COS 318: Operating Systems

Journaling, NFS and WAFL

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(http://www.cs.princeton.edu/courses/cos318/)

Topics

- Journaling and LFS
- Network File System
- NetApp File System

Revisit Implementation of Transactions

- BeginTransaction
  - Start using a “write-ahead” log on disk
  - Log all updates
- Commit
  - Write “commit” at the end of the log
  - Then “write-behind” to disk by writing updates to disk
  - Clear the log
- Rollback
  - Clear the log
- Crash recovery
  - If there is no “commit” in the log, do nothing
  - If there is “commit,” replay the log and clear the log

- Issues
  - All updates on the log must be idempotent
  - Each transaction has an Id or TID
  - Must have a way to confirm that a disk write completes

Journaling File System

- Example: Append a data block to a file on disk
  - Allocate disk blocks for data and i-node (update bitmap)
  - Update i-node and data blocks
- Journaling all updates
  - Execute the following transaction:

  BeginTransaction
  Update i-node
  Update bitmap
  Write data block
  Commit
- Journaling only metadata
  - Write data block
  - Execute the following transaction:

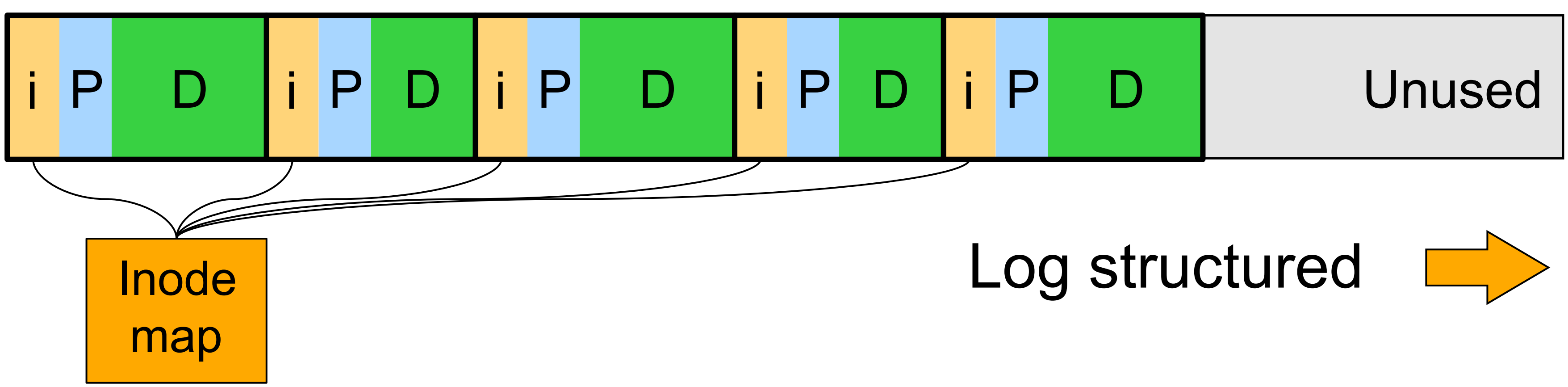
    BeginTransaction
    Update i-node
    Update bitmap
    Commit

About Journaling File System

- Consistent updates using transactions
  - Recovery is simple
- Store the log on disk storage
  - Overhead is high for journaling all updates
  - SW for commodity hardware journaling only metadata (Microsoft NTFS and various Linux file systems)
- Store the log on NVRAM
  - Efficient to journal all updates
  - Can achieve fast writes (many IOPS)
- "Write behind" performs real updates
  - Where to updates (i-nodes and data blocks)?
  - File layout is critical to performance

