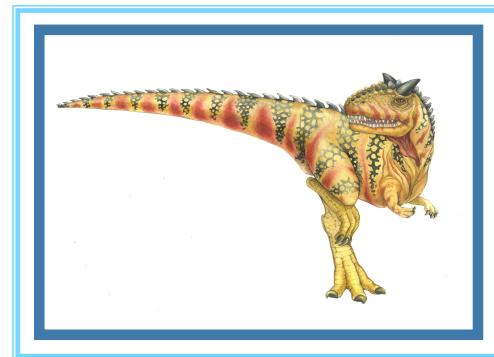


Chapter 10: File System Implementation





Chapter 10: File System Implementation

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





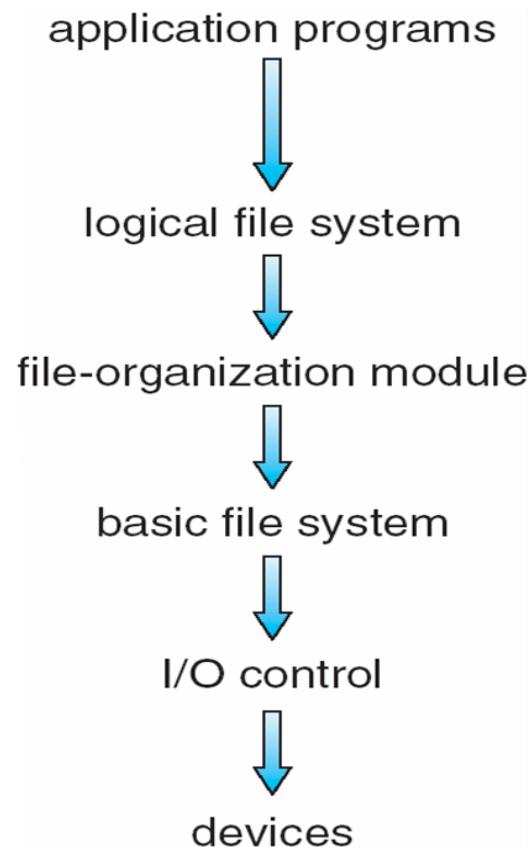
File-System Structure

- File structure
 - Logical storage unit
 - Collection of related information
- **File system** resides on secondary storage (disks)
 - 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





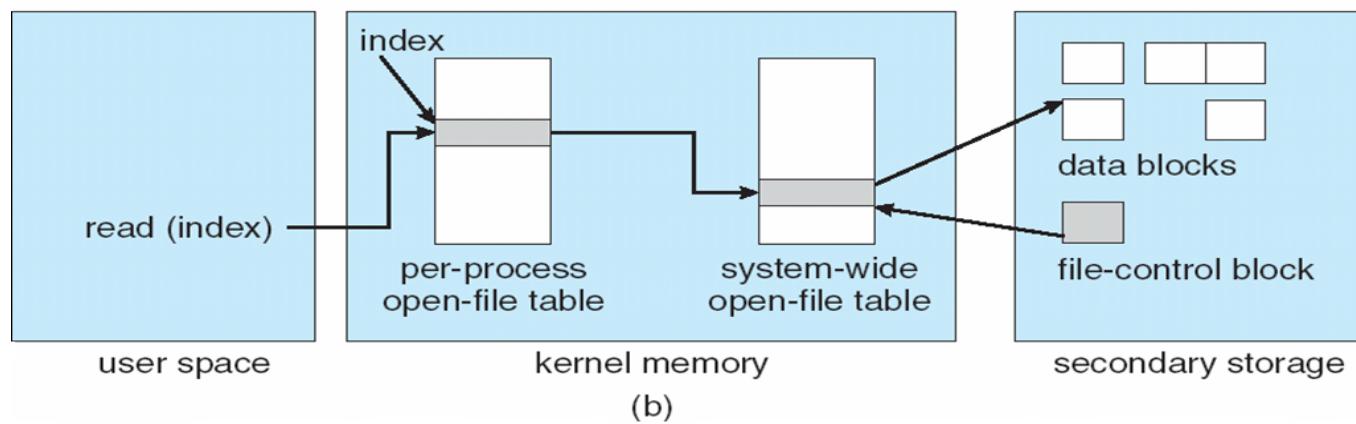
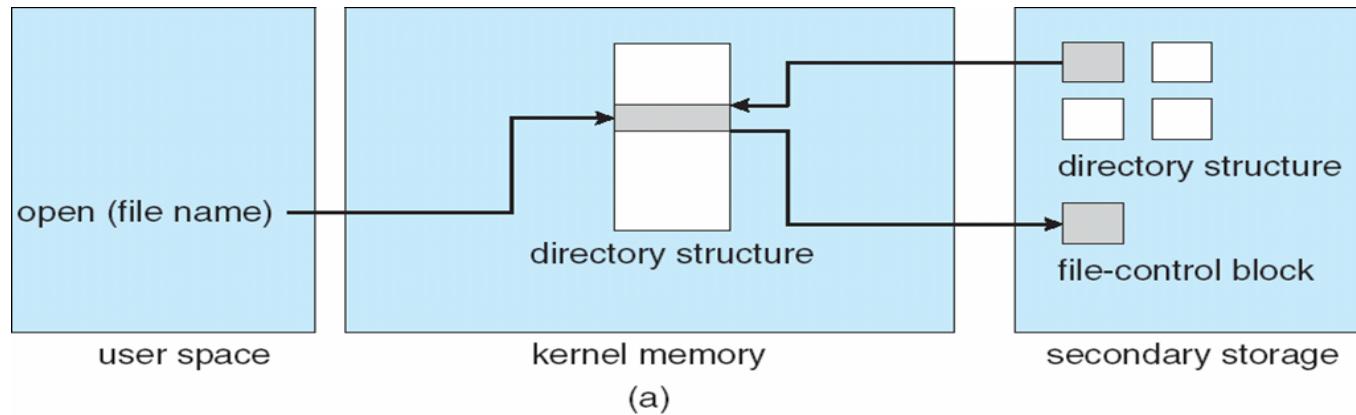
In-Memory File System Structures

