CS162
Operating Systems and Systems Programming
Lecture 19

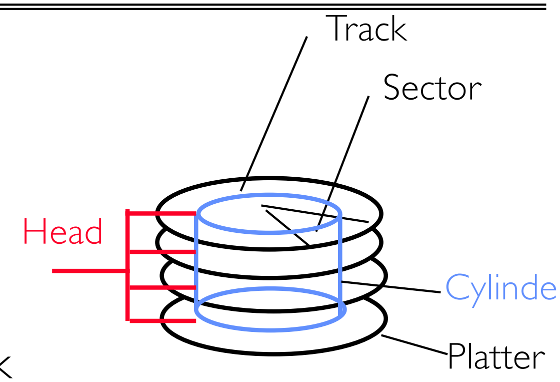
Filesystems 1: Filesystem Design, Filesystem Case Studies

April 6th, 2021

Profs. Natacha Crooks and Anthony D. Joseph

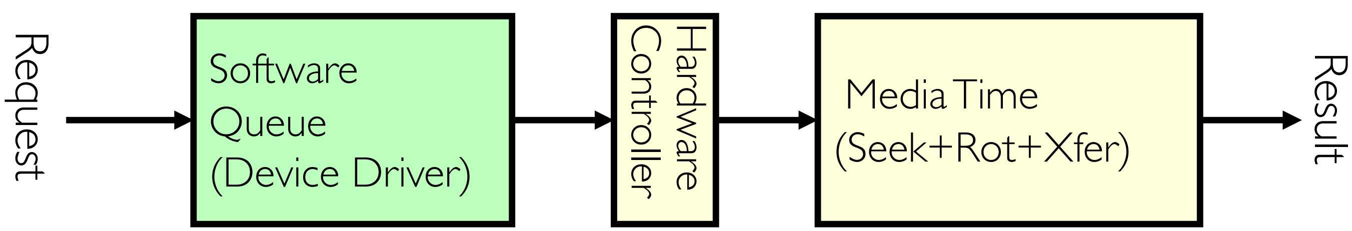
http://cs162.eecs.Berkeley.edu

Recall: Magnetic Disks



- Cylinders: all the tracks under the head at a given point on all surfaces
- Read/write data is a three-stage process:
  - Seek time: position the head/arm over the proper track
  - Rotational latency: wait for desired sector to rotate under r/w head
  - Transfer time: transfer a block of bits (sector) under r/w head

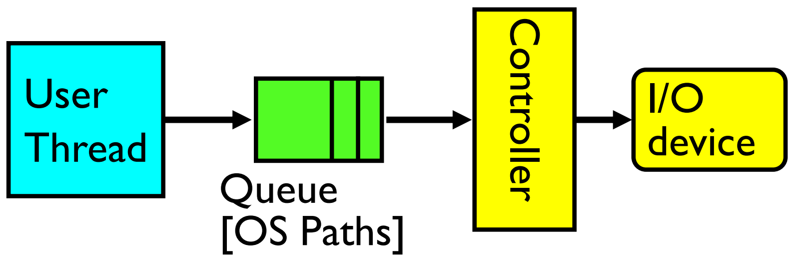
Disk Latency = Queueing Time + Controller time +
Seek Time + Rotation Time + Xfer Time



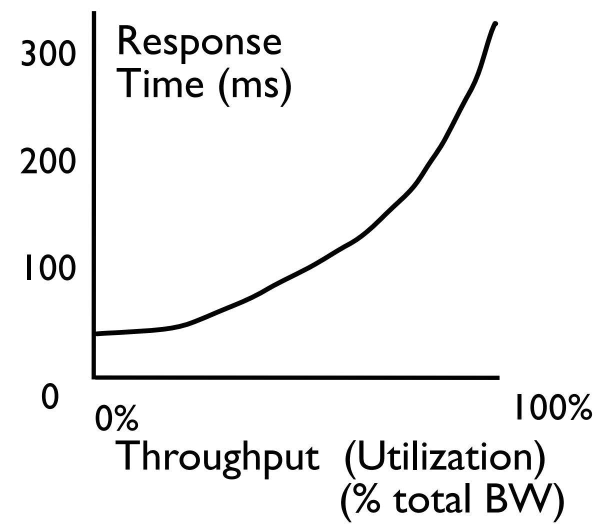
Recall: Typical Numbers for Magnetic Disk

Parameter	Info/Range
Space/Density	Space: 18TB (Seagate), 9 platters, in 3½ inch form factor! Areal Density: **≥ 1 Terabit/square inch! (PMR, Helium, …)**
Average Seek Time	Typically 4-6 milliseconds
Average Rotational Latency	Most laptop/desktop disks rotate at 3600-7200 RPM (16-8 ms/rotation). Server disks up to 15K RPM. Average latency is halfway around disk so 4-8 milliseconds
Controller Time	Depends on controller hardware
Transfer Time	Typically 50 to 250 MB/s. Depends on: • Transfer size (usually a sector): 512B – 1KB per sector • Rotation speed: 3600 RPM to 15000 RPM • Recording density: bits per inch on a track • Diameter: ranges from 1 in to 5.25 in
Cost	Used to drop by a factor of two every 1.5 years (or faster), now slowing down

Recall: Overall Performance for I/O Path

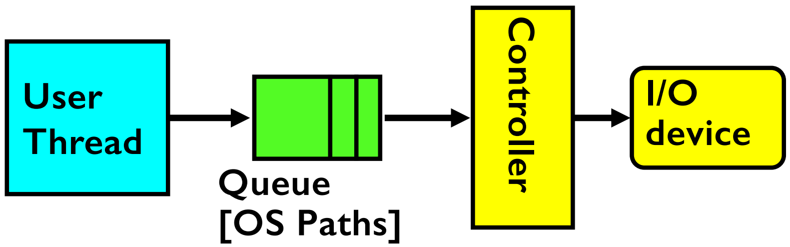


Response Time = Queue + I/O device service time

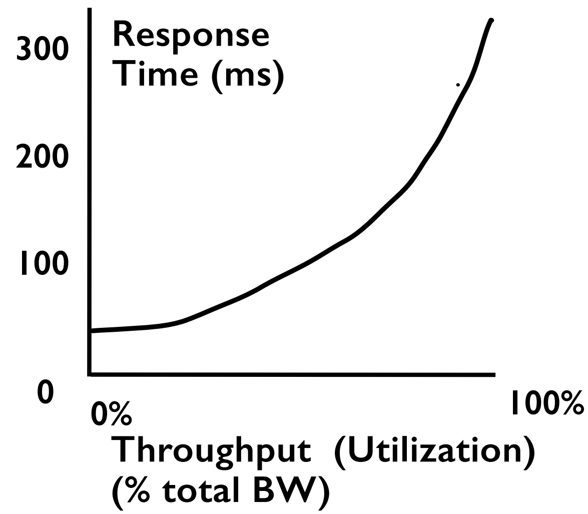


- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW = transfer size / response time
  - Contributing factors to latency:
    - » Software paths (can be loosely modeled by a queue)
    - » Hardware controller
    - » I/O device service time
- Queuing behavior:
  - Can lead to big increases of latency as utilization increases
  - Solutions?

Recall: Optimize I/O Performance



Response Time = Queue + I/O device service time



- How to improve performance?
  - Make everything faster ☺
  - More Decoupled (Parallelism) systems
    - » multiple independent buses or controllers
  - Optimize the bottleneck to increase service rate
    - » Use the queue to optimize the service
  - Do other useful work while waiting
- Queues absorb bursts and smooth the flow
- Admissions control (finite queues)
  - Limits delays, but may introduce unfairness and livelock

When is Disk Performance Highest?

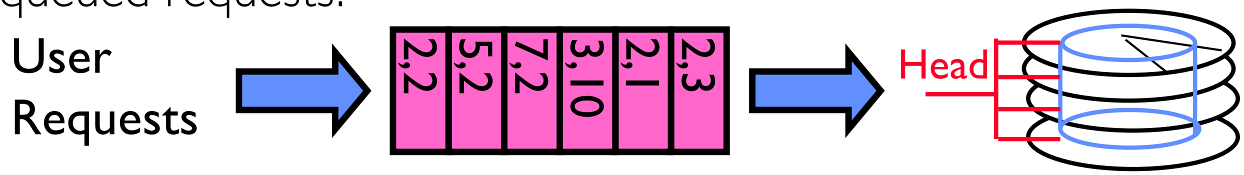
- When there are big sequential reads, or
- When there is so much work to do that they can be piggy backed (reordering queues—one moment)

- OK to be inefficient when things are mostly idle
- Bursts are both a threat and an opportunity
- <your idea for optimization goes here>
  – Waste space for speed?

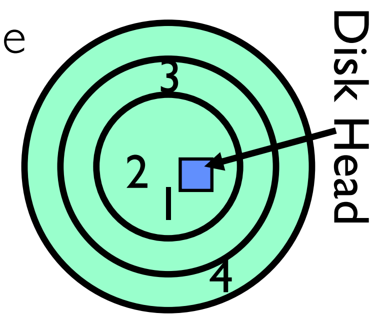
- Other techniques:
  – Reduce overhead through user level drivers
  – Reduce the impact of I/O delays by doing other useful work in the meantime

Disk Scheduling (1/3)

- Disk can do only one request at a time; What order do you choose to do queued requests?

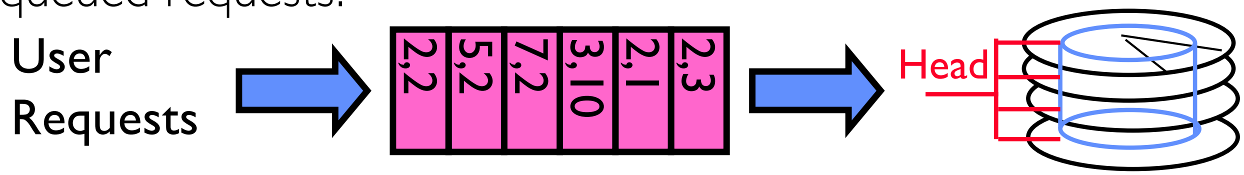


- FIFO Order
  – Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks
- SSTF: Shortest seek time first
  – Pick the request that's closest on the disk
  – Although called SSTF, today must include rotational delay in calculation, since rotation can be as long as seek
  – Con: SSTF good at reducing seeks, but may lead to starvation

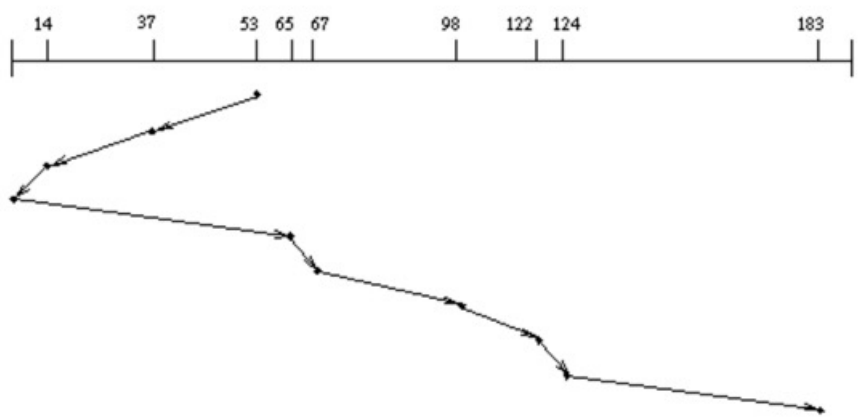


Disk Scheduling (2/3)

- Disk can do only one request at a time; What order do you choose to do queued requests?

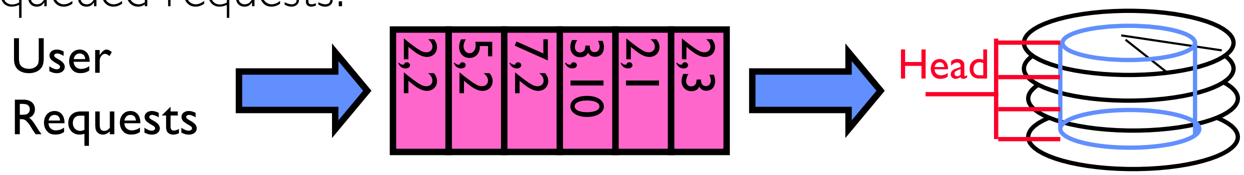


- SCAN: Implements an Elevator Algorithm: take the closest request in the direction of travel
  - No starvation, but retains flavor of SSTF

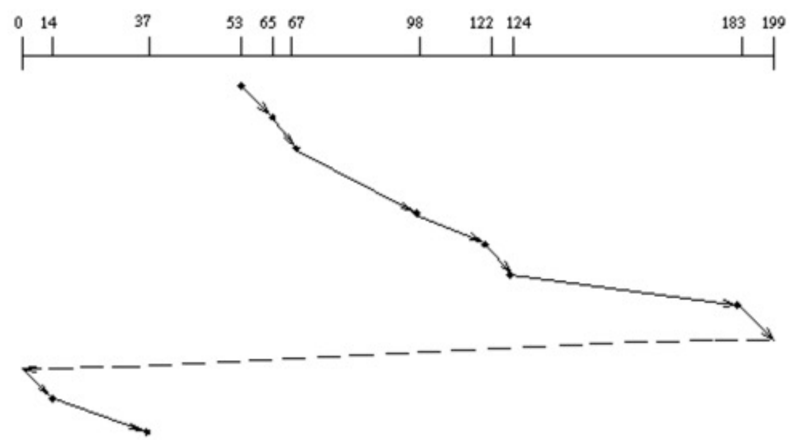


Disk Scheduling (3/3)

- Disk can do only one request at a time; What order do you choose to do queued requests?