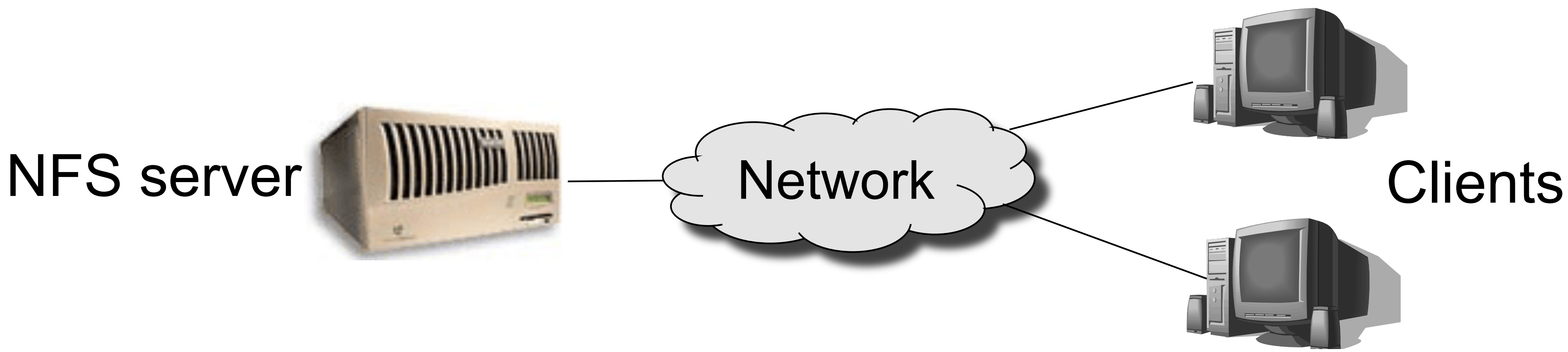
Log-structured File System (LFS)

- Structure the entire file system as a log with segments
  - A segment has i-nodes, indirect blocks, and data blocks
  - An i-node map to map i-node number to i-node locations
  - All writes are sequential
- Issues
  - There will be holes when deleting files
  - Need garbage collection to get rid of holes
  - Read performance?
- Goal is to improve write performance
  - Not to confuse with the log for transactions/journaling
  - Also useful for write and wear-leveling with NAND Flash



