# CSE 153
# Design of Operating Systems

## Winter 2023

Lecture 22: File system – optimizations and advanced topics

# There's more to filesystems ☺

- Standard Performance improvement techniques
- Alternative important File systems
  - FFS: Unix Fast File system
  - JFS: making File systems reliable
  - LFS: Optimizing write performance
- Improve the performance/reliability of disk drives?
  - RAID
- Generalizations
  - Network file systems
  - Distributed File systems
  - Internet scale file systems

# Improving Performance

- Disk reads and writes take order of milliseconds
  - Very slow compared to CPU and memory speeds
- How to speed things up?
  - File buffer cache
  - Cache writes
  - Read ahead

# File Buffer Cache

- Applications exhibit significant locality for reading and writing files
- Idea: Cache file blocks in memory to capture locality
  - This is called the file buffer cache
  - Cache is system wide, used and shared by all processes
  - Reading from the cache makes a disk perform like memory
  - Even a 4 MB cache can be very effective
- Issues
  - The file buffer cache competes with VM (tradeoff here)
  - Like VM, it has limited size
  - Need replacement algorithms again (LRU usually used)

# Caching Writes

- On a write, some applications assume that data makes it through the buffer cache and onto the disk
  - As a result, writes are often slow even with caching
- Several ways to compensate for this
  - "write-behind"
    - » Maintain a queue of uncommitted blocks
    - » Periodically flush the queue to disk
    - » Unreliable
  - Battery backed-up RAM (NVRAM)
    - » As with write-behind, but maintain queue in NVRAM
    - » Expensive
  - Log-structured file system
    - » Always write next block after last block written
    - » Complicated

# Read Ahead

- Many file systems implement “read ahead”
  - FS predicts that the process will request next block
  - FS goes ahead and requests it from the disk
  - This can happen while the process is computing on previous block
    - » Overlap I/O with execution
  - When the process requests block, it will be in cache
  - Compliments the disk cache, which also is doing read ahead
- For sequentially accessed files can be a big win
  - Unless blocks for the file are scattered across the disk
  - File systems try to prevent that, though (during allocation)

# FFS, JFS, LFS, RAID

- Now we're going to look at some example file and storage systems
  - BSD Unix Fast File System (FFS)
  - Journaling File Systems (JFS)
  - Log-structured File System (LFS) – Not going to cover
  - Redundant Array of Inexpensive Disks (RAID)

# Fast File System

- The original Unix file system had a simple, straightforward implementation
  - Easy to implement and understand
  - But very poor utilization of disk bandwidth (lots of seeking)
- BSD Unix folks did a redesign (mid 80s) that they called the Fast File System (FFS)
  - Improved disk utilization, decreased response time
  - McKusick, Joy, Leffler, and Fabry
- Now the FS to which all other Unix FS's are compared
- Good example of being device-aware for performance

# Data and Inode Placement

Original Unix FS had two placement problems:

1. Data blocks allocated randomly in aging file systems
   - Blocks for the same file allocated sequentially when FS is new
   - As FS "ages" and fills, need to allocate into blocks freed up when other files are deleted
   - Problem: Deleted files essentially randomly placed
   - So, blocks for new files become scattered across the disk
2. Inodes allocated far from blocks
   - All inodes at beginning of disk, far from data
   - Traversing file name paths, manipulating files, directories requires going back and forth from inodes to data blocks

Both of these problems generate many long seeks

# Cylinder Groups

- BSD FFS addressed these problems using the notion of a cylinder group
  - Disk partitioned into groups of cylinders
  - Data blocks in same file allocated in same cylinder
  - Files in same directory allocated in same cylinder
  - Inodes for files allocated in same cylinder as file data blocks
- Free space requirement
  - To be able to allocate according to cylinder groups, the disk must have free space scattered across cylinders
  - 10% of the disk is reserved just for this purpose
    - » Only used by root – this is why "df" may report >100%

# Other Problems

- Small blocks (1K) caused two problems:
  - Low bandwidth utilization
  - Small max file size (function of block size)
- Fix: Use a larger block (4K)
  - Very large files, only need two levels of indirection for 2^32
  - Problem: internal fragmentation
  - Fix: Introduce "fragments" (1K pieces of a block)
- Problem: Media failures
  - Replicate master block (superblock)
- Problem: Device oblivious
  - Parameterize according to device characteristics

