CS162
Operating Systems and Systems Programming
Lecture 22

Filesystems 2: Filesystem Design (Con't), Filesystem Case Studies

April 11th, 2023

Prof. John Kubiatowicz

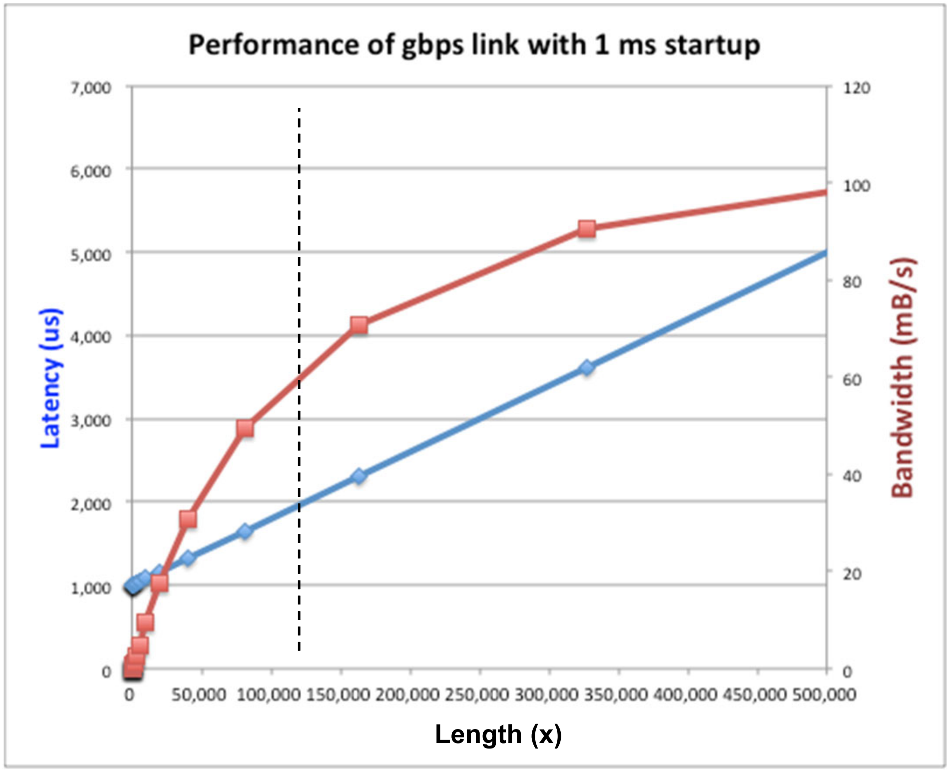
http://cs162.eecs.Berkeley.edu

Recall: I/O Performance (Network Example)

- Consider a $1\ \mathrm{Gb/s}$ link ($B_w = 125\ \mathrm{MB/s}$) with startup cost $S = 1\ \mathrm{ms}$
- Latency: $L(x) = S + \frac{x}{B_w}$
- Effective Bandwidth:

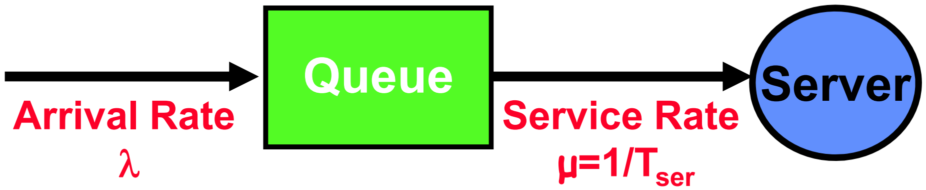
$$E(x) = \frac{x}{S + \frac{x}{B_w}} = \frac{B_w \cdot x}{B_w \cdot S + x} = \frac{B_w}{\frac{B_w \cdot S}{x} + 1}$$

- Half-power Bandwidth: $E(x) = \frac{B_w}{2}$
- For this example, half-power bandwidth occurs at x = $125\ \mathrm{KB}$



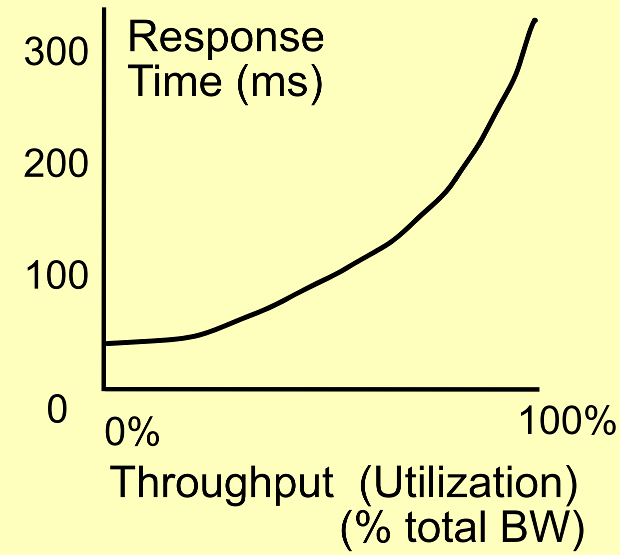
Recall: A Few Queuing Theory Results

- Assumptions:
  - System in equilibrium; No limit to the queue
  - Time between successive arrivals is random and memoryless

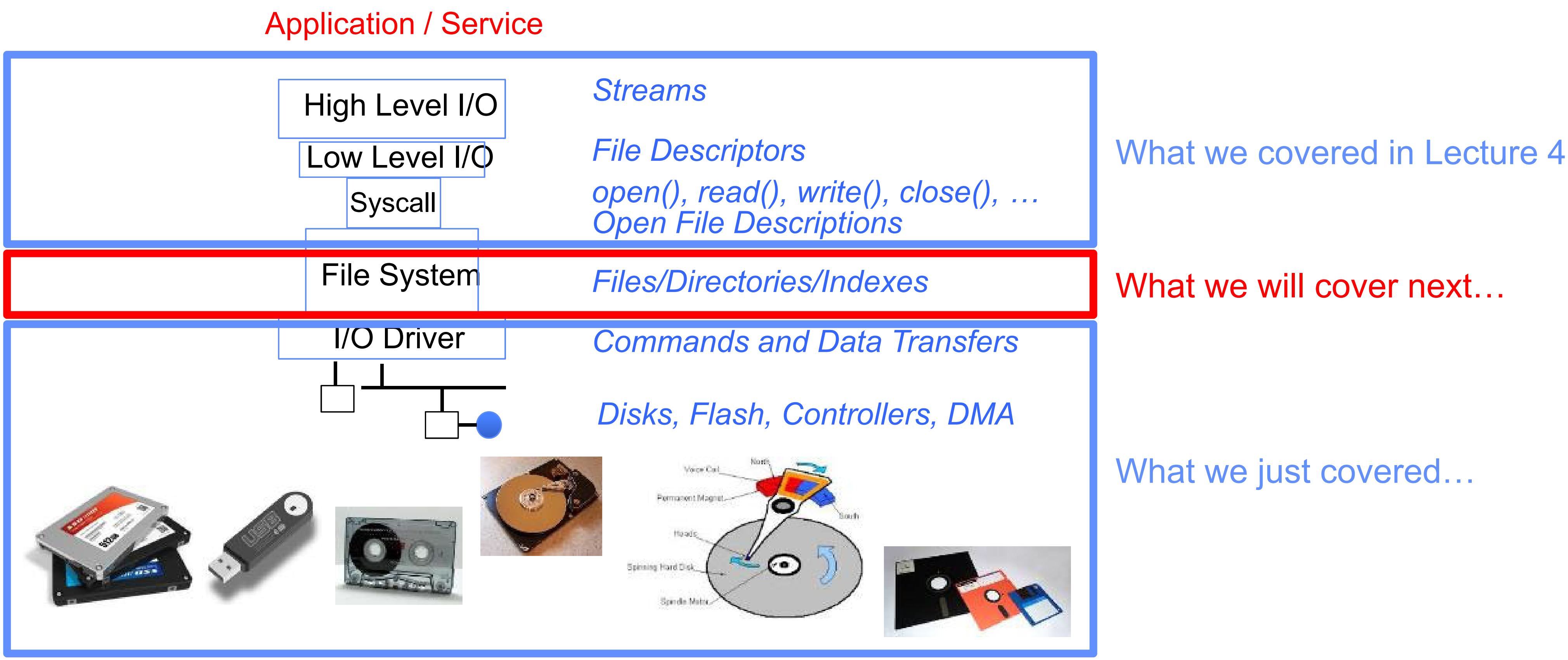


- Parameters that describe our system:
  - λ: mean number of arriving customers/second
  - T_{ser}: mean time to service a customer ("m1")
  - C: squared coefficient of variance = $\sigma^2/m1^2$
  - μ: service rate = $1/T_{ser}$
  - u: server utilization ($0 \le u \le 1$): $u = \lambda/\mu = \lambda \times T_{ser}$
- Parameters we wish to compute:
  - T_q: Time spent in queue
  - L_q: Length of queue = $\lambda \times T_q$ (by Little's Law)
- Results:
  - Memoryless service distribution (C = 1): (an "M/M/1 queue"):
    - » $T_q = T_{ser} \times u/(1 - u)$
  - General service distribution (no restrictions), 1 server (an "M/G/1 queue"):
    - » $T_q = T_{ser} \times ½(1+C) \times u/(1 - u)$

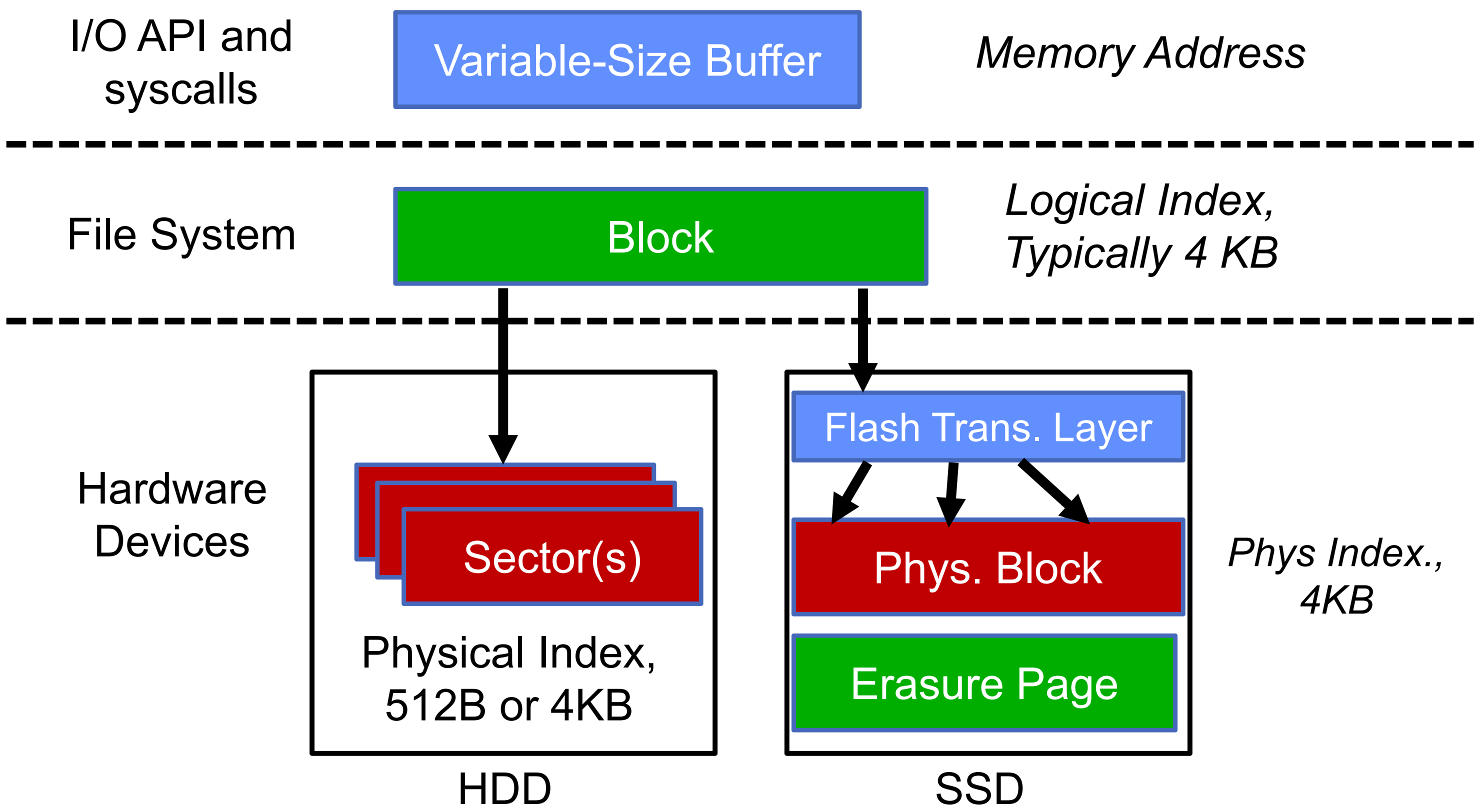
Why does response/queueing delay grow unboundedly even though the utilization is < 1 ?



