Classic File Systems: LFS and FFS

CS 6410: Advanced Systems

Fall 2025

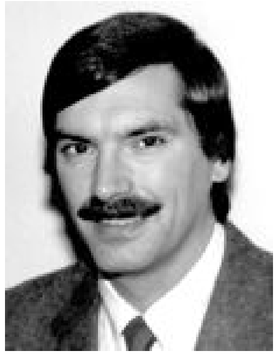
Hakim Weatherspoon

A Fast File System for UNIX

Marshall K. McKusick, William N. Joy, Samuel J Leffler, and Robert S Fabry

- Bob Fabry
  - Professor at Berkeley. Started CSRG (Computer Science Research Group) developed the Berkeley SW Dist (BSD)

- Bill Joy
  - Key developer of BSD, sent 1BSD in 1977
  - Co-Founded Sun in 1982



- Marshall (Kirk) McKusick (Cornell Alum)
  - Key developer of the BSD FFS (magic number based on his birthday, soft updates, snapshot and fsck. USENIX

- Sam Leffler
  - Key developer of BSD, author of *Design and Implementation*

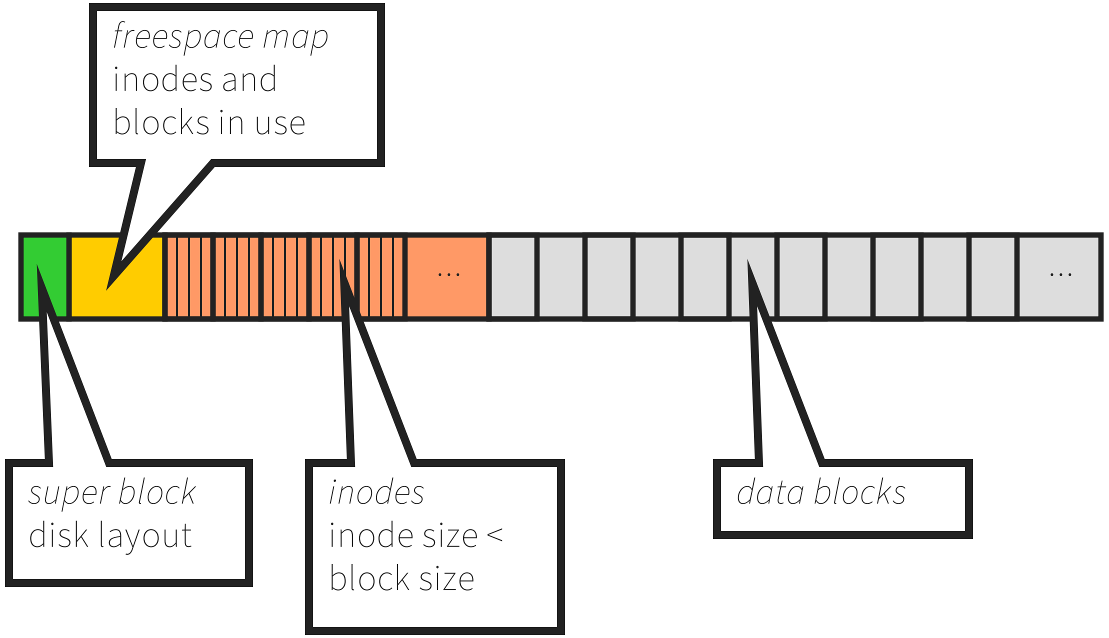
Background: Unix Fast File Sys

- Original UNIX File System (UFS)
  - Simple, elegant, but slow
  - 20 KB/sec/arm; ~2% of 1982 disk bandwidth
- Problems
  - blocks too small
  - consecutive blocks of files not close together
    (random placement for mature file system)
  - i-nodes far from data
    (all i-nodes at the beginning of the disk, all data afterward)
  - i-nodes of directory not close together
  - no read-ahead

