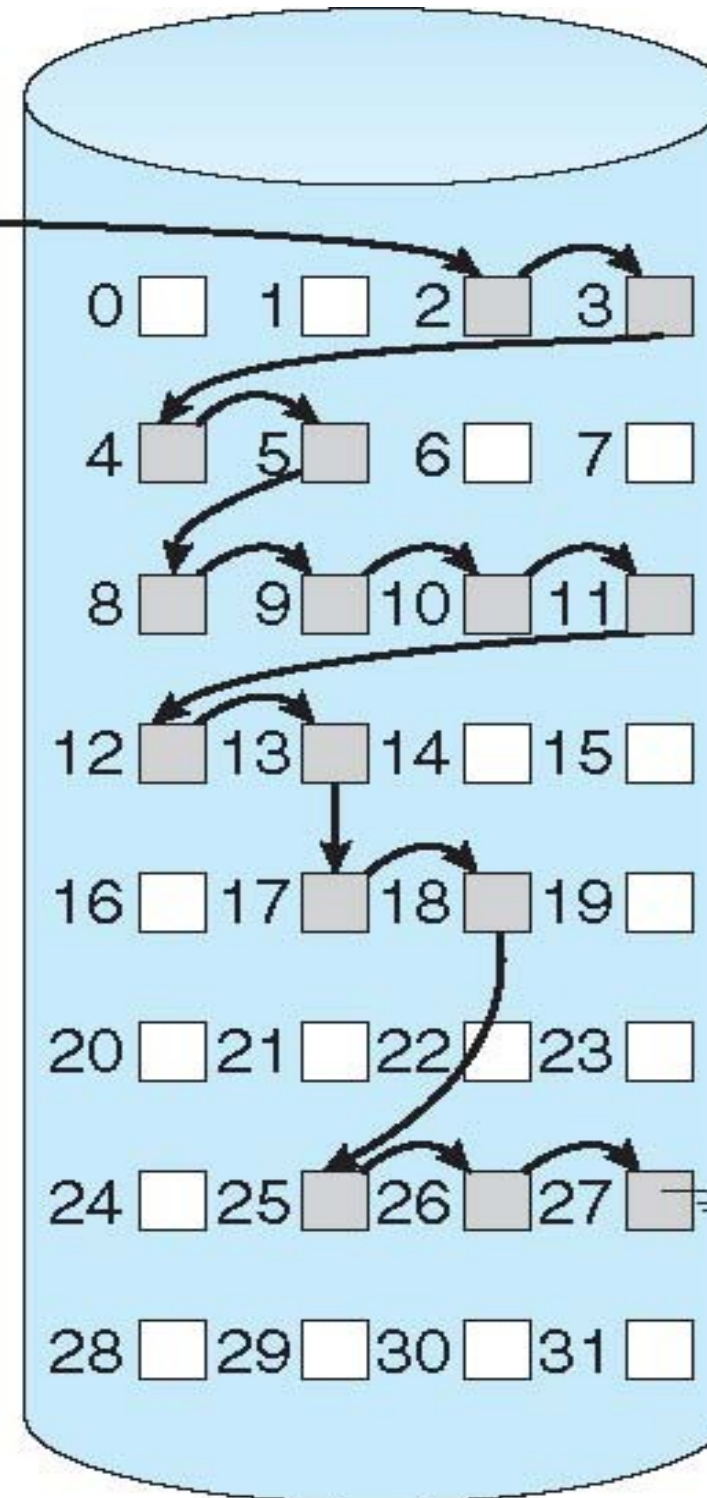
- Bit map requires extra space
  - Example:
    - block size = 4KB =  $2^{12}$  bytes
    - disk size =  $2^{40}$  bytes (1 terabyte)
    - $n = 2^{40}/2^{12} = 2^{28}$  bits (or 256 MB)
    - if clusters of 4 blocks -> 64MB of memory
- Easy to get contiguous files
- Linked list (free list)
  - Cannot get contiguous space easily
  - No waste of space
  - No need to traverse the entire list (if # free blocks recorded)