# The Results

Table IIa. Reading Rates of the Old and New UNIX File Systems

| Type of file system | Processor and bus measured | Speed (Kbytes/s) | Read bandwidth % | % CPU |
|---|---|---|---|---|
| Old 1024 | 750/UNIBUS | 29 | 29/983 3 | 11 |
| New 4096/1024 | 750/UNIBUS | 221 | 221/983 22 | 43 |
| New 8192/1024 | 750/UNIBUS | 233 | 233/983 24 | 29 |
| New 4096/1024 | 750/MASSBUS | 466 | 466/983 47 | 73 |
| New 8192/1024 | 750/MASSBUS | 466 | 466/983 47 | 54 |

Table IIb. Writing Rates of the Old and New UNIX File Systems

| Type of file system | Processor and bus measured | Speed (Kbytes/s) | Write bandwidth % | % CPU |
|---|---|---|---|---|
| Old 1024 | 750/UNIBUS | 48 | 48/983 5 | 29 |
| New 4096/1024 | 750/UNIBUS | 142 | 142/983 14 | 43 |
| New 8192/1024 | 750/UNIBUS | 215 | 215/983 22 | 46 |
| New 4096/1024 | 750/MASSBUS | 323 | 323/983 33 | 94 |
| New 8192/1024 | 750/MASSBUS | 466 | 466/983 47 | 95 |

# Problem: crash consistency

- Updates to data and meta data are not atomic

- Consider, what happens when you delete a file
    1. Remove directory entry
    2. Remove the inode(s)
    3. Remove the data blocks
    4. Mark the free map (for all the i-node and data blocks you freed)
    - What happens if you crash somewhere in the middle?

# Journaling File Systems

- Journaling File systems make updates to a log
  - Log plans for updates to a journal first
  - When a crash happens you can replay the journal to restore consistency
- What if we crash when writing journal?
  - Problem.  Possible solution, bracket the changes
    - » Introduce checksum periodically
    - » Replay only parts where there is checksum that matches
- Journal choices (regular file? Special partition?)
- Log meta-data and data?

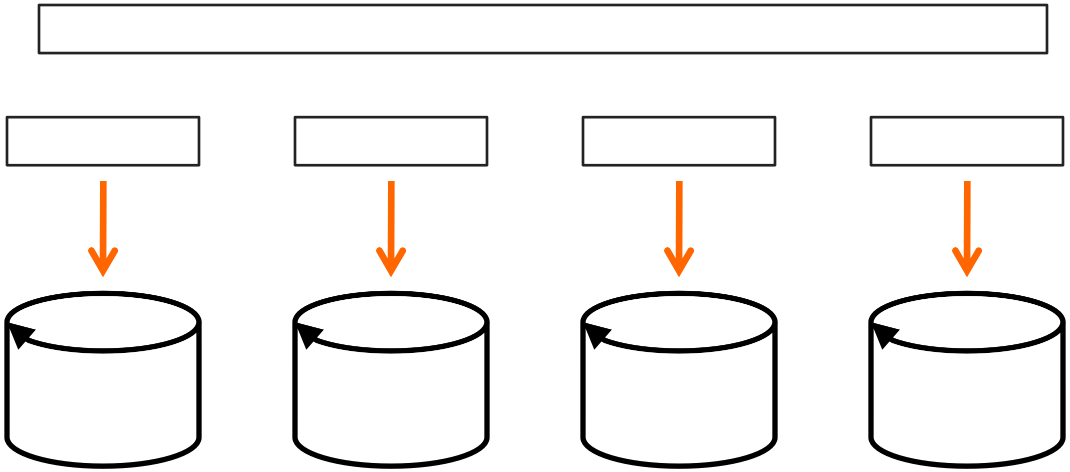
# Log-structured File System

- The Log-structured File System (LFS) was designed in response to two trends in workload and technology:
  1. Disk bandwidth scaling significantly (40% a year)
     - » While seek latency is not
  2. Large main memories in machines
     - » Large buffer caches
     - » Absorb large fraction of read requests
     - » Can use for writes as well
     - » Coalesce small writes into large writes
- LFS takes advantage of both of these to increase FS performance
  - Rosenblum and Ousterhout (Berkeley, 1991)