Recall: I/O and Storage Layers



Recall: From Storage to File Systems



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

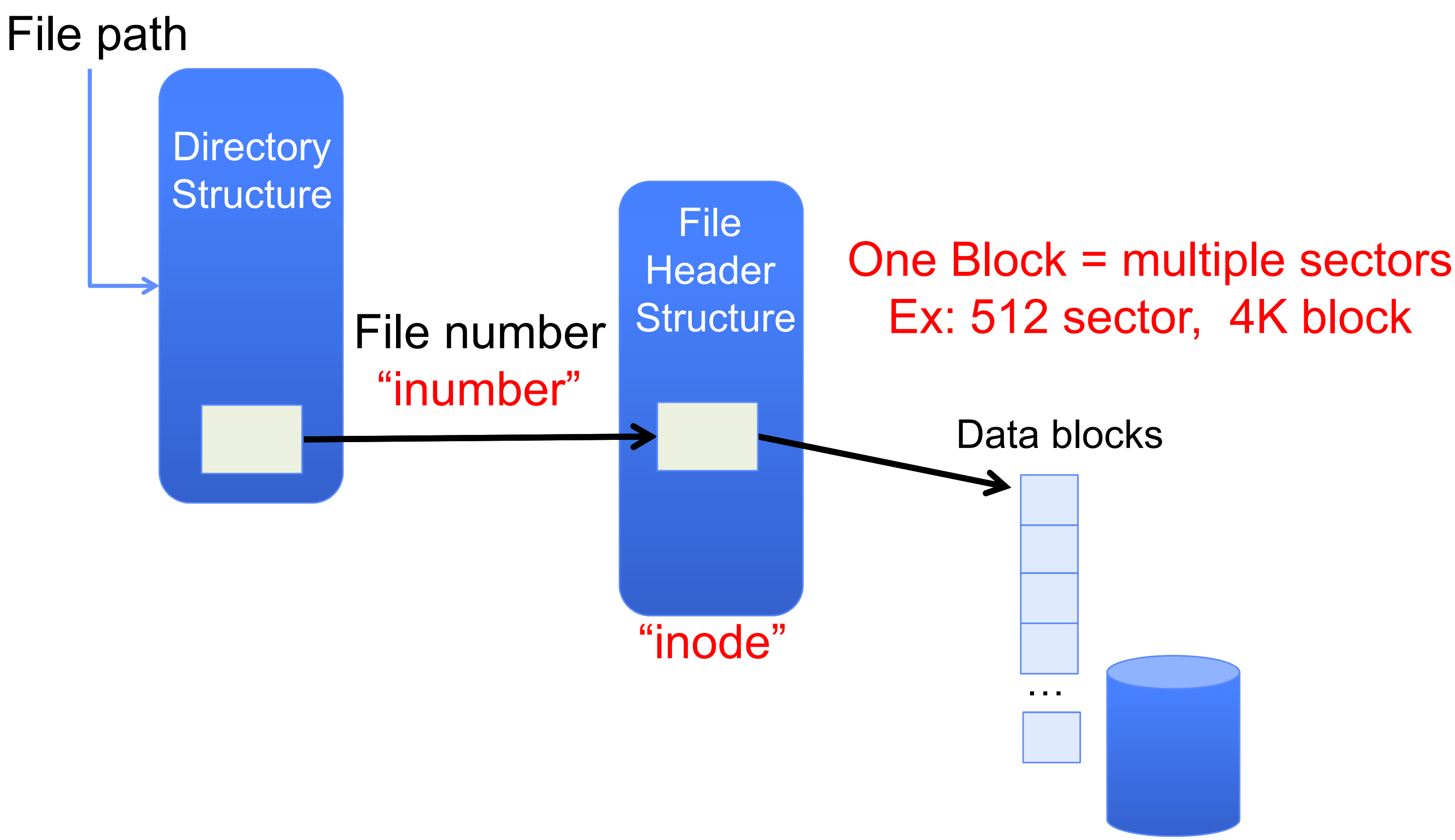
- Different than data structures in memory
  - Must load from disk into memory to manipulate
  - Modifications to disk data are *really* expensive, so only change when needed
- Access a block at a time
  - Can't efficiently read/write a single word
  - Have to read/write full block containing it
  - Ideally want sequential access patterns
- Durability
  - Ideally, file system is in meaningful state upon shutdown
  - This obviously isn't always the case…

FILE SYSTEM DESIGN

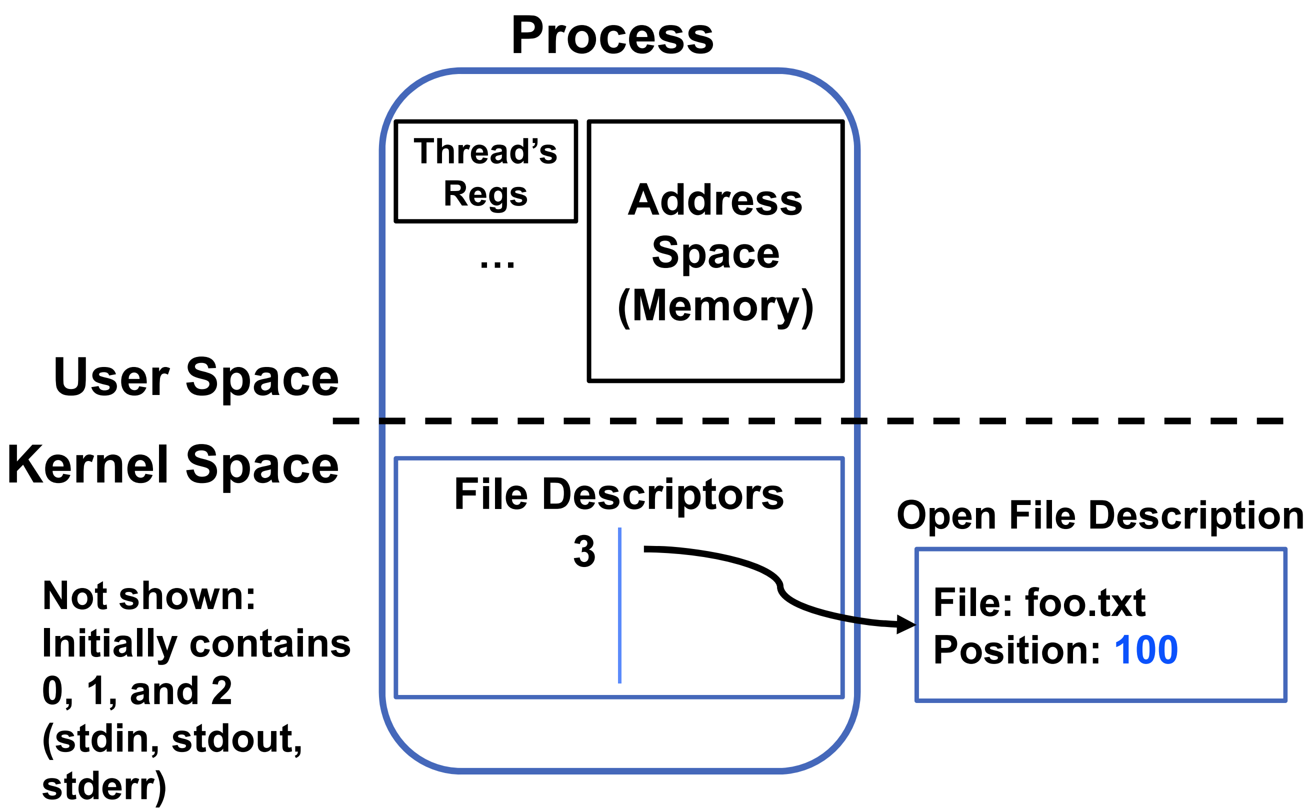
Critical Factors in File System Design

- (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



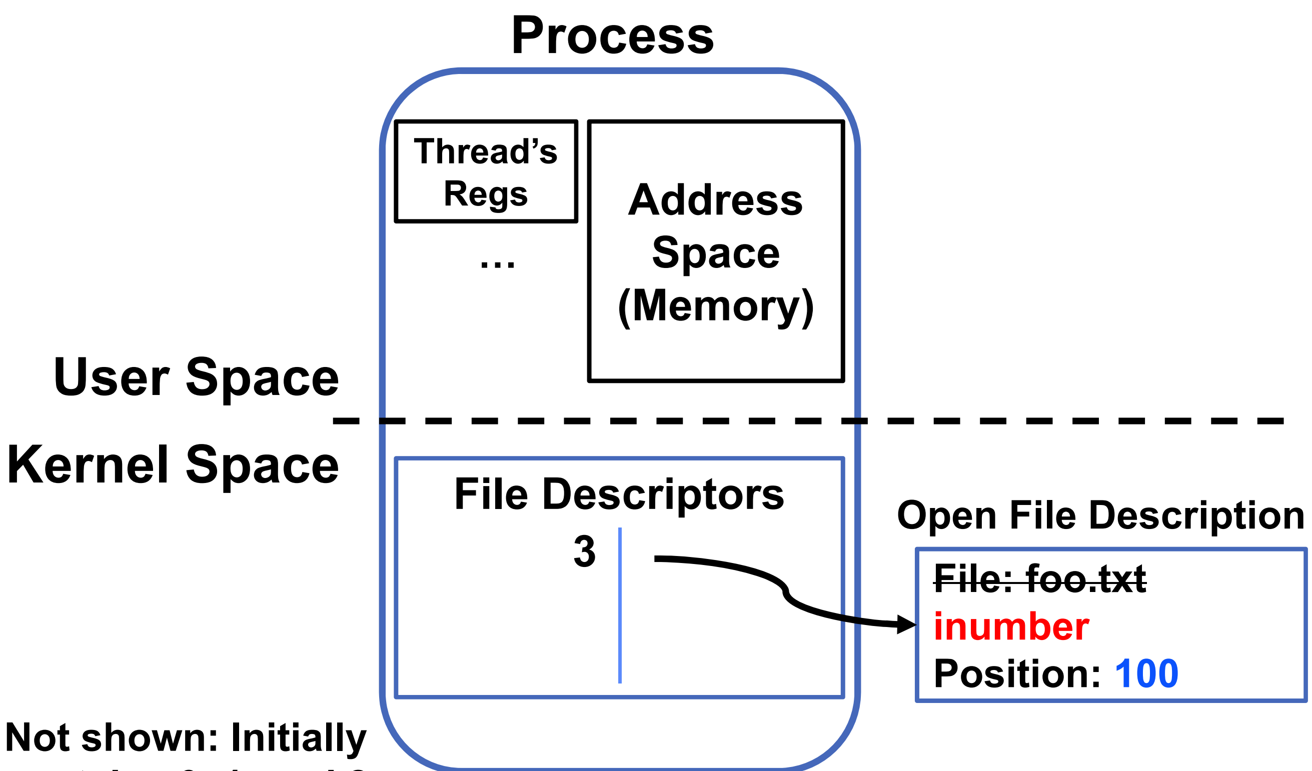
Recall: Abstract Representation of a Process



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 → **d**irectory structure → *file number offset* → index structure ("inode") → ***s**torage 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**