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





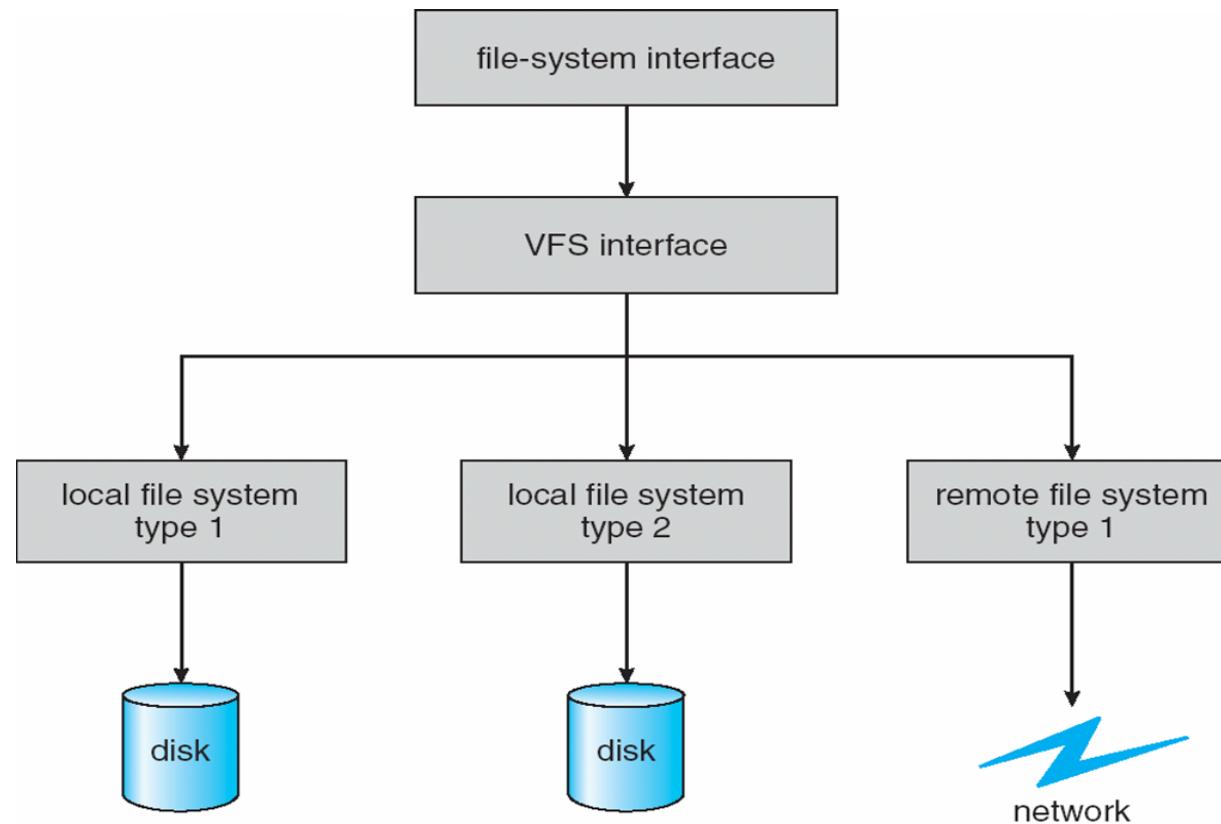
Virtual File Systems

- 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

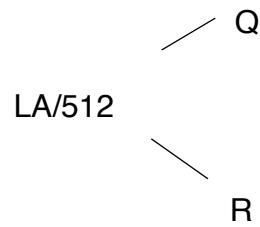
- An allocation method refers to how disk blocks are allocated for files:
- **Contiguous allocation** – each file occupies set of contiguous blocks
 - Best performance in most cases
 - Simple – only starting location (block #) and length (number of blocks) are required
 - Problems include finding space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





Contiguous Allocation

- Mapping from logical to physical



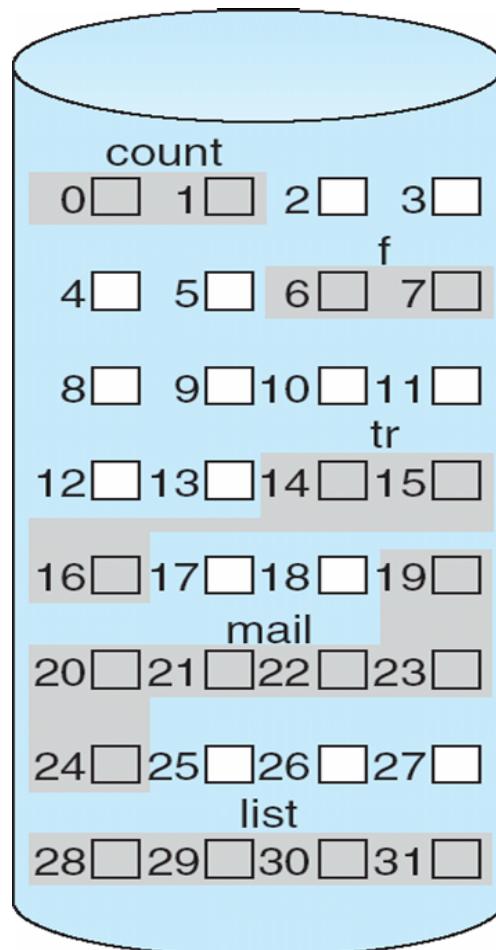
Block to be accessed = $Q + \text{starting address}$

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

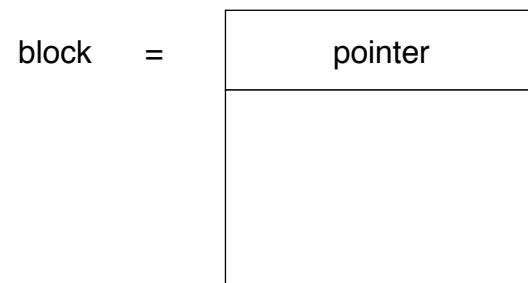
- **Linked allocation** – each file a linked list of blocks
 - File ends at nil pointer
 - No external fragmentation
 - Each block contains pointer to next block
 - No compaction, external fragmentation
 - Free space management system called when new block needed
 - Improve efficiency by clustering blocks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

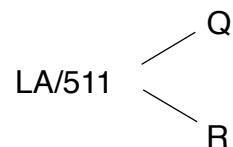
- Each file is a linked list of disk blocks: blocks may be scattered anywhere on the disk





