File System Reliability (part 2)

Main Points

- Approaches to reliability
  - Careful sequencing of file system operations
  - Copy-on-write (WAFL, ZFS)
  - Journalling (NTFS, linux ext4)
  - Log structure (flash storage)
- Approaches to availability
  - RAID

Last Time: File System Reliability

- Transaction concept
  - Group of operations
  - Atomicity, durability, isolation, consistency
- Achieving atomicity and durability
  - Careful ordering of operations
  - Copy on write

Reliability Approach #1: Careful Ordering

- Sequence operations in a specific order
  - Careful design to allow sequence to be interrupted safely
- Post-crash recovery
  - Read data structures to see if there were any operations in progress
  - Clean up/finish as needed
- Approach taken in FAT, FFS (fsck), and many app-level recovery schemes (e.g., Word)

Reliability Approach #2: Copy on Write File Layout

- To update file system, write a new version of the file system containing the update
  - Never update in place
  - Reuse existing unchanged disk blocks
- Seems expensive! But
  - Updates can be batched
  - Almost all disk writes can occur in parallel
- Approach taken in network file server appliances (WAFL, ZFS)

Copy On Write

- Pros
  - Correct behavior regardless of failures
  - Fast recovery (root block array)
  - High throughput (best if updates are batched)
- Cons
  - Potential for high latency
  - Small changes require many writes
  - Garbage collection essential for performance

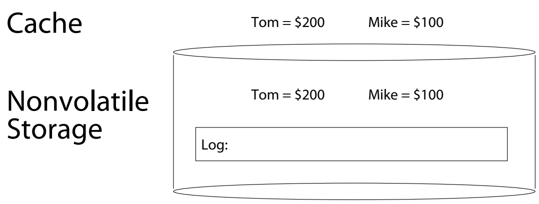
Logging File Systems

- Instead of modifying data structures on disk directly, write changes to a journal/log
  - Intention list: set of changes we intend to make
  - Log/Journal is **append-only**
- Once changes are on log, safe to apply changes to data structures on disk
  - Recovery can read log to see what changes were intended
- Once changes are copied, safe to remove log

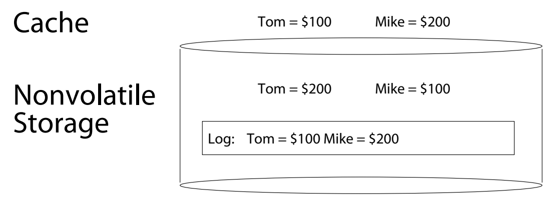
Redo Logging

- Prepare
  - Write all changes (in transaction) to log
- Commit
  - Single disk write to make transaction durable
- Redo
  - Copy changes to disk
- Garbage collection
  - Reclaim space in log
- Recovery
  - Read log
  - Redo any operations for committed transactions
  - Garbage collect log

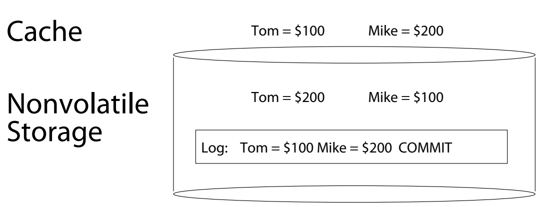
Before Transaction Start



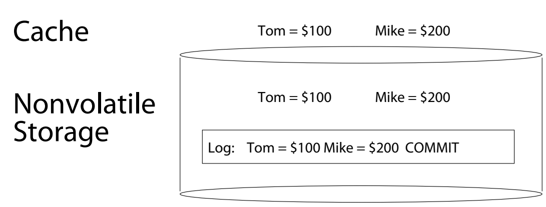
After Updates Are Logged



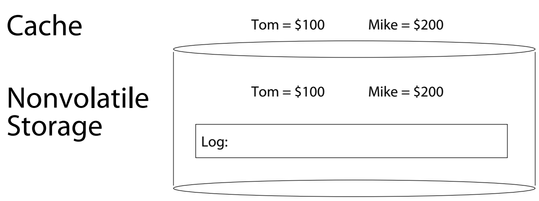
After Commit Logged



After Copy Back



After Garbage Collection



Redo Logging

- Prepare
  - Write all changes (in transaction) to log
- Commit
  - Single disk write to make transaction durable
- Redo
  - Copy changes to disk
- Garbage collection
  - Reclaim space in log
- Recovery
  - Read log
  - Redo any operations for committed transactions
  - Garbage collect log

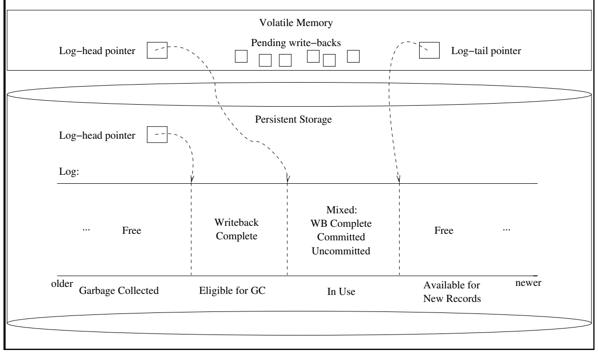
Questions

- What happens if machine crashes?
  - Before transaction start
  - After transaction start, before operations are logged
  - After operations are logged, before commit
  - After commit, before write back
  - After write back before garbage collection
- What happens if machine crashes during recovery?

