# Operating Systems (Honor Track)

# File System 4: Transactions & Distributed Decision Making

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Spring 2026

Acknowledgments: Ion Stoica, Berkeley CS 162

# Recap: Two Reliability Approaches

**Careful Ordering and Recovery**

- FAT & FFS + fsck
- Each step builds structure
- Data block ⇐ inode ⇐ free ⇐ directory
- Last step links it in to rest of FS
- Recover scans structure looking for incomplete actions

**Versioning and Copy-on-Write**

- ZFS, …
- Version files at some granularity
- Create new structure linking back to unchanged parts of old
- Last step is to declare that the new version is ready

# 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 file system structure/metadata
  - Many app-level recovery schemes (e.g., Word, emacs autosaves)

# Question

- Assume you need to store
  - A piece of data
  - A directory entry / pointer for the data
- Assume each of these operations is atomic

- Which one you should write first ? Data or Pointer ?

# Berkeley 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*

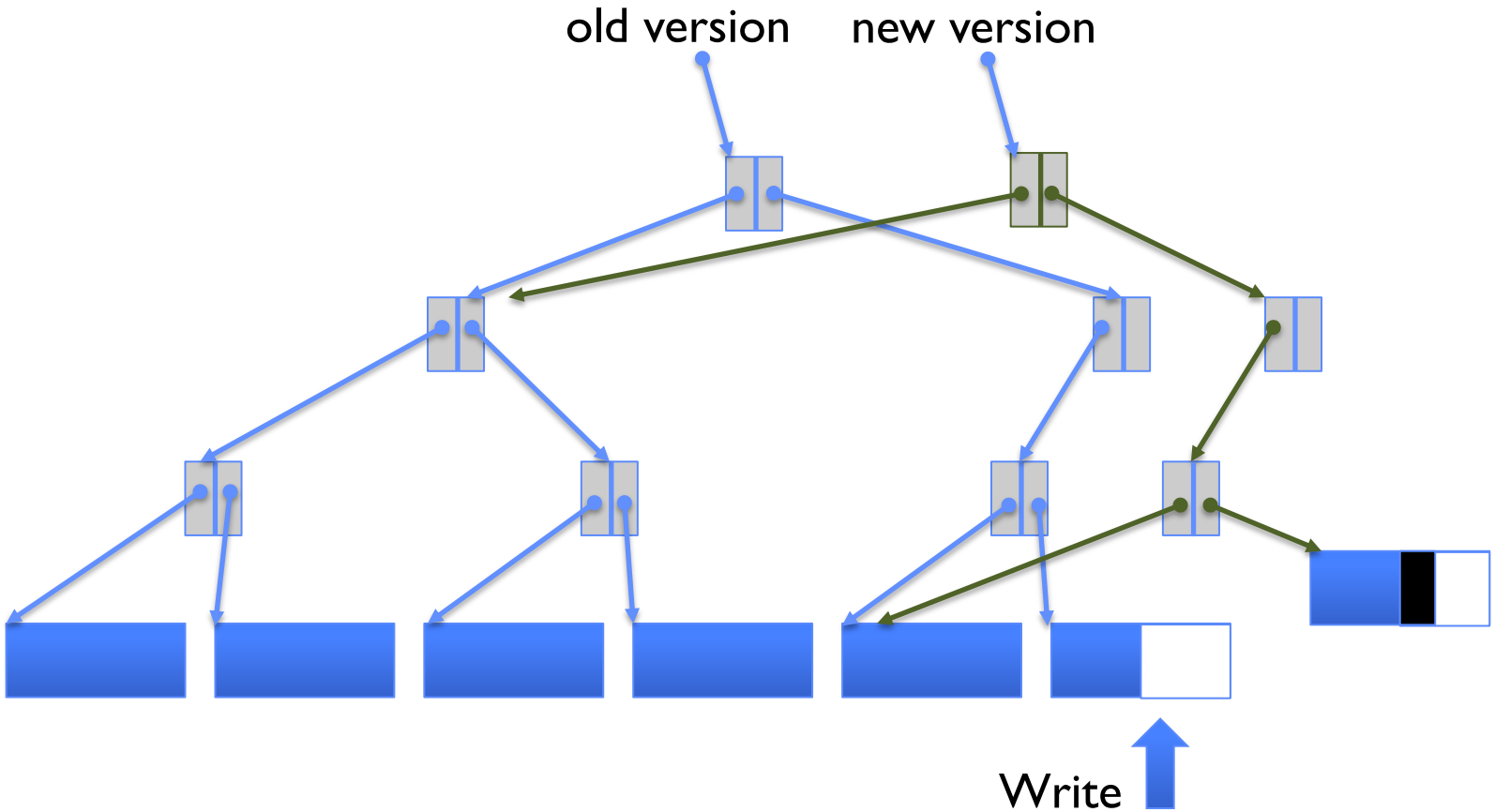
# Reliability Approach #2: Copy on Write File Layout

- Recall: multi-level index structure lets us find the data blocks of a file
- Instead of over-writing existing data blocks and updating the index structure:
  - Create a new version of the file with the updated data
  - Reuse blocks that don't change much of what is already in place
  - This is called: Copy On Write (COW)

- 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

# Example: 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 free space (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

- A *transaction* is an atomic sequence of reads and writes that takes the system from consistent state to another.


- Recall: Code in a critical section appears atomic to other threads
- Transactions extend the concept of atomic updates from *memory* to *persistent storage*