# Linked Free Space List on Disk

free-space list head





# 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



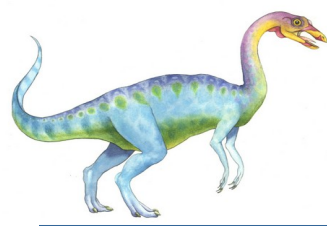




# Efficiency and Performance (Cont.)

- 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



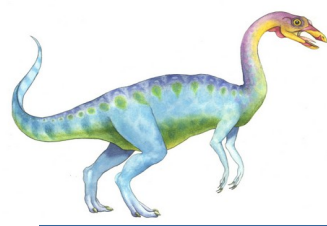


# Page Cache

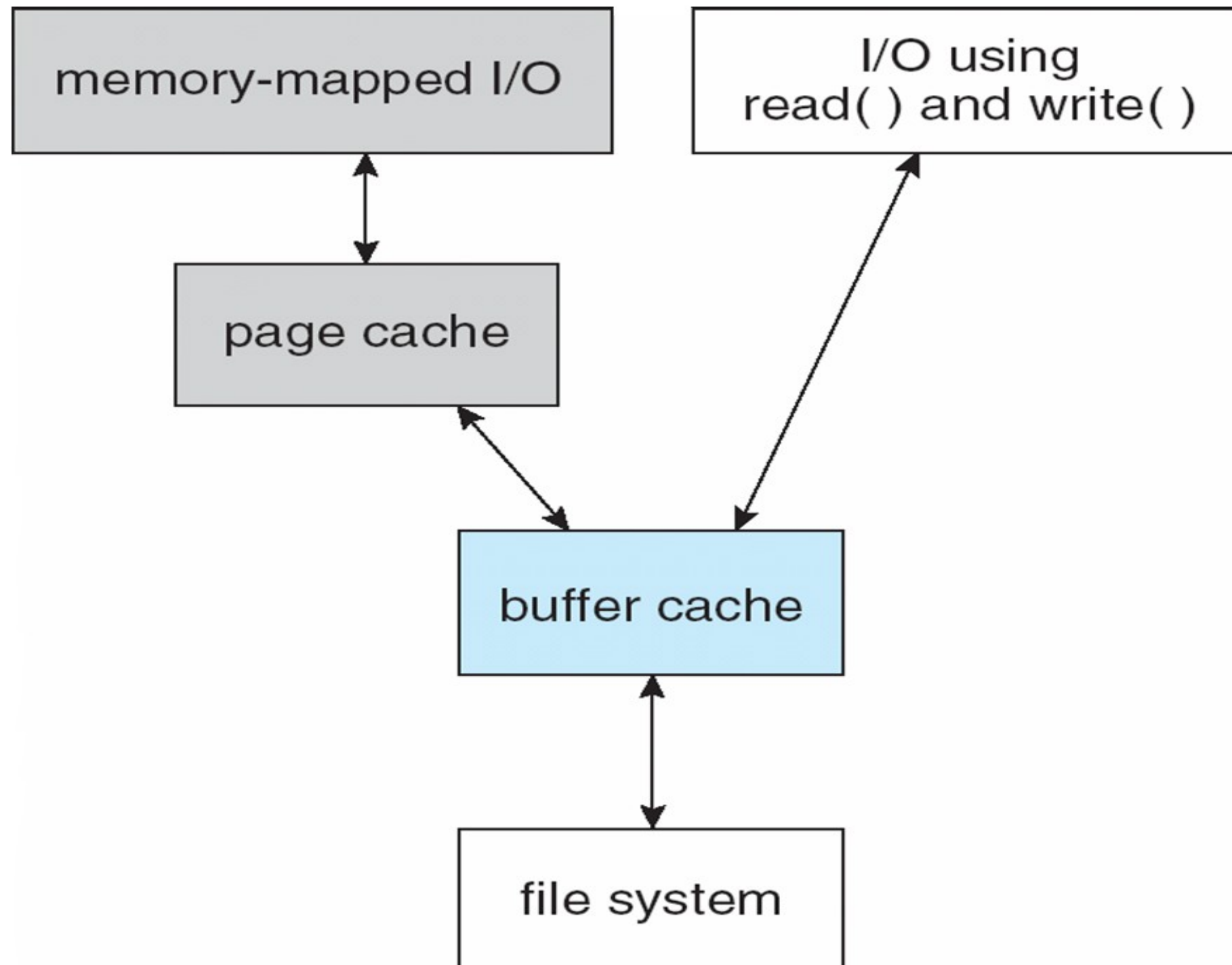
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- A **page cache** caches pages rather than disk blocks using virtual memory techniques and addresses
- Memory-mapped I/O uses a page cache
- Routine I/O through the file system uses the buffer (disk) cache
- This leads to the following figure





