Chap. 11) Implementing File Systems

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방 재 훈

Overview

- User's view on file systems:
  - ✓ How files are named?
  - ✓ What operations are allowed on them?
  - ✓ What the directory tree looks like?

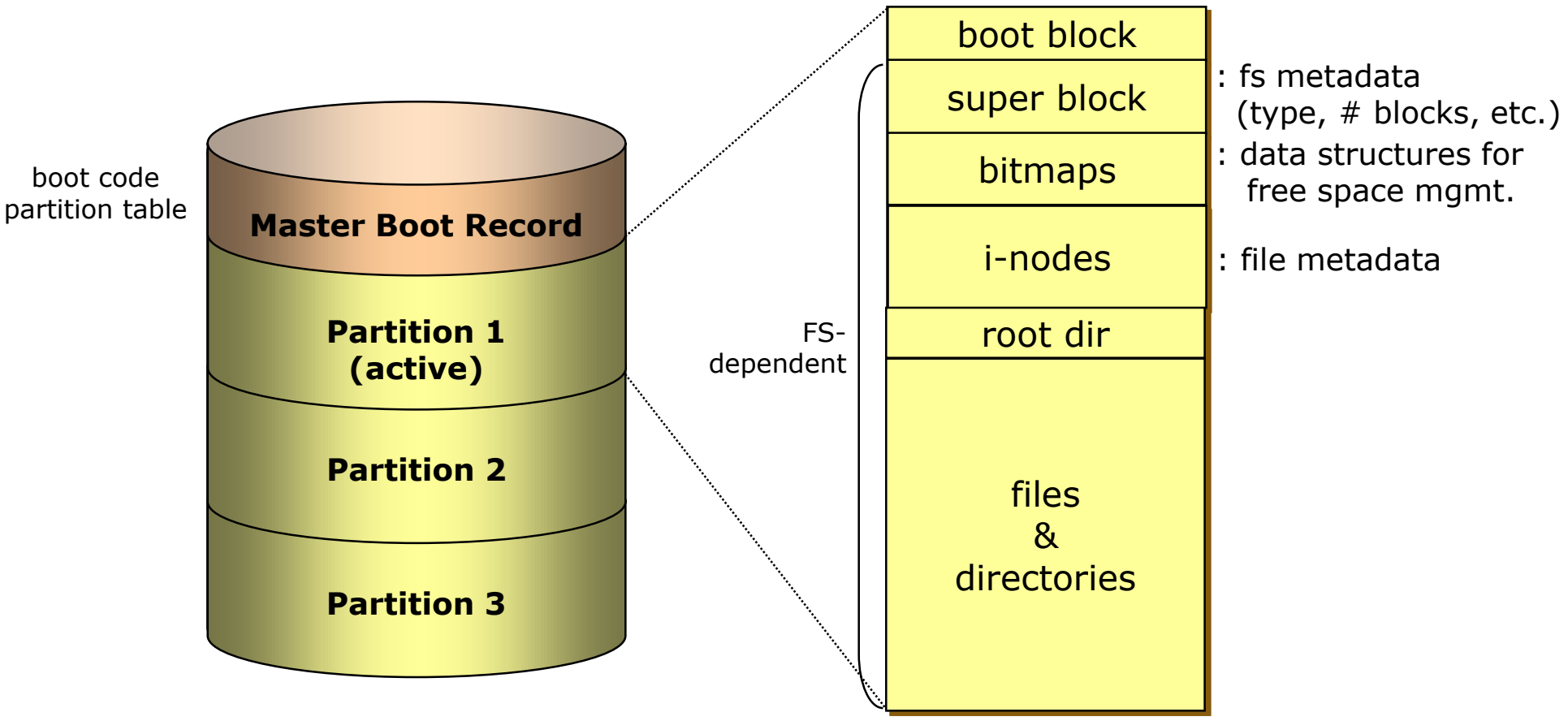
- Implementer's view on file systems:
  - ✓ How files and directories are stored?
  - ✓ How disk space is managed?
  - ✓ How to make everything work efficiently and reliably?

File-System Implementation

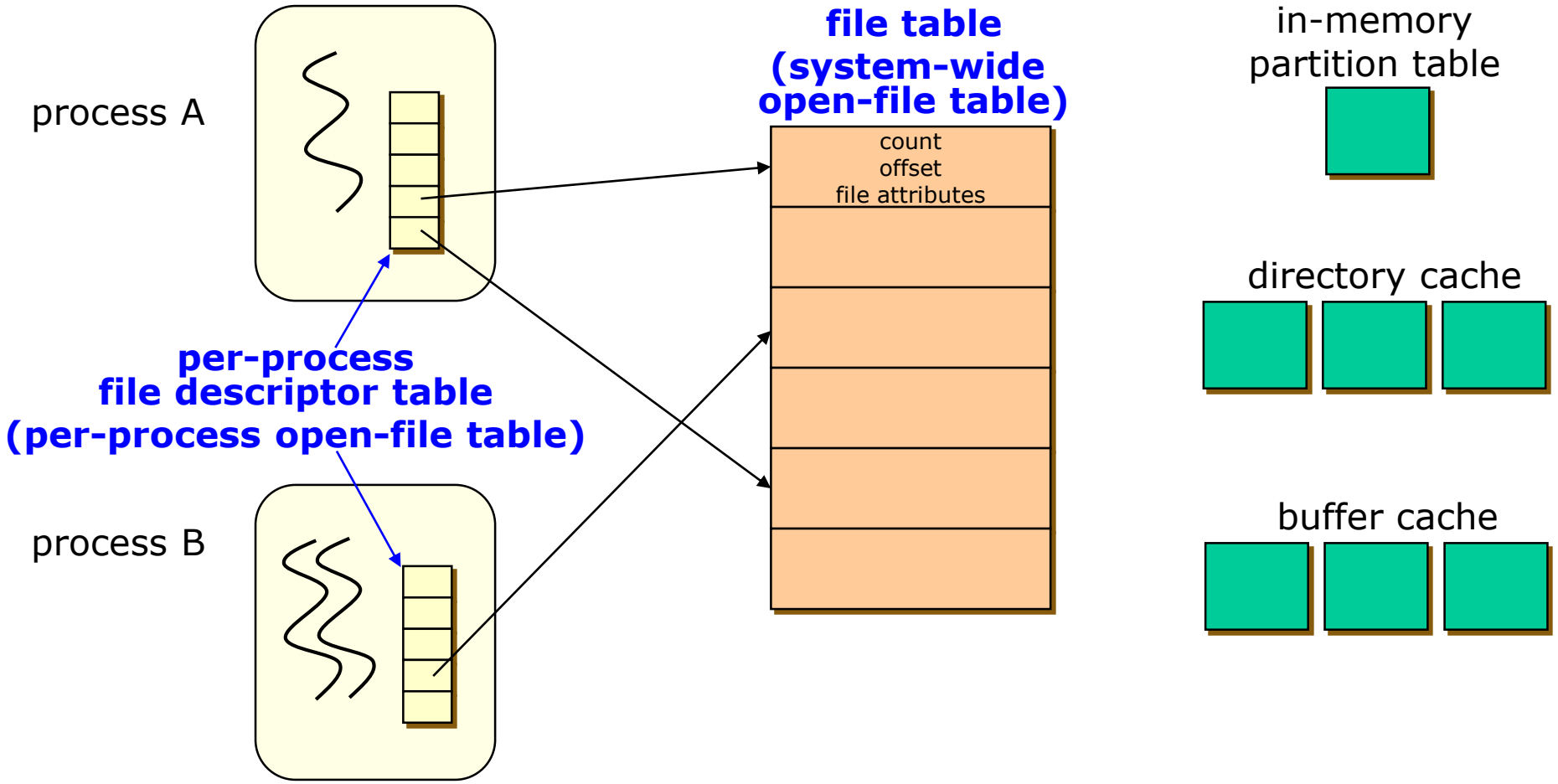
- On-disk structure
  - ✓ Boot control block
    - Boot block(UFS) or Boot sector(NTFS)
  - ✓ Partition control block
    - Super block(UFS) or Master file table(NTFS)
  - ✓ Directory structure
  - ✓ File control block (FCB)
    - I-node(UFS) or In master file table(NTFS)

- In-memory structure
  - ✓ In-memory partition table
  - ✓ In-memory directory structure
  - ✓ System-wide open file table
  - ✓ Per-process open file table