# 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

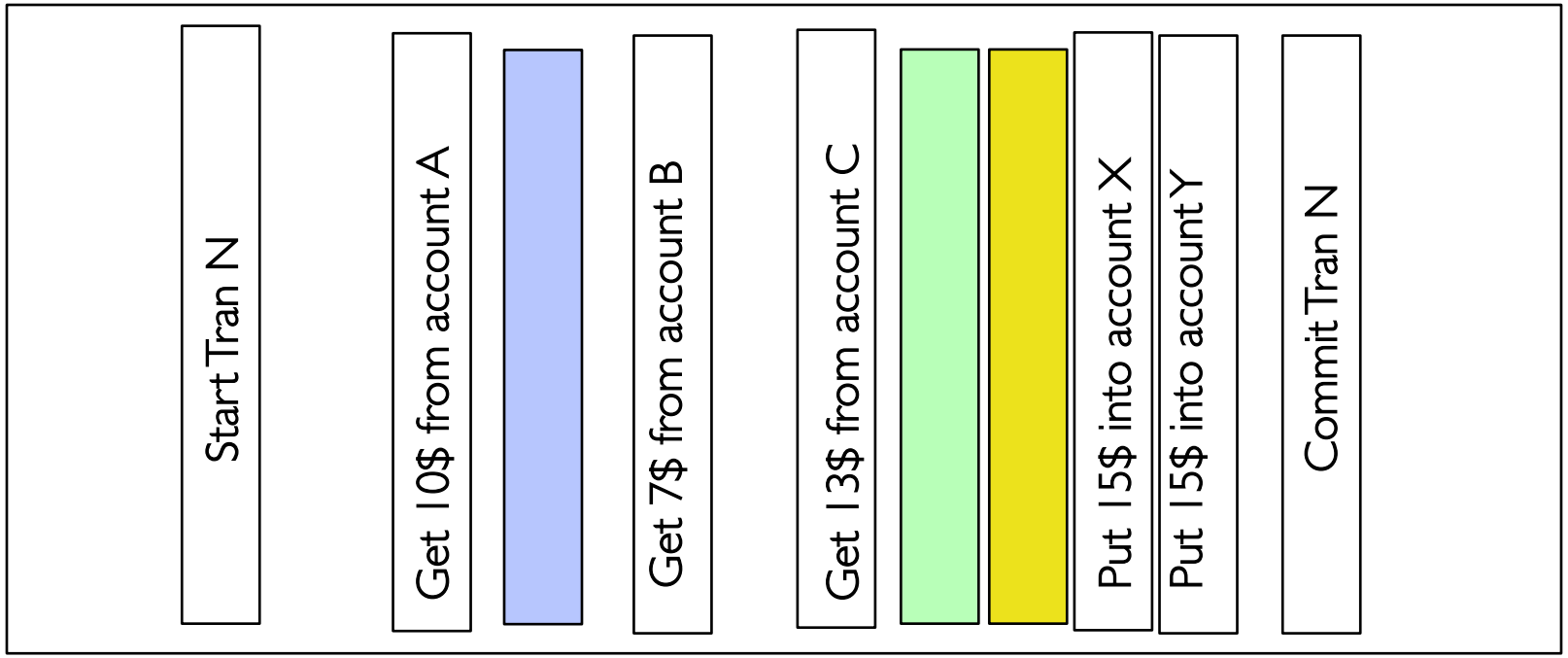
# “Classic” Example: Transaction

```
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

# Concept of a log

- One simple action is atomic – write/append a basic item
- Use that to seal the commitment to a whole series of actions



# Transactional File Systems

- Better reliability through use of log
  - 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 Systems

- Don’t modify data structures on disk directly
- Write each update as transaction recorded in a log
  - Commonly called a journal or intention list
  - Also maintained on disk (allocate blocks for it when formatting)
- Once changes are in the log, they can be safely applied to file system
  - e.g. modify inode pointers and directory mapping
- Garbage collection: once a change is applied, remove its entry from the log

- Linux took original FFS-like file system (ext2) and added a journal to get ext3!
  - Some options: whether or not to write all data to journal or just metadata

- Other examples: NTFS, Apple HFS+, Linux XFS, JFS, ext4

# Creating a File (No Journaling Yet)

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

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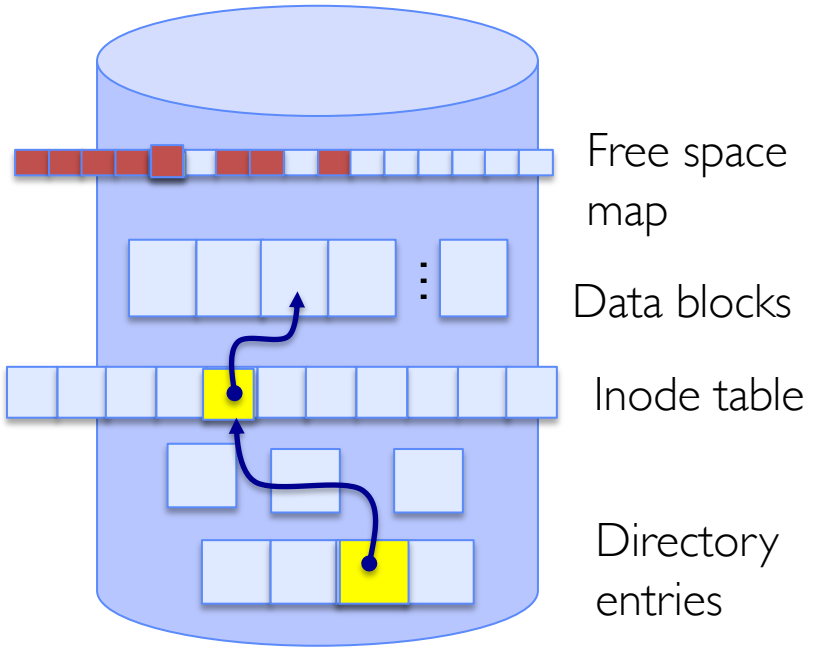
- Write map (i.e., mark used)
- Write inode entry to point to block(s)
- Write dirent to point to inode



# Creating a File (With Journaling)

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

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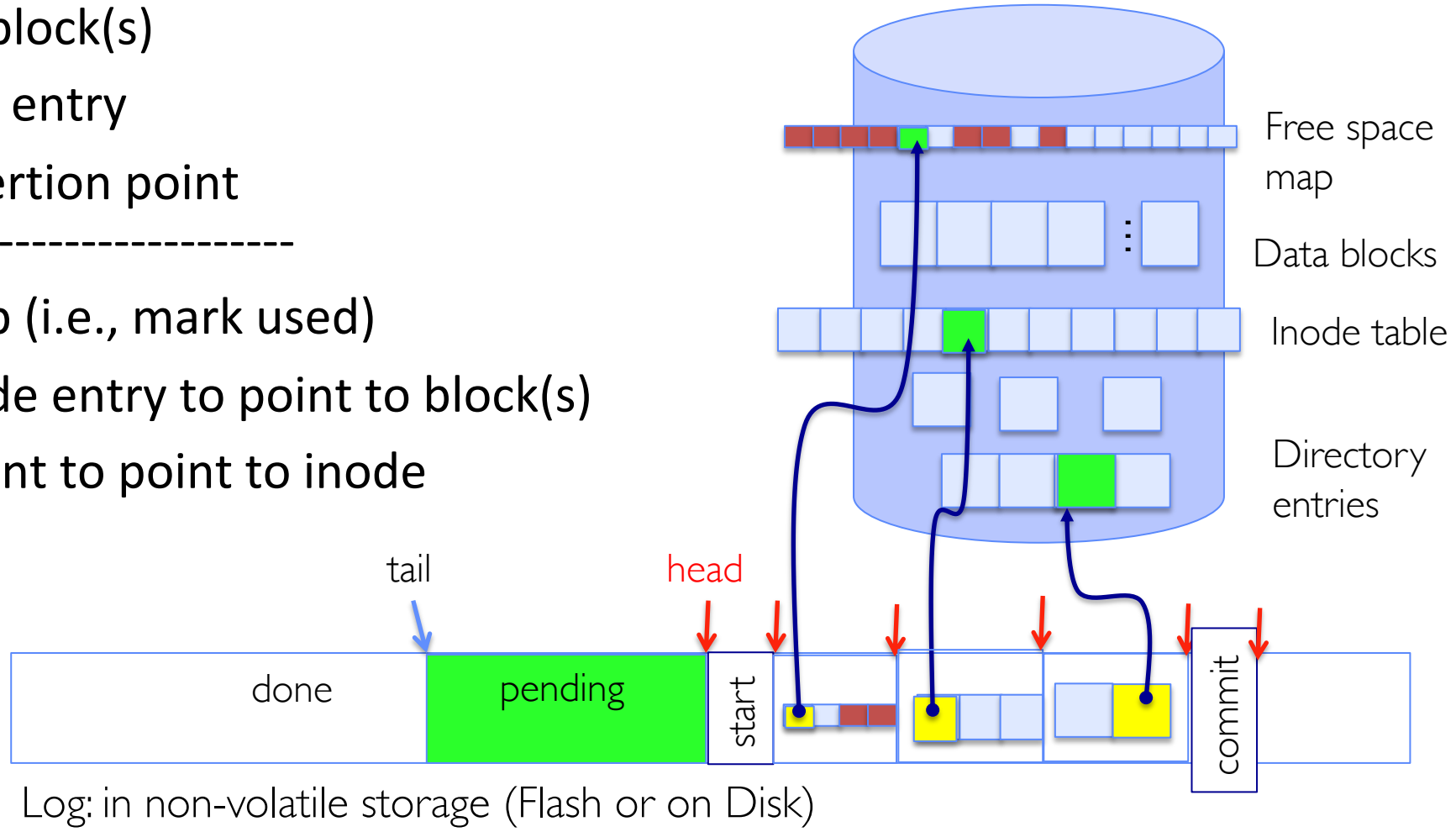
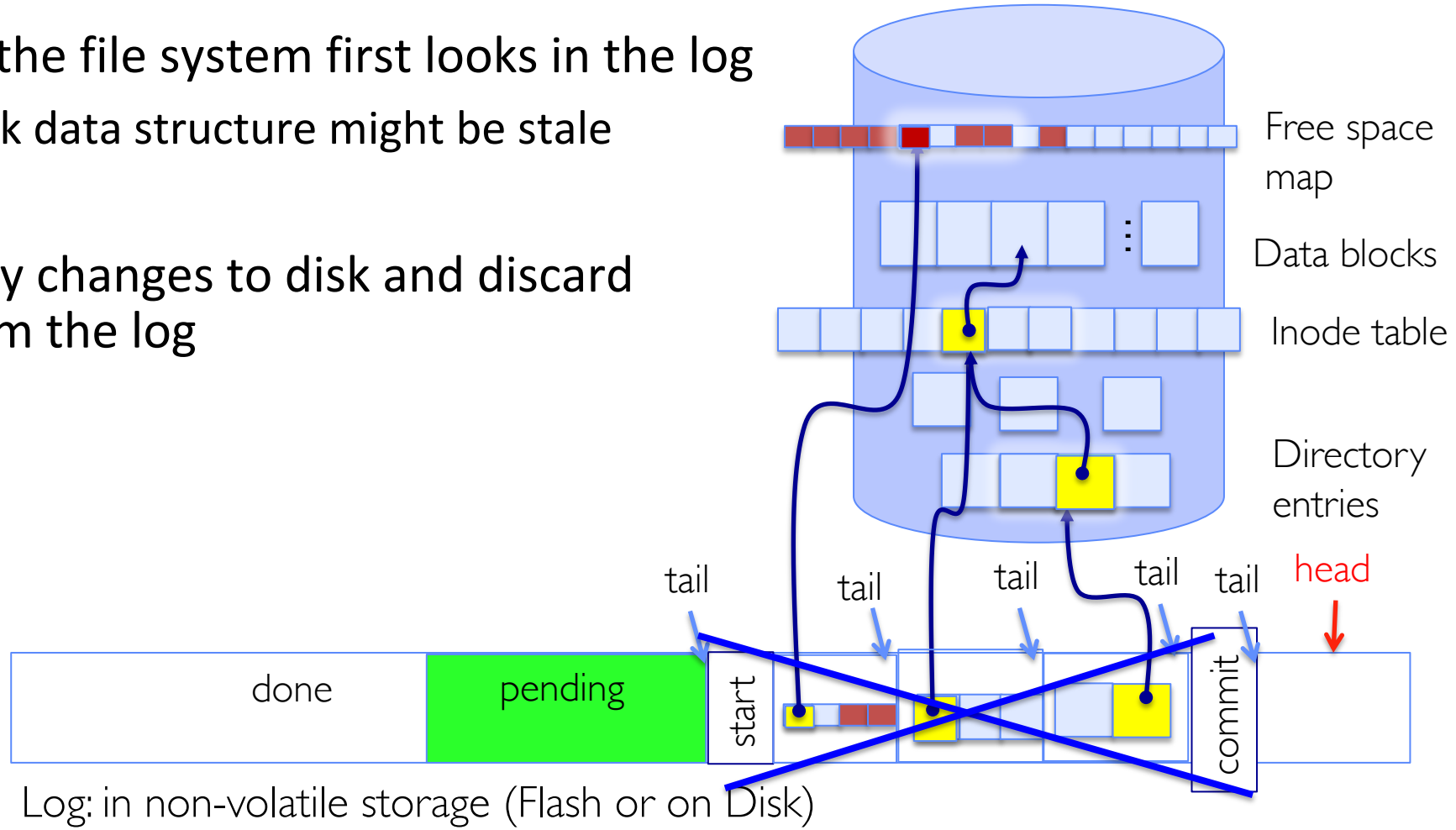