# I/O Without a Unified Buffer Cache





# Unified Buffer Cache

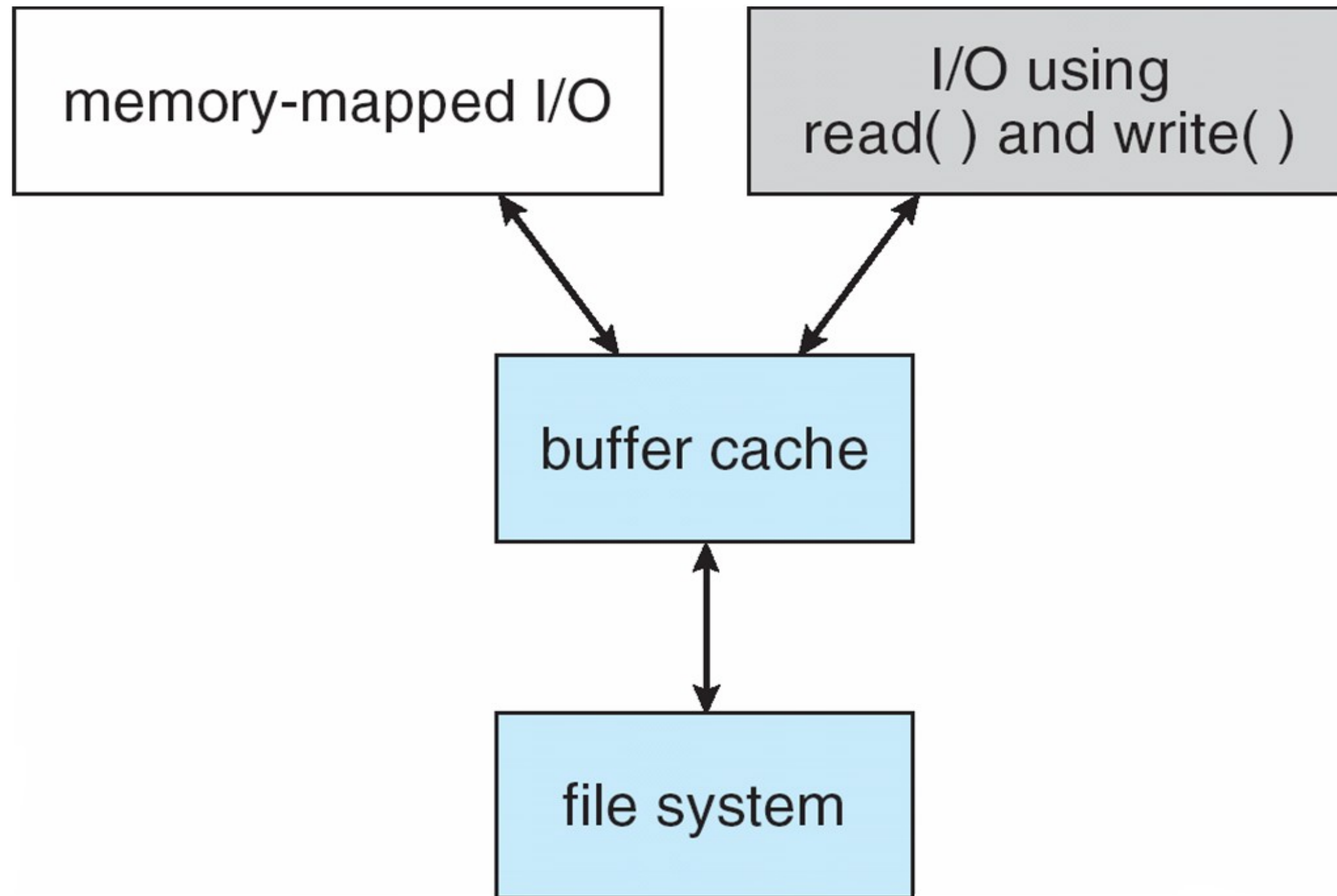
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- A **unified buffer cache** uses the same page cache to cache both memory-mapped pages and ordinary file system I/O to avoid **double caching**
- But which caches get priority, and what replacement algorithms to use?





# 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





# 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)



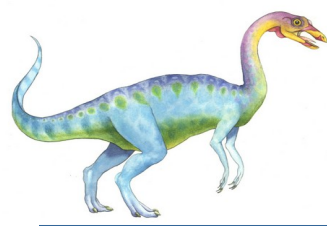




# NFS (Cont.)

- 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.)