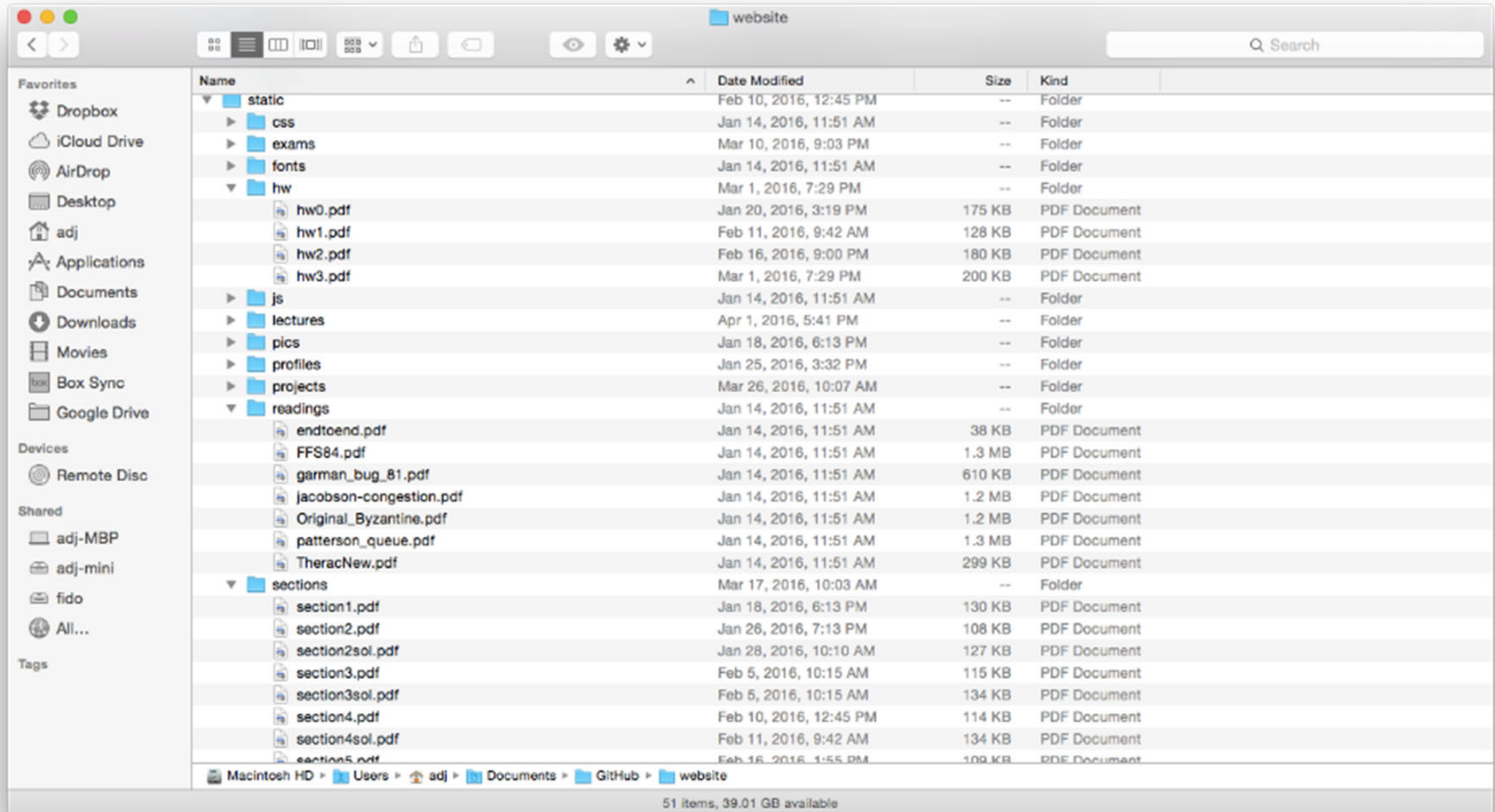
Administrivia

- Homework 5: RPC deadline this Thursday (4/13)
- Project 3: Design doc due Monday (4/17)
- Midterm 3: April 27th
  - Everything is fair game, although focus is on last 1/3 of class
  - Three *hand-written* cheat-sheets, double sided

How to get the File Number?

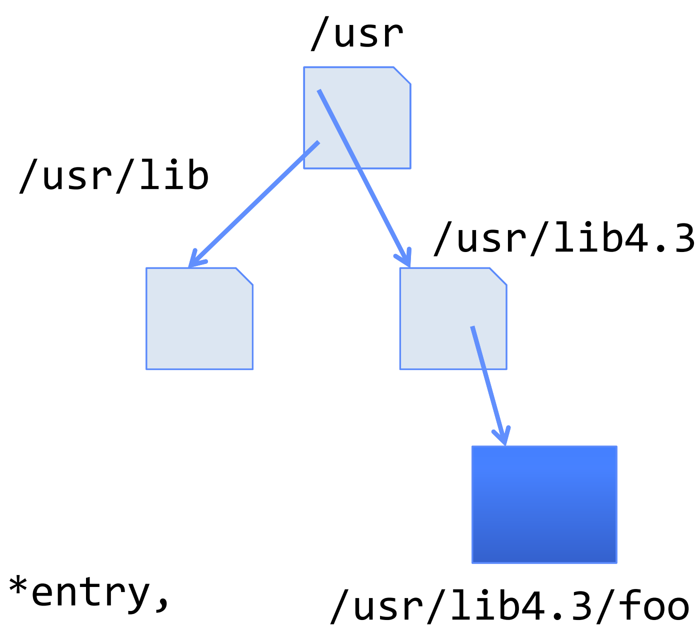
- Look up in ***directory structure***
- A directory is a file containing <file_name : file_number> mappings
  - File number could be a file or another directory
  - Operating system stores the mapping in the directory in a format it interprets
  - Each <file_name : file_number> mapping is called a directory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

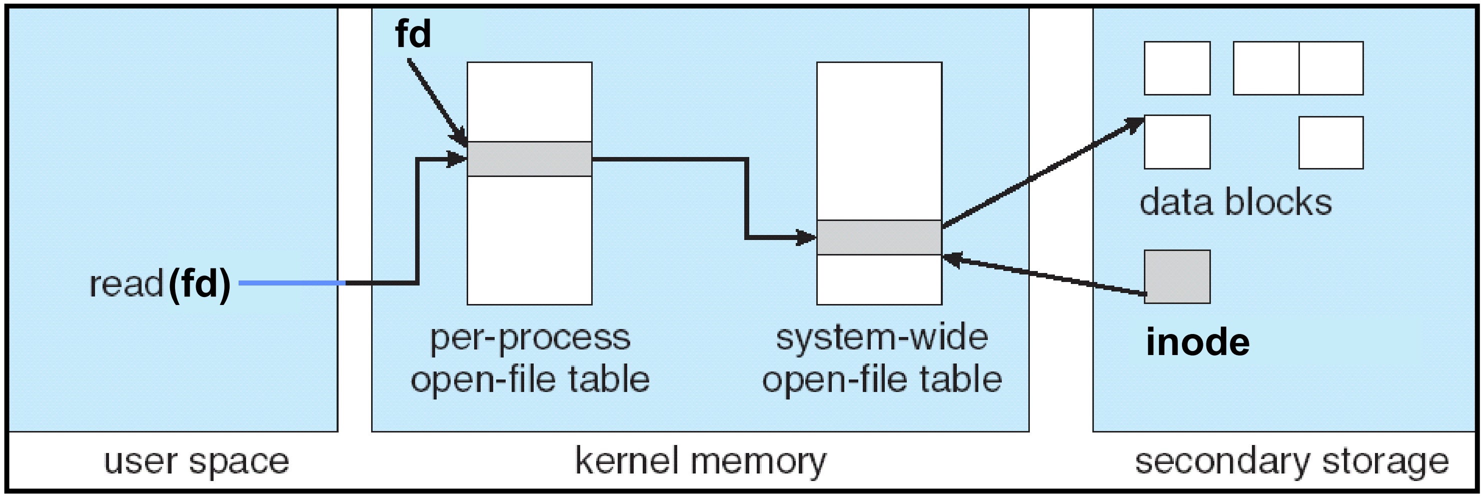
- Directories are specialized files
  - Contents: **List of pairs <file name, file number>**
- System calls to access directories
  - `open` / `creat` / `readdir` traverse the structure
  - `mkdir` / `rmdir` add/remove entries
  - `link` / `unlink` (`rm`)
- libc support
  - `DIR * opendir (const char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

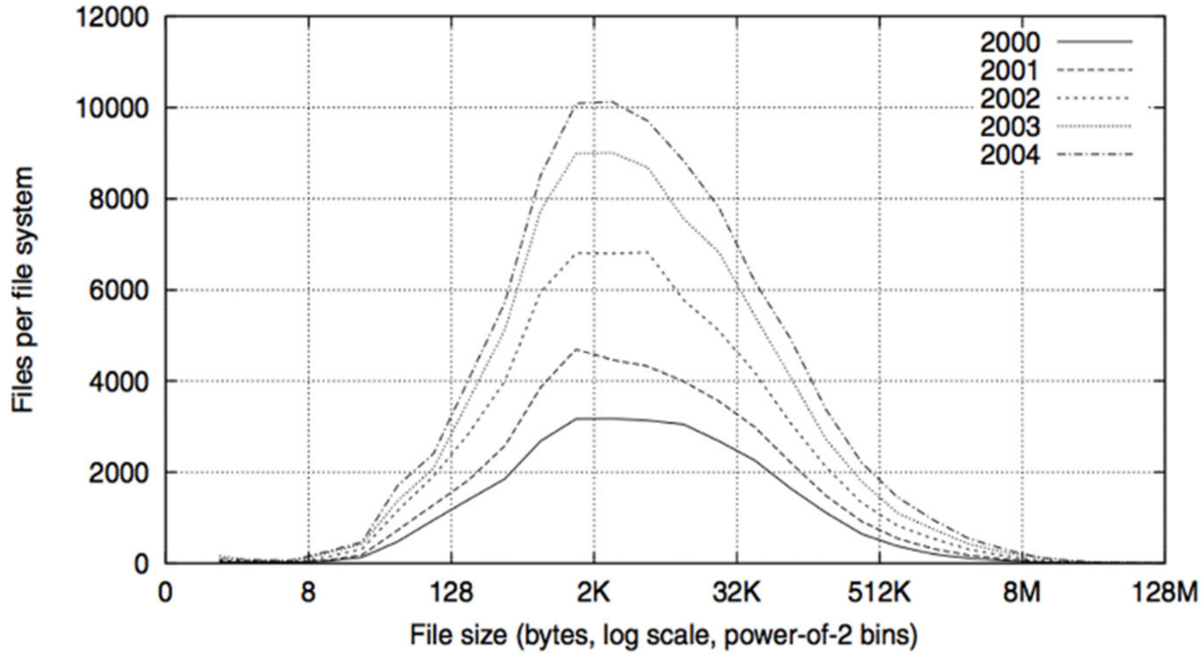


Fig. 2. Histograms of files by size.

