CS162
Operating Systems and Systems Programming
Lecture 20

Reliability, Transactions
Distributed Systems

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Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes*. When slides are obtained from other sources, a a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

Recall: File System Caching

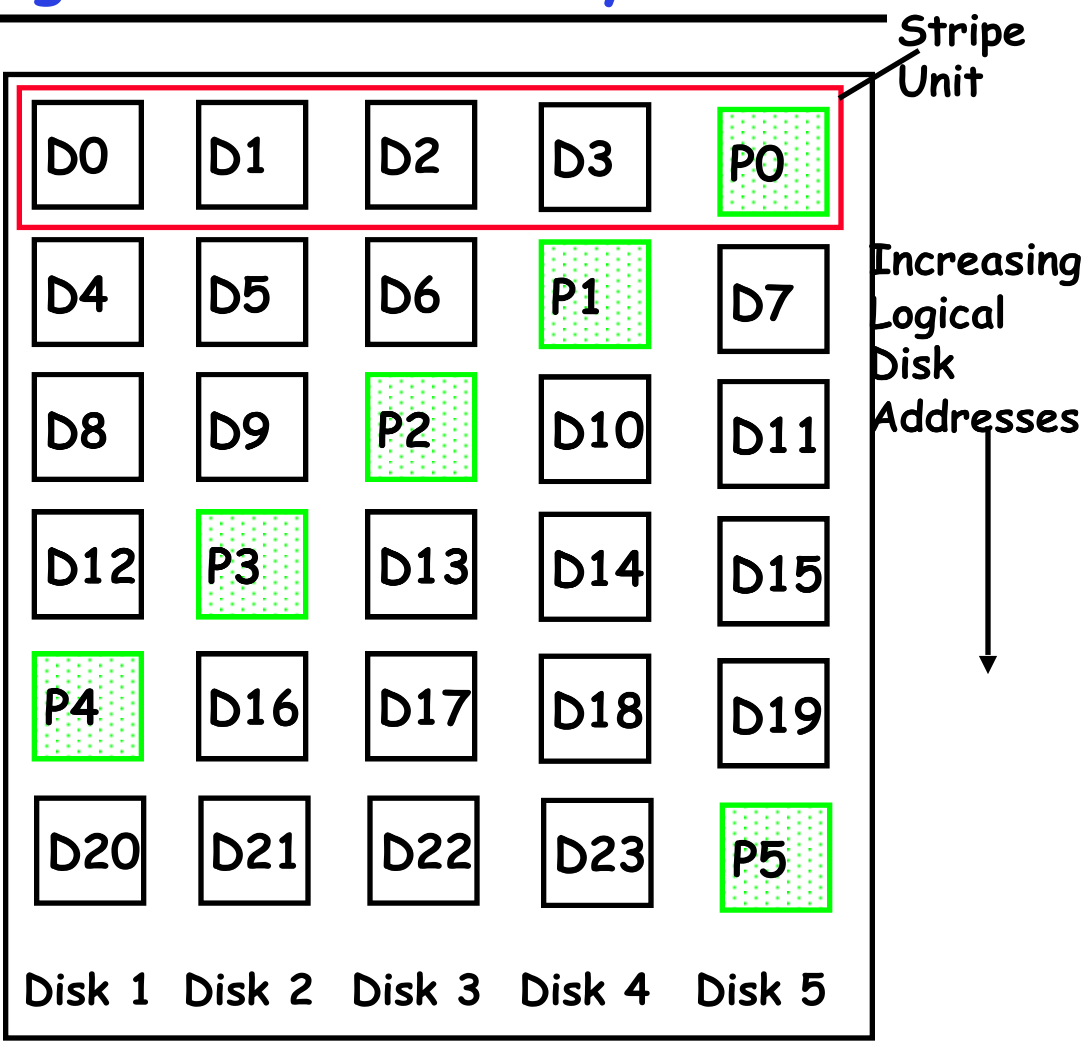
- **Buffer Cache:** Memory used to cache kernel resources, including disk blocks and name translations
  - Can contain "dirty" blocks (blocks yet on disk)
- **Read Ahead Prefetching:** fetch sequential blocks early
  - exploit fact that most common file access is sequential
  - Elevator algorithm can efficiently interleave prefetches from different applications
  - How much to prefetch? it's a balance
- **Delayed Writes:** Writes not immediately sent out to disk
  - `write()` copies data from user space buffer to kernel buffer
    - » other application read data from cache instead of disk
  - 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!)

Recall: 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

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 D3 fails, then can reconstruct: $D3=D0\oplus D1\oplus D2\oplus P0$



- Later in term: talk about spreading information widely across internet for durability.

