CS162
Operating Systems and Systems Programming
Lecture 20

Reliability, Transactions Distributed Systems

April 16th, 2019
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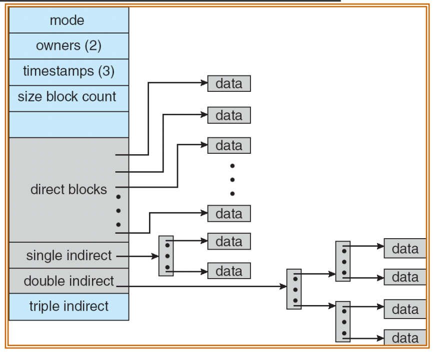
Recall: Multilevel Indexed Files (Original 4.1 BSD)



- Sample file in multilevel indexed format:
  - 10 direct ptrs, 1K blocks
  - How many accesses for block #23? (assume file header accessed on open)?
    - » Two: One for indirect block, one for data
  - How about block #5?
    - » One: One for data
  - Block #340?
    - » Three: double indirect block, indirect block, and data
- UNIX 4.1 Pros and cons
  - Pros: Simple (more or less)
    Files can easily expand (up to a point)
    Small files particularly cheap and easy
  - Cons: Lots of seeks (lead to 4.2 Fast File System Optimizations)
- Ext2/3 (Linux):
  - 12 direct ptrs, triply-indirect blocks, settable block size (4K is common)

Recall: File System Caching

- Key Idea: Exploit locality by caching data in memory
  - Name translations: Mapping from paths→inodes
  - Disk blocks: Mapping from block address→disk content
- Buffer Cache: Memory used to cache kernel resources, including disk blocks and name translations
  - Can contain "dirty" blocks (blocks yet on disk)
- Replacement policy? LRU
  - Can afford overhead full LRU implementation
  - Advantages:
    - » Works very well for name translation
    - » Works well in general as long as memory is big enough to accommodate a host's working set of files.
  - Disadvantages:
    - » Fails when some application scans through file system, thereby flushing the cache with data used only once
    - » Example: `find . -exec grep foo {} \;`
- Other Replacement Policies?
  - Some systems allow applications to request other policies
  - Example, 'Use Once':
    - » File system can discard blocks as soon as they are used

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File System Caching (con't)

- Cache Size: How much memory should the OS allocate to the buffer cache vs virtual memory?
  - Too much memory to the file system cache ⇒ won't be able to run many applications at once
  - Too little memory to file system cache ⇒ many applications may run slowly (disk caching not effective)
  - Solution: adjust boundary dynamically so that the disk access rates for paging and file access are balanced
- Read Ahead Prefetching: fetch sequential blocks early
  - Key Idea: exploit fact that most common file access is sequential by prefetching subsequent disk blocks ahead of current read request (if they are not already in memory)
  - Elevator algorithm can efficiently interleave groups of prefetches from concurrent applications
  - How much to prefetch?
    - » Too many imposes delays on requests by other applications
    - » Too few causes many seeks (and rotational delays) among concurrent file requests

File System Caching (con't)

- Delayed Writes: Writes to files not immediately sent out to disk
  - Instead, `write()` copies data from user space buffer to kernel buffer (in cache)
    - » Enabled by presence of buffer cache: can leave written file blocks in cache for a while
    - » If some other application tries to read data before written to disk, file system will read from cache
  - Flushed to disk periodically (e.g. in UNIX, every 30 sec)
  - Advantages:
    - » Disk scheduler can efficiently order lots of requests
    - » Disk allocation algorithm can be run with correct size value for a file
    - » Some files need never get written to disk! (e..g temporary scratch files written /tmp often don't exist for 30 sec)
  - Disadvantages
    - » What if system crashes before file has been written out?
    - » Worse yet, what if system crashes before a directory file has been written out? (lose pointer to inode!)

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, other problems

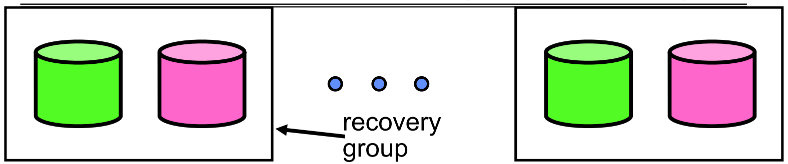
How to Make File System Durable?