Observation #2: Most Bytes are in Large Files

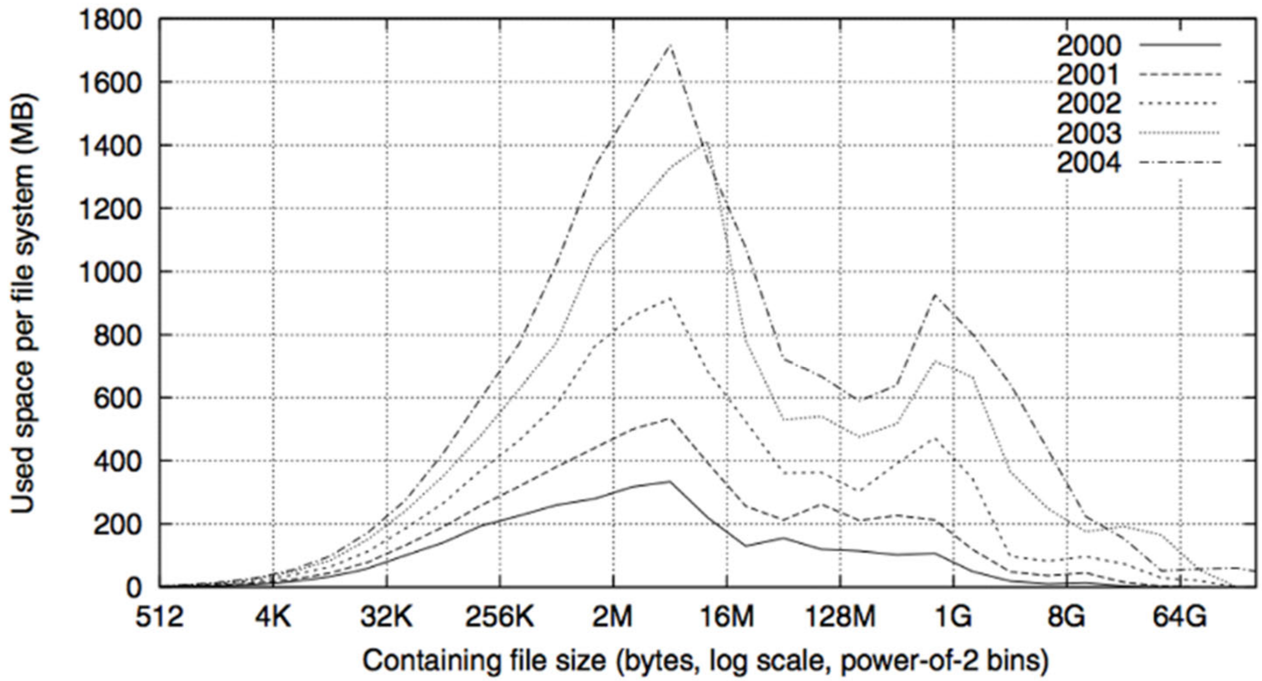


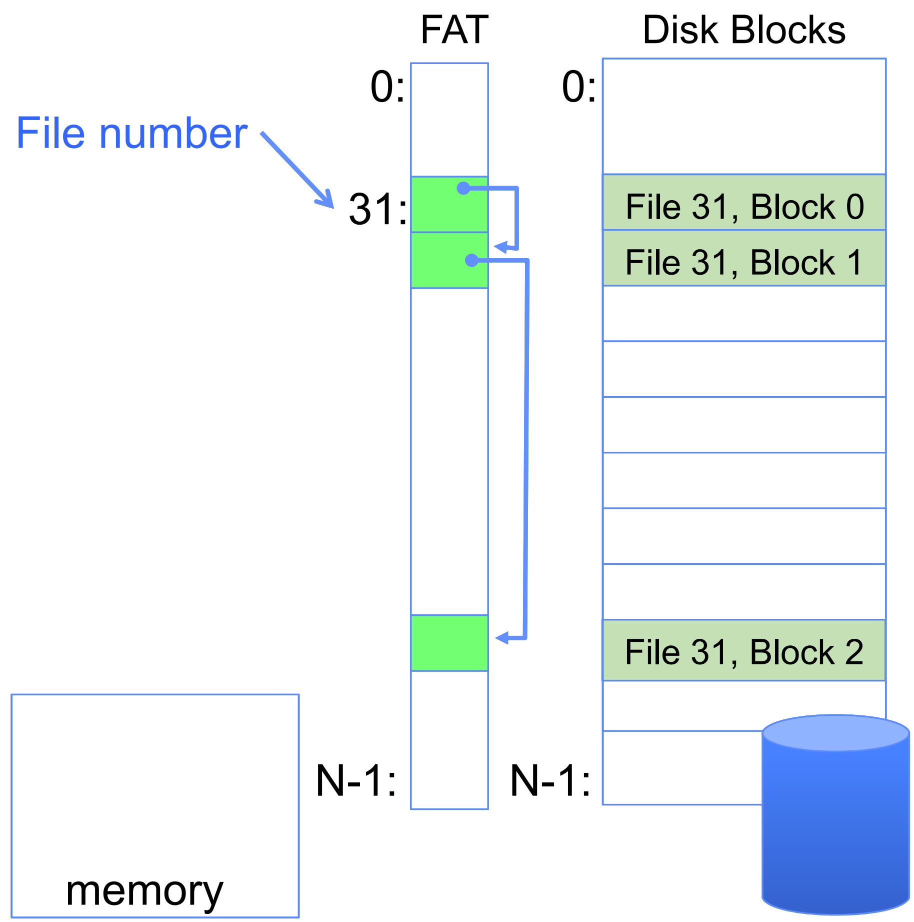
Fig. 4. Histograms of bytes by containing file size.

CASE STUDY: FAT: FILE ALLOCATION TABLE

- MS-DOS, 1977
- Still widely used!

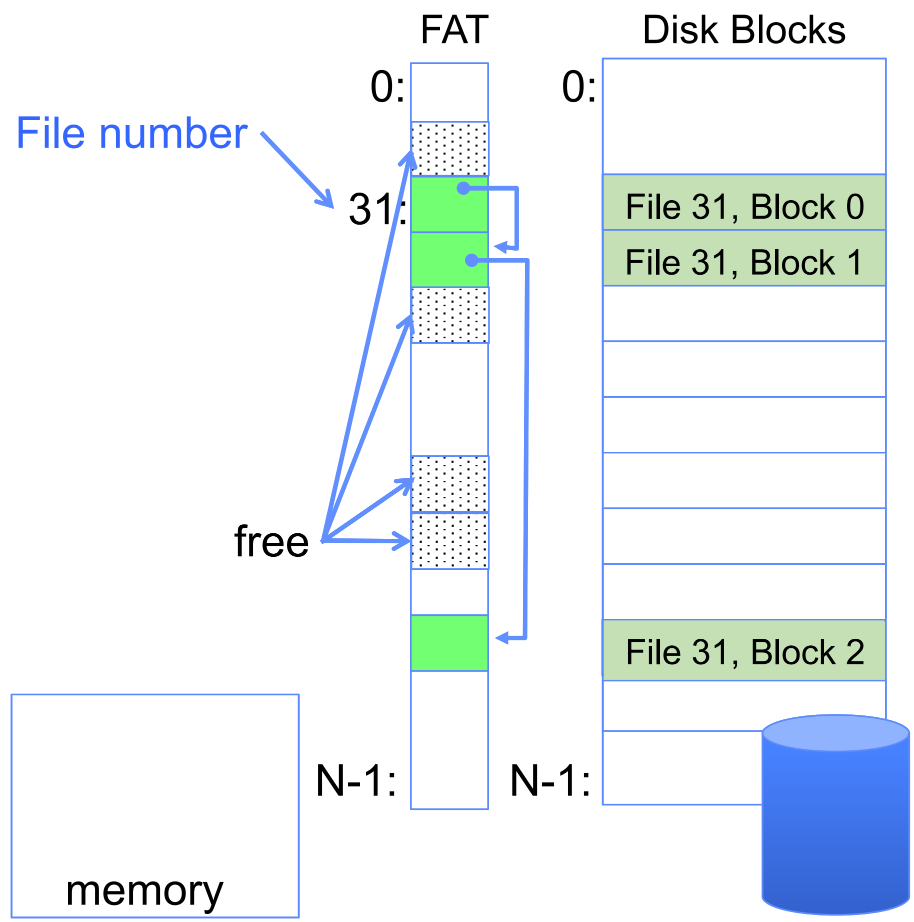
FAT (File Allocation Table)

- 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



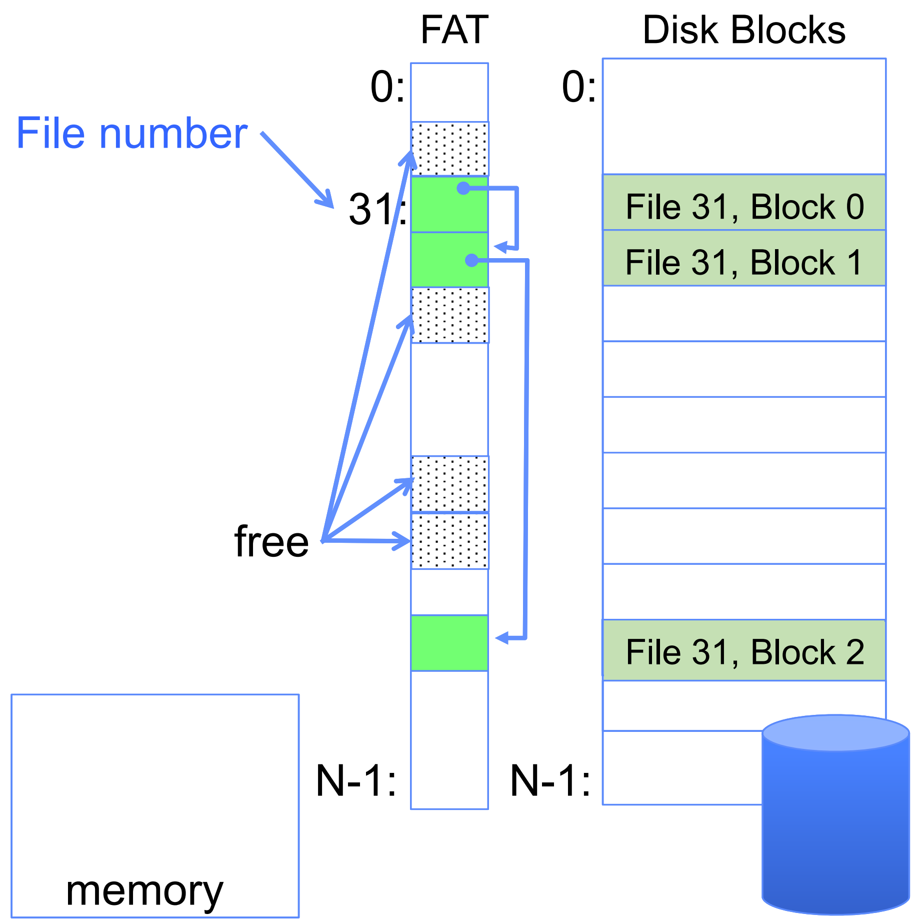
FAT (File Allocation Table)

- 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



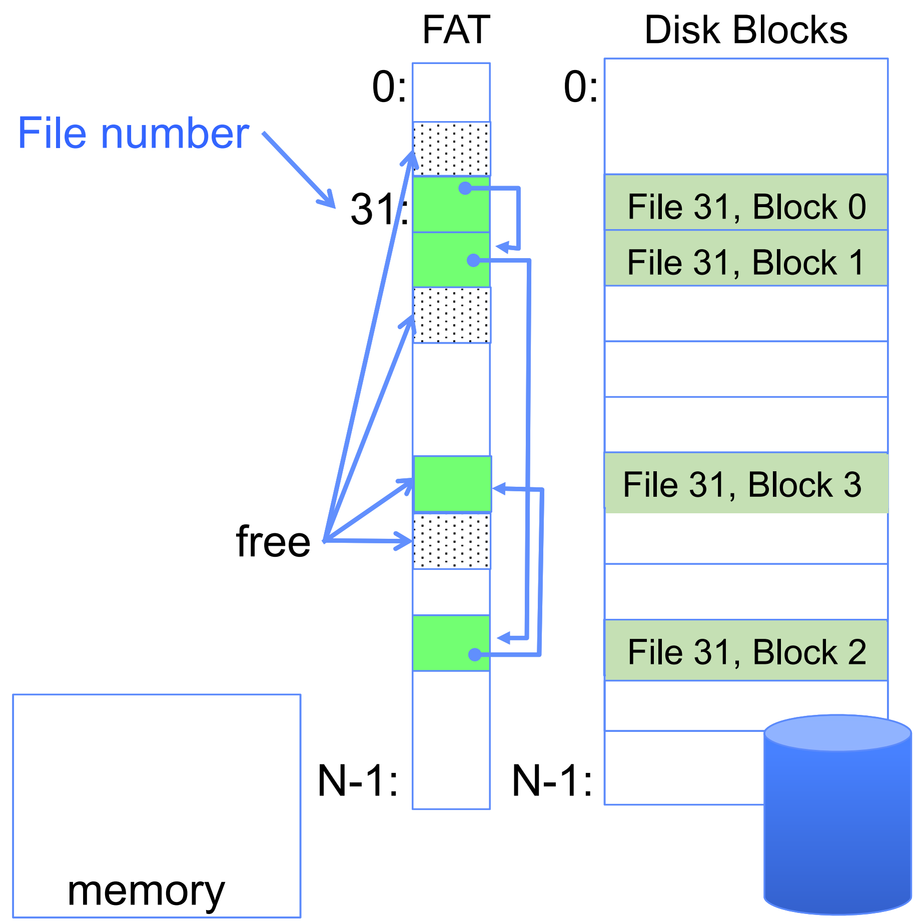
FAT (File Allocation Table)