- C-SCAN: Circular-Scan: only goes in one direction
  – Skips any requests on the way back
  – Fairer than SCAN, not biased towards pages in middle

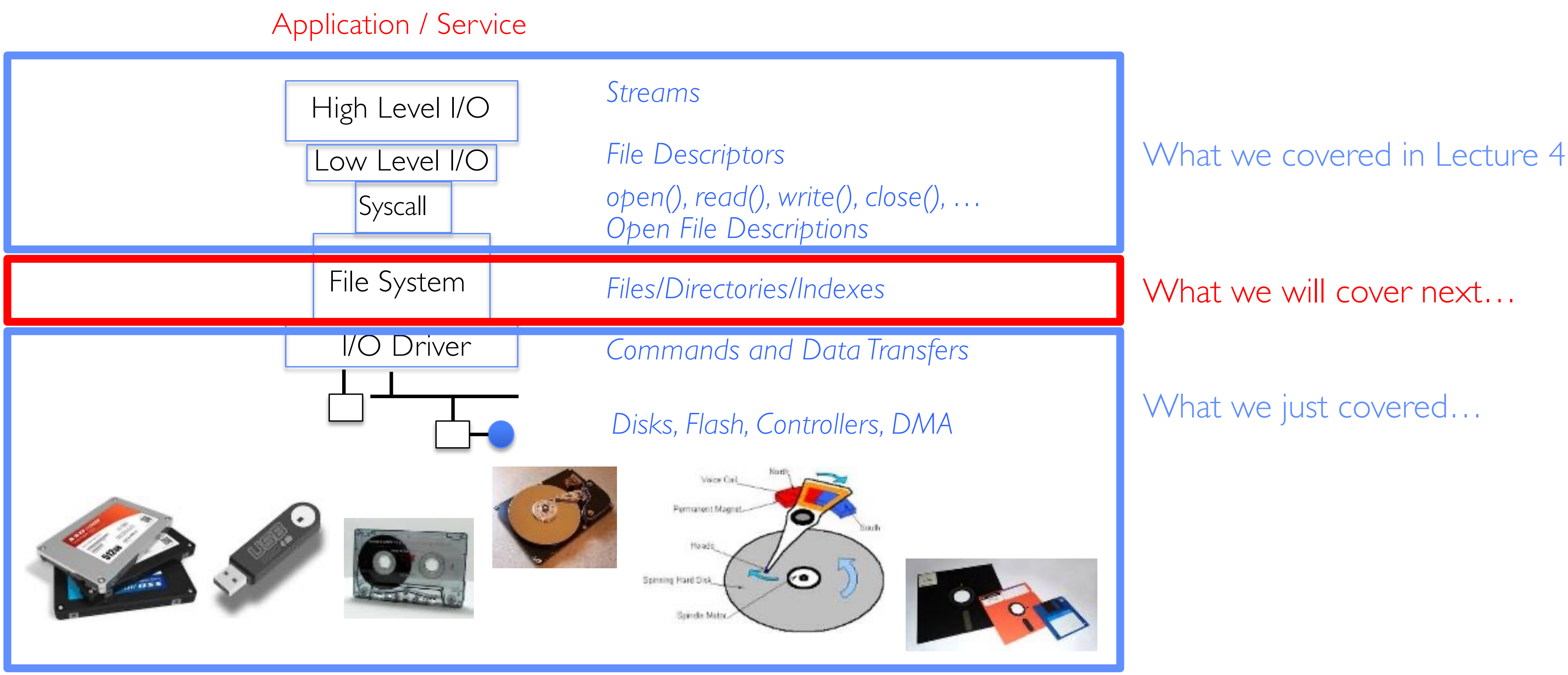


[redacted]

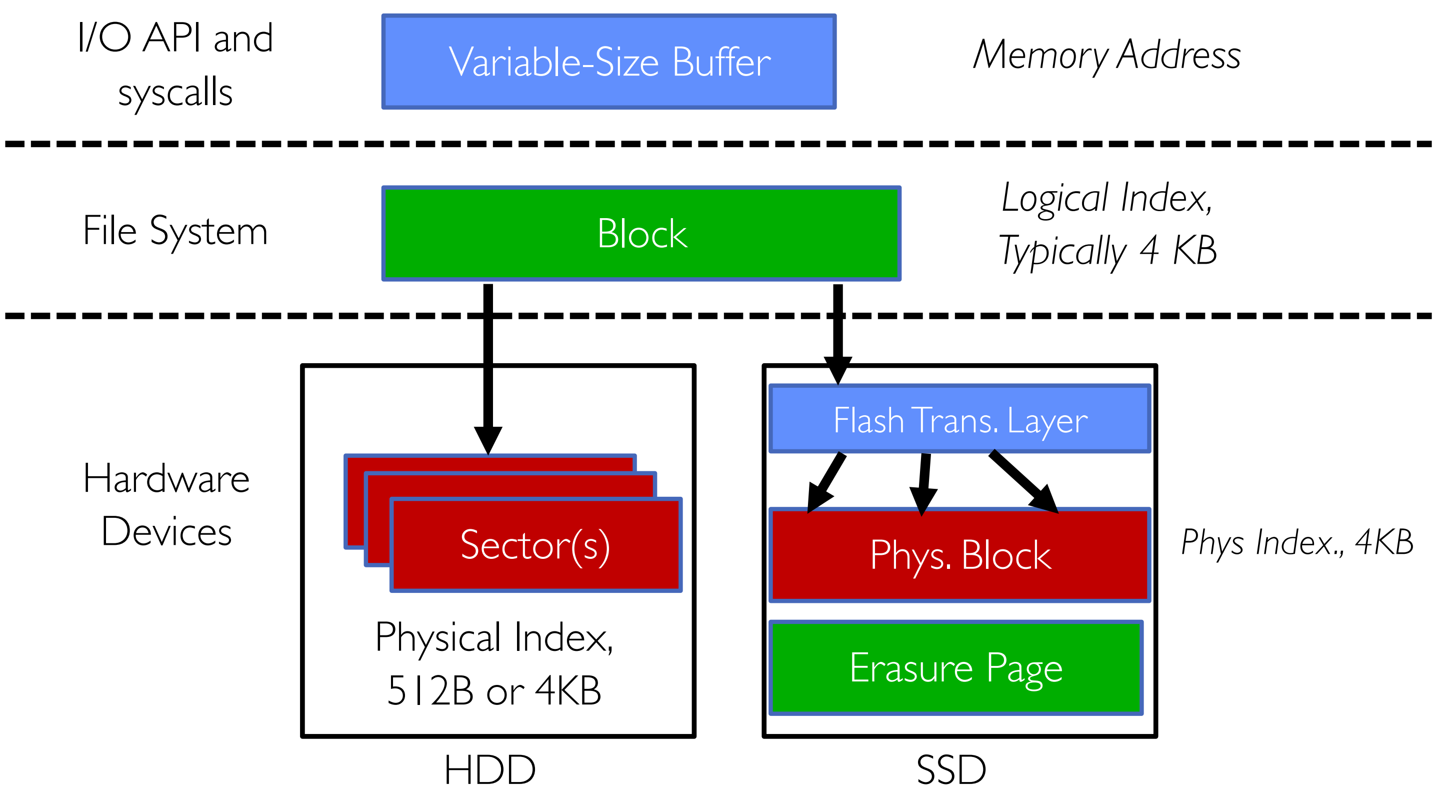
Recall: How Do We Hide I/O Latency?

- Blocking Interface: "Wait"
  – When request data (e.g., read() system call), put process to sleep until data is ready
  – When write data (e.g., write() system call), put process to sleep until device is ready for data
- Non-blocking Interface: "Don't Wait"
  – Returns quickly from read or write request with count of bytes successfully transferred to kernel
  – Read may return nothing, write may write nothing
- Asynchronous Interface: "Tell Me Later"
  – When requesting data, take pointer to user's buffer, return immediately; later kernel fills buffer and notifies user
  – When sending data, take pointer to user's buffer, return immediately; later kernel takes data and notifies user

Recall: I/O and Storage Layers



From Storage to File Systems



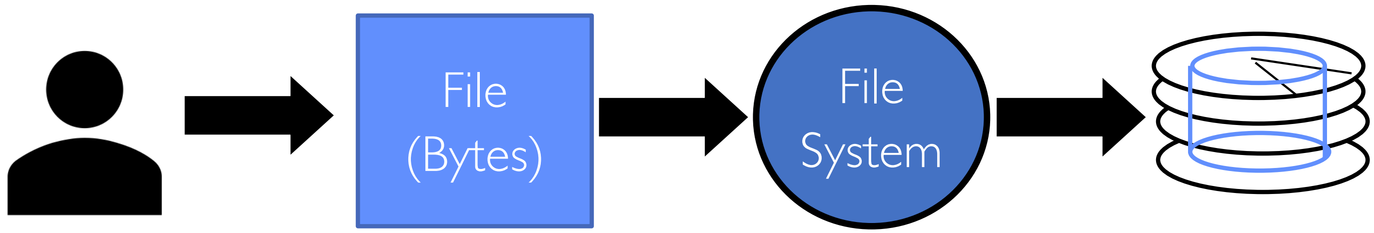
Building a File System

- **File System**: Layer of OS that transforms block interface of disks (or other block devices) into Files, Directories, etc.
- Classic OS situation: Take limited hardware interface (array of blocks) and provide a more convenient/useful interface with:
  – Naming: Find file by name, not block numbers
  – Organize file names with directories
  – Organization: Map files to blocks
  – Protection: Enforce access restrictions
  – Reliability: Keep files intact despite crashes, hardware failures, etc.

Recall: User vs. System View of a File

- User's view:
  – Durable Data Structures
- System's view (system call interface):
  – Collection of Bytes (UNIX)
  – Doesn't matter to system what kind of data structures you want to store on disk!
- System's view (inside OS):
  – Collection of blocks (a block is a logical transfer unit, while a sector is the physical transfer unit)
  – Block size ≥ sector size; in UNIX, block size is 4KB

Translation from User to System View



- What happens if user says: "give me bytes 2 – 12?"
  - Fetch block corresponding to those bytes
  - Return just the correct portion of the block
- What about writing bytes 2 – 12?
  - Fetch block, modify relevant portion, write out block
- Everything inside file system is in terms of whole-size blocks
  - Actual disk I/O happens in blocks
  - read/write smaller than block size needs to translate and buffer

Disk Management

- Basic entities on a disk:
  - File: user-visible group of blocks arranged sequentially in logical space
  - Directory: user-visible index mapping names to files

- The disk is accessed as linear array of sectors
- How to identify a sector?
  - Physical position
    - » Sectors is a vector [cylinder, surface, sector]
    - » Not used anymore
    - » OS/BIOS must deal with bad sectors
  - Logical Block Addressing (LBA)
    - » Every sector has integer address
    - » Controller translates from address ⇒ physical position
    - » Shields OS from structure of disk

What Does the File System Need?

