CS162
Operating Systems and Systems Programming
Lecture 20

Reliability, Transactions
Distributed Systems

April 10th, 2017
Prof. Ion Stoica
http://cs162.eecs.Berkeley.edu

Important "ilities"

- Availability: the probability that the system can accept and process requests
  - Often measured in "nines" of probability. So, a 99.9% probability is considered "3-nines of availability"
  - Key idea here is independence of failures
- Durability: the ability of a system to recover data despite faults
  - This idea is fault tolerance applied to data
  - Doesn't necessarily imply availability: information on pyramids was very durable, but could not be accessed until discovery of Rosetta Stone
- Reliability: the ability of a system or component to perform its required functions under stated conditions for a specified period of time (IEEE definition)
  - Usually stronger than simply availability: means that the system is not only "up", but also working correctly
  - Includes availability, security, fault tolerance/durability
  - Must make sure data survives system crashes, disk crashes, etc

How to Make File System Durable?

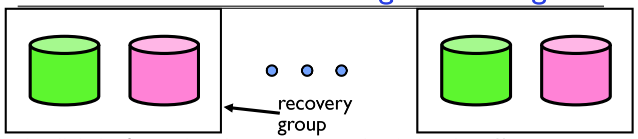
- Disk blocks contain Reed-Solomon error correcting codes (ECC) to deal with small defects in disk drive
  - Can allow recovery of data from small media defects
- Make sure writes survive in short term
  - Either abandon delayed writes or
  - Use special, battery-backed RAM (called non-volatile RAM or NVRAM) for dirty blocks in buffer cache
- Make sure that data survives in long term
  - Need to replicate! More than one copy of data!
  - Important element: independence of failure
    - » Could put copies on one disk, but if disk head fails…
    - » Could put copies on different disks, but if server fails…
    - » Could put copies on different servers, but if building is struck by lightning….
    - » Could put copies on servers in different continents…

World Backup Day March 31

RAID: Redundant Arrays of Inexpensive Disks

- Invented by David Patterson, Garth A. Gibson, and Randy Katz here at UCB in 1987
- Data stored on multiple disks (redundancy)
- Either in software or hardware
  - In hardware case, done by disk controller; file system may not even know that there is more than one disk in use
- Initially, five levels of RAID (more now)

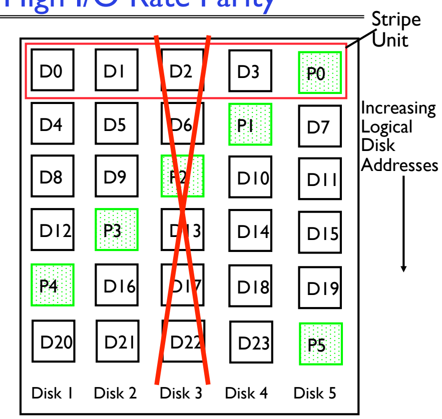
RAID 1: Disk Mirroring/Shadowing



- Each disk is fully duplicated onto its "shadow"
  - For high I/O rate, high availability environments
  - Most expensive solution: 100% capacity overhead
- Bandwidth sacrificed on write:
  - Logical write = two physical writes
  - Highest bandwidth when disk heads and rotation fully synchronized (hard to do exactly)
- Reads may be optimized
  - Can have two independent reads to same data
- Recovery:
  - Disk failure ⇒ replace disk and copy data to new disk
  - Hot Spare: idle disk already attached to system to be used for immediate replacement

RAID 5+: High I/O Rate Parity

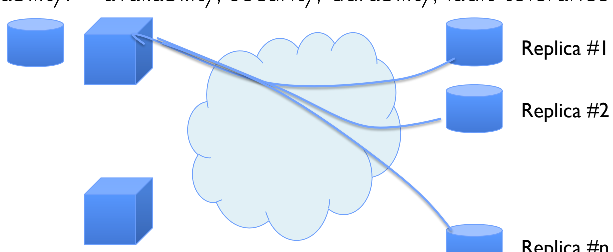
- Data stripped across multiple disks
  - Successive blocks stored on successive (non-parity) disks
  - Increased bandwidth over single disk
- Parity block (in green) constructed by XORing data bocks in stripe
  - $P0=D0 \oplus D1 \oplus D2 \oplus D3$
  - Can destroy any one disk and still reconstruct data
  - Suppose Disk 3 fails, then can reconstruct: $D2=D0 \oplus D1 \oplus D3 \oplus P0$