- 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)

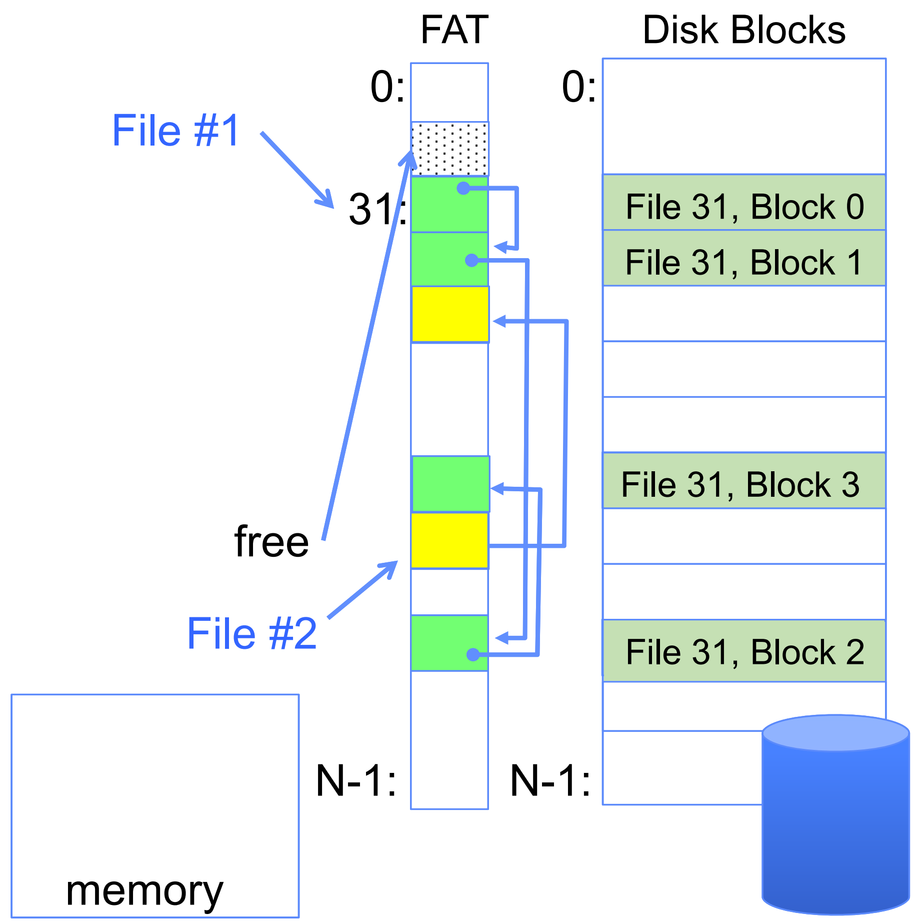
- File is a collection of disk blocks
- FAT is linked list 1-1 with blocks
- File number is index of root of block list for the file
- File offset: block number and offset within block
- Follow list to get block number
- Unused blocks marked free
  - Could require scan to find
  - Or, could use a free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



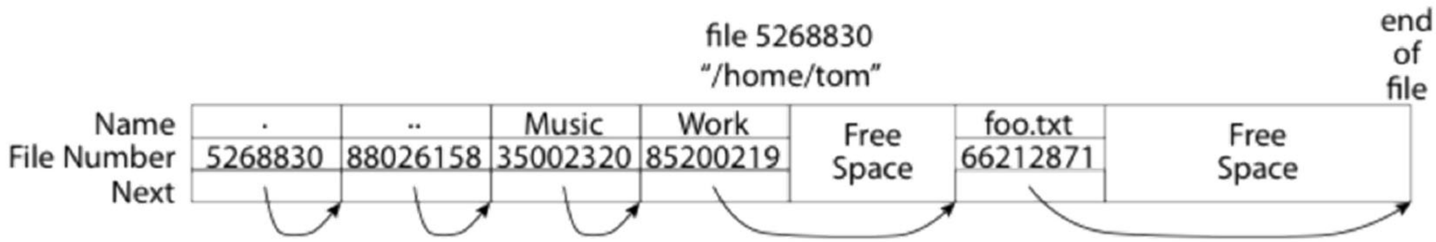
FAT (File Allocation Table)

- Where is FAT stored?
  - On disk
- 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

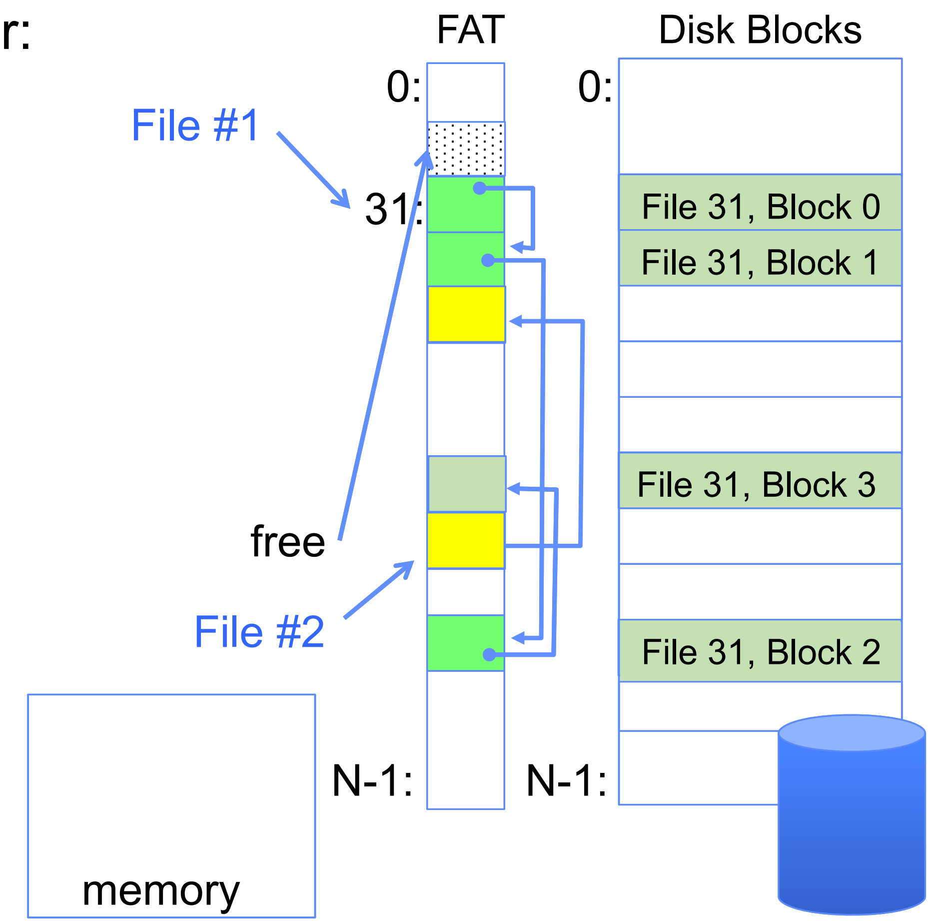


- A directory is a file containing <file_name: file_number> mappings
- Free space for new/deleted entries
- In FAT: file attributes are kept in directory (!!!)
  - Not directly associated with the file itself
- Each directory a linked list of entries
  - Requires linear search of directory to find particular 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?



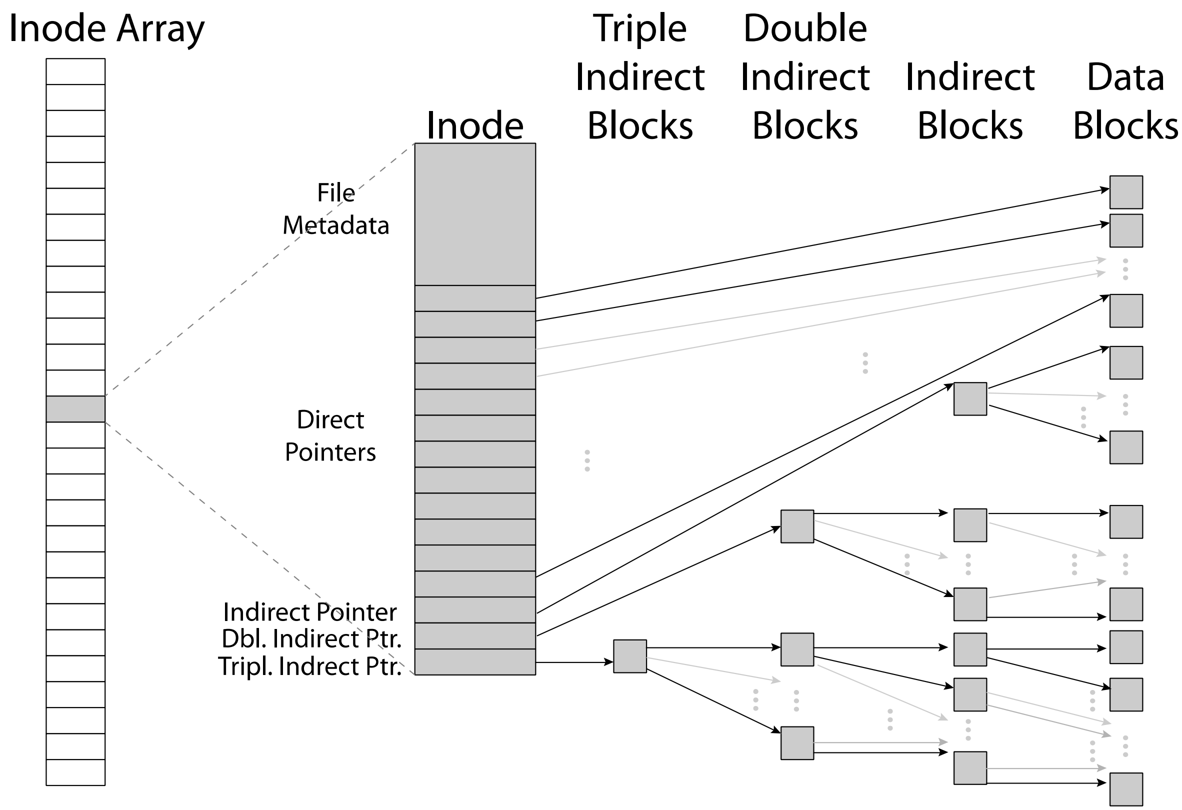
CASE STUDY:
UNIX FILE SYSTEM (BERKELEY FFS)

Inodes in Unix (Including Berkeley FFS)