Linked Allocation

- Mapping

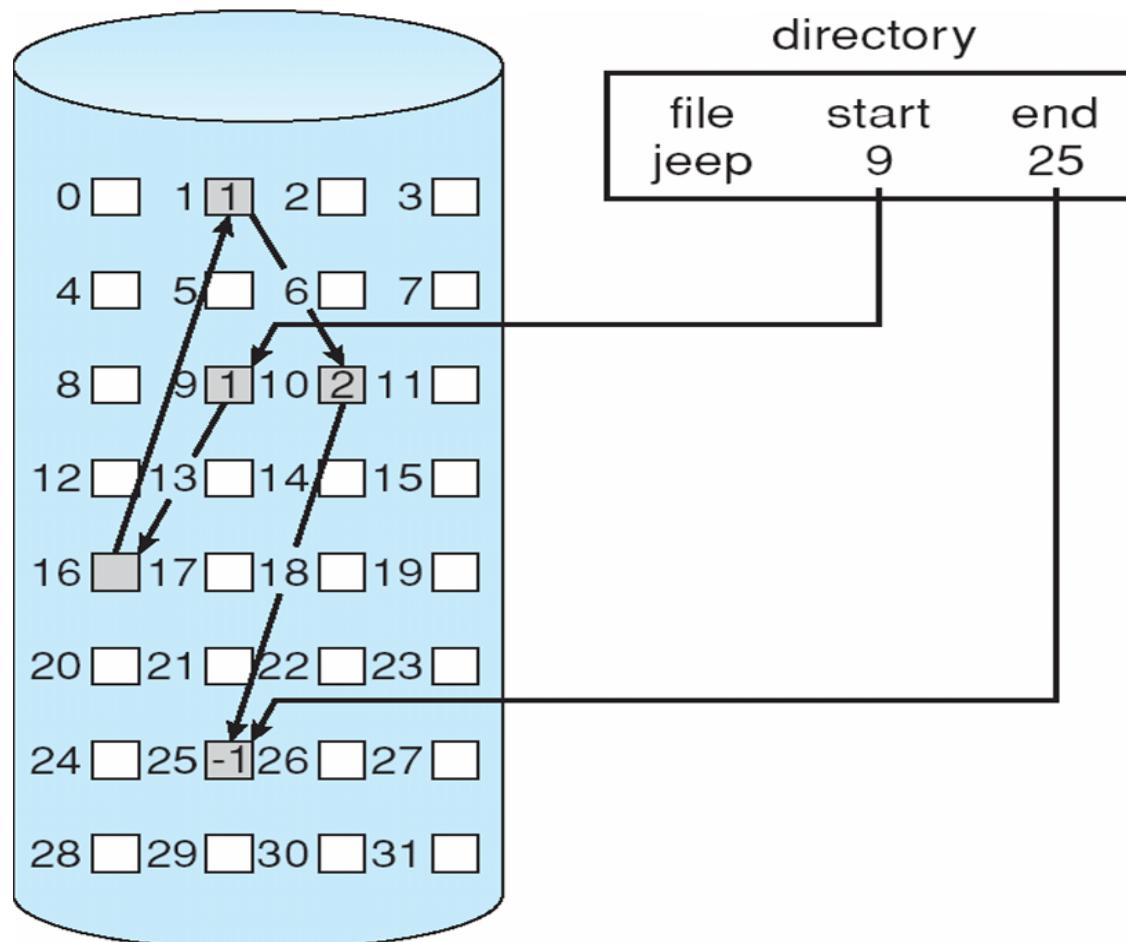


Block to be accessed is the Qth block in the linked chain of blocks representing the file.
Displacement into block = R + 1





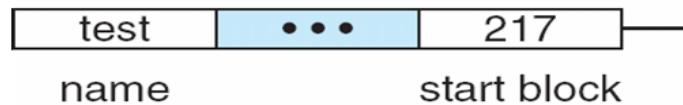
Linked Allocation





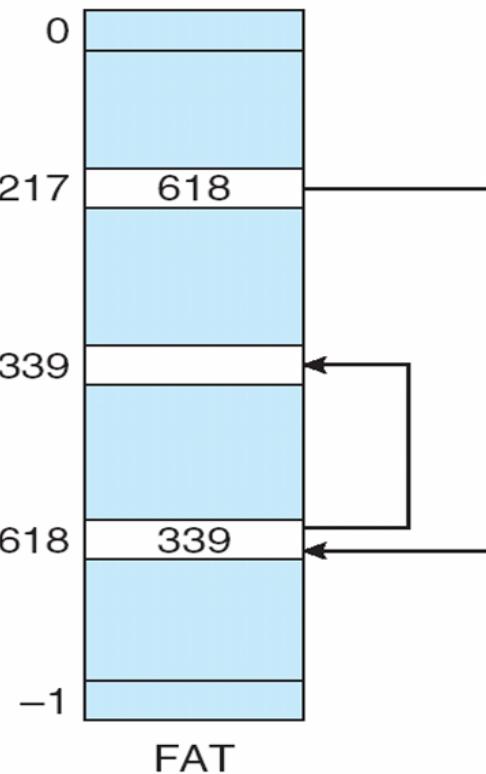
File-Allocation Table

directory entry



start block

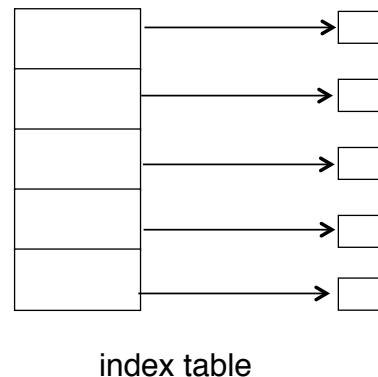
no. of disk blocks





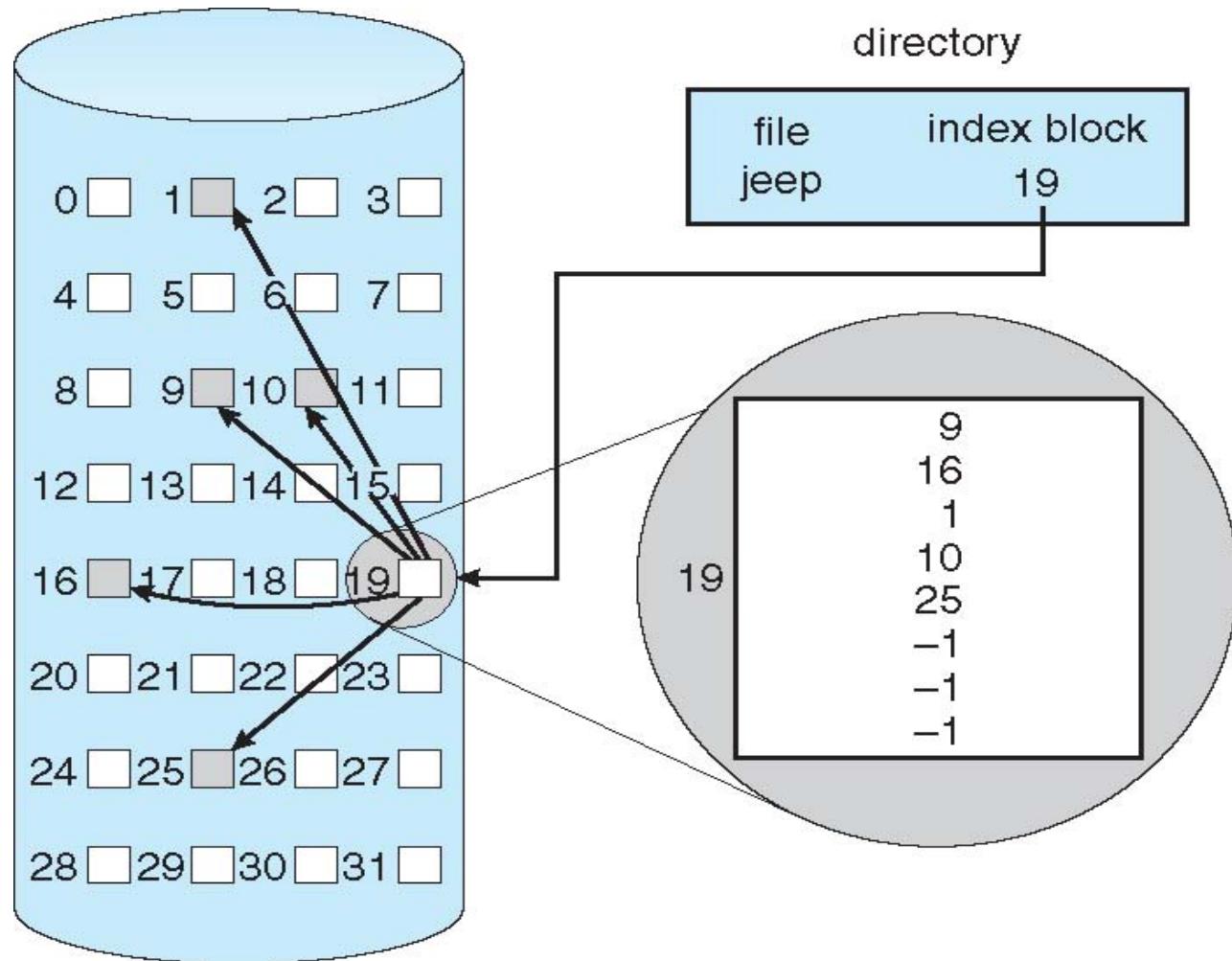
Allocation Methods - Indexed

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





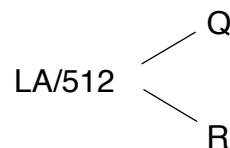
Example of Indexed Allocation





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



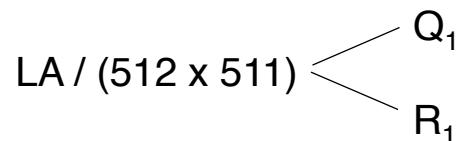
Q = displacement into index table
R = displacement into block



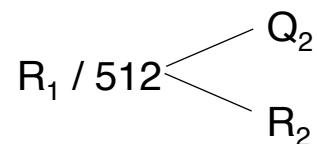


Indexed Allocation – Mapping (Cont.)

