Chapter 11: File System Implementation

肖 卿 俊

办公室：九龙湖校区计算机楼212室

电邮：csqjxiao@seu.edu.cn

主页： https://csqjxiao.github.io/PersonalPage

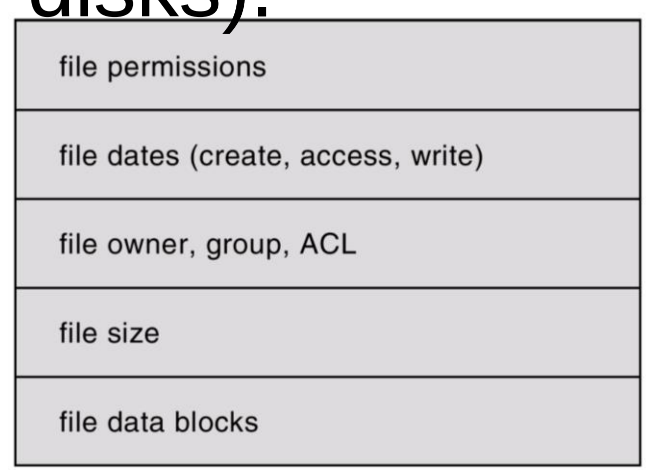
电话：025-52091022

Chapter 11: File System Implementation

- File System Structure
- File System Implementation
- Free-Space Management
- Directory Implementation
- Allocation Methods
- Efficiency and Performance
- Recovery
- Log-Structured File Systems
- NFS

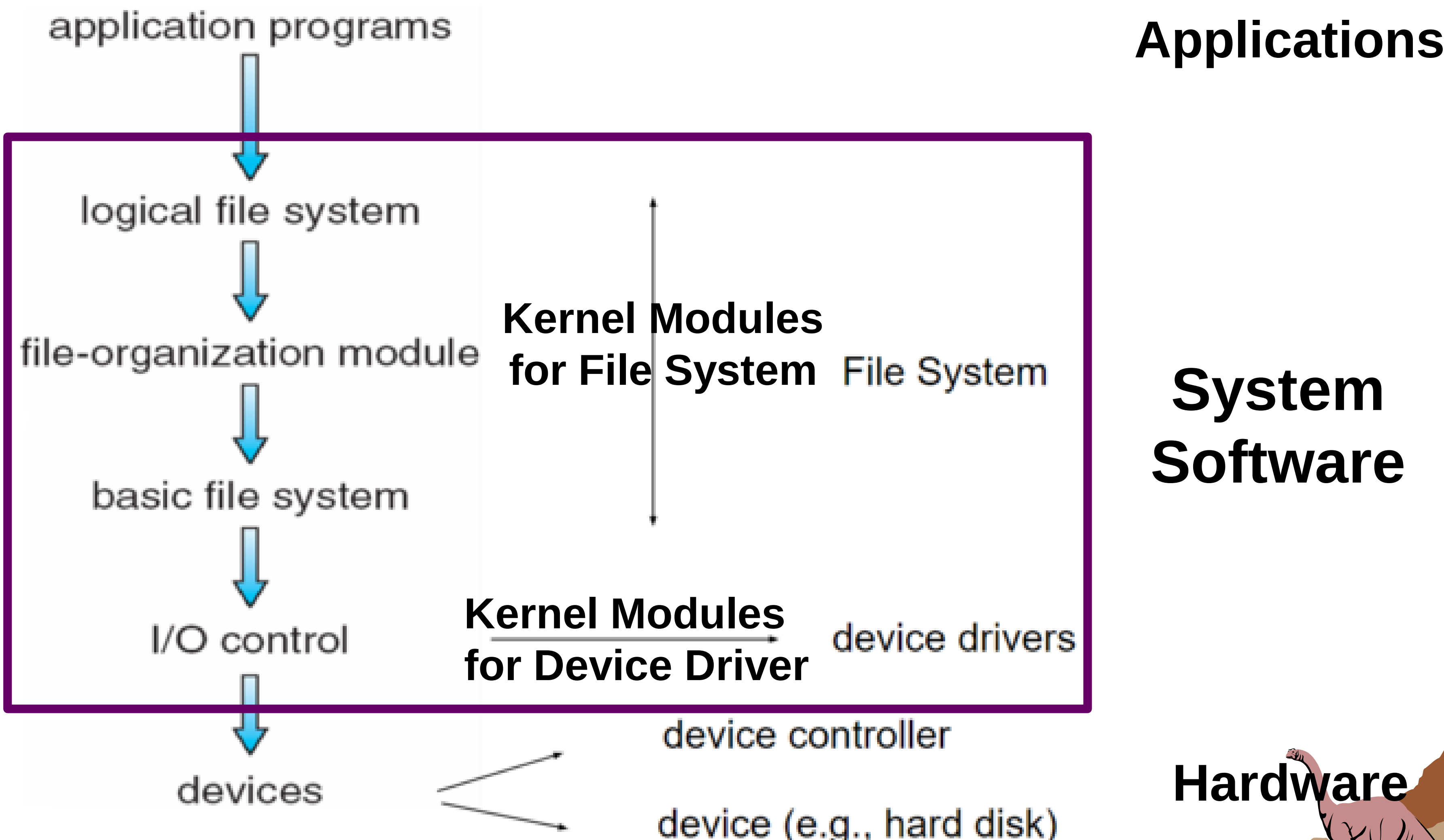
File-System Structure

- In this chapter, “file” refers to either an ordinary file or a directory file
- File structure
  - Logical storage unit
  - Collection of related information
- File system resides on secondary storage (either local disks or remote disks).
- *File control block* (FCB) – storage structure consisting of information about a file.



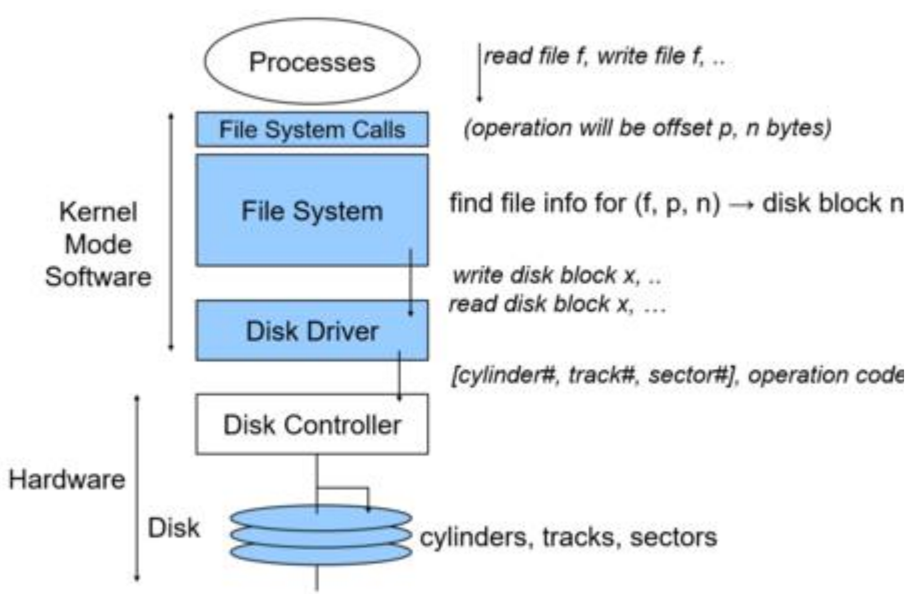
Layered File System

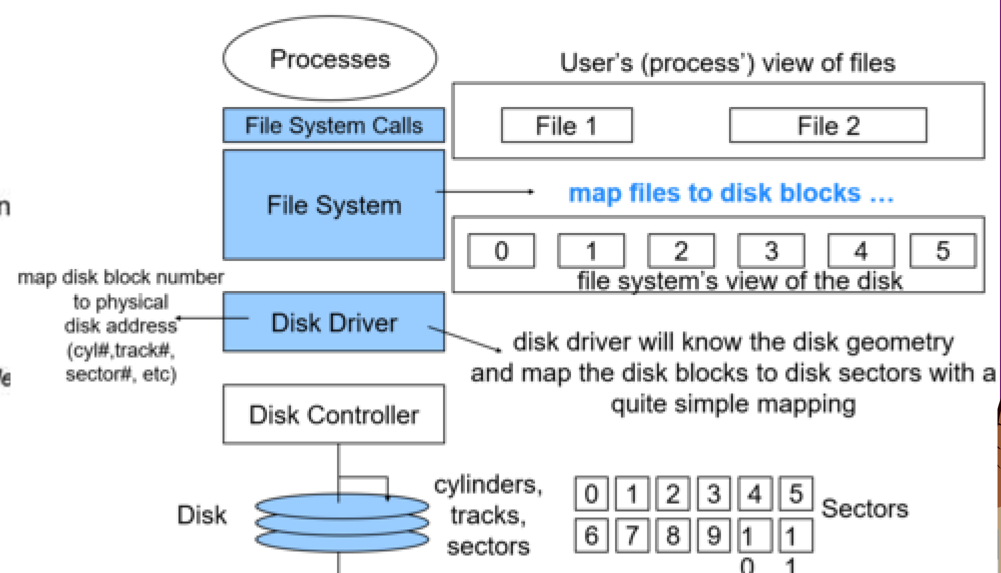
File system is organized into layers



File System Layers

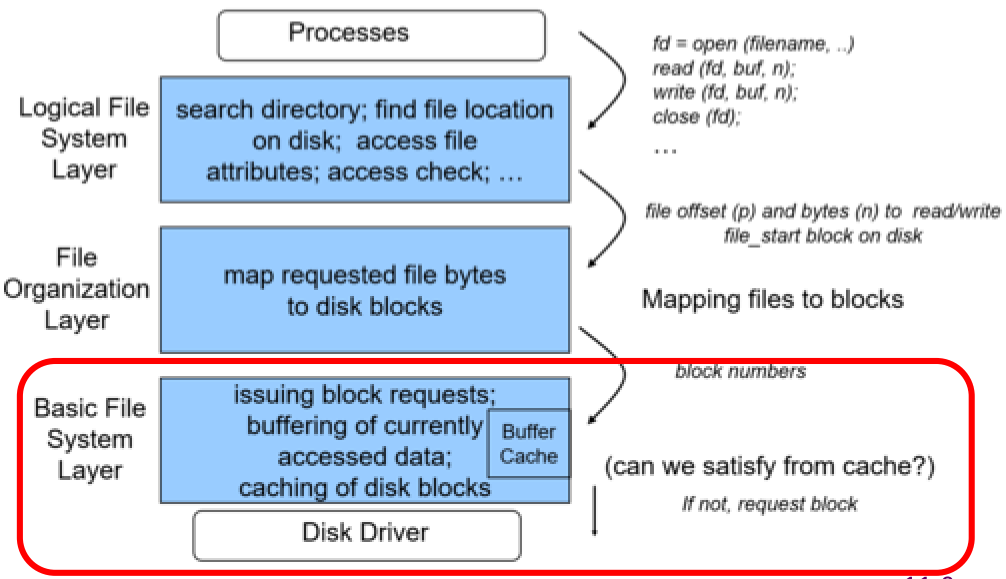
- **Device drivers** manage I/O devices at the I/O control layer
  - Given commands “read/write disk block 587”, outputs low-level hardware specific commands to hardware controller, like “read drive1, cylinder 72, track 2, sector 10, into memory location 1060”

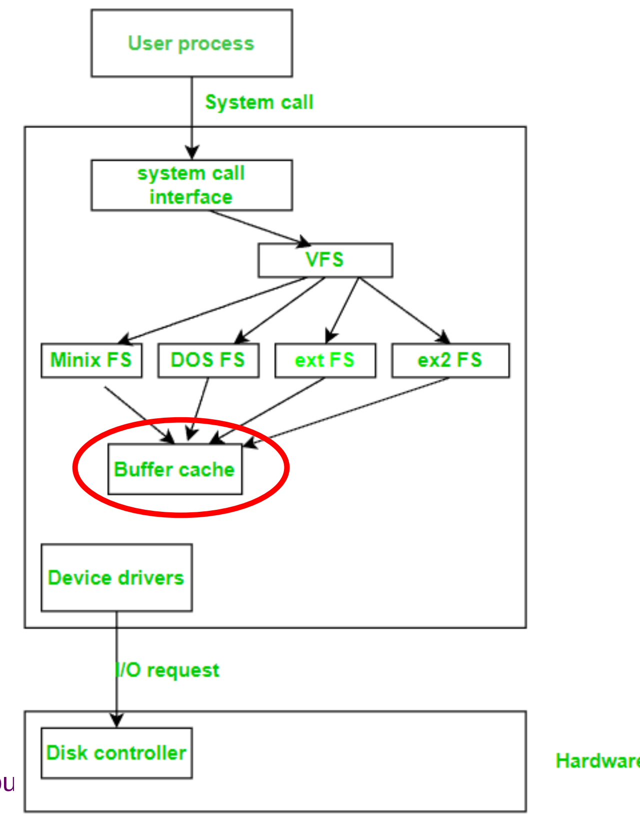




File System Layers (Cont.)