- Can spread information widely across internet for durability
  - Overview now, more later in semester

Higher Durability/Reliability through Geographic Replication

- Highly durable – hard to destroy all copies
- Highly available for reads – read any copy
- Low availability for writes
  - Can't write if any one replica is not up
  - Or – need relaxed consistency model
- Reliability? – availability, security, durability, fault-tolerance



File System Reliability

- What can happen if disk loses power or software crashes?
  - Some operations in progress may complete
  - Some operations in progress may be lost
  - Overwrite of a block may only partially complete
- Having RAID doesn't necessarily protect against all such failures
  - No protection against writing bad state
  - What if one disk of RAID group not written?
- File system needs durability (as a minimum!)
  - Data previously stored can be retrieved (maybe after some recovery step), regardless of failure

Storage Reliability Problem

- Single logical file operation can involve updates to multiple physical disk blocks
  - inode, indirect block, data block, bitmap, …
  - With sector remapping, single update to physical disk block can require multiple (even lower level) updates to sectors
- At a physical level, operations complete one at a time
  - Want concurrent operations for performance
- How do we guarantee consistency regardless of when crash occurs?

Threats to Reliability

- Interrupted Operation
  - Crash or power failure in the middle of a series of related updates may leave stored data in an *inconsistent state*
  - Example: Transfer funds from one bank account to another
  - What if transfer is interrupted after withdrawal and before deposit?
- Loss of stored data
  - Failure of non-volatile storage media may cause previously stored data to disappear or be corrupted

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 by
  - FAT and FFS (`fsck`) to protect filesystem structure/metadata
  - Many app-level recovery schemes (e.g., Word, emacs autosaves)

FFS: Create a File

Normal operation:

- Allocate data block
- Write data block
- Allocate inode
- Write inode block
- Update bitmap of free blocks and inodes
- Update directory with file name → inode number
- Update modify time for directory

Recovery:

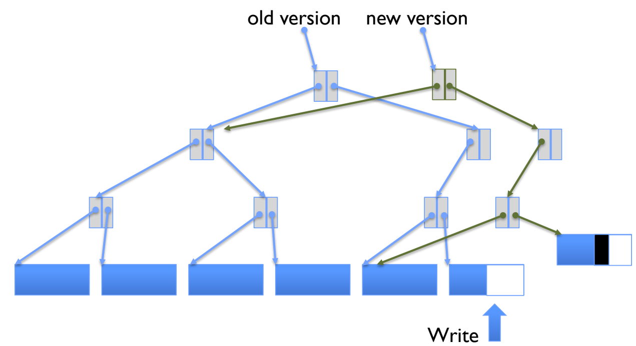
- Scan inode table
- If any unlinked files (not in any directory), delete or put in lost & found dir
- Compare free block bitmap against inode trees
- Scan directories for missing update/access times

Time proportional to disk size

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
  - NetApp's Write Anywhere File Layout (WAFL)
  - ZFS (Sun/Oracle) and OpenZFS

COW with Smaller-Radix Blocks



- If file represented as a tree of blocks, just need to update the leading fringe

ZFS and OpenZFS

- Variable sized blocks: 512 B – 128 KB
- Symmetric tree
  - Know if it is large or small when we make the copy
- Store version number with pointers
  - Can create new version by adding blocks and new pointers
- Buffers a collection of writes before creating a new version with them
- Free space represented as tree of extents in each block group
  - Delay updates to freespace (in log) and do them all when block group is activated

More General Reliability Solutions

- Use *Transactions* for atomic updates
  - Ensure that multiple related updates are performed atomically
  - i.e., if a crash occurs in the middle, the state of the systems reflects either *all or none* of the updates
  - Most modern file systems use transactions internally to update filesystem structures and metadata
  - Many applications implement their own transactions
- Provide *Redundancy* for media failures
  - Redundant representation on media (Error Correcting Codes)
  - Replication across media (e.g., RAID disk array)