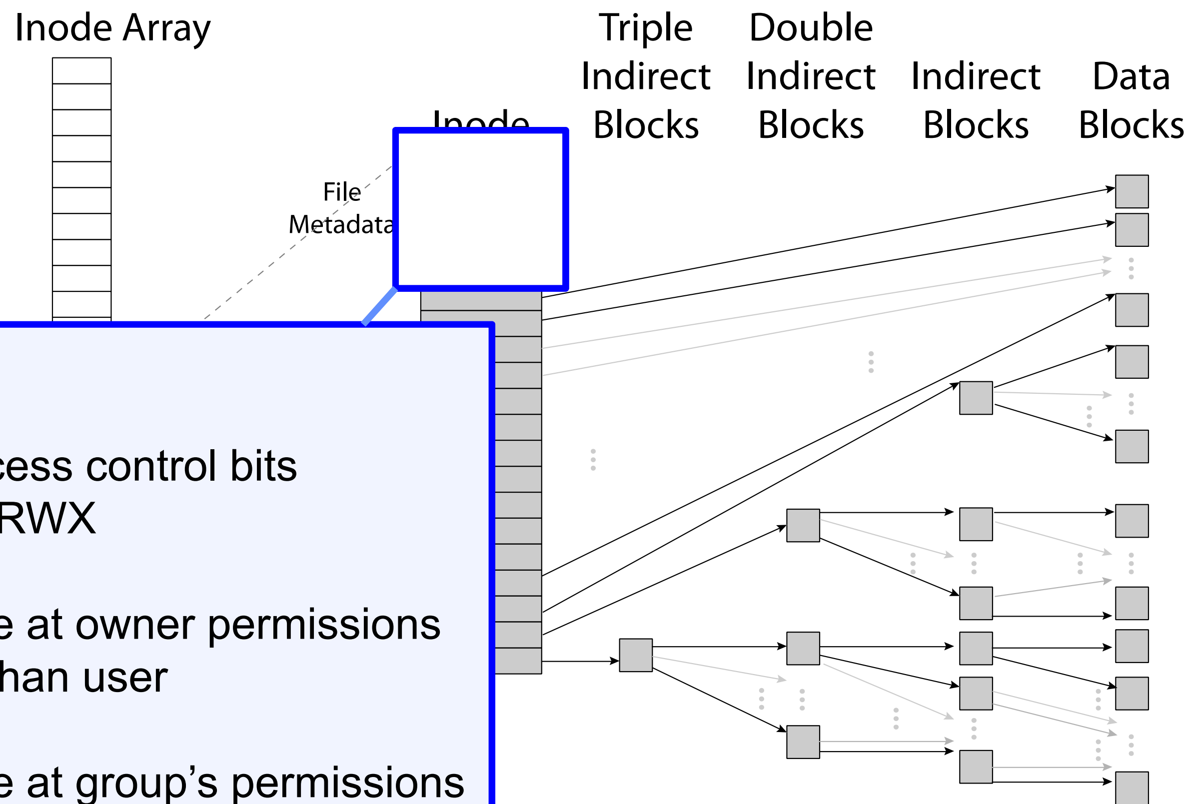
- File Number is index into set of inode arrays
- Index structure is an array of *inodes*
  - File Number (inumber) is an index into the array of inodes
  - Each inode corresponds to a file and contains its metadata
    - » So, things like read/write permissions are stored with *file,* not in directory
    - » 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 Atributes



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

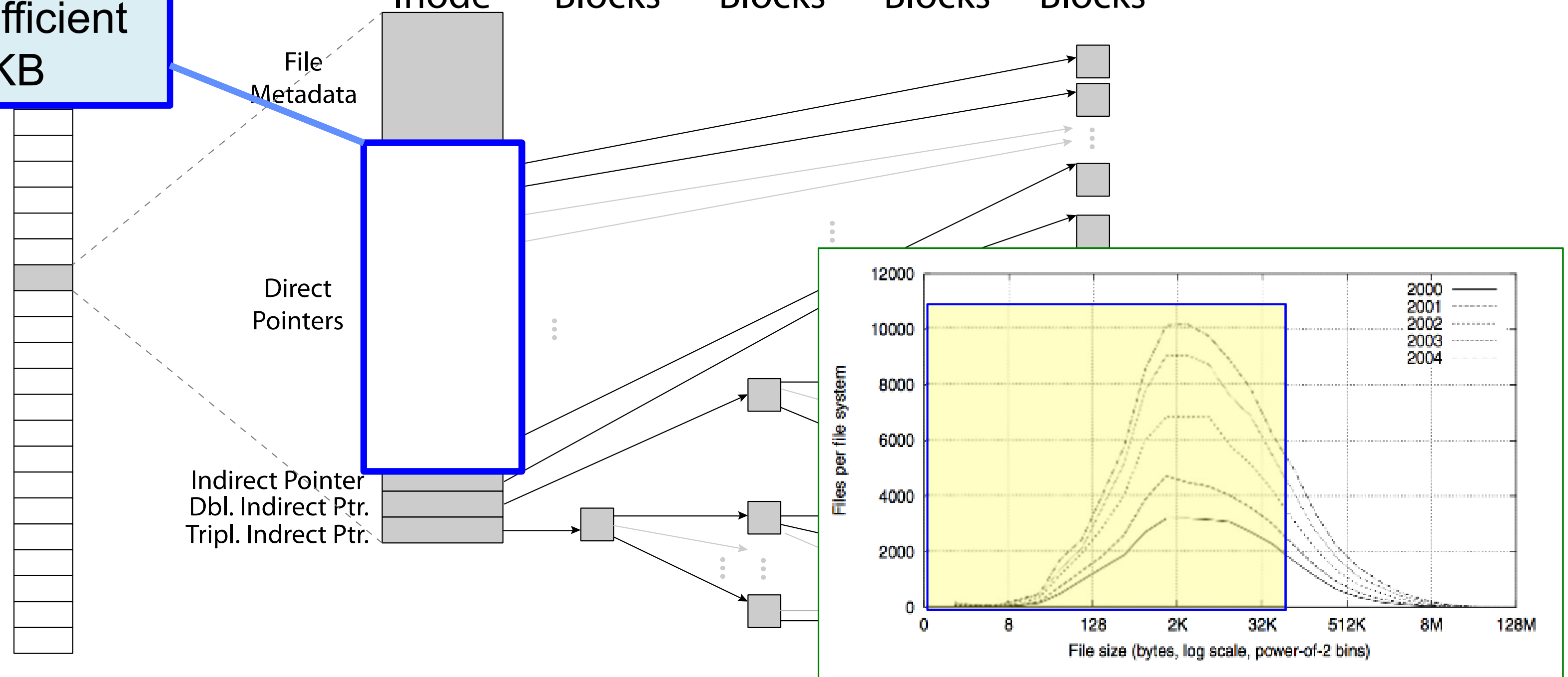


Fig. 2. Histograms of files by size.

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

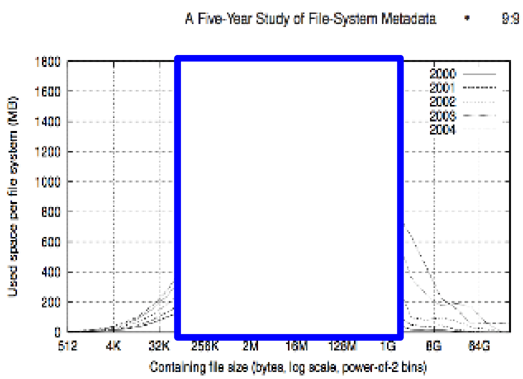
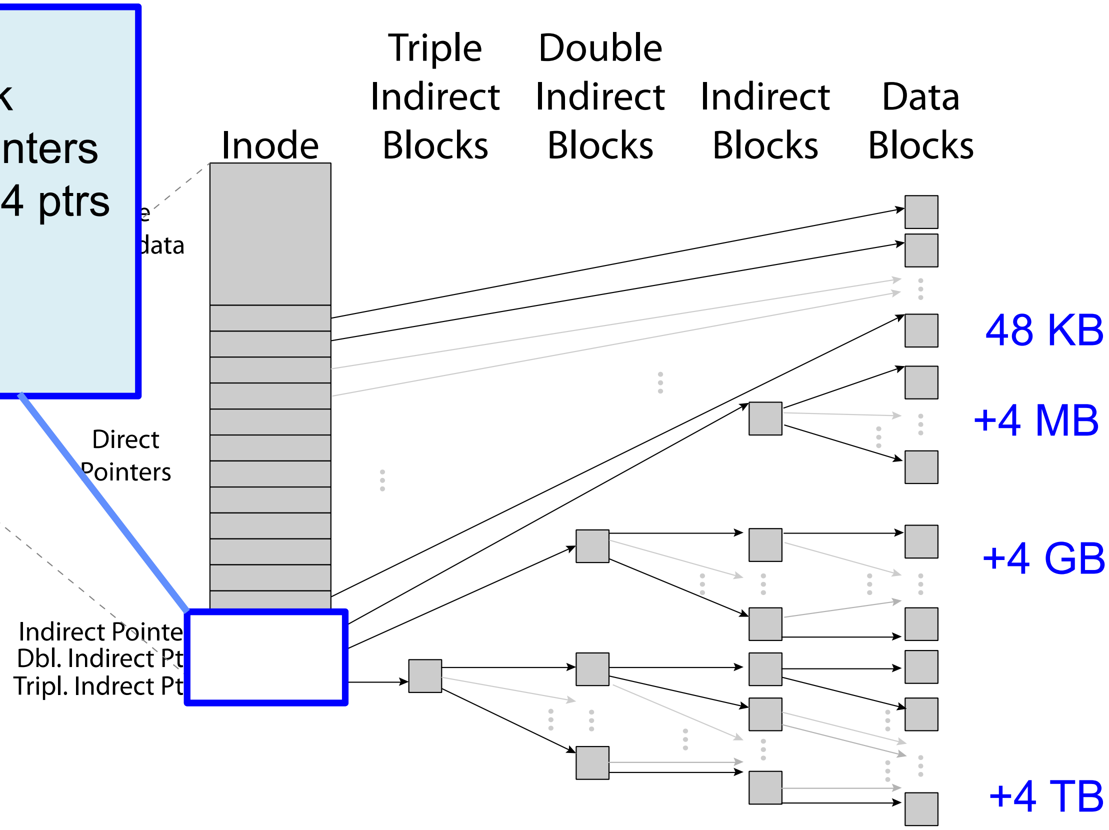
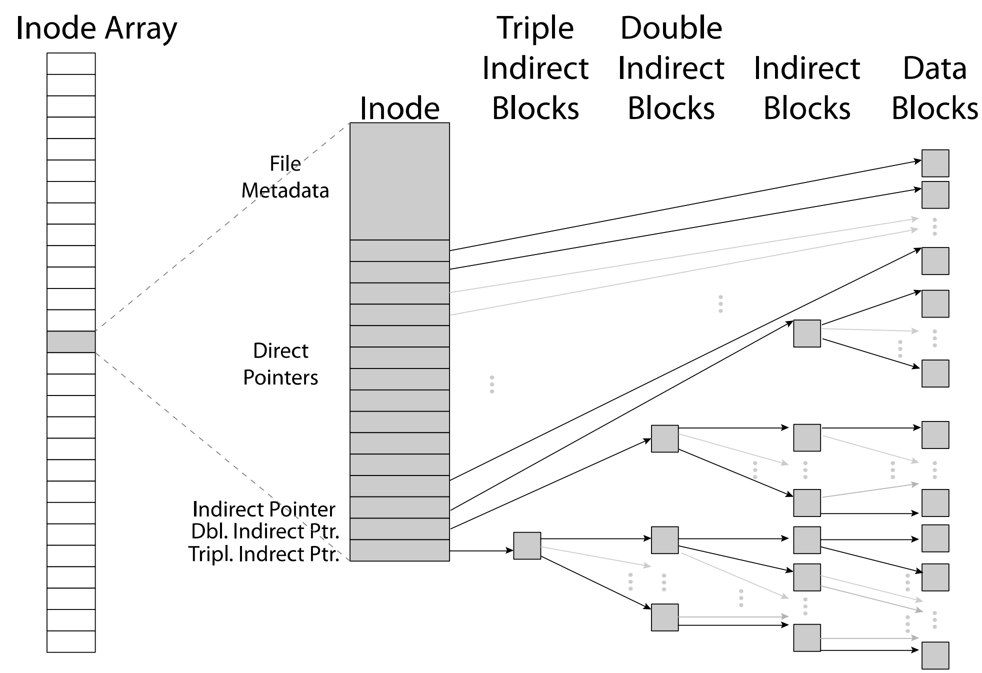


Fig. 4. Histograms of bytes by containing file size.