- 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)



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



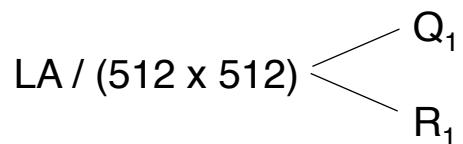
Q_2 = displacement into block of index table
 R_2 displacement into block of file:





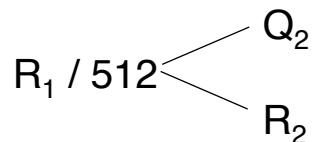
Indexed Allocation – Mapping (Cont.)

- 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)



Q_1 = displacement into outer-index

R_1 is used as follows:



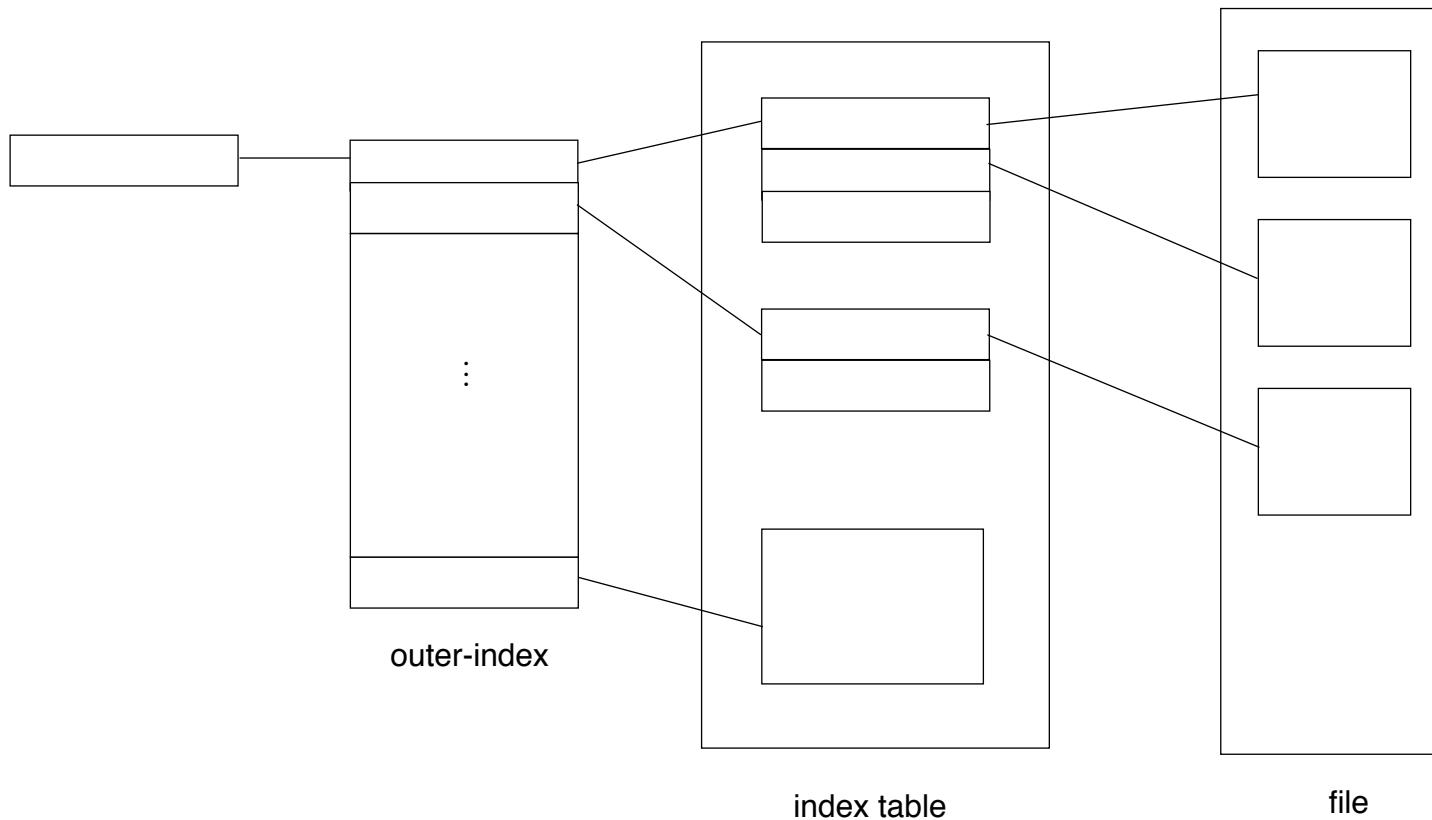
Q_2 = displacement into block of index table

R_2 displacement into block of file:



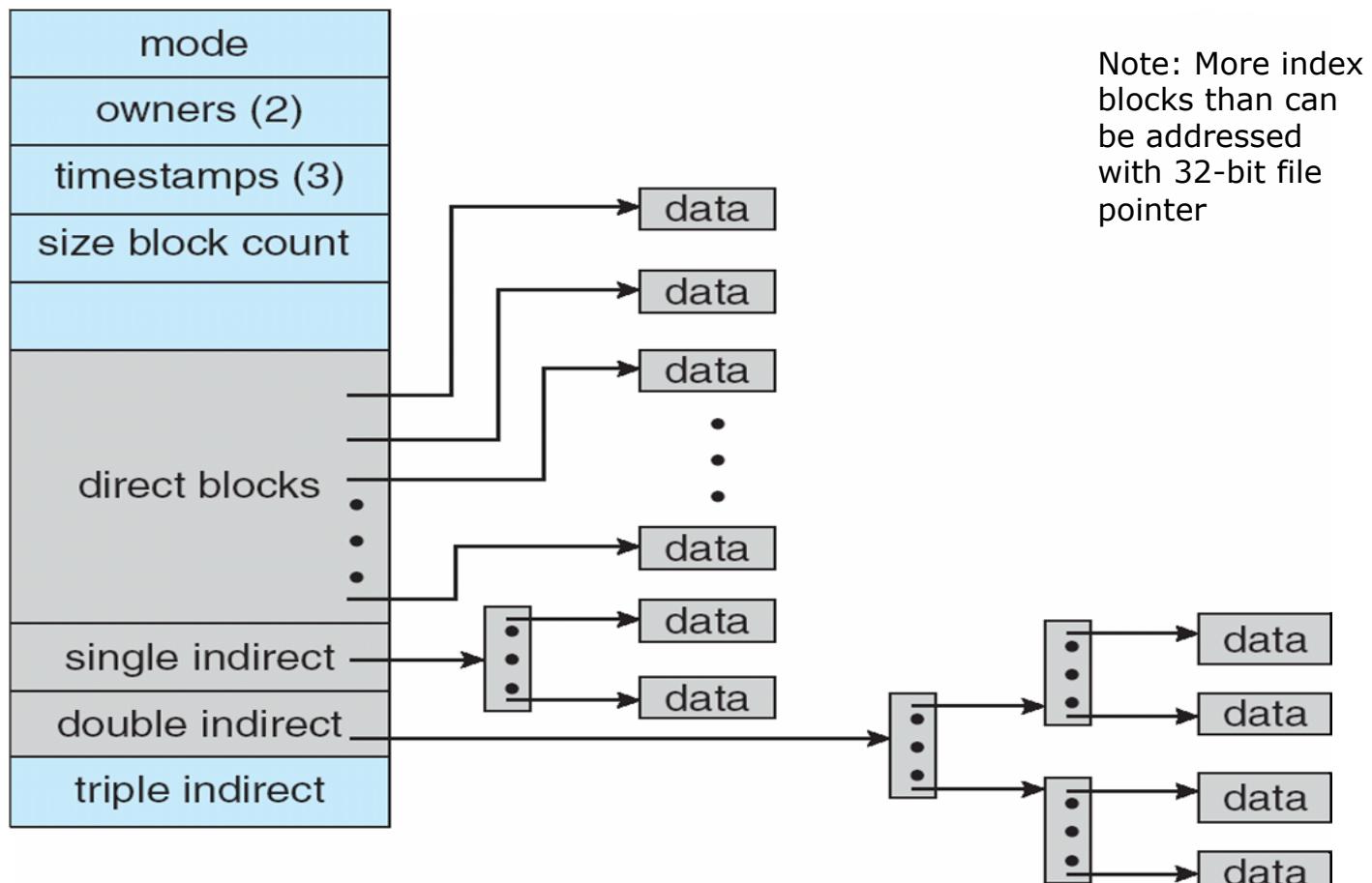


Indexed Allocation – Mapping (Cont.)





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.)

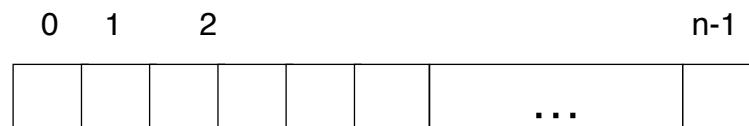
- Adding instructions to the execution path to save one disk I/O is reasonable
 - Intel Core i7 Extreme Edition 990x (2011) at 3.46Ghz = 159,000 MIPS
 - ▶ http://en.wikipedia.org/wiki/Instructions_per_second
 - Typical disk drive at 250 I/Os per second
 - ▶ $159,000 \text{ MIPS} / 250 = 630 \text{ million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



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

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





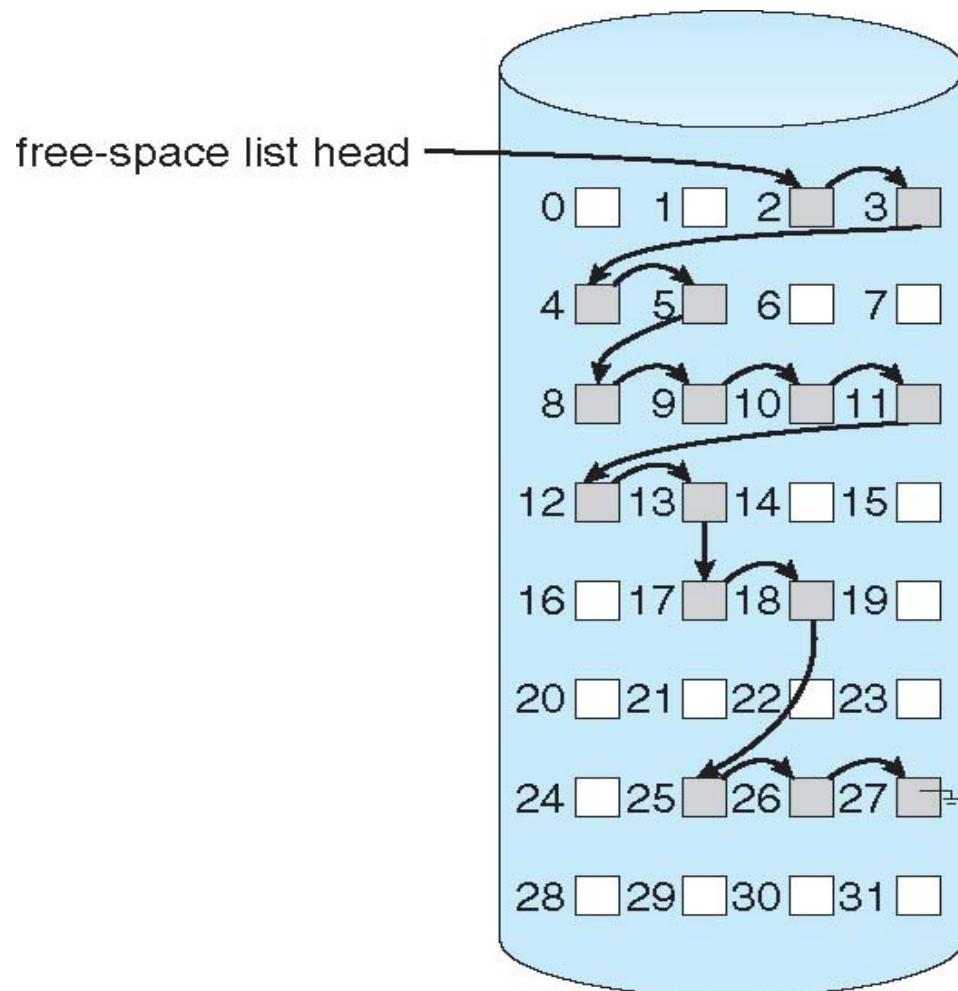
Free-Space Management (Cont.)

- Bit map requires extra space
 - Example:
 - block size = 4KB = 2^{12} bytes
 - disk size = 2^{40} bytes (1 terabyte)
 - $n = 2^{40}/2^{12} = 2^{28}$ 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 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