- **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

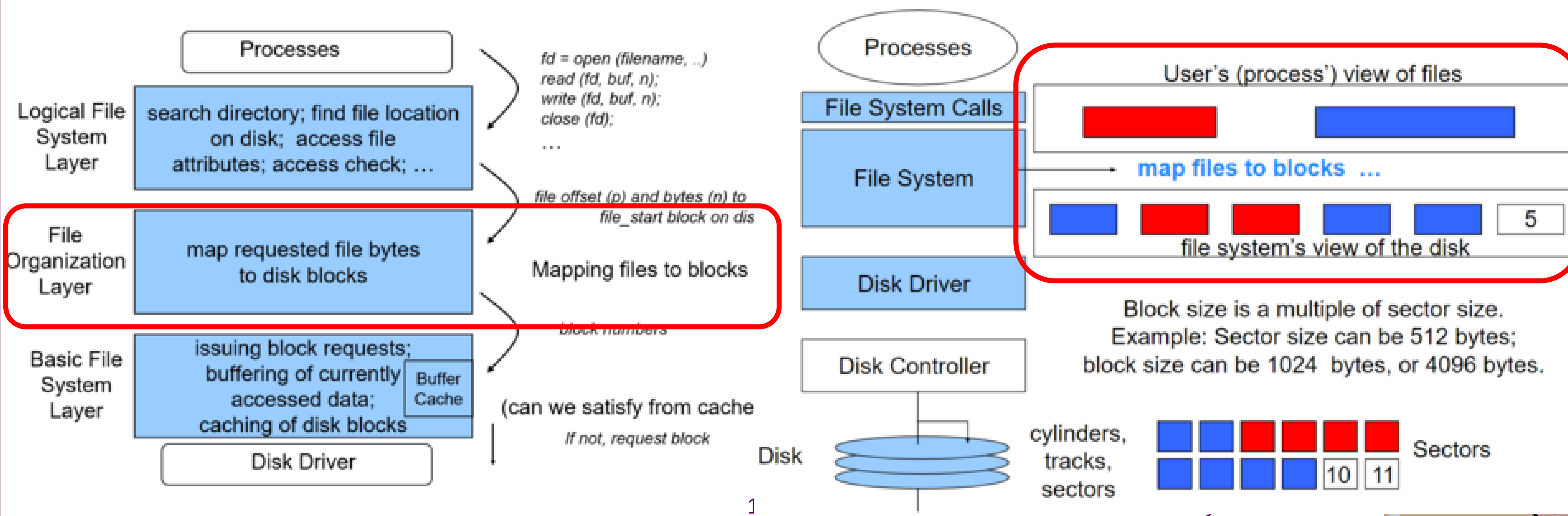




Sou

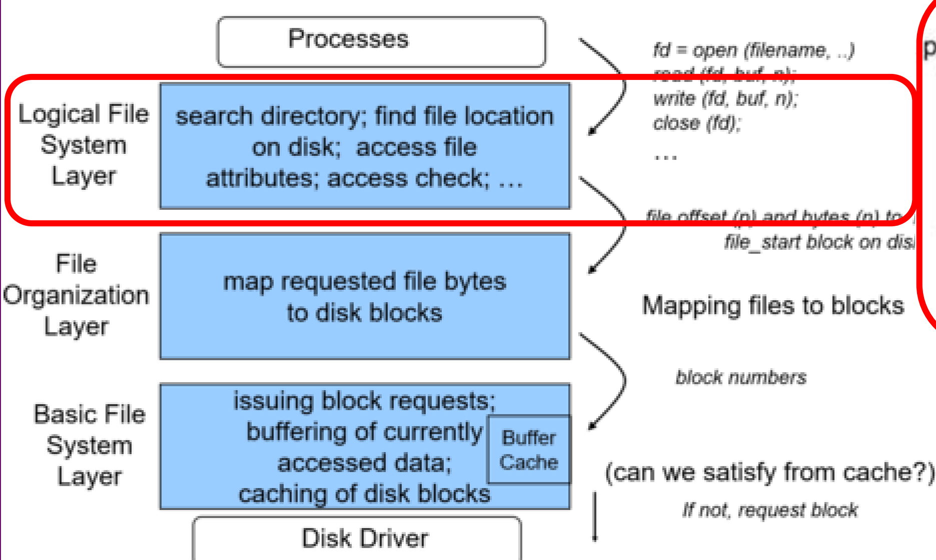
File System Layers (Cont.)

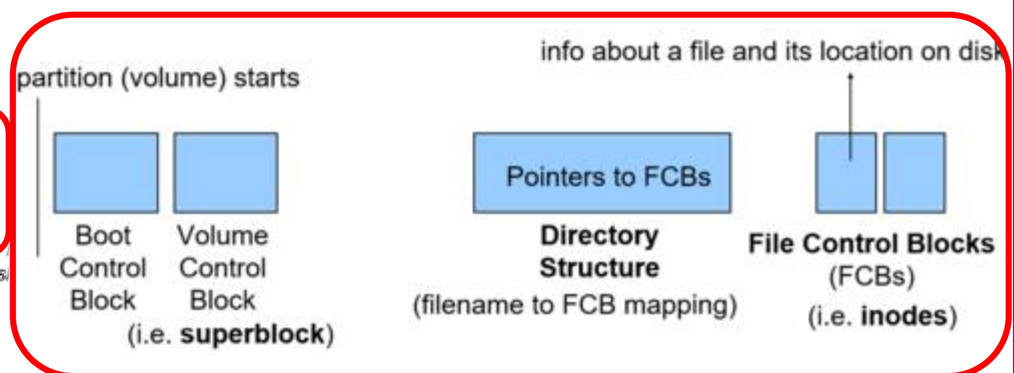
- **File organization module** understands files, logical address, and physical blocks
  - Translates logical block # to physical block #
  - Manages free space, disk allocation



File System Layers (Cont.)

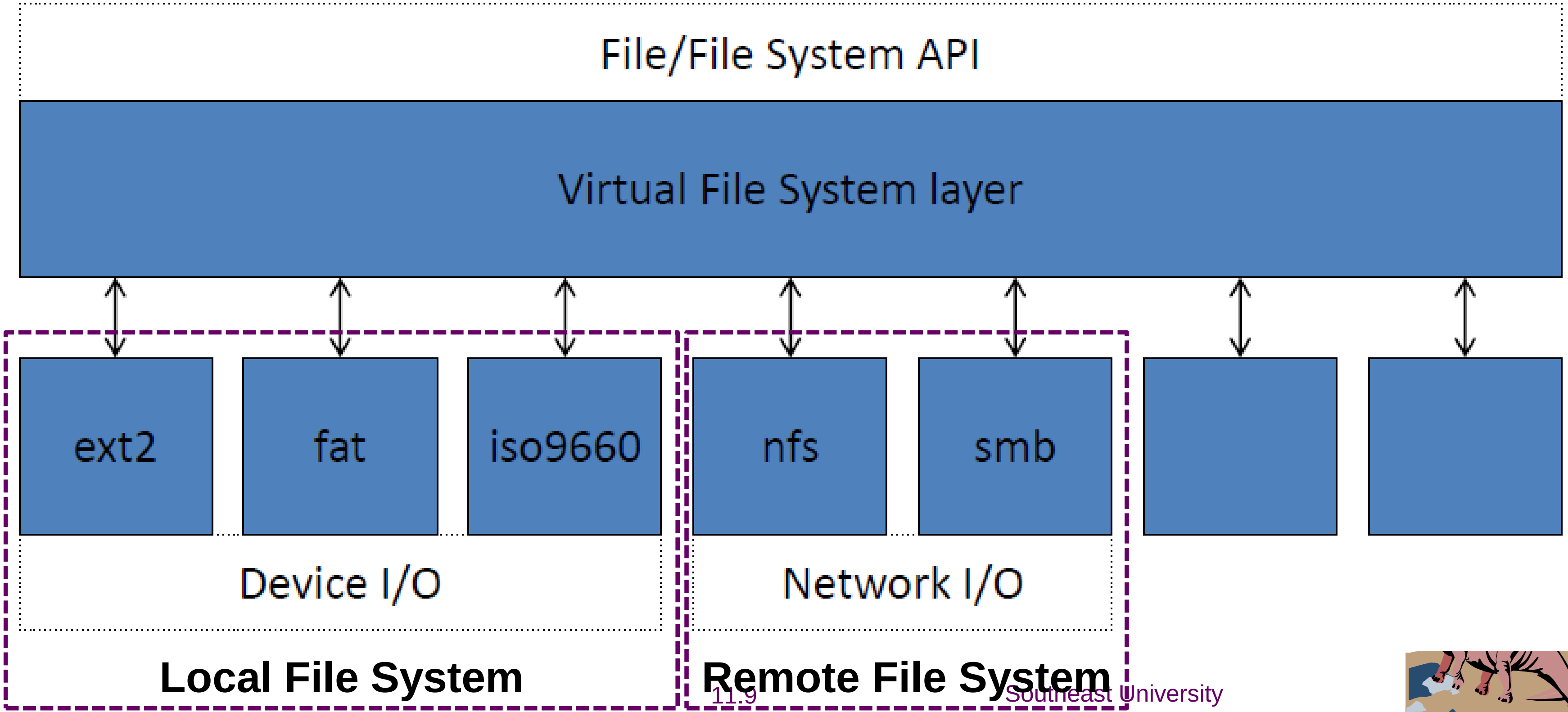
- **Logical file system** manages metadata information
  - Translates file name into file number, file handle, location by maintaining file control blocks (inodes in Unix)
  - Directory management
  - Protection





Each OS with its own supported file system 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



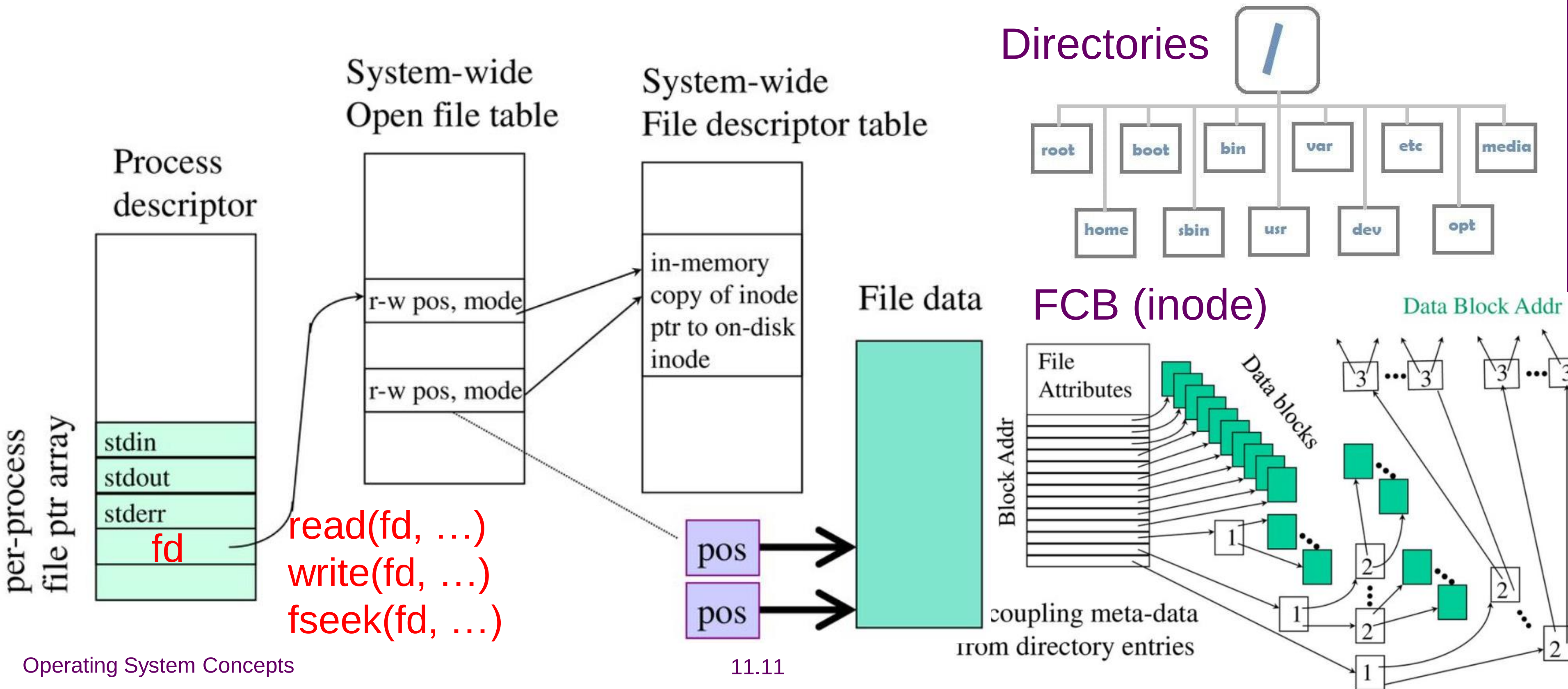
Chapter 11: File System Implementation

- File System Structure
- File System Implementation
- Free-Space Management
- Directory Implementation
- Allocation Methods
- Efficiency and Performance
- Recovery
- Log-Structured File Systems
- NFS