- 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…

RAID: Redundant Arrays of Inexpensive Disks

- Classified by David Patterson, Garth A. Gibson, and Randy Katz here at UCB in 1987
  - Classic paper was first to evaluate multiple schemes
- Data stored on multiple disks (redundancy)
  - Berkeley researchers were looking for alternatives to big expensive disks
  - Redundancy necessary because cheap disks were more error prone
- 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

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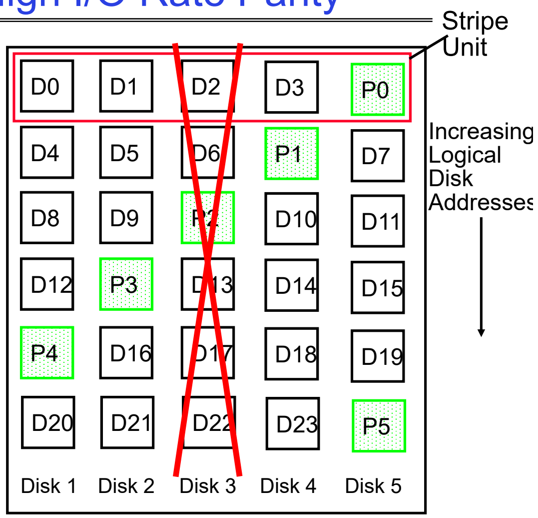
RAID 5+: High I/O Rate Parity

- 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: $D2=D0\oplus D1\oplus D3\oplus P0$



Disk 1	Disk 2	Disk 3	Disk 4	Disk 5
D0	D1	D2	D3	P0
D4	D5	D6	P1	D7
D8	D9	P2	D10	D11
D12	P3	D13	D14	D15
P4	D16	D17	D18	D19
D20	D21	D22	D23	P5

- Can spread information widely across internet for durability
  - RAID algorithms work over geographic scale

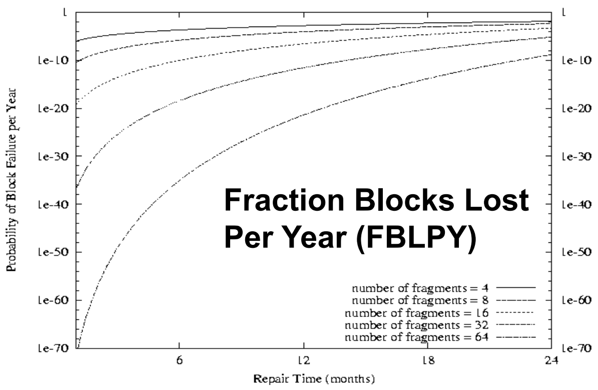
Allow more disks to fail!

- In general: RAIDX is an “erasure code”
  - Must have ability to know which disks are bad
  - Treat missing disk as an “Erasure”
- Today, Disks so big that: RAID 5 not sufficient!
  - Time to repair disk sooooo long, another disk might fail in process!
  - “RAID 6” – allow 2 disks in replication stripe to fail
- But – must do something more complex that just XORing together blocks!
  - Already used up the simple XOR operation across disks
- Simple option: Check out EVENODD code in readings
  - Will generate one additional check disks to support RAID 6
- More general option for general erasure code: Reed-Solomon codes
  - Based on polynomials in $GF(2^k)$ (I.e. k-bit symbols)
    - » Gailois Field is finite version of real numbers
  - Data as coefficients (a_j), code space as values of polynomial:
    - » $P(x)=a_0+a_1x^1+\ldots a_{m-1}x^{m-1}$
    - » Coded: P(0),P(1),P(2)….,P(n-1)
  - Can recover polynomial (i.e. data) as long as get any m of n; allows n-m failures!