Putting it All Together: On-Disk Index

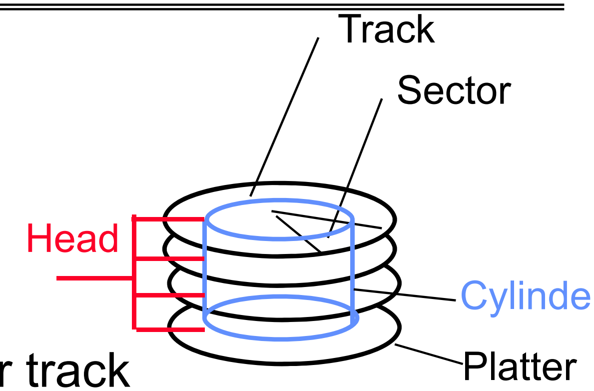
- Sample file in multilevel indexed format:
  - 10 direct ptrs, 1K blocks
  - How many accesses for block #23? (assume file header accessed on open)?
    - » Two: One for indirect block, one for data
  - How about block #5?
    - » One: One for data
  - Block #340?
    - » Three: double indirect block,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



Recall: Critical Factors in File System Design

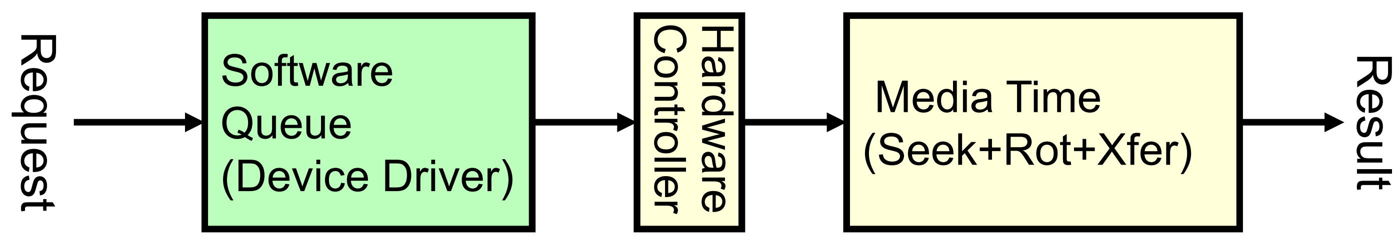
- **(Hard) Disk Performance !!!**
  - **Maximize sequential access, minimize seeks**
- Open before Read/Write
  - Can perform protection checks and look up where the actual file resource are, in advance
- Size is determined as they are used !!!
  - Can write (or read zeros) to expand the file
  - Start 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!

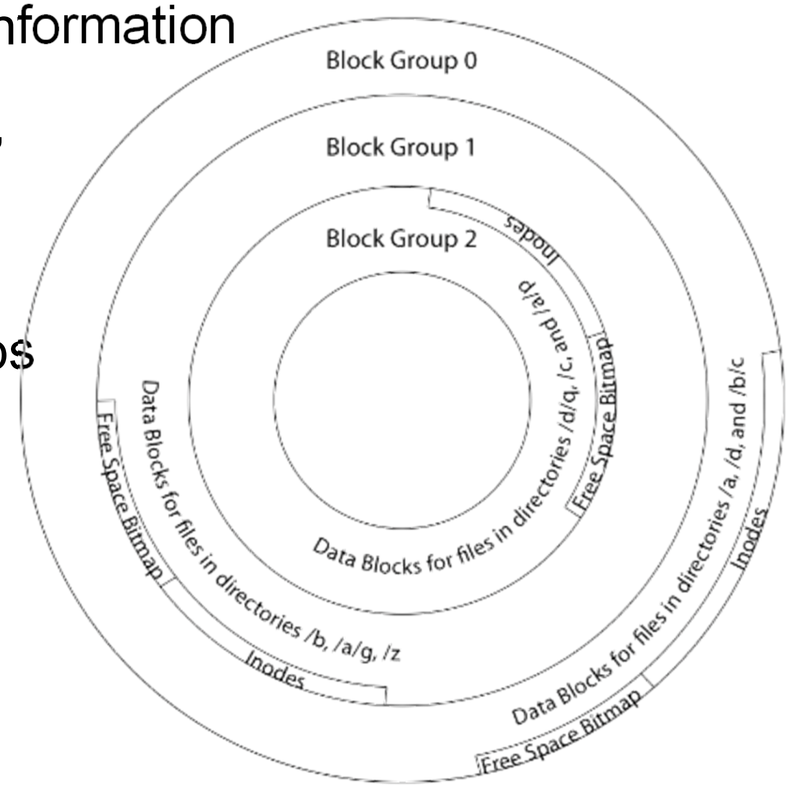
- Optimization for Performance and Reliability:
  – Distribute inodes among different tracks to be closer to data
  – Uses bitmap allocation in place of freelist
  – Attempt to allocate files contiguously
  – 10% reserved disk space
  – Skip-sector positioning (mentioned later)

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

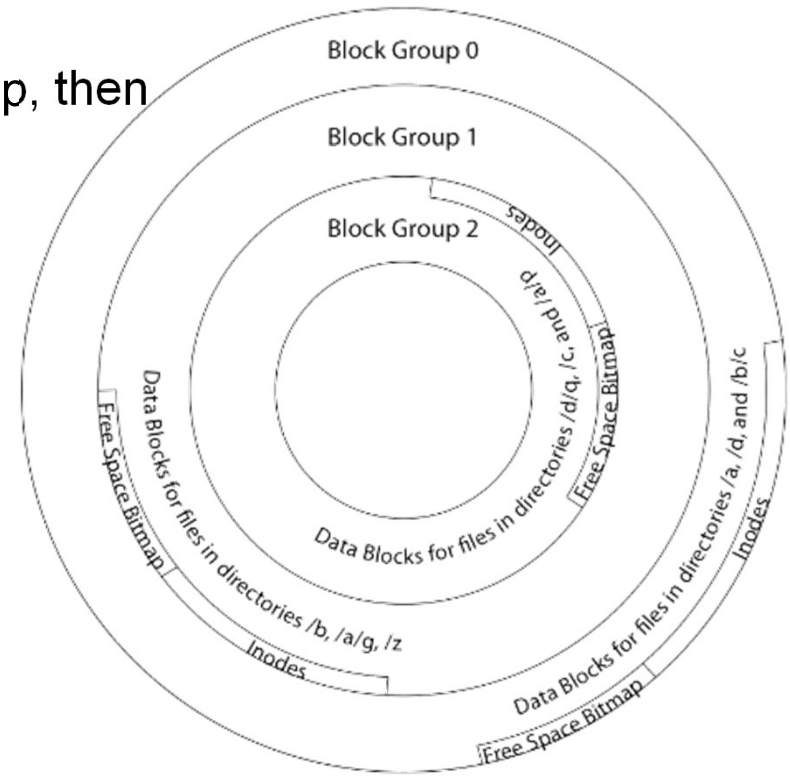
FFS Locality: Block Groups

- 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

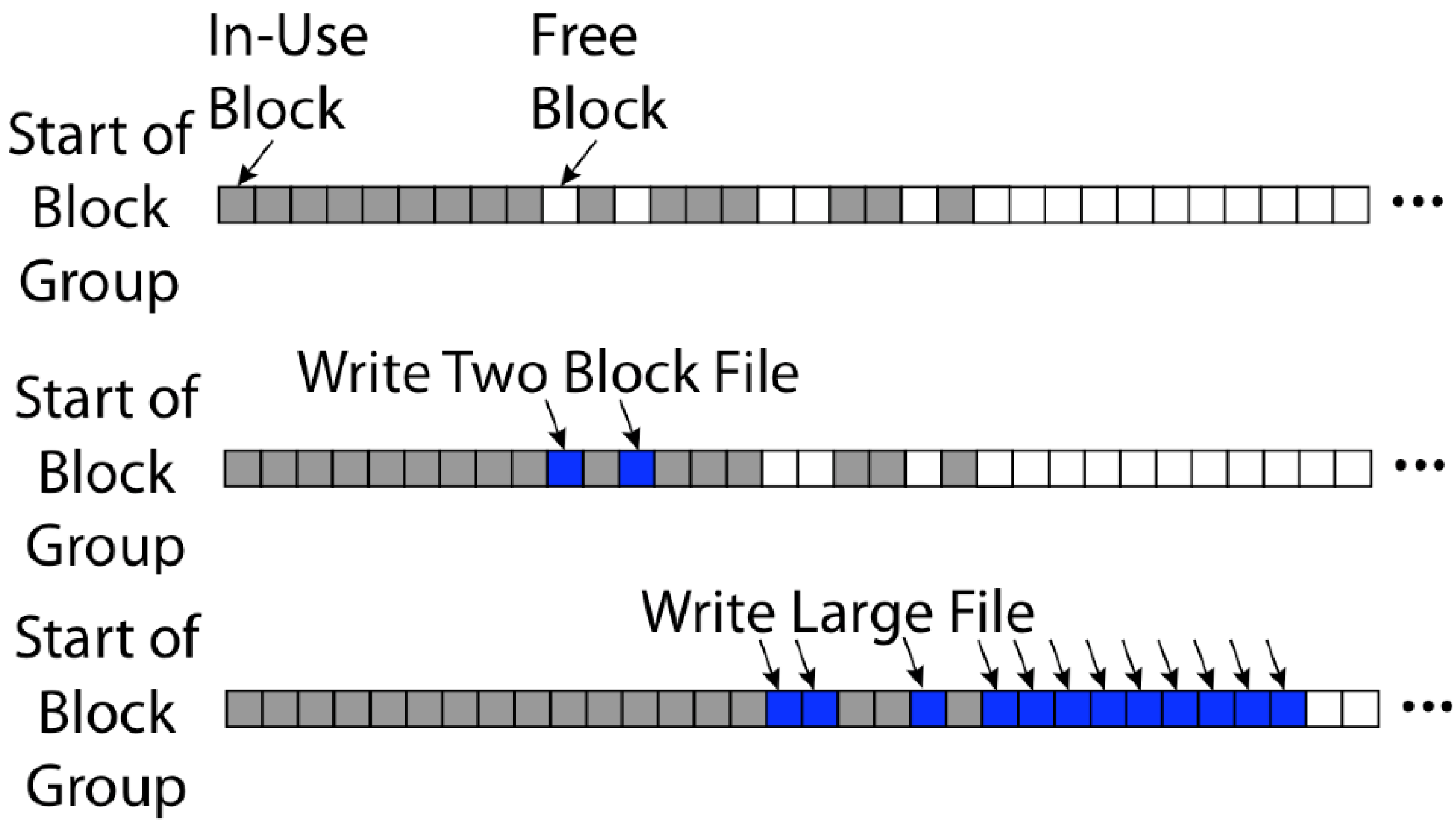


FFS Locality: Block Groups (Con't)

- 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)

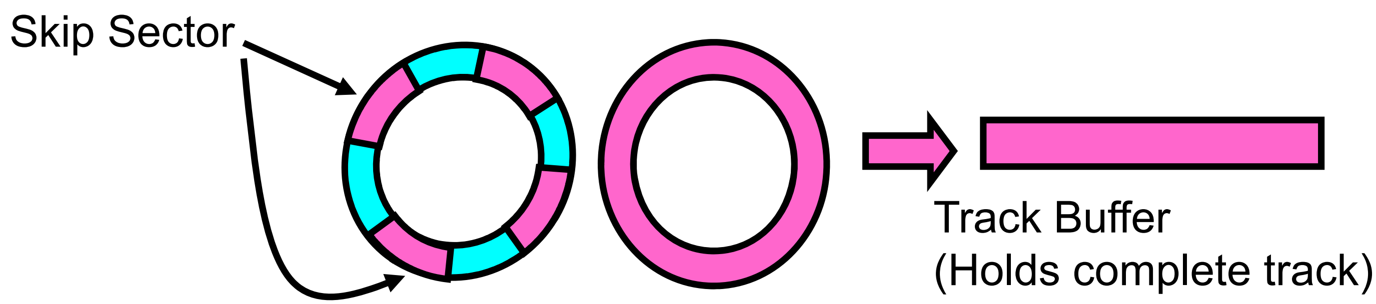


UNIX 4.2 BSD FFS First Fit Block Allocation



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!