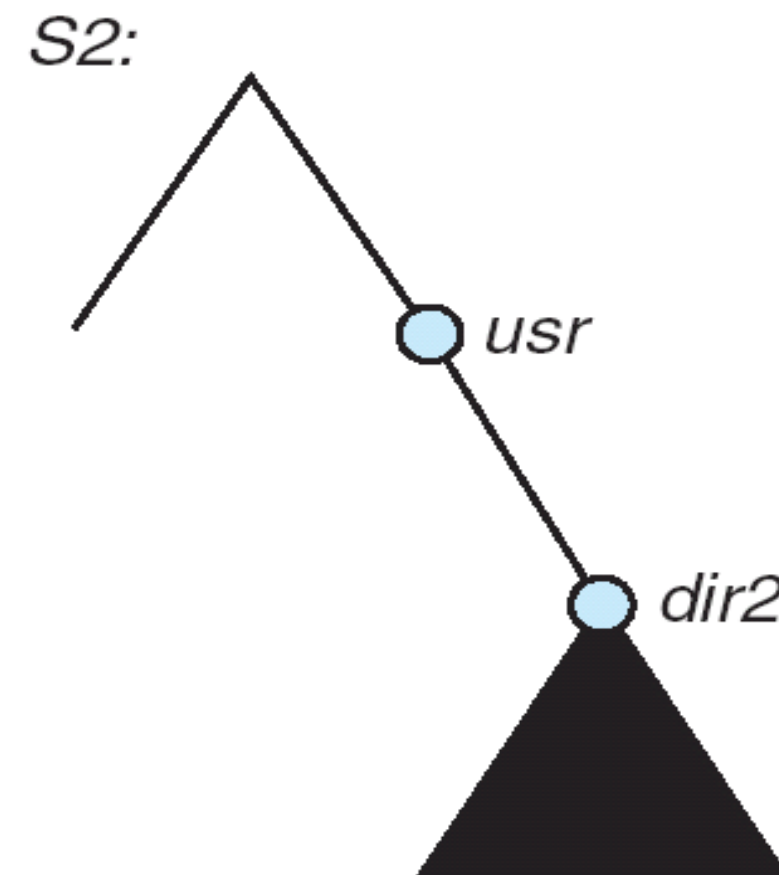
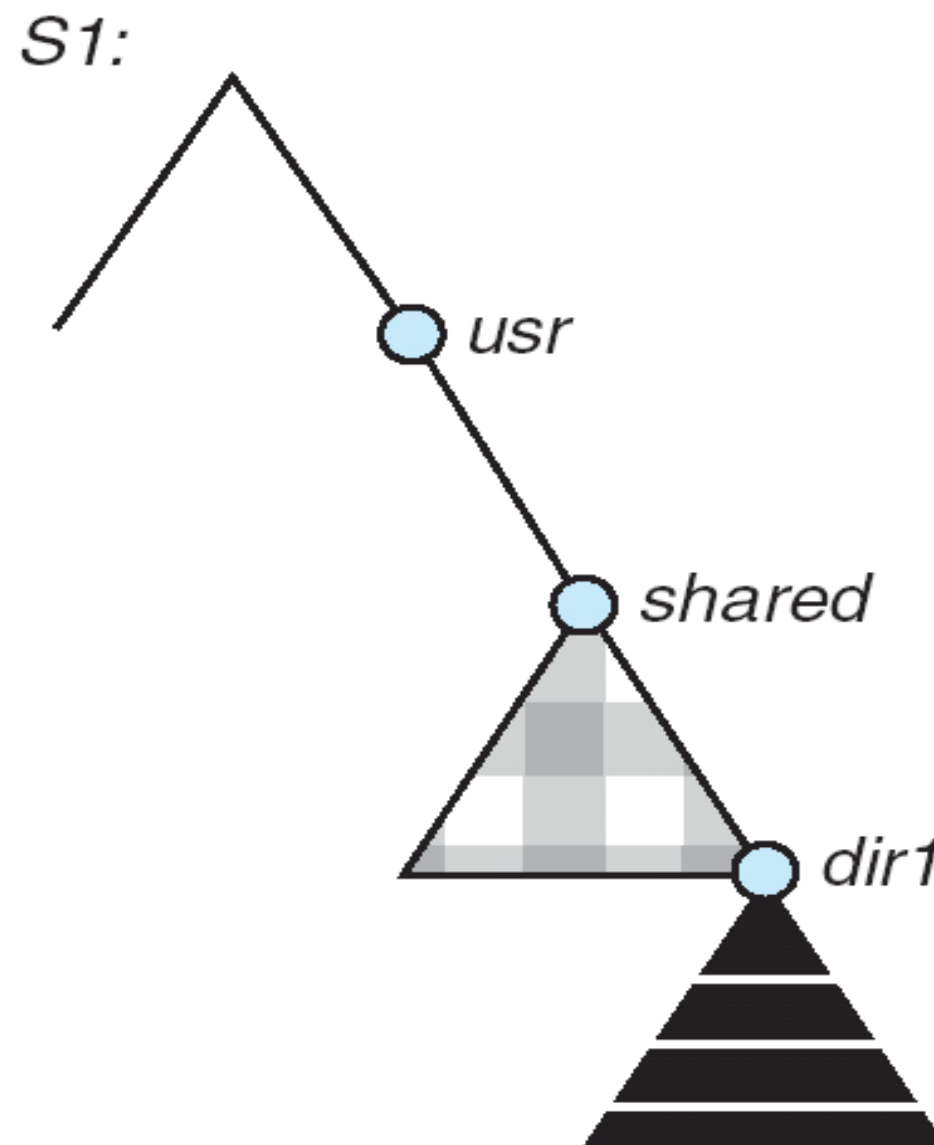
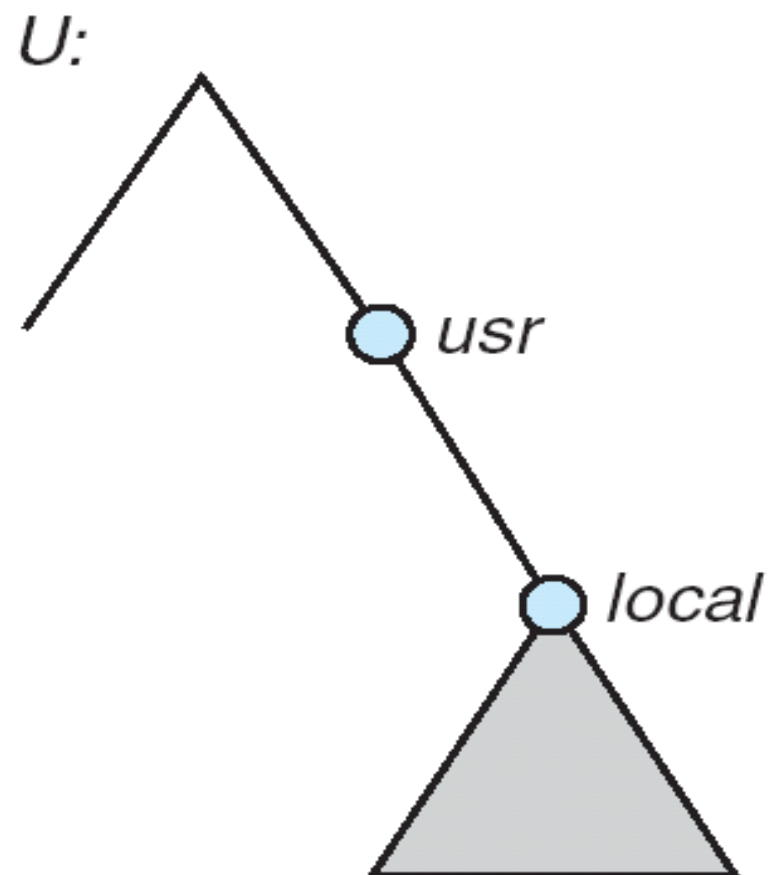
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- NFS is designed to operate in a heterogeneous environment of different machines, operating systems, and network architectures; the NFS specifications independent of these media
- This independence is achieved through the use of RPC primitives built 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