File System Reliability

- What can happen if disk loses power or machine 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
  - Bit-for-bit protection of bad state?
  - What if one disk of RAID group not written?
- File system wants 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 remapping, single update to physical disk block can require multiple (even lower level) updates
- 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.
  - e.g.: transfer funds from BofA to Schwab. 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 in FAT, FFS (fsck), and many app-level recovery schemes (e.g., Word)

FFS: Create a File

Normal operation:

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

Recovery:

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

Recovery time proportional to size of disk

Application Level

Normal operation:

- Write name of each open file to app folder
- Write changes to backup file
- Rename backup file to be file (atomic operation provided by file system)
- Delete list in app folder on clean shutdown

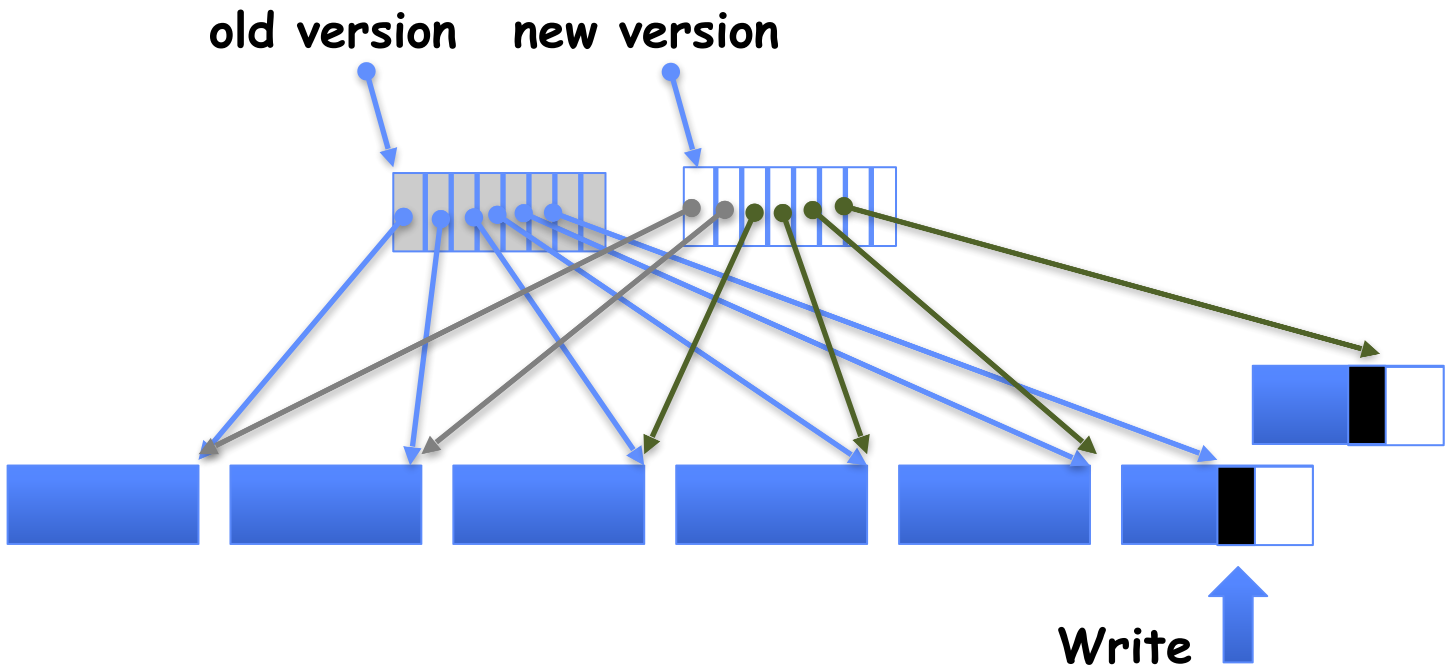
Recovery:

- On startup, see if any files were left open
- If so, look for backup file
- If so, ask user to compare versions

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)