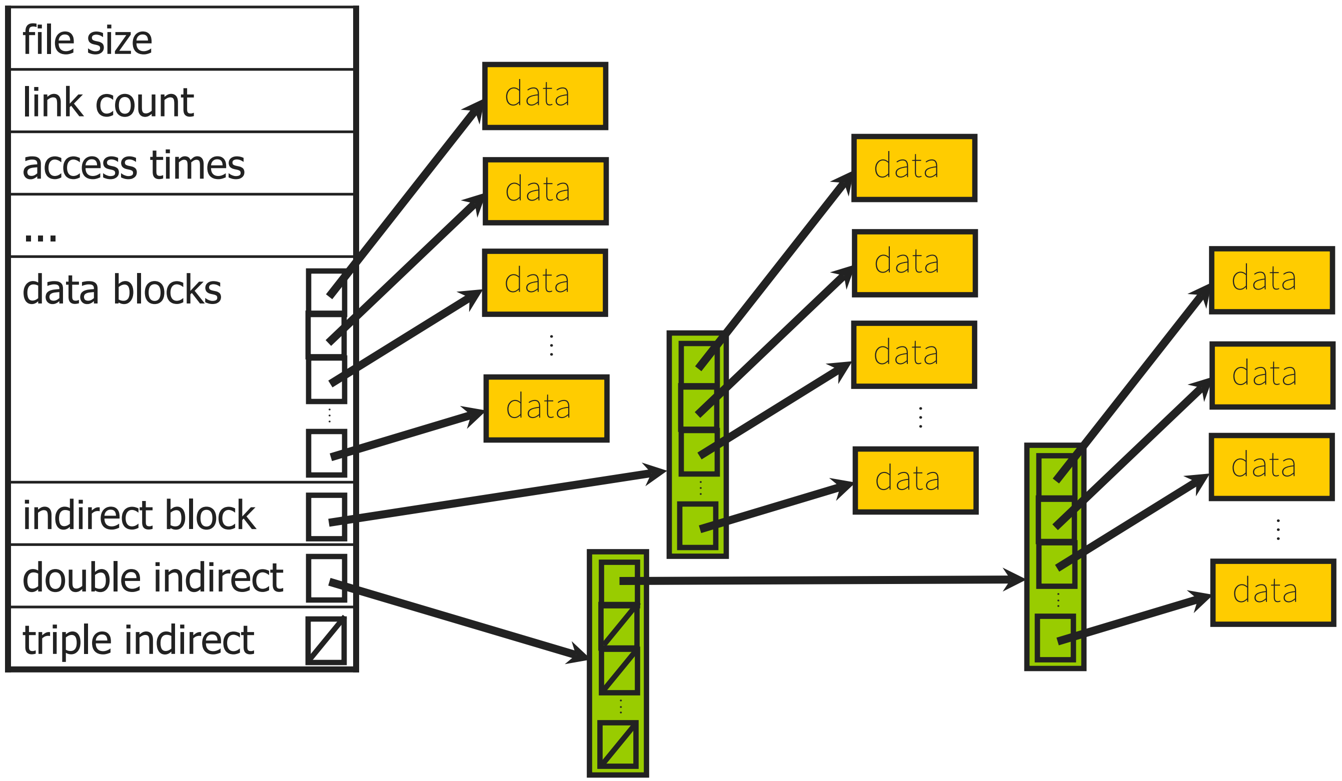
Inodes and directories

- Inode doesn't contain a file name
- Directories map files to inodes
  - Multiple directory entries can point to same Inode
  - Low-level file system doesn't distinguish files and directories
  - Separate system calls for directory operations

File system on disk



File representation



The Unix Berkeley Fast File System

- Berkeley Unix (4.2BSD)

- 4kB and 8kB blocks
  - (why not larger?)
  - Large blocks and small fragments
- Reduces seek times by better placement of file blocks
  - i-nodes correspond to files
  - Disk divided into cylinders
    - contains superblock, i-nodes, bitmap of free blocks, summary info
  - Inodes and data blocks grouped together
  - Fragmentation can still affect performance

FFS implementation

- Most operations do multiple disk writes
  - File write: update block, inode modify time
  - Create: write freespace map, write inode, write directory entry
- Write-back cache improves performance
  - Benefits due to high write locality
  - Disk writes must be a whole block
  - Syncer process flushes writes every 30s

FFS Goals

- keep dir in cylinder group, spread out different dir’s
- Allocate runs of blocks within a cylinder group, every once in a while switch to a new cylinder group (jump at 1MB).
- layout policy: global and local
  - global policy allocates files & directories to cylinder groups. Picks “optimal” next block for block allocation.
  - local allocation routines handle specific block requests. Select from a sequence of alternative if need to.