On-Disk Structure



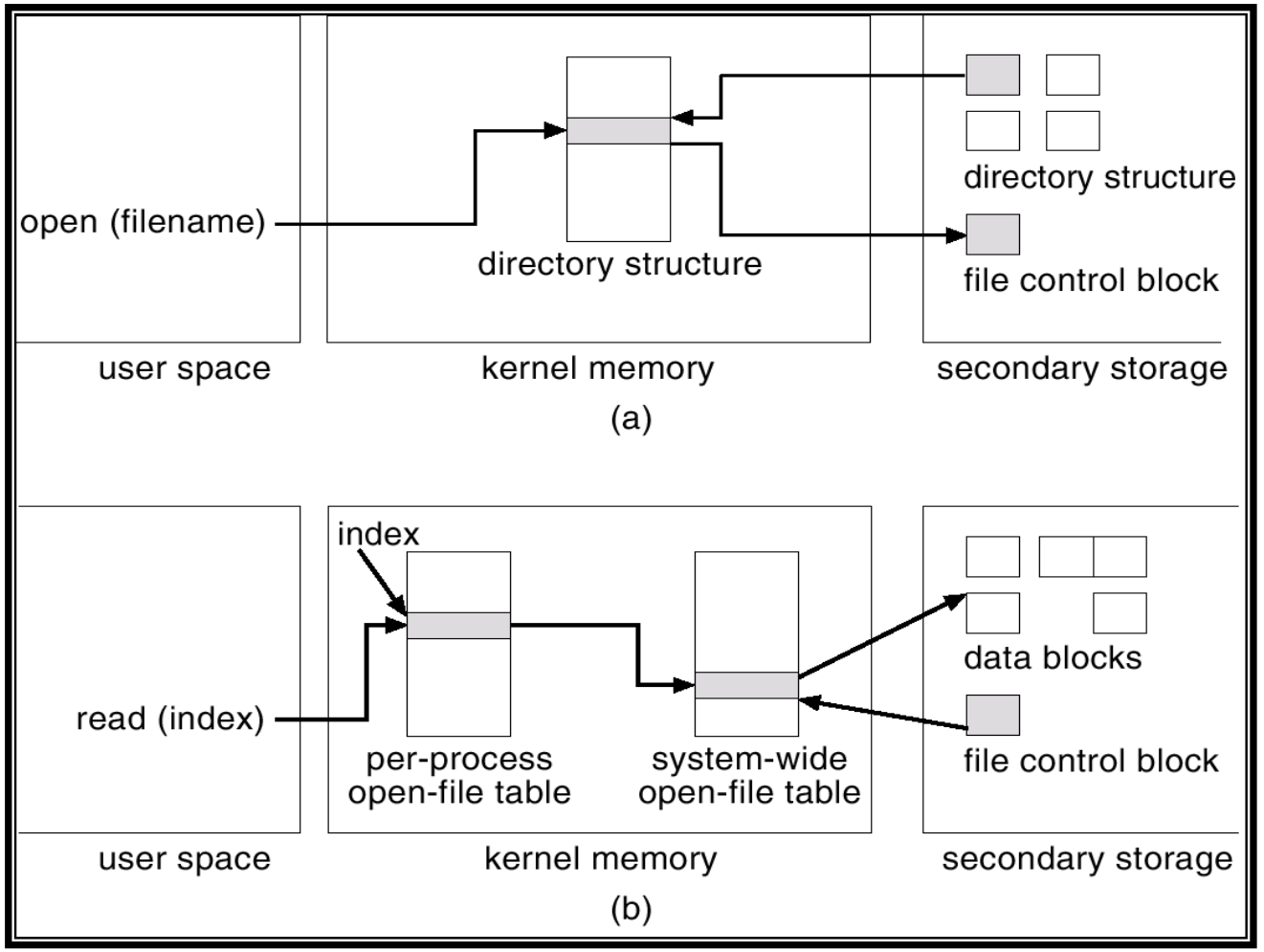
In-Memory Structure



In-Memory File System Structures

- 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

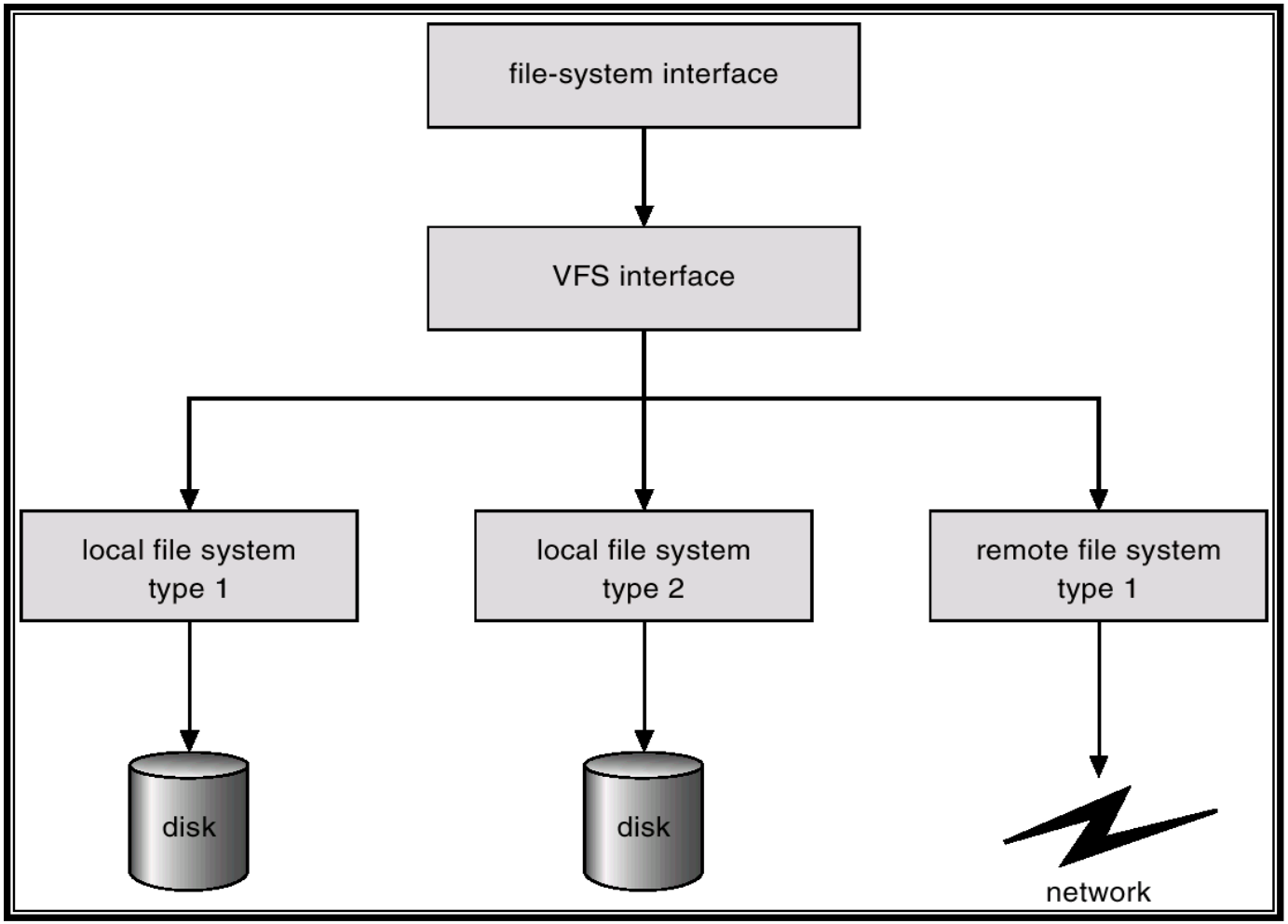
In-Memory File System Structures



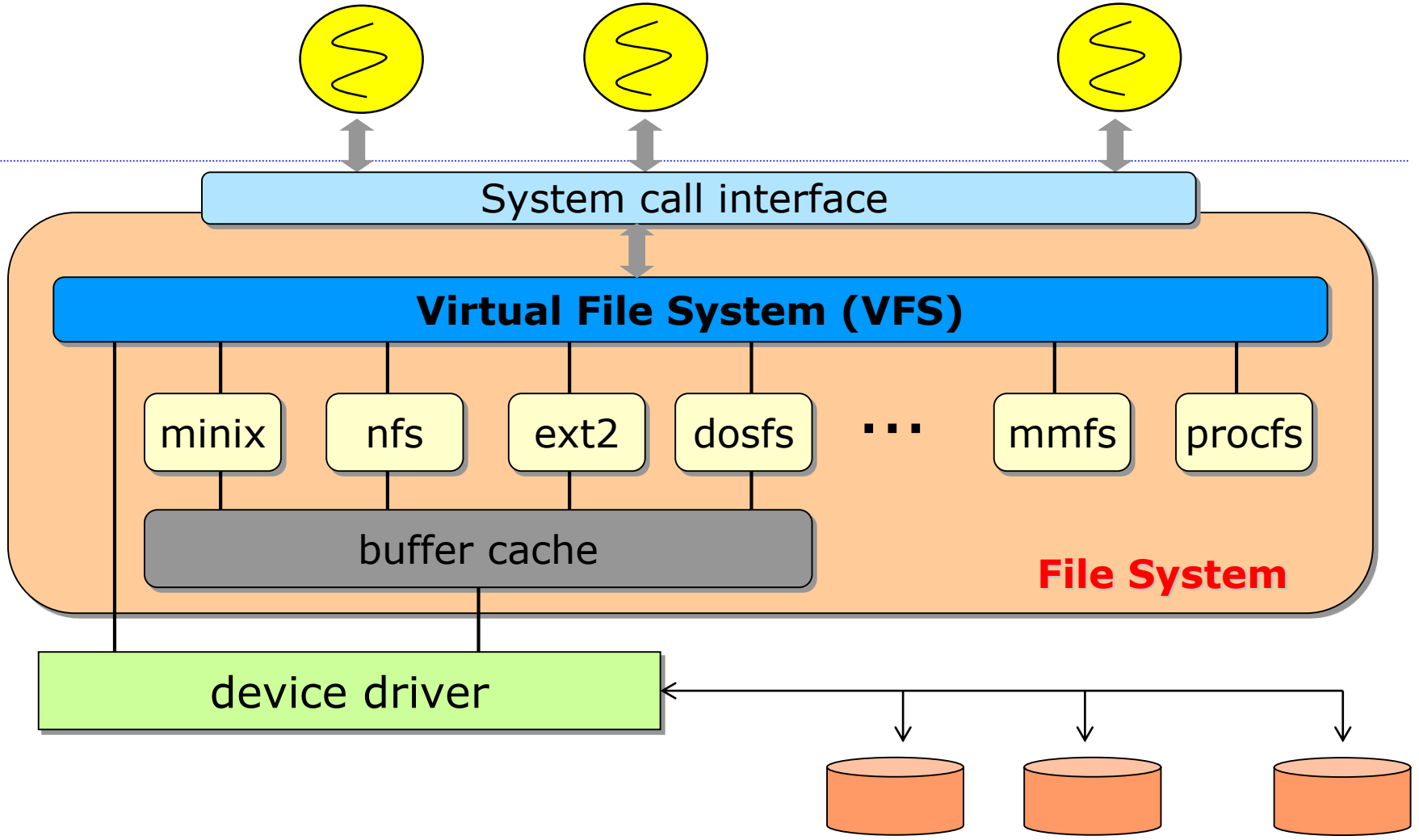
Virtual File Systems

- 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

Schematic View of Virtual File System



File System Internals



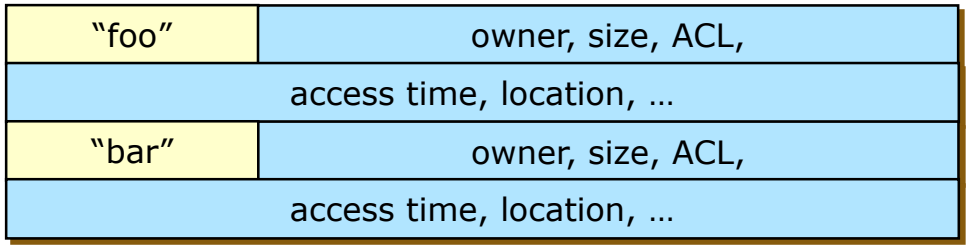
Directory Implementation

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

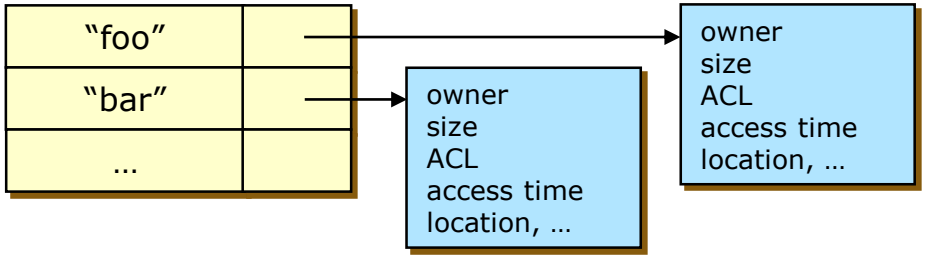
- Hash Table
  - ✓ linear list with hash data structure
  - ✓ decreases directory search time
  - ✓ *collisions*
    - situations where two file names hash to the same location
  - ✓ fixed size