- [log] Write map (i.e., mark used)
- [log] Write inode entry to point to block(s)
- [log] Write dirent to point to inode



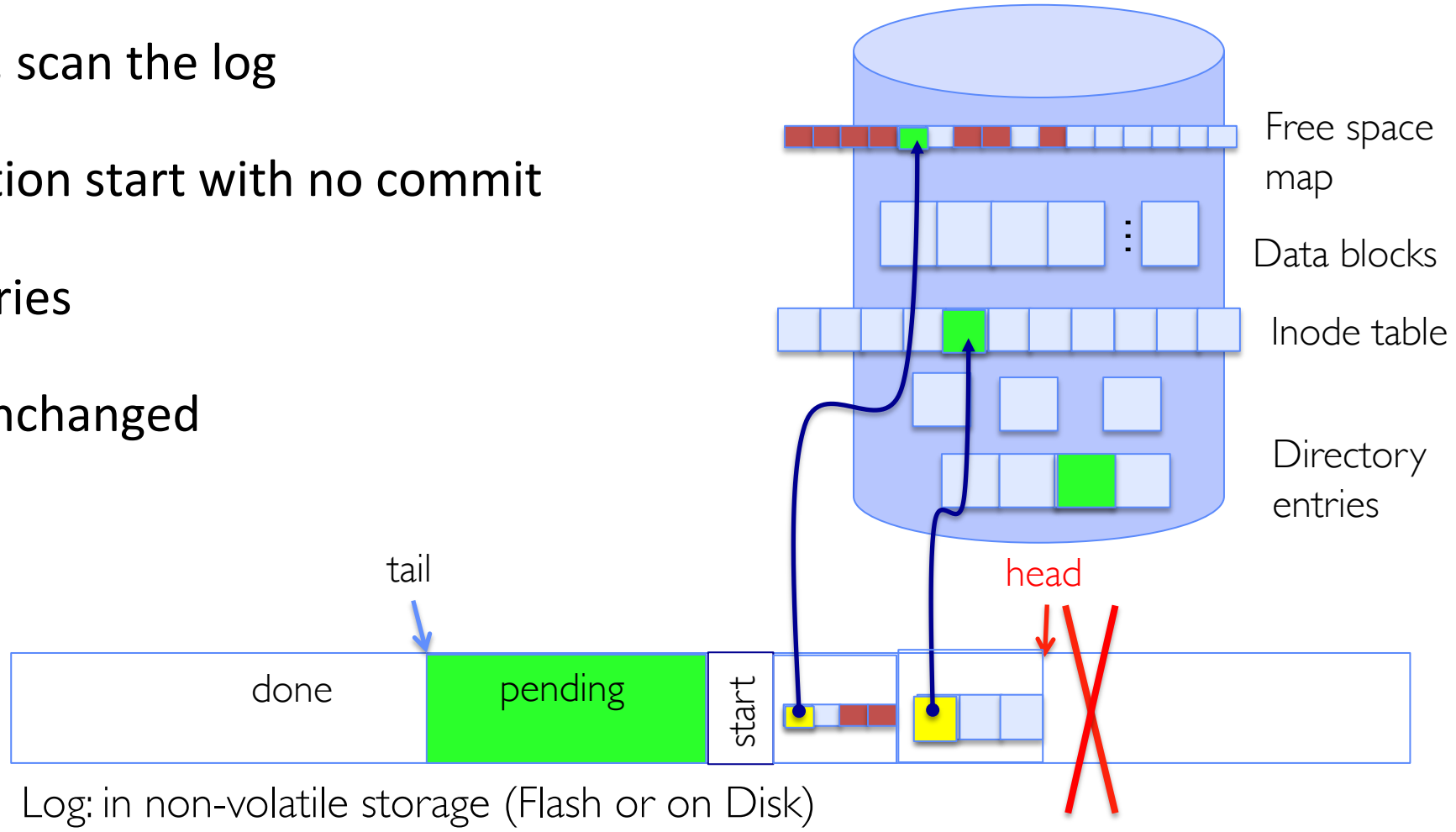
# After Commit, Eventually Replay Transaction

- All accesses to the file system first looks in the log
  - Actual on-disk data structure might be stale
- Eventually, copy changes to disk and discard transaction from the log



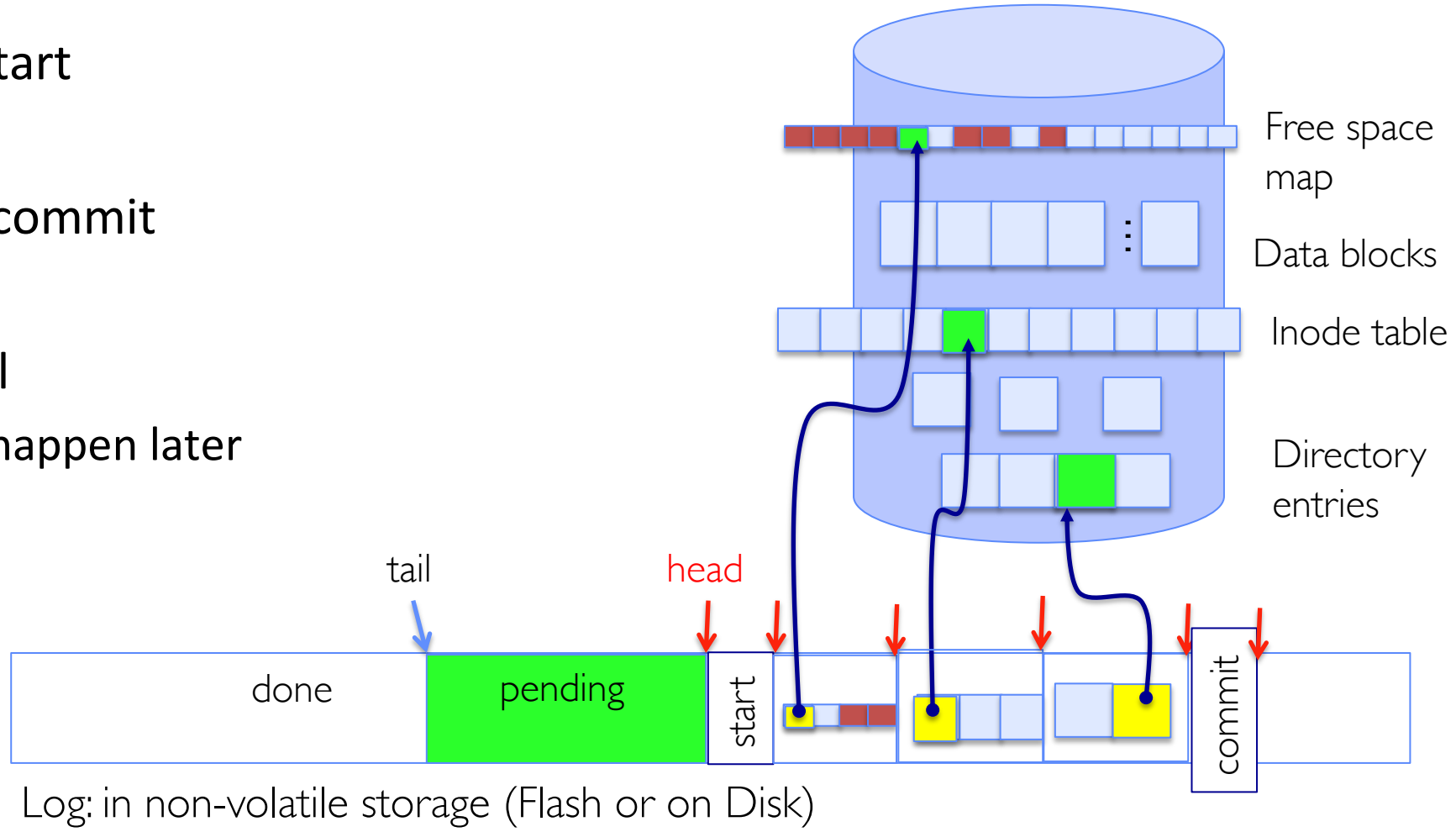
# Crash Recovery: Discard Partial Transactions

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



# Crash Recovery: Keep Complete Transactions

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



# Journaling Summary

Why go through all this trouble?

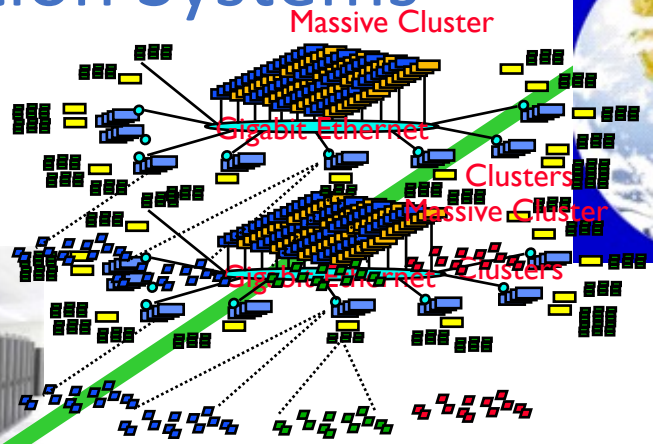
- Updates atomic, even if we crash:
  - Update either gets fully applied or discarded
  - All physical operations *treated as a logical unit*

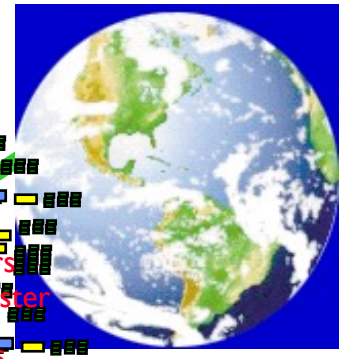
Isn’t this expensive?

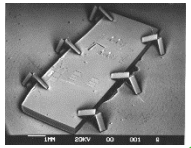
- Yes! We're now writing all data twice (once to log, once to actual data blocks in target file)
- Modern filesystems journal metadata updates only
  - Record modifications to file system data structures
  - But apply updates to a file’s contents directly

# Recall: Societal Scale Information Systems

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





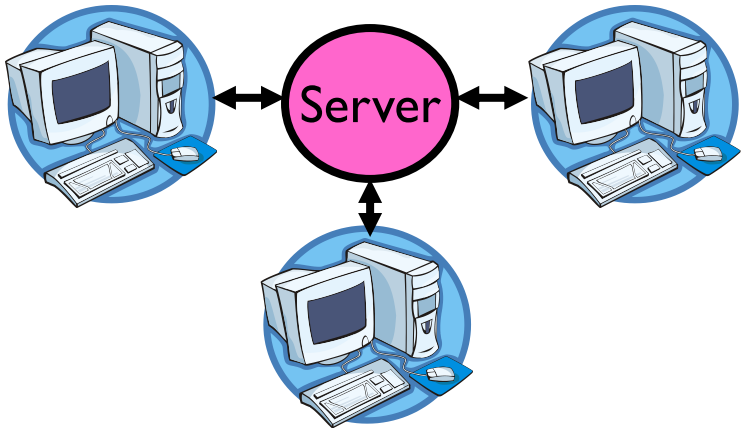
Internet Connectivity

Scalable, Reliable, Secure Services

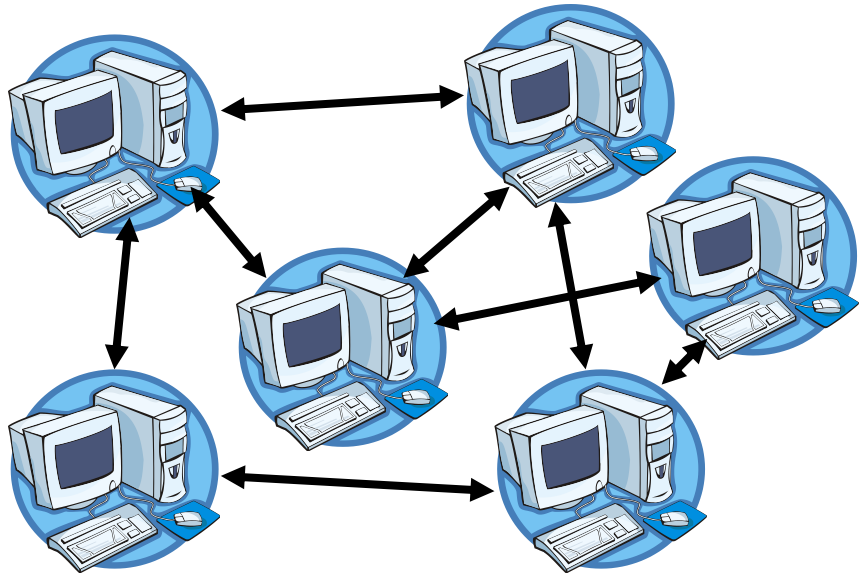
Databases
Information Collection
Remote Storage
Online Games
Commerce
…

MEMS for Sensor Nets

# Centralized vs Distributed Systems



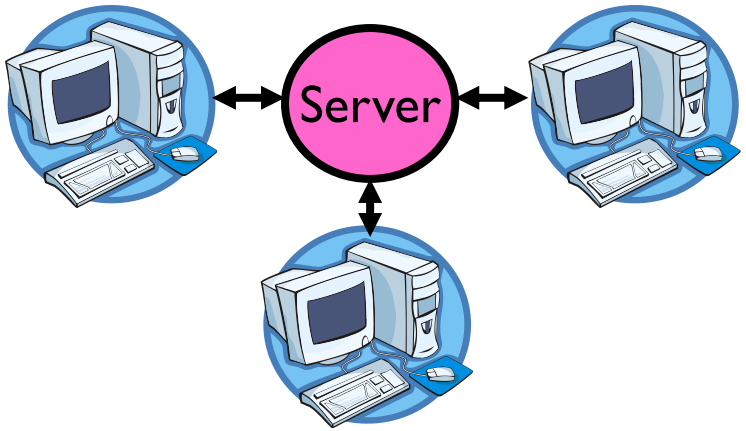