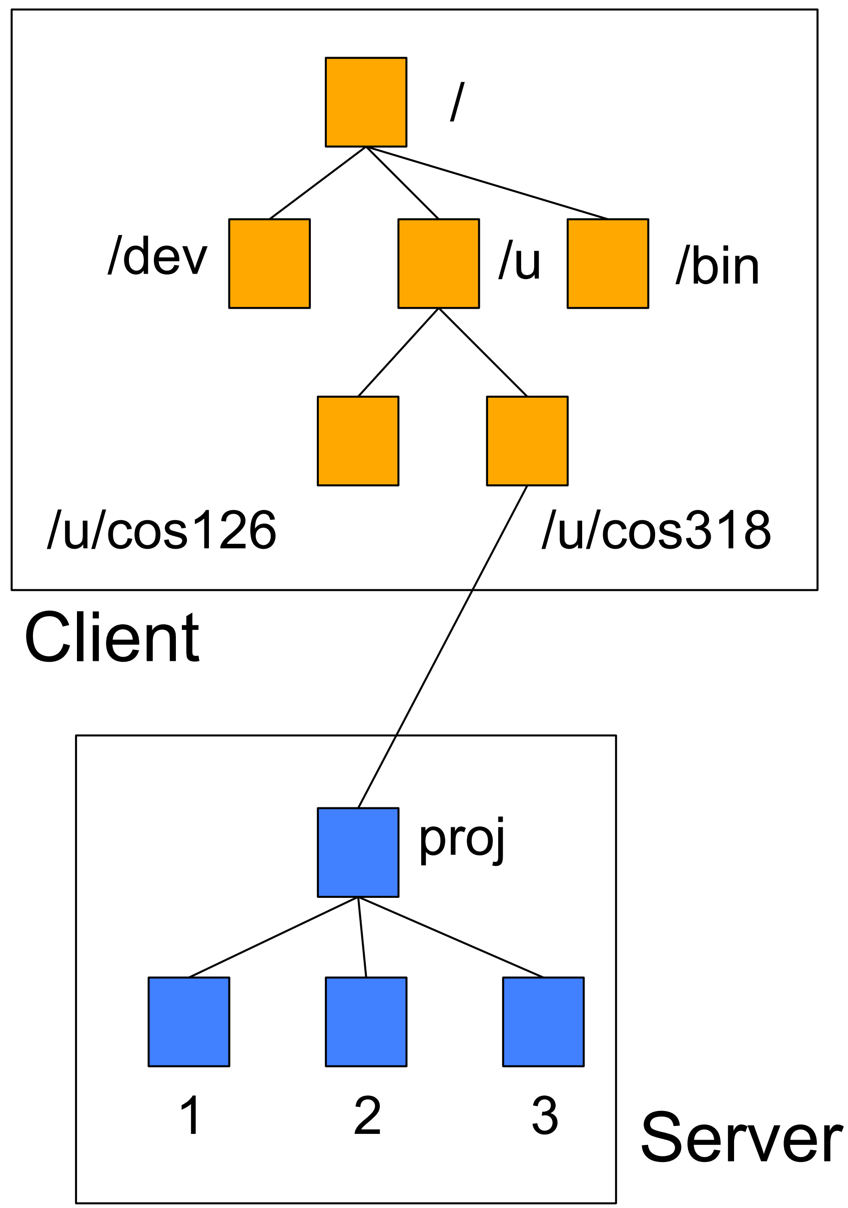
Network File System

- Multiple clients share a NFS server
- NFS v2 was introduced in early 80s



NFS Protocols

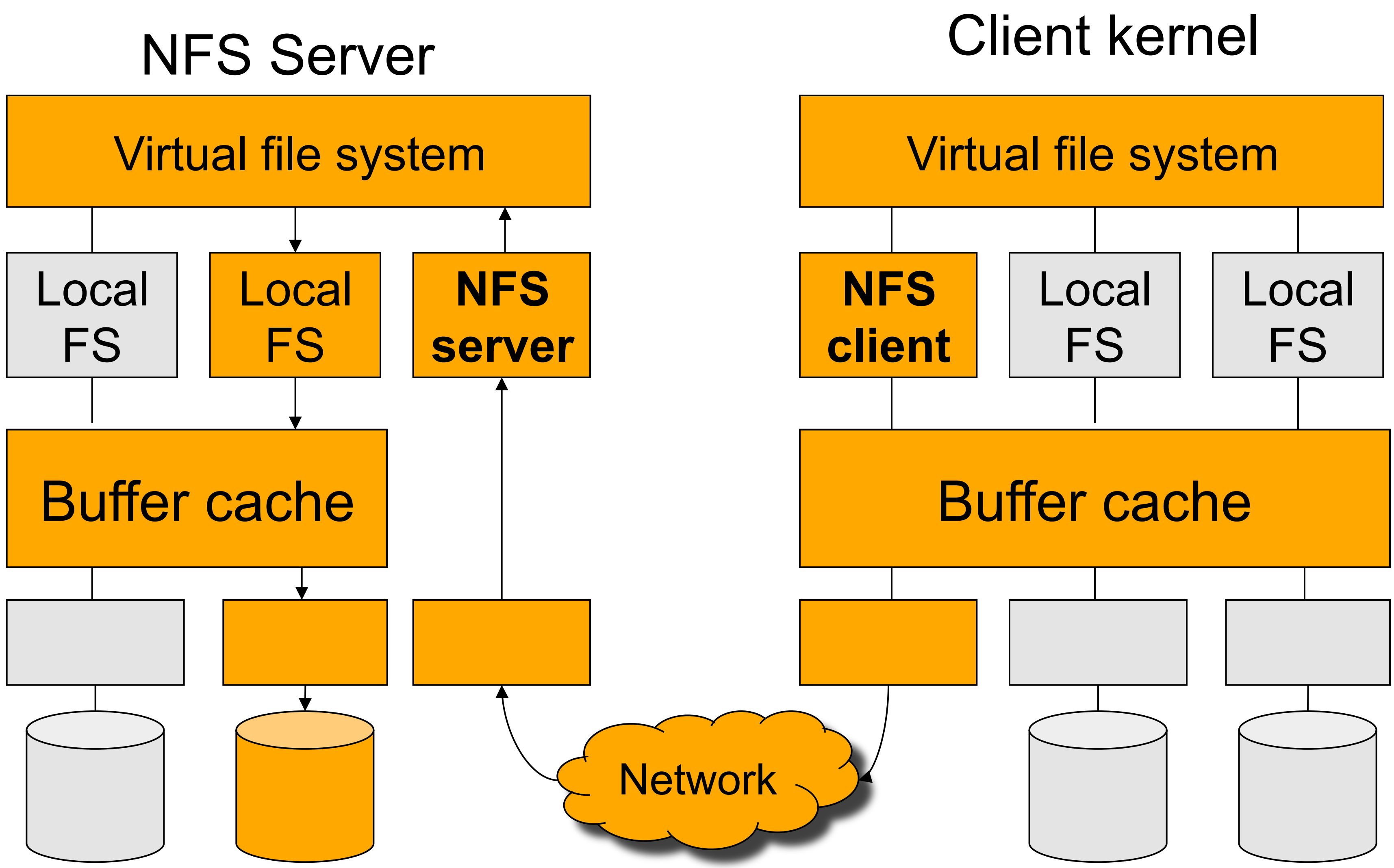
- Mounting
  - NFS server can export directories for remote accesses
  - Client sends a path name to server to request for mounting
  - Server returns a handle (file system type, disk, i-node of the directory, security info)
  - Automount
- Directory and file accesses
  - No open and close
  - Use handles to read and write
  - Stateless