FFS locality

- don’t let disk fill up in any one area
- paradox: for locality, spread unrelated things far apart
- note: FFS got 175KB/sec because free list contained sequential blocks

  (it did generate locality), but an old UFS had randomly ordered blocks and only got 30 KB/sec

FFS Results

- 20-40% of disk bandwidth for large reads/writes
- 10-20x original UNIX speeds
- Size: 3800 lines of code vs. 2700 in old system
- 10% of total disk space unusable

FFS Enhancements

- long file names (14 -> 255)
- advisory file locks (shared or exclusive)
  - process id of holder stored with lock => can reclaim the lock if process is no longer around
- symbolic links (contrast to hard links)
- atomic rename capability
  - (the only atomic read-modify-write operation, before this there was none)
- Disk Quotas
- Overallocation
  - More likely to get sequential blocks; use later if not

FFS crash recovery

- Asynchronous writes are lost in a crash
  - **`Fsync`** system call flushes dirty data
  - Incomplete metadata operations can cause disk corruption (order is important)
- FFS metadata writes are synchronous
  - Large potential decrease in performance
  - Some OSes cut corners

After the crash

- **`Fsck`** file system consistency check
  - Reconstructs freespace maps
  - Checks inode link counts, file sizes
- Very time consuming
  - Has to scan all directories and inodes

Perspective

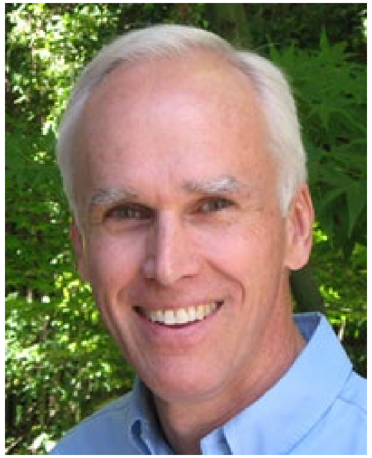
- Features
  - parameterize FS implementation for the HW in use
  - measurement-driven design decisions
  - locality “wins”
- Flaws
  - measurements derived from a single installation.
  - ignored technology trends
- Lessons
  - Do not ignore underlying HW characteristics
- Contrasting research approach
  - Improve status quo vs design something new

The Design and Impl of a Log-structured File System

Mendel Rosenblum and John K. Ousterhout

- Mendel Rosenblum
  - Designed LFS, PhD from Berkeley
  - Professor at Stanford, designed SimOS
  - Founder of VM Ware

- John Ousterhout
  - Professor at Berkeley 1980-1994
  - Created Tcl scripting language and TK platform
  - Research group designed Sprite OS and LFS
  - Now professor at Stanford after 14 years in industry



