Chapter 11: File System Implementation

File Systems

- Tmpfs, a temporary file system in memory, fast but not persistent
- Squashfs, a read-only compressed file system supporting fast access
- Ext4, the main Linux journaling file system, reliable
- Ceph, an open source distributed and scalable file system
- FAT, simple and robust file system widely used for compatibility

- Why so many file systems?
- File system is still one of the most active areas of OS research!

Chapter 11: File System Implementation

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

Objectives

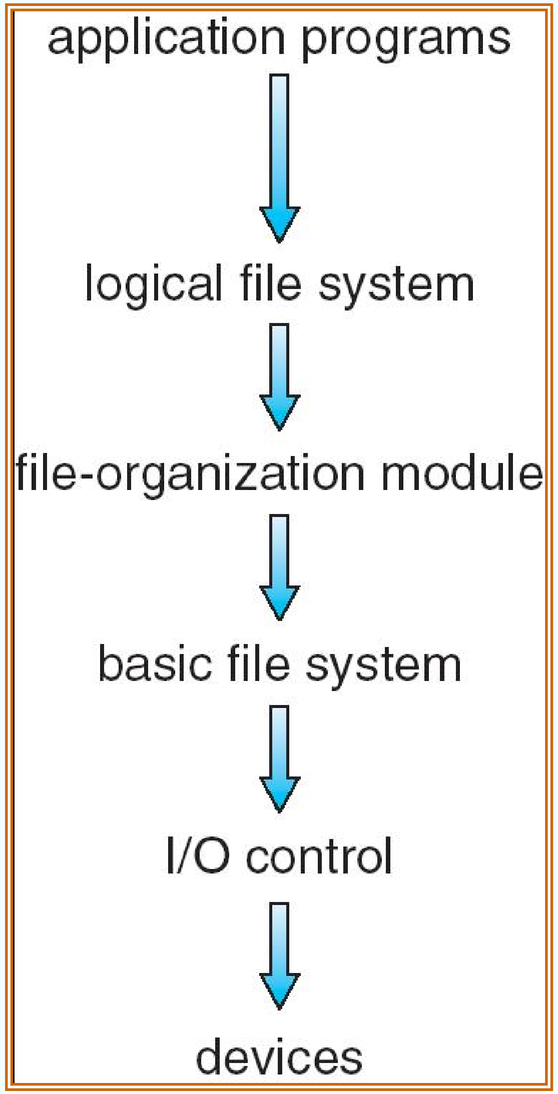
- To describe the details of implementing local file systems and directory structures
- To discuss block allocation and free-block algorithms and trade-offs

File-System Structure

- File structure
  - Logical storage unit
  - Collection of related information
- File system resides on secondary storage (disks)
- File system is composed of many layers

Layered File System

Question: Why layers?



Manages metadata of files, Protection and security

Translates logical block addr To physical addr. Free space mgmt

aka. block I/O subsystem

Commands to r/w physical blocks, I/O schedule, buffer

Device drivers/ interrupt handlers

Translates ‘r/w block x’ to low-level hw instructions

Data Structures Used to Implement FS

- Disk structures
  - Boot control block (per volume)
  - Volume control block per volume (superblock in Unix)
  - Directory structure per file system
  - Per-file FCB (inode in Unix)
- In-memory structures (see fig)
  - *In-memory mount table* about each mounted volume
  - *Directory cache* for recently accessed directories
  - System-wide open-file table
  - Per-process open-file table

Question: Why directory cache works?

A Typical File Control Block

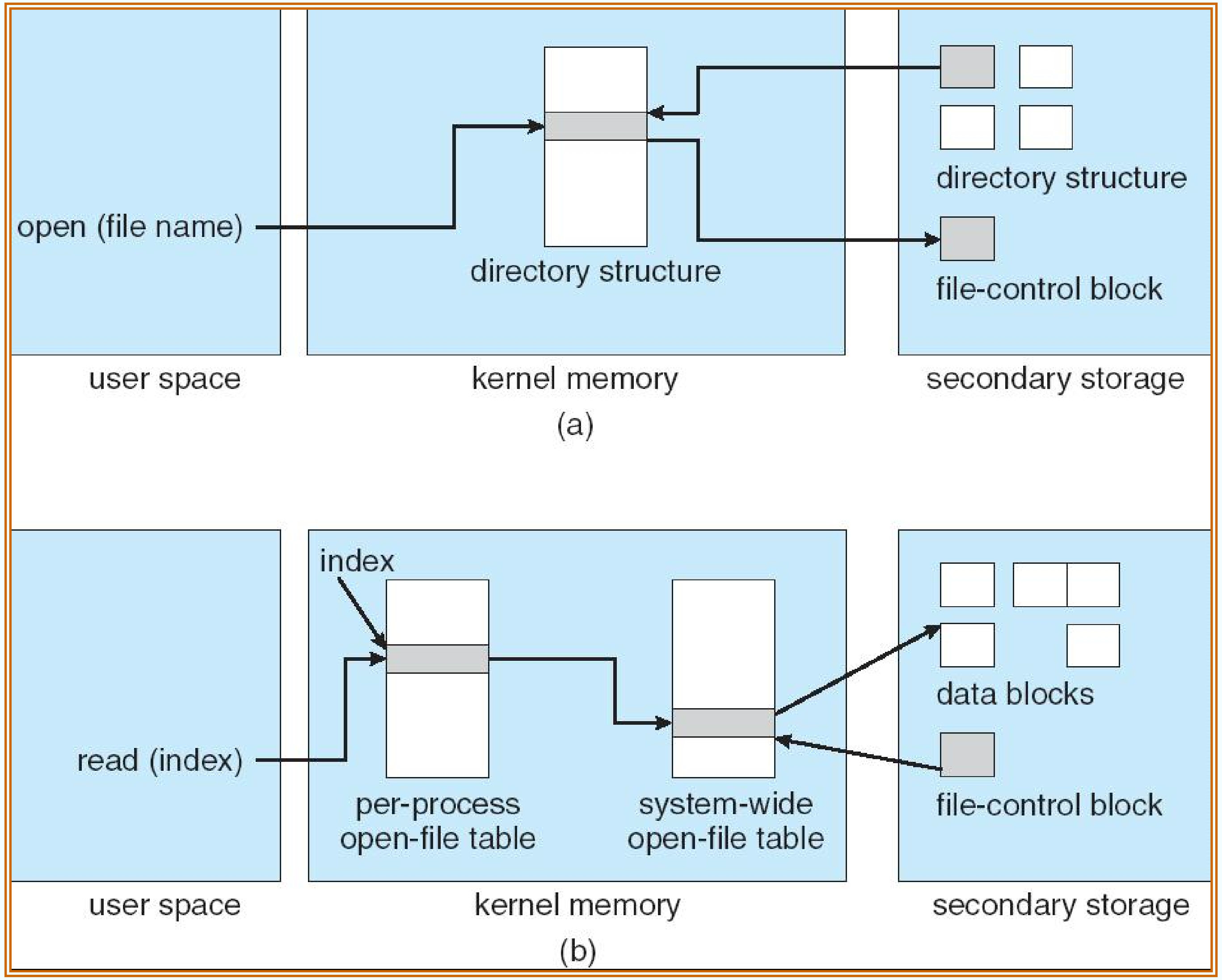
File control block – storage structure consisting of information about a file

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

- 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.