Transactions

- Closely related to critical sections for manipulating shared data structures
- They extend concept of atomic update from memory to stable storage
  - Atomically update multiple persistent data structures
- Many ad hoc approaches
  - FFS carefully ordered the sequence of updates so that if a crash occurred while manipulating directory or inodes the disk scan on reboot would detect and recover the error (`fsck`)
  - Applications use temporary files and rename

Key Concept: Transaction

- An atomic sequence of actions (reads/writes) on a storage system (or database)
- That takes it from one consistent state to another

Typical Structure

- Begin a transaction – get transaction id
- Do a bunch of updates
  - If any fail along the way, roll-back
  - Or, if any conflicts with other transactions, roll-back
- Commit the transaction

"Classic" Example: Transaction

```
BEGIN;    --BEGIN TRANSACTION
 UPDATE accounts SET balance = balance - 100.00 WHERE
   name = 'Alice';

 UPDATE branches SET balance = balance - 100.00 WHERE
   name = (SELECT branch_name FROM accounts WHERE name
   = 'Alice');

 UPDATE accounts SET balance = balance + 100.00 WHERE
   name = 'Bob';

 UPDATE branches SET balance = balance + 100.00 WHERE
   name = (SELECT branch_name FROM accounts WHERE name
   = 'Bob');
COMMIT;    --COMMIT WORK
```

Transfer $100 from Alice's account to Bob's account

The ACID properties of Transactions

- **Atomicity:** all actions in the transaction happen, or none happen
- **Consistency:** transactions maintain data integrity, e.g.,
  - Balance cannot be negative
  - Cannot reschedule meeting on February 30
- **Isolation:** execution of one transaction is isolated from that of all others; no problems from concurrency
- **Durability:** if a transaction commits, its effects persist despite crashes

Administrivia

- Project 3 – Design Doc due Wednesday 4/12

Transactional File Systems (1/2)

- Better reliability through use of log
  - All changes are treated as *transactions*
  - A transaction is *committed* once it is written to the log
    - » Data forced to disk for reliability (improve perf. w/ NVRAM)
  - File system may not be updated immediately, data preserved in the log
- Difference between "Log Structured" and "Journaling"
  - In a Log Structured filesystem, data stays in log form
  - In a Journaling filesystem, Log used for recovery

Transactional File Systems (2/2)

- Journaling File System
  - Applies updates to system metadata using transactions (using logs, etc.)
  - Updates to non-directory files (i.e., user stuff) can be done in place (without logs), full logging optional
  - Ex: NTFS, Apple HFS+, Linux XFS, JFS, ext3, ext4

Logging File Systems (1/2)

- Full Logging File System
  - All updates to disk are done in transactions
- 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**
  - Single commit record commits transaction
- Once changes are in log, it is safe to apply changes to data structures on disk
  - Recovery can read log to see what changes were intended
  - Can take our time making the changes
    - » As long as new requests consult the log first

Logging File Systems (2/2)

- Once changes are copied, safe to remove log
- But, …
  - If the last atomic action is not done … poof … all gone
- Basic assumption:
  - Updates to sectors are atomic and ordered
  - Not necessarily true unless very careful, but key assumption
- Performance
  - Great for random writes: replace with appends to log
  - Impact read performance, but can alleviate this by caching

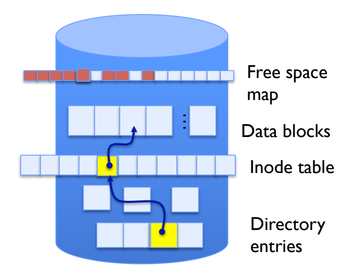
Redo Logging

- 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

Example: Creating a File

- Find free data block(s)
- Find free inode entry
- Find dirent insertion point

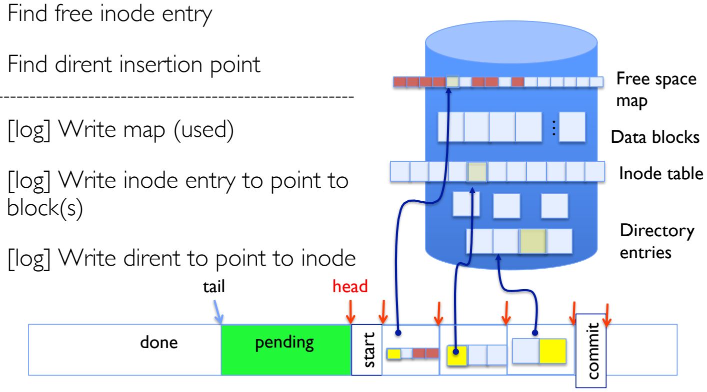
- Write map (i.e., mark used)
- Write inode entry to point to block(s)
- Write dirent to point to inode