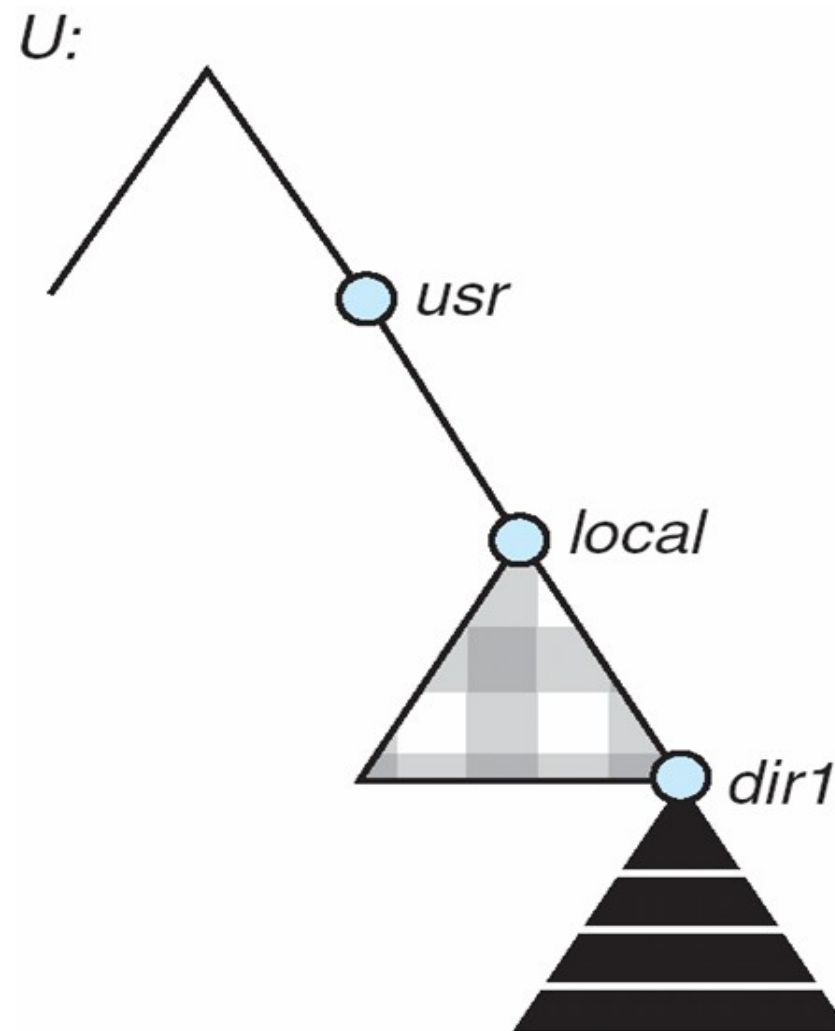


# Three Independent File Systems



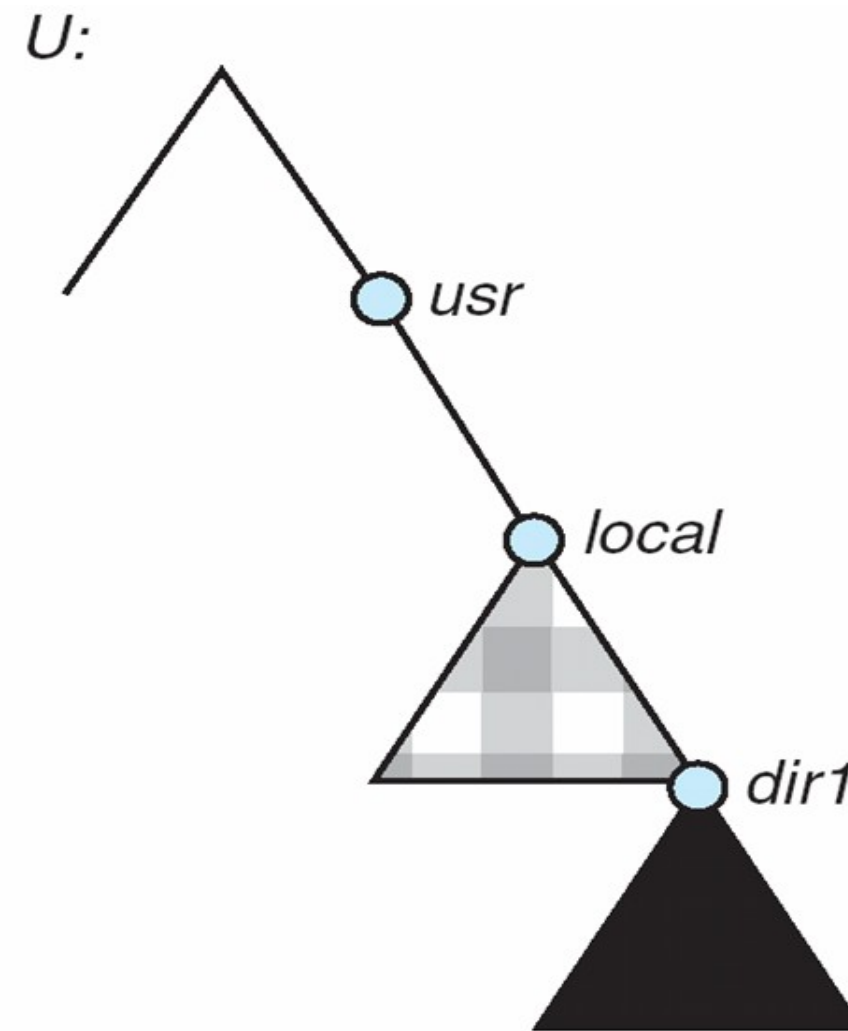


# Mounting in NFS



(a)

Mounts



(b)

Cascading mounts





# 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



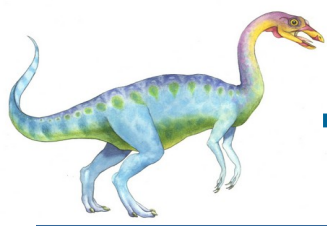


# NFS Protocol

---

- 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 (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