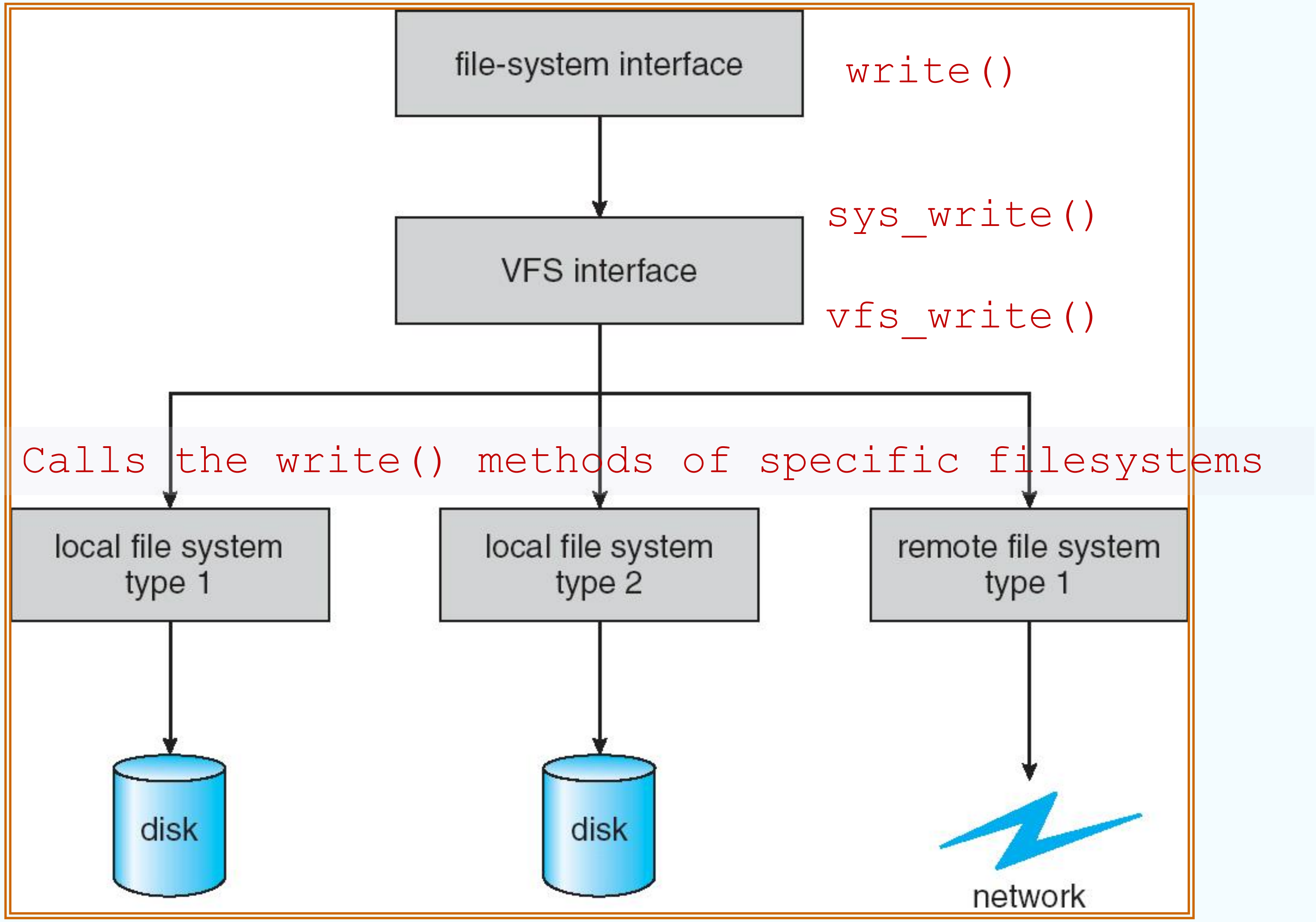
In-Memory File System Structures



Virtual File Systems

- Virtual File Systems (VFS) provide an object-oriented way of implementing file systems. VFS is NOT a disk file system!
- 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



In-Memory VFS Objects

- The four primary object types of VFS:
  - superblock object: a specific mounted filesystem，对应(但不是)磁盘文件系统的文件系统超级块或控制块。
  - inode object: a specific file, 对应(但不是)磁盘文件系统的文件控制块
  - dentry object: an individual directory entry
  - file object: an *open file* as associated with a process, 只要文件一直打开，这个对象就一直存在于内存。

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
  - Or rehashing to another larger 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

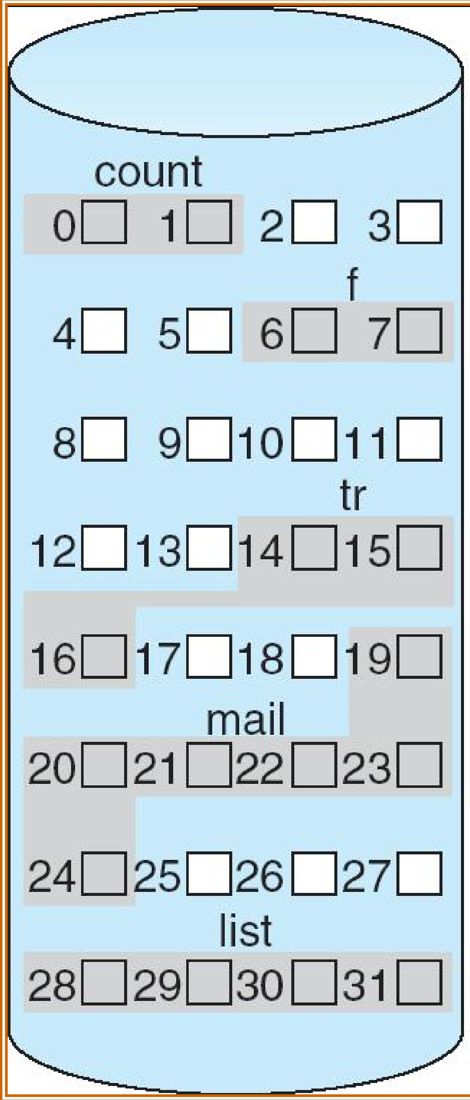
Q

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

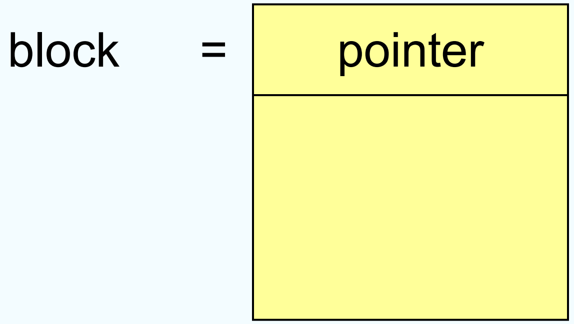
- Many newer file systems use a modified contiguous allocation scheme

- 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.)