Two kinds of Structures of File System

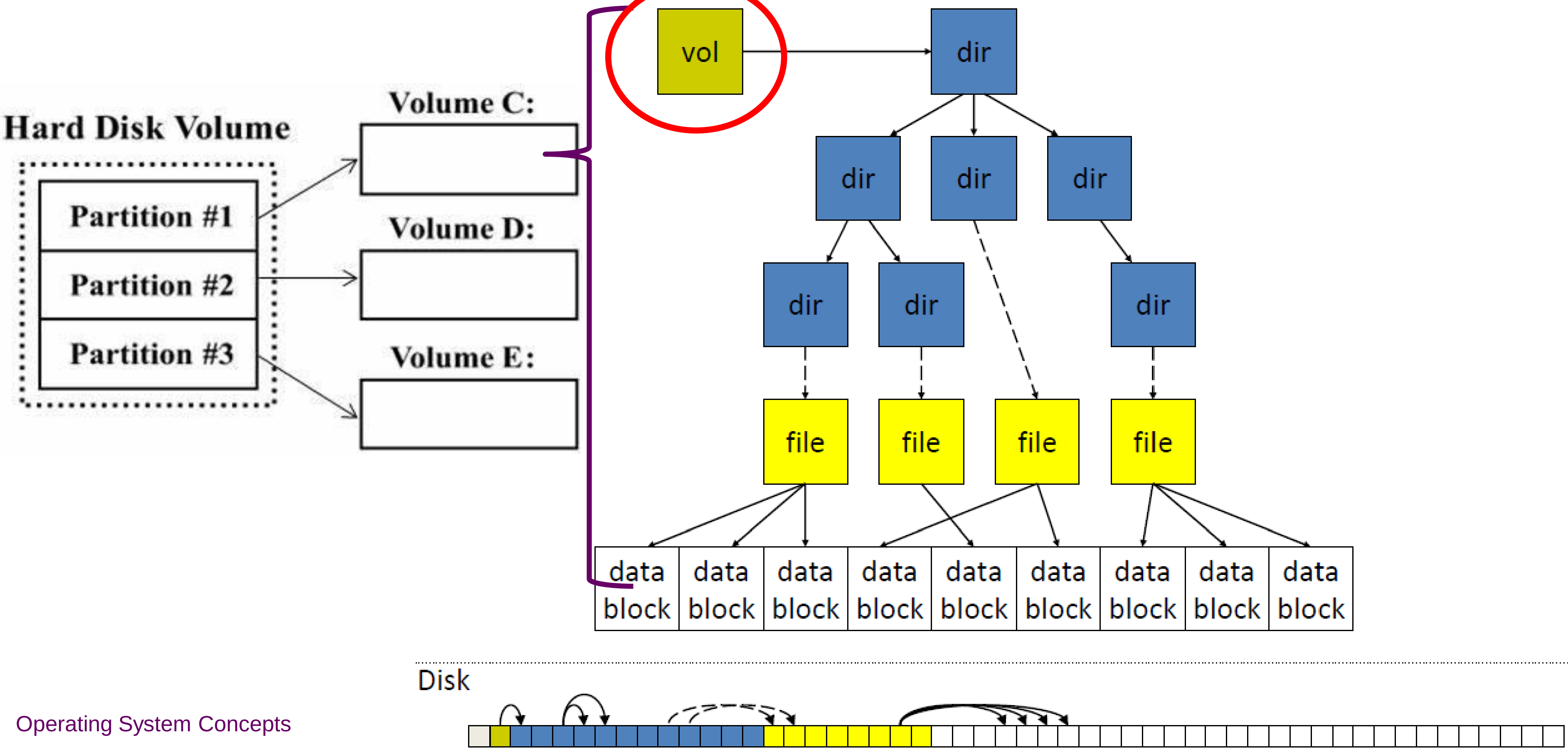
- We have file system calls at the API level, but how do we implement their functions?
  - In-memory and on-disk structures

In-memory data structure　　　　On-disk data structure



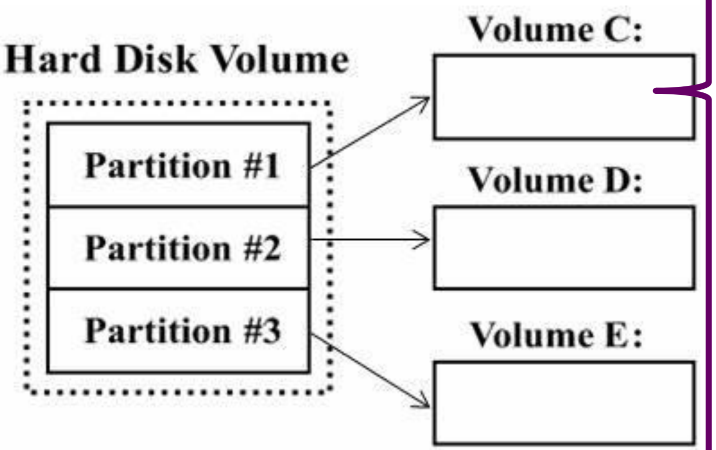
On-disk Structures of File System

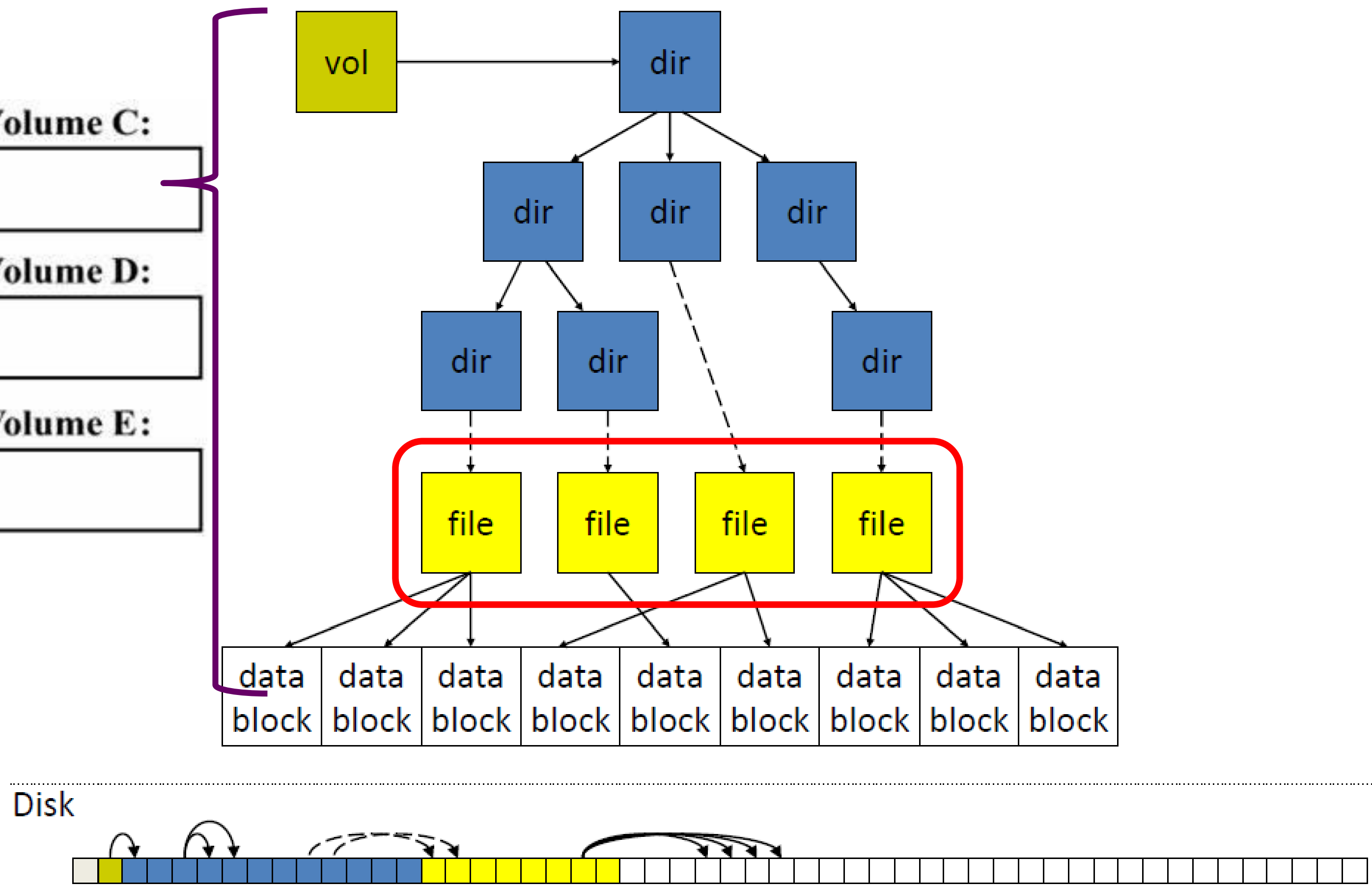
- Volume Control Block (Unix: "superblock")
  - One per file system
  - Detail information about the file system
  - # of blocks, block size, free-block count/pointer, etc.



On-disk Structures of File System

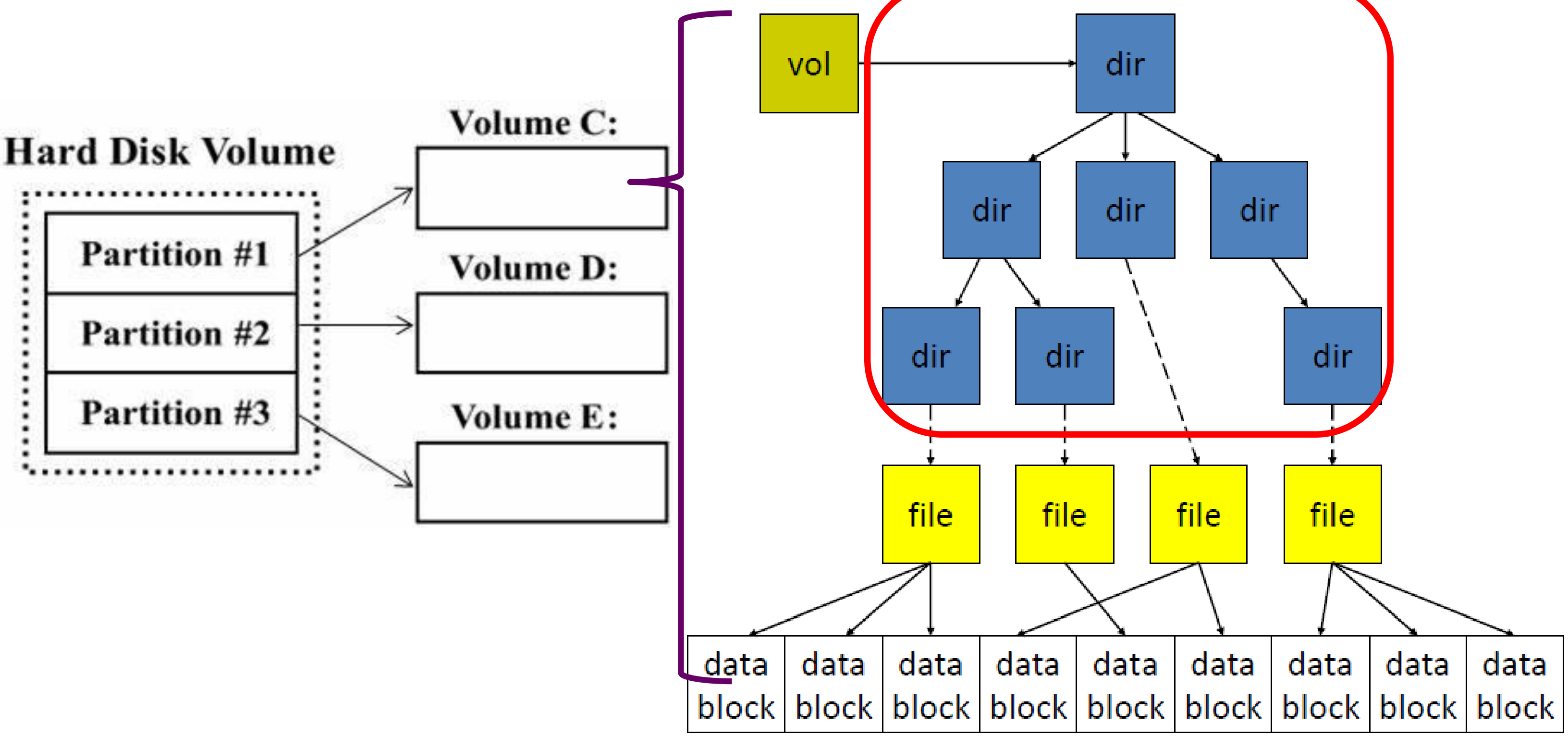
- File Control Block (Unix: "vnode" or "inode")
  - One per file to provide detailed information about the file
  - Permission, owner, size, data block locations, etc.

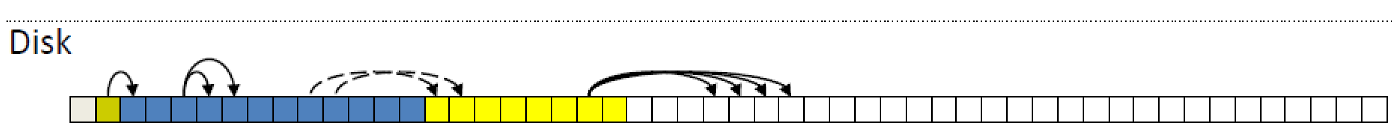




On-disk Structures of File System

- Directory Node (Linux: "dentry")
  - One per directory entry (directory or file)
  - Pointer to file control block, parent, list of entries, etc.