Directory Implementation

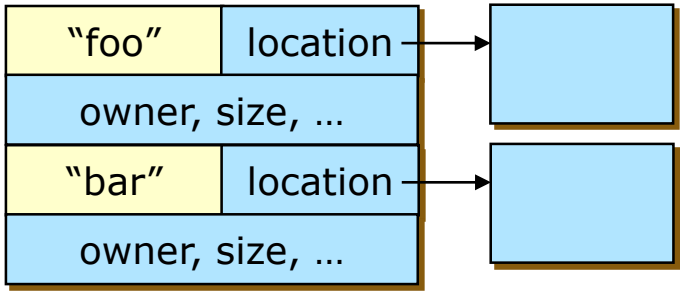
- The location of metadata
  - ✓ In the directory entry



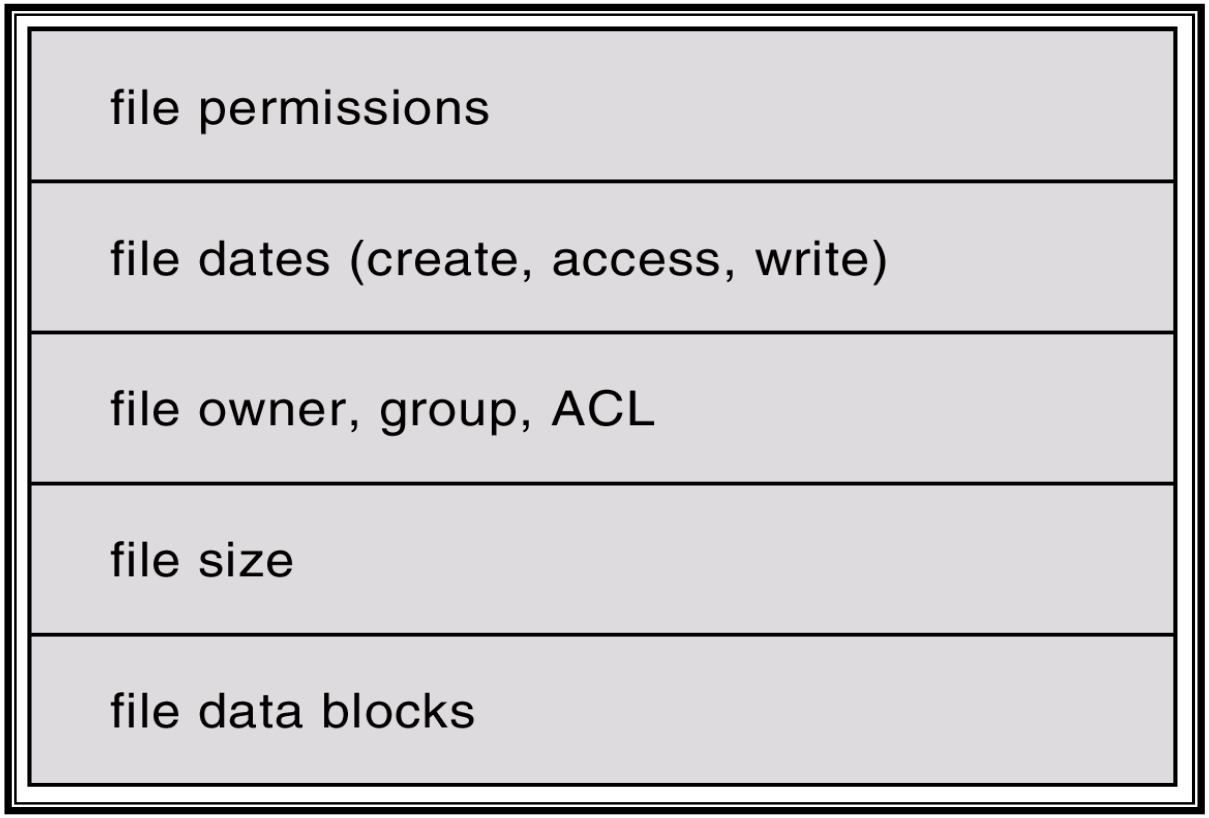
  - ✓ In the separate data structure (e.g., i-node)



  - ✓ A hybrid approach



A Typical File Control Block



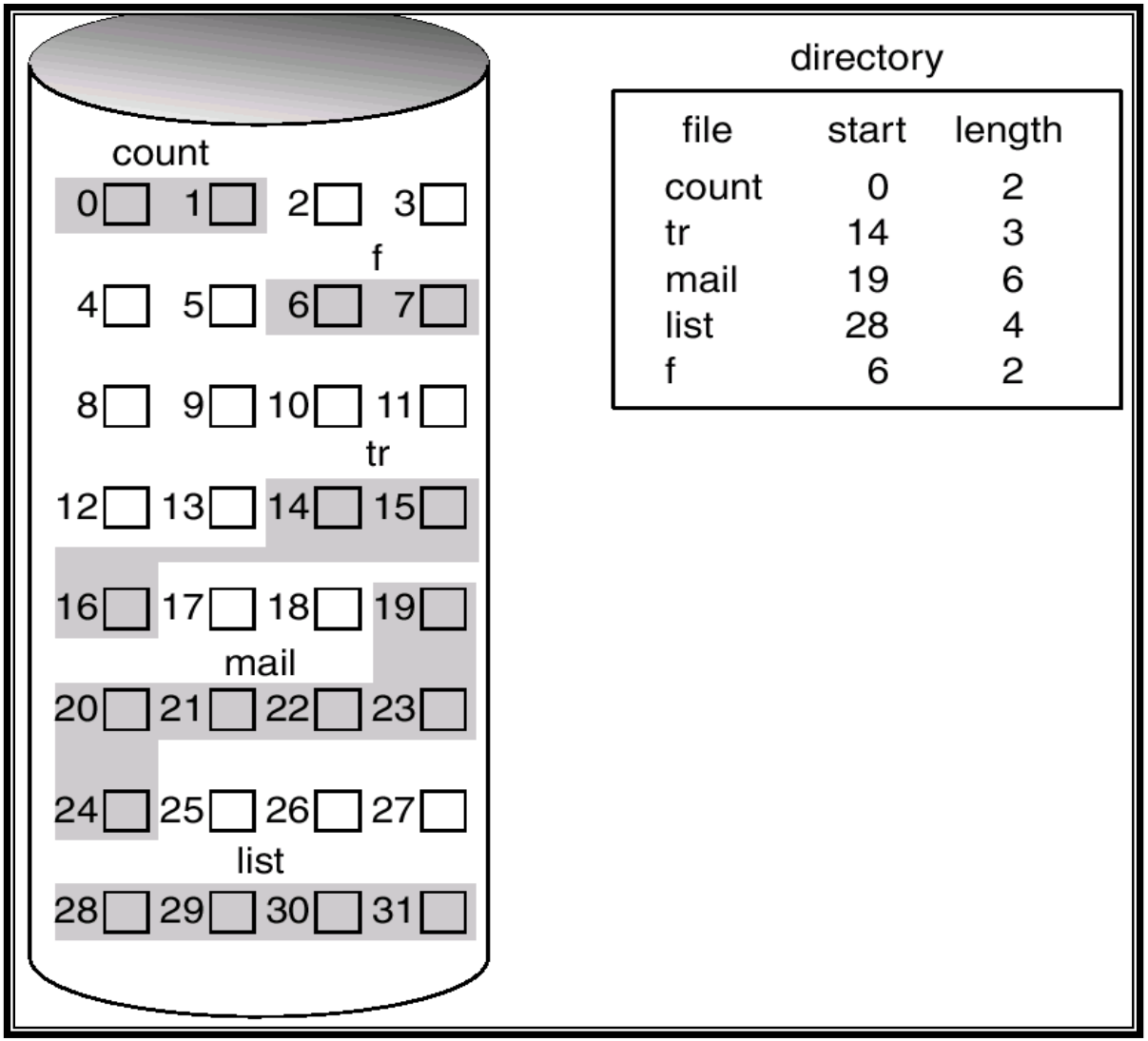
Allocation Methods

- 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
- Wasteful of space (dynamic storage-allocation problem)
- Files cannot grow

Contiguous Allocation of Disk Space



directory

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

Contiguous Allocation

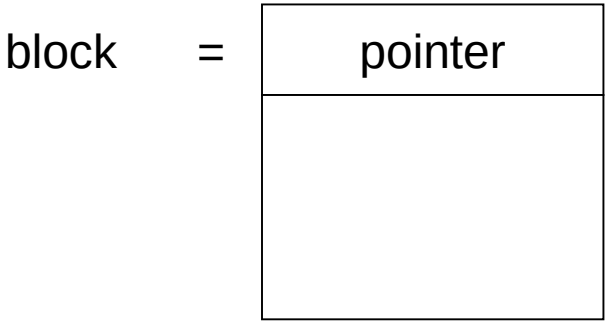
- Advantages
  - ✓ The number of disk seeks is minimal
  - ✓ Directory entries can be simple:
    <file name, starting disk block, length, etc.>

