File System Implementation

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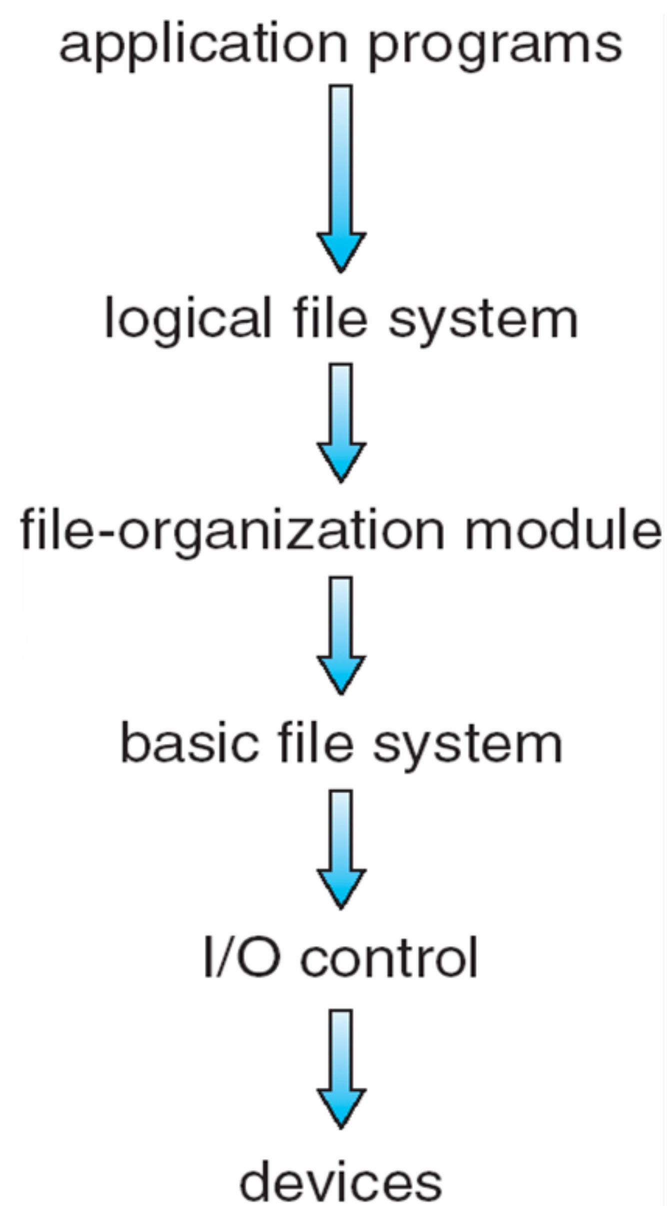
Review

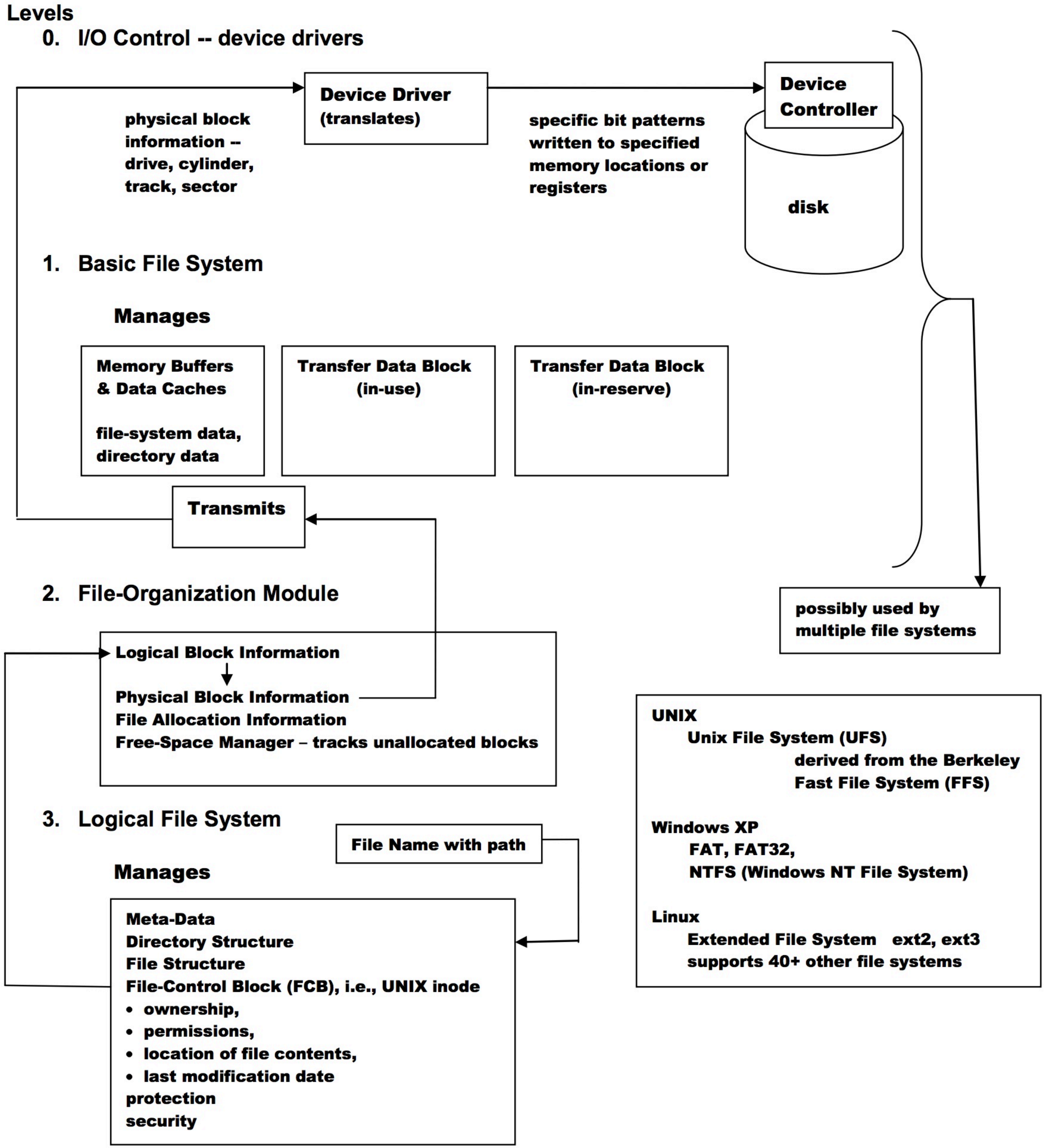
- File sharing
- File protection: what can be done by whom
- ACL
- Unix access control

File-System Structure

- File is a logical storage unit for a collection of related information
- There are many file systems; OS may support several **simultaneously**
  - Linux has Ext2/3/4, Reiser FS/4, Btrfs…
  - Windows has FAT, FAT32, NTFS…
  - new ones still arriving – ZFS, GoogleFS, Oracle ASM, FUSE
- File system resides on **secondary storage** (disks)
  - disk driver provides interfaces to read/write disk blocks
  - **fs provides user/program interface to storage, mapping logical to physical**
    - file control block – storage structure consisting of information about a file
- File system is usually implemented and organized into **layers**