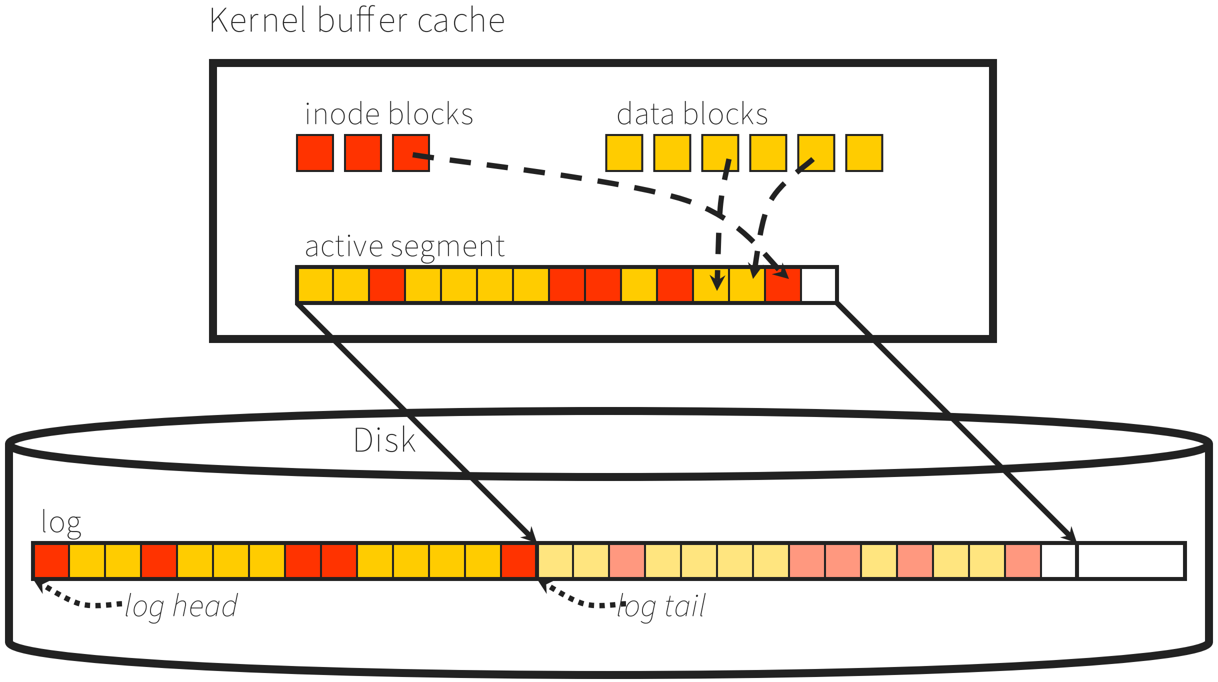
The Log-Structured File System

- Technology Trends
  - I/O becoming more and more of a bottleneck
  - CPU speed increases faster than disk speed
  - Big Memories: Caching improves read performance
  - Most disk traffic are writes
- Little improvement in write performance
  - Synchronous writes to metadata
  - Metadata access dominates for small files
  - e.g. Five seeks and I/Os to create a file
    - file i-node (create), file data, directory entry, file i-node (finalize), directory i-node (modification time).

LFS in a nutshell

- Boost write throughput by writing all changes to disk contiguously
  - Disk as an array of blocks, append at end
  - Write data, indirect blocks, inodes together
  - No need for a free block map
- Writes are written in *segments*
  - ~1MB of continuous disk blocks
  - Accumulated in cache and flushed at once
- Data layout on disk
  - "temporal locality" (good for writing)
    rather than "logical locality" (good for reading).
  - Why is this a better?
    - Because caching helps reads but not writes!

Log operation



LFS design

- Increases write throughput from 5-10% of disk to 70%
  - Removes synchronous writes
  - Reduces long seeks
- Improves over FFS
  - "Not more complicated"
  - Outperforms FFS except for one case

LFS challenges

- Log retrieval on cache misses
  - Locating inodes
- What happens when end of disk is reached?

Locating inodes

- Positions of data blocks and inodes change on each write
  - Write out inode, indirect blocks too!
- Maintain an inode map
  - Compact enough to fit in main memory
  - Written to disk periodically at *checkpoints*
    - Checkpoints (map of inode map) have special location on disk
    - Used during crash recovery

Cleaning the log: “Achilles Heel”

- Log is infinite, but disk is finite
  - Reuse the old parts of the log
- Clean old segments to recover space
  - Writes to disk create holes
  - Segments ranked by "liveness", age
  - Segment cleaner "runs in background"
- Group slowly-changing blocks together
  - Copy to new segment or "thread" into old

Cleaning policies

- Simulations to determine best policy
  - Greedy: clean based on low utilization
  - Cost-benefit: use age (time of last write)

$$\text{write cost} = \frac{\text{total bytes read and written}}{\text{new data written}}$$

$$= \frac{\text{read segs} + \text{write live} + \text{write new}}{\text{new data written}}$$