In-Memory Structures of File System

- The following figure illustrates the necessary file system structures provided by the operating systems.
- Figure (a)/(b) refers to opening/reading a file

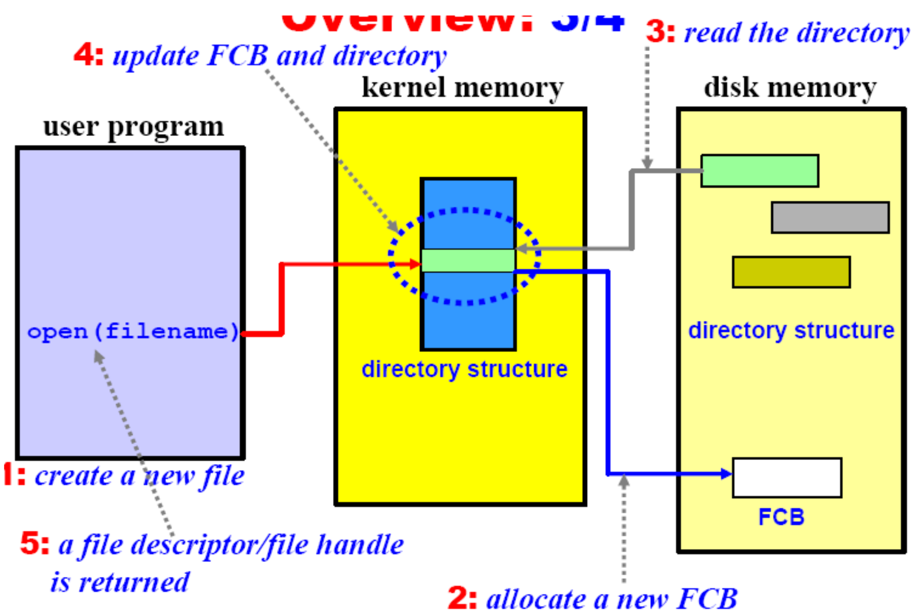


Figure (a)

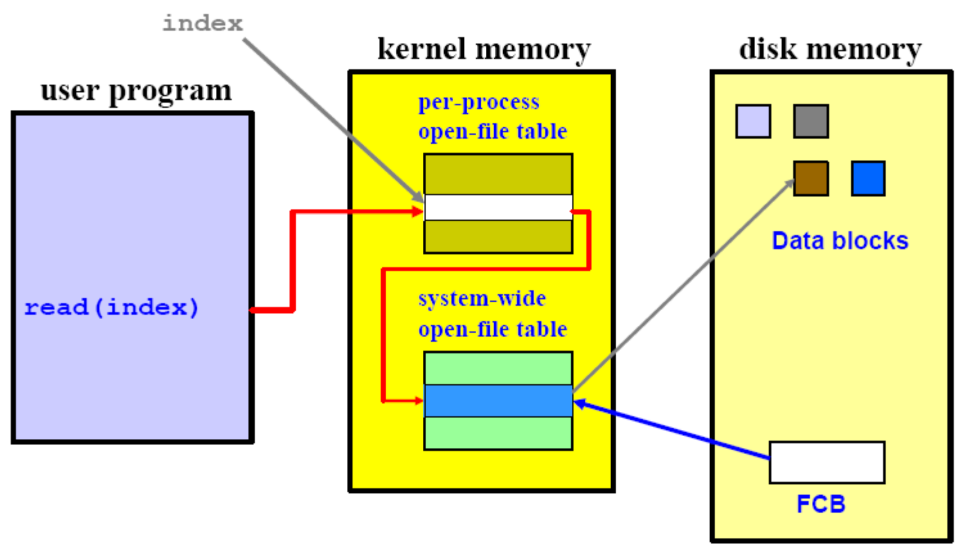


Figure (b)

In-Memory Structures of File System (cont

- 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

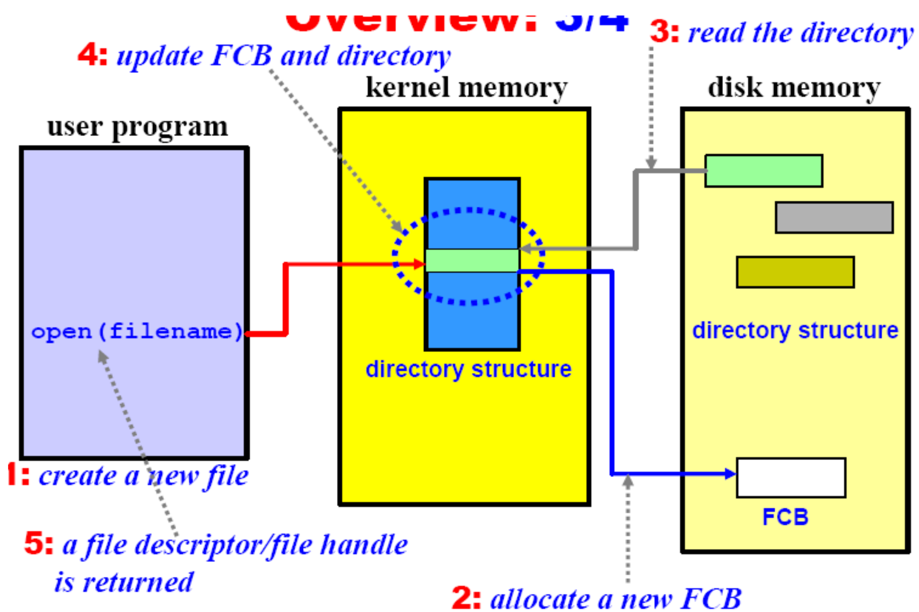


Figure (a)

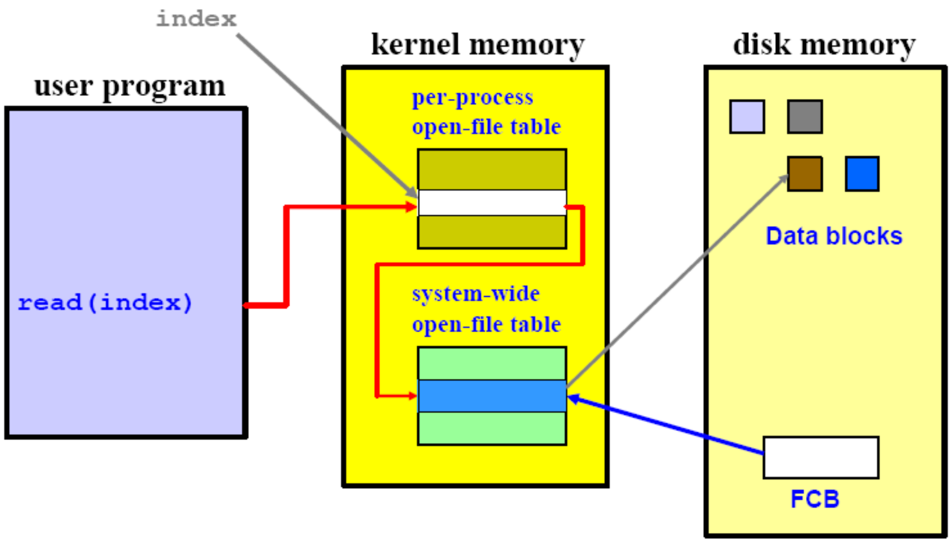
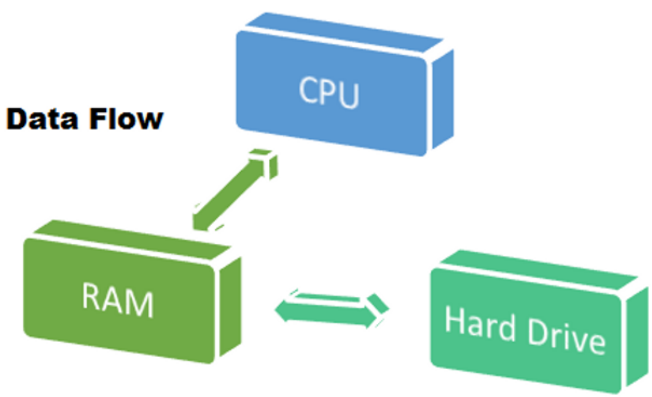
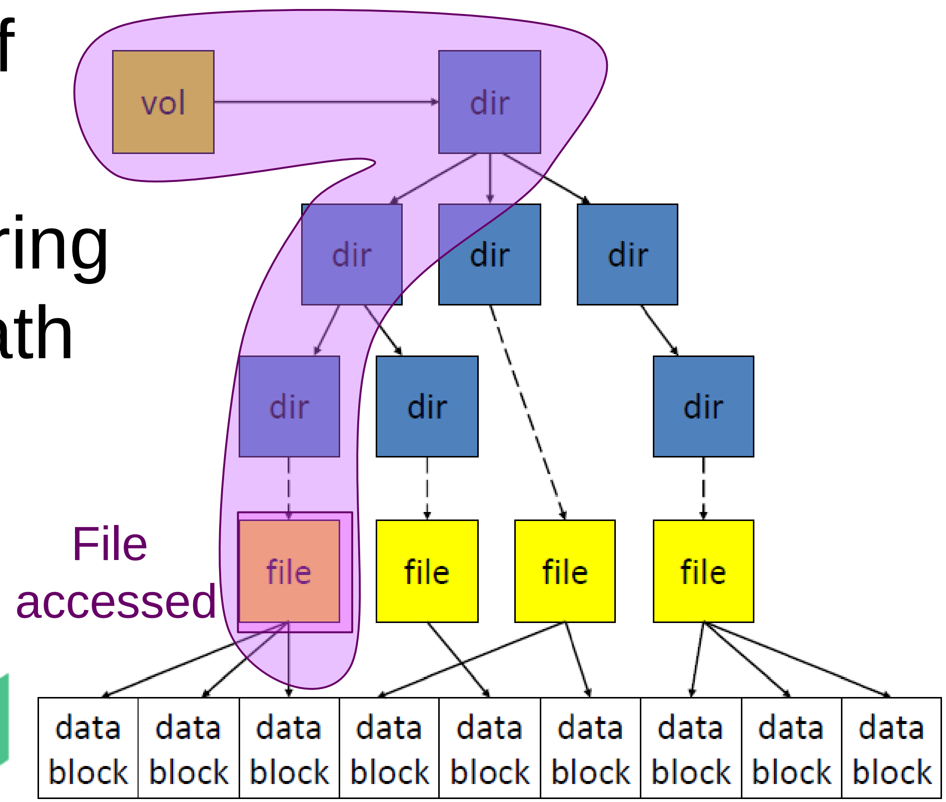


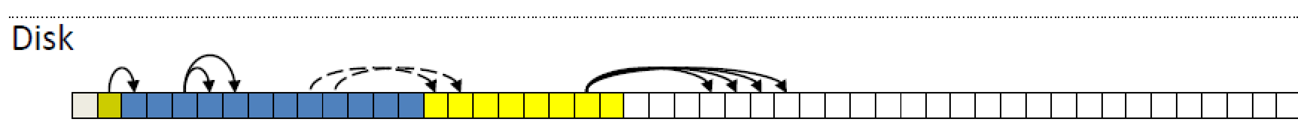
Figure (b)

On-demand Loading of On-disk Structures into Main Memory

- Loaded to memory when needed
  - Volume control block: in memory if file system is mounted
  - File control block: if the file is accessed
  - Directory node: during traversal of a file path







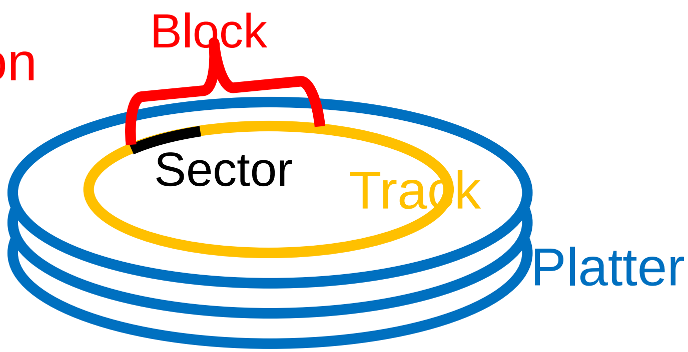
Chapter 11: File System Implementation

- File System Structure
- File System Implementation
- Free-Space Management
- Directory Implementation
- Allocation Methods
- Efficiency and Performance
- Recovery
- Log-Structured File Systems
- NFS

Free-Space Management

- How do we keep track of free blocks on a disk?

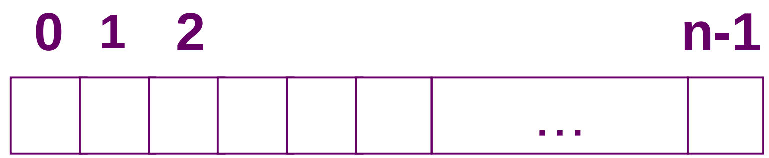
What is a block on magnetic disk?



- The techniques below are commonly used:
  - Bit Vector or Bit Map
  - Linked List: A free-list is maintained. When a new block is requested, we search this list to find one.
  - Linked List + Grouping
  - Linked List + Address + Count

Bit Vector

- Bit vector   (*n* blocks)



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

CPUs have instructions to return offset within word of first “1” bit

The first free block number calculation:

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

Question: What the time cost of finding the number of 0-value words? Why it doesn’t matter?

Free-Space Management

- Advantage of bit vector method: Easy to get contiguous files

- Disadvantage: Bitmap requires extra space.
- An Example:

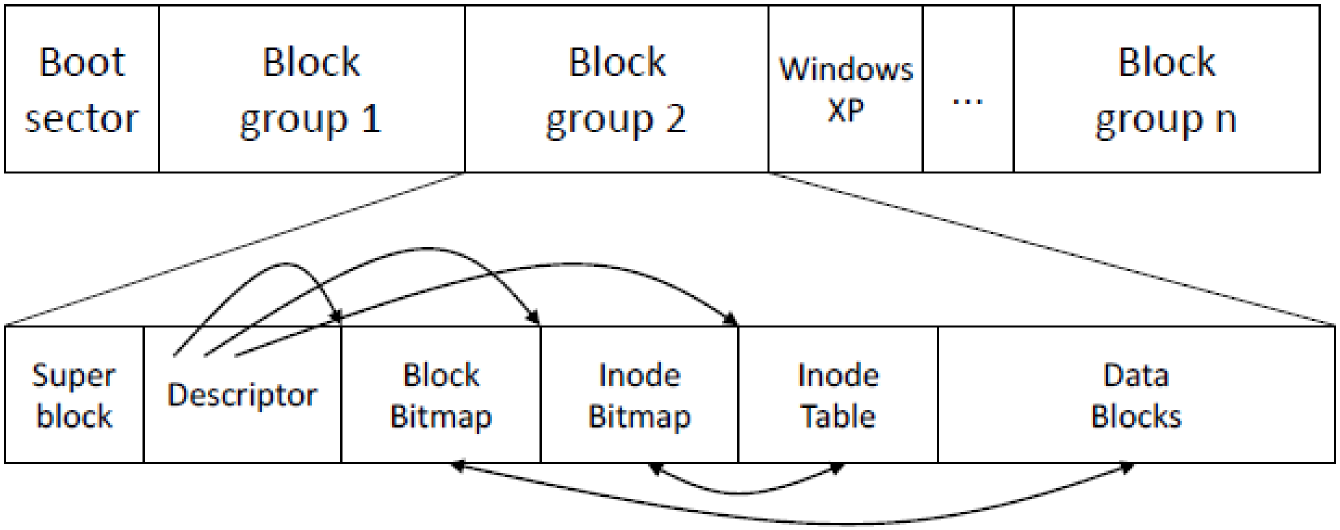
  block size = 2^{12} bytes

  disk size = 2^{40} bytes (1 tera bytes)