Performance

- Log written sequentially
  - Often kept in flash storage
- Asynchronous write back
  - Any order as long as all changes are logged before commit, and all write backs occur after commit
- Can process multiple transactions
  - Transaction ID in each log entry
  - Transaction completed iff its commit record is in log

Redo Log Implementation



Transaction Isolation

Process A

move file from x to y
mv x/file y/

Process B

grep across x and y
grep x/* y/* > log

What if grep starts after changes are logged, but before commit?

Two Phase Locking

- Two phase locking: release locks only AFTER transaction commit
  - Prevents a process from seeing results of another transaction that might not commit

Transaction Isolation

Process A

Lock x, y
move file from x to y
mv x/file y/
Commit and release x,y

Process B

Lock x, y, log
grep across x and y
grep x/* y/* > log
Commit and release x, y, log

Grep occurs either before or after move

Serializability

- With two phase locking and redo logging, transactions appear to occur in **a** sequential order (serializability)
  - Either: grep then move or move then grep
- Other implementations can also provide serializability
  - Optimistic concurrency control: abort any transaction that would conflict with serializability

Caveat

- Most file systems implement a transactional model internally
  - Copy on write
  - Redo logging
- Most file systems provide a transactional model for individual system calls
  - File rename, move, …
- Most file systems do NOT provide a transactional model for user data
  - Historical artifact (imo)

Question

- Do we need the copy back?
  - What if update in place is very expensive?
  - Ex: flash storage, RAID

Log Structure

- Log is the data storage; no copy back
  - Storage split into contiguous fixed size segments
    - Flash: size of erasure block
    - Disk: efficient transfer size (e.g., 1MB)
  - Log new blocks into empty segment
    - Garbage collect dead blocks to create empty segments
  - Each segment contains extra level of indirection
    - Which blocks are stored in that segment
- Recovery
  - Find last successfully written segment

Reliability vs. Availability

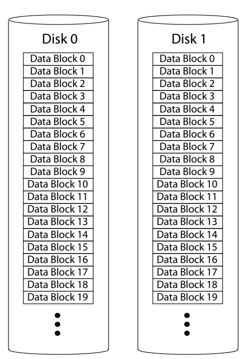
- Storage reliability: data fetched is what you stored
  - Transactions, redo logging, etc.
- Storage availability: data is there when you want it
  - What if there is a disk failure?
- What if you have more data than fits on a single disk?
  - If failures are independent and data is spread across k disks, data available ~ Prob(disk working)^k

RAID

- Replicate data for availability
  - RAID 0: no replication
  - RAID 1: mirror data across two or more disks
    - Google File System replicated all data on three disks, spread across multiple racks
  - RAID 5: split data across disks, with redundancy to recover from a single disk failure
  - RAID 6: RAID 5, with extra redundancy to recover from two disk failures

RAID 1: Mirroring

- Replicate writes to both disks
- Reads can go to either disk



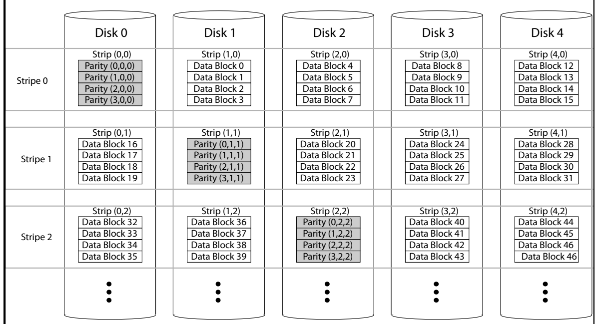
Parity

- Parity block:
  - Block1 xor block2 xor block3 …

100011
011011
110001

101001

RAID 5



RAID Update

- Mirroring
  - Write every mirror
- RAID-5: one block
  - Read old data block
  - Read old parity block
  - Write new data block
  - Write new parity block
    - Old data xor old parity xor new data
- RAID-5: entire stripe
  - Write data blocks and parity

Non-Recoverable Read Errors

- Disk devices can lose data
  - One sector per 10^15 bits read
  - Causes:
    - Physical wear
    - Repeated writes to nearby tracks
- What impact does this have on RAID recovery?

Read Errors and RAID recovery

- Example
  - 10 1TB disks
  - 1 fails
  - Read remaining disks to reconstruct missing data
- Probability of recovery =
  (1 – 10^15)^(9 disks * 8 bits * 10^12 bytes/disk)
  = 93%
- Solutions:
  - RAID-6 (more redundancy)
  - Scrubbing – read disk sectors in background to find latent errors