- Disadvantages
  - ✓ Requires a dynamic storage allocation: First / best fit
  - ✓ External fragmentation: may require a compaction
  - ✓ The file size is hard to predict and varying over time

- Feasible and widely used for CD-ROMS
  - ✓ All the file sizes are known in advance
  - ✓ Files will never change during subsequent use

Linked Allocation

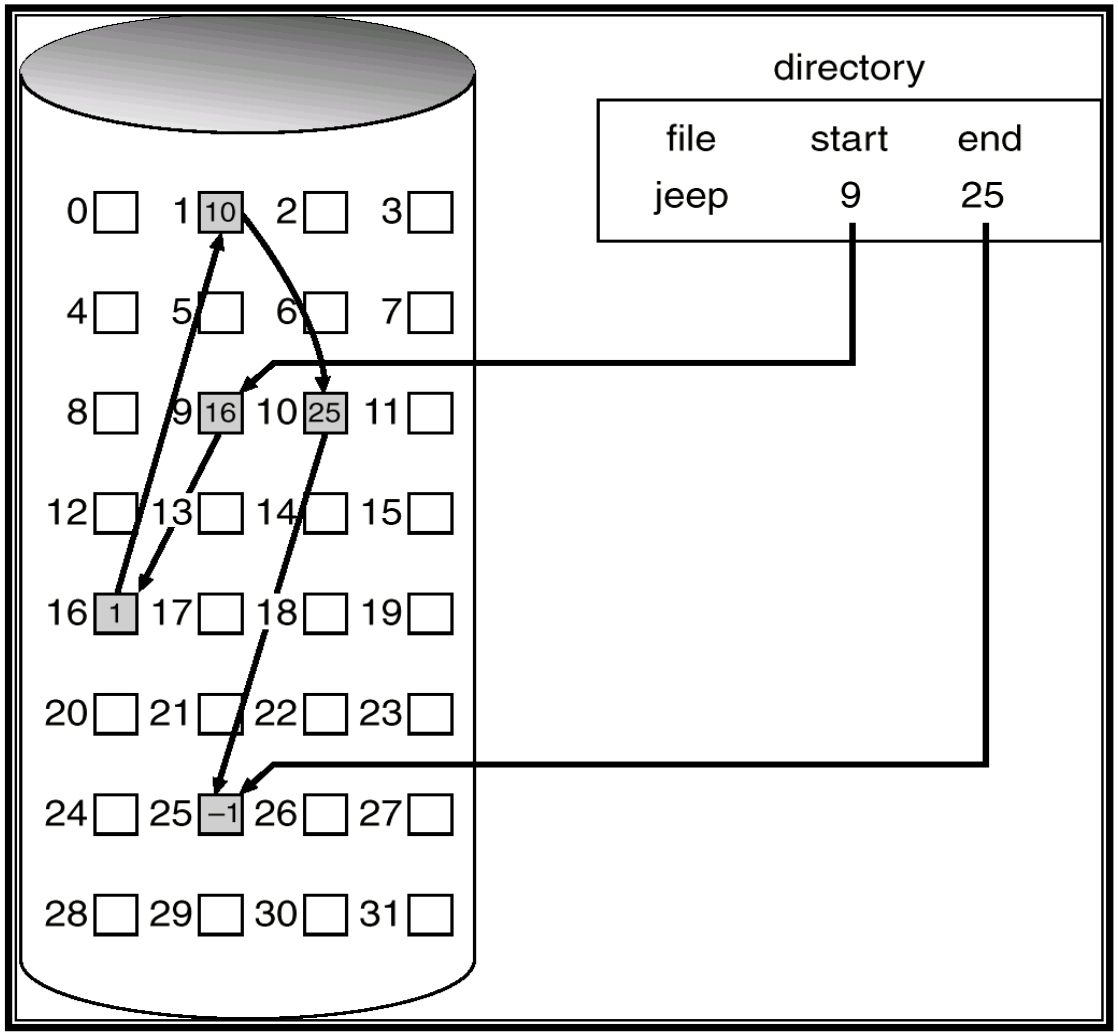
- Each file is a linked list of disk blocks
  - ✓ Blocks may be scattered anywhere on the disk



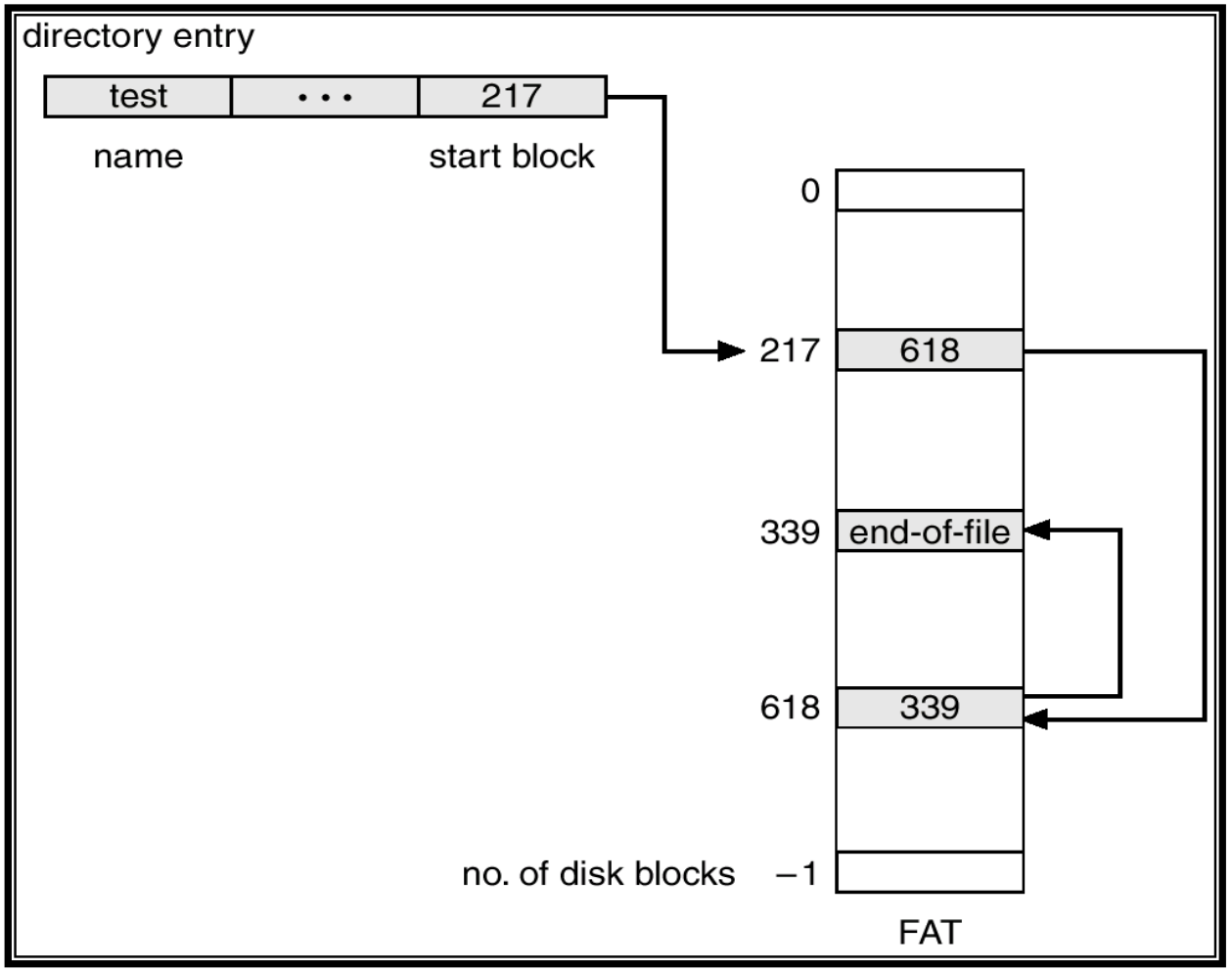
Linked Allocation (Cont'd)

- Simple
  - ✓ need only starting address
- Free-space management system
  - ✓ no waste of space
- No random access
- File-allocation table (FAT)
  - ✓ disk-space allocation used by MS-DOS and OS/2

Linked Allocation



File-Allocation Table



Linked Allocation

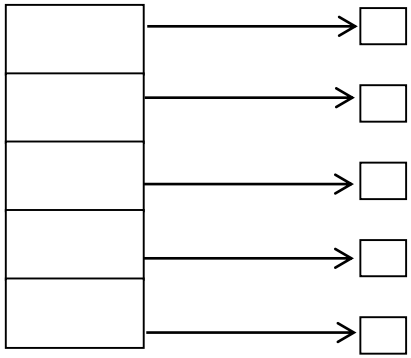
- Advantages
  - ✓ Directory entries are simple:

    <file name, starting block, ending block, etc.>
  - ✓ No external fragmentation
    - the disk blocks may be scattered anywhere on the disk
  - ✓ A file can continue to grow as long as free blocks are available

- Disadvantages
  - ✓ It can be used only for sequentially accessed files
  - ✓ Space overhead for maintaining pointers to the next disk block
  - ✓ The amount of data storage in a block is no longer a power of two because the pointer takes up a few bytes
  - ✓ Fragile: a pointer can be lost or damaged