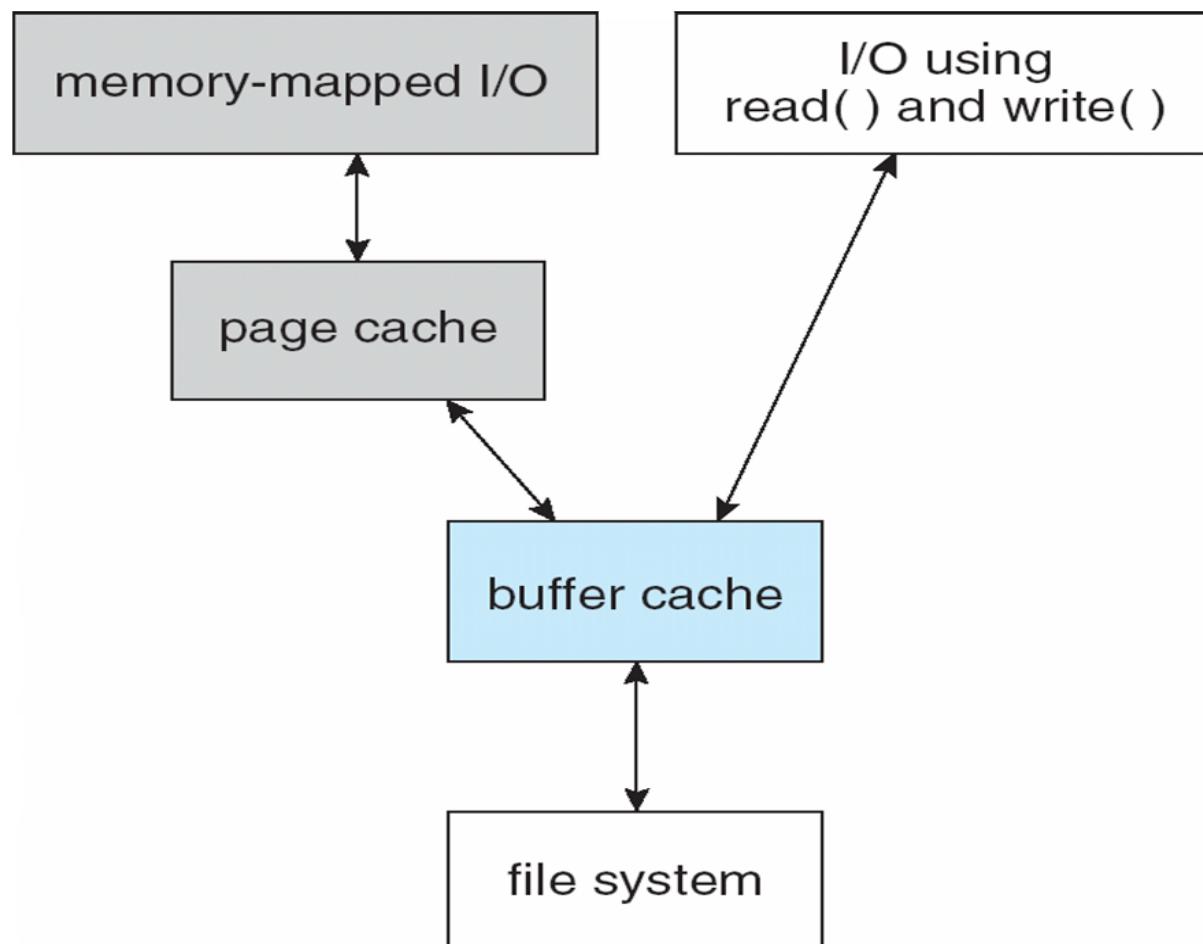
Page Cache

- 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





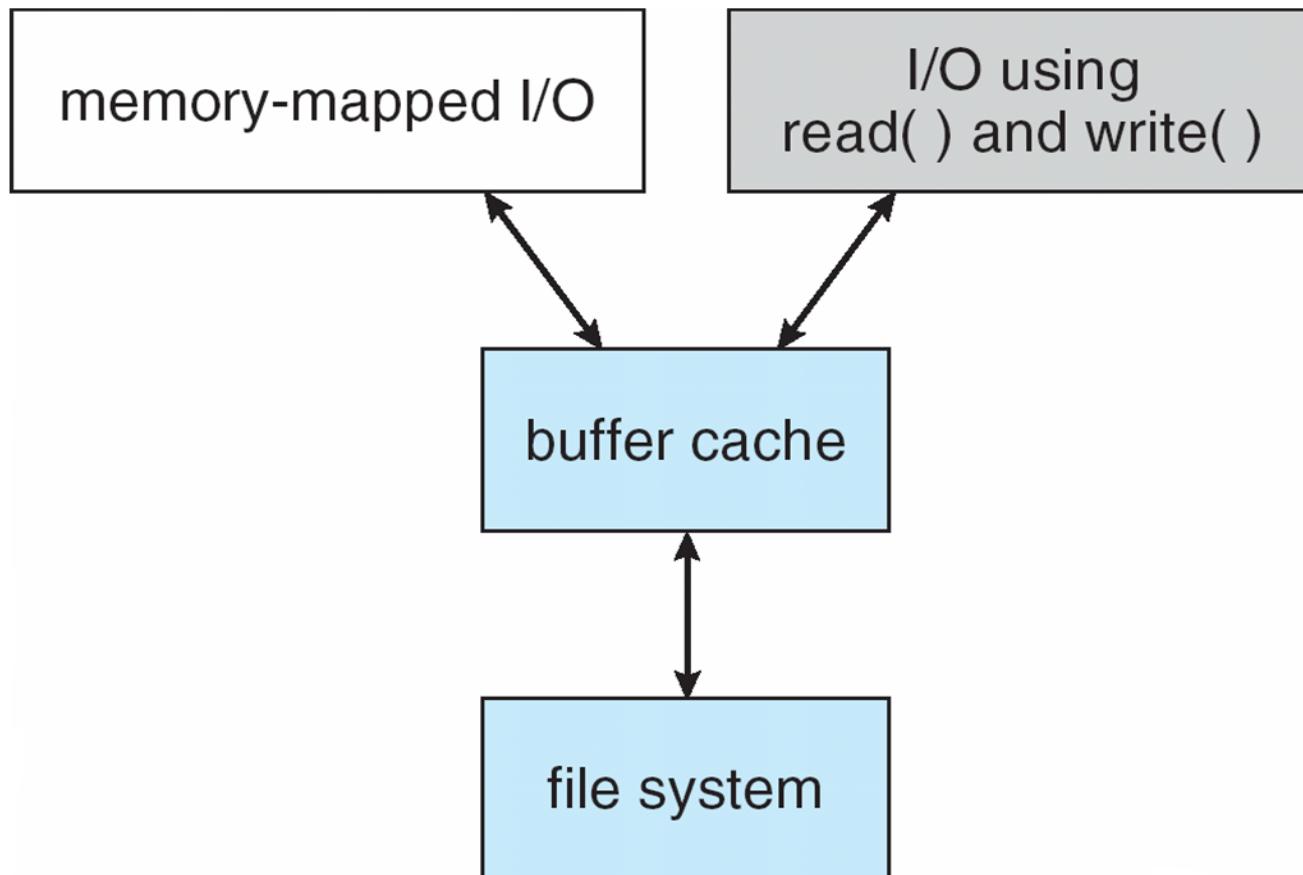
Unified Buffer Cache

- 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





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





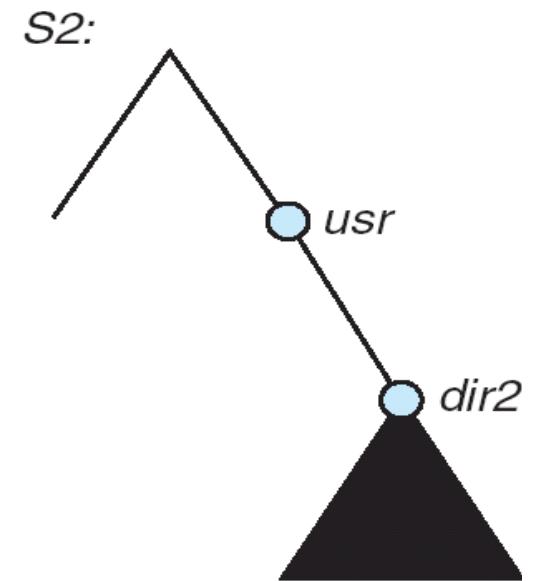
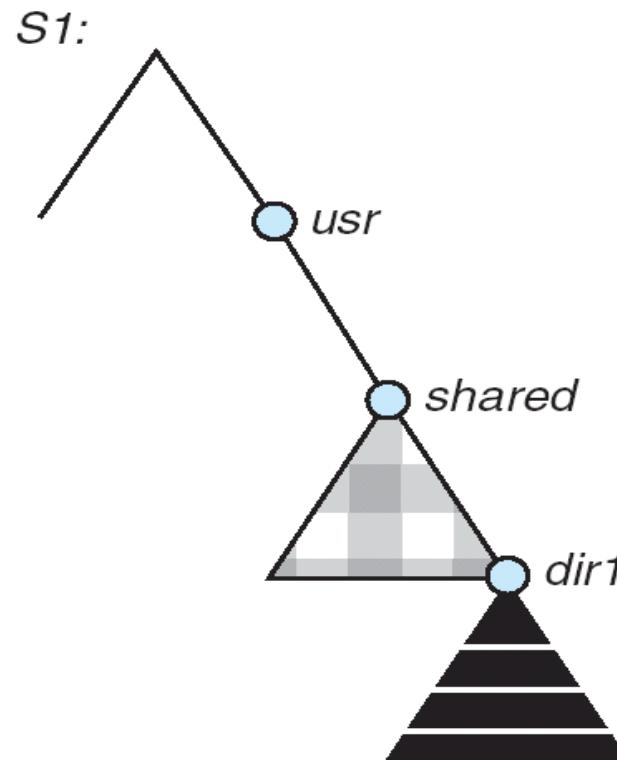
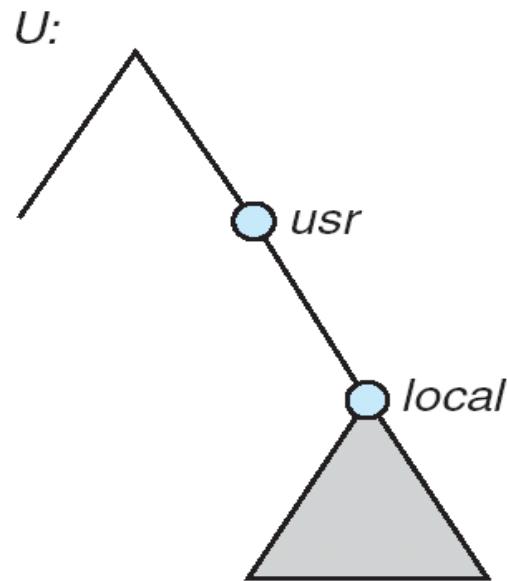
NFS (Cont.)