NFS Protocol (v3)

1. NULL: Do nothing
2. GETATTR: Get file attributes
3. SETATTR: Set file attributes
4. LOOKUP: Lookup filename
5. ACCESS: Check Access Permission
6. READLINK: Read from symbolic link
7. READ: Read From file
8. WRITE: Write to file
9. CREATE: Create a file
10. MKDIR: Create a directory
11. SYMLINK: Create a symbolic link
12. MKNOD: Create a special device
13. REMOVE: Remove a File
14. RMDIR: Remove a Directory
15. RENAME: Rename a File or Directory
16. LINK: Create Link to an object
17. READDIR: Read From Directory
18. READDIRPLUS: Extended read from directory
19. FSSTAT: Get dynamic file system information
20. FSINFO: Get static file system Information
21. PATHCONF: Retrieve POSIX information
22. COMMIT: Commit cached data on a server to stable storage

NFS Architecture



NFS Client Caching Issues

- Consistency among multiple client caches
  - Client cache contents may not be up-to-date
  - Multiple writes can happen simultaneously
- Solutions
  - Expiration
    - Read-only file and directory data (expire in 60 seconds)
    - Data written by the client machine (write back in 30 seconds)
  - No shared caching
    - A file can be cached at only one client cache
  - Network lock manager
    - Sequential consistency (one writer or N readers)

NFS Protocol Development

- Version 2 issues
  - 18 operations
  - Size: limit to 4GB file size
  - Write performance: server writes data synchronously
  - Several other issues
- Version 3 changes (most products still use this)
  - 22 operations
  - Size: increase to 64 bit
  - Write performance: WRITE and COMMIT
  - Fixed several other issues
  - Still stateless
- Version 4 changes
  - 42 operations
  - Solve the consistency issues
  - Security issues
  - **Stateful**

NetApp's NFS File Server

- WAFL: Write Anywhere File Layout
  - The basic NetApp's file system
- Design goals
  - Fast services (more operations/sec and higher bandwidth)
  - Support large file systems and allow growing smoothly
  - High-performance software RAID
  - Restart quickly after a crash
- Special features
  - Introduce snapshots
  - Journaling by using NVRAM to implement write-ahead log
  - Layout inspired by LFS