- Track free disk blocks
  - Need to know where to put newly written data
- Track which blocks contain data for which files
  - Need to know where to read a file from
- Track files in a directory
  - Find list of file's blocks given its name
- Where do we maintain all of this?
  - Somewhere on disk

Data Structures on Disk

- Bit different than data structures in memory
- Access a block at a time
  - Can't efficiently read/write a single word
  - Have to read/write full block containing it
  - Ideally want sequential access patterns
- Durability
  - Ideally, file system is in meaningful state upon shutdown
  - This obviously isn't always the case…

[redacted]

Administrivia

- Make sure to fill out post midterm survey
  - Let us know how we are doing or what we could improve
- If you have any group issues going on, make sure you:
  - Make sure that your TA understands what is happing
  - Make sure that you reflect these issues on your group evaluations
- Take care of your mental health:
  - For course-related issues, reach out to us via Piazza private message
  - Talk with your Student Advisor about your options
  - For urgent concerns:
    - » https://uhs.berkeley.edu/counseling/urgent
    - » Business hours support (510) 642-9494
    - » After-hours support (855) 817-5667

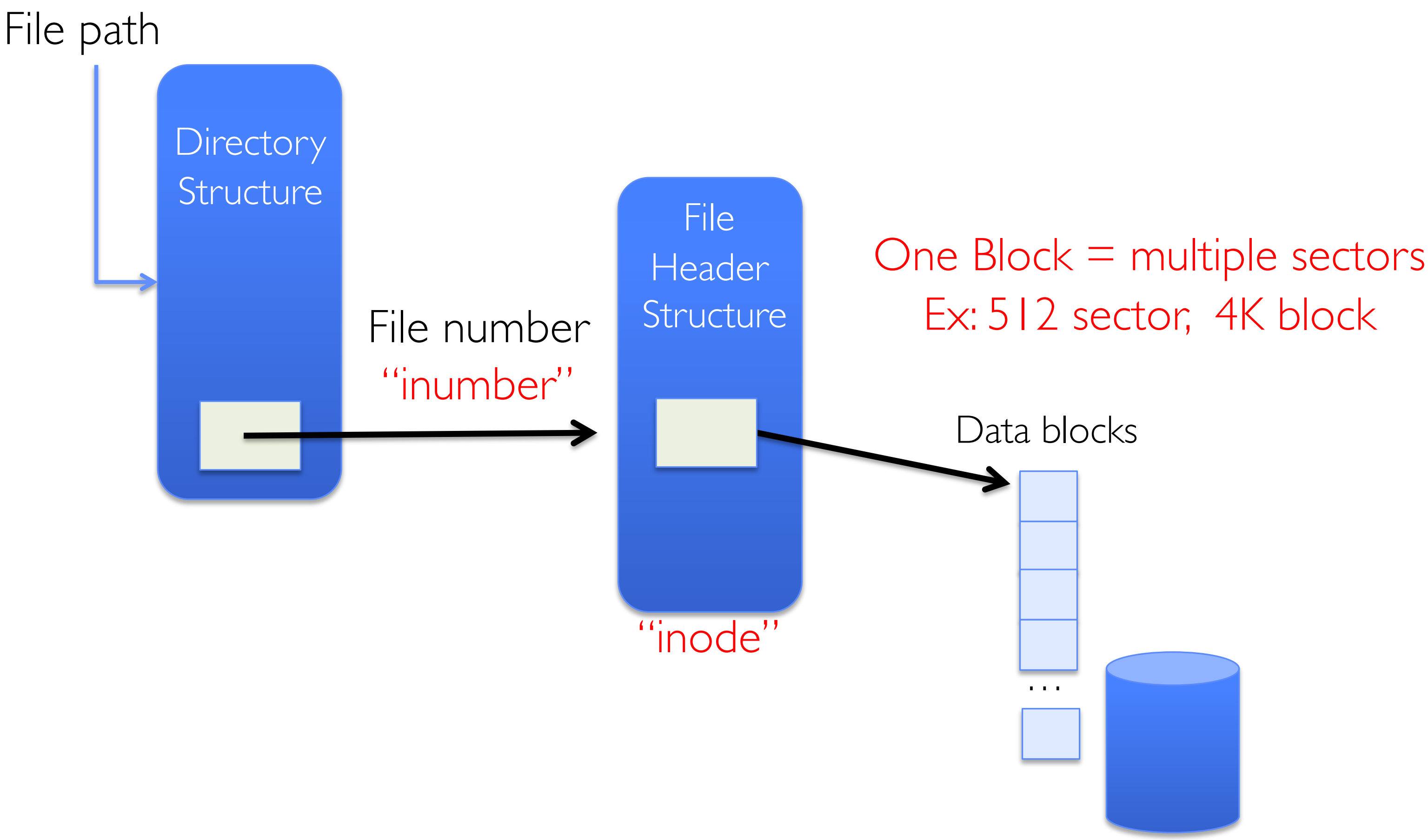
[redacted]

FILE SYSTEM DESIGN

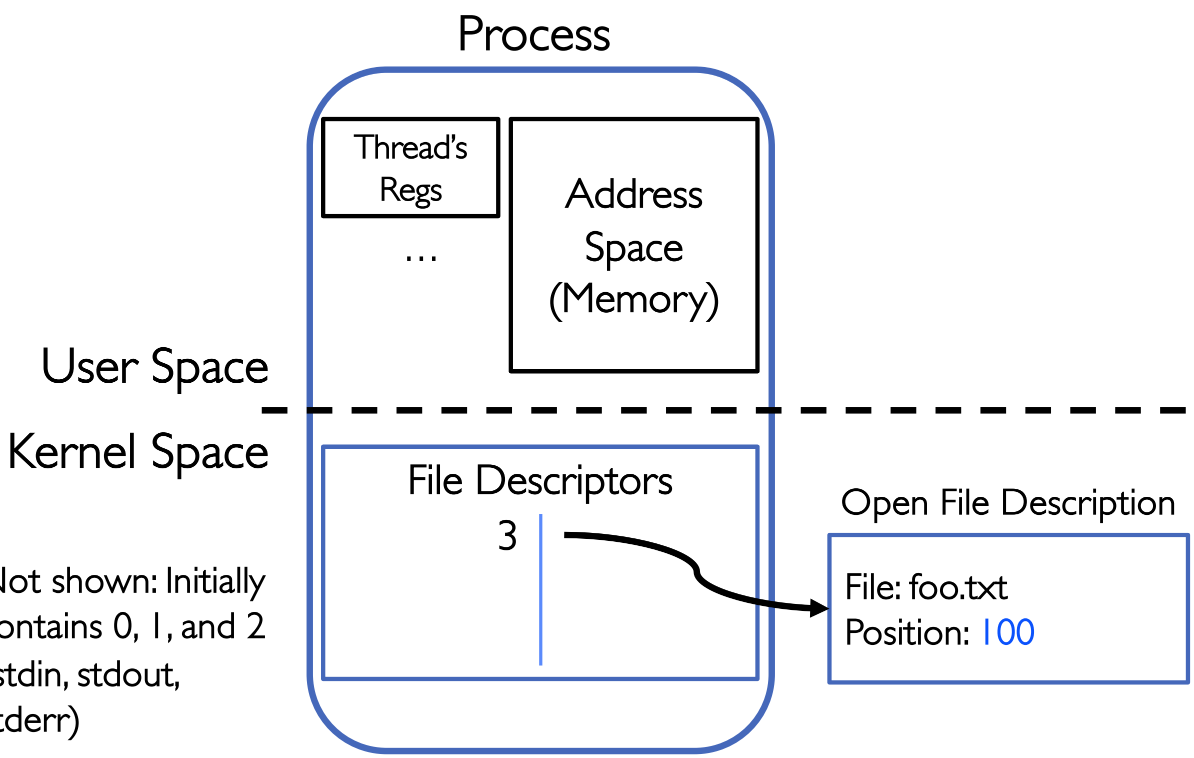
Critical Factors in File System Design

- (Hard) Disks Performance !!!
  – Maximize sequential access, minimize seeks
- Open before Read/Write
  – Can perform protection checks and look up where the actual file resource are, in advance
- Size is determined as they are used !!!
  – Can write (or read zeros) to expand the file
  – Start small and grow, need to make room
- Organized into directories
  – What data structure (on disk) for that?
- Need to carefully allocate / free blocks
  – Such that access remains efficient

Components of a File System



Recall: Abstract Representation of a Process

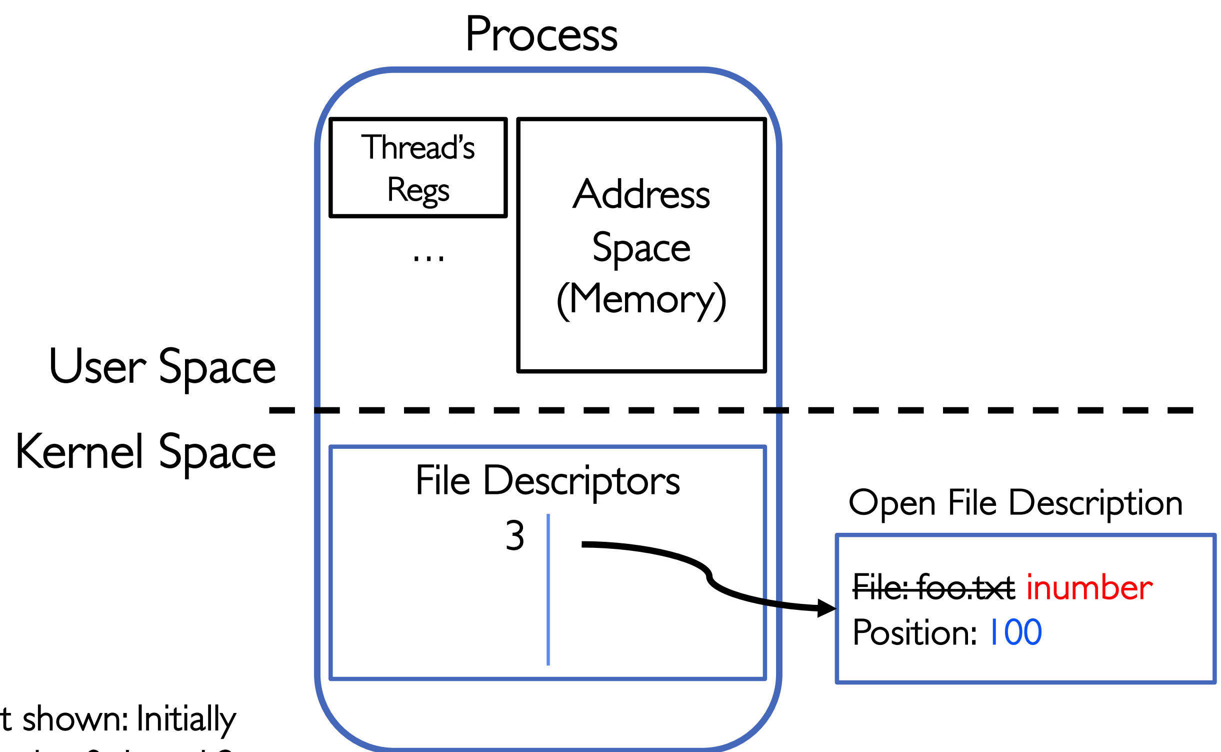


Not shown: Initially contains 0, 1, and 2 (stdin, stdout, stderr)

Suppose that we execute open("foo.txt") and that the result is 3

Next, suppose that we execute read(3, buf, 100) and that the result is 100

Components of a File System



Open file description is better described as remembering the inumber (file number) of the file, not its name

Not shown: Initially contains 0, 1, and 2 (stdin, stdout, stderr)

Components of a File System

file name offset → directory structure → *file number offset* → index structure ("inode") → *storage block*

- Open performs *Name Resolution*
  - Translates path name into a "file number"
- Read and Write operate on the file number
  - Use file number as an "index" to locate the blocks

- 4 components:
  - directory, index structure, storage blocks, free space map

How to Get the File Number?