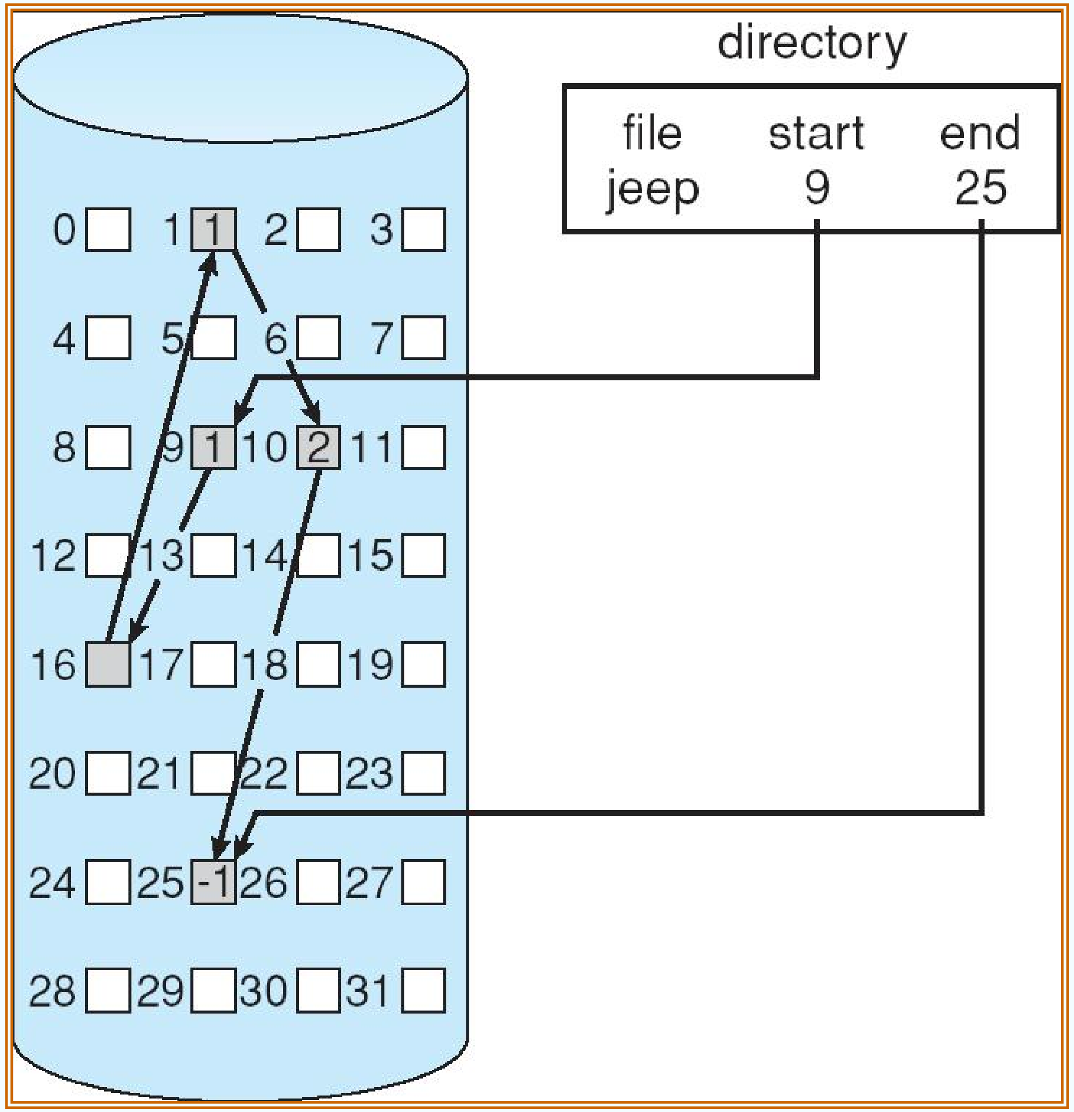
- Simple – need only starting address
- Free-space management system – no waste of space
- No random access, poor reliability
- Mapping

$$\text{LA}/511 \begin{cases} Q \\ R \end{cases}$$

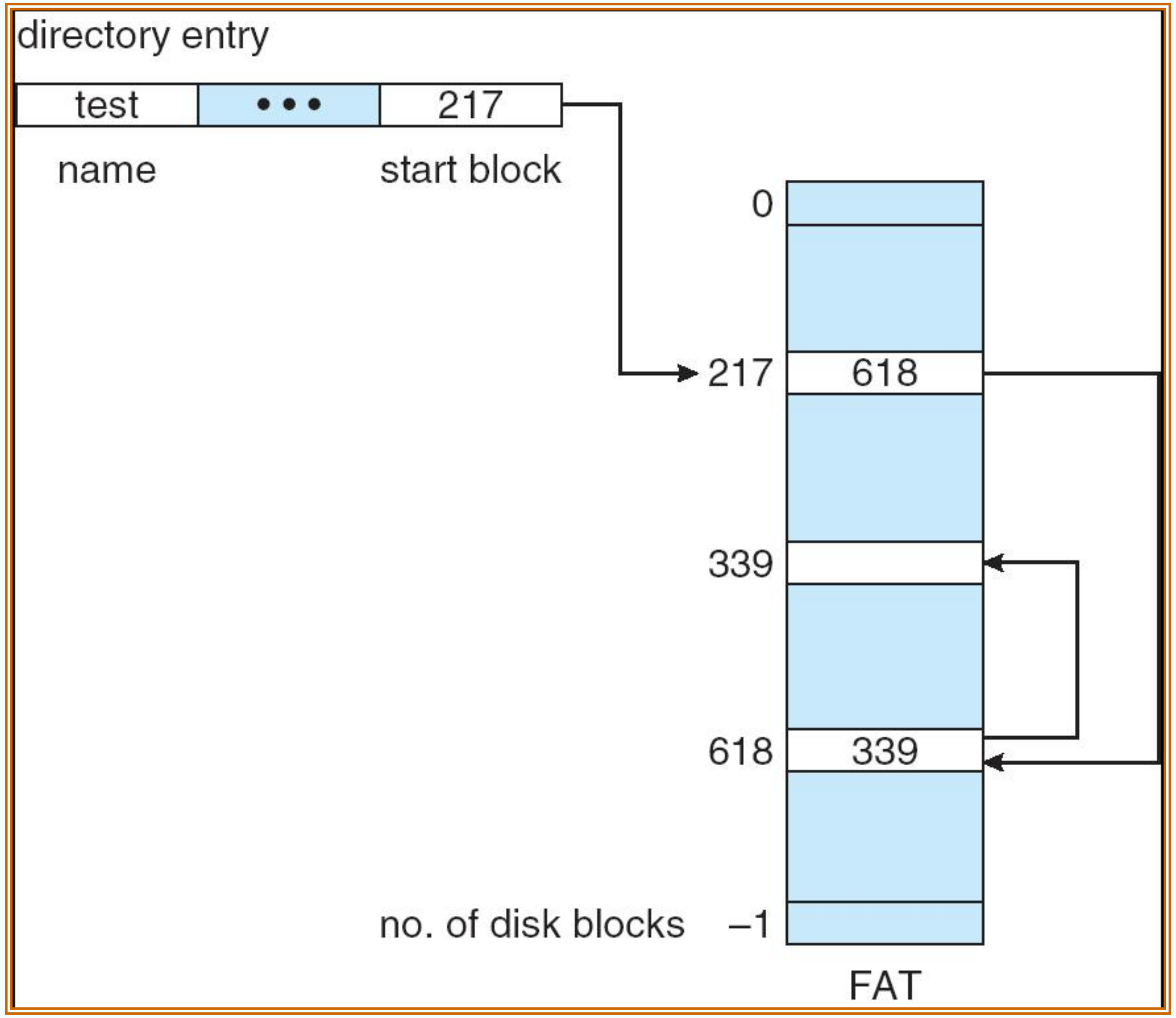
Block to be accessed is the Qth block in the linked chain of blocks representing the file.
Displacement into block = R + 1