Snapshots

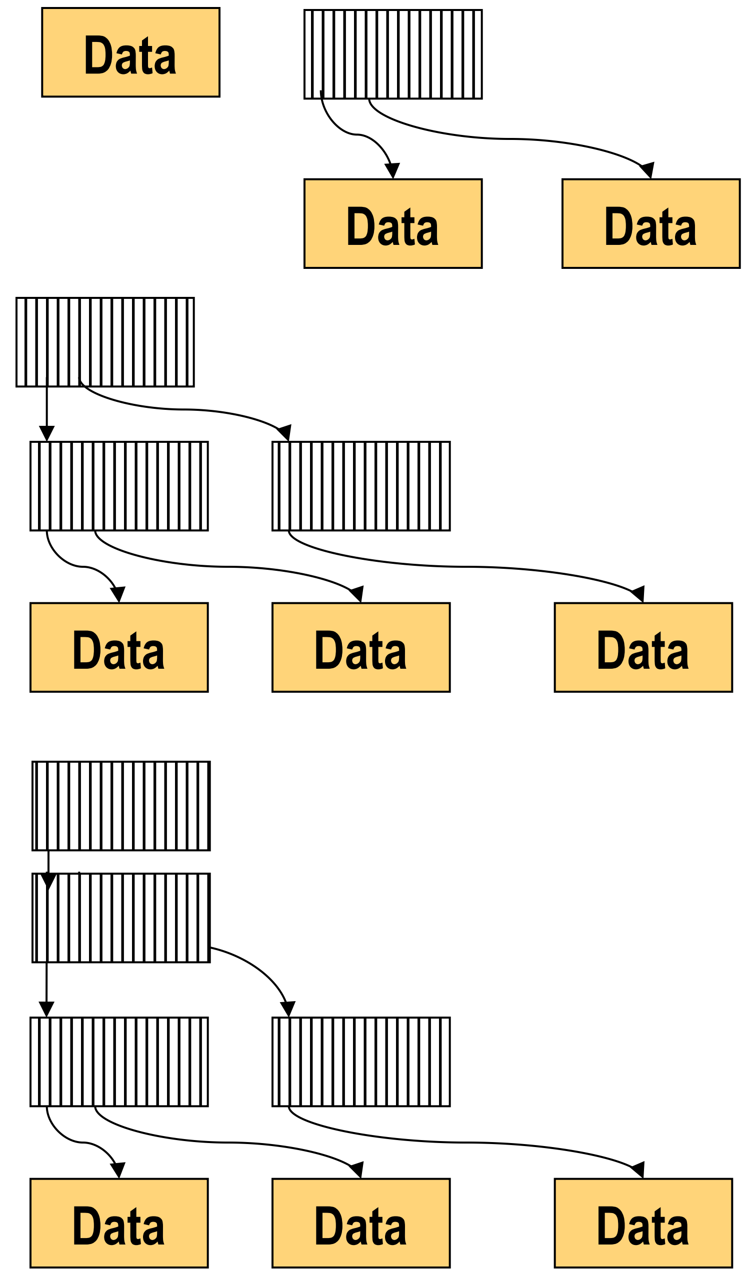
- A snapshot is a read-only copy of the file system
  - Introduced in 1993
  - It has become **a standard feature** of today's file server
- Use snapshots
  - System administrator configures the number and frequency of snapshots
  - An initial system can keep up to 20 snapshots
  - Use snapshots to recover individual files
- An example

```
phoenix% cd .snapshot
phoenix% ls
hourly.0 hourly.2 hourly.4 nightly.0 nightly.2 weekly.1
hourly.1 hourly.3 hourly.5 nightly.1 weekly.0
phoenix%
```

- How much space does a snapshot consume?

i-node, Indirect and Data Blocks

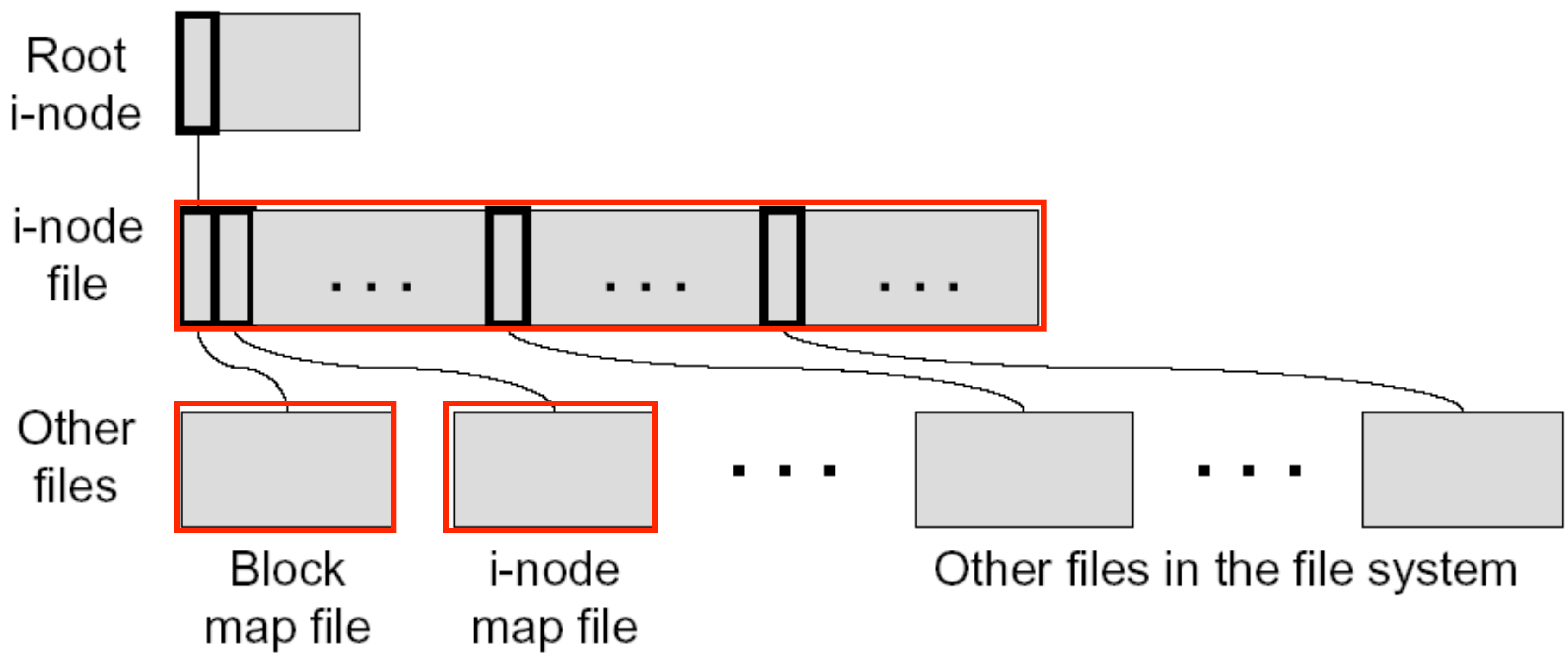
- WAFL uses 4KB blocks
  - i-nodes (evolved from UNIX's)
  - Data blocks
- File size < 64 bytes
  - i-node stores data directly
- File size < 64K bytes
  - i-node stores 16 pointers to data
- File size < 64M bytes
  - i-node stores 16 pointers to indirect blocks
  - Each indirect pointer block stores 1K pointers to data
- File size > 64M bytes
  - i-node stores pointers to doubly indirect blocks