COW integrated with file system



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

More General Solutions

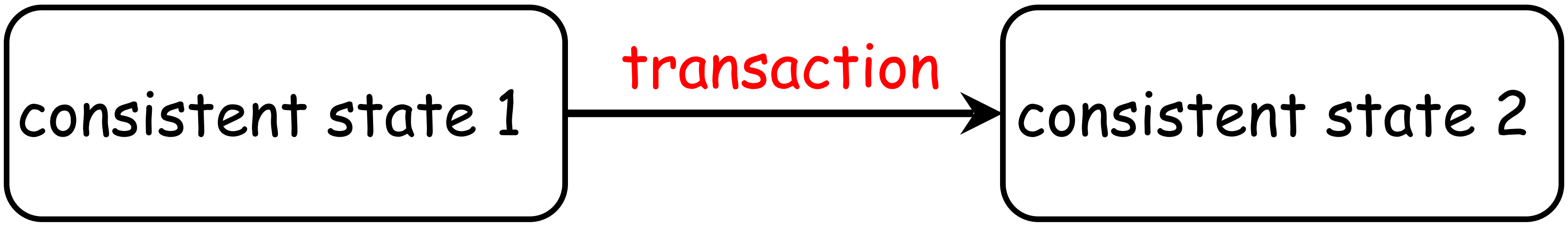
- Transactions for Atomic Updates
  - Ensure that multiple related updates are performed atomically
  - i.e., if a crash occurs in the middle, the state of the systems reflects either all or none of the updates
  - Most modern file systems use transactions internally to update the many pieces
  - Many applications implement their own transactions
- Redundancy for media failures
  - Redundant representation (error correcting codes)
  - Replication
  - E.g., RAID disks

Transactions

- Closely related to critical sections in manipulating shared data structures
- 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

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

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
  - 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

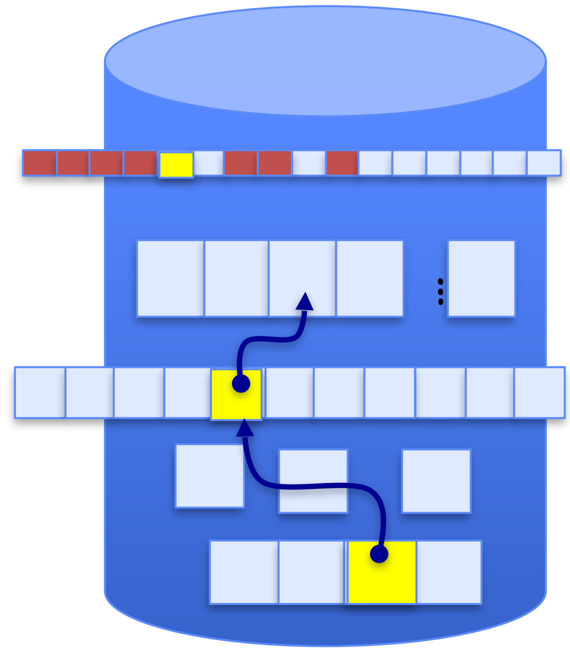
Redo Logging

- 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

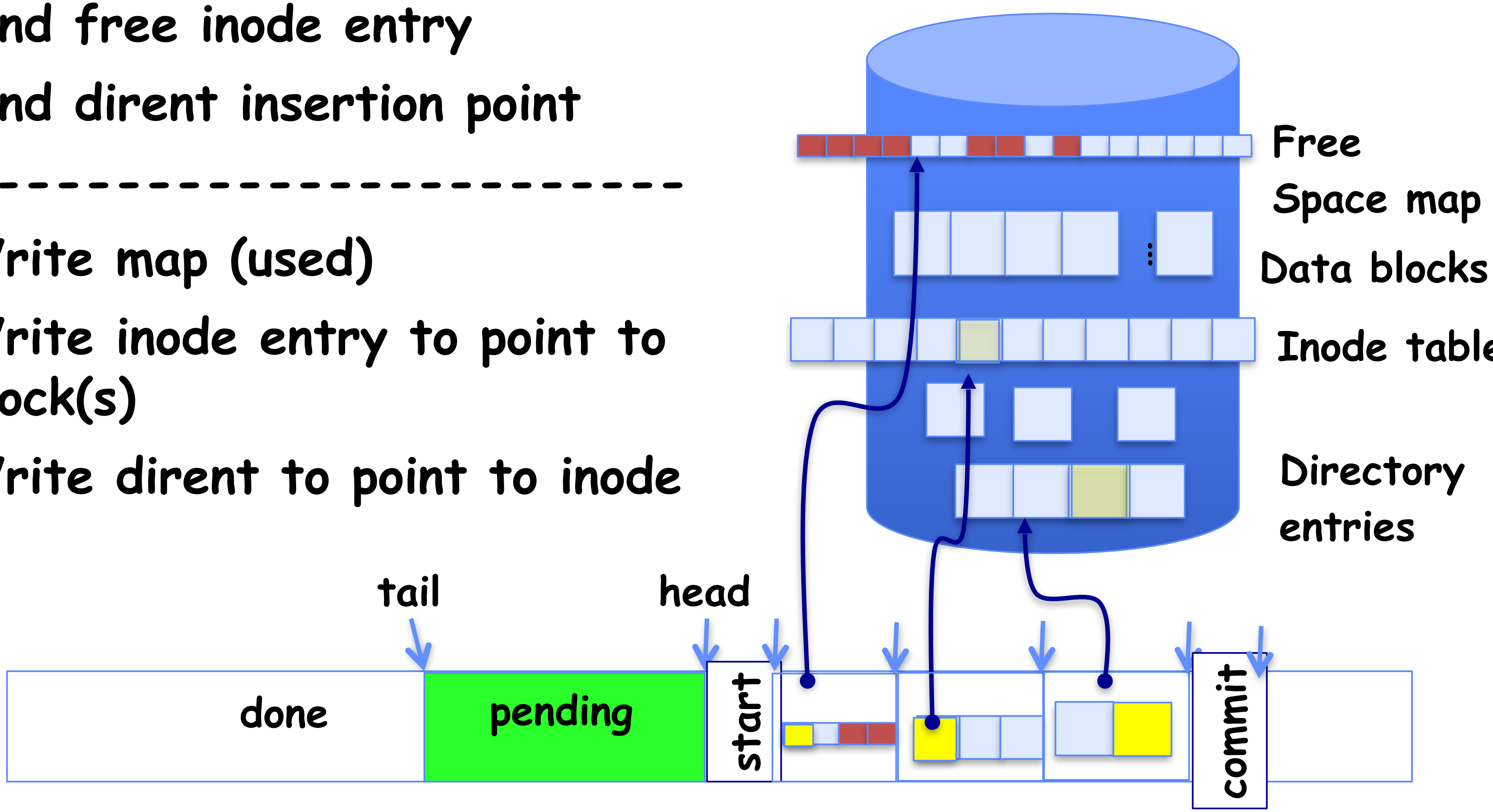
- Write map (i.e., mark used)
- Write inode entry to point to block(s)
- Write dirent to point to inode