Layered File System




Levels
0. I/O Control -- device drivers
Device Driver (translates)
physical block information -- drive, cylinder, track, sector
specific bit patterns written to specified memory locations or registers
Device Controller
disk
1. Basic File System
Manages
Memory Buffers & Data Caches
file-system data, directory data
Transfer Data Block (in-use)
Transfer Data Block (in-reserve)
Transmits
possibly used by multiple file systems
2. File-Organization Module
Logical Block Information
Physical Block Information
File Allocation Information
Free-Space Manager – tracks unallocated blocks
UNIX
Unix File System (UFS)
derived from the Berkeley Fast File System (FFS)
Windows XP
FAT, FAT32,
NTFS (Windows NT File System)
Linux
Extended File System ext2, ext3
supports 40+ other file systems
3. Logical File System
File Name with path
Manages
Meta-Data
Directory Structure
File Structure
File-Control Block (FCB), i.e., UNIX inode
• ownership,
• permissions,
• location of file contents,
• last modification date
protection
security

Layered File System

- **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

Layered File System

- **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
  - FCB(file control block)
- Layering useful for **reducing complexity** and redundancy, but adds overhead and can **decrease performance**
  - Translates file name into file number, file handle, location by maintaining file control blocks (**inodes** in UNIX)
  - Logical layers can be implemented by any coding method according to OS designer

File-System Implementation

- partition == volume == file system storage space
- File-system needs to maintain **on-disk** and **in-memory** structures
  - on-disk for data storage, in-memory for data access
- **On-disk structure** has several control blocks
  - **boot control block** contains info to boot OS from that volume - per volume
    - only needed if volume contains OS image, usually first block of volume
  - **volume control block** (e.g., *superblock*) contains volume details - per volume
    - total # of blocks, # of free blocks, block size, free block pointers, free FCB count, free FCB pointers
  - **directory structure** organizes the directories and files - per file system
    - A list of **(file names and associated inode numbers)**
  - **per-file file control block** contains many **details about the file - per file**
    - permissions, size, dates, data blocks or pointer to data blocks

A Typical File Control Block

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

In-Memory File System Structures

- **In-memory structures** reflects and extends **on-disk structures**
  - **Mount table** storing file system mounts, mount points, file system types
  - In-memory directory-structure cache: holds the directory information about recently accessed directories
  - **system-wide open-file table** contains a copy of the FCB of each file and other info
  - **per-process open-file table** contains pointers to appropriate entries in system-wide open-file table as well as other info
  - **I/O Memory Buffers**: hold file-system blocks while they are being read from or written to disk

File Creation

- application process requests the creation of a new file
- logical file system allocates a new FCB, i.e., inode structure
- appropriate directory is updated with the new file name and FCB, i.e., inode

Directory

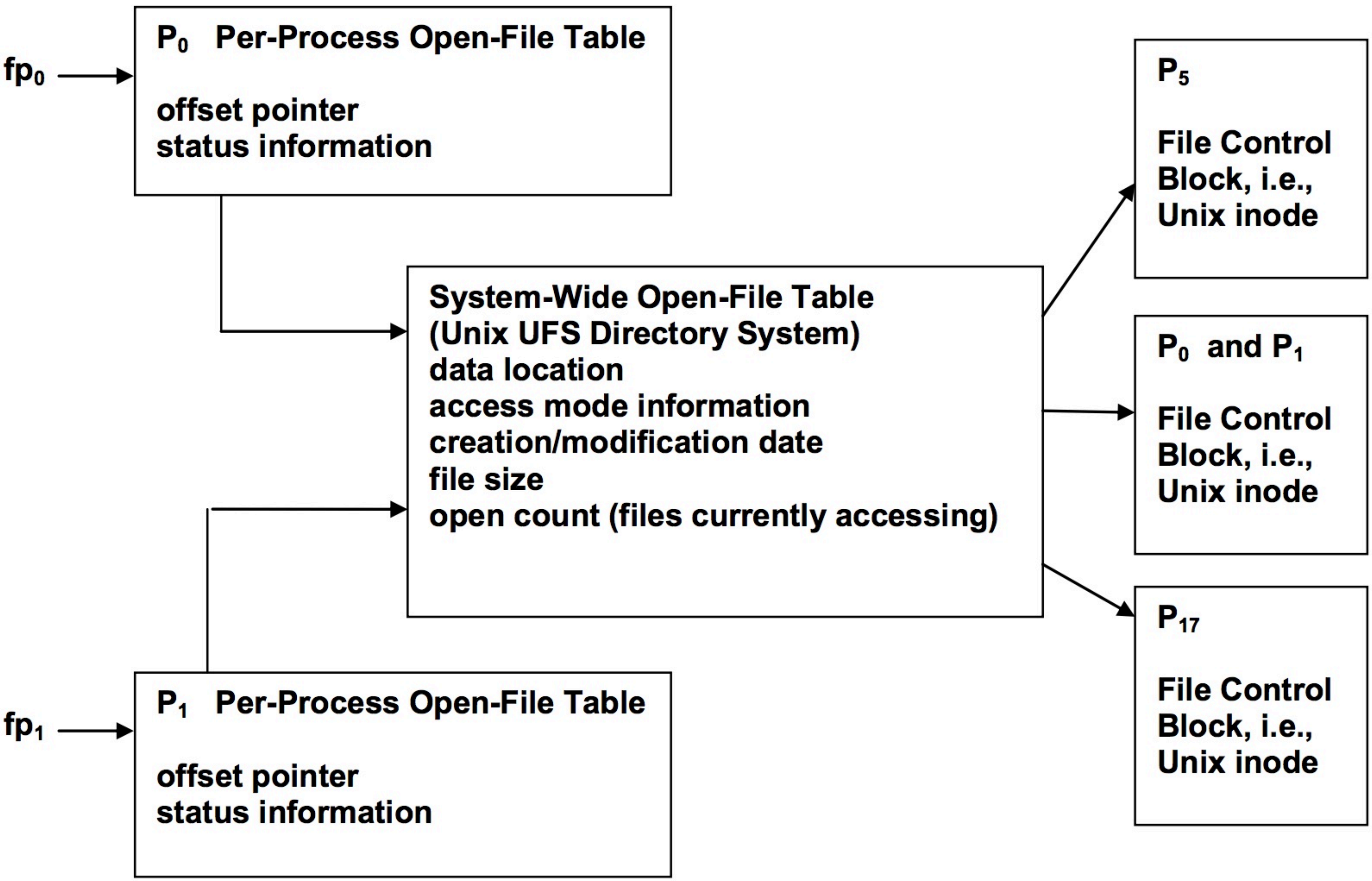
- Unix – directories are treated as files containing special data
- Windows – directories differently from files;
    - they require a separate set of systems calls to create, manipulate, etc

Operations - open()