Allow more disks to fail! (Con’t)

- How to use Reed-Solomon code in practice?
  - Each coefficient has a fixed (k) number of bits. So, must encode with symbols that size
  - Example: k=16 bit symbols, m=4, encoding 16x4 bits at a time
    - » Take original data, split into 4 chunks. On each encoding step, grab 16 bits from each chunk to use as coefficients
    - » Each data point yields a 16-bit symbol, which you distributed to final encoded chunks
  - (better version of Reed-Solomon code for erasure channels is the “Cauchy Reed-Solomon” code; it is isomorphic to the version here)
- Examples (with k=16):
  - Suppose have 6 disks, want to tolerate 2 failures
    - » Split data into 4 chunks, encode 16 bits from each chunk at a time, by generating 6 points (of 16 bits) on 3rd-degree polynomial
    - » Distribute data from polynomial to 6 disks – each disk will ultimately hold data that is ¼ size of original data
    - » Can handle 2 lost disks for 50% overhead
  - More interesting extreme for Internet-level replication:
    - » Split data into 4 chunks, produce 16 chunks
    - » Each chunk is ¼ total size of original data, Overhead = factor of 4
    - » But – only need 4 of 16 fragments! REALLY DURABLE!

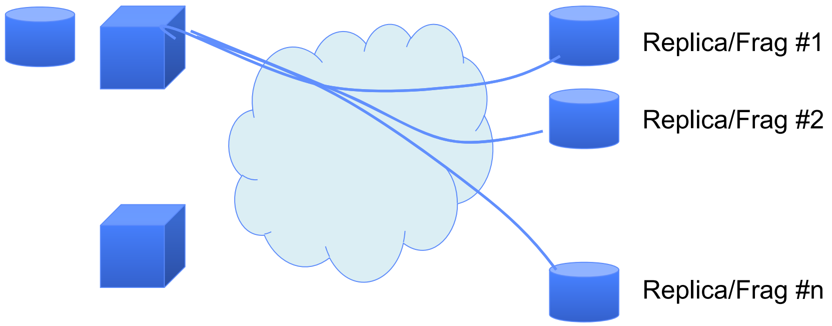
Use of Erasure Coding in general: High Durability/overhead ratio!



- Exploit law of large numbers for durability!
- 6 month repair, FBLPY with 4x increase in total size of data:
  - Replication (4 copies): 0.03
  - Fragmentation (16 of 64 fragments needed): 10^{-35}

Higher Durability/Reliability through Geographic Replication

- Highly durable – hard to destroy all copies
- Highly available for reads
  - Simple replication: read any copy
  - Erasure coded: read m of n
- 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



Administrivia

- Last Midterm: 5/2
  - Can have 3 handwritten sheets of notes – both sides
  - Focus on material from lecture 17-24, but all topics fair game!
- Don't forget to do your group evaluations!
  - Very important to help us understand your group dynamics
- Optional HW4 will come out soon
  - Will give you a chance to try out using the language "Go" to build a two-phase commit protocol
  - You will be testing it out for next term
    - » Not sure that we will be giving out points for it. Stay tuned!

File System Reliability: (Difference from Block-level 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:

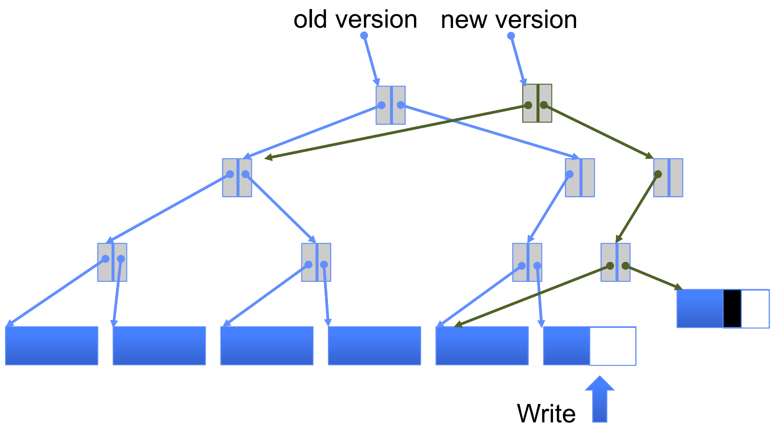
- Scan inode table
- If any unlinked files (not in any directory), delete or put in lost & found dir
- Compare free block bitmap against inode trees
- Scan directories for missing update/access times