Indexed Allocation

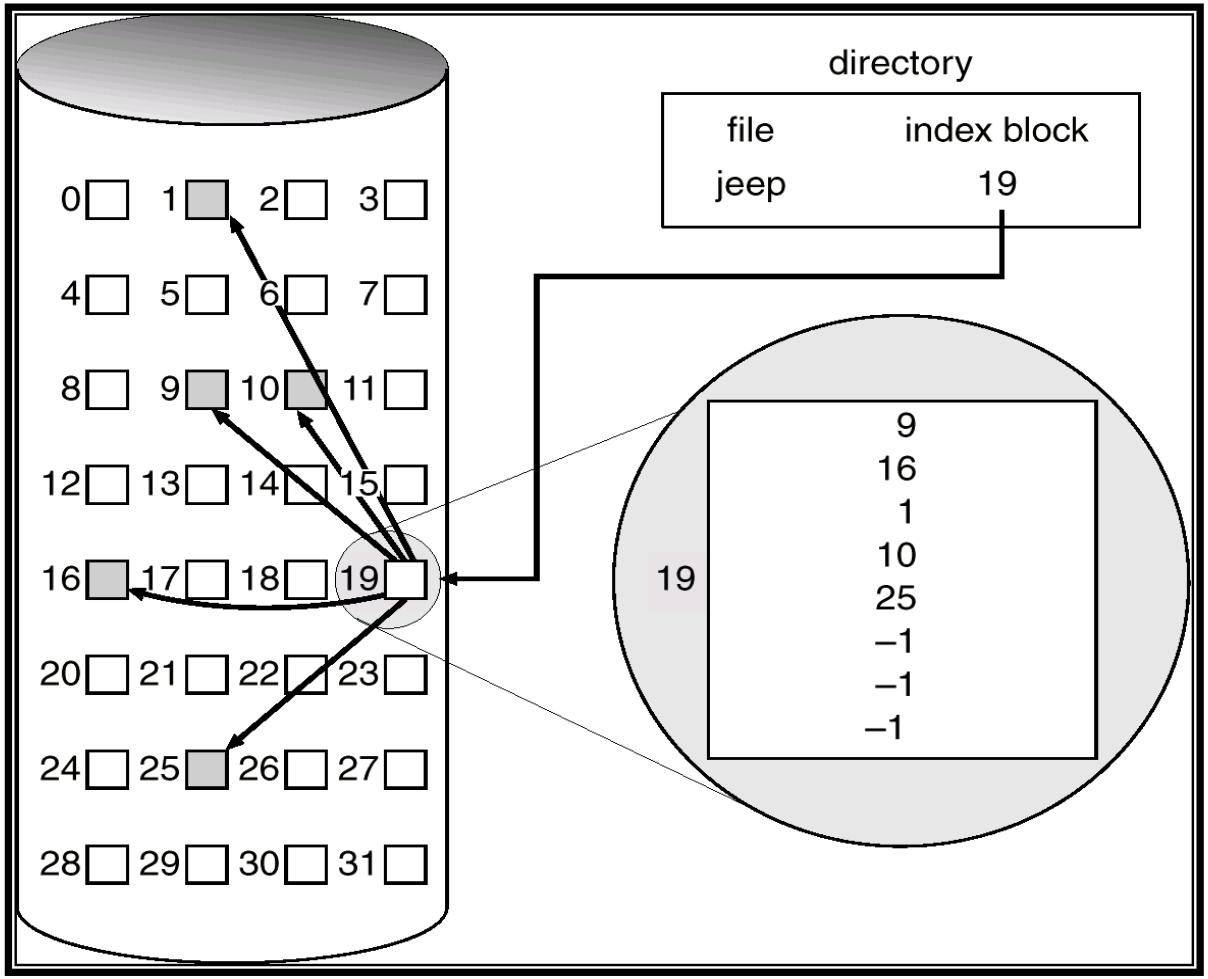
- Brings all pointers together into the *index block*
- Logical view



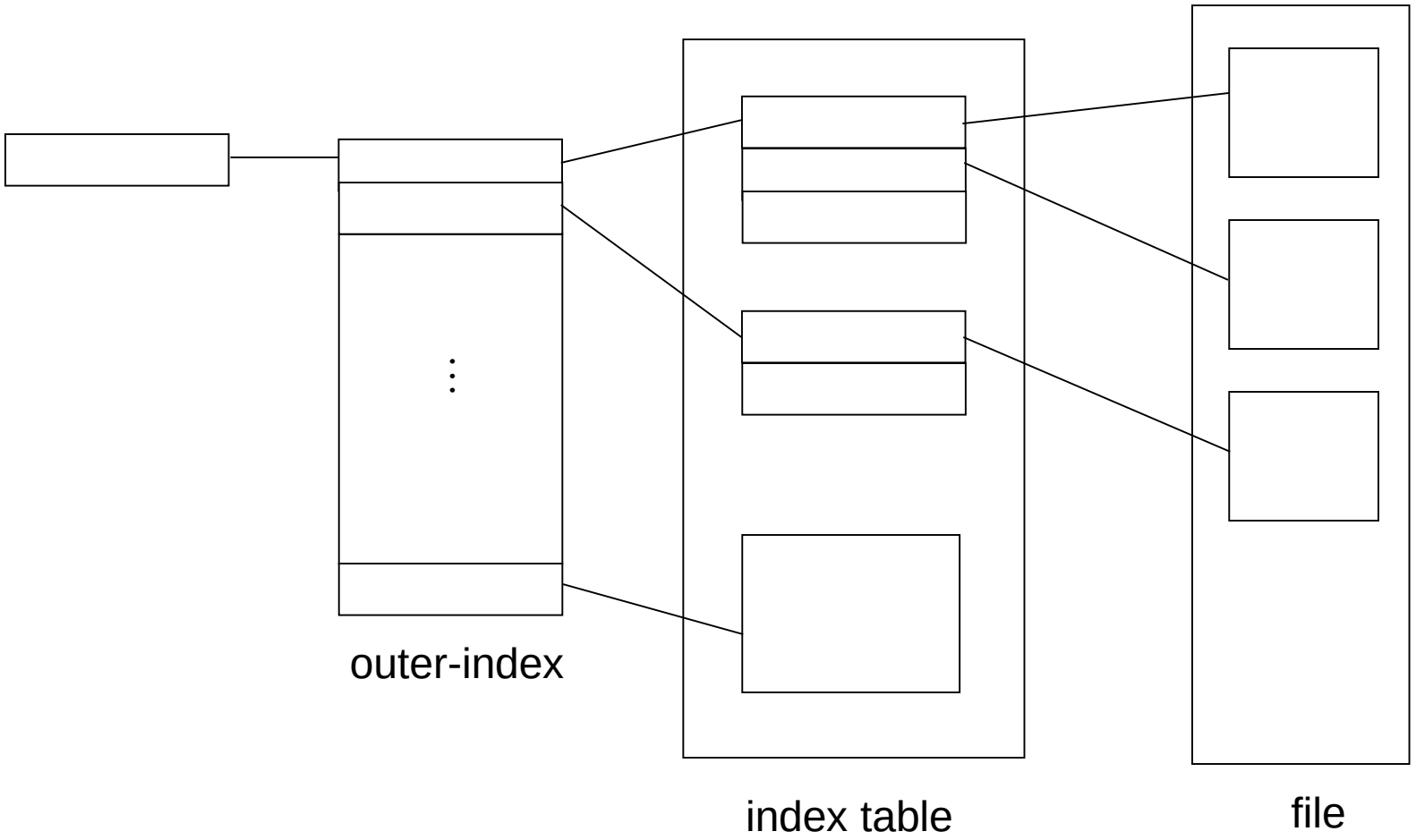
index table

- Need index table
- Random access
- Dynamic access without external fragmentation, but have overhead of index block

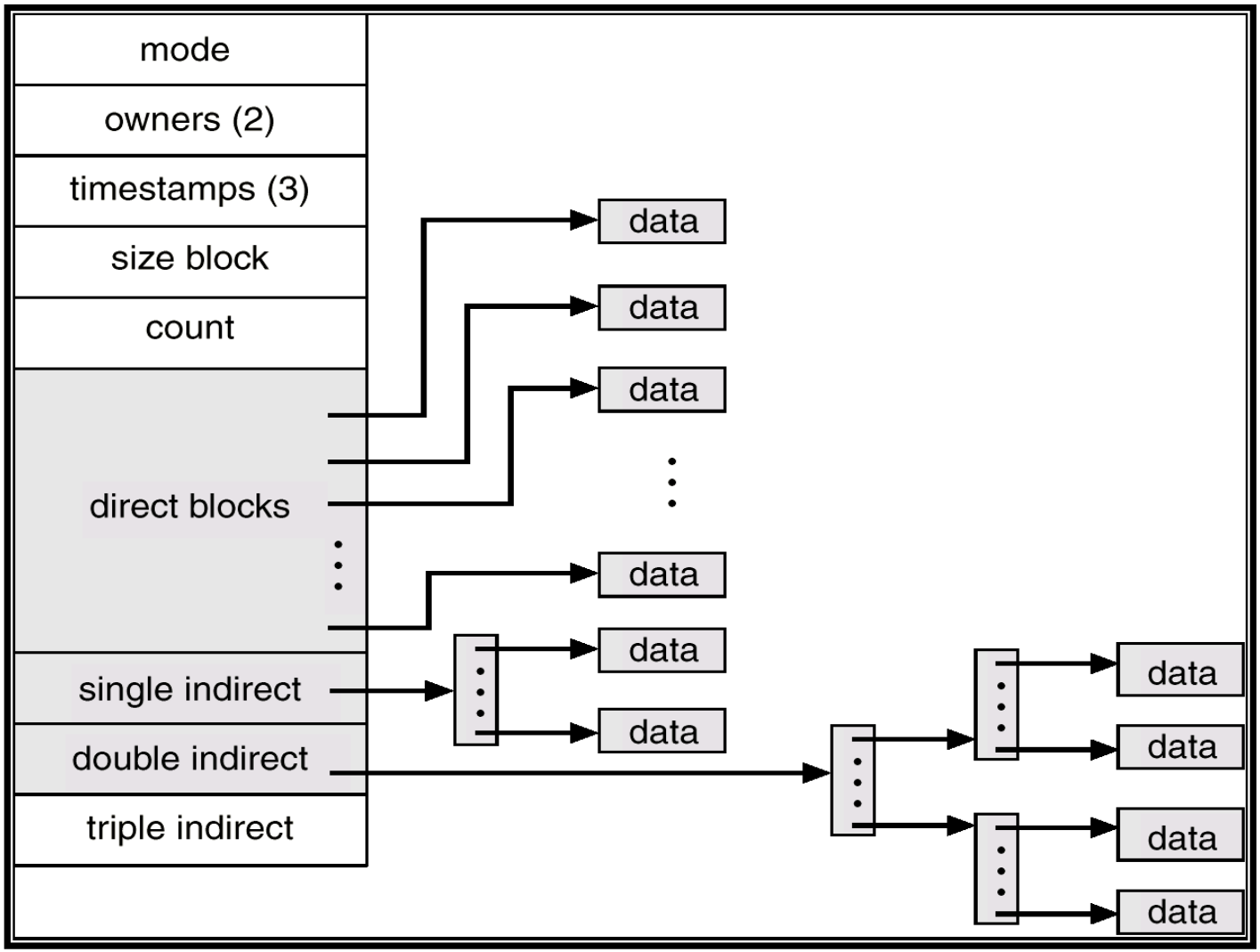
Example of Indexed Allocation



Indexed Allocation – Mapping (Cont'd)