Client/Server Model



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

# Centralized vs Distributed Systems

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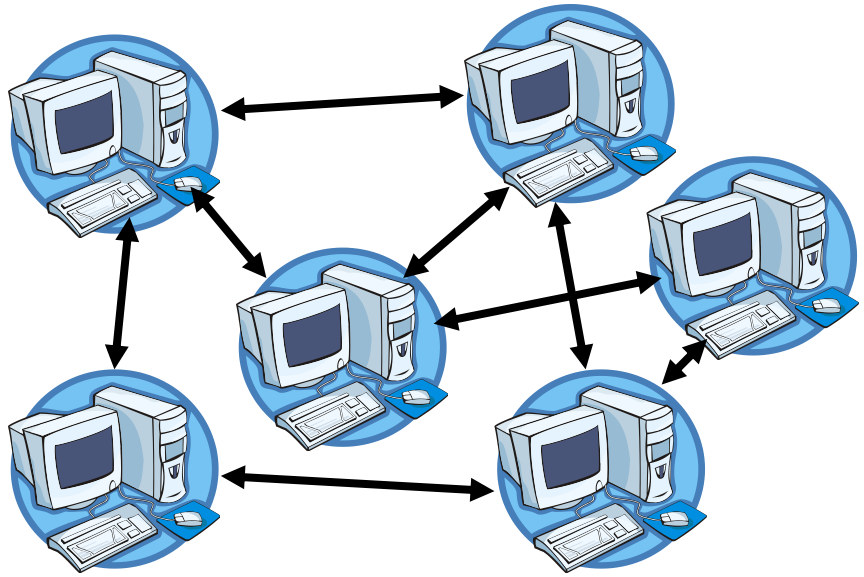


Peer-to-Peer Model

- 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

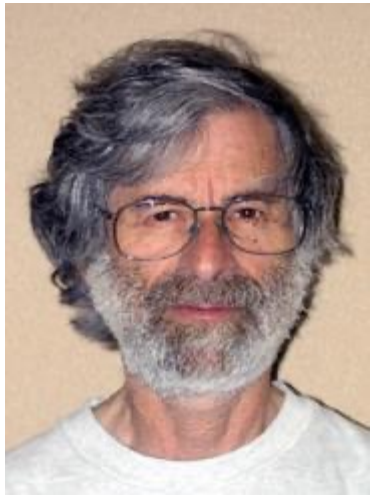
# Distributed Systems: Motivation/Issues/Promise

- 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

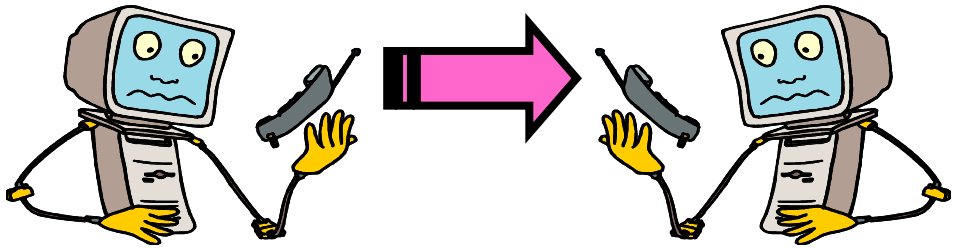
- Reality has been disappointing
  - *Worse availability*: depend on every machine being up
    - » Lamport: "A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable."
  - *Worse reliability*: can lose data if any machine crashes
  - *Worse security*: anyone in world can break into system
- Coordination is more difficult
  - Must coordinate multiple copies of shared state information
  - What would be easy in a centralized system becomes a lot more difficult
- Trust/Security/Privacy/Denial of Service
  - Many new variants of problems arise as a result of distribution
  - Can you trust the other members of a distributed application enough to even perform a protocol correctly?
  - Corollary of Lamport's quote: "A distributed system is one where you can't do work because some computer you didn't even know existed is successfully coordinating an attack on my system!"



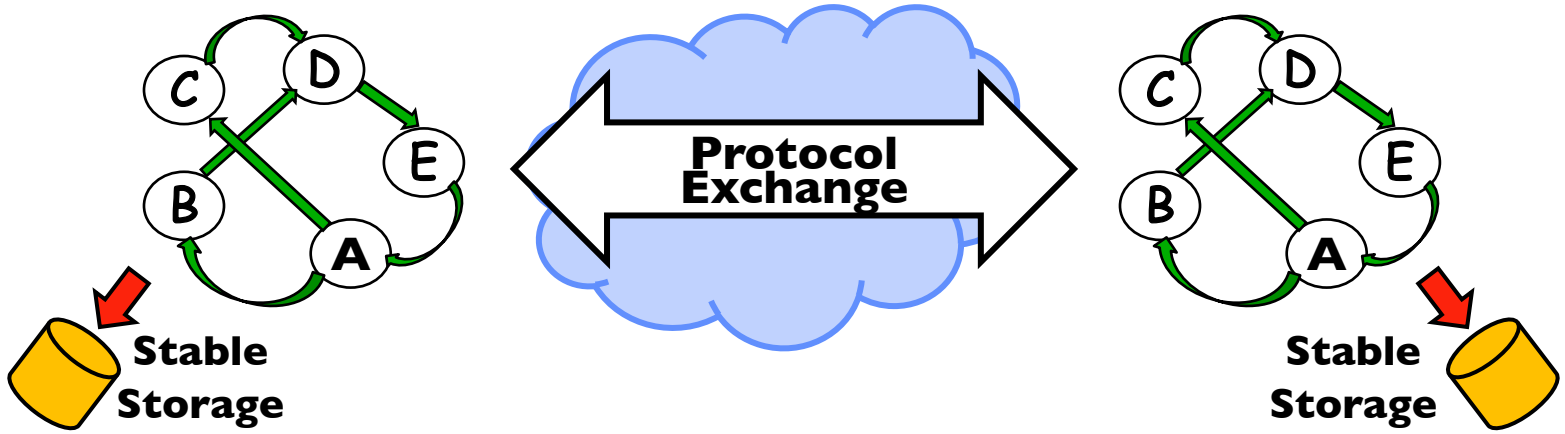
**Leslie Lamport**

# 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



# How do entities communicate? A Protocol!



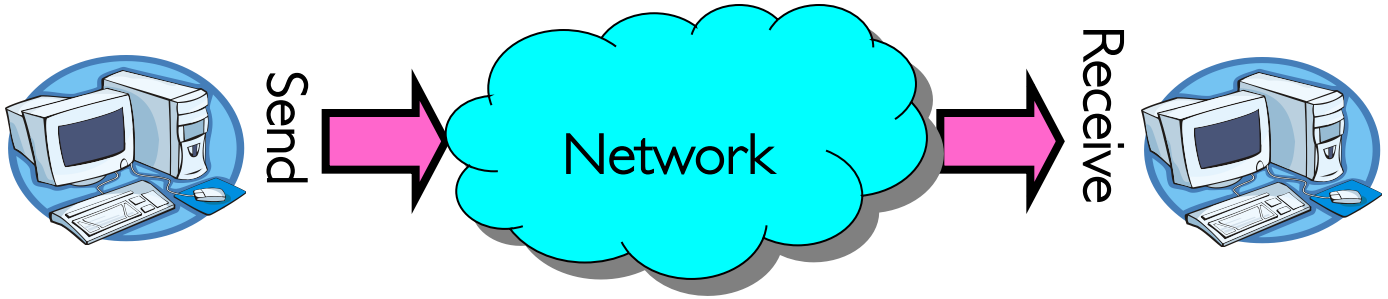

- A protocol is an agreement on how to communicate, including:
  - Syntax: how a communication is specified & structured
    - » Format, order messages are sent and received
  - Semantics: what a communication means
    - » Actions taken when transmitting, receiving, or when a timer expires
- Described formally by a state machine
  - Often represented as a message transaction diagram
  - Can be a partitioned state machine: two parties synchronizing duplicate sub-state machines between them
  - Stability in the face of failures!

# 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

# Distributed Applications

- How do you actually program a distributed application?
  - Need to synchronize multiple threads, running on different machines
    - » No shared memory, so cannot use test&set




  - One Abstraction: send/receive messages
    - » Already atomic: no receiver gets portion of a message and two receivers cannot get same message
- Interface:
  - Mailbox (mbox): temporary holding area for messages
    - » Includes both destination location and queue
  - Send(message,mbox)
    - » Send message to remote mailbox identified by mbox
  - Receive(buffer,mbox)
    - » Wait until mbox has message, copy into buffer, and return
    - » If threads sleeping on this mbox, wake up one of them

# Distributed Consensus Making

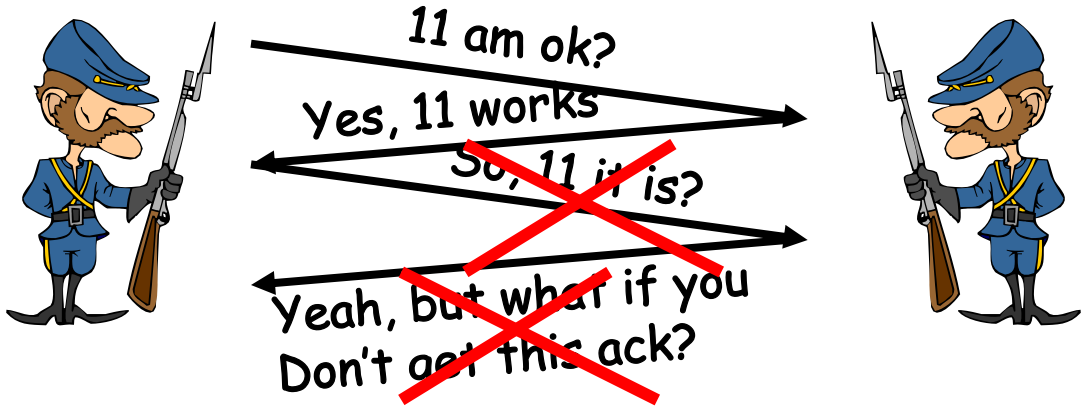
- Consensus problem
  - All nodes propose a value
  - Some nodes might crash and stop responding
  - Eventually, all remaining nodes decide on the same value from set of proposed values
- Distributed Decision Making
  - Choose between “true” and “false”
  - Or Choose between “commit” and “abort”
- Equally important (but often forgotten!): make it durable!