$$= \frac{N + N^*u + N^*(1-u)}{N^*(1-u)} = \frac{2}{1-u}$$

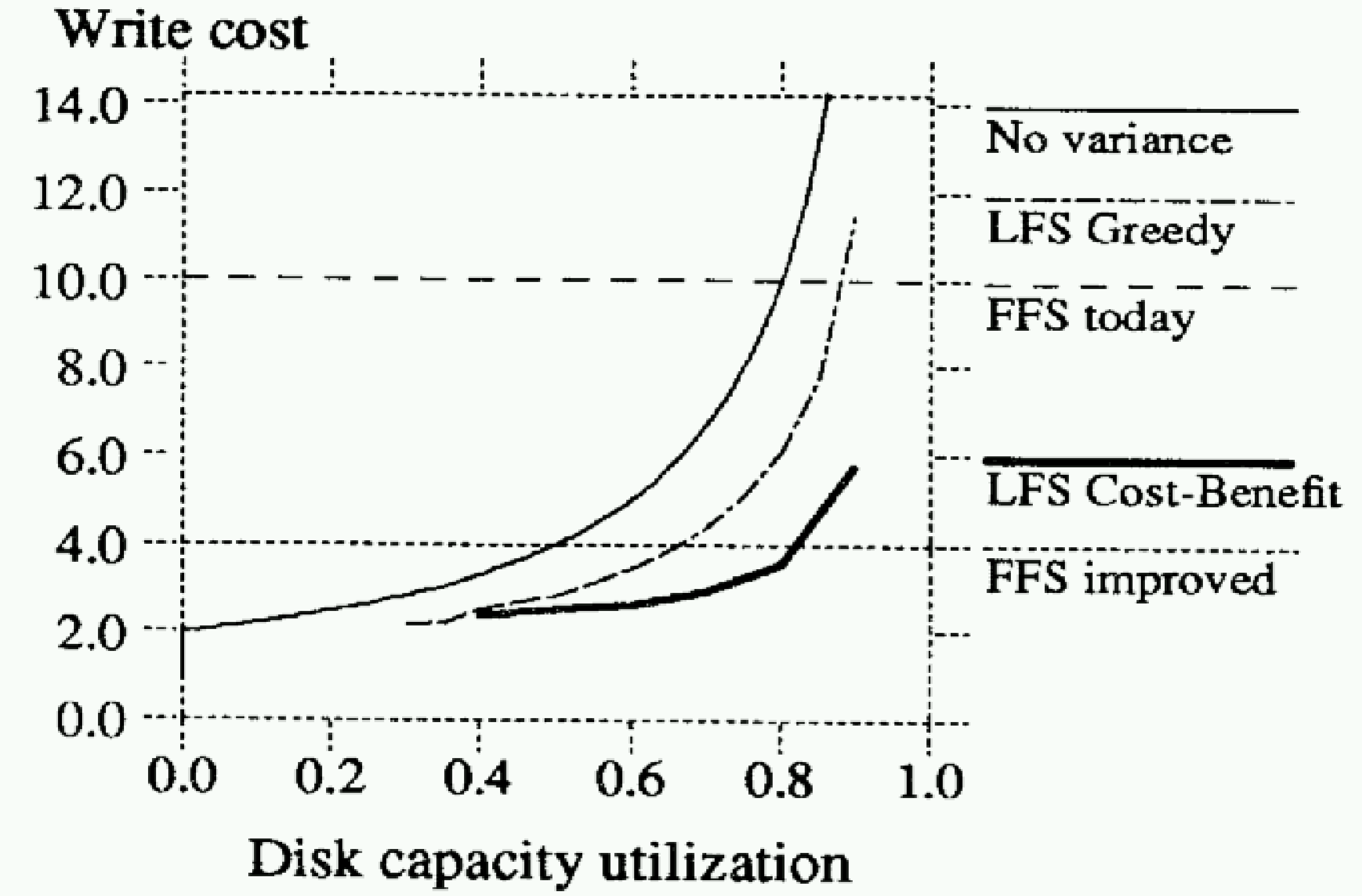
- Measure *write cost*
  - Time disk is busy for each byte written
  - Write cost 1.0 = no cleaning