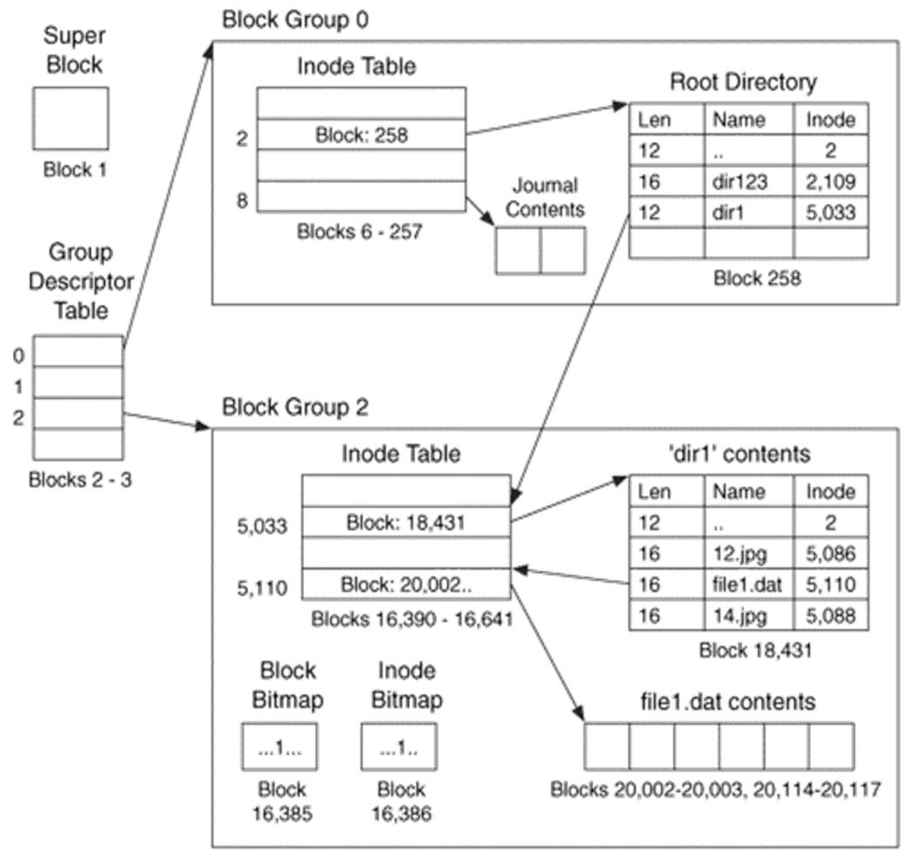
  - Solution1: Skip sector positioning ("interleaving")
    - » Place the blocks from one file on every other block of a track: give time for processing to overlap rotation
    - » Can be done by OS or in modern drives by the disk controller
  - Solution 2: Read ahead: read next block right after first, 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

Linux Example: Ext2/3 Disk Layout

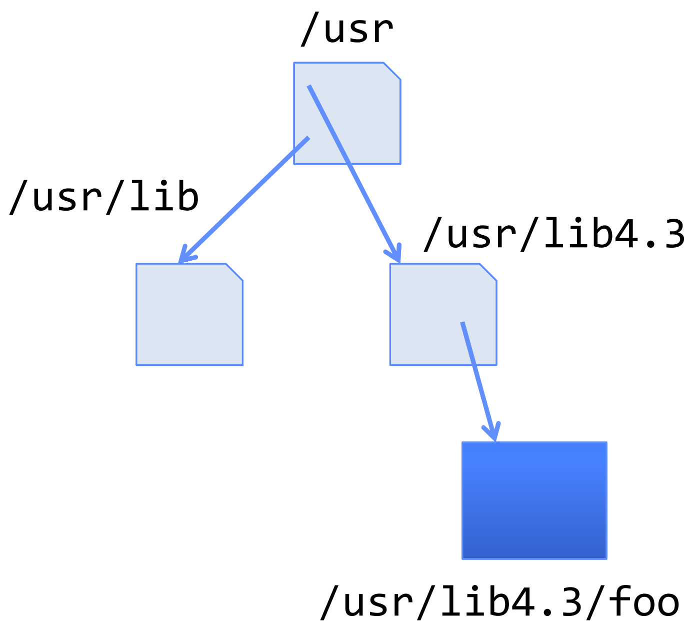
- Disk divided into block groups
  - Provides locality
  - Each group has two block-sized bitmaps (free blocks/inodes)
  - Block sizes settable at format time: 1K, 2K, 4K, 8K…
- Actual inode structure similar to 4.2 BSD
  - with 12 direct pointers
- Ext3: Ext2 with Journaling
  - Several degrees of protection with comparable overhead
  - We will talk about Journalling later



- Example: create a `file1.dat` under `/dir1/` in Ext3

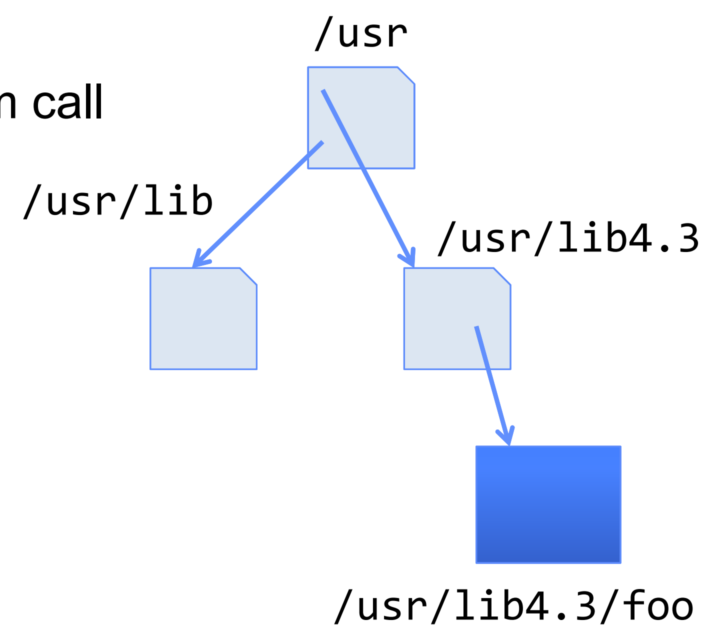
Recall: Directory Abstraction

- Directories are specialized files
  - Contents: **List of pairs <file name, file number>**
- System calls to access directories
  - `open` / `creat` 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)`



Hard Links

- Hard link
  - Mapping from name to file number in the directory structure
  - First hard link to a file is made when file created
  - Create extra hard links to a file with the link() system call
  - Remove links with unlink() system call
- When can file contents be deleted?
  - When there are no more hard links to the file
  - Inode maintains reference count for this purpose



Soft Links (Symbolic Links)

- Soft link or Symbolic Link or Shortcut
  - Directory entry contains the path and name of the file
  - Map one name to another name

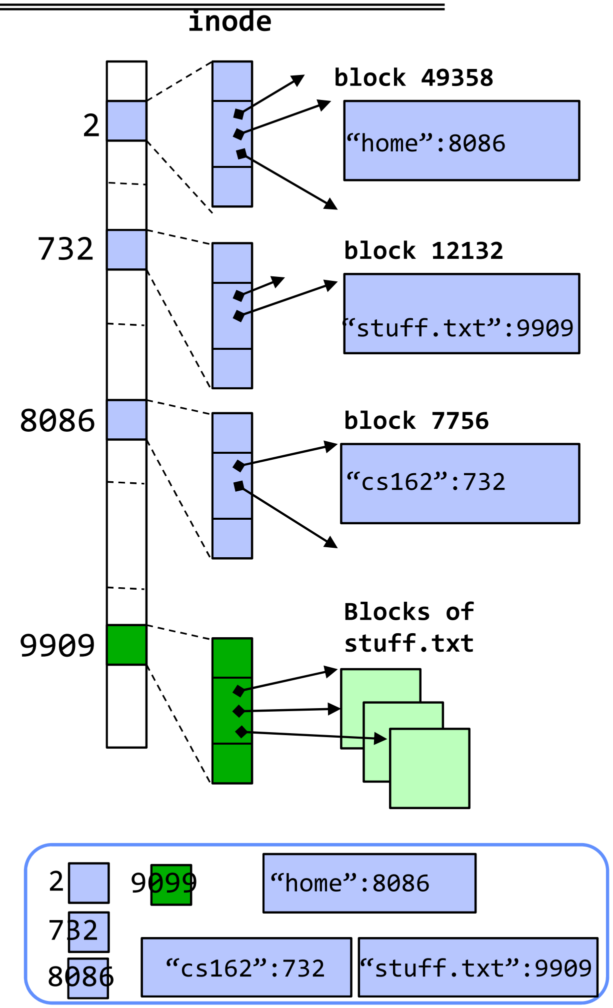
- Contrast these two different types of directory entries:
  - Normal directory entry: <file name, file #>
  - Symbolic link: <file name, dest. file name>

- OS looks up destination file name **each time** program accesses source file name
  - Lookup can fail (error result from **`open`**)

- Unix: Create soft links with **`symlink`** syscall

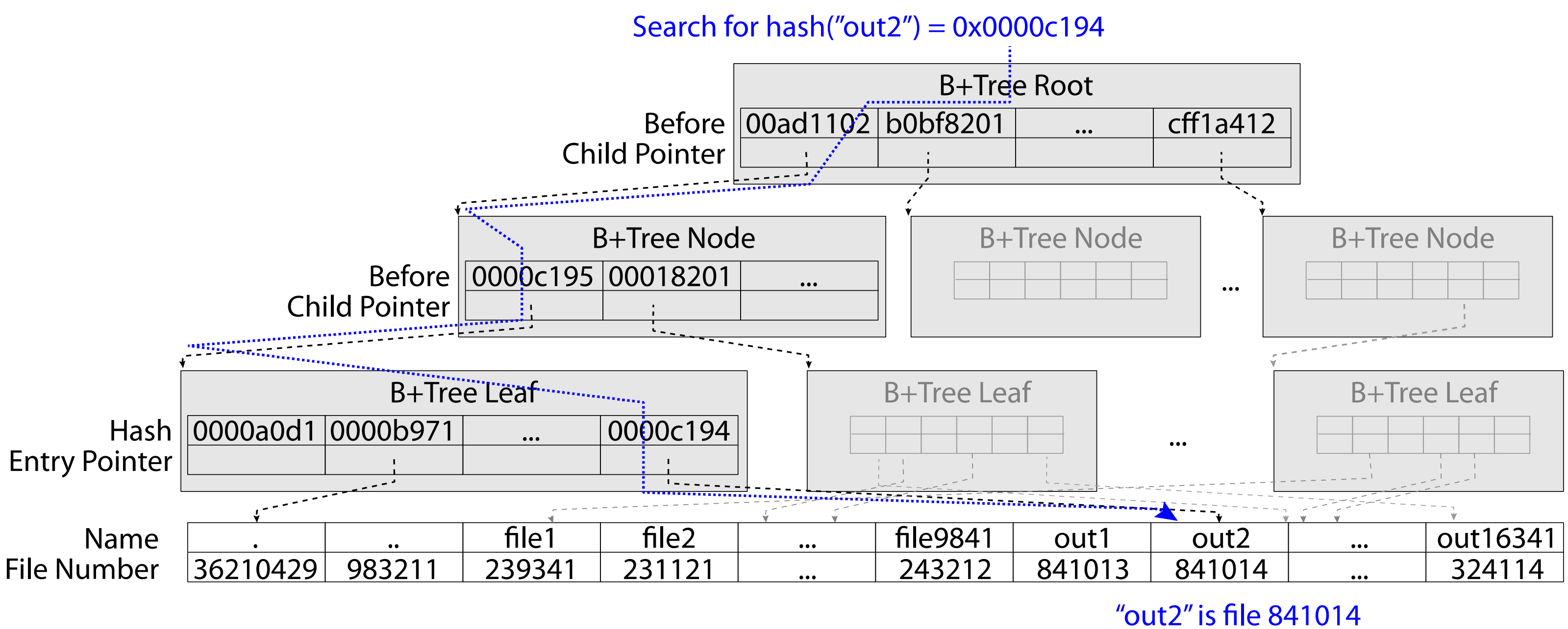
Directory Traversal

- What happens when we open `/home/cs162/stuff.txt?`
- "/" - inumber for root inode configured into kernel, say 2
  – Read inode 2 from its position in inode array on disk
  – Extract the direct and indirect block pointers
  – Determine block that holds root directory (say block 49358)
  – Read that block, scan it for "home" to get inumber for this directory (say 8086)
- Read inode 8086 for /home, extract its blocks, read block (say 7756), scan it for "cs162" to get its inumber (say 732)
- Read inode 732 for /home/cs162, extract its blocks, read block (say 12132), scan it for "stuff.txt" to get its inumber, say 9909
- Read inode 9909 for /home/cs162/stuff.txt
- Set up file description to refer to this inode so reads / write can access the data blocks referenced by its direct and indirect pointers
- **Check permissions on the final inode and each directory's inode…**



Large Directories: B-Trees (dirhash)

in FreeBSD, NetBSD, OpenBSD



Conclusion

- 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”
- Naming: translating from user-visible names to actual sys 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