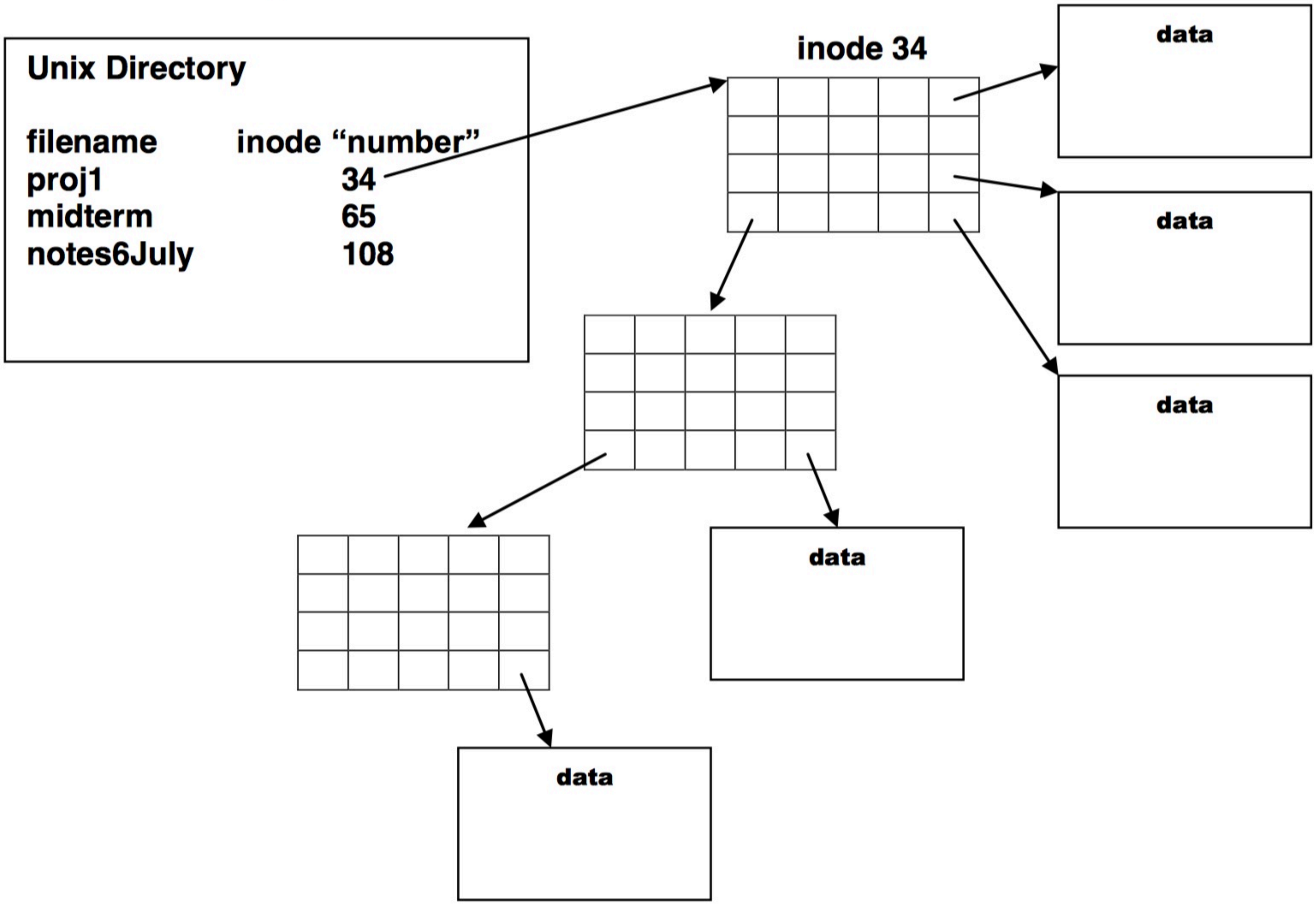
- search **System-Wide Open-File Table** to see if file is currently in use
  - if it is, create a Per-Process Open-File table entry pointing to the existing System-Wide Open-File Table
  - if it is not, search the directory for the file name; once found, place the **FCB** in the System-Wide Open-File Table
- make an entry, i.e., Unix file descriptor, Windows file handle in the **Per-Process Open-File Table**, with pointers to the entry in the **System-Wide Open-File Table** and other fields which include a pointer to the current location in the file and the access mode in which the file is open

Operations - open()

- increment the open cont in the System-Wide Open-File Table
- returns a pointer to the appropriate entry in the Per-Process Open-File Table
- all subsequent operations are performed with **this pointer**
- process closes file -> Per-Process Open-File Table entry is removed; **open count decremented**
- all processes close file -> copy in-memory directory information to disk and System-Wide Open-File Table is removed from memory


fp0
P0 Per-Process Open-File Table
offset pointer
status information
System-Wide Open-File Table
(Unix UFS Directory System)
data location
access mode information
creation/modification date
file size
open count (files currently accessing)
fp1
P1 Per-Process Open-File Table
offset pointer
status information
P5
File Control Block, i.e., Unix inode
P0 and P1
File Control Block, i.e., Unix inode
P17
File Control Block, i.e., Unix inode

Unix i-node System



Unix (UFS)

- System-Wide Open-File Table holds inodes for files, directories, devices, and network connections
- inode numbering system is only unique within a given file system

Mounting File Systems

- Boot Block – series of sequential blocks containing a memory image of a program, call the boot loader, that locates and mounts the root partition; the partition contains the kernel; the boot loader locates, loads, and starts the kernel executing

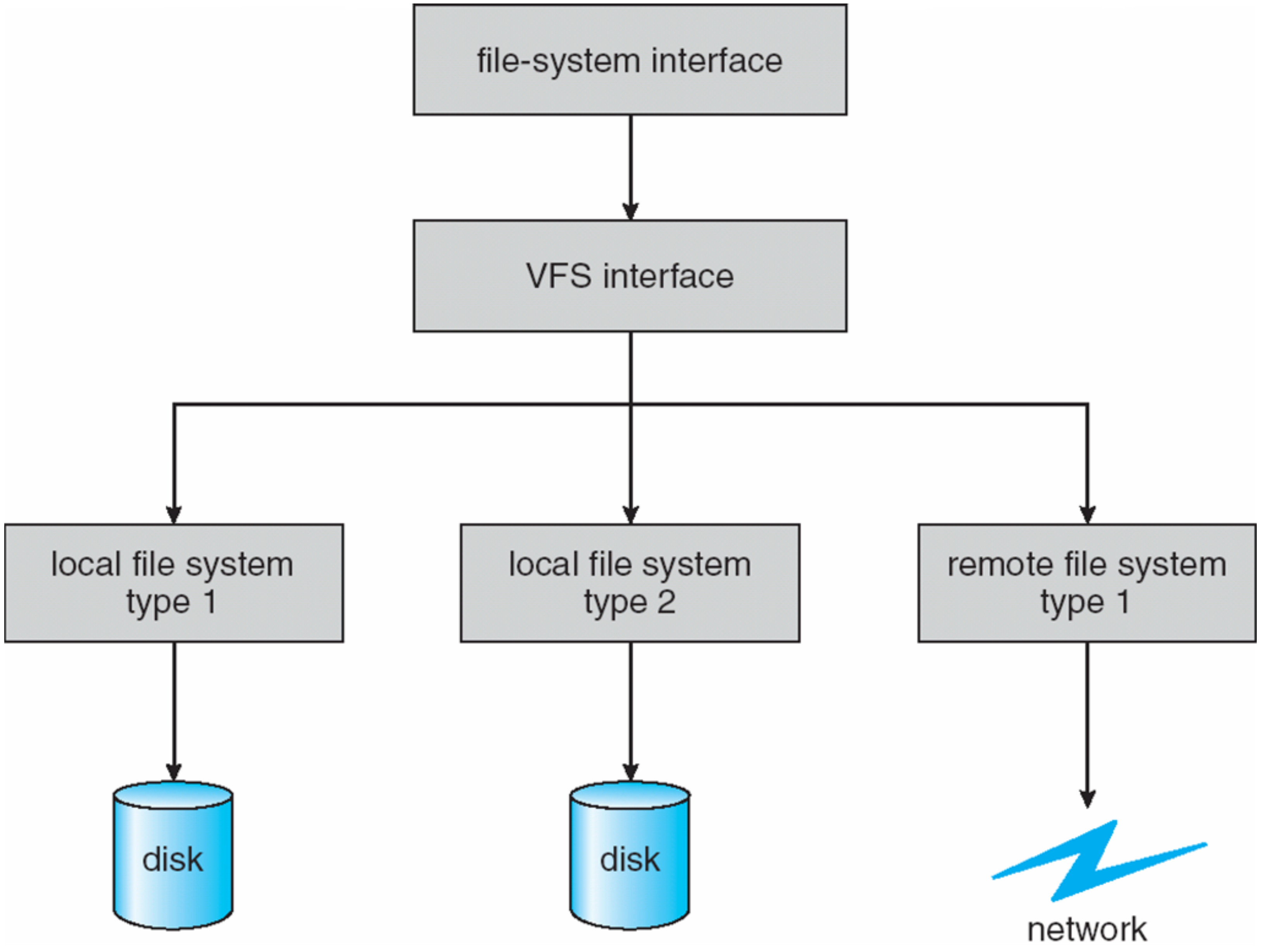
- In-memory mount table – external file systems must be mounted on devices, the mount table records the mount points, types of file systems mounted, and an access path to the desired file system