  - How do we make sure that decisions cannot be forgotten?
    - » This is the “D” of “ACID” in a regular database
  - In a global-scale system?
    - » What about erasure coding or massive replication?

# Two General's Paradox

- Two General's paradox:
  - Constraints of problem:
    - » Two generals, on separate mountains
    - » Can only communicate via messengers
    - » Messengers can be captured
  - Problem: need to coordinate attack
    - » If they attack at different times, they all die
    - » If they attack at same time, they win
  - Named after Custer, who died at Little Big Horn because he arrived a couple of days too early

# Two General's Paradox (con't)

- Can messages over an unreliable network be used to guarantee two entities do something simultaneously?
  - Remarkably, "no", even if all messages get through




  - No way to be sure last message gets through!
  - In real life, use radio for simultaneous (out of band) communication
- So, clearly, we need something other than simultaneity!

# Two-Phase Commit

- Since we can't solve the Two General's Paradox (i.e., simultaneous action), let's solve a related problem

- Distributed transaction: Two or more machines agree to do something, or not do it, atomically
  - No constraints on time, just that it will eventually happen!

- Two-Phase Commit protocol: Developed by Turing award winner Jim Gray
  - (first Berkeley CS PhD, 1969)
  - Many important database breakthroughs also from Jim Gray

**Jim Gray**

# Two-Phase Commit Protocol

- Persistent stable log on each machine: keep track of whether commit has happened
  - If a machine crashes, when it wakes up it first checks its log to recover state of world at time of crash