Greedy: smallest μ

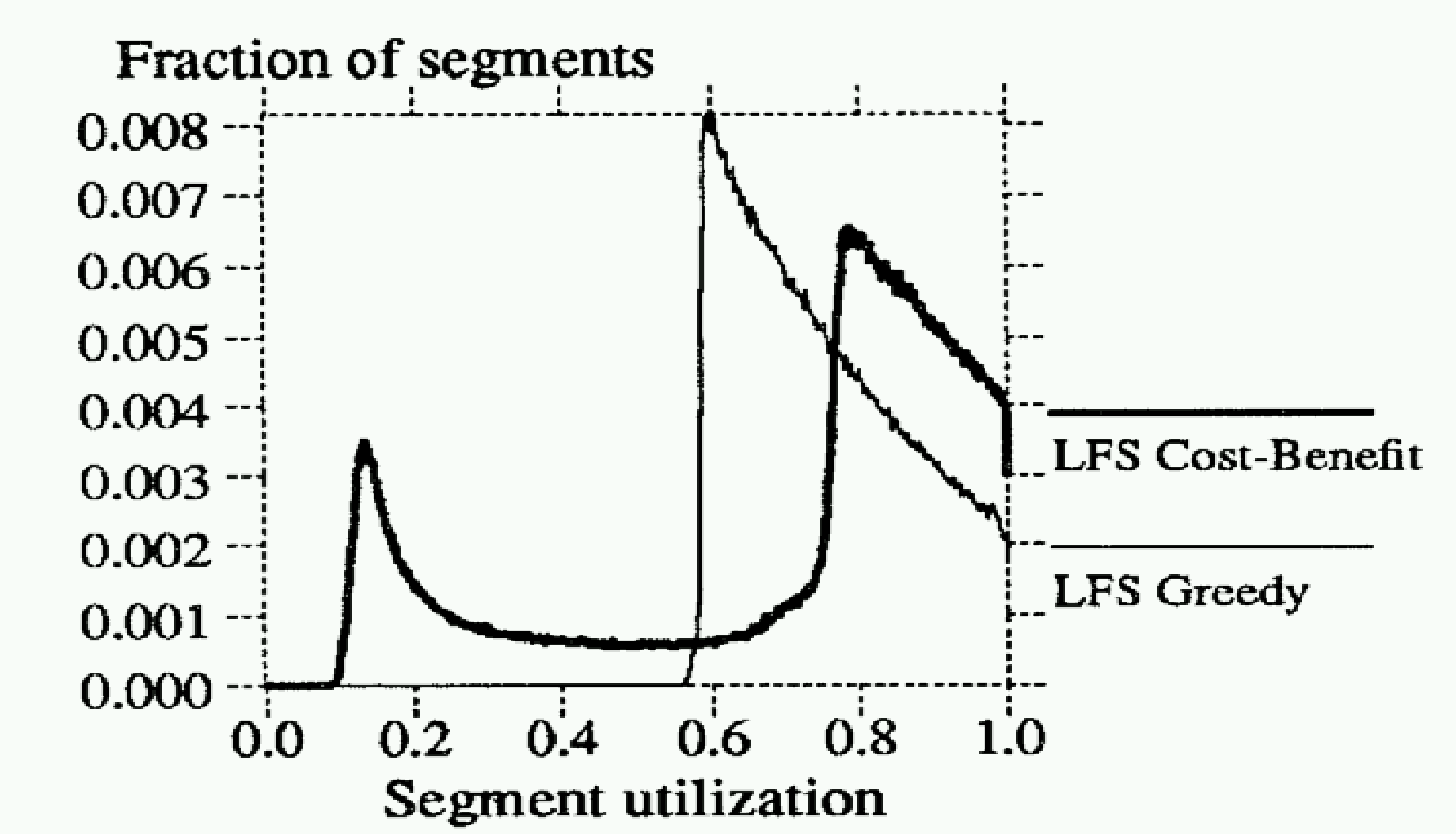
Cost-benefit:

$$\frac{\text{benefit}}{\text{cost}} = \frac{\text{free space generated} * \text{age of data}}{\text{cost}} = \frac{(1-u)^*\text{age}}{1+u}$$