- Unix – the in-memory mount table contains a pointer to the **superblock** of the file system on that device

Virtual File Systems

- **VFS** provides an **object-oriented** way of implementing file systems
  - OS defines **a common interface for FS**, all FSes implement them
  - *system call is implemented based on this common interface*
    - it allows the same syscall API to be used for different types of FS
- VFS separates FS generic operations from implementation details
  - implementation can be one of many FS types, or network file system
  - OS can dispatches syscalls to appropriate FS implementation routines

Virtual File System



Virtual File System Example

- Linux defines four **VFS object types**:
  - **superblock**: defines the file system type, size, status, and other metadata
  - **inode**: contains metadata about a **file** (location, access mode, owners…)
  - **dentry**: associates names to inodes, and the directory layout
  - **file**: actual data of the file
- VFS defines set of operations on the objects that must be implemented
  - the set of operations is saved in a function table

```
struct file_operations {
        int (*lseek) (struct inode *, struct file *, off_t, int);
        int (*read) (struct inode *, struct file *, char *, int);
        int (*write) (struct inode *, struct file *, const char *, int);
        int (*readdir) (struct inode *, struct file *, void *, filldir_t);
        int (*select) (struct inode *, struct file *, int, select_table *);
        int (*ioctl) (struct inode *, struct file *, unsigned int, unsigned long);
        int (*mmap) (struct inode *, struct file *, struct vm_area_struct *);
        int (*open) (struct inode *, struct file *);
        void (*release) (struct inode *, struct file *);
        int (*fsync) (struct inode *, struct file *);
        int (*fasync) (struct inode *, struct file *, int);
        int (*check_media_change) (kdev_t dev);
        int (*revalidate) (kdev_t dev);
};
```

Review

- File system layers
- File system implementation
  - On-disk structure, in-memory structure
- File creation(), open()
- VFS

Directory Implementation

- **Linear list of file names** with pointer to the file metadata
    - simple to program, but **time-consuming to search** (e.g., linear search)
        - could keep files ordered alphabetically via linked list or use B+ tree
- **Hash table**: linear list with hash data structure to reduce search time
    - collisions are possible: two or more file names hash to the same location

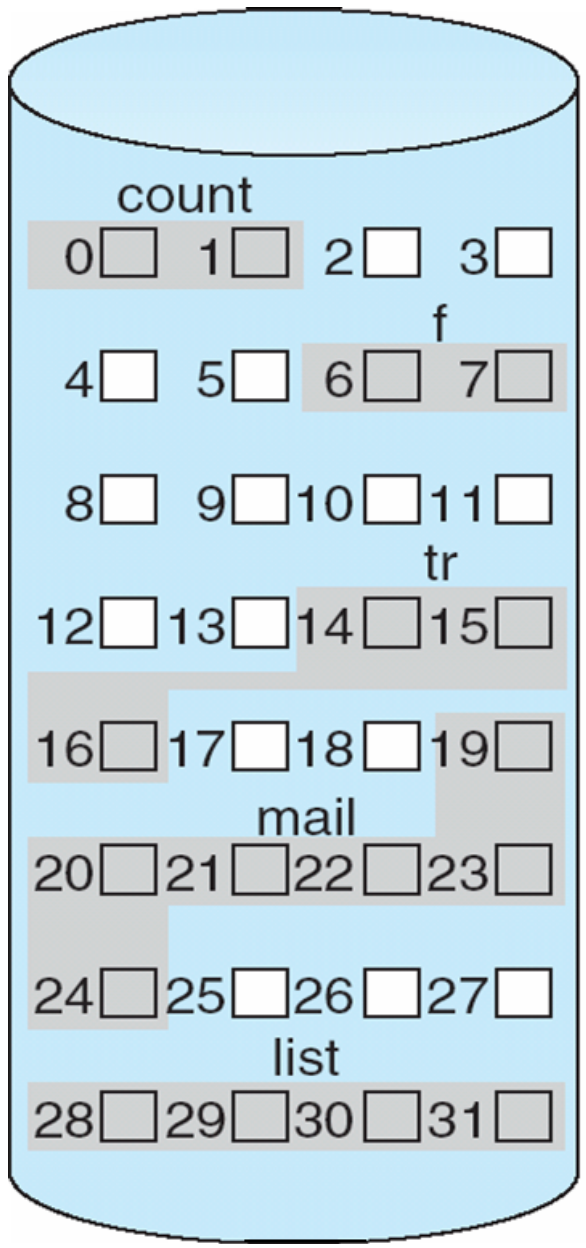
Disk Block Allocation

- **Files** need to be allocated with disk blocks to store data
  - different allocation strategies have different complexity and performance
- Many allocation strategies:
  - contiguous
  - linked
  - indexed
  - …

Contiguous Allocation

- Contiguous allocation: each file occupies set of **contiguous blocks**
  - best performance in most cases
  - simple to implement: only starting location and length are required
- Contiguous allocation is not flexible
  - how to *increase/decrease* file size?
    - need to know file size at the file creation?
  - **external fragmentation**
    - how to compact files offline or online to reduce external fragmentation
  - need for **compaction** off-line (downtime) or on-line
  - appropriate for sequential disks like **tape**
- Some file systems use **extent-based contiguous allocation**
  - extent is a set of contiguous blocks
  - a file consists of extents, extents are not necessarily adjacent to each other