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

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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

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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

consistent state 1 → transaction → consistent state 2

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

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Transactional File Systems

- 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
    - » Process can be accelerated with NVRAM
  - Although File system may not be updated immediately, data preserved in the log
- Difference between "Log Structured" and "Journaled"
  - In a Log Structured filesystem, data stays in log form
  - In a Journaled filesystem, Log used for recovery
- 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
- Full Logging File System
  - All updates to disk are done in transactions

Journalled 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
  - Single commit record commits transaction
- Once changes are in the 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
- 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

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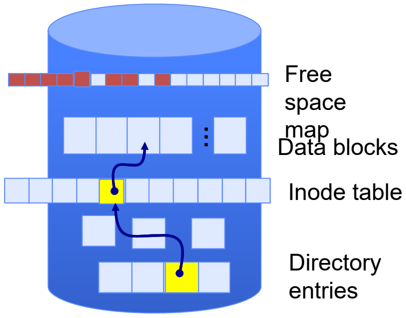
Redo Logging

- 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

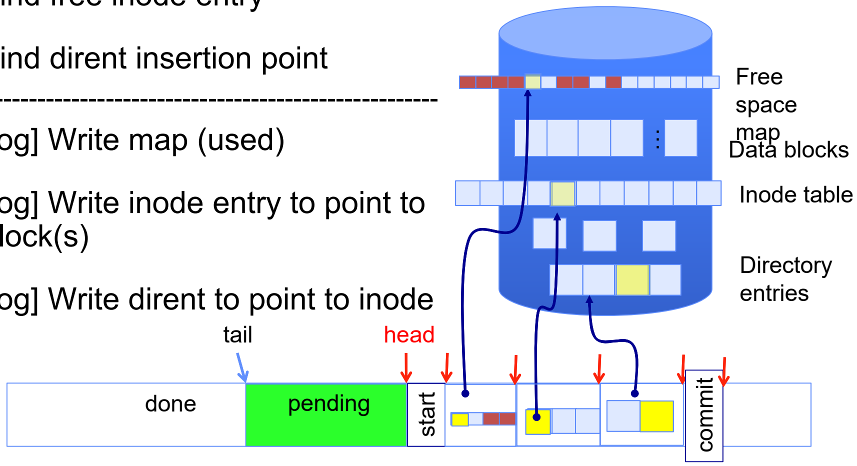
Example: Creating a File

- 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)

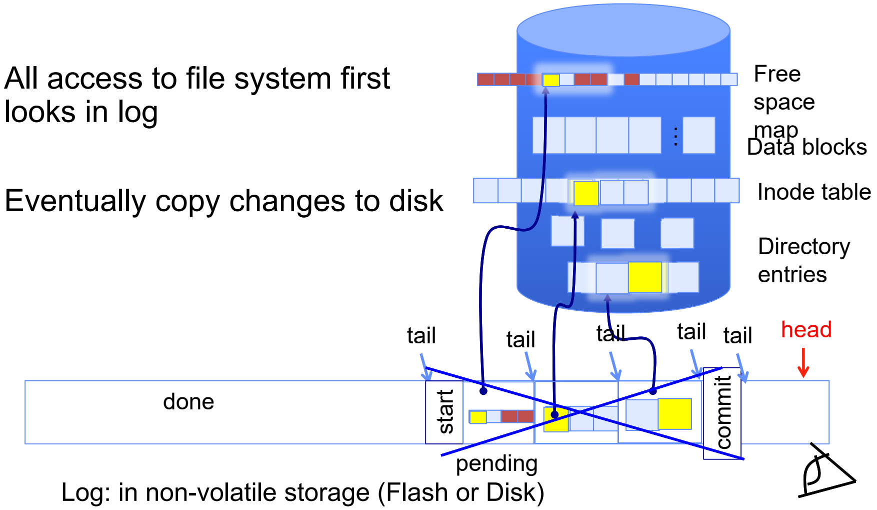
- Find free data block(s)
- Find free inode entry
- Find dirent insertion point
- [log] Write map (used)
- [log] Write inode entry to point to block(s)
- [log] Write dirent to point to inode