- Prepare Phase:
  - The global coordinator requests that all participants will promise to commit or rollback the transaction
  - Participants record promise in log, then acknowledge
  - If anyone votes to abort, coordinator writes "Abort" in its log and tells everyone to abort; each records "Abort" in log
- Commit Phase:
  - After all participants respond that they are prepared, then the coordinator writes "Commit" to its log
  - Then asks all nodes to commit; they respond with ACK
  - After receive ACKs, coordinator writes "Got Commit" to log
- Log used to guarantee that all machines either commit or don’t

# Two-Phase Commit Algorithm

- One coordinator
- N workers (replicas)
- High level algorithm description:
  - Coordinator asks all workers if they can commit
  - If all workers reply "VOTE-COMMIT", then coordinator broadcasts "GLOBAL-COMMIT"

    Otherwise, coordinator broadcasts "GLOBAL-ABORT"
  - Workers obey the GLOBAL messages
- Use a persistent, stable log on each machine to keep track of what you are doing
  - If a machine crashes, when it wakes up it first checks its log to recover state of world at time of crash

# Two-Phase Commit: Setup

- One machine *(coordinator)* initiates the protocol
- It asks *every* machine to **vote** on transaction

- Two possible votes:
  - **Commit**
  - **Abort**

- Commit transaction only if unanimous approval

# Two-Phase Commit: Preparing

**Worker Agrees to Commit**

- Machine has **guaranteed** that it will accept transaction
- Must be **recorded in log** so machine will remember this decision if it fails and restarts