Contiguous Allocation



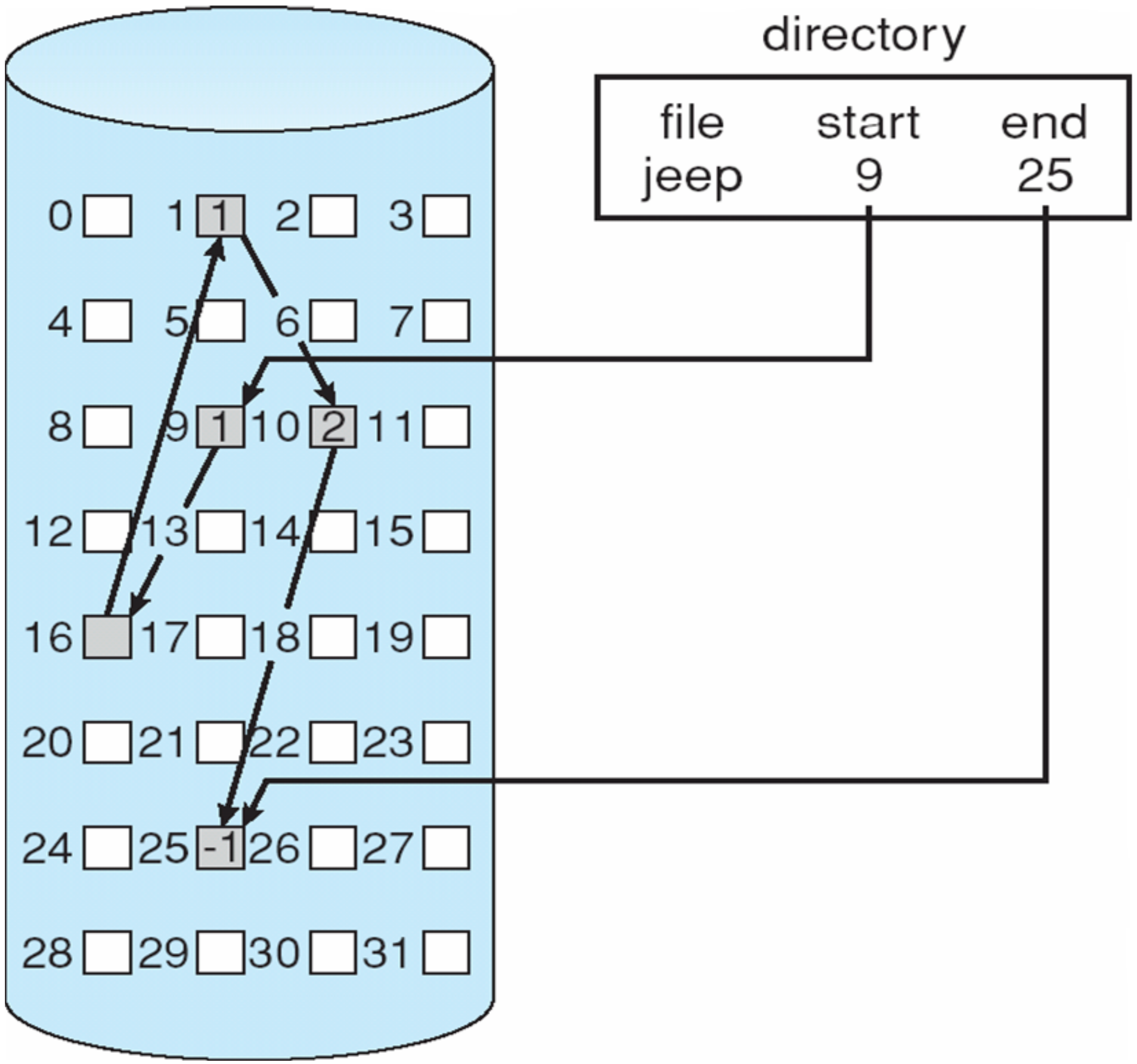
directory

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

Linked Allocation

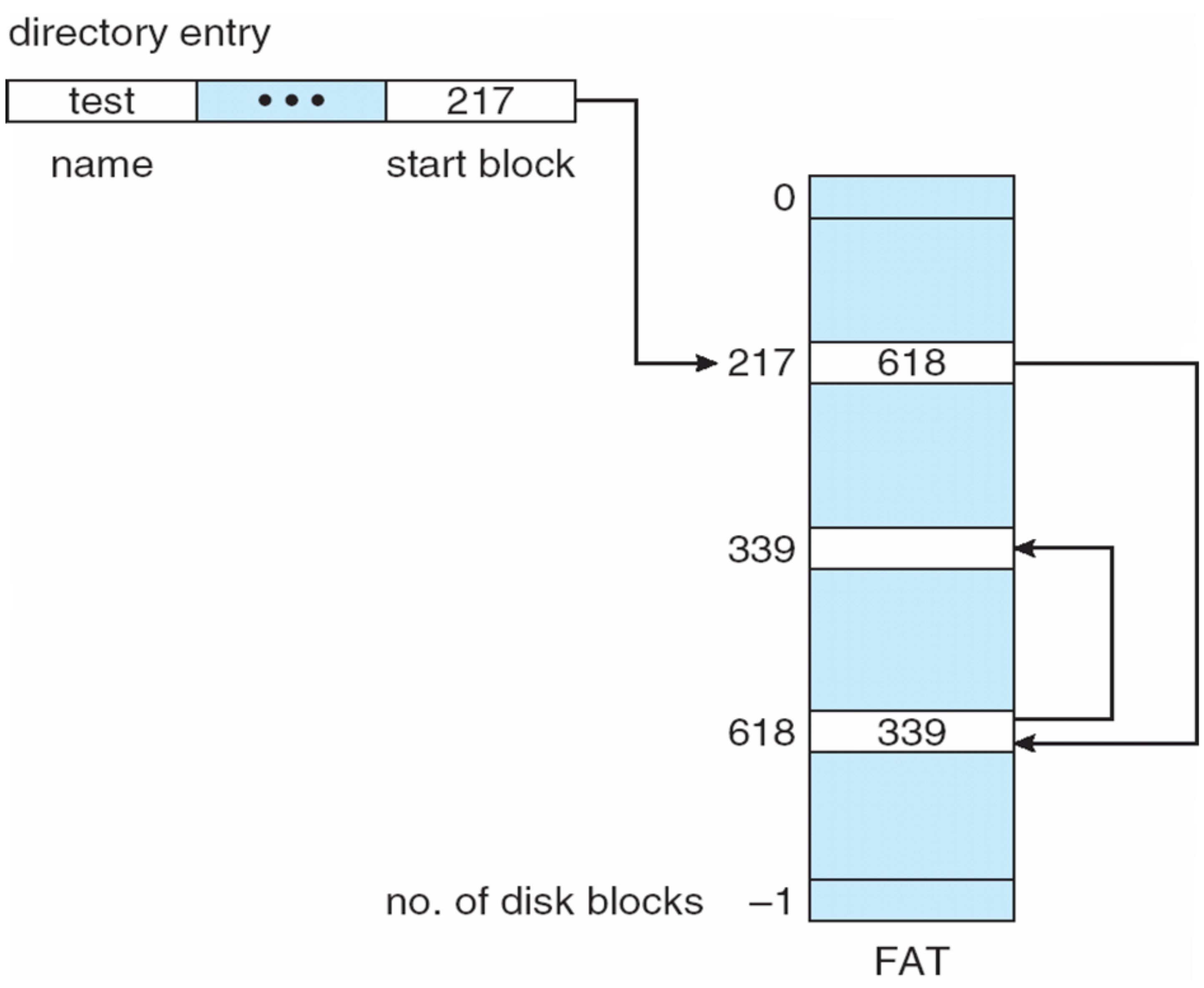
- Linked allocation: each file is a **linked list of disk blocks**
    - each block contains pointer to **next block**, file ends at nil pointer
    - blocks may be scattered anywhere on the disk (no **external fragmentation, no compaction**)
    - *Disadvantages*
        - *locating a file block can take many I/Os and disk seeks*
        - *Pointer size: 4 of 512 bytes are used for pointer - 0.78% space is wasted*
        - *Reliability: what about the pointer has corrupted!*
    - *Improvements: cluster the blocks - like 4 blocks*
        - *however, has internal fragmentation*