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

ReDo Log

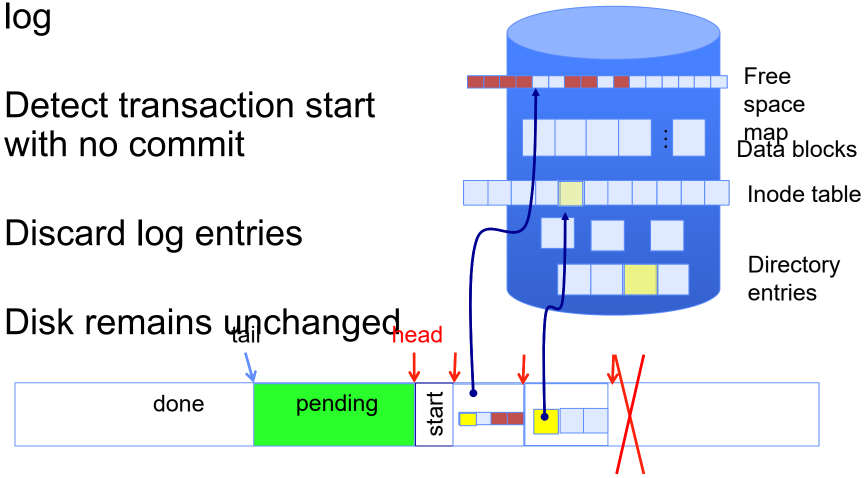
- After Commit
- All access to file system first looks in log
- Eventually copy changes to disk



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

Crash During Logging – Recover

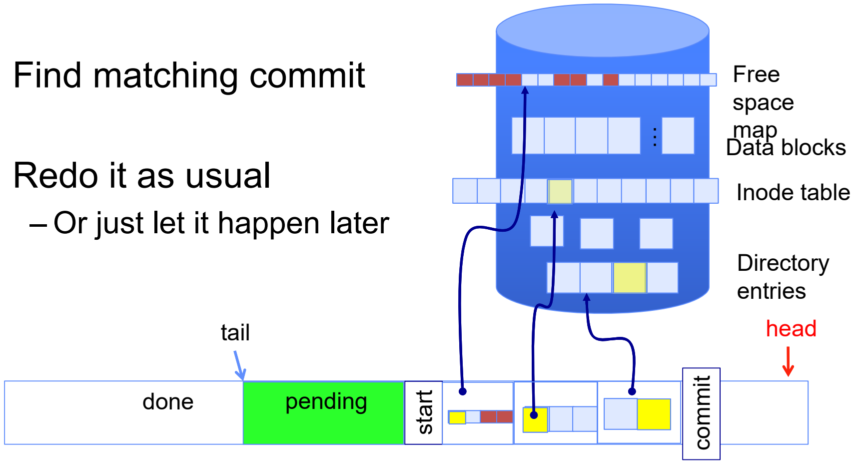
- Upon recovery scan the log
- Detect transaction start with no commit
- Discard log entries
- Disk remains unchanged