Greedy versus Cost-benefit



Cost-benefit segment utilization



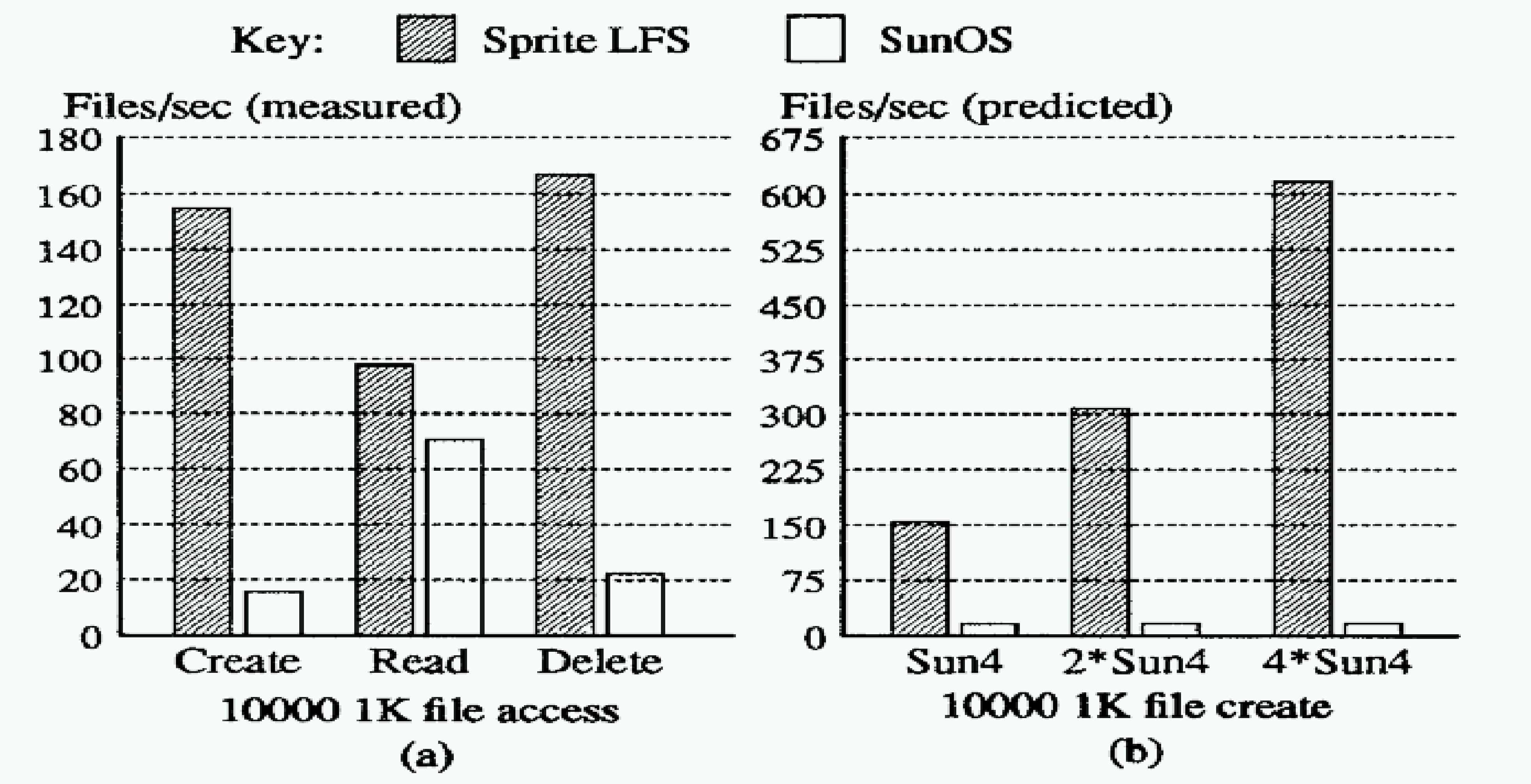
LFS crash recovery

- Log and checkpointing
  - Limited crash vulnerability
  - At checkpoint flush active segment, inode map
- No **`fsck`** required