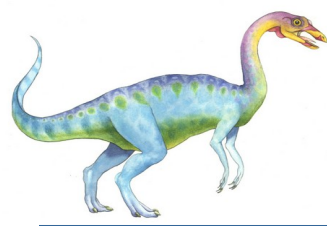


# Three Major Layers of NFS Architecture

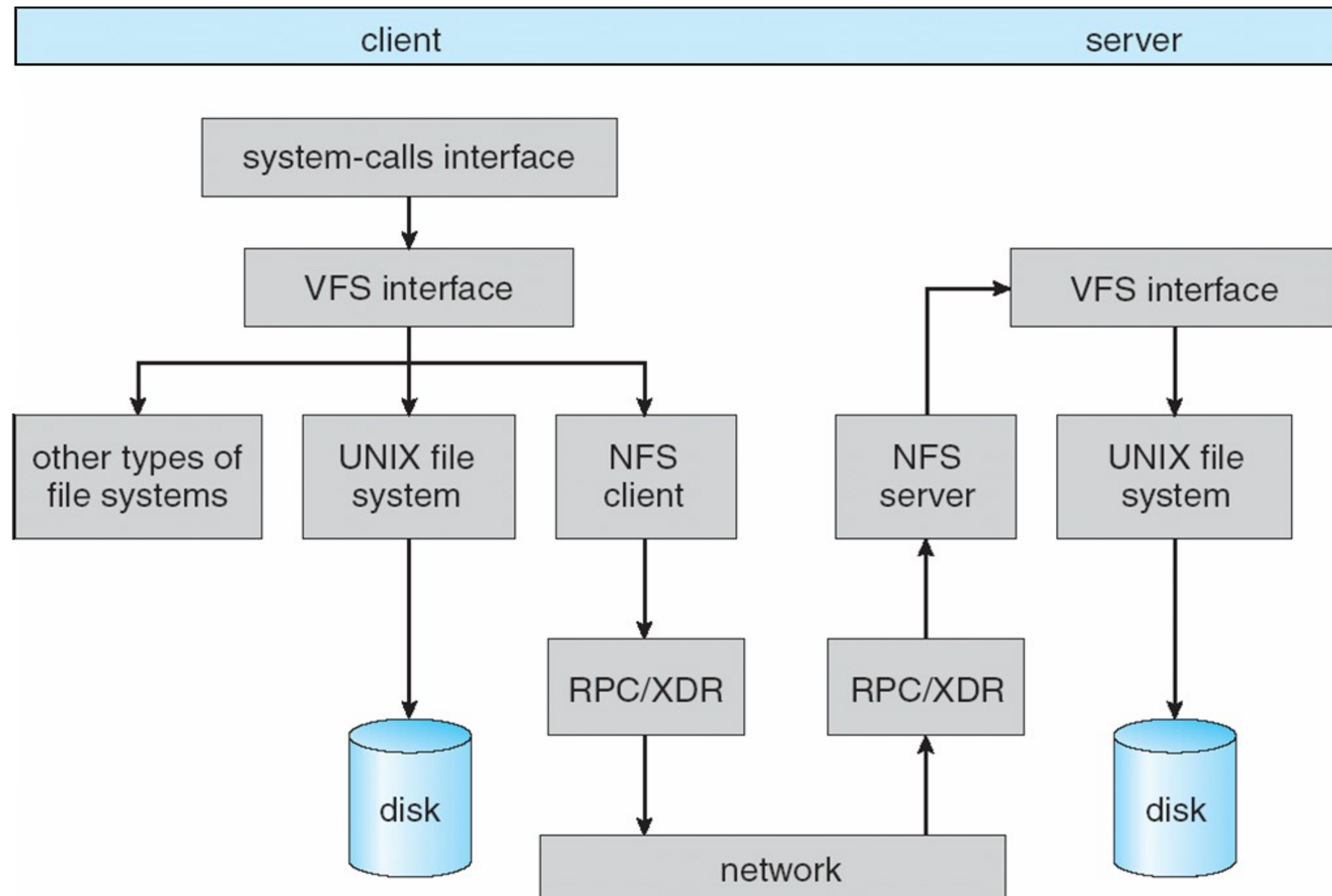
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- UNIX file-system interface (based on the **open**, **read**, **write**, and **close** calls, and **file descriptors**)
- *Virtual File System* (VFS) layer – distinguishes local files from remote ones, and local files are further distinguished according 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





# Schematic View of NFS Architecture







# 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

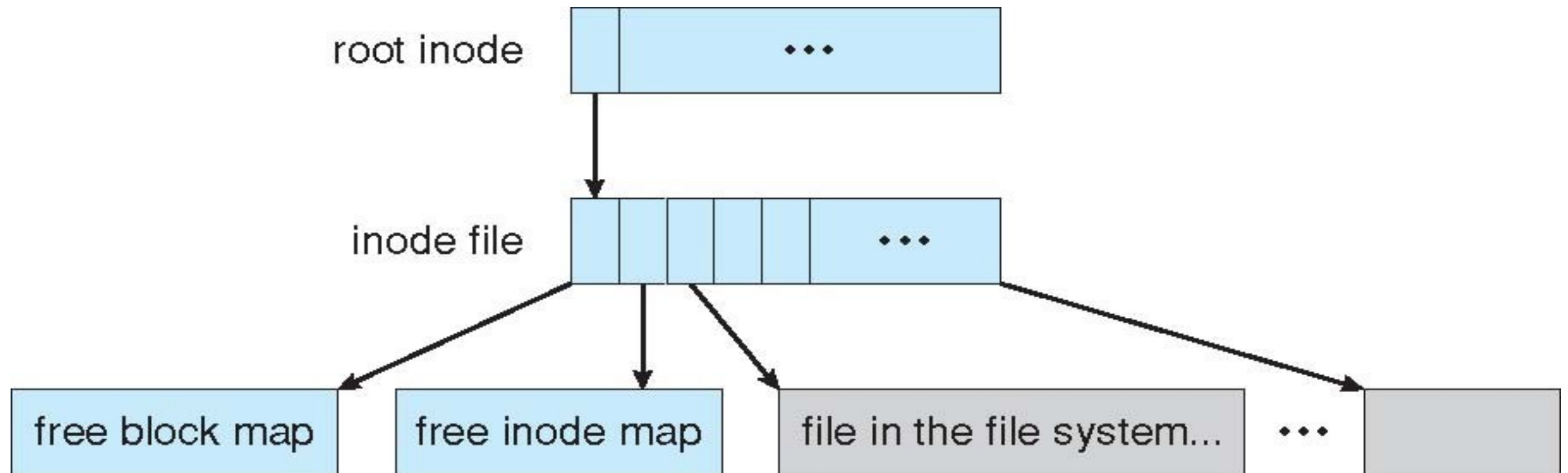
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- Used on Network Appliance “Filers” – distributed file system appliances
- “Write-anywhere file layout”
- Serves up NFS, CIFS, http, ftp
- Random I/O optimized, write optimized
  - NVRAM for write caching
- Similar to Berkeley Fast File System, with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