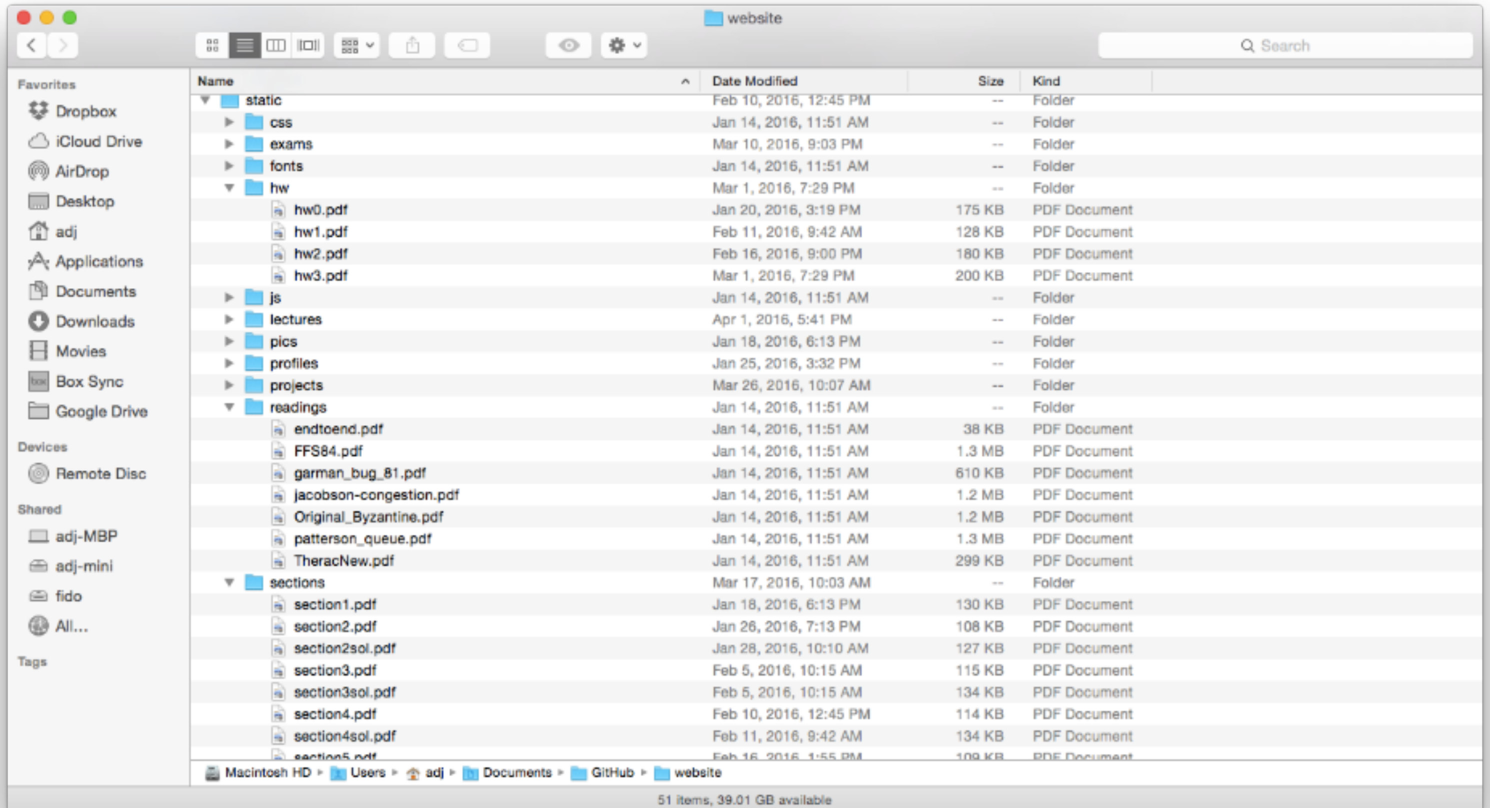
- Look up in ***directory structure***

- A directory is a file containing <file_name : file_number> mappings
  - File number could be a file or another directory
  - Operating system stores the mapping in the directory in a format it interprets
  - Each <file_name : file_number> mapping is called a directory entry

- Process isn't allowed to read the raw bytes of a directory
  - The **`read`** function doesn't work on a directory
  - Instead, see **`readdir`**, which iterates over the map without revealing the raw bytes

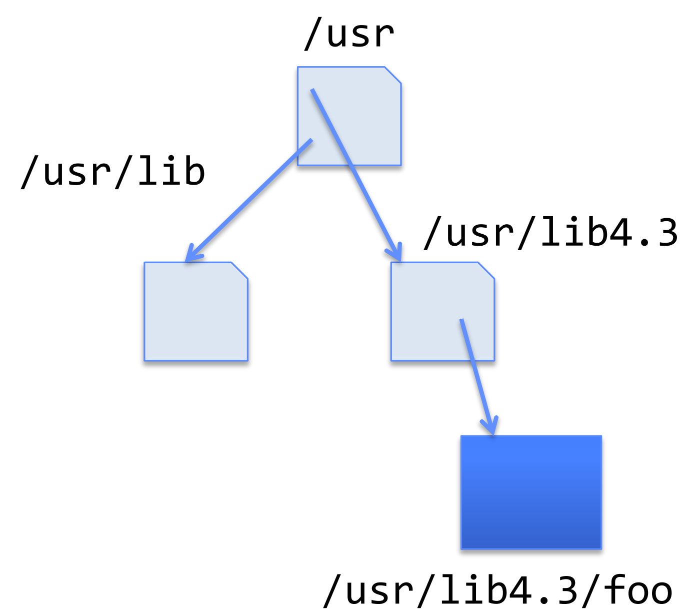
- Why shouldn't the OS let processes read/write the bytes of a directory?