# RAID

- Redundant Array of Inexpensive Disks (RAID)
  - A storage system, not a file system
  - Patterson, Katz, and Gibson (Berkeley, 1988)
- Idea: Use many disks in parallel to increase storage bandwidth, improve reliability
  - Files are striped across disks
  - Each stripe portion is read/written in parallel
  - Bandwidth increases with more disks

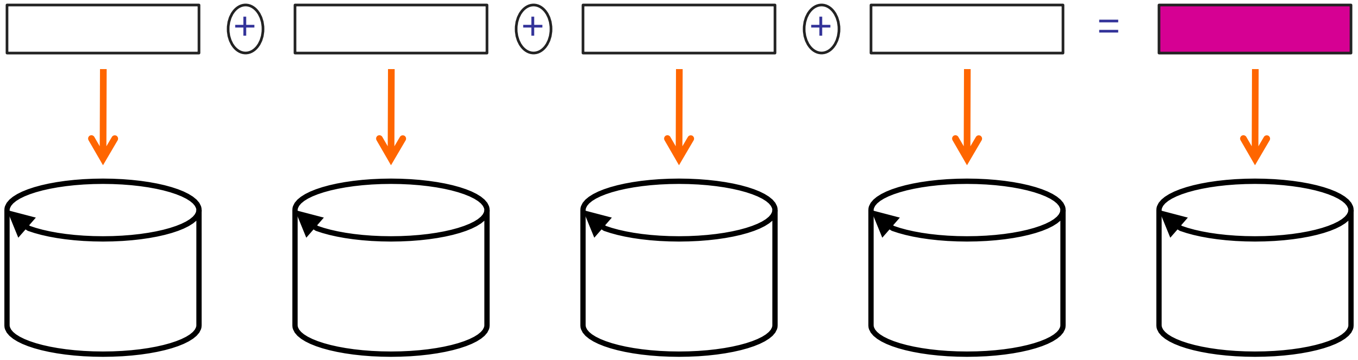
# RAID



# RAID Challenges

- Small files (small writes less than a full stripe)
  - Need to read entire stripe, update with small write, then write entire stripe out to disks
- Reliability
  - More disks increases the chance of media failure (MTBF)
- Turn reliability problem into a feature
  - Use one disk to store parity data
    - XOR of all data blocks in stripe
  - Can recover any data block from all others + parity block
  - Hence "redundant" in name
  - Introduces overhead, but, hey, disks are "inexpensive"

# RAID with parity



# RAID Levels

- In marketing literature, you will see RAID systems advertised as supporting different "RAID Levels"
- Here are some common levels:
  - RAID 0: Striping
    - » Good for random access (no reliability)
  - RAID 1: Mirroring
    - » Two disks, write data to both (expensive, 1X storage overhead)
  - RAID 2,3 and 4: bit, byte and block level parity. Rarely used.
  - RAID 5, 6: Floating parity
    - » Parity blocks for different stripes written to different disks
    - » No single parity disk, hence no bottleneck at that disk
  - RAID "10": Striping plus mirroring
    - » Higher bandwidth, but still have large overhead
    - » See this on PC RAID disk cards

# Other file system topics

- Network File systems (NFS)
  - Can a file system be shared across the network
  - The file system is on a single server, the clients access it remotely
- Distributed file systems: Can a file system be stored (and possibly replicated) across multiple machines
  - What if they are geographically spread?
  - Hadoop Distributed File System (HDFS), Google File System (GFS)
- File systems is an exciting research area
  - Take cs202 if interested!

# Summary

- UNIX file system
  - Indexed access to files using inodes
- FFS
  - Improve performance by localizing files to cylinder groups
- JFS
  - Improve reliability by logging operations in a journal
- LFS
  - Improve write performance by treating disk as a log
  - Need to clean log complicates things
- RAID
  - Spread data across disks and store parity on separate disk