- 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



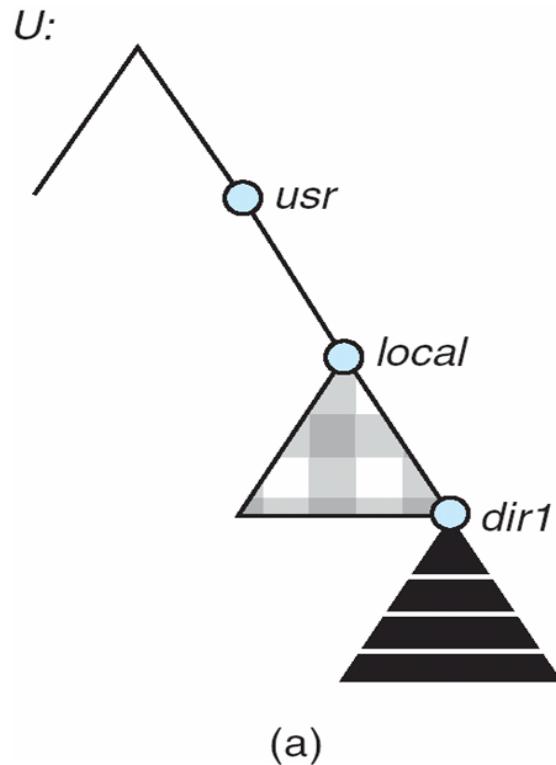


Three Independent File Systems

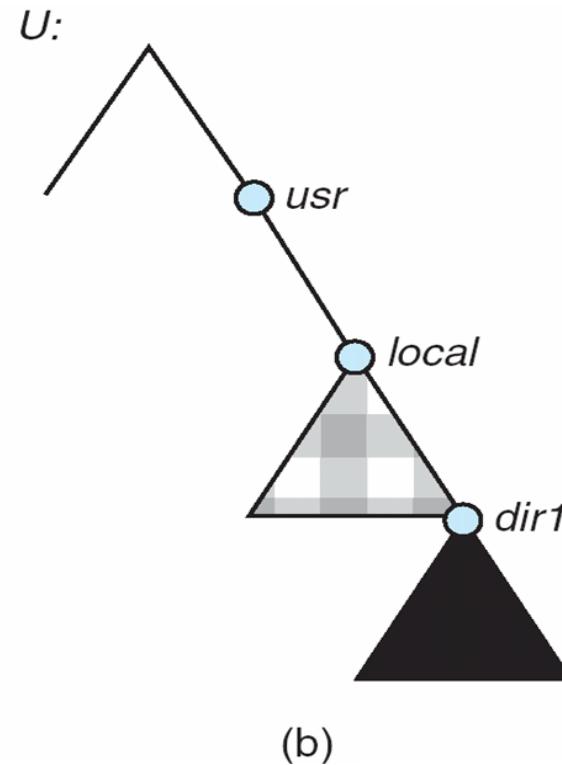




Mounting in NFS



Mounts



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





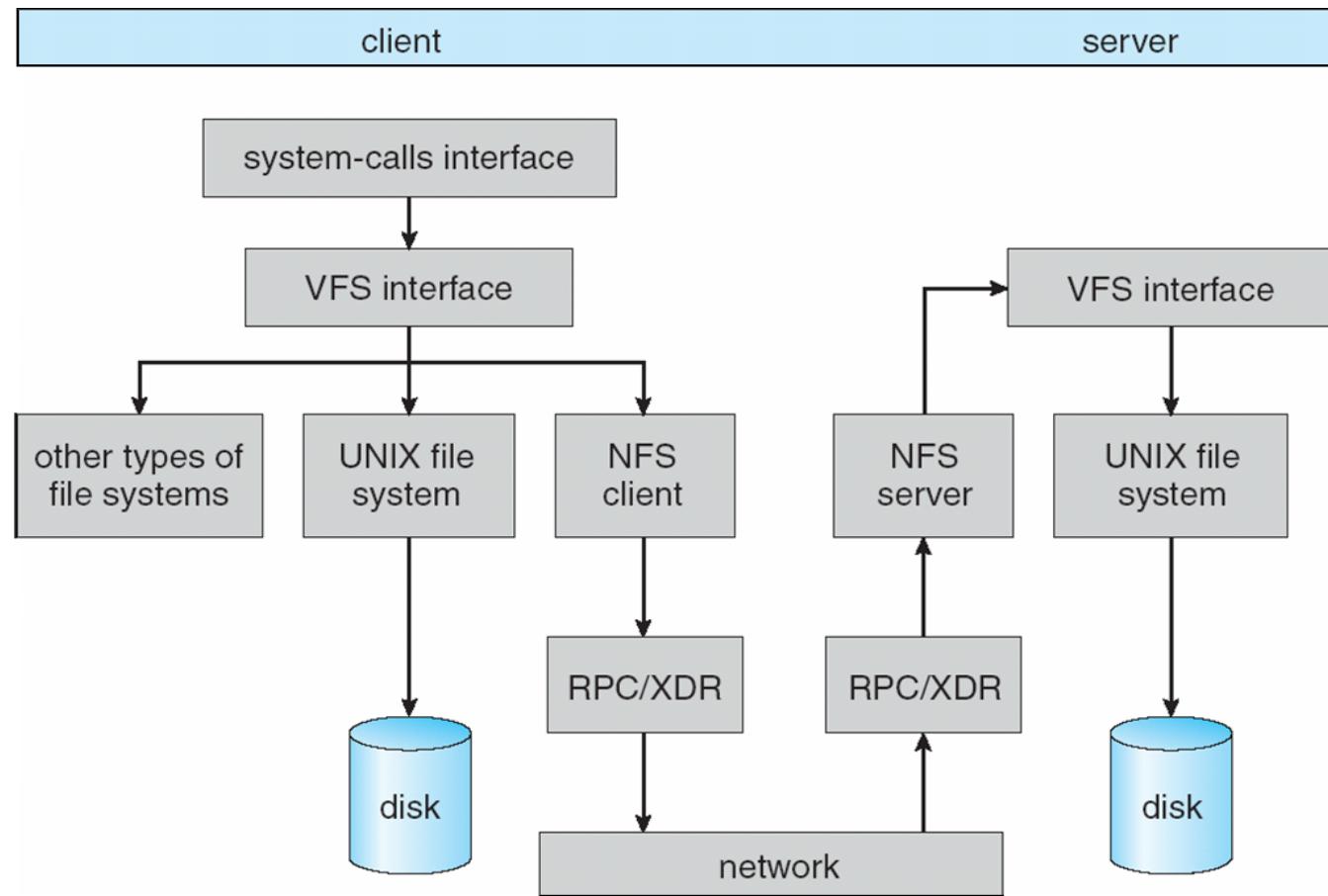
Three Major Layers of NFS Architecture

- 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





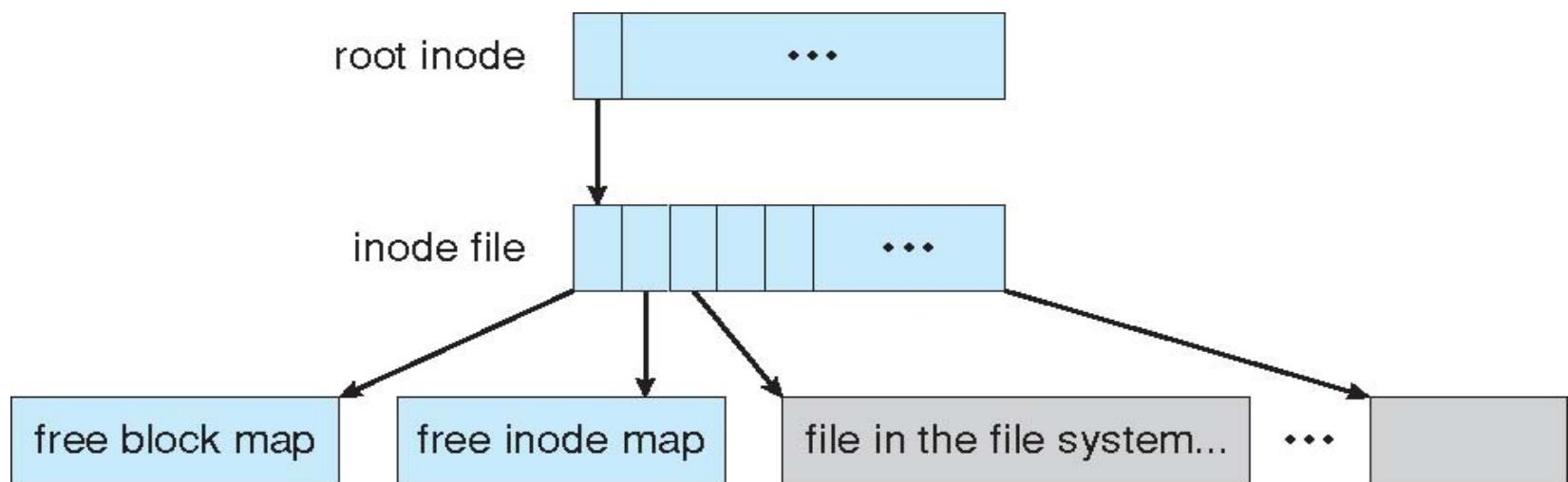
Example: WAFL File System

- 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



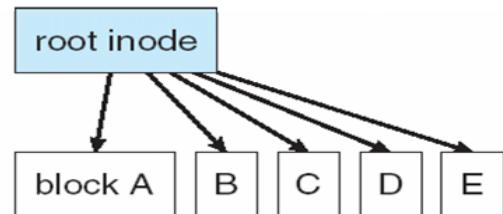


The WAFL File Layout