Combined Scheme: UNIX (4K bytes per block)



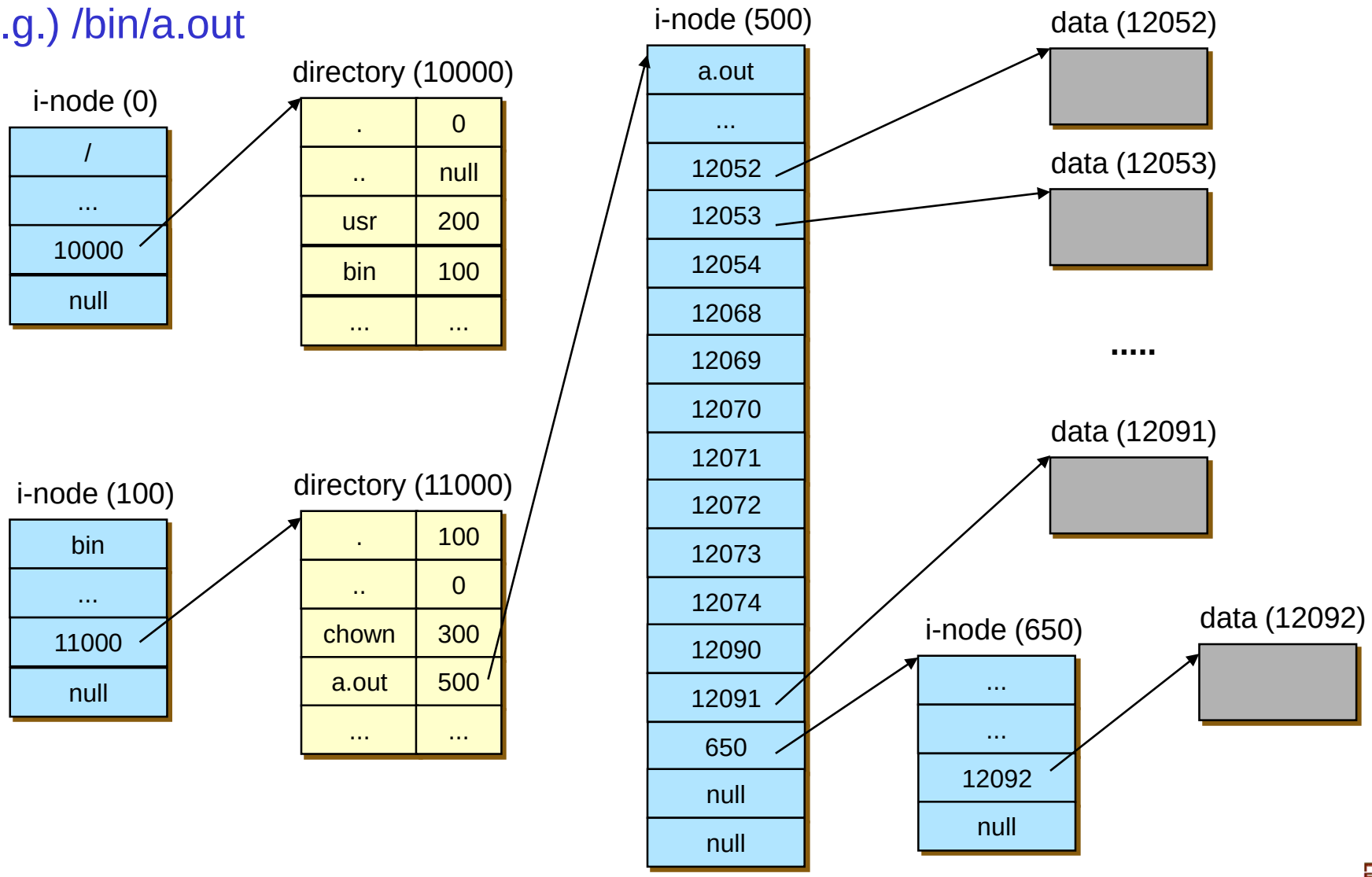
Indexed Allocation

- Advantages
  - ✓ Supports direct access, without suffering from external fragmentation
  - ✓ I-node need only be in memory when the corresponding file is open

- Disadvantages
  - ✓ Space overhead for indexes:
    (1) Linked scheme: link several index blocks
    (2) Multilevel index blocks
    (3) Combined scheme: UNIX
    - 12 direct blocks, single indirect block, double indirect block, triple indirect block

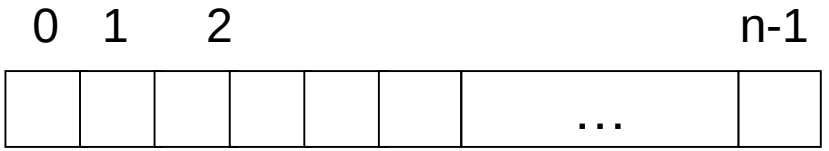
UNIX File System Structure

- E.g.) /bin/a.out



Free-Space Management

- Bit vector (*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

Free-Space Management (Cont'd)

- 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)

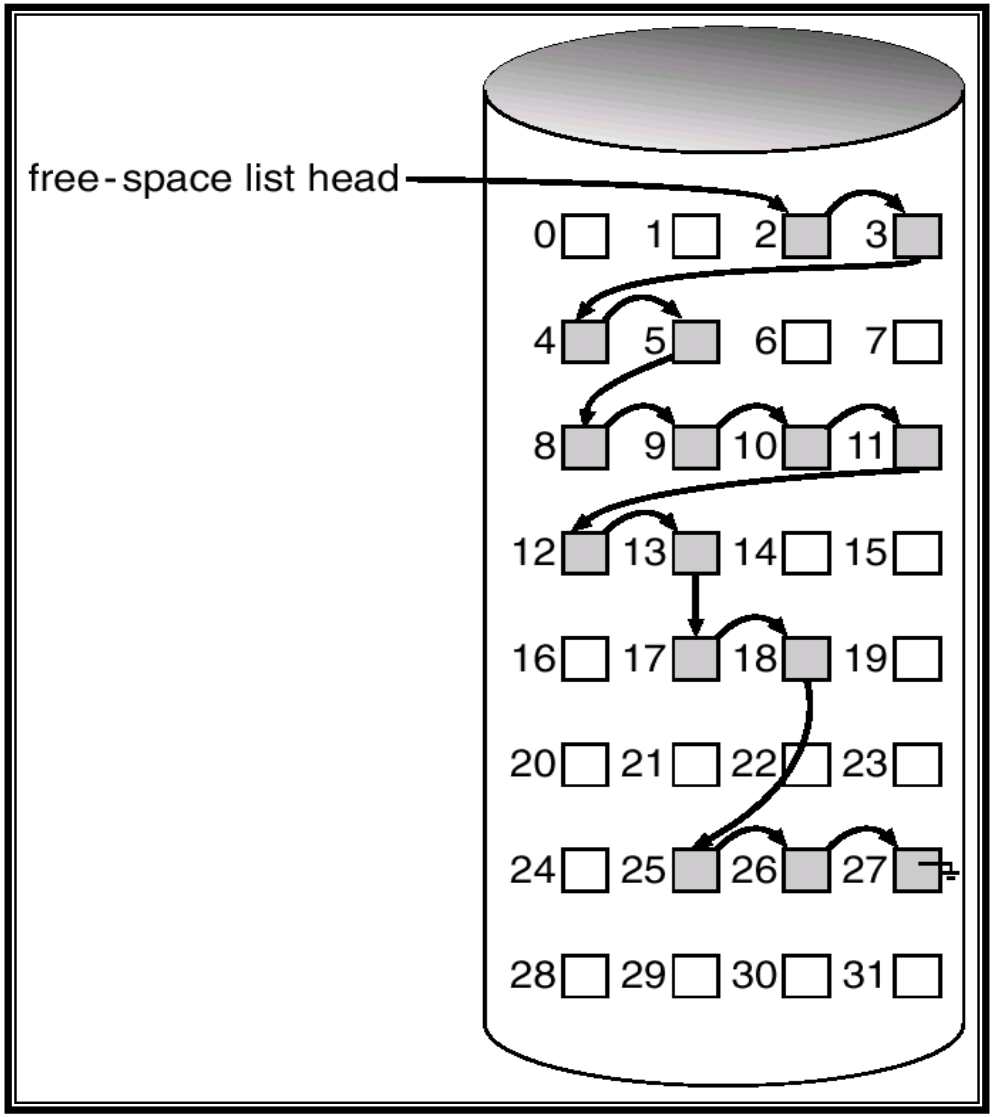
- Easy to get contiguous files

- Linked list (free list)
  - ✓ Cannot get contiguous space easily
  - ✓ No waste of space

- Grouping

- Counting

Linked Free Space List on Disk



Efficiency and Performance

- Efficiency dependent on:
  - ✓ Disk allocation and directory algorithms
  - ✓ Types of data kept in file's directory entry
- 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