  $n = 2^{40}/2^{12} = 2^{28}$ bits (or 32 mega bytes)

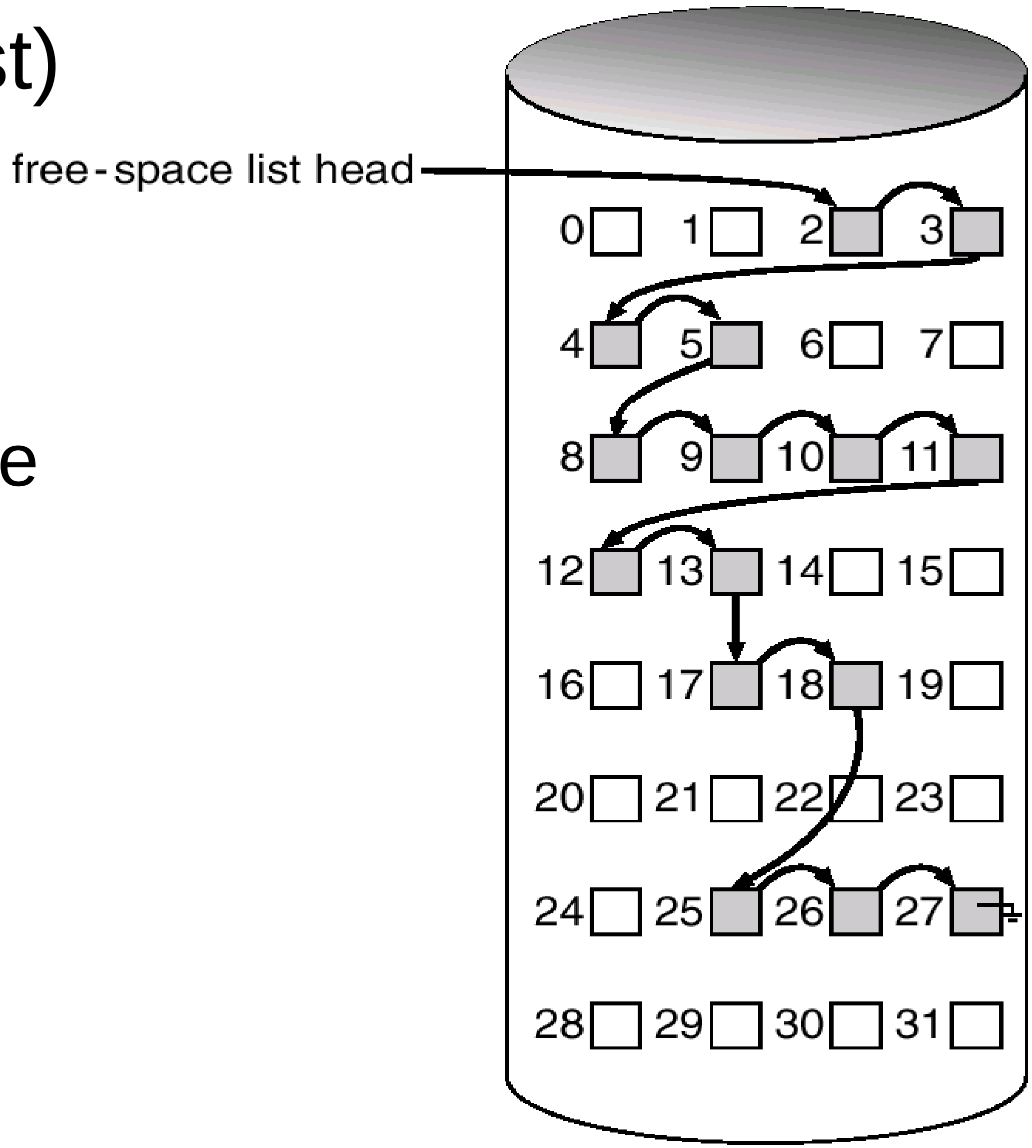
Linux Ext2 Disk Layout

- Block bitmap is used by Linux Ext2 to manage the disk free space.



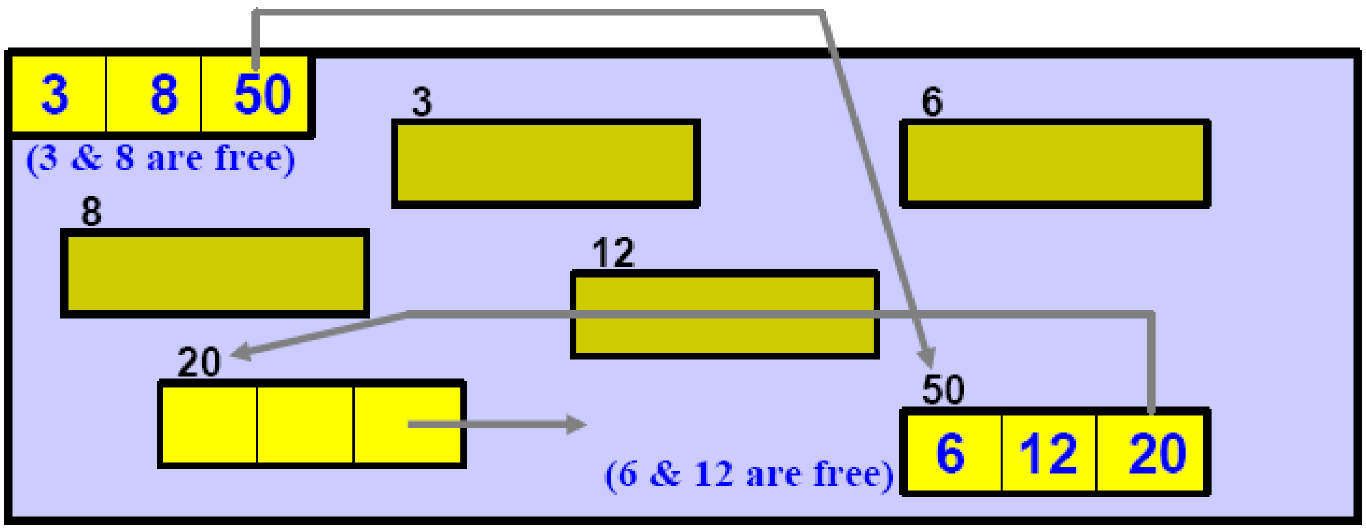
Linked Free Space List on Disk

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



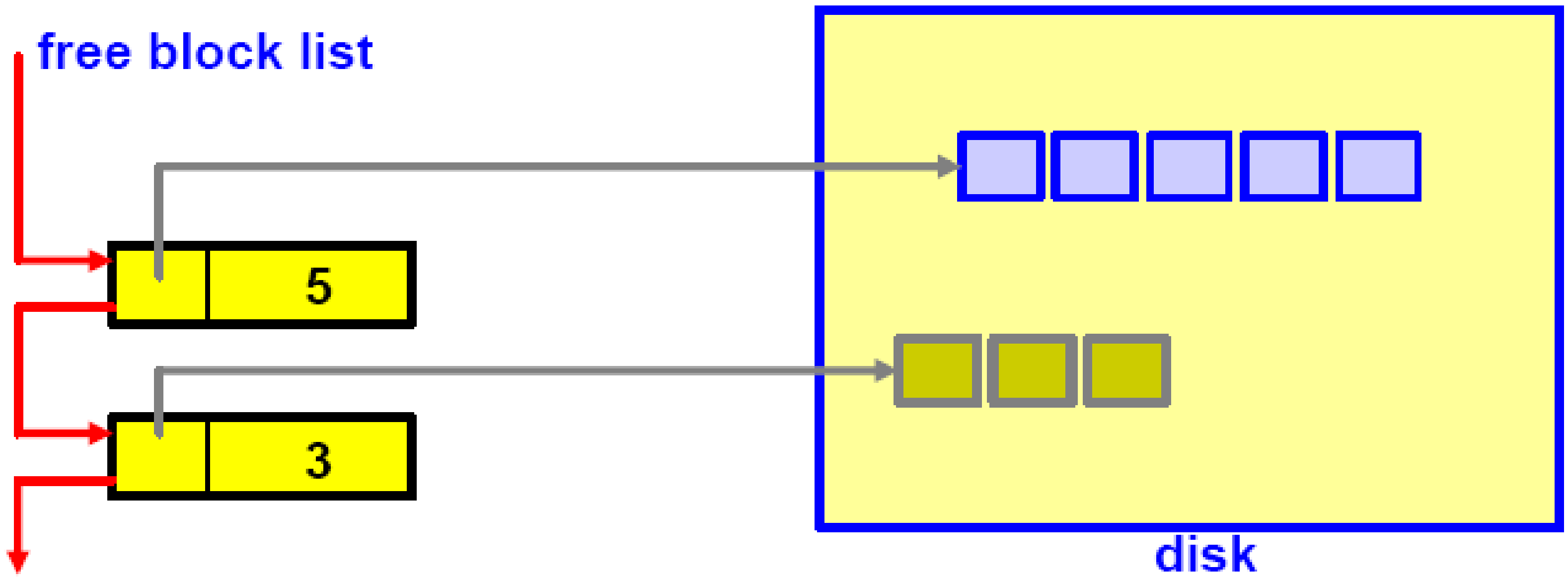
Grouping of Multiple Free Blocks

- The first free block contains the addresses of *n* other free blocks.
- For each group, the first *n-1* blocks are actually free and the last (i.e., *n-th*) block contains the addresses of the next group.
- In this way, we can quickly locate free blocks.



Address Counting of Contiguous Free Blocks

- We can make the list short with the following trick:
  - Blocks are often allocated and freed in groups
  - We can store the address of the first free block and the number of the following *n* free blocks.

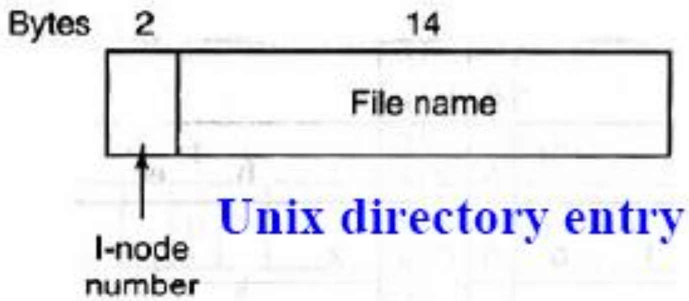


Chapter 11: File System Implementation

- File System Structure
- File System Implementation
- Free-Space Management
- Directory Implementation
- Allocation Methods
- Efficiency and Performance
- Recovery
- Log-Structured File Systems
- NFS

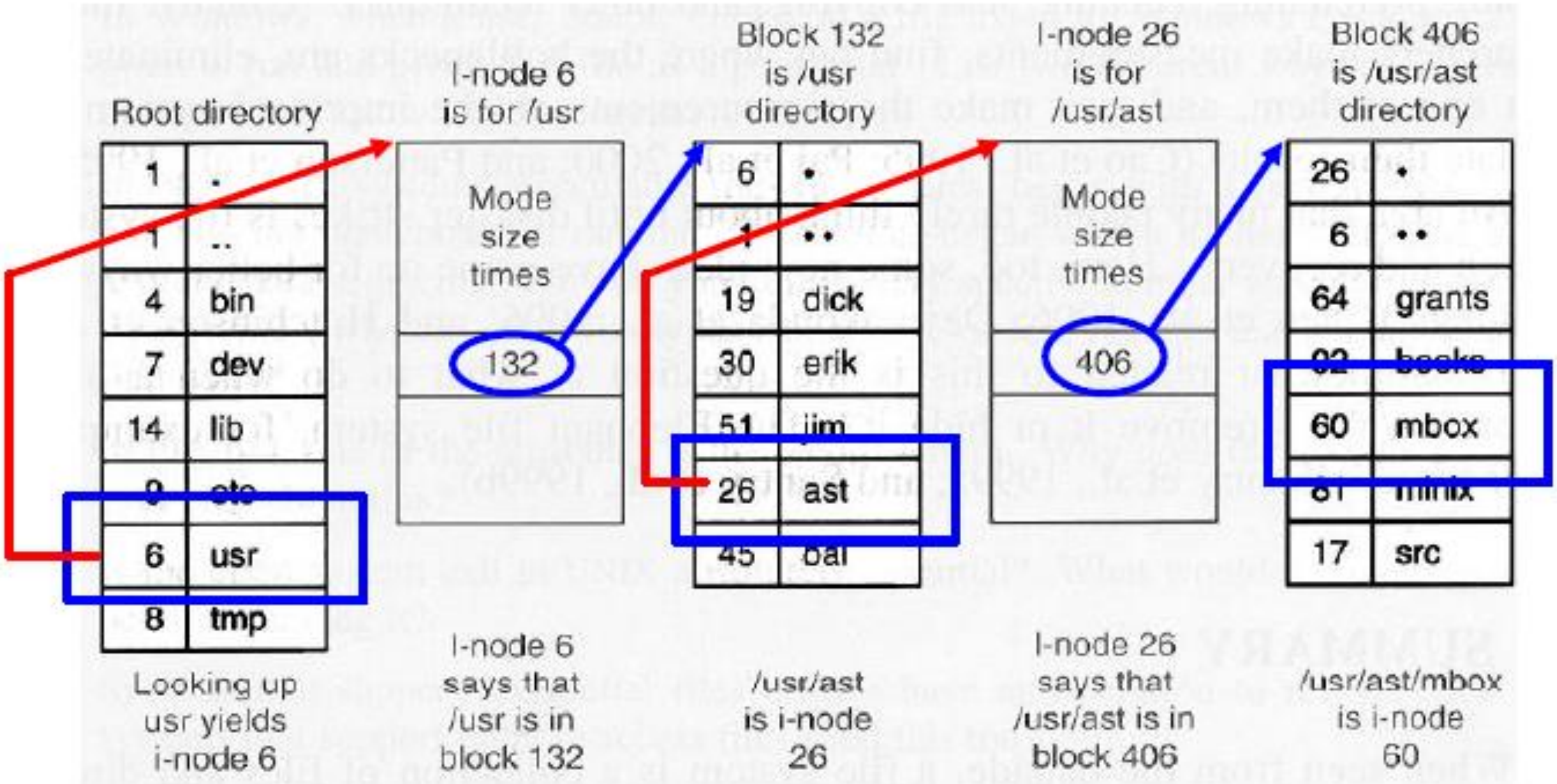
Directory Implementation

- 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



Unix directory entry

find /usr/ast/mbox



Chapter 11: File System Implementation

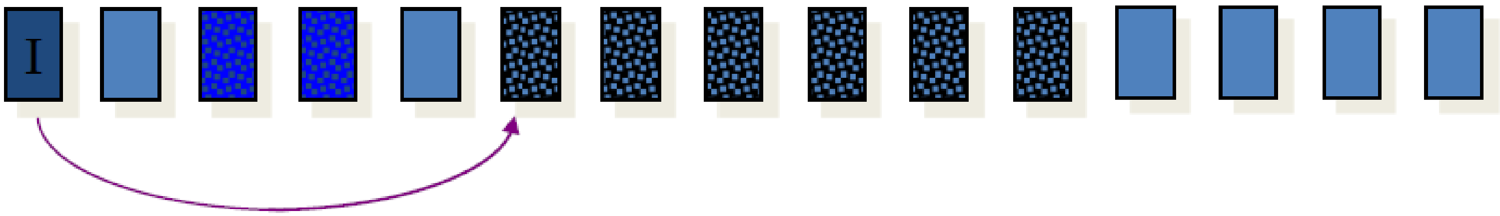
- File System Structure
- File System Implementation
- Free-Space Management
- Directory Implementation
- Allocation Methods
- Efficiency and Performance
- Recovery
- Log-Structured File Systems
- NFS