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

Linked Allocation

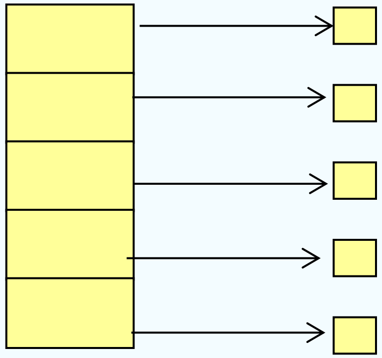


File-Allocation Table



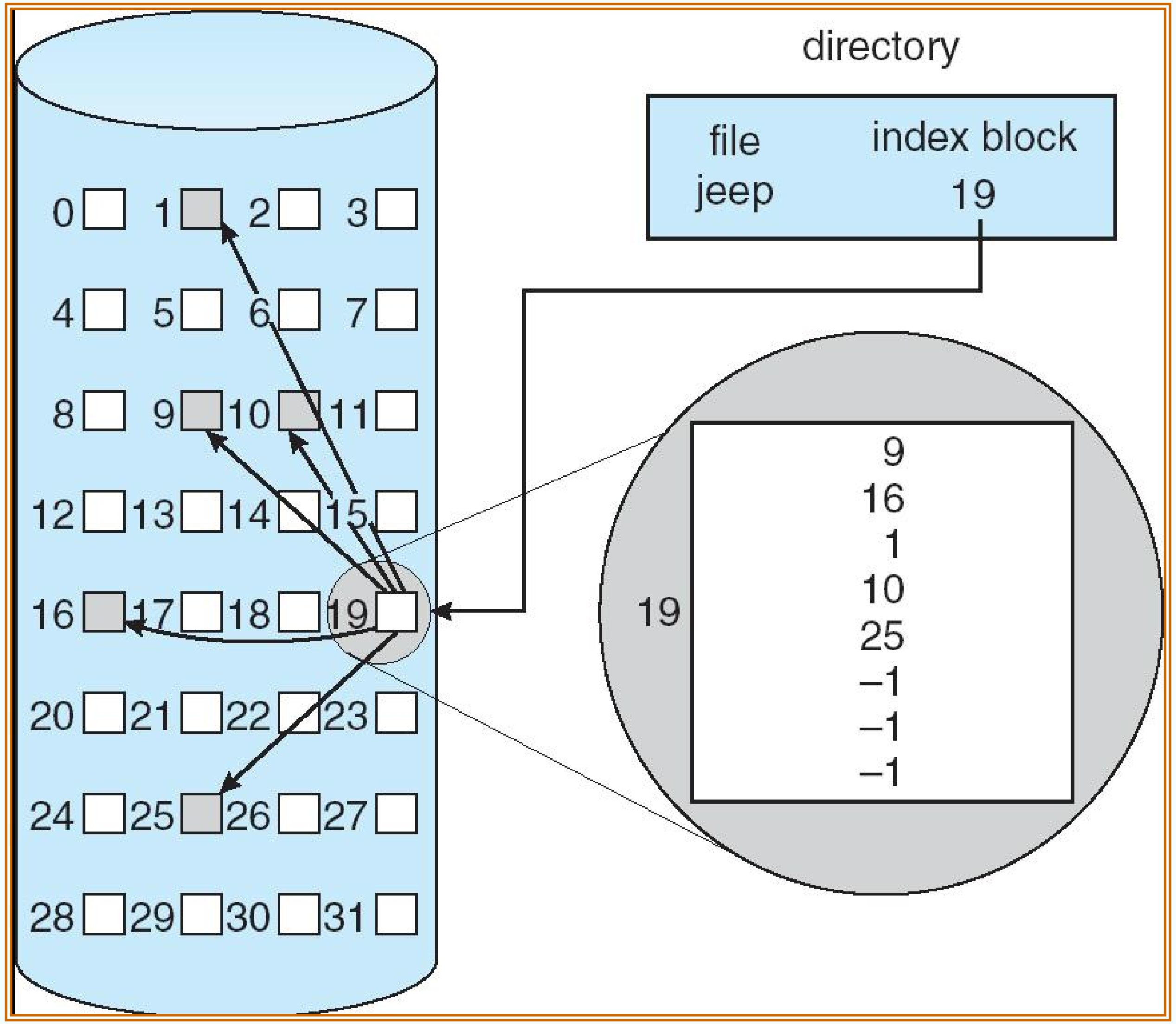
Indexed Allocation

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



index table

Example of Indexed Allocation



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. We need only 1 block for index table.

$$LA/512 \begin{cases} Q \\ R \end{cases}$$

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)