Directories



Directory Abstraction

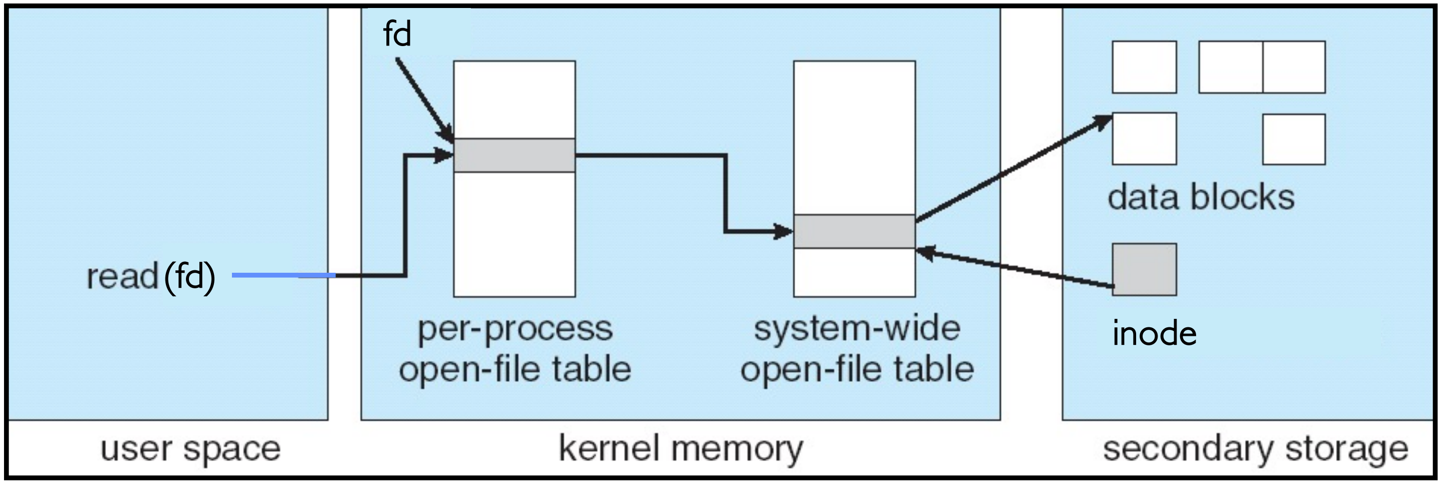
- Directories are specialized files
  - Contents: List of pairs
    <file name, file number>
- System calls to access directories
  - `open` / `creat` / `readdir` traverse the structure
  - `mkdir` / `rmdir` add/remove entries
  - `link` / `unlink` (`rm`)
- libc support
  - `DIR * opendir (const char *dirname)`
  - `struct dirent * readdir (DIR *dirstream)`
  - ```
    int readdir_r (DIR *dirstream,
                   struct dirent *entry,
                   struct dirent **result)
    ```


    ```

Directory Structure

- How many disk accesses to resolve "/my/book/count"?
  - Read in file header for root (fixed spot on disk)
  - Read in first data block for root
    - » Table of file name/index pairs.
    - » Search linearly – ok since directories typically very small
  - Read in file header for "my"
  - Read in first data block for "my"; search for "book"
  - Read in file header for "book"
  - Read in first data block for "book"; search for "count"
  - Read in file header for "count"
- Current working directory: Per-address-space pointer to a directory used for resolving file names
  - Allows user to specify relative filename instead of absolute path (say CWD="/my/book" can resolve "count")

In-Memory File System Structures



- Open syscall: find inode on disk from pathname (traversing directories)
  – Create "in-memory inode" in system-wide open file table
  – One entry in this table no matter how many instances of the file are open
- Read/write syscalls look up in-memory inode using the file handle

Characteristics of Files

A Five-Year Study of File-System Metadata

NITIN AGRAWAL
University of Wisconsin, Madison
and
WILLIAM J. BOLOSKY, JOHN R. DOUCEUR, and JACOB R. LORCH
Microsoft Research

Published in FAST 2007

Observation #1: Most Files Are Small

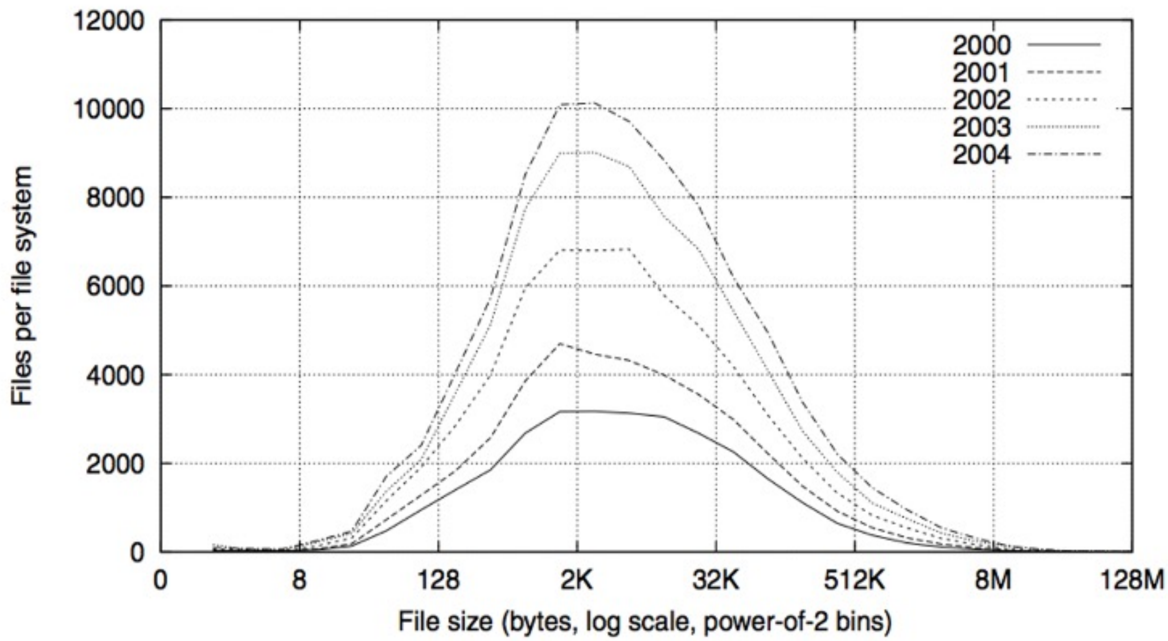


Fig. 2. Histograms of files by size.

Observation #2: Most Bytes are in Large Files

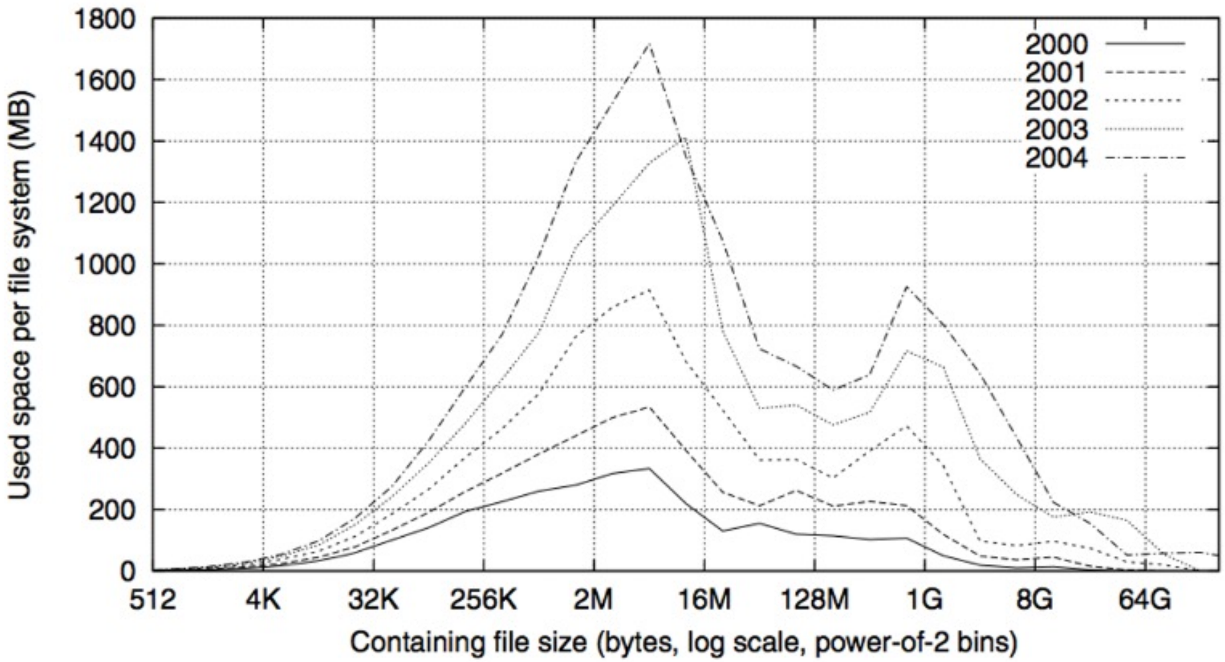


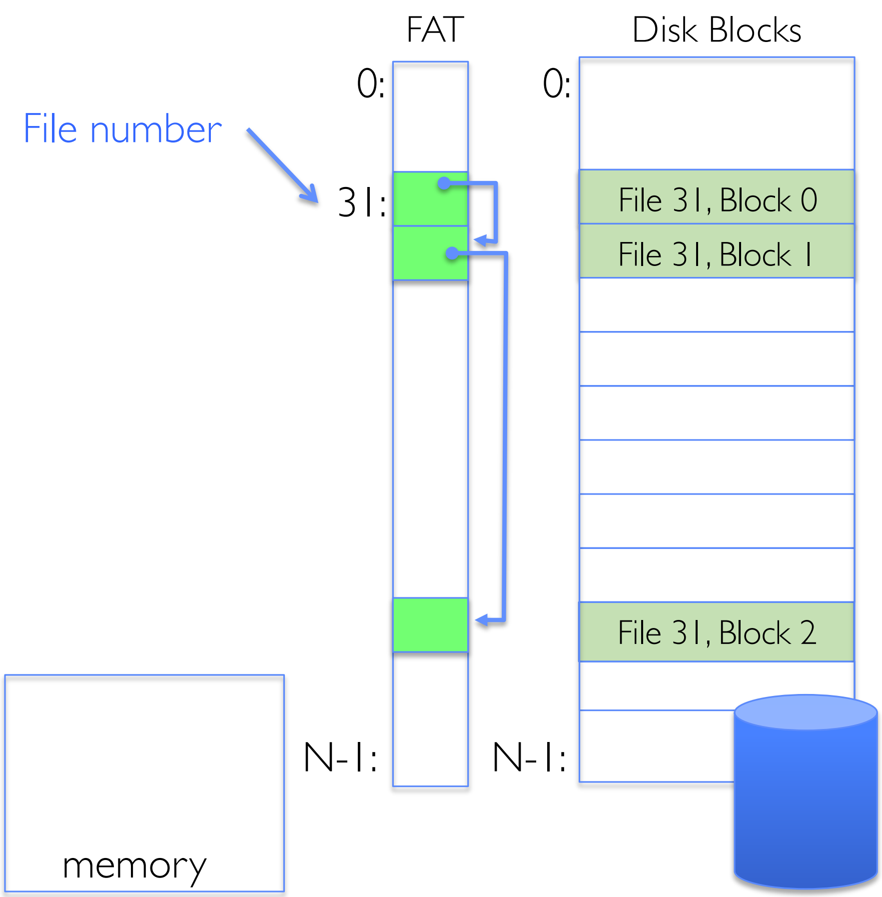
Fig. 4. Histograms of bytes by containing file size.

[redacted]

CASE STUDY:
FAT: FILE ALLOCATION TABLE

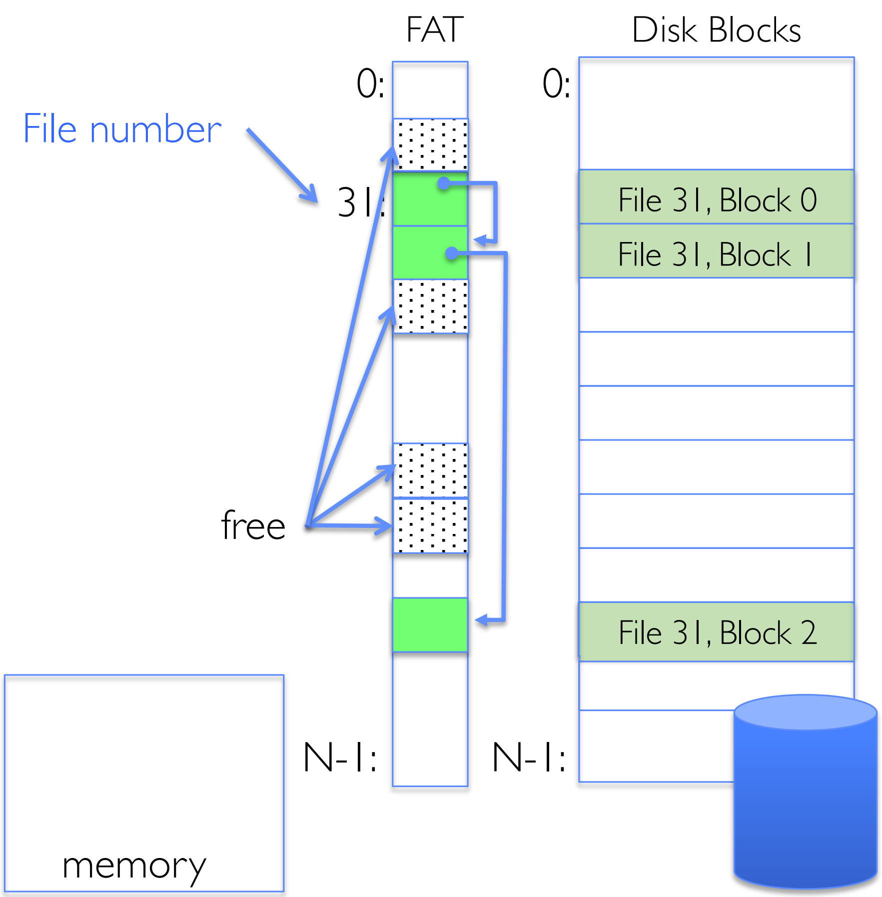
- MS-DOS, 1977
- Still widely used!

FAT (File Allocation Table)



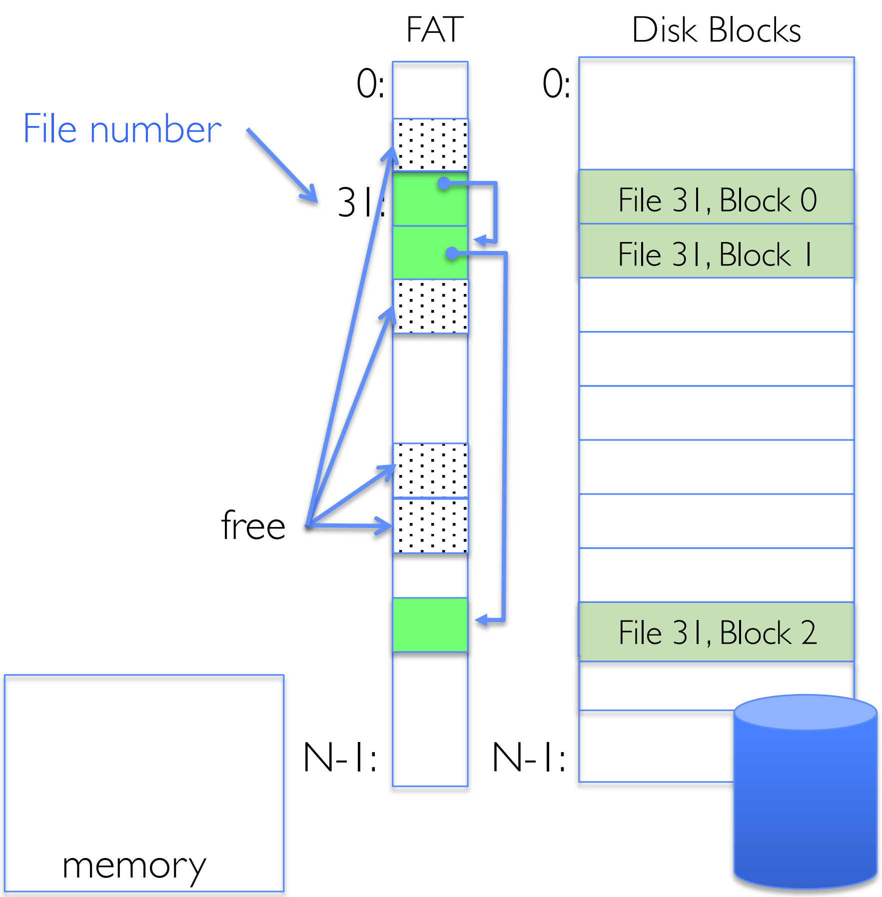
- Assume (for now) we have a way to translate a path to a "file number"
  - i.e., a directory structure
- Disk Storage is a collection of Blocks
  - Just hold file data (offset o = < B, x >)
- Example: file_read 31, < 2, x >
  - Index into FAT with file number
  - Follow linked list to block
  - Read the block from disk into memory

FAT (File Allocation Table)



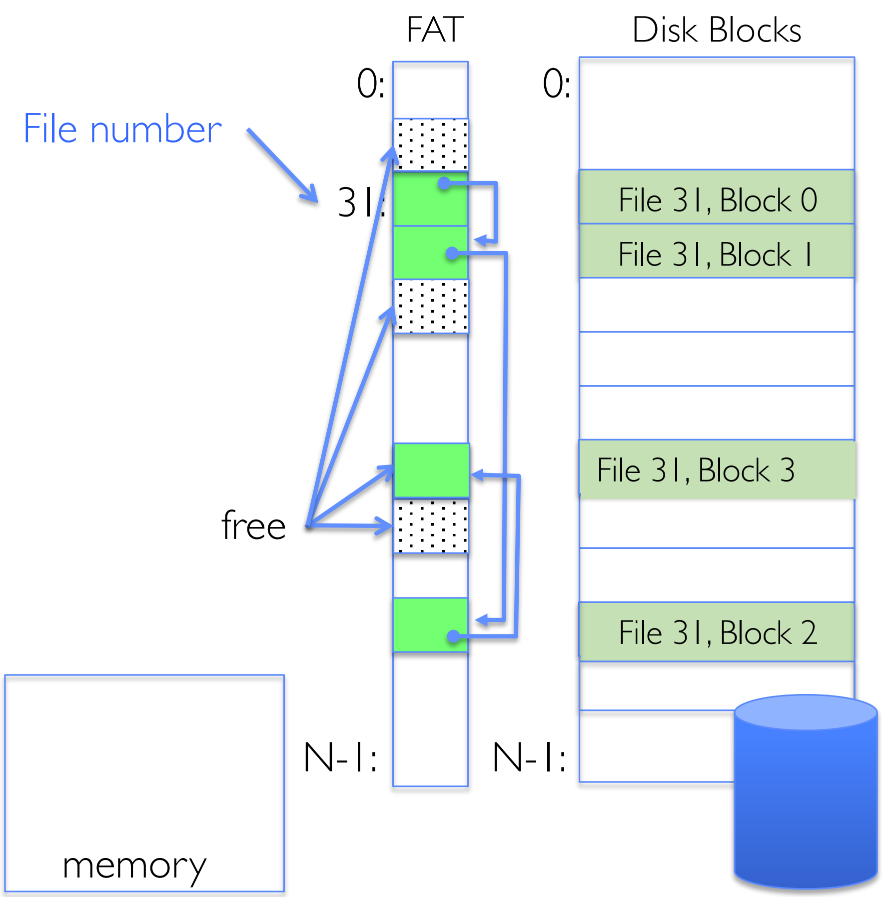
- File is a collection of disk blocks
- FAT is linked list 1-1 with blocks
- File number is index of root of block list for the file
- File offset: block number and offset within block
- Follow list to get block number
- Unused blocks marked free
  - Could require scan to find
  - Or, could use a free list

FAT (File Allocation Table)



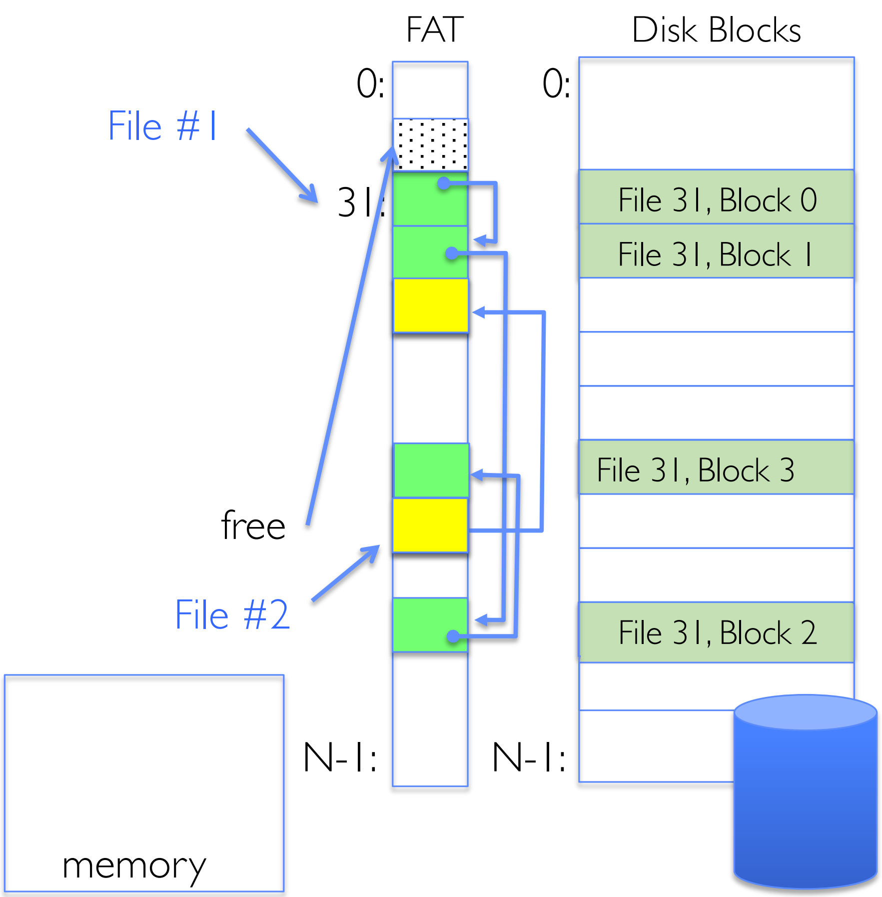
- File is a collection of disk blocks
- FAT is linked list 1-1 with blocks
- File number is index of root of block list for the file
- File offset: block number and offset within block
- Follow list to get block number