WAFL Layout

- A WAFL file system has
  - A root i-node: root of everything
  - An i-node file: contains all i-nodes
  - A block map file: indicates free blocks
  - An i-node map file: indicates free i-nodes

Metadata in files

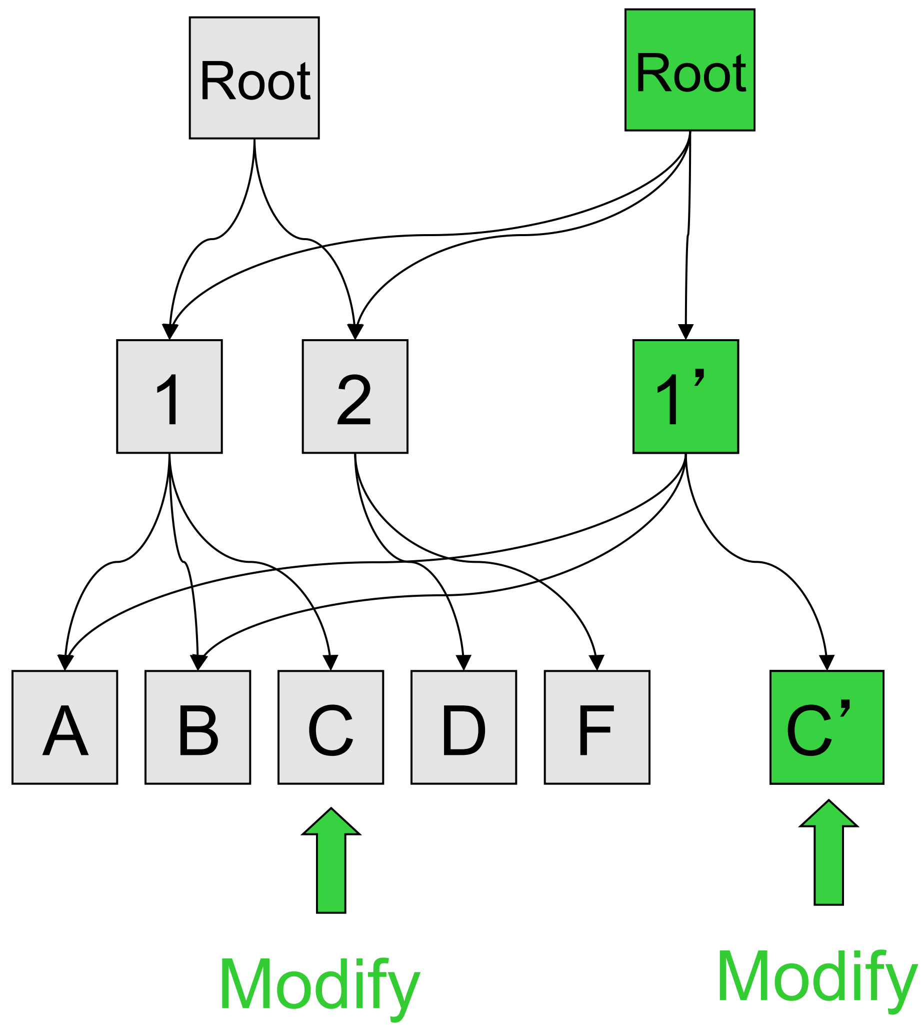


Why Keeping Metadata in Files

- Allow meta-data blocks to be written anywhere on disk
  - This is the origin of "Write Anywhere File Layout"
  - Any performance advantage?
- Easy to increase the size of the file system dynamically
  - Add a disk can lead to adding i-nodes
  - Integrate volume manager with WAFL
- Enable copy-on-write to create snapshots
  - Copy-on-write new data and metadata on new disk locations
  - Fixed metadata locations are cumbersome

Snapshot Implementation

- WAFL file system is a tree of blocks
- Snapshot step 1
  - Replicate the root i-node
  - New root i-node is the active file system
  - Old root i-node is the snapshot
- Snapshot step 2…n
  - Copy-on-write blocks to the root
  - Active root i-node points to the new blocks
  - Writes to the new block
  - Future writes into the new blocks will not trigger copy-on-write
- An "add-on" snapshot mechanism for a traditional file system?



File System Consistency

- Create a snapshot
  - Create a consistency point or snapshot every 10 seconds
  - On a crash, revert the file system to this snapshot
  - Not visible by users
- Many requests between consistency points
  - Consistency point i
  - Many writes
  - Consistency point i+1 (advanced atomically)
  - Many writes
  - …
- What are these consistent points?

Non-Volatile RAM

- Non-Volatile RAM
  - Flash memory (slower)
  - Battery-backed DRAM (fast but battery lasts for only days)
- Use an NVRAM to buffer writes
  - Buffer all write requests since the last consistency point
  - A clean shutdown empties NVRAM, creates one more snapshot, and turns off NVRAM
  - A crash recovery needs to recover data from NVRAM to the most recent snapshot and turn on the system
- Use two logs
  - Buffer one while writing another
- Issues
  - What is the main disadvantage of NVRAM?
  - How large should the NVRAM be?

Write Allocation

- WAFL can write to any blocks on disk
  - File metadata (i-node file, block map file and i-node map file) is in the file system
- WAFL can write blocks in any order
  - Rely on consistency points to enforce file consistency
  - NVRAM to buffer writes to implement ordering
- WAFL can allocate disk space for many NFS operations at once in a single write episode
  - Reduce the number of disk I/Os
  - Allocate space that is low latency
- Issue
  - What about read performance?

Snapshot Data Structure

- WAFL uses 32-bit entries in the block map file
  - 32-bit for each 4KB disk block
  - 32-bit entry = 0: the block is free
- Bit 0 = 1:
  active file system references the block
- Bit 1 = 1:
  the most recent snapshot references the block

Time	Block map entry	Description
T1	0 0 0 0 0 0 0 0	Block is free
T2	0 0 0 0 0 0 0 1	Active FS uses it
T3	0 0 0 0 0 0 1 1	Create snapshot 1
T4	0 0 0 0 0 1 1 1	Create snapshot 2
T5	0 0 0 0 0 1 1 0	Active FS deletes it
T6	0 0 0 0 0 1 0 0	Delete snapshot 1
T7	0 0 0 0 0 0 0 0	Delete snapshot 2

Set for active FS

Set for snapshot 1

Set for snapshot 2

Set for snapshot 3

Snapshot Creation

- Problem
  - Many NFS requests may arrive while creating a snapshot
  - File cache may need replacements
  - Undesirable to suspend the NFS request stream
- WAFL solution
  - Before a creation, mark dirty cache data "in-snapshot" and suspend NFS request stream
  - Defer all modifications to "in-snapshot" data
  - Modify cache data not marked "in-snapshot"
  - Do not flush cache data not marked "in-snapshot"