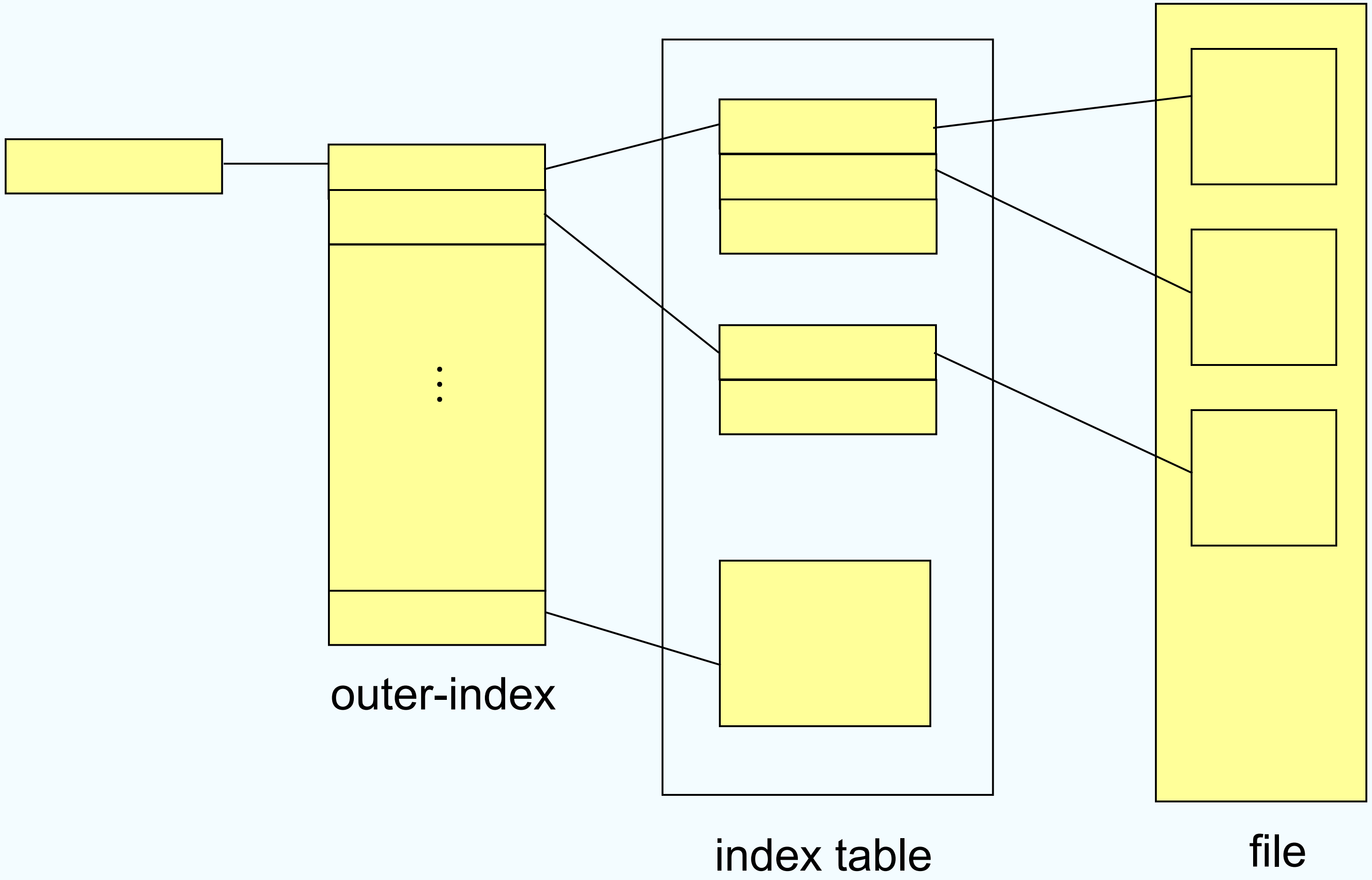
$$LA / (512 \times 512) \begin{cases} Q_1 \\ R_1 \end{cases}$$

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

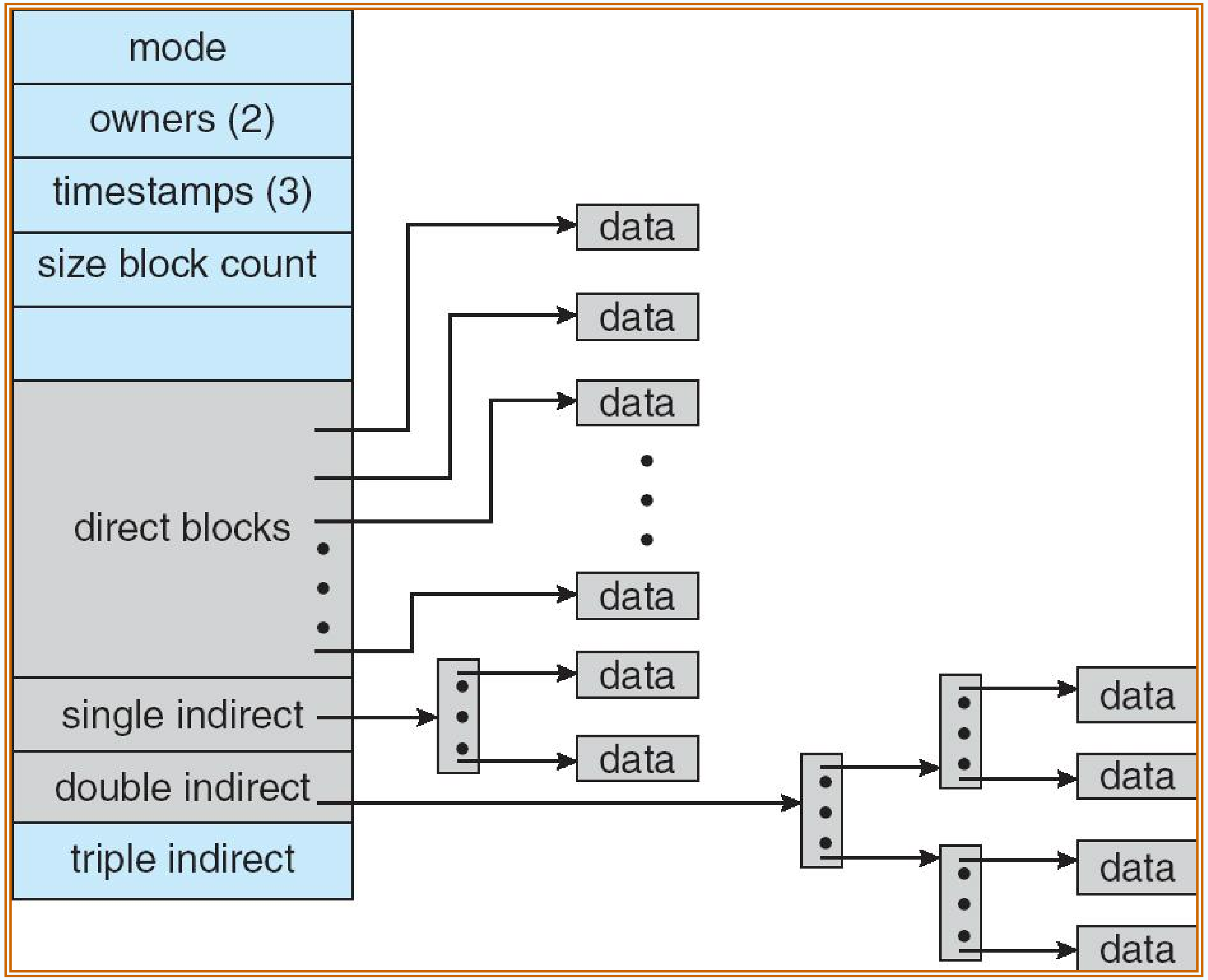
$$R_1 / 512 \begin{cases} Q_2 \\ R_2 \end{cases}$$

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

Indexed Allocation – Mapping (Cont.)