Ex: Creating a file (as a transaction)

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

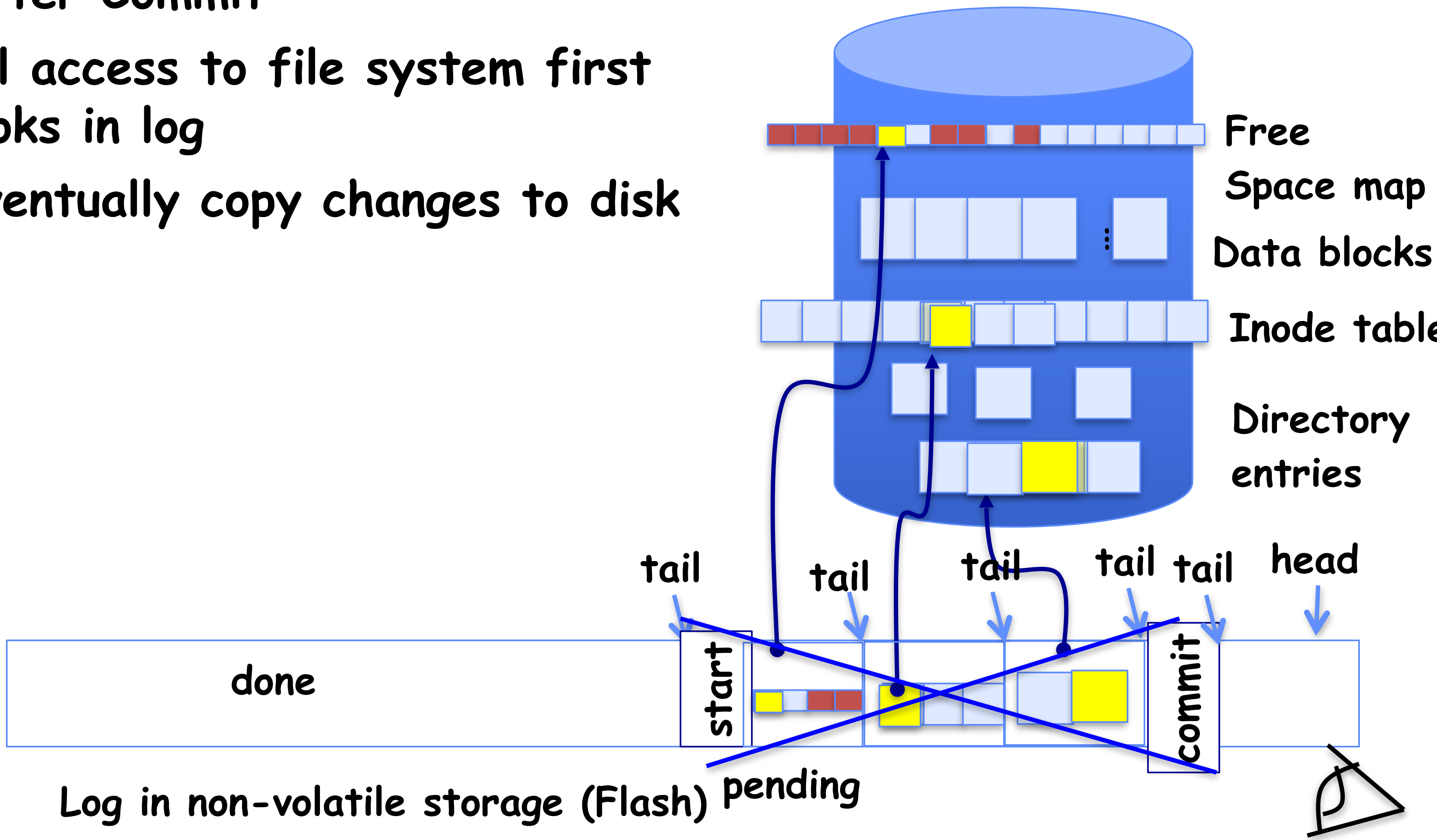
- Write map (used)
- Write inode entry to point to block(s)
- Write dirent to point to inode