Ex: Creating a file (as a transaction)

- Find free data block(s)
- Find free inode entry
- Find dirent insertion point

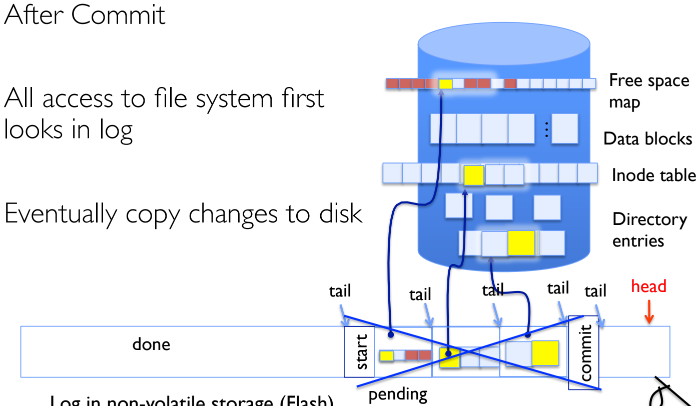
- [log] Write map (used)
- [log] Write inode entry to point to block(s)
- [log] Write dirent to point to inode



Log in non-volatile storage (Flash or on Disk)

ReDo Log

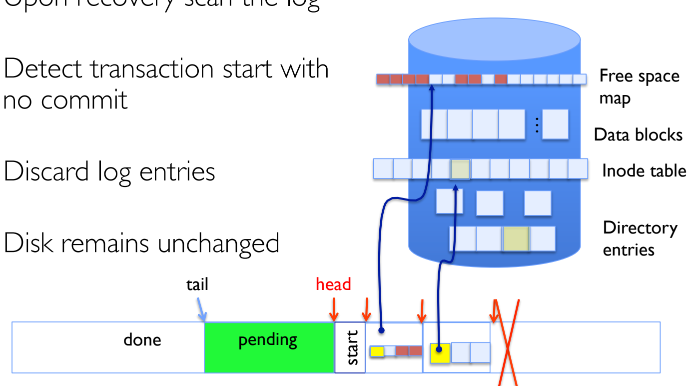
- After Commit
- All access to file system first looks in log
- Eventually copy changes to disk



Log in non-volatile storage (Flash)

Crash During Logging – Recover

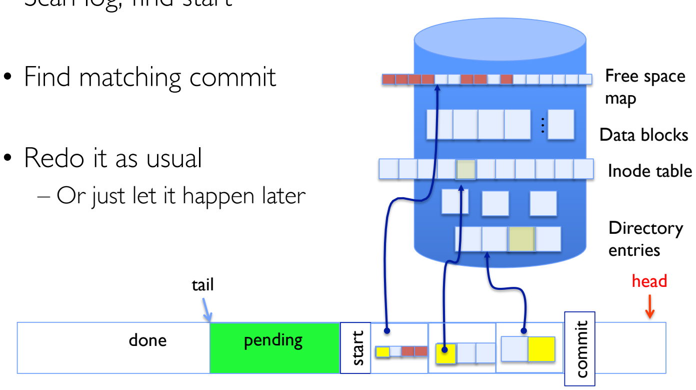
- Upon recovery scan the log
- Detect transaction start with no commit
- Discard log entries
- Disk remains unchanged



Log in non-volatile storage (Flash or on Disk)

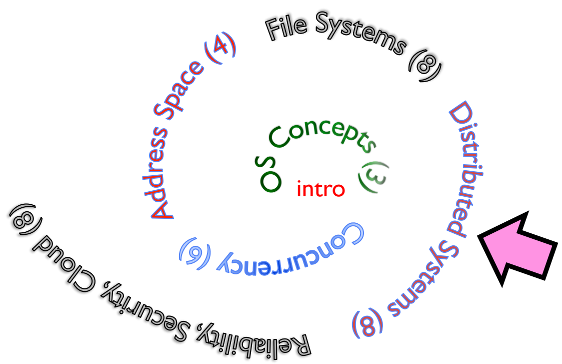
Recovery After Commit

- Scan log, find start
- Find matching commit
- Redo it as usual
  - Or just let it happen later