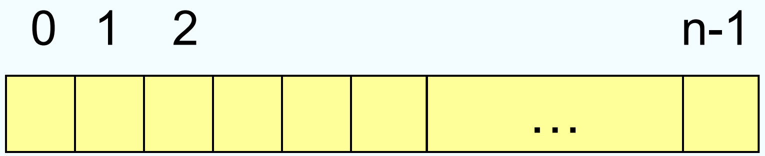


Combined Scheme: UNIX (4K bytes per block)



Free-Space Management

- Bit vector (*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 (finding the first free block)

(number of bits per word) *
(number of 0-value words) +
offset of first 1 bit

Free-Space Management (Cont.)

- Bit map requires extra space
  - Example:

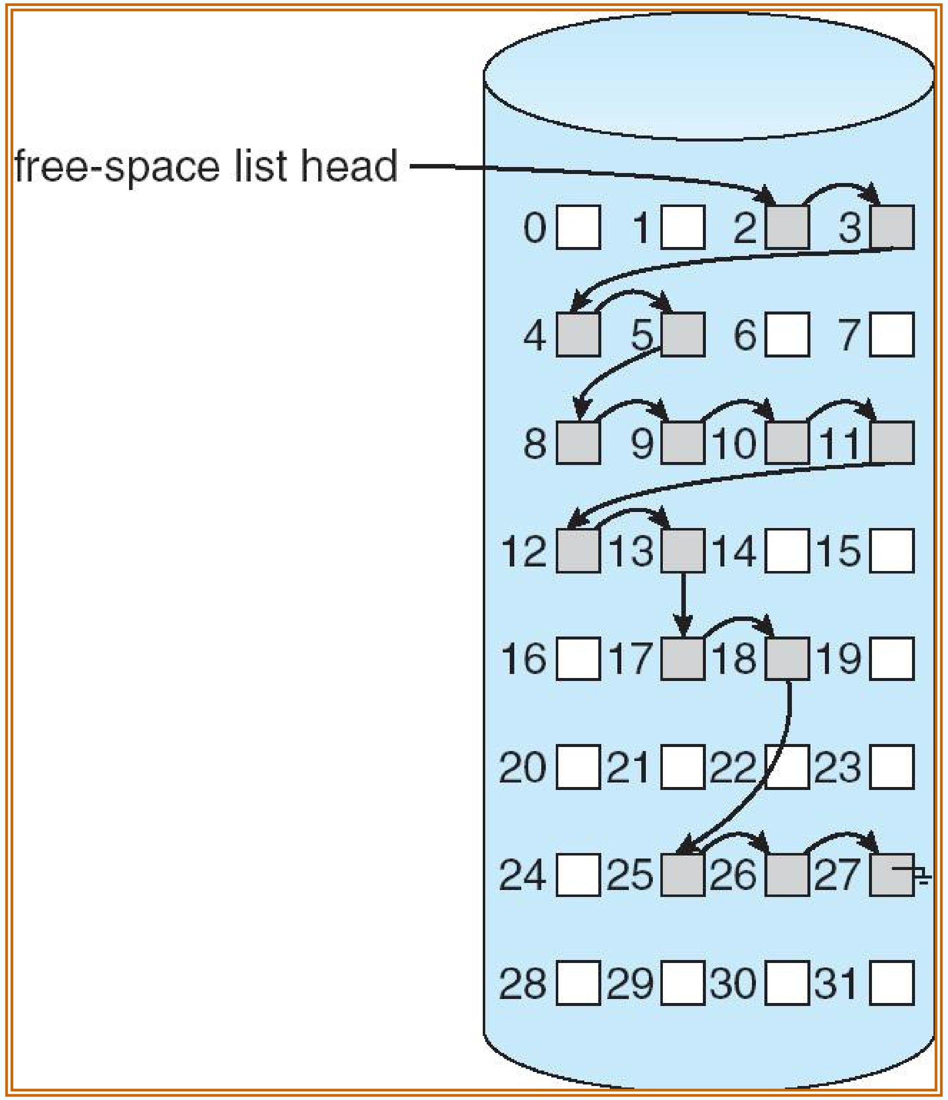
    block size = 2^{12} bytes

    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

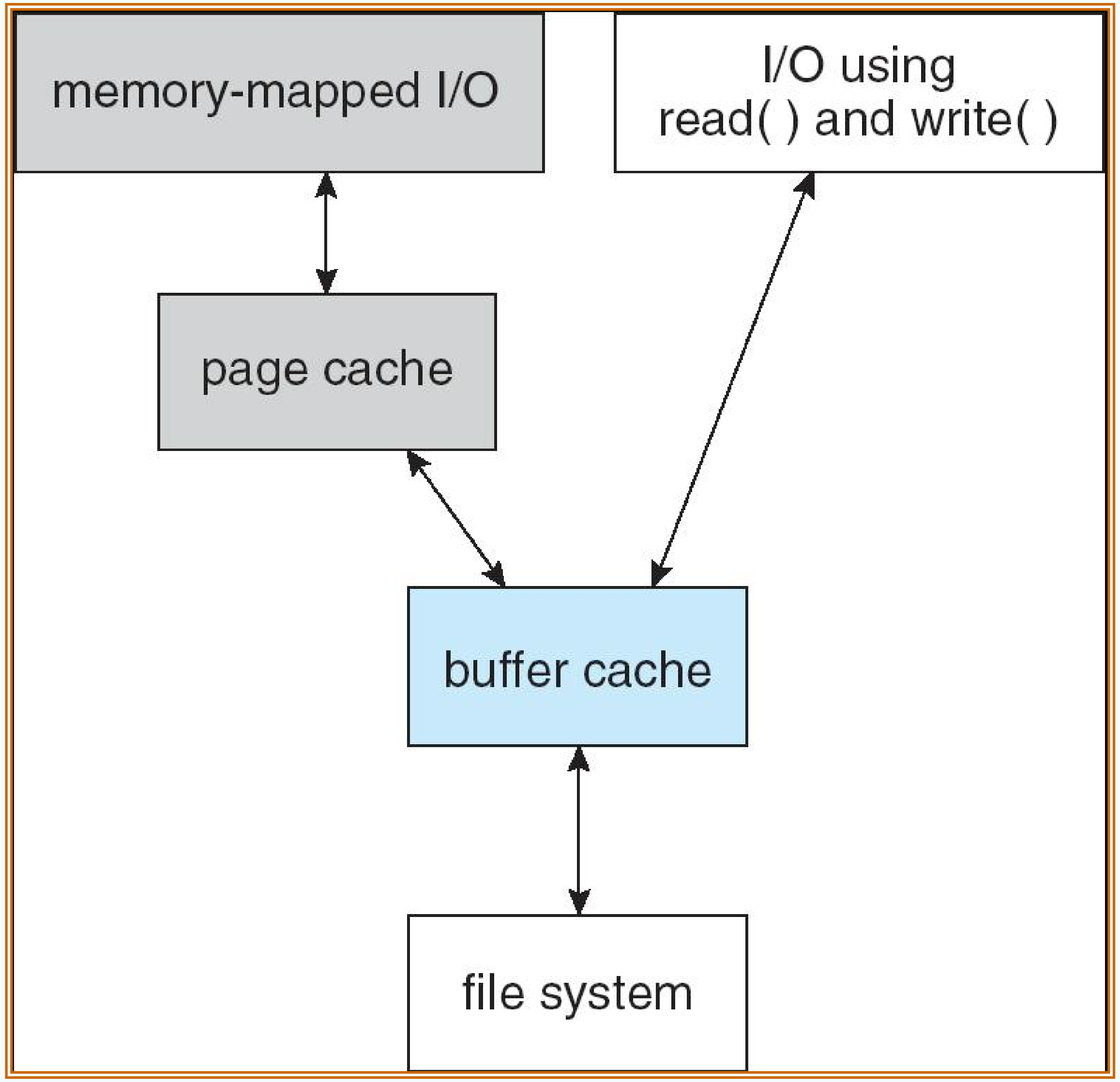
- A **page cache** caches pages rather than disk blocks using virtual memory techniques