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

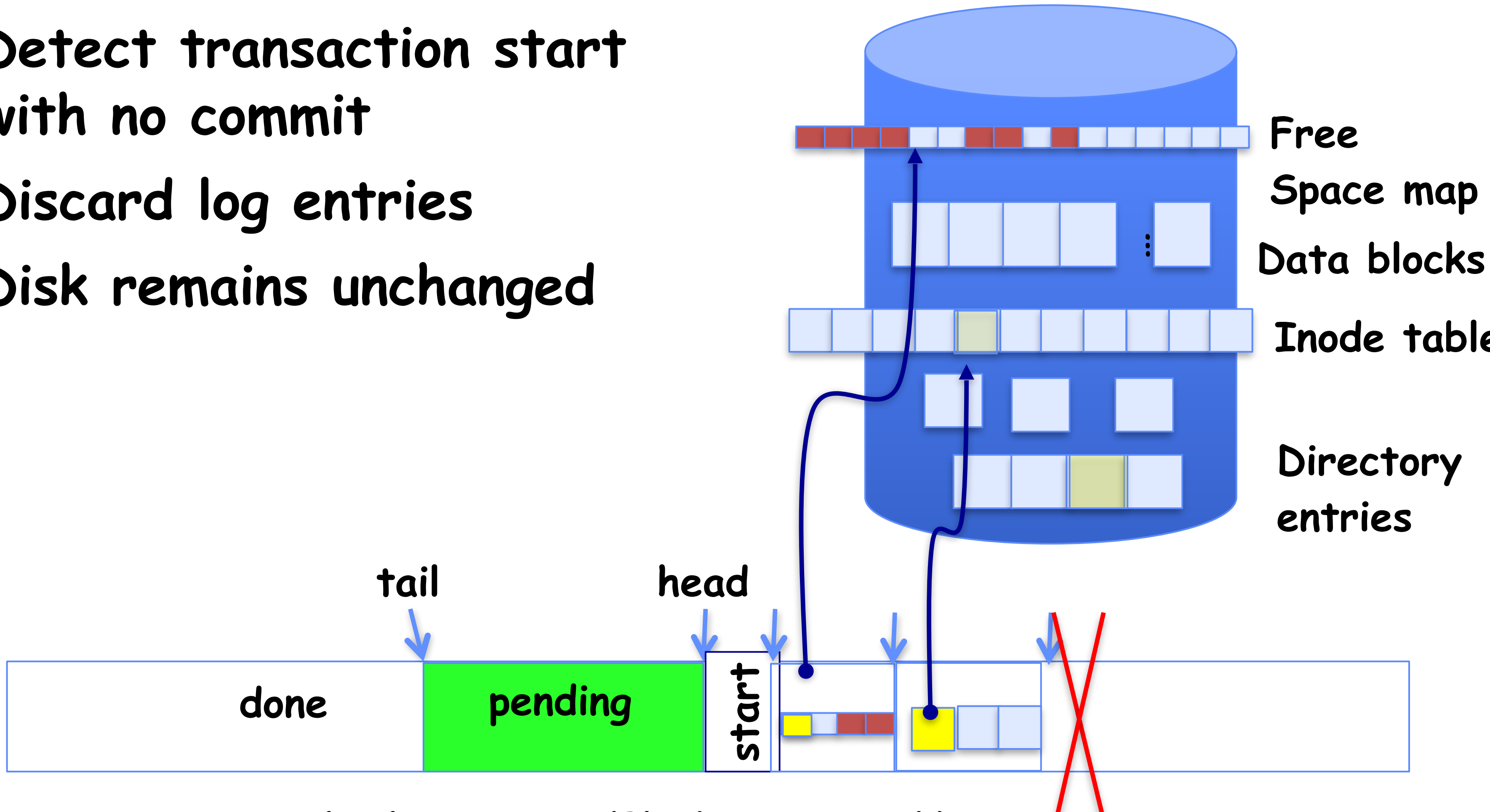
ReDo log

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