File Allocation Methods

- An allocation method refers to how disk blocks are allocated for files:
- Allocation methods
  - Contiguous allocation
  - Linked allocation
  - Indexed allocation

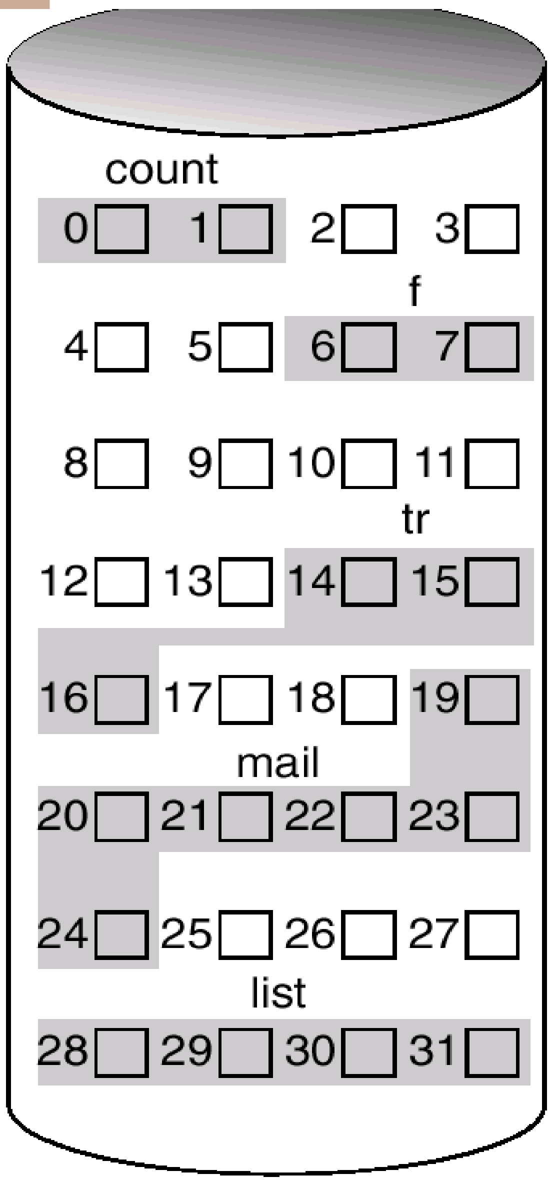
Contiguous Allocation

- 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 (recall the dynamic storage-allocation problem and external fragmentation).
- Files may not be able to grow.

Contiguous Allocation of Disk Space



directory

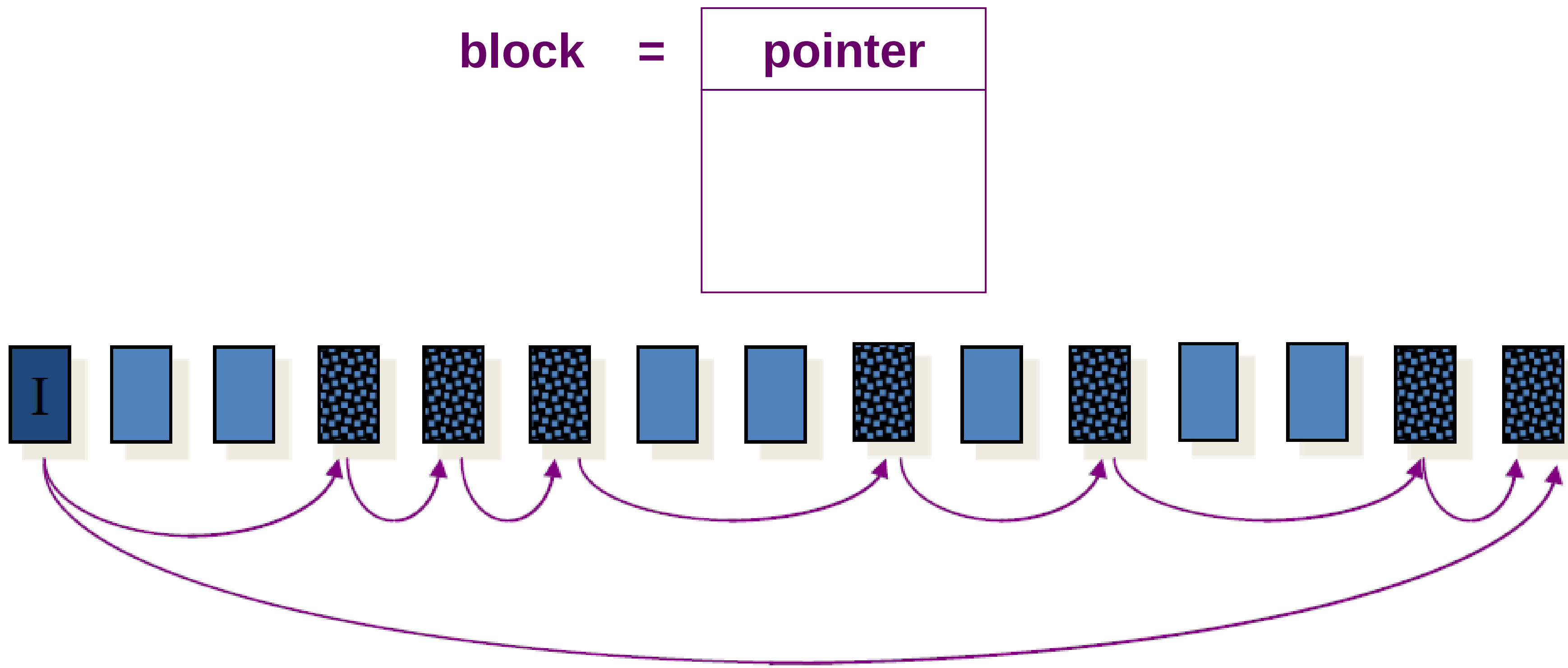
file	start	length
count	0	2
tr	14	3
mail	19	6
list	28	4
f	6	2

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 sequence of contiguous disk blocks. Extents are allocated for file allocation. A file consists of one or more extents.
- Basic idea is similar to the **slab-based** kernel memory management (slab is continuous, but a cache can consists of multiple slabs)

Linked Allocation

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

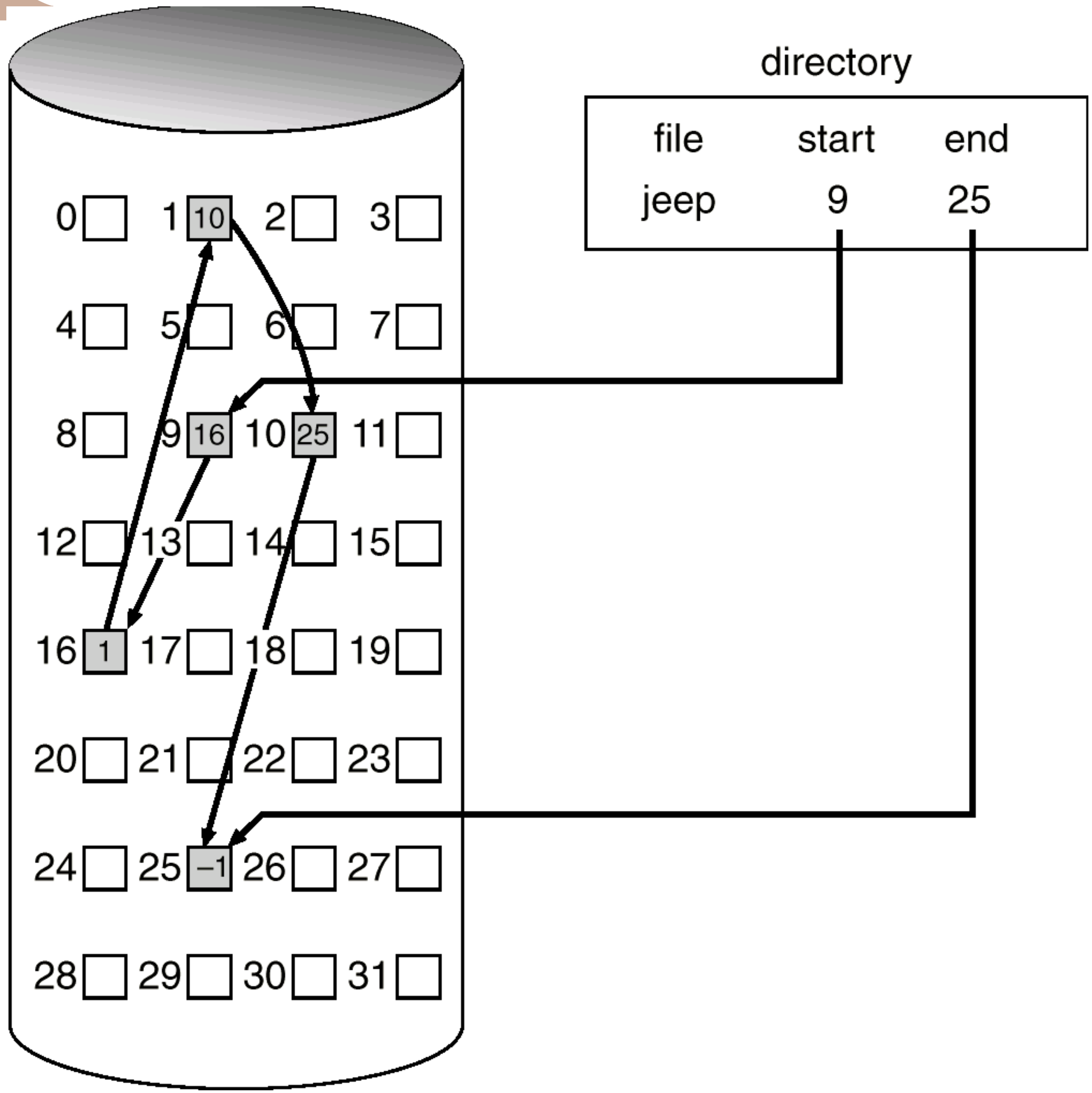


Linked Allocation (Cont.)

- Simple – need only starting address
- Free-space management system – no waste of space
- Files can easily grow, if there are free blocks

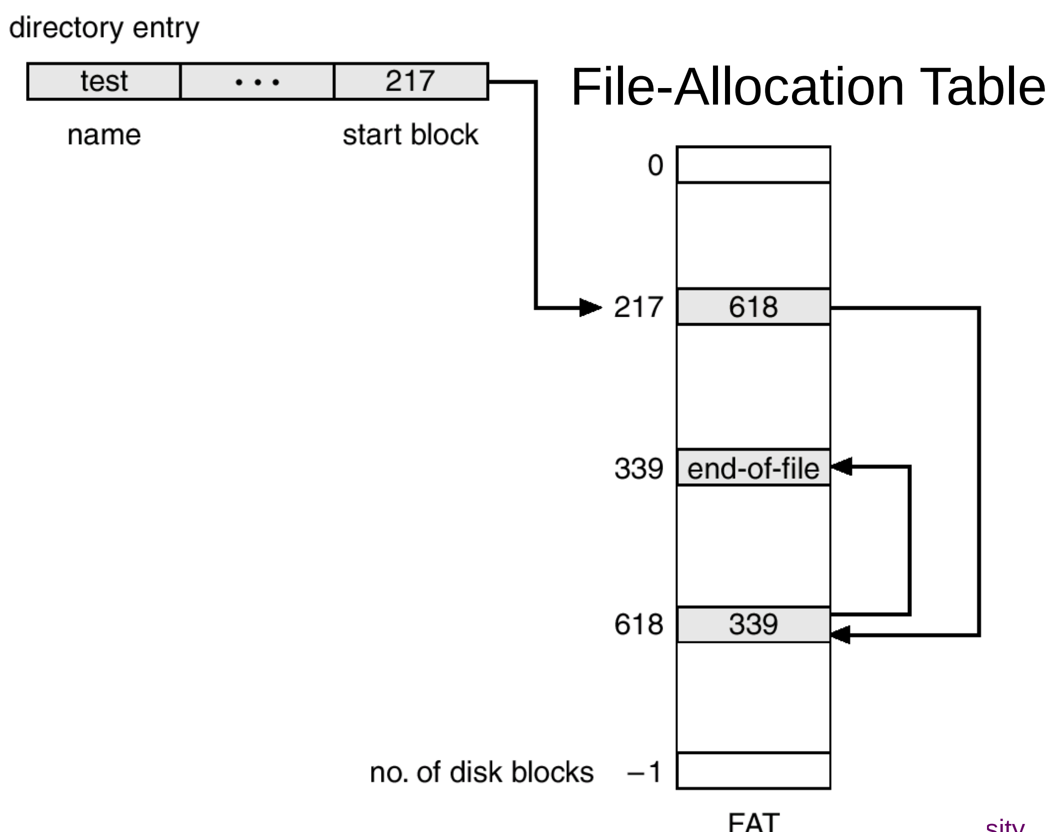
- No random access
- Each block contains a pointer, wasting space
- Blocks scatter everywhere and a large number of disk seeks may be necessary
- Reliability: what if a pointer is lost or damaged?