- Unused blocks marked free
  - Could require scan to find
  - Or, could use a free list

FAT (File Allocation Table)



- File is a collection of disk blocks
- FAT is linked list 1-1 with blocks
- File number is index of root of block list for the file
- File offset: block number and offset within block
- Follow list to get block number
- Unused blocks marked free
  - Could require scan to find
  - Or, could use a free list
- Ex: file_write(31, < 3, y >)
  - Grab free block
  - Linking them into file

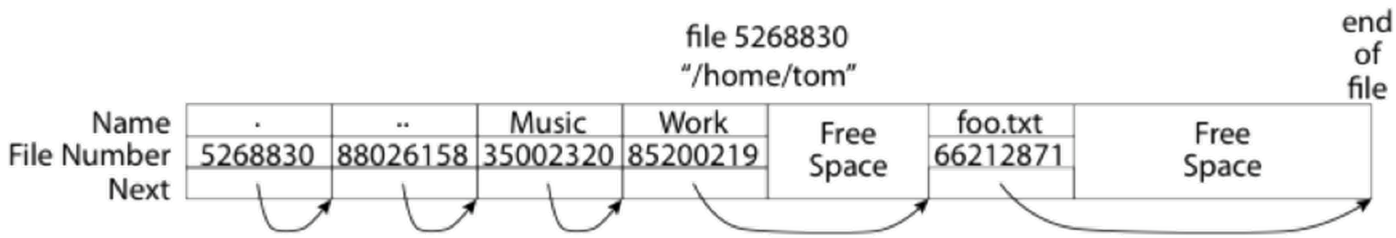
FAT (File Allocation Table)



- Where is FAT stored?
  - On disk
  - Usually 2 copies (to handle errors)
- How to format a disk?
  - Zero the blocks, mark FAT entries "free"
- How to quick format a disk?
  - Mark FAT entries "free"

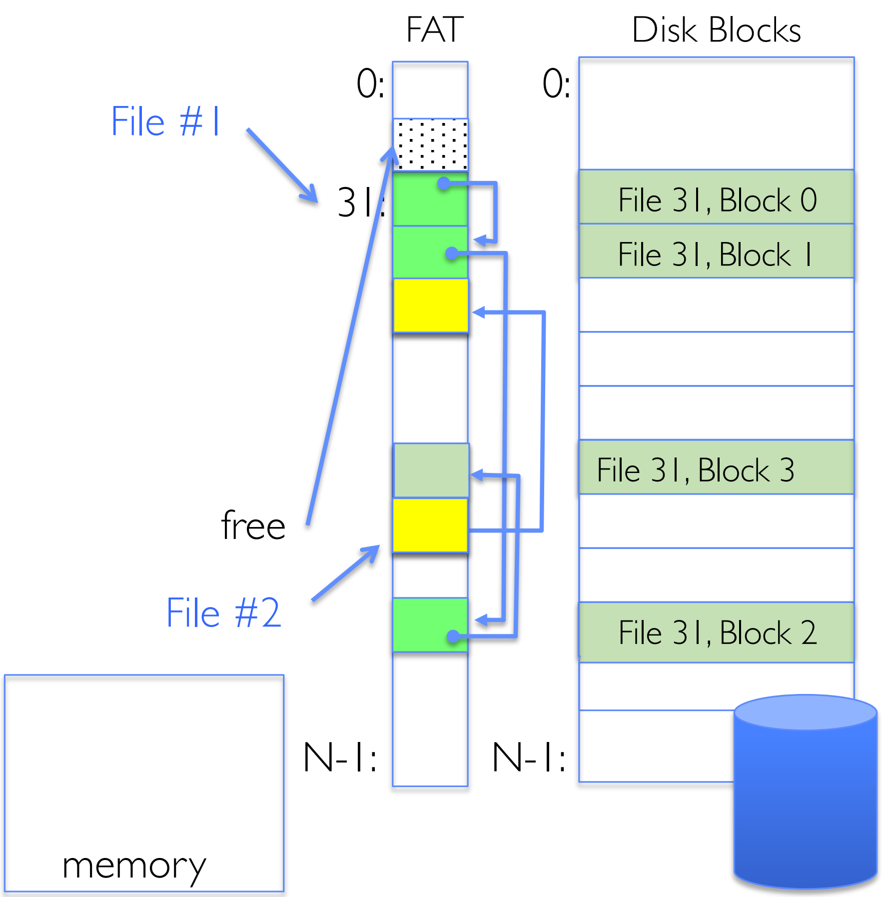
- Simple: can implement in device firmware

FAT: Directories



- A directory is a file containing <file_name: file_number> mappings
- Free space for new/deleted entries
- In FAT: file attributes are kept in directory (!!!)
  – Not directly associated with the file itself
- Each directory a linked list of entries
  – Requires linear search of directory to find particular entry
- Where do you find root directory ("/")?
  – At well-defined place on disk
  – For FAT, this is at block 2 (there are no blocks 0 or 1)
  – Remaining directories

FAT Discussion



Suppose you start with the file number:

- Time to find block?
- Block layout for file?
- Sequential access?
- Random access?
- Fragmentation?
- Small files?
- Big files?

[redacted]

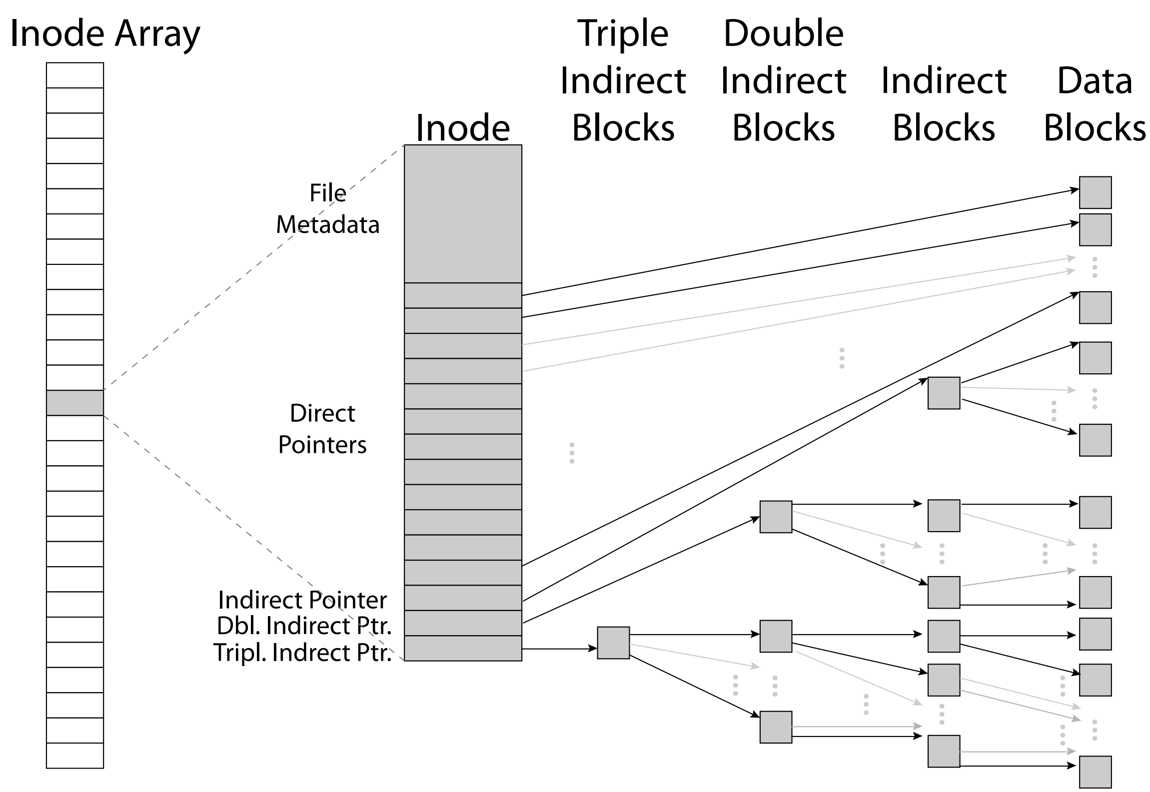
CASE STUDY:
UNIX FILE SYSTEM (BERKELEY FFS)

Inodes in Unix (Including Berkeley FFS)

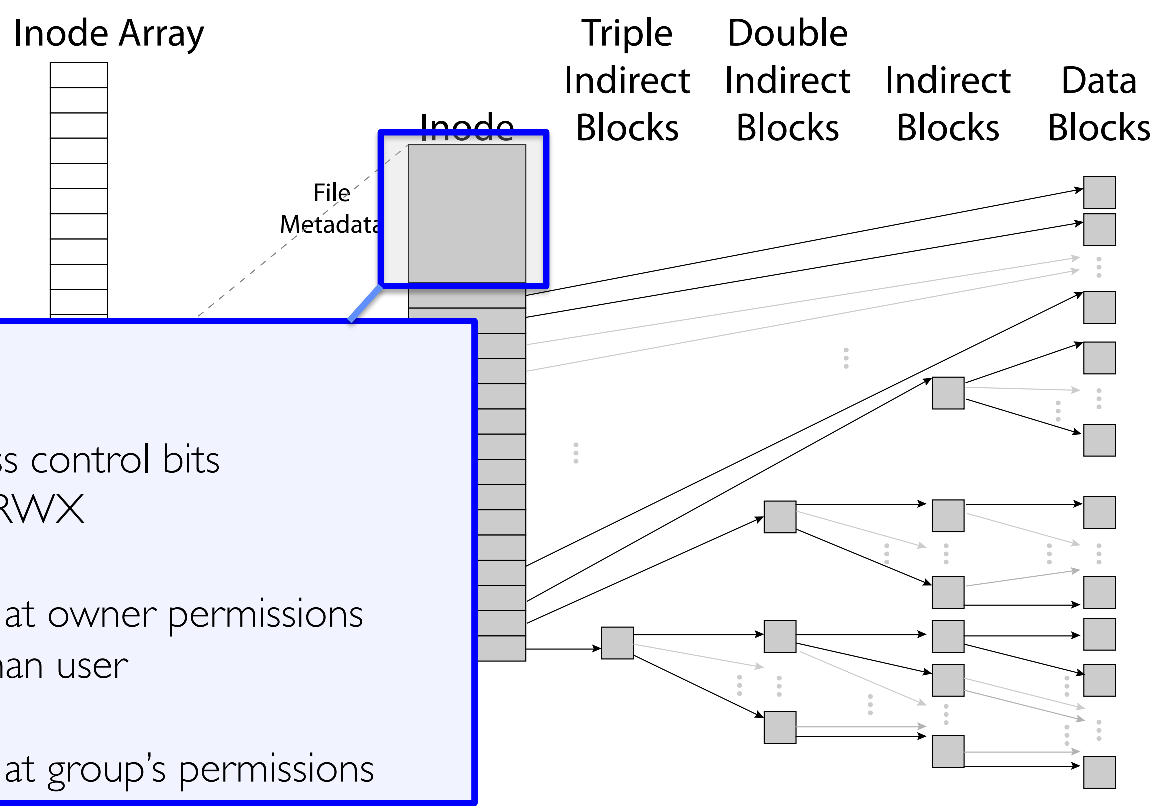
- File Number is index into set of inode arrays
- Index structure is an array of *inodes*
  - File Number (inumber) is an index into the array of inodes
  - Each inode corresponds to a file and contains its metadata
    - » So, things like read/write permissions are stored with *file,* not in directory
    - » Allows multiple names (directory entries) for a file
- Inode maintains a multi-level tree structure to find storage blocks for files
  - Great for little and large files
  - Asymmetric tree with fixed sized blocks

- Original ***inode*** format appeared in BSD 4.1 (more following)
  - Berkeley Standard Distribution Unix!
  - Part of your heritage!
  - Similar structure for Linux Ext 2/3

Inode Structure



File Attributes

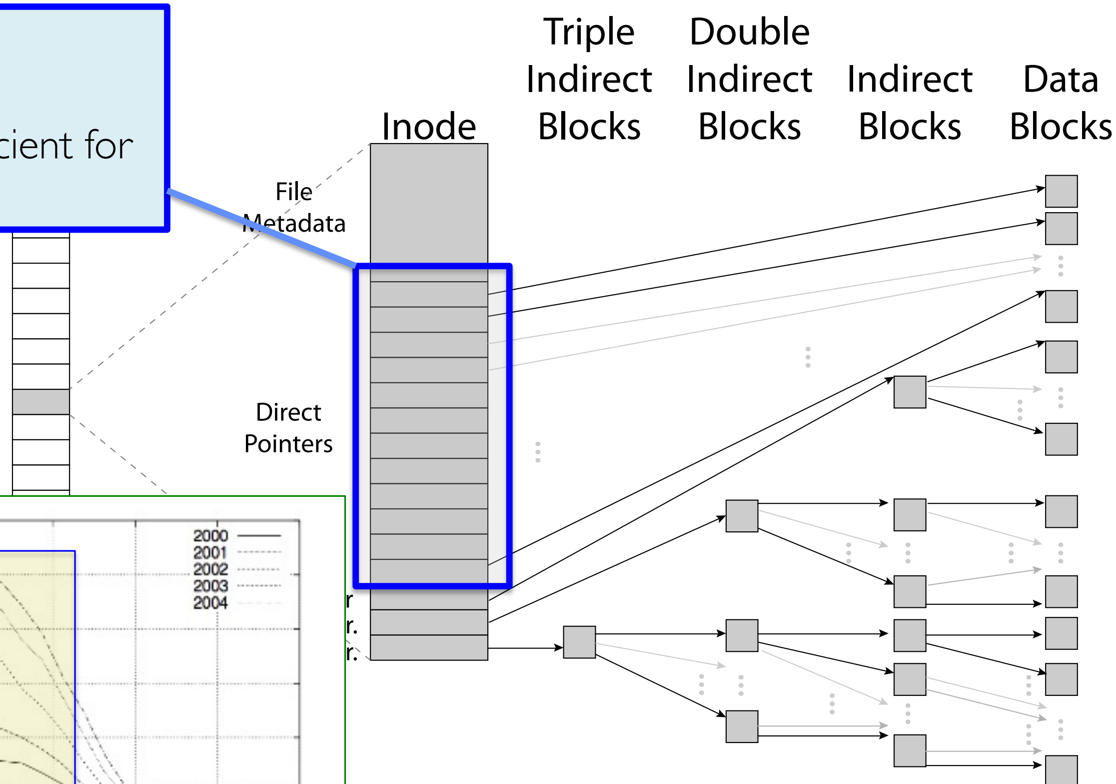


User
Group
9 basic access control bits
- UGO x RWX
SetUID bit
- execute at owner permissions rather than user
SetGID bit
- execute at group's permissions

Small Files: 12 Pointers Direct to Data Blocks

Direct pointers

4kB blocks ⇒ sufficient for files up to 48KB



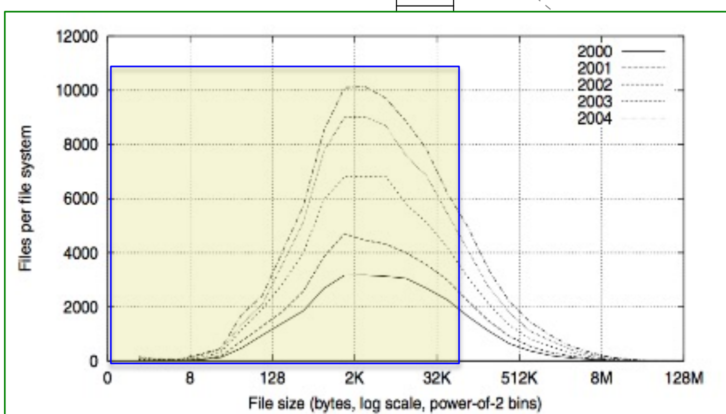
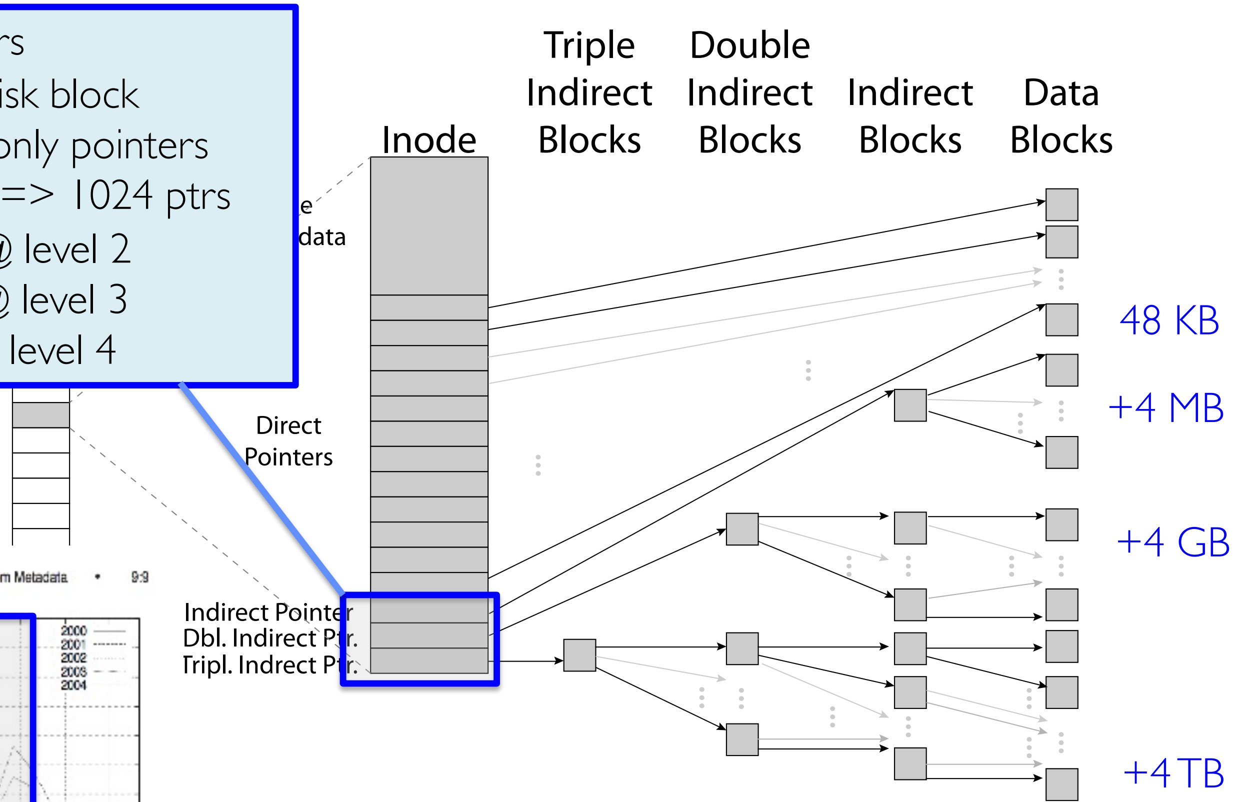


Fig. 2. Histograms of files by size.

Large Files: 1-, 2-, 3-level indirect pointers

Indirect pointers
- point to a disk block containing only pointers
- 4 kB blocks => 1024 ptrs
  - => 4 MB @ level 2
  - => 4 GB @ level 3
  - => 4 TB @ level 4



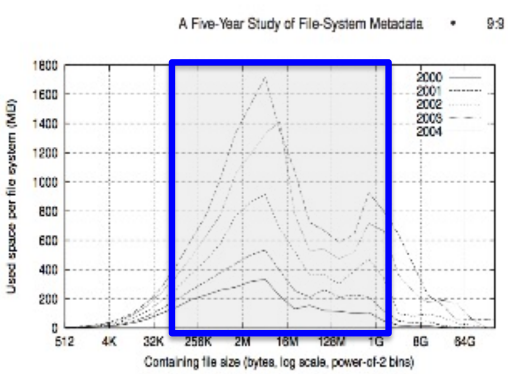
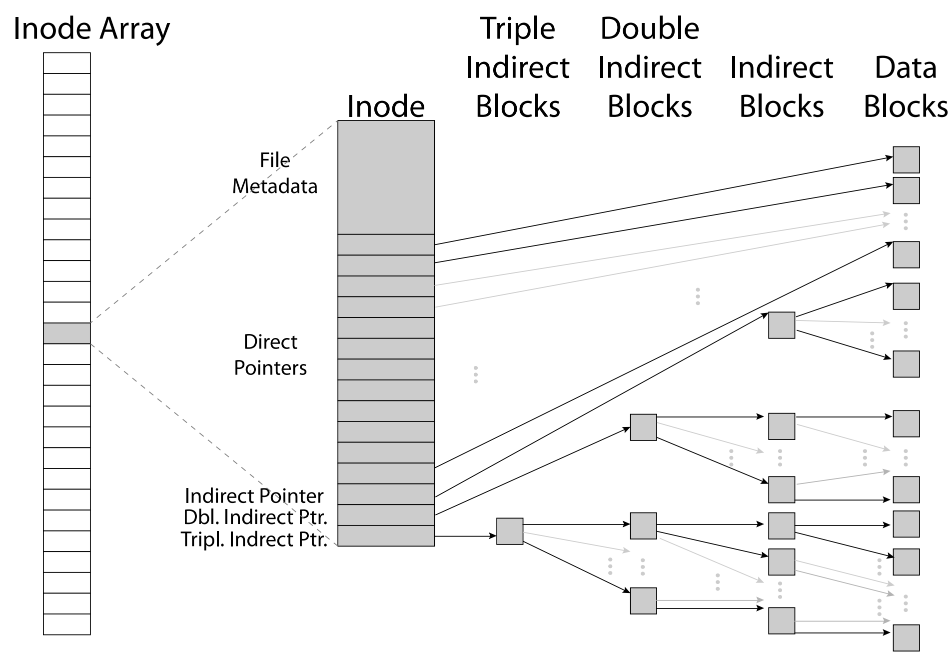


Fig. 4. Histograms of bytes by containing file size.

Putting it All Together: On-Disk Index

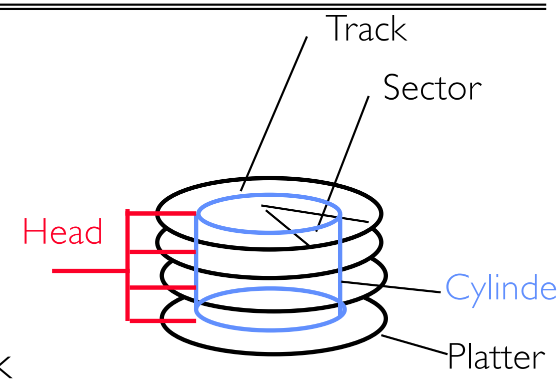