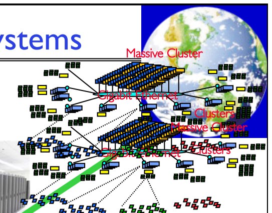


Log in non-volatile storage (Flash or on Disk)

Course Structure: Spiral

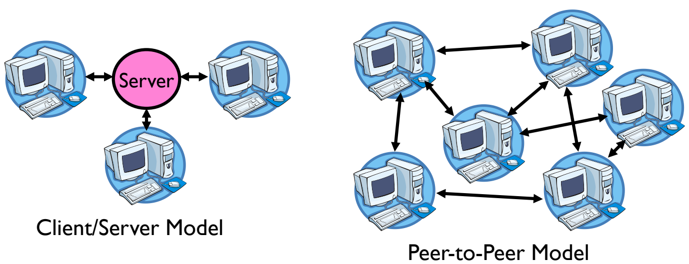


Societal Scale Information Systems



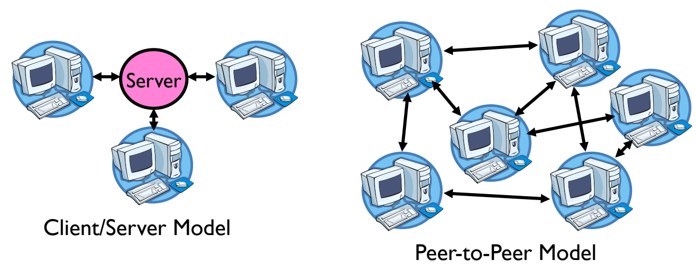
- The world is a large distributed system
  - Microprocessors in everything
  - Vast infrastructure behind them

Centralized vs Distributed Systems



- Centralized System: System in which major functions are performed by a single physical computer
  - Originally, everything on single computer
  - Later: client/server model

Centralized vs Distributed Systems



- Distributed System: physically separate computers working together on some task
  - Early model: multiple servers working together
    - » Probably in the same room or building
    - » Often called a "cluster"
  - Later models: peer-to-peer/wide-spread collaboration

Distributed Systems: Motivation/Issues/Promise

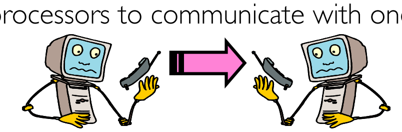
- Why do we want distributed systems?
  - Cheaper and easier to build lots of simple computers
  - Easier to add power incrementally
  - Users can have complete control over some components
  - Collaboration: much easier for users to collaborate through network resources (such as network file systems)
- The *promise* of distributed systems:
  - Higher availability: one machine goes down, use another
  - Better durability: store data in multiple locations
  - More security: each piece easier to make secure

Distributed Systems: Reality

- Reality has been disappointing
  - Worse availability: depend on every machine being up
    - » Lamport: "a distributed system is one where I can't do work because some machine I've never heard of isn't working!"
  - Worse reliability: can lose data if any machine crashes
  - Worse security: anyone in world can break into system
- Coordination is more difficult
  - Must coordinate multiple copies of shared state information (using only a network)
  - What would be easy in a centralized system becomes a lot more difficult

Distributed Systems: Goals/Requirements

- Transparency: the ability of the system to mask its complexity behind a simple interface
- Possible transparencies:
  - Location: Can't tell where resources are located
  - Migration: Resources may move without the user knowing
  - Replication: Can't tell how many copies of resource exist
  - Concurrency: Can't tell how many users there are
  - Parallelism: System may speed up large jobs by splitting them into smaller pieces
  - Fault Tolerance: System may hide various things that go wrong
- Transparency and collaboration require some way for different processors to communicate with one another



Summary

- RAID: Redundant Arrays of Inexpensive Disks
  - RAID1: mirroring, RAID5: Parity block
- Use of Log to improve Reliability
  - Journaling file systems such as ext3, NTFS
- Transactions: ACID semantics
  - Atomicity
  - Consistency
  - Isolation
  - Durability