- 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

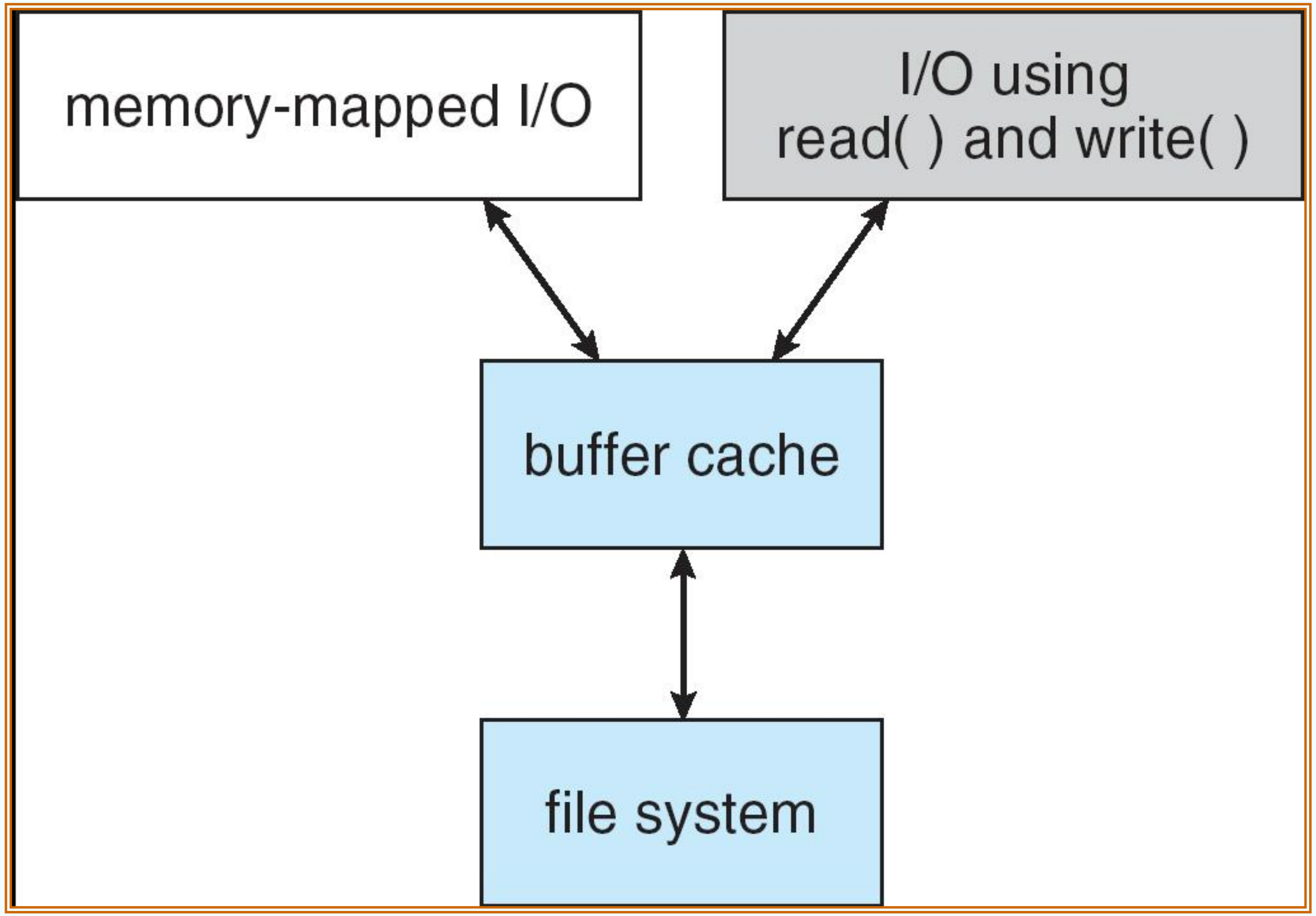
I/O Without a Unified Buffer Cache



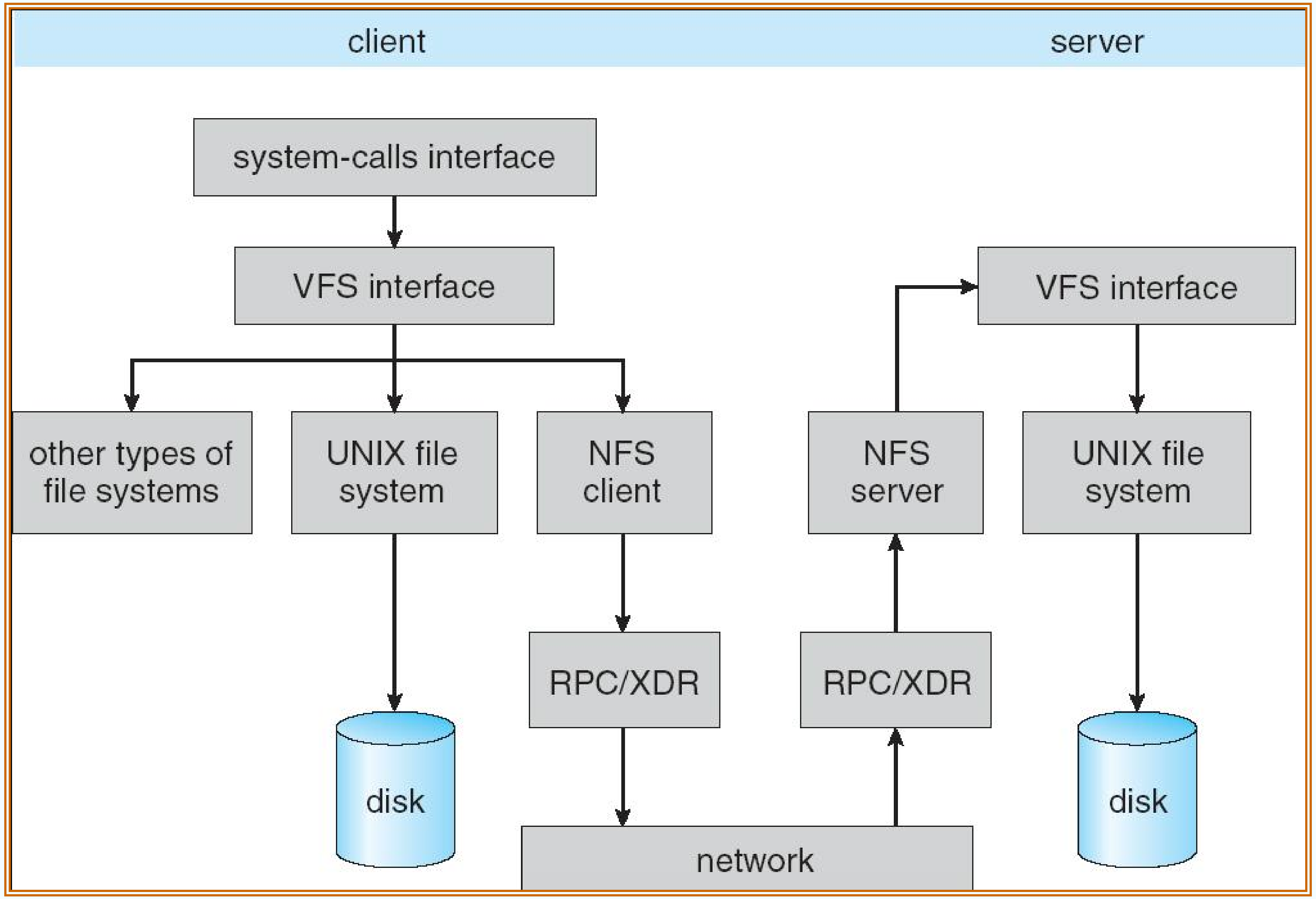
Unified Buffer Cache

- 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



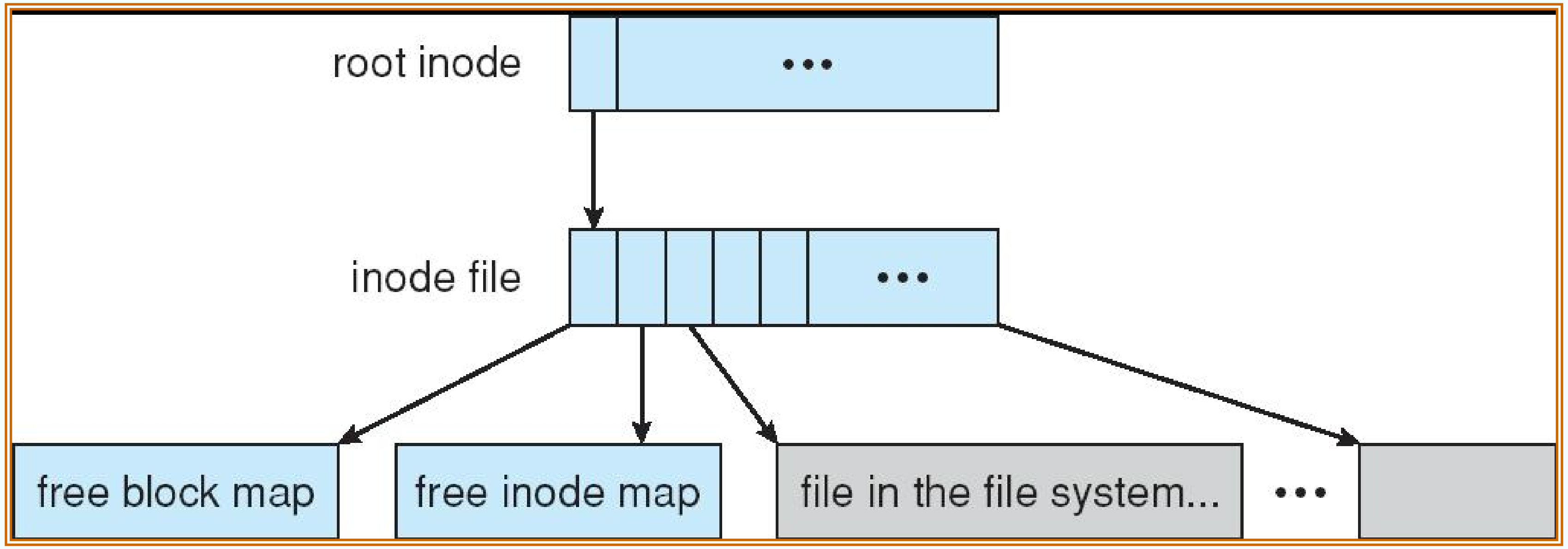
Schematic View of NFS Architecture



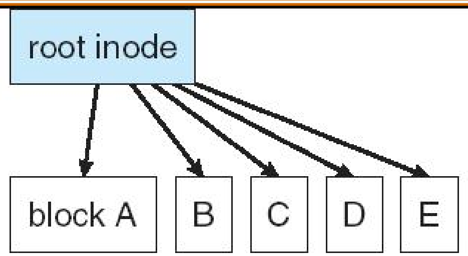
Example: WAFL File System

- 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

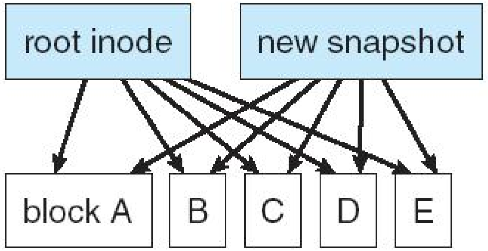
The WAFL File Layout



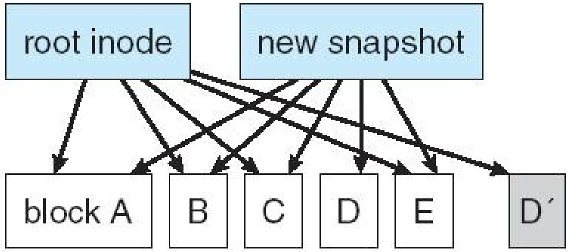
Snapshots in WAFL



(a) Before a snapshot.



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



(c) After block D has changed to D´.

11.02

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

End of Chapter 11

Write/Read Amplification

- *Write amplification* is the ratio of the amount of data written to the storage device versus the amount of data written to the database.
- If you are writing 10 MB to the file, and you observe 30 MB disk write, your write amplification is 3.
- Write amplification is bad for *flash-based storage* lifetime.