Linked Allocation (Cont.)



Linked Allocation (Cont.)

- FAT (File Allocation Table) variation
  - Beginning of volume has a table, indexed by block number
  - Much like a linked list, but faster on disk and cacheable
  - Make new block allocation simple



Question about FAT

- Given the values in the FAT, mark the block addresses that start a file

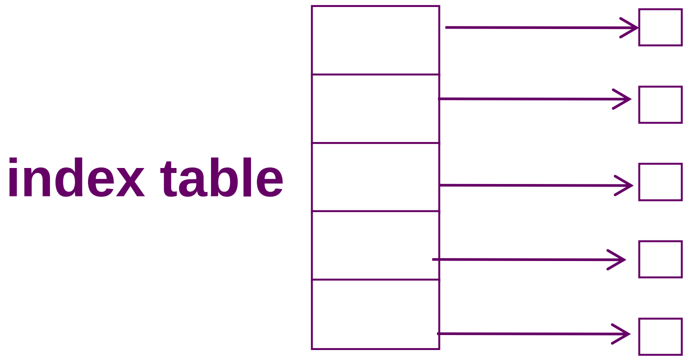
	Busy	Next	
0	0	-1	
1	1	6	
2	1	-1	
3	1	1	✓
4	0	-1	
5	1	-1	✓
6	1	-1	
7	1	2	✓

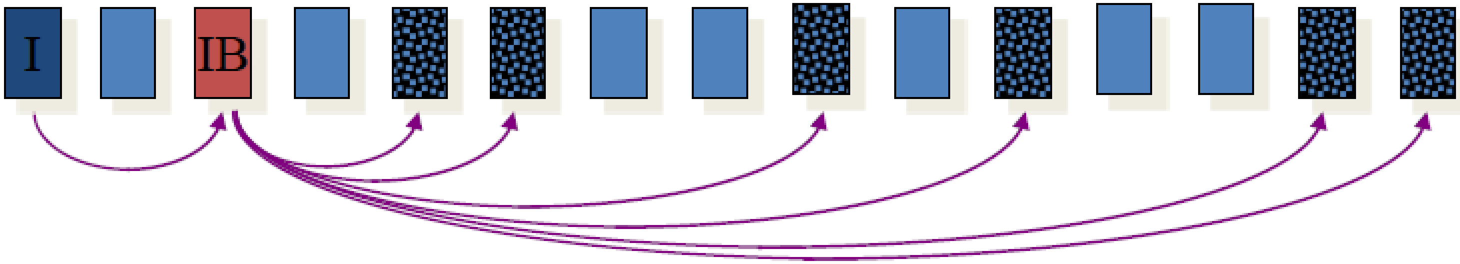
Problem about FAT

- Assume:
  - Disk Size = 32GB
  - Block Size = 4 kB
- Then,
  - Number of Blocks = 8M
  - Size of FAT table = 8B * 8M = 64MB, **CAN FIT IN MEMORY**
- However, if we assume
  - Disk Size = 4TB
  - Block Size = 4 kB
- Then,
  - Number of Blocks = 1Giga
  - Size of FAT table = 8B * 1G = 8GB, **CANNOT FIT IN MEM**

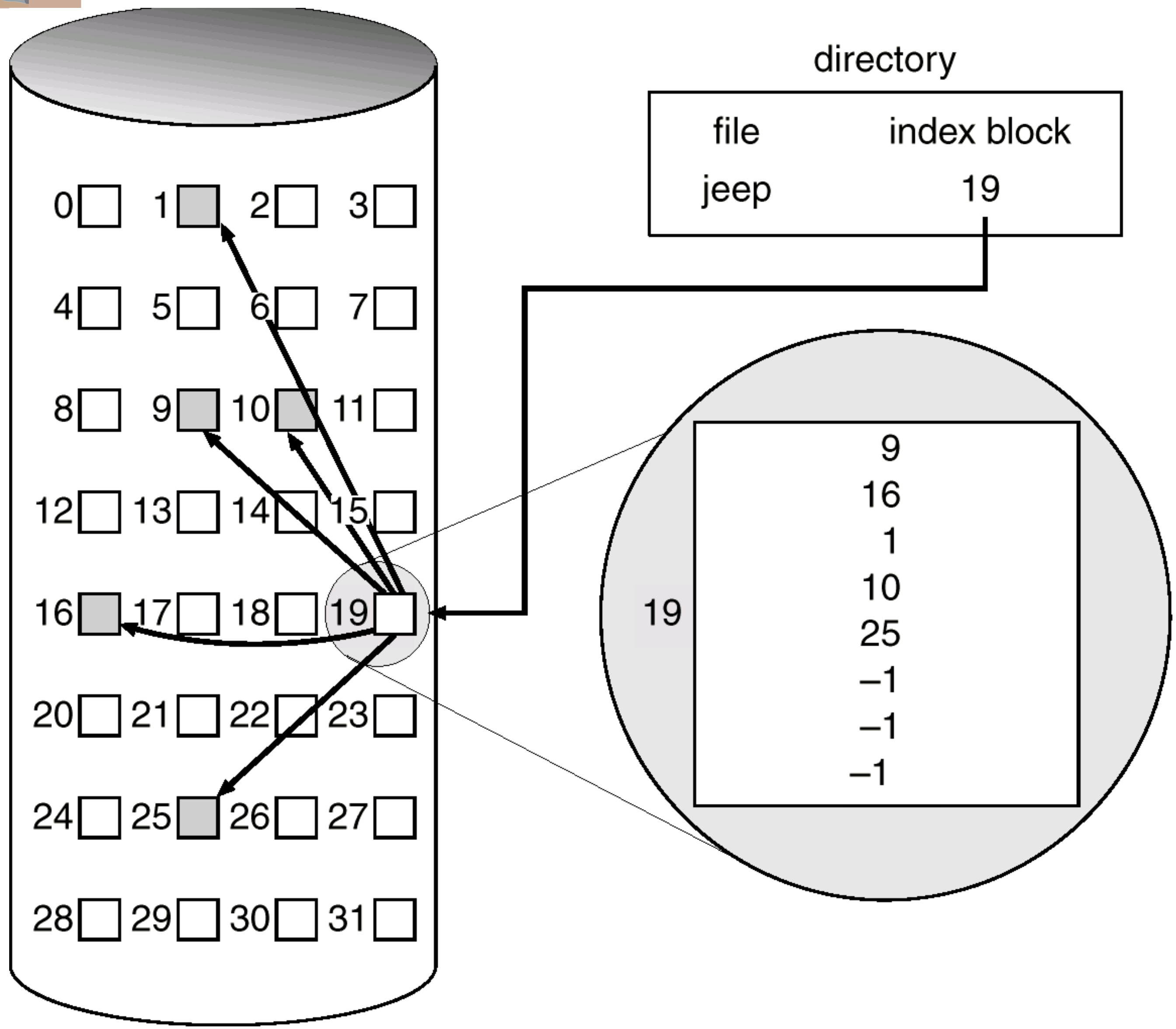
Indexed Allocation

- Brings all pointers together into the index block.
- A file's directory entry contains a pointer to its index block.
- Hence, the index block of an indexed allocation plays the same role as the page table.
- Logical view.





Example of Indexed Allocation

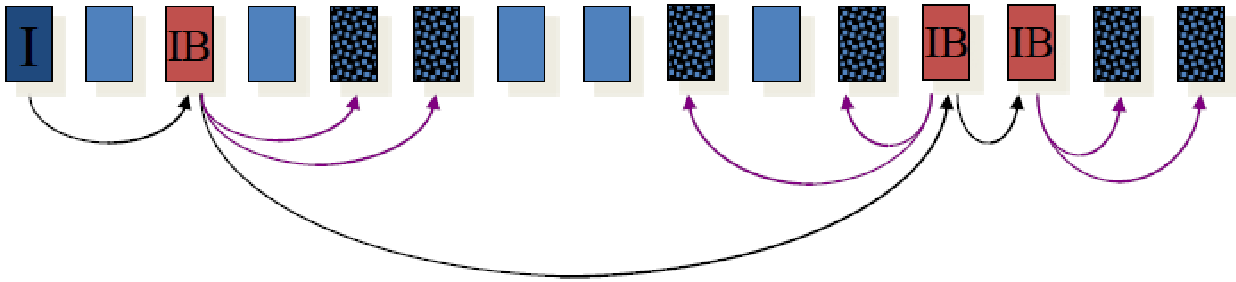


Indexed Allocation (cont.)

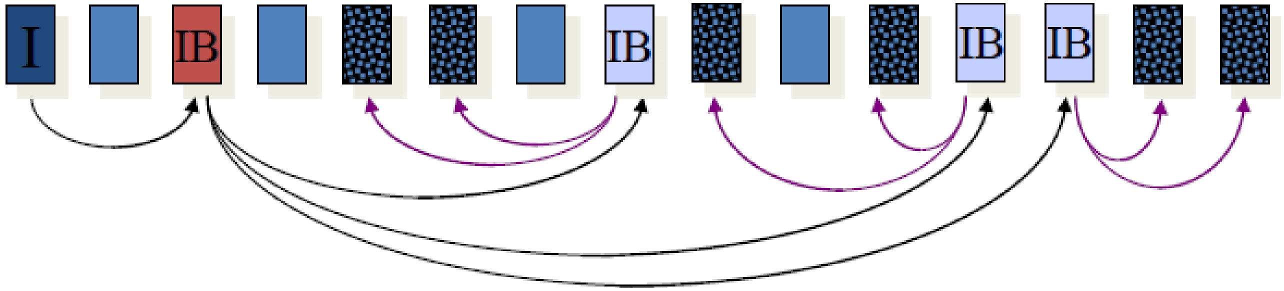
- Support the random access
- The indexed allocation suffers from wasted space. The index block may not be fully used (i.e., internal fragmentation).
- The number of entries of an index table determines the upper bound for the size of a file. But the file size may exceed the bound.
- To overcome this problem, we must extend the indexed allocation method.

Indexed Allocation (cont.)

- Improve index allocation method for large files
  - multiple index blocks, chain them into a linked-list

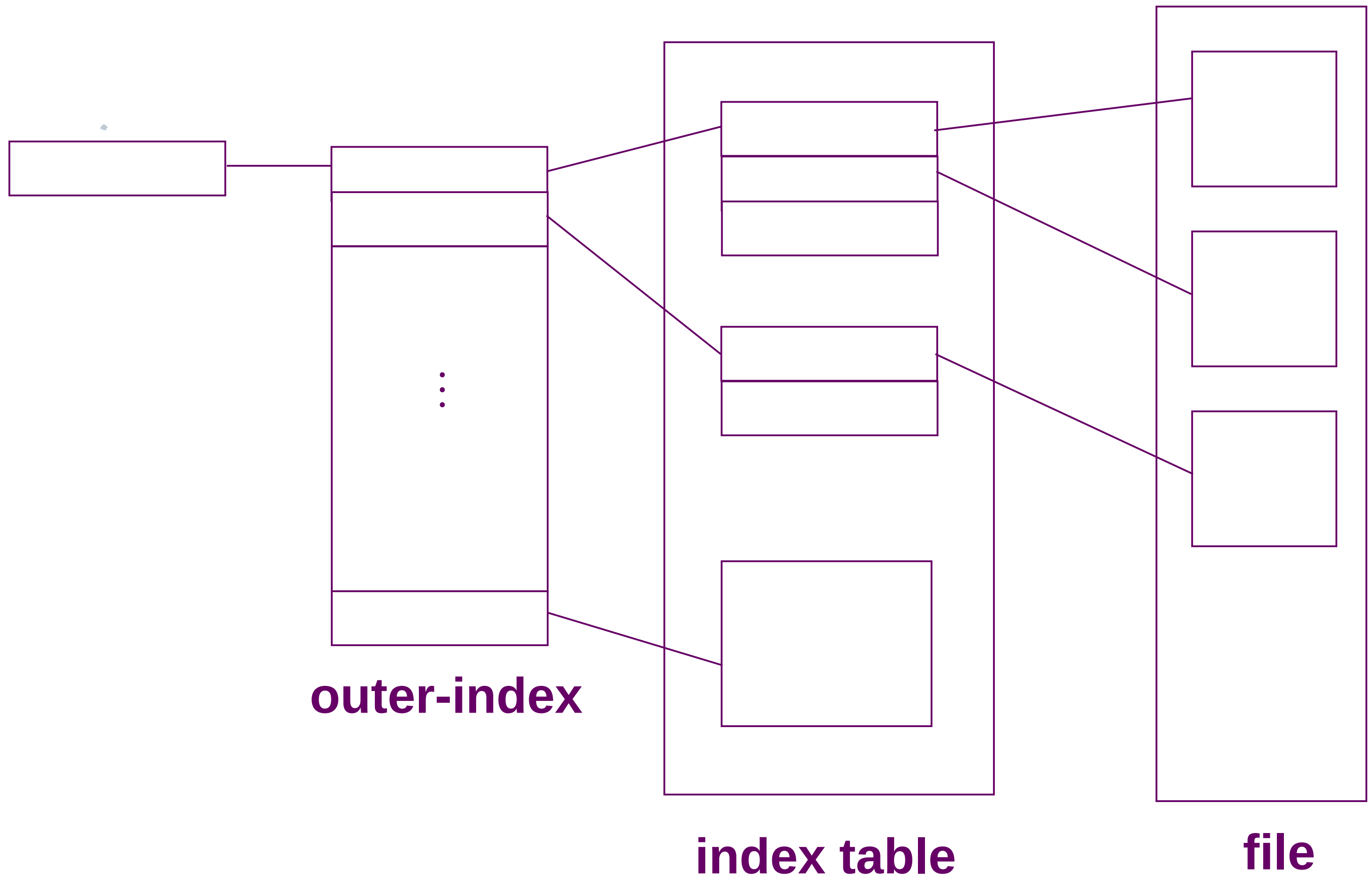


  - multiple index blocks, but make them a tree just like the multiple-level indexed access method