Crash during logging - Recover

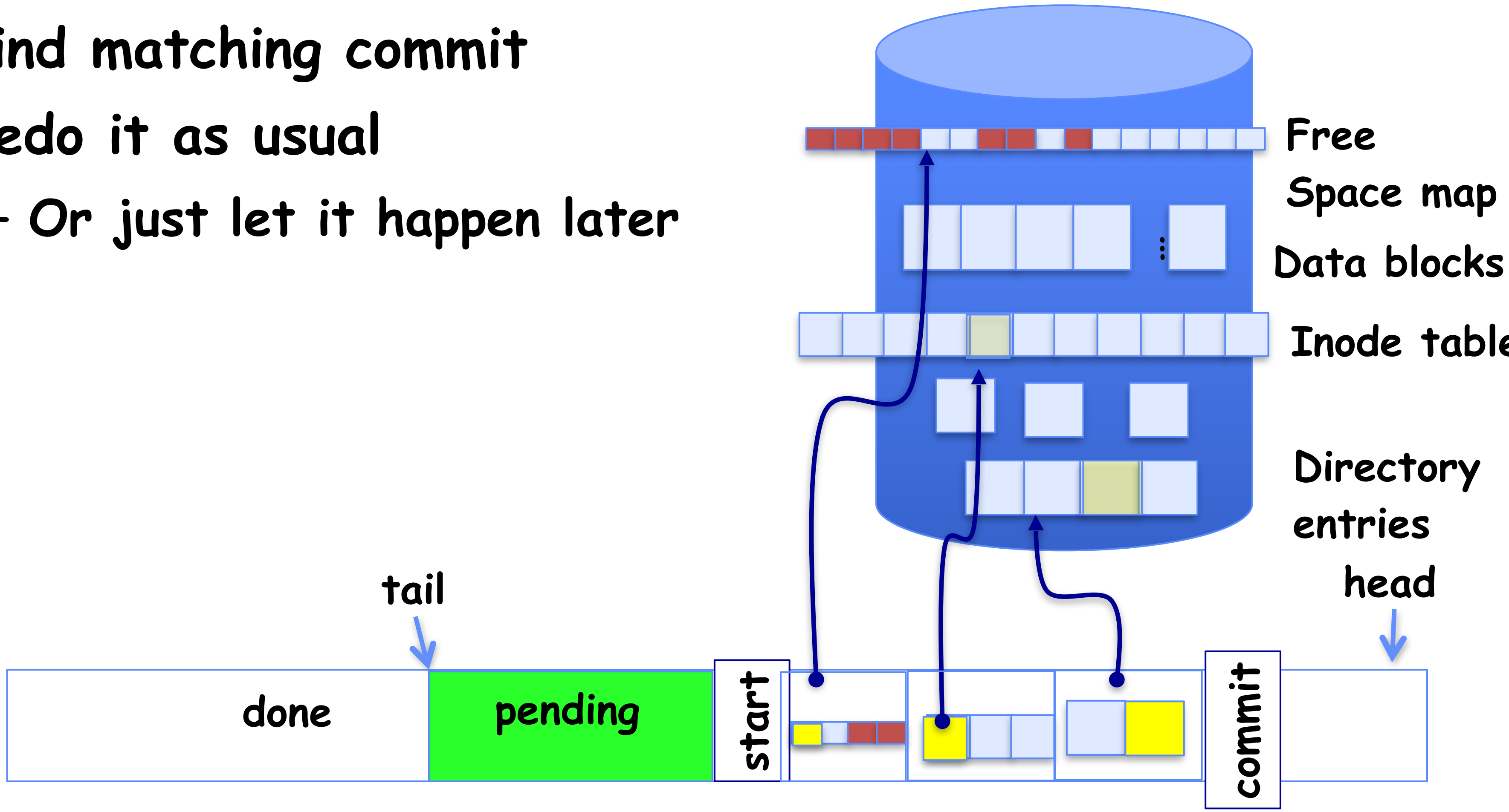
- Upon recovery scan the long
- Detect transaction start with no commit
- Discard log entries
- Disk remains unchanged