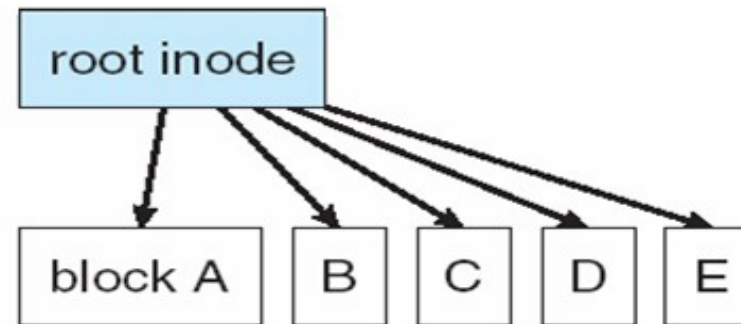


# The WAFL File Layout

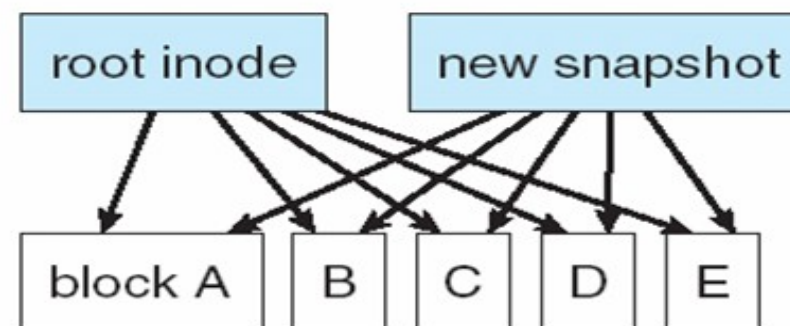




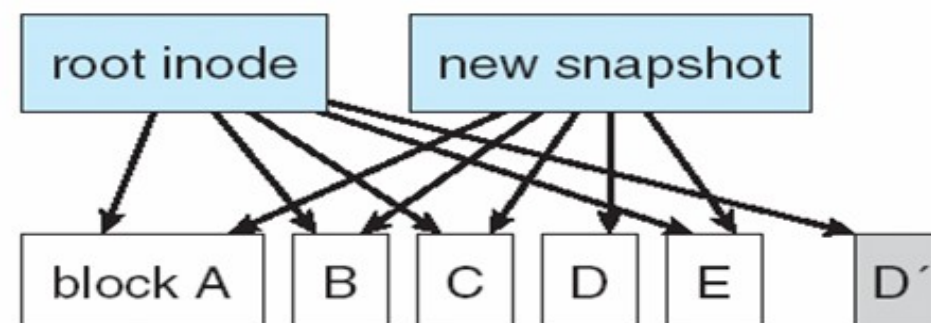
# Snapshots in WAFL



(a) Before a snapshot.



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

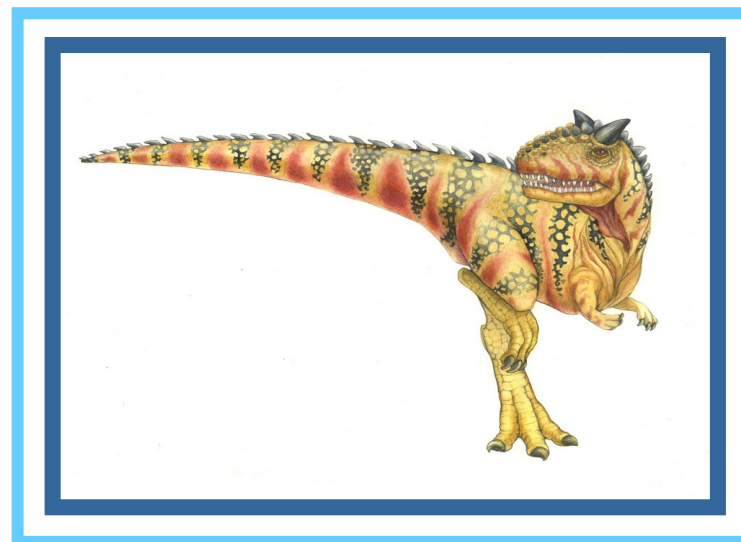


(c) After block D has changed to D'.



# End of Chapter 10

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# Free-Space Management (Cont.)

- Need to protect:
  - Pointer to free list
  - Bit map
    - ▶ Must be kept on disk
    - ▶ 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
    - ▶ Allocate block[*i*]
    - ▶ Set bit[*i*] = 1 in memory