- Sample file in multilevel indexed format:
  - 10 direct ptrs, 1K blocks
  - How many accesses for block #23? (assume file header accessed on open)?
    - » Two: One for indirect block, one for data
  - How about block #5?
    - » One: One for data
  - Block #340?
    - » Three: double indirect block, indirect block, and data



Recall: Critical Factors in File System Design

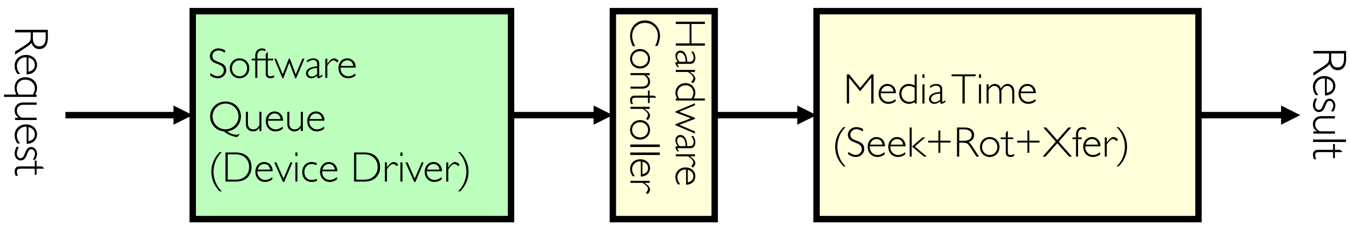
- (Hard) Disk Performance !!!
  - Maximize sequential access, minimize seeks
- Open before Read/Write
  - Can perform protection checks and look up where the actual file resource are, in advance
- Size is determined as they are used !!!
  - Can write (or read zeros) to expand the file
  - Start small and grow, need to make room
- Organized into directories
  - What data structure (on disk) for that?
- Need to carefully allocate / free blocks
  - Such that access remains efficient

Recall: Magnetic Disks



- Cylinders: all the tracks under the head at a given point on all surfaces
- Read/write data is a three-stage process:
  - Seek time: position the head/arm over the proper track
  - Rotational latency: wait for desired sector to rotate under r/w head
  - Transfer time: transfer a block of bits (sector) under r/w head

Disk Latency = Queueing Time + Controller time +
Seek Time + Rotation Time + Xfer Time



Fast File System (BSD 4.2, 1984)

- Same inode structure as in BSD 4.1
  - same file header and triply indirect blocks like we just studied
  - Some changes to block sizes from 1024 ⇒ 4096 bytes for performance
- Paper on FFS: "A Fast File System for UNIX"
  - Marshall McKusick, William Joy, Samuel Leffler and Robert Fabry
  - Off the "resources" page of course website – Take a look!

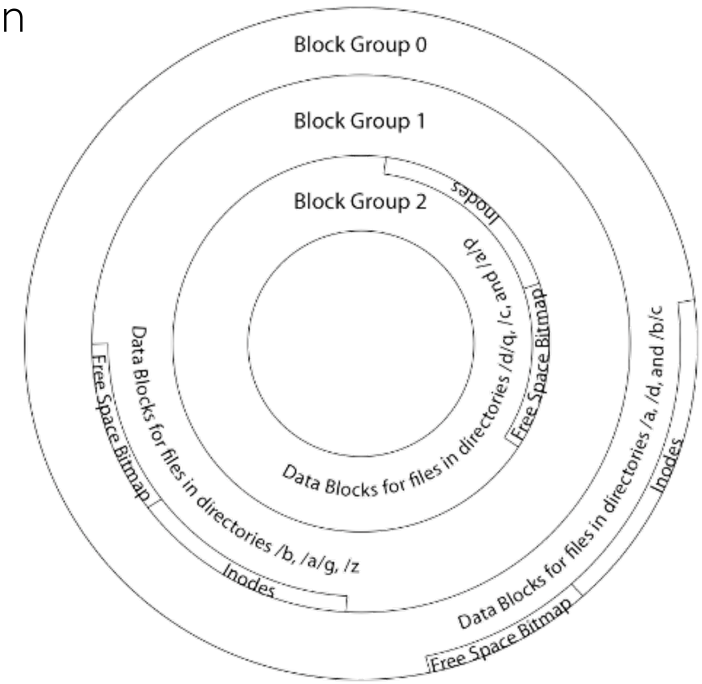
- Optimization for Performance and Reliability:
  - Distribute inodes among different tracks to be closer to data
  - Uses bitmap allocation in place of freelist
  - Attempt to allocate files contiguously
  - 10% reserved disk space
  - Skip-sector positioning (mentioned later)

FFS Changes in Inode Placement: Motivation

- In early UNIX and DOS/Windows' FAT file system, headers stored in special array in outermost cylinders
  - Fixed size, set when disk is formatted
    - » At formatting time, a fixed number of inodes are created
    - » Each is given a unique number, called an "inumber"
- Problem #1: Inodes all in one place (outer tracks)
  - Head crash potentially destroys all files by destroying inodes
  - Inodes not close to the data that the point to
    - » To read a small file, seek to get header, seek back to data
- Problem #2: When create a file, don't know how big it will become (in UNIX, most writes are by appending)
  - How much contiguous space do you allocate for a file?
  - Makes it hard to optimize for performance

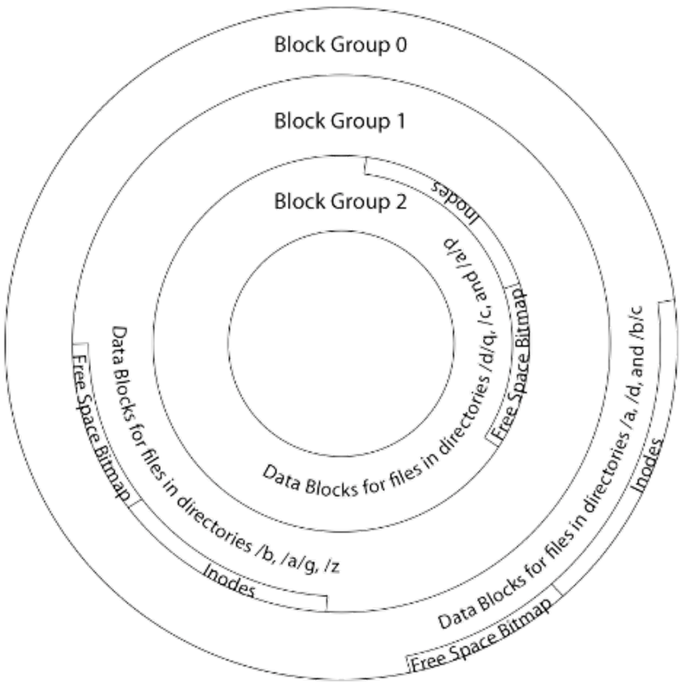
FFS Locality: Block Groups

- The UNIX BSD 4.2 (FFS) distributed the header information (inodes) closer to the data blocks
  - Often, inode for file stored in same "cylinder group" as parent directory of the file
  - makes an "ls" of that directory run very fast
- File system volume divided into set of block groups
  - Close set of tracks
- Data blocks, metadata, and free space interleaved within block group
  - Avoid huge seeks between user data and system structure