Linked Allocation



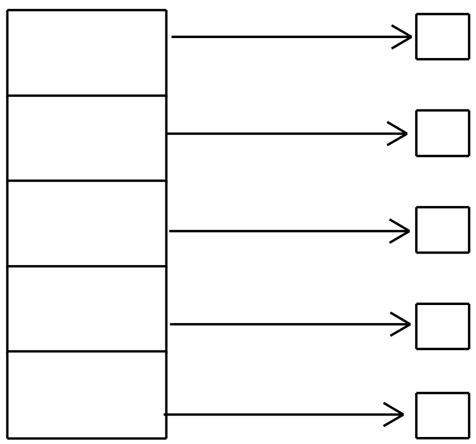
File-Allocation Table (FAT): MS-DOS

- FAT (File Allocation Table) uses linked allocation



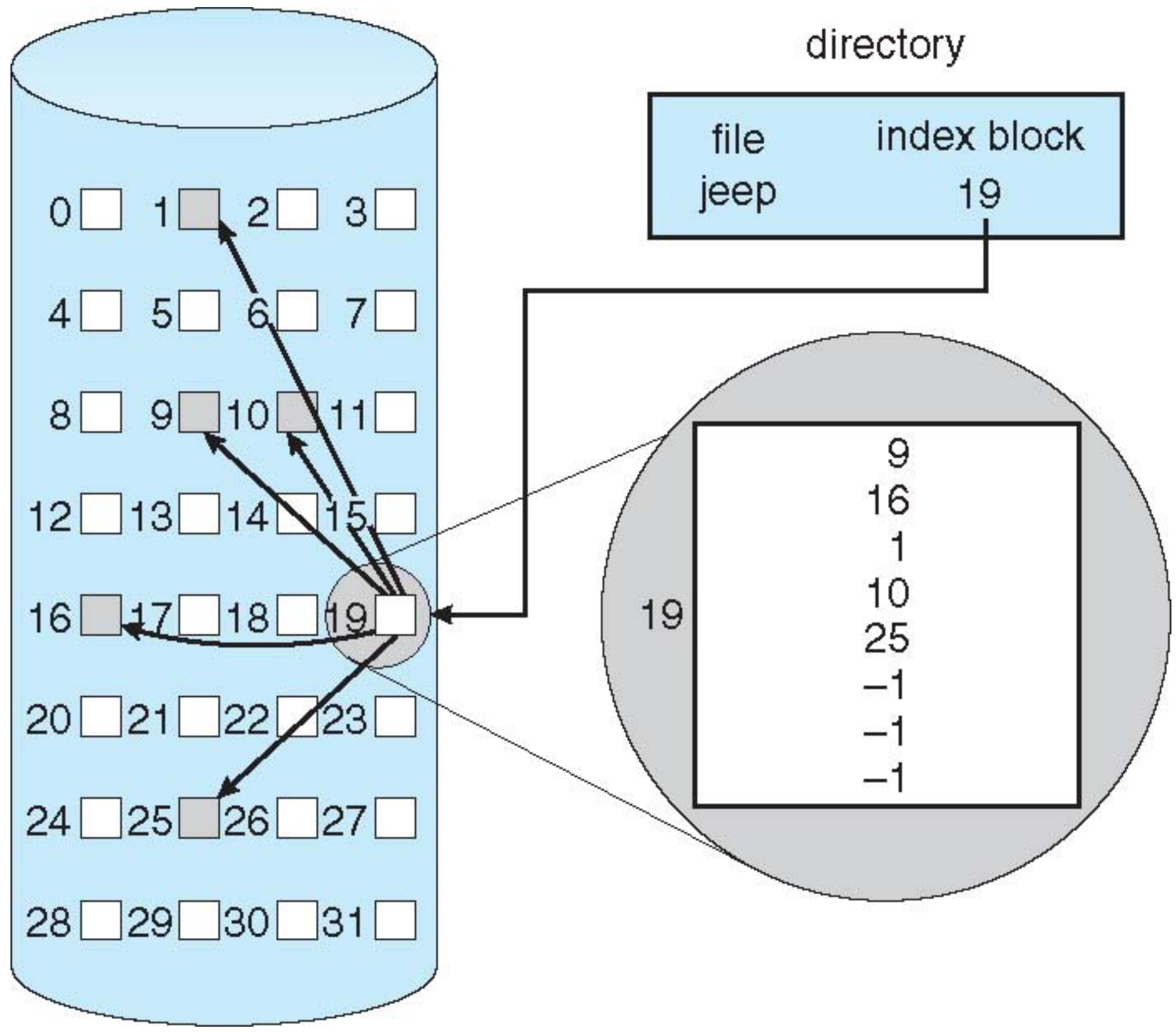
Indexed Allocation

- Indexed allocation: each file has its own **index blocks of pointers to its data blocks**
  - index table provides **random access** to file data blocks
  - no **external fragmentation**, but overhead of index blocks
  - allows **holes** in the file
  - Index block needs space - waste for small files