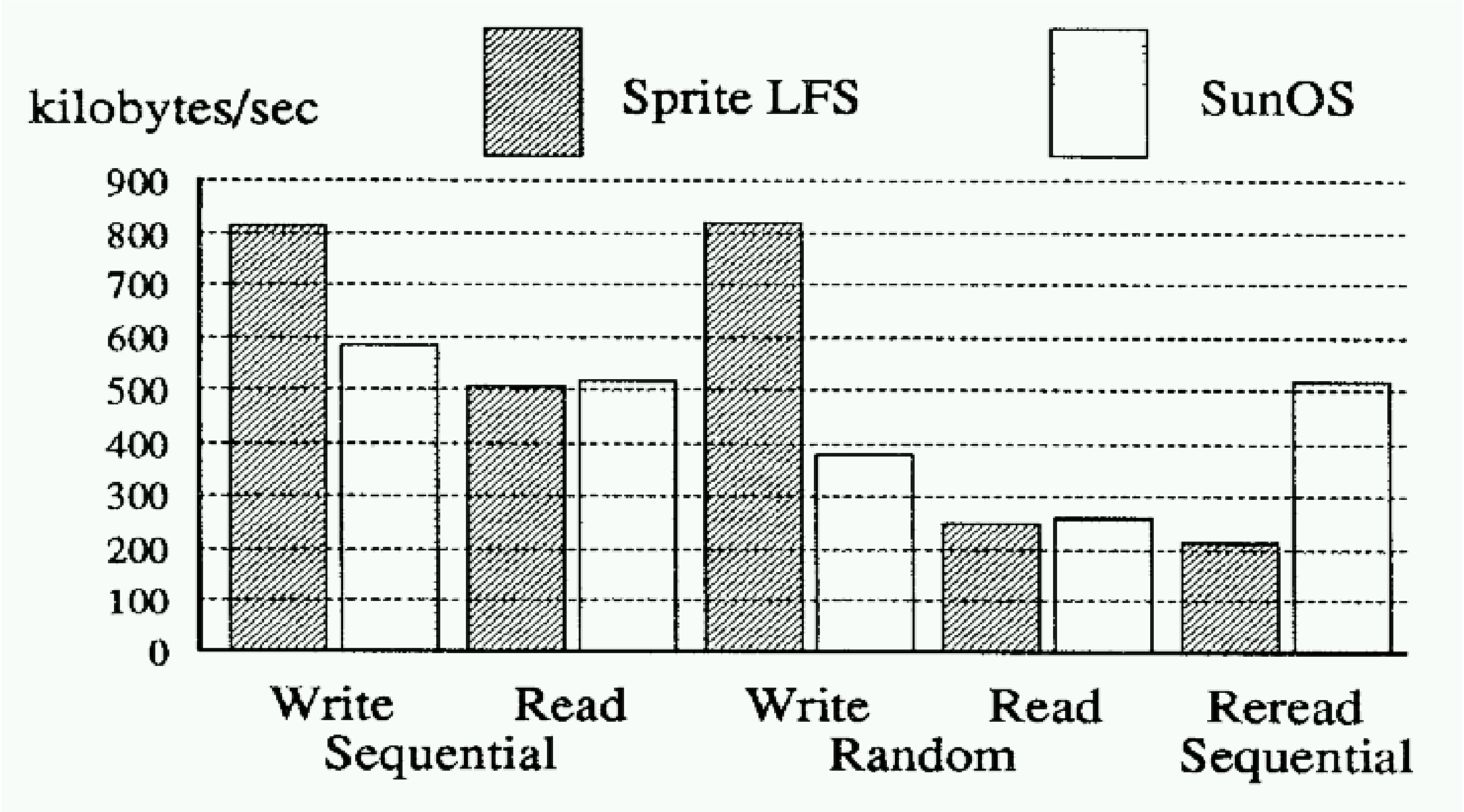
LFS performance

- Cleaning behavior better than simulated predictions
- Performance compared to SunOS FFS
  - Create-read-delete 10000 1k files
  - Write 100-MB file sequentially, read back sequentially and randomly

Small-file performance



Large-file performance



Perspective

- Features
  - CPU speed increasing faster than disk => I/O is bottleneck
  - Write FS to log and treat log as truth; use cache for speed
  - Problem
    - Find/create long runs of (contiguous) disk space to write log
  - Solution
    - clean live data from segments,
    - picking segments to clean based on a cost/benefit function
- Flaws
  - Intra-file Fragmentation: LFS assumes entire files get written
  - If small files "get bigger", how would LFS compare to UNIX?
- Lesson
  - Assumptions about primary and secondary in a design
  - LFS made log the truth instead of just a recovery aid

Conclusions

- Papers were separated by 8 years
  - Much controversy regarding LFS-FFS comparison
- Both systems have been influential
  - IBM Journaling file system
  - Ext3 filesystem in Linux
  - Soft updates come enabled in FreeBSD
  - Solid-state disks (SSD)

Next Time

- Read and write review:
  - Required: On the duality of operating system structures, H. C. Lauer and R. M. Needham. *ACM SIGOPS Operating Systems Review* Volume 12, Issue 2, April 1979, pages 3-19.

  https://dl.acm.org/doi/10.1145/850657.850658

  - Optional: Capriccio: scalable threads for internet services, R. von Behren, J. Condit, F. Zhou, G. C. Necula, E. Brewer.*ACM SIGOPS Operating Systems Review*, Volume 37, Issue 5, 2003, pages 268-281. https://dl.acm.org/doi/abs/10.1145/1165389.945471

Next Time

- Read and write review:

- Gossip miniproj
  - getting started session last week. Do we need another?

- Project Proposal due *this week*, Thu, Sep 11
  - talk to me and other faculty and email and talk to me

- Check website for updated schedule