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

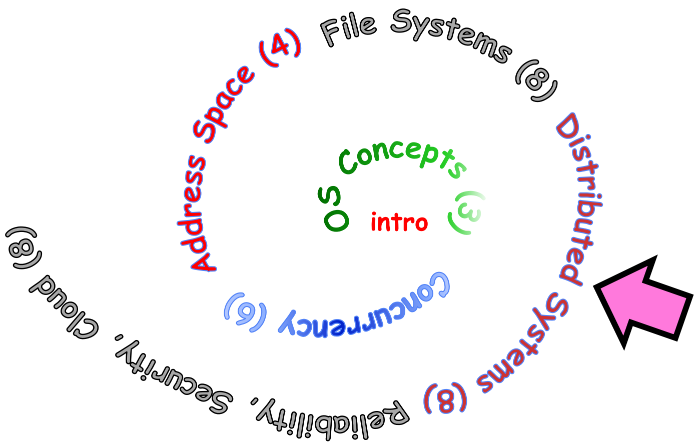
Recovery After Commit

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



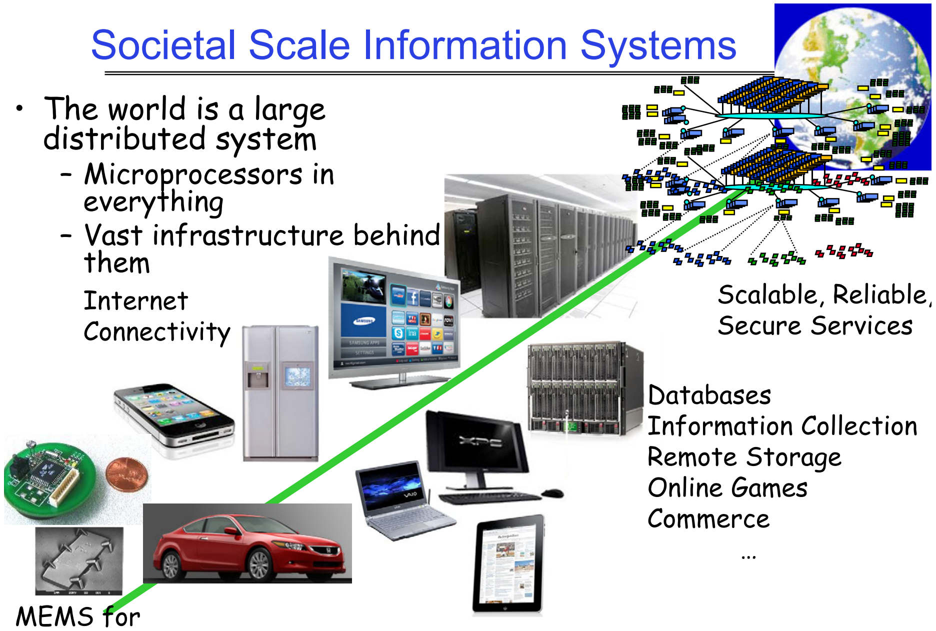
Log: in non-volatile storage (Flash or on Disk)

Course Structure: Spiral

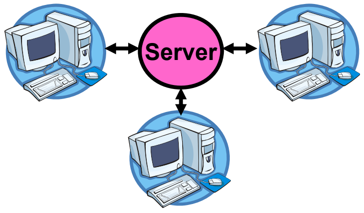


Societal Scale Information Systems

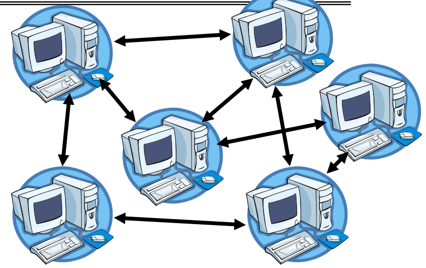
- The world is a large distributed system
  - Microprocessors in everything
  - Vast infrastructure behind them



Centralized vs Distributed Systems



Client/Server Model



Peer-to-Peer Model

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

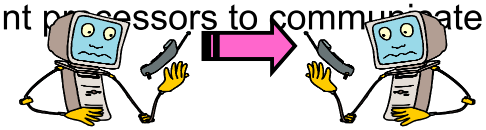
- Why do we want distributed systems?
  - Cheaper and easier to build lots of simple computers
  - Easier to add power incrementally
  - Users can have complete control over some components
  - Collaboration: much easier for users to collaborate through network resources (such as network file systems)
- 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

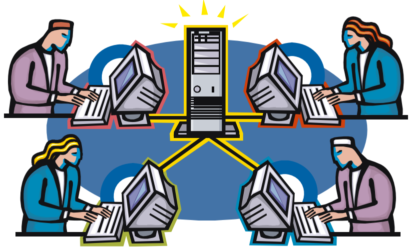
- Reality has been disappointing
  - Worse availability: depend on every machine being up
    - » Lamport: "a distributed system is one where I can't do work because some machine I've never heard of isn't working!"
  - Worse reliability: can lose data if any machine crashes
  - Worse security: anyone 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



Networking Definitions



- Network: physical connection that allows two computers to communicate
- Packet: unit of transfer, sequence of bits carried over the network
  - Network carries packets from one CPU to another
  - Destination gets interrupt when packet arrives
- Protocol: agreement between two parties as to how information is to be transmitted

What Is A Protocol?