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

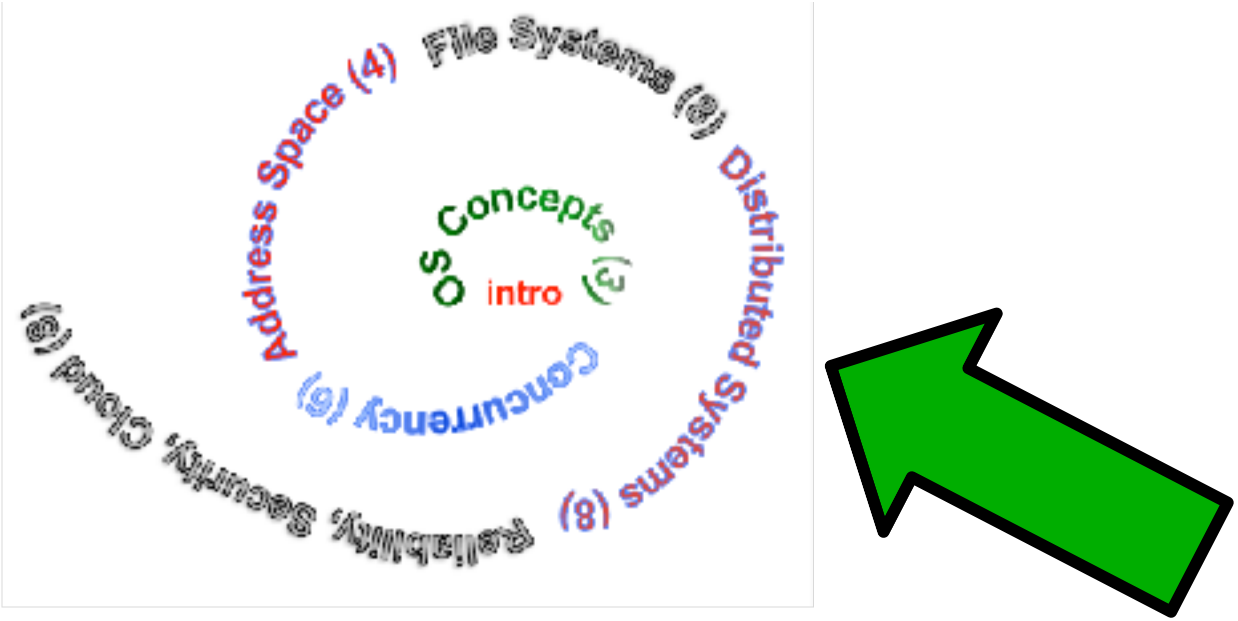
Recovery After Commit

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

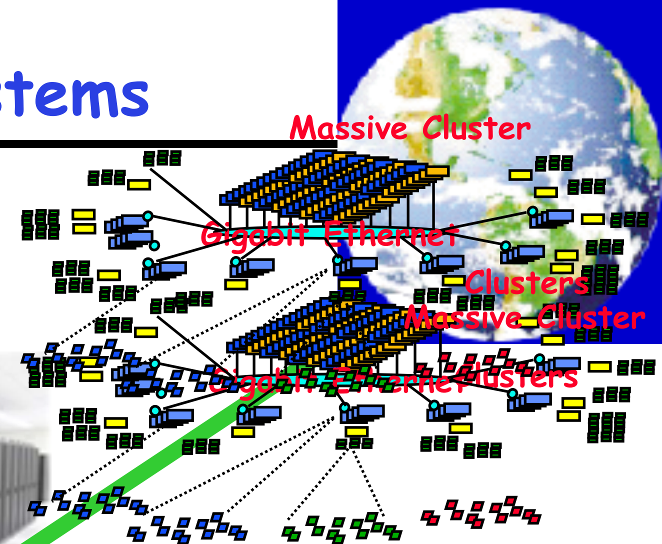


Log in non-volatile storage (Flash or on Disk)