Algorithm

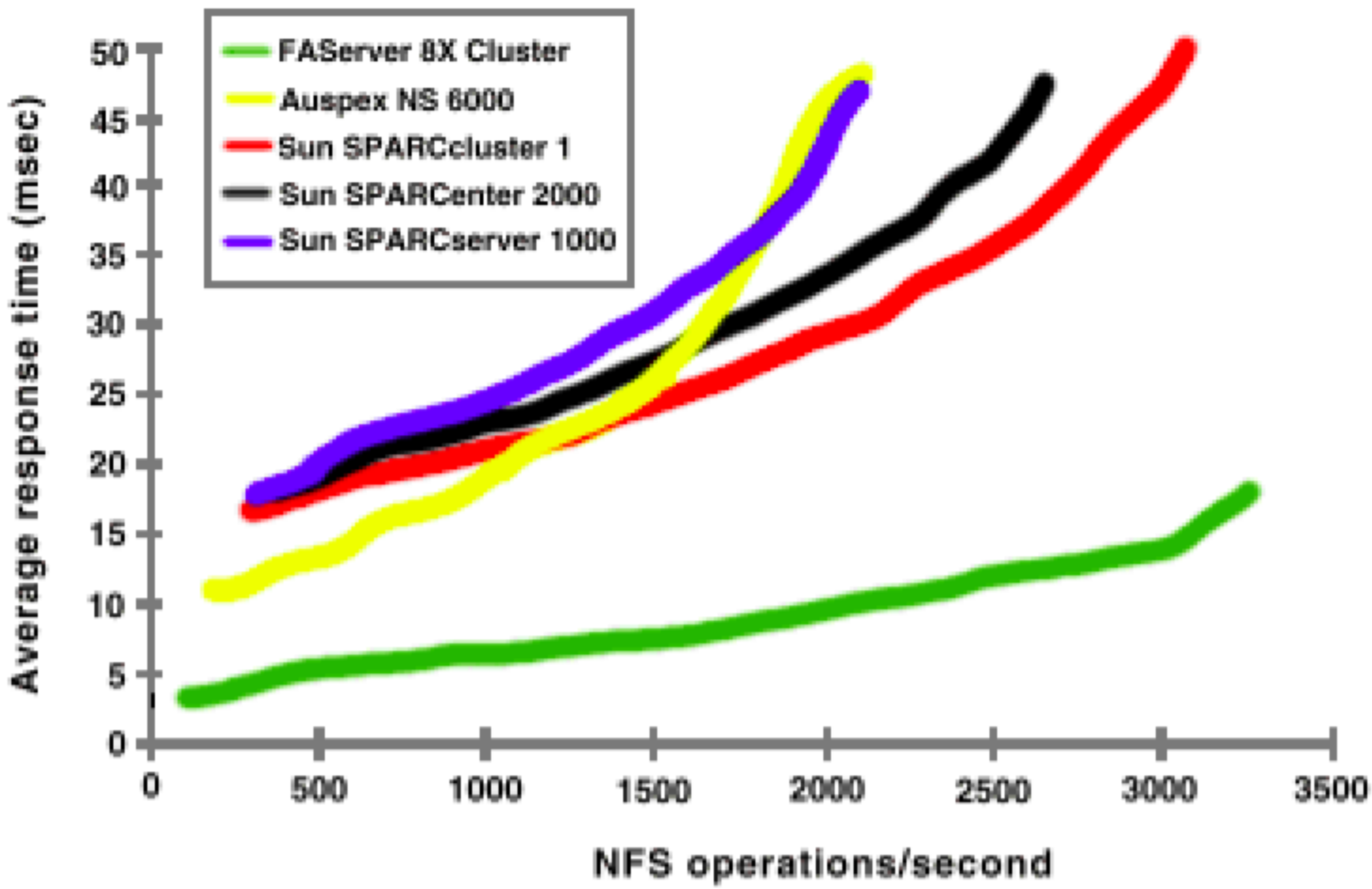
- Steps
  - Allocate disk space for "in-snapshot" cached i-nodes
    - Copy these i-nodes to disk buffer
    - Clear "in-snapshot" bit of all cached i-nodes
  - Update the block-map file
    - For each entry, copy the bit for active FS to the new snapshot
  - Flush
    - Write all "in-snapshot" disk buffers to their new disk locations
    - Restart NFS request stream
  - Duplicate the root i-node
- Performance
  - Typically it takes less than a second

Snapshot Deletion

- Delete a snapshot's root i-node
- Clear bits in block-map file
  - For each entry in block-map file, clear the bit representing the snapshot

Performance

- SPEC SFS benchmark shows 8X faster than others



Summary

- Journaling and LFS
  - Journaling uses transactions to achieve consistency
  - LFS improves write performance
- NFS
  - Stateless network file system protocol
  - Client and server caching
- WAFL
  - Write anywhere layout (inspired by LFS)
  - Snapshots have become a standard feature
  - Journaling with NVRAM