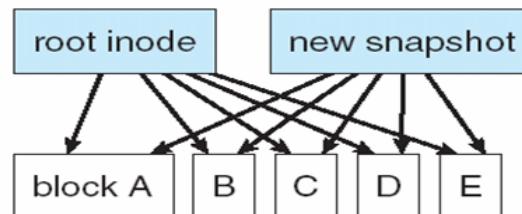




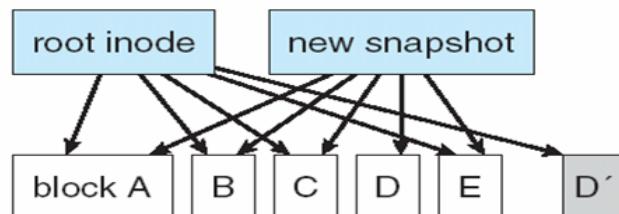
Snapshots in WAFL



(a) Before a snapshot.



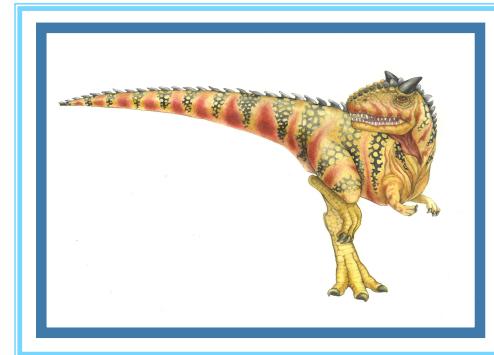
(b) After a snapshot, before any blocks change.



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



End of Chapter 10





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 $\text{block}[i]$ to have a situation where $\text{bit}[i] = 1$ in memory and $\text{bit}[i] = 0$ on disk
 - Solution:
 - ▶ Set $\text{bit}[i] = 1$ in disk
 - ▶ Allocate $\text{block}[i]$
 - ▶ Set $\text{bit}[i] = 1$ in memory