index table

Indexed Allocation

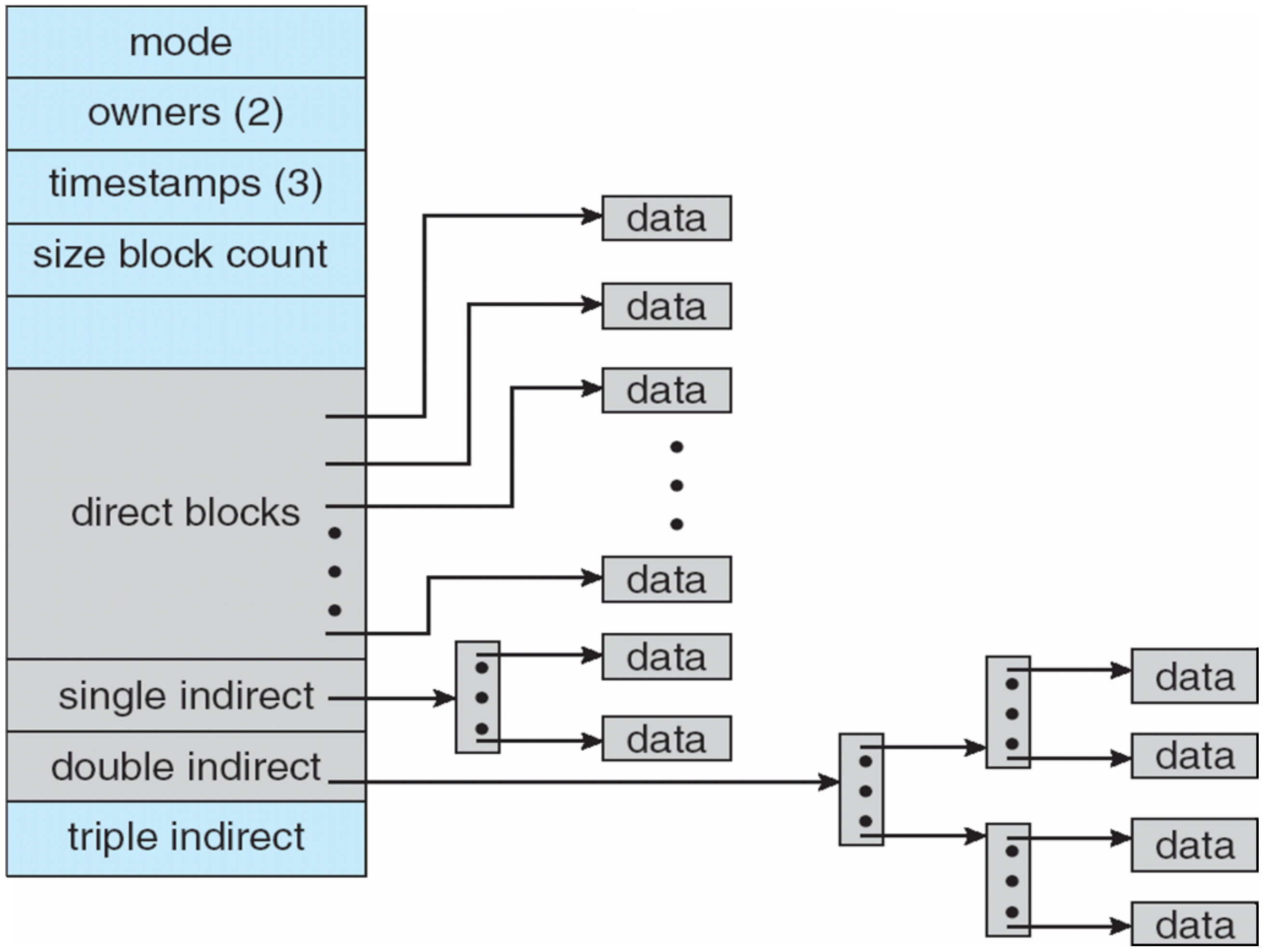


Indexed Allocation

- Need a method to allocate index blocks - cannot too big or too small
  - linked index blocks: link index blocks to support huge file
  - multiple-level index blocks (e.g., 2-level)

Indexed Allocation

- combined scheme
  - First 15 pointers are in inode
    - Direct block: first 12 pointers
    - Indirect block: next 3 pointers



Allocation Methods

- Best allocation method depends on file access type
  - **contiguous** is great for **sequential** and **random**
  - **linked** is good for **sequential**, not random
  - **indexed** (combined) is more complex
    - single block access may require 2 index block reads then data block read
    - clustering can help improve throughput, reduce CPU overhead
    - cluster is a set of contiguous blocks
- Disk I/O is slow, reduce as many disk I/Os as possible
  - Intel Core i7 extreme edition 990x (2011) at 3.46Ghz = 159,000 MIPS
  - typical disk drive at 250 I/Os per second
    - 159,000 MIPS / 250 = 630 million instructions during one disk I/O
  - fast SSD drives provide 60,000 IOPS
    - 159,000 MIPS / 60,000 = 2.65 millions instructions during one disk I/O

Free-Space Management

- File system maintains free-space list to track available blocks/clusters
  - The space of deleted files should be reclaimed
- Many allocation methods:
  - bit vector or bit map
  - linked free space
  - …

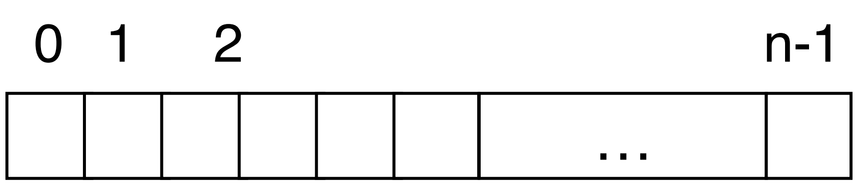
Bitmap Free-Space Management

- Use one bit for each block, track its allocation status
  - relatively easy to find contiguous blocks
  - 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