Next Objective



Societal Scale Information Systems



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

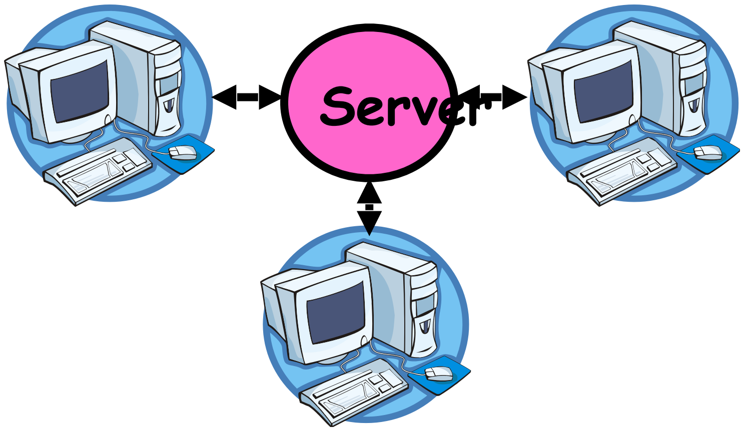
Internet Connectivity

Scalable, Reliable, Secure Services

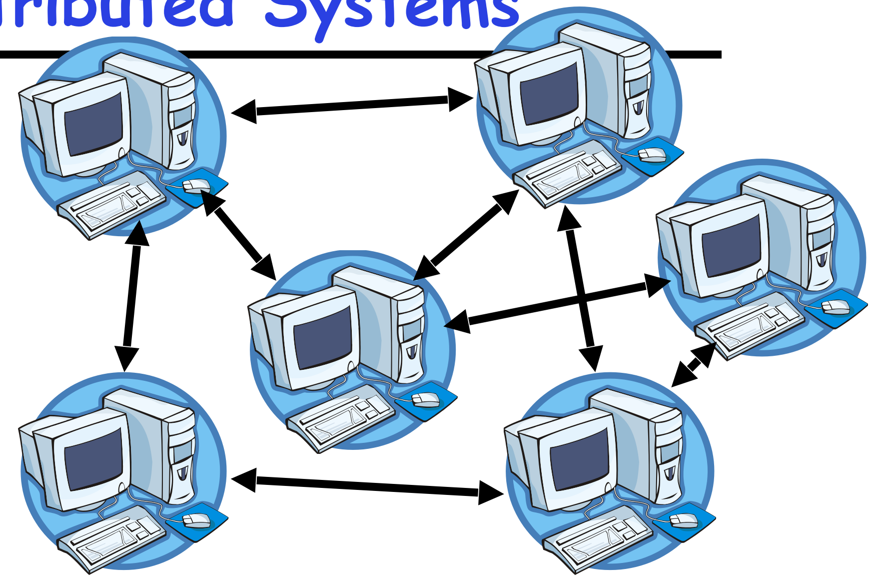
Databases
Information Collect
Remote Storage
Online Games
Commerce
…

MEMS for Sensor Nets

Centralized vs Distributed Systems



Client/Server Model



Peer-to-Peer Model

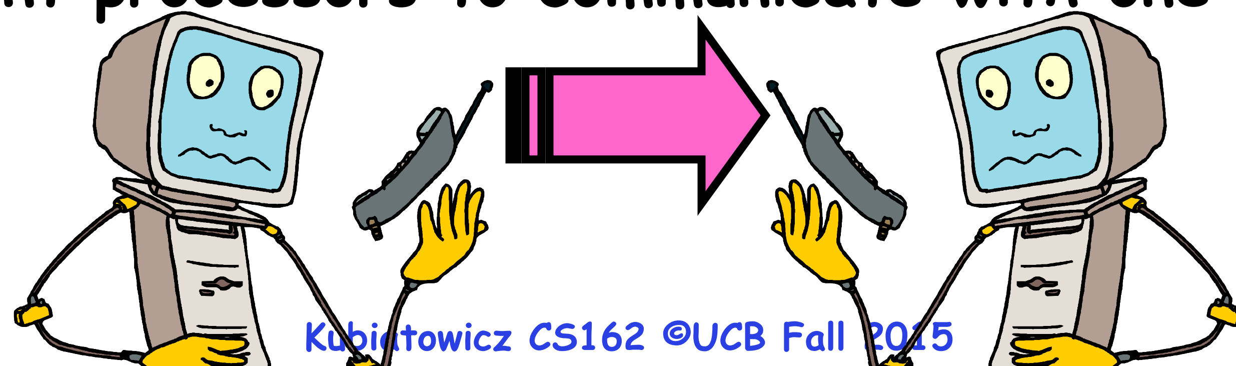
- **Centralized System:** System in which major functions are performed by a single physical computer
  - Originally, everything on single computer
  - Later: client/server model
- **Distributed System:** physically separate computers working together on some task
  - Early model: multiple servers working together
    - » Probably in the same room or building
    - » Often called a "cluster"
  - Later models: peer-to-peer/wide-spread collaboration

Distributed Systems: Motivation/Issues

- 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
- 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 spliting them into smaller pieces
  - Fault Tolerance: System may hide varoius things that go wrong in the system
- Transparency and collaboration require some way for different processors to communicate with one another



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