- A protocol is an agreement on how to communicate
- Includes
  - Syntax: how a communication is specified & structured
    - » Format, order messages are sent and received
  - Semantics: what a communication means
    - » Actions taken when transmitting, receiving, or when a timer expires
- Described formally by a state machine
  - Often represented as a message transaction diagram

Examples of Protocols in Human Interactions

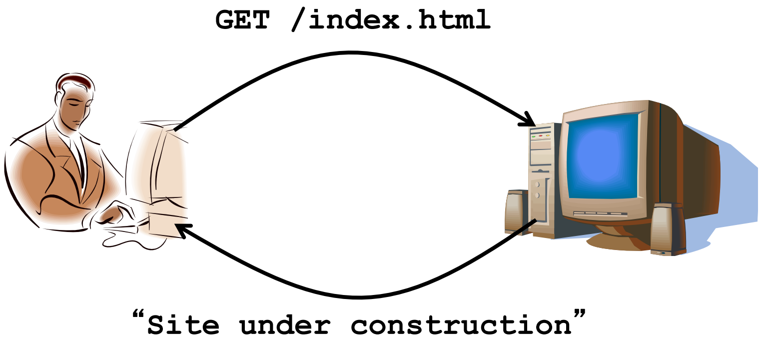
- Telephone

1. (Pick up / open up the phone)
2. Listen for a dial tone / see that you have service
3. Dial
4. Should hear ringing …
5. Callee: “Hello?”
6. Caller: “Hi, it’s John….”
   Or: “Hi, it’s me” (← what’s *that* about?)
7. Caller: “Hey, do you think … blah blah blah …” **pause**

1. Callee: “Yeah, blah blah blah …” **pause**
2. Caller: Bye
3. Callee: Bye
4. Hang up

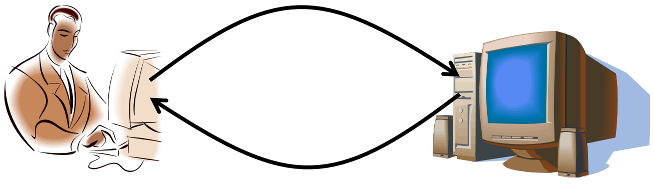
Clients and Servers

- Client program
  - Running on end host
  - Requests service
  - E.g., Web browser
- Server program
  - Running on end host
  - Provides service
  - E.g., Web server



Client-Server Communication

- Client “sometimes on”
  - Initiates a request to the server when interested
  - E.g., Web browser on your laptop or cell phone
  - Doesn’t communicate directly with other clients
  - Needs to know the server’s address
- Server is “always on”
  - Services requests from many client hosts
  - E.g., Web server for the *www.cnn.com* Web site
  - Doesn’t initiate contact with the clients
  - Needs a fixed, well-known address



Peer-to-Peer Communication

- No always-on server at the center of it all
  - Hosts can come and go, and change addresses
  - Hosts may have a different address each time
- Example: peer-to-peer file sharing (e.g., BitTorrent)
  - Any host can request files, send files, query to find where a file is located, respond to queries, and forward queries
  - Scalability by harnessing millions of peers
  - Each peer acting as both a client and server

Summary

- Important system properties
  - Availability: how often is the resource available?
  - Durability: how well is data preserved against faults?
  - Reliability: how often is resource performing correctly?
- RAID: Redundant Arrays of Inexpensive Disks
  - RAID1: mirroring, RAID5: Parity block
- Use of Log to improve Reliability
  - Journaled file systems such as ext3, NTFS
- Transactions: ACID semantics
  - Atomicity
  - Consistency
  - Isolation
  - Durability