- Put directory and its files in common block group

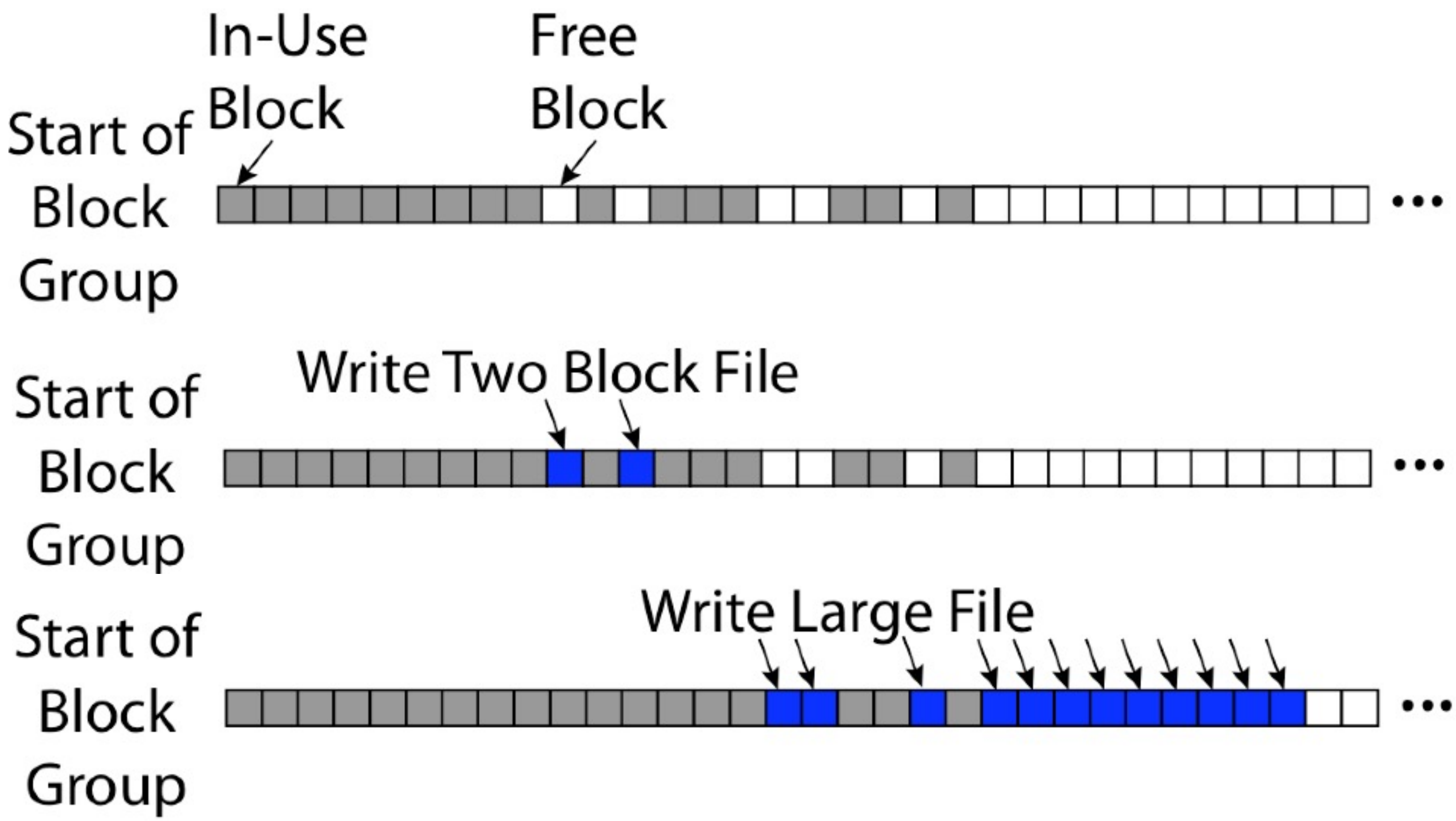


FFS Locality: Block Groups (Con't)

- First-Free allocation of new file blocks
  - To expand file, first try successive blocks in bitmap, then choose new range of blocks
  - Few little holes at start, big sequential runs at end of group
  - Avoids fragmentation
  - Sequential layout for big files
- Important: keep 10% or more free!
  - Reserve space in the Block Group
- Summary: FFS Inode Layout Pros
  - For small directories, can fit all data, file headers, etc. in same cylinder ⇒ no seeks!
  - File headers much smaller than whole block (a few hundred bytes), so multiple headers fetched from disk at same time
  - Reliability: whatever happens to the disk, you can find many of the files (even if directories disconnected)

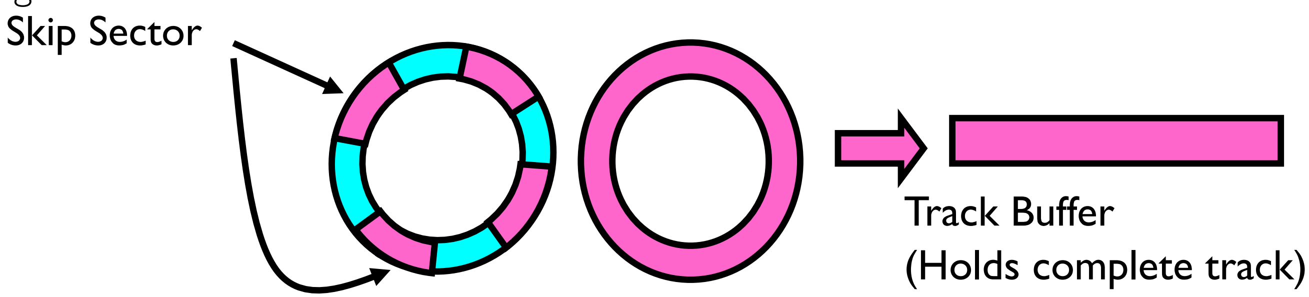


UNIX 4.2 BSD FFS First Fit Block Allocation



Attack of the Rotational Delay

- Problem 3: Missing blocks due to rotational delay
  - Issue: Read one block, do processing, and read next block. In meantime, disk has continued turning: missed next block! Need 1 revolution/block!



  - Solution1: Skip sector positioning ("interleaving")
    - » Place the blocks from one file on every other block of a track: give time for processing to overlap rotation
    - » Can be done by OS or in modern drives by the disk controller
  - Solution 2: Read ahead: read next block right after first, even if application hasn't asked for it yet
    - » This can be done either by OS (read ahead)
    - » By disk itself (track buffers) - many disk controllers have internal RAM that allows them to read a complete track
- Modern disks + controllers do many things "under the covers"
  - Track buffers, elevator algorithms, bad block filtering

UNIX 4.2 BSD FFS

- Pros
  - Efficient storage for both small and large files
  - Locality for both small and large files
  - Locality for metadata and data
  - No defragmentation necessary!

- Cons
  - Inefficient for tiny files (a 1-byte file requires both an inode and a data block)
  - Inefficient encoding when file is mostly contiguous on disk
  - Need to reserve 10-20% of free space to prevent fragmentation

Conclusion (1/2)

- Systems (e.g., file system) designed to optimize performance and reliability
  – Relative to performance characteristics of underlying device
- File System:
  – Transforms blocks into Files and Directories
  – Optimize for access and usage patterns
  – Maximize sequential access, allow efficient random access
- File (and directory) defined by header, called "inode"

Conclusion (2/2)

- Naming: translating from user-visible names to actual system resources
  - Directories used for naming for local file systems
  - Linked or tree structure stored in files
- File Allocation Table (FAT) Scheme
  - Linked-list approach
  - Very widely used: Cameras, USB drives, SD cards
  - Simple to implement, but poor performance and no security
- Look at actual file access patterns
  - Many small files, but large files take up all the space!
- 4.2 BSD Fast File System: Multi-level inode header to describe files
  - Inode contains ptrs to actual blocks, indirect blocks, double indirect blocks, etc.
  - Optimizations for sequential access: start new files in open ranges of free blocks, rotational optimization