Buffer Cache

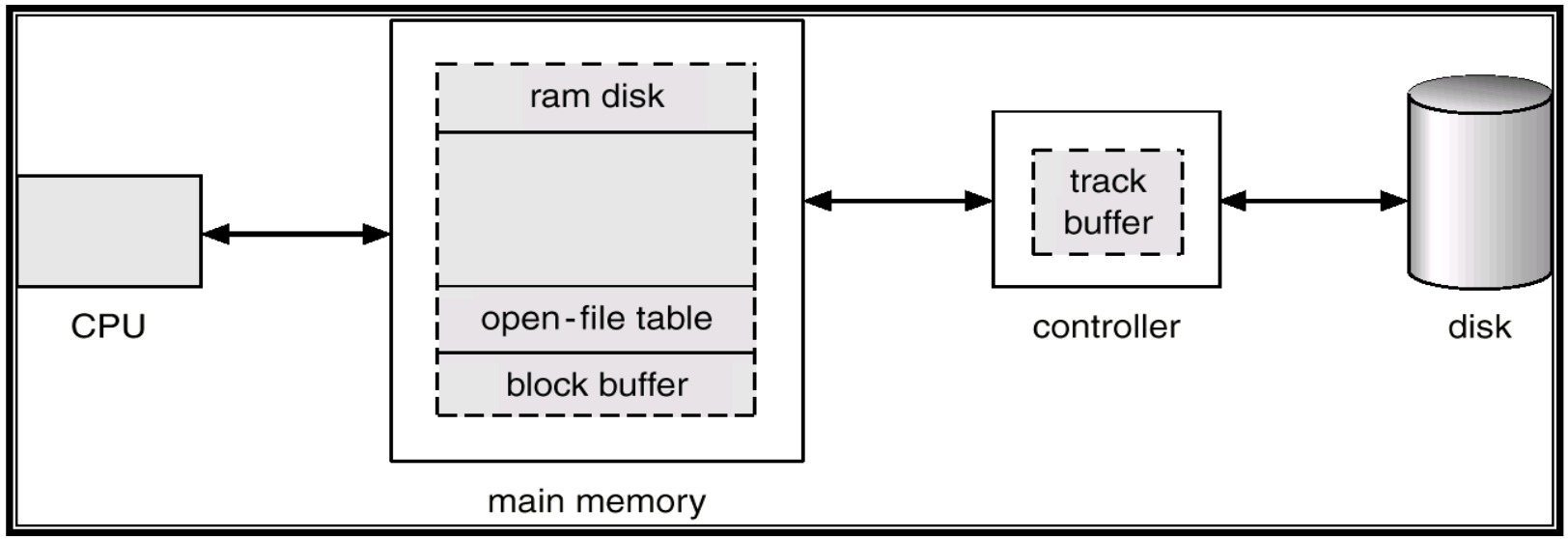
- Applications exhibit significant locality for reading and writing files

- Idea: cache file blocks in memory to capture locality in buffer cache (or disk cache)
  - ✓ Cache is system wide, used and shared by all processes
  - ✓ Reading from the cache makes a disk perform like memory
  - ✓ Even a 4MB cache can be very effective

- Issues
  - ✓ The buffer cache competes with VM
  - ✓ Like VM, it has limited size
  - ✓ Need replacement algorithms again

    (References are relatively infrequent, so it is feasible to keep all the blocks in exact LRU order)

Various Disk-Caching Locations



Caching Writes

- Synchronous writes are very slow

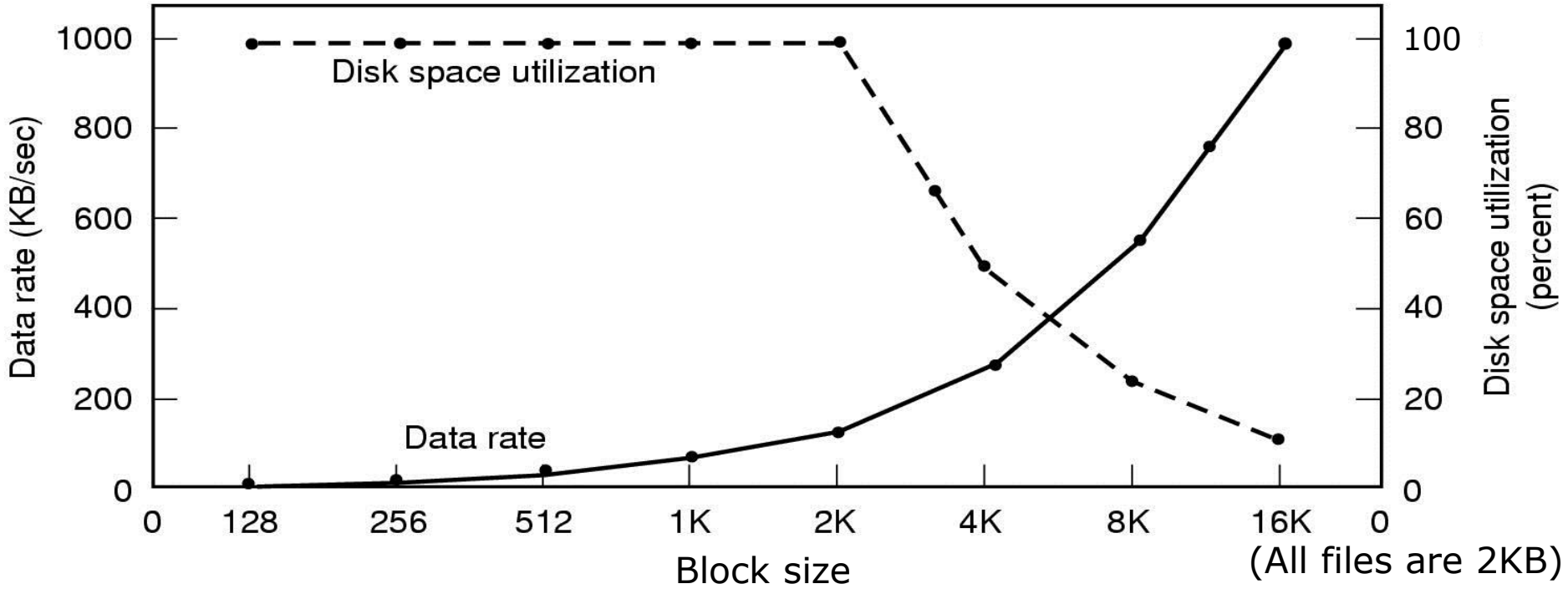
- Asynchronous writes (or write-behind, write-back)
  - ✓ Maintain a queue of uncommitted blocks
  - ✓ Periodically flush the queue to disk
  - ✓ Unreliable: metadata requires synchronous writes (with small files, most writes are to metadata)

Read-Ahead

- File system predicts that the process will request next block
  - ✓ File system goes ahead and requests it from the disk
  - ✓ This can happen while the process is computing on previous block, overlapping I/O with execution
  - ✓ When the process requests block, it will be in cache
- Compliments the disk cache, which also is doing read ahead
- Very effective for sequentially accessed files
- File systems try to prevent blocks from being scattered across the disk during allocation or by restructuring periodically
- Cf) Free-behind

Block Size Performance vs. Efficiency

- Block size
  - ✓ Disk block size vs. file system block size
  - ✓ The median file size in UNIX is about 1KB



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)
- Recover lost file or disk by *restoring* data from backup

- File system consistency
  - ✓ File system can be left in an inconsistent state if cached blocks are not written out due to the system crash
  - ✓ It is especially critical if some of those blocks are i-node blocks, directory blocks, or blocks containing the free list
  - ✓ Most systems have a utility program that checks file system consistency
    - Windows: scandisk
    - UNIX: fsck

Log Structured File Systems

- Journaling file systems
  - ✓ Fsck'ing takes a long time, which makes the file system restart slow in the event of system crash
  - ✓ Record a log, or journal, of changes made to files and directories to a separate location (preferably a separate disk)
  - ✓ If a crash occurs, the journal can be used to undo any partially completed tasks that would leave the file system in an inconsistent state
  - ✓ IBM JFS for AIX, Linux

    Veritas VxFS for Solaris, HP-UX, Unixware, etc.

    SGI XFS for IRIX, Linux

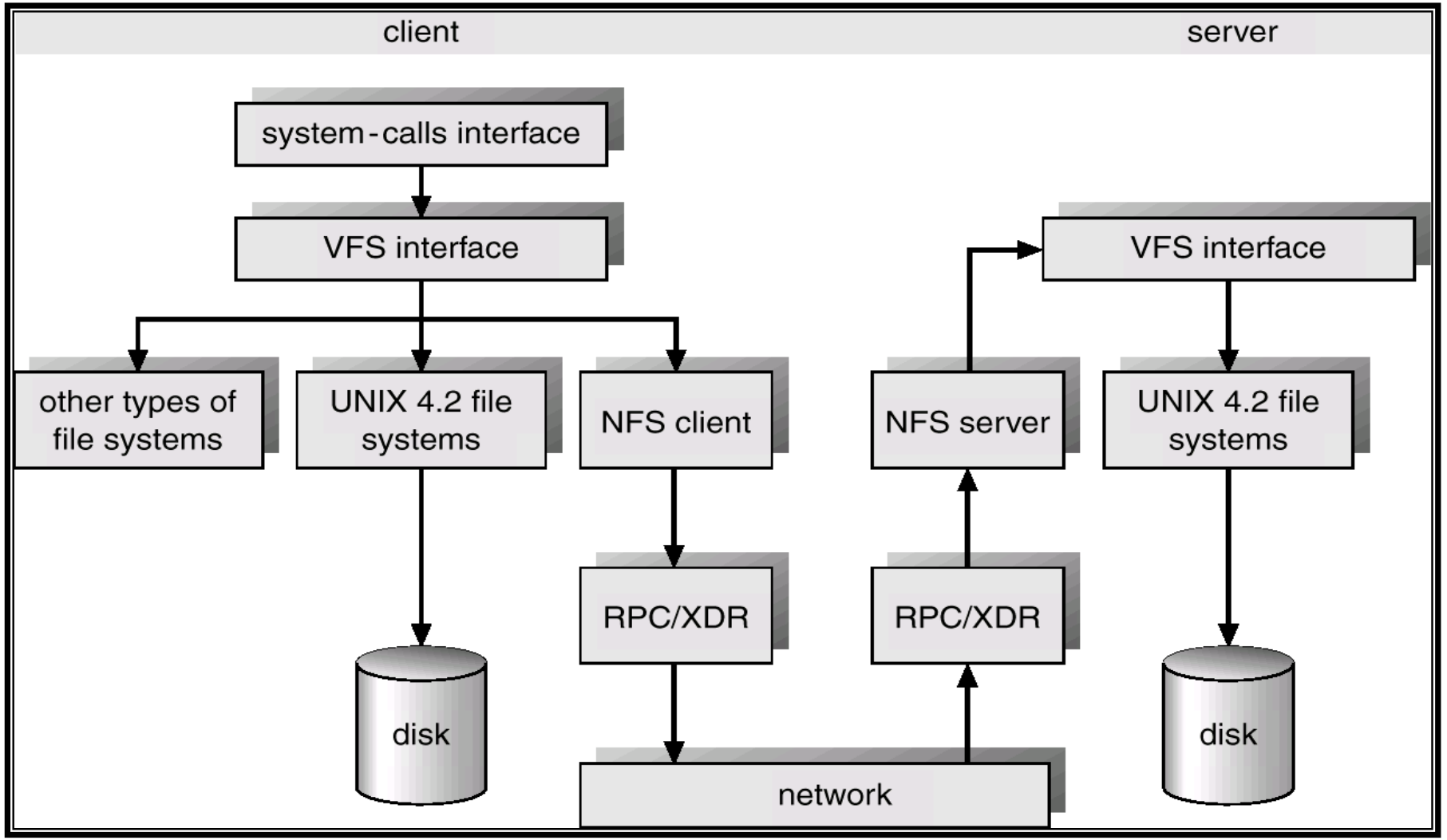
    Reiserfs, ext3 for Linux

    NTFS for Windows

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)