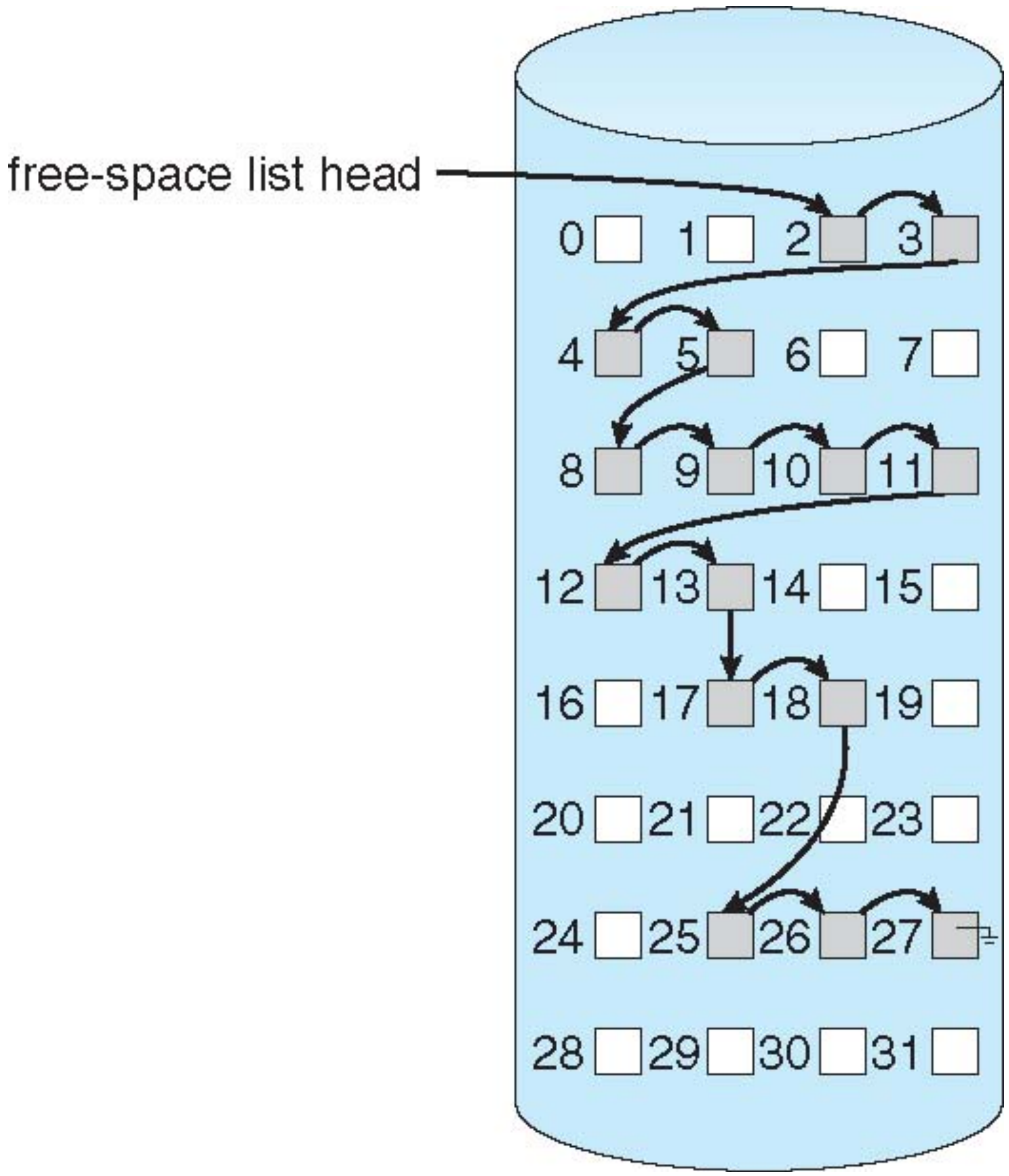


$$\text{bit}[i] = \begin{cases} 1 \rightarrow \text{block}[i] \text{ free} \\ 0 \rightarrow \text{block}[i] \text{ occupied} \end{cases}$$

Linked Free Space

- Keep free blocks in linked list
  - no waste of space, just use the memory in the free block for pointers
  - cannot get contiguous space easily
  - Usually no need to traverse the entire list: return the first one

Linked Free Space



Grouping and Counting

- Simple linked list of free-space is inefficient
  - one extra disk I/O to allocate one free block (disk I/O is extremely slow)
    - allocating **multiple free blocks** require traverse the list
  - difficult to allocate contiguous free blocks
- **Grouping**: use indexes to group free blocks
  - store address of **n-1** free blocks in the **first free block**, plus a pointer to the next **index block**
  - allocating **multiple free blocks does not need to traverse the list**
- **Counting**: a link of clusters (starting block + **#** of contiguous blocks)
  - space is frequently contiguously used and freed
  - in link node, keep address of first free block and # of following free blocks

File System Performance

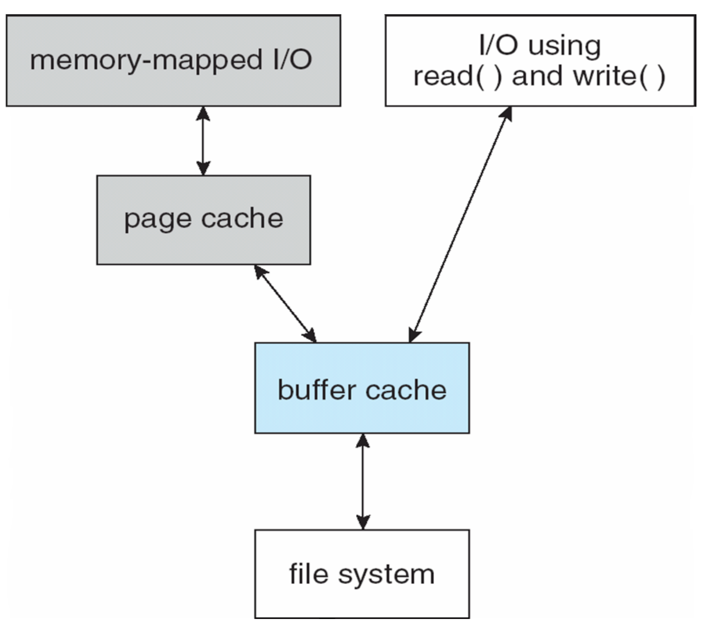
- File system efficiency and performance dependent on:
  - disk allocation and directory algorithms
  - types of data kept in file's directory entry
  - pre-allocation or as-needed allocation of metadata structures
  - fixed-size or varying-size data structures

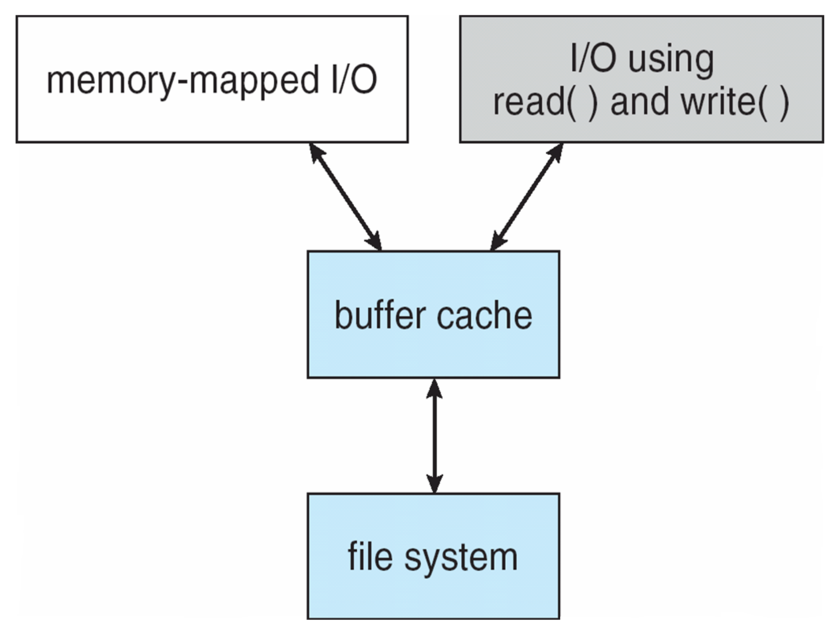
File System Performance

- To improve file system performance:
  - keeping **data and metadata close together**
  - use cache: separate section of main memory for frequently used blocks
  - use **asynchronous writes**, it can be buffered/cached, thus faster
    - cannot cache synchronous write, writes must hit disk before return
    - synchronous writes sometimes requested by apps or needed by OS
  - **free-behind and read-ahead**: techniques to optimize sequential access - remove the previous page from the buffer, read multiple pages ahead
  - **Reads frequently slower than write**: really?

Page Cache

- OS has different levels of cache:
  - a **page cache** caches pages for MMIO, such as memory mapped files
  - file systems uses **buffer** (disk) **cache** for disk I/O
    - memory mapped I/O may be cached twice in the system
- A unified buffer cache uses the same page cache to cache both memory-mapped pages and disk I/O to avoid double caching





Recovery

- File system needs consistency checking to ensure consistency
  - compares data in directory with some metadata on disk for consistency
  - fs recovery an be slow and sometimes fails
- File system recovery methods
  - backup
  - log-structured file system

Log Structured File Systems

- In LSFS, metadata for updates sequentially written to a **circular log**
  - once changes written to the log, it is committed, and syscall can return
    - log can be located on the other disk/partition
  - meanwhile, log entries are replayed on the file system to actually update it
    - when a transaction is replayed, it is removed from the log
    - a log is circular, but un-committed entries will not be overwritten
    - garbage collection can reclaim/compact log entries
  - upon system crash, only need to replay transactions existing in the log

Will Talk Log Structured File System Later hw14 is out