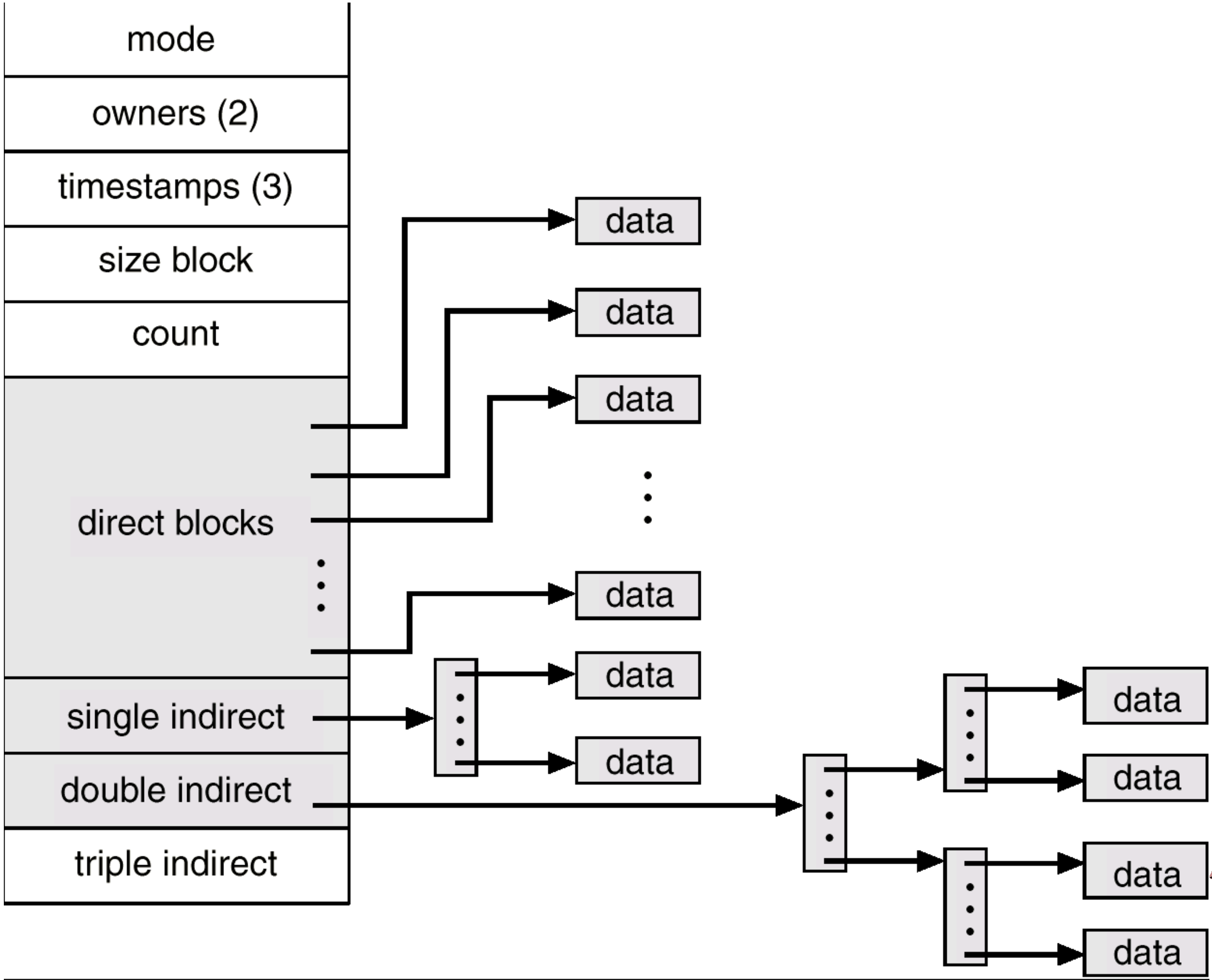


  - a combination of both

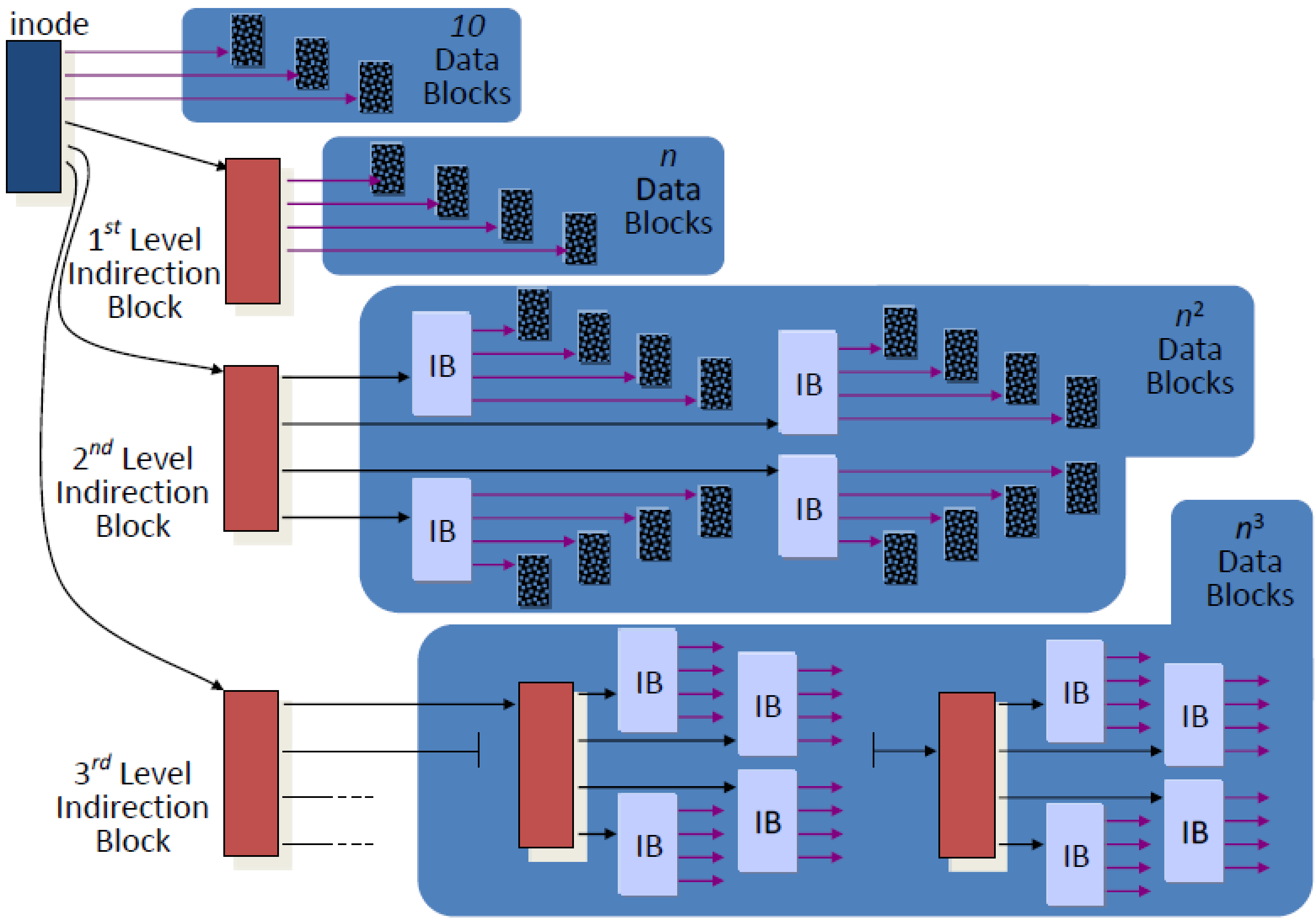
Indexed Allocation (cont.)



Combined Scheme: UNIX inode (4K Bytes per Block)



Another Illustration of Multi-level Indexed Allocation in UNIX



Performance

- Best method depends on file access type
  - Contiguous great for both sequential and random
- Linked good for sequential, but not random
- Declare access type at creation -> select either contiguous or linked
- Indexed more complex
  - Single block access could require 2 index block reads and then data block read
  - Clustering can help improve throughput, and 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 MIPS / 250 = 630 million instructions during one disk I/O
  - Fast SSD drives provide 60,000 I/Os per second
    - ✓ 159,000 MIPS / 60,000 = 2.65 millions instructions during one disk I/O

Chapter 11: File System Implementation

- File System Structure
- File System Implementation
- Free-Space Management
- Directory Implementation
- Allocation Methods
- Efficiency and Performance
- Recovery
- Log-Structured File Systems
- NFS

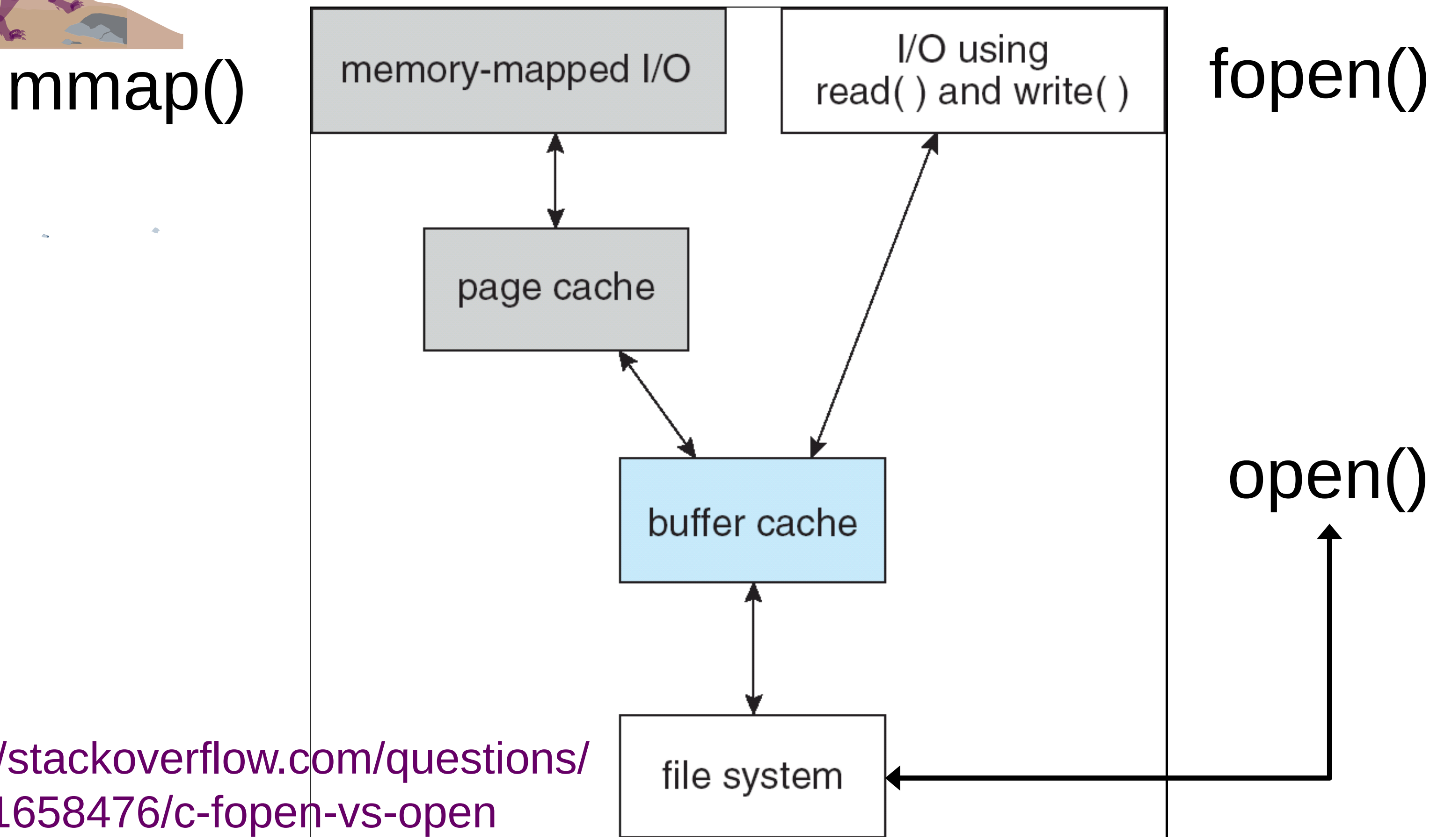
Efficiency and Performance

- 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

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
  - Buffer cache – separate section of main memory for frequently used blocks
- This leads to the following figure

I/O Without a Unified Buffer Cache



http://stackoverflow.com/questions/1658476/c-fopen-vs-open

There are three main reasons to use fopen instead of open.

- fopen provides you with buffering IO that may turn out to be a lot faster than what you're doing with open.
- fopen does line ending translation if the file is not opened in binary mode, which can be helpful if your program is ported to a non-Unix environment.
- A FILE * gives you the ability to use fscanf and other stdio functions.

Unified Buffer Cache

- A unified buffer cache uses the same page cache to cache both memory-mapped pages and ordinary file system I/O