Schematic View of NFS Architecture



Summary

- Implementer's view on file systems
  - ✓ How files and directories are stored?
  - ✓ How disk space is managed?
  - ✓ How to make everything work efficiently and reliably?
- In-memory structure of file system
  - ✓ In-memory partition table
  - ✓ In-memory directory structure
  - ✓ System-wide open file table
  - ✓ Per-process open file table

Summary (Cont'd)

- On-disk structure of file system
  - ✓ Boot control block
    - Boot block(UFS) or Boot sector(NTFS)
  - ✓ Partition control block
    - Super block(UFS) or Master file table(NTFS)
  - ✓ Free space management block
    - Bitmaps (UFS, NTFS)
  - ✓ File control block (FCB)
    - I-node(UFS) or In master file table(NTFS)
  - ✓ Data block
    - Directory entry
    - File data
- Directory implementation
  - ✓ Linear list of file names with pointer to their FCB

Summary (Cont'd)

- Data block allocation methods
  - ✓ How disk blocks (logical blocks) are allocated for a file
  - ✓ Contiguous allocation
    - Each file is a set of contiguous blocks
    - Simple, easy to implement, but fragmentation, no growth of file size
    - Used for CD-ROM
  - ✓ Linked allocation
    - Each file is a linked list of disk blocks
    - No fragmentation, but no random access, fragile
    - FAT (File-Allocation Table): more reliable
  - ✓ Indexed allocation
    - Index block has a pointer list for data blocks
    - Reliable, random access, but space overhead
    - Examples: NTFS and ext3

Summary (Cont'd)

- Performance issues
  - ✓ Buffer cache
    - Motivation: applications exhibit significant locality for reading and writing files
    - Idea: cache file blocks in memory to capture locality
  - ✓ Read-ahead
    - File system predicts that the process will request next block
    - Effective for sequentially accessed files
  - ✓ Block size tradeoff
    - Disk space utilization vs. Data rate (throughput)
- Reliability issue
  - ✓ Journaling file systems (or log-structured file systems)
    - Record a log, or journal, of changes made to files and directories to a separate location
    - Example: NTFS, ext3

Appendix) Implementation Examples

Fast File System

- Fast file system (FFS)
  - ✓ The original Unix file system (70's) was very simple and straightforwardly implemented:
    - Easy to implement and understand
    - But very poor utilization of disk bandwidth (lots of seeking)
  - ✓ BSD Unix folks redesigned file system called FFS
    - McKusick, Joy, Fabry, and Leffler (mid 80's)
    - Now it is the file system from which all other UNIX file systems have been compared
  - ✓ The basic idea is aware of disk structure
    - Place related things on nearby cylinders to reduce seeks
    - Improved disk utilization, decreased response time

Fast File System (Cont'd)

- Data and i-node placement
  - ✓ Original Unix FS had two major problems:

  (1) Data blocks are allocated randomly in aging file systems
    - Blocks for the same file allocated sequentially when FS is new
    - As FS "ages" and fills, need to allocate blocks freed up when other files are deleted
    - Problem: Deleted files essentially randomly placed
    - So, blocks for new files become scattered across the disk

  (2) i-nodes are allocated far from blocks
    - All i-nodes at the beginning of disk, far from data
    - Traversing file name paths, manipulating files and directories require going back and forth from i-nodes to data blocks
  - ✓ Both of these problems generate many long seeks!

Fast File System (Cont'd)

- Cylinder groups
  - ✓ BSD FFS addressed these problems using the notion of a cylinder group
  - ✓ Disk partitioned into groups of cylinders
  - ✓ Data blocks from a file all placed in the same cylinder group
  - ✓ Files in same directory placed in the same cylinder group
  - ✓ I-nodes for files allocated in the same cylinder group as file's data blocks

Fast File System (Cont'd)

- Free space reserve
  - ✓ If the number of free blocks falls to zero, the file system throughput tends to be cut in half, because of the inability to localize blocks in a file
  - ✓ A parameter, called free space reserve, gives the minimum acceptable percentage of file system blocks that should be free
  - ✓ If the number of free blocks drops below this level, only the system administrator can continue to allocate blocks
  - ✓ Normally 10%; this is why df may report > 100%

Fast File System (Cont'd)

- Fragments
  - ✓ Small blocks (1KB) caused two problems:
    - Low bandwidth utilization
    - Small max file size (function of block size)
  - ✓ FFS fixes by using a larger block (4KB)
    - Allows for very large files
      (1MB only uses 2 level indirect)
    - But introduces internal fragmentation: there are many small files (i.e., < 4KB)
  - ✓ FFS introduces "fragments" to fix internal fragmentation
    - Allows the division of a block into one or more fragments (1K pieces of a block)

Fast File System (Cont'd)

- Media failures
  - ✓ Replicate master block (superblock)

- File system parameterization
  - ✓ Parameterize according to disk and CPU characteristics
    - Maximum blocks per file in a cylinder group
    - Minimum percentage of free space
    - Sectors per track
    - Rotational delay between contiguous blocks
    - Tracks per cylinder, etc.
  - ✓ Skip according to rotational rate and CPU latency

Linux Ext2 File System

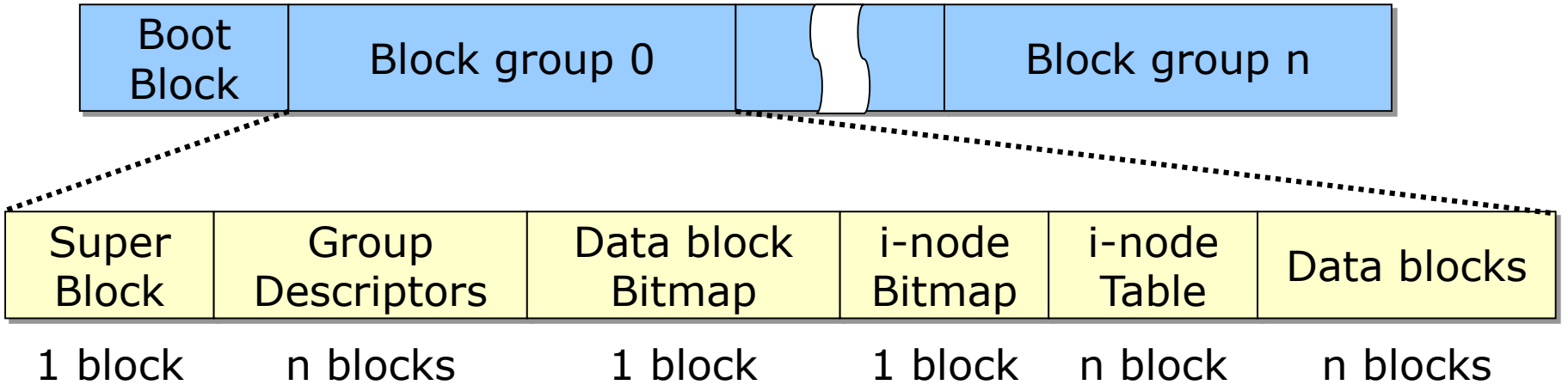
- History
  - ✓ Evolved from Minix file system
    - Block addresses are stored in 16bit integers – maximal file system size is restricted to 64MB
    - Directories contain fixed-size entries and the maximal file name was 14 characters
  - ✓ Virtual File System (VFS) is added
  - ✓ Extended Filesystem (Ext FS), 1992
    - Added to Linux 0.96c
    - Maximum file system size was 2GB, and the maximal file name size was 255 characters
  - ✓ Second Extended File-system (Ext2 FS), 1994

Linux Ext2 File System (Cont'd)

- Ext2 Features
  - ✓ Configurable block sizes (from 1KB to 4KB)
    - depending on the expected average file size
  - ✓ Configurable number of i-nodes
    - depending on the expected number of files
  - ✓ Partitions disk blocks into groups
    - lower average disk seek time
  - ✓ Preallocates disk data blocks to regular files
    - reduces file fragmentation
  - ✓ Fast symbolic links
    - If the pathname of the symbolic link has 60 bytes or less, it is stored in the i-node
  - ✓ Automatic consistency check at boot time

Linux Ext2 File System (Cont'd)

- Disk layout
  - ✓ Boot block
    - reserved for the partition boot sector
  - ✓ Block group
    - Similar to the cylinder group in FFS
    - All the block groups have the same size and are stored sequentially



Linux Ext2 File System (Cont'd)

- Block group
  - ✓ Superblock: stores file system metadata
    - Total number of i-nodes
    - File system size in blocks
    - Free blocks / i-nodes counter
    - Number of blocks / i-nodes per group
    - Block size, etc.
  - ✓ Group descriptor
    - Number of free blocks / i-nodes / directories in the group
    - Block number of block / i-node bitmap, etc.
  - ✓ Both the superblock and the group descriptors are duplicated in each block group
    - Only those in block group 0 are used by the kernel
    - fsck copies them into all other block groups
    - When data corruption occurs, fsck uses old copies to bring the file system back to a consistent state

Linux Ext2 File System (Cont'd)

- Block group size
  - ✓ The block bitmap must be stored in a single block
    - In each block group, there can be at most 8xb blocks, where b is the block size in bytes
  - ✓ The smaller the block size, the larger the number of block groups
  - ✓ Example: 8GB Ext2 partition with 4KB block size
    - Each 4KB block bitmap describes 32K data blocks
      = 32K * 4KB = 128MB
    - At most 64 block groups are needed

Linux Ext2 File System (Cont'd)

- Directory structure