**Worker Agrees to Abort**

- Machine has **guaranteed** that it will **never accept** this transaction
- Must be **recorded in log** so machine will remember this decision if it fails and restarts

# Two-Phase Commit: Finishing

**Commit Transaction**

- Coordinator learns *all machines have agreed to commit*
- Record decision to commit in local log
- Apply transaction, inform voters

**Abort Transaction**

- Coordinator learns *at least on machine has voted to abort*
- Record decision to abort in local log
- Do not apply transaction, inform voters

# Two-Phase Commit: Finishing

**Commit Transaction**

- Coordinator learns *all machines have agreed to commit*
- Record decision to commit in local log
- Apply transaction, inform voters

**Abort Transaction**

- Coordinator learns *at least one machine has voted to abort*
- Record decision to abort in local log
- Do not apply transaction, inform voters

Because no machine can take back its decision, exactly one of these will happen

# Detailed Algorithm

## Coordinator Algorithm

Coordinator sends **VOTE-REQ** to all workers

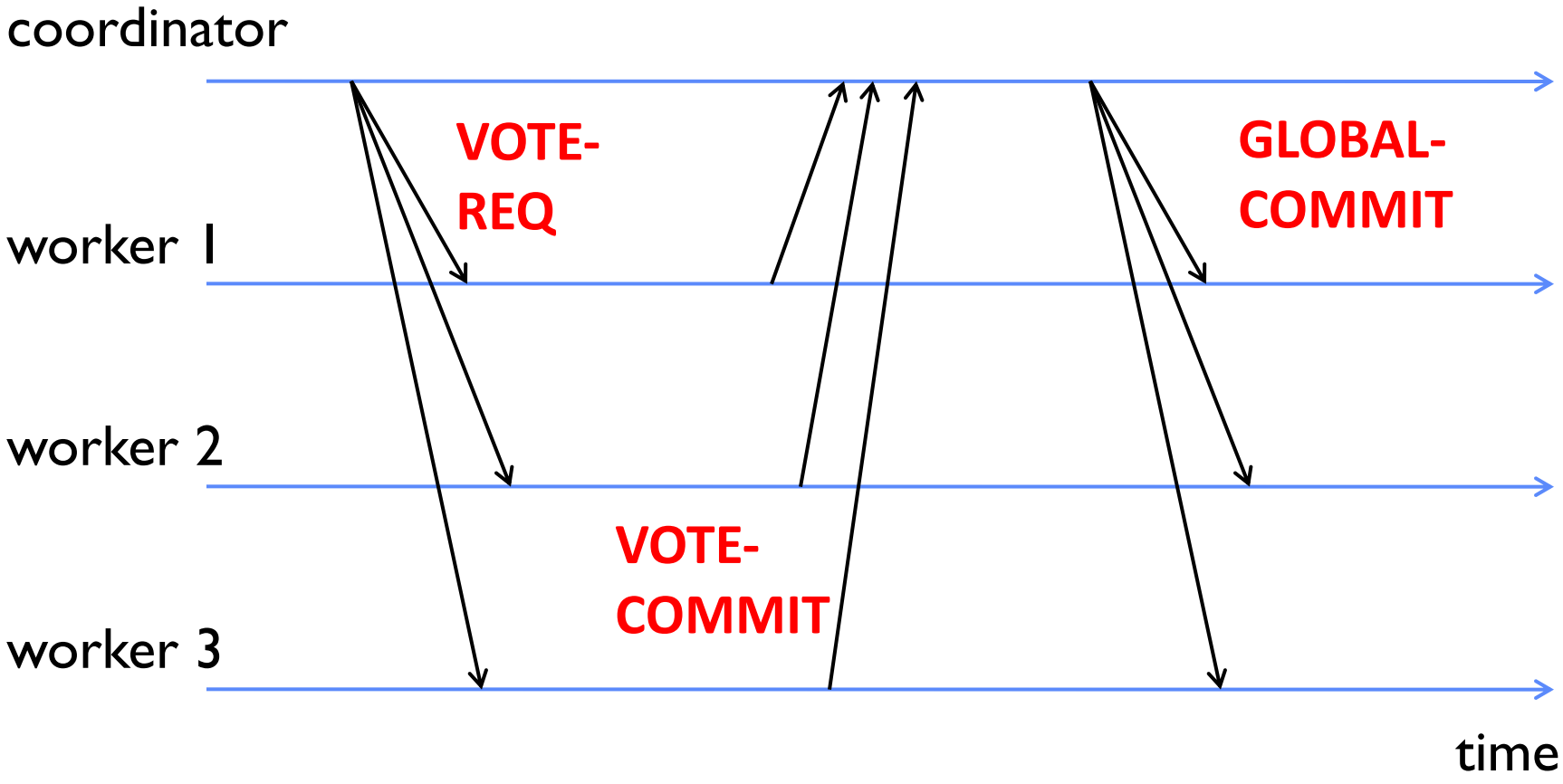
- If receive **VOTE-COMMIT** from all N workers, send **GLOBAL-COMMIT** to all workers
- If don't receive **VOTE-COMMIT** from all N workers, send **GLOBAL-ABORT** to all workers

## Worker Algorithm

- Wait for **VOTE-REQ** from coordinator
- If ready, send **VOTE-COMMIT** to coordinator
- If not ready, send **VOTE-ABORT** to coordinator
  - And immediately abort

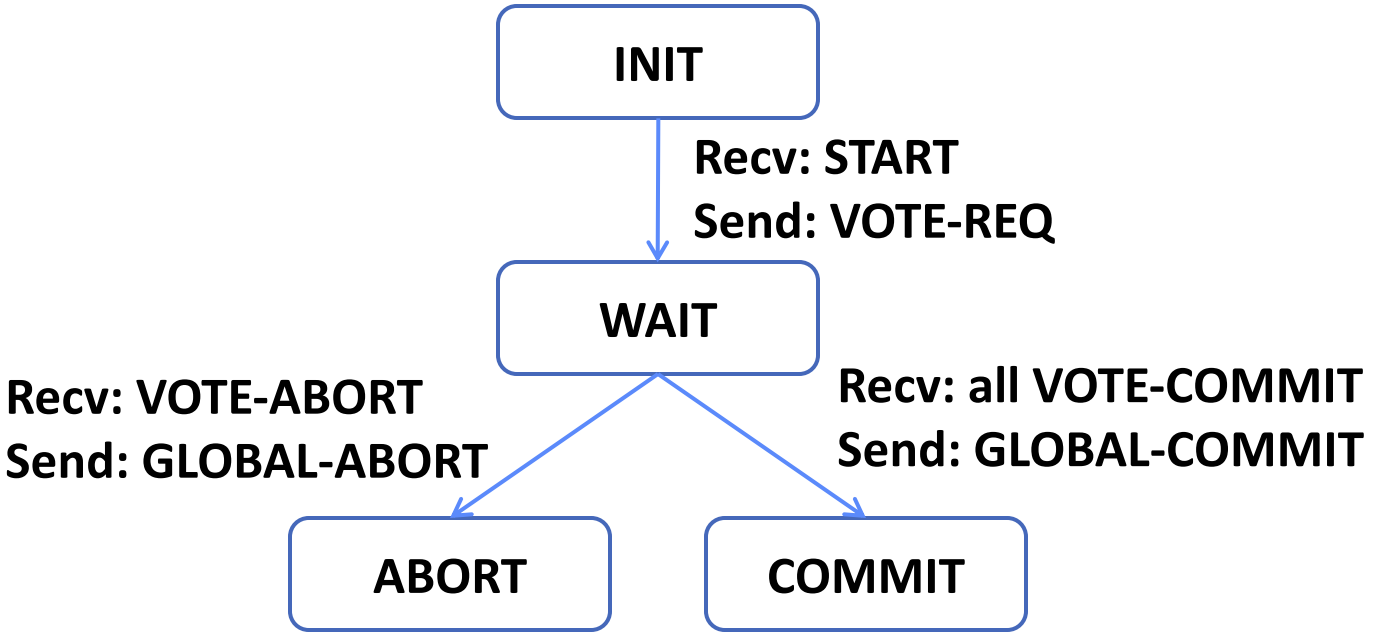
- If receive **GLOBAL-COMMIT** then commit
- If receive **GLOBAL-ABORT** then abort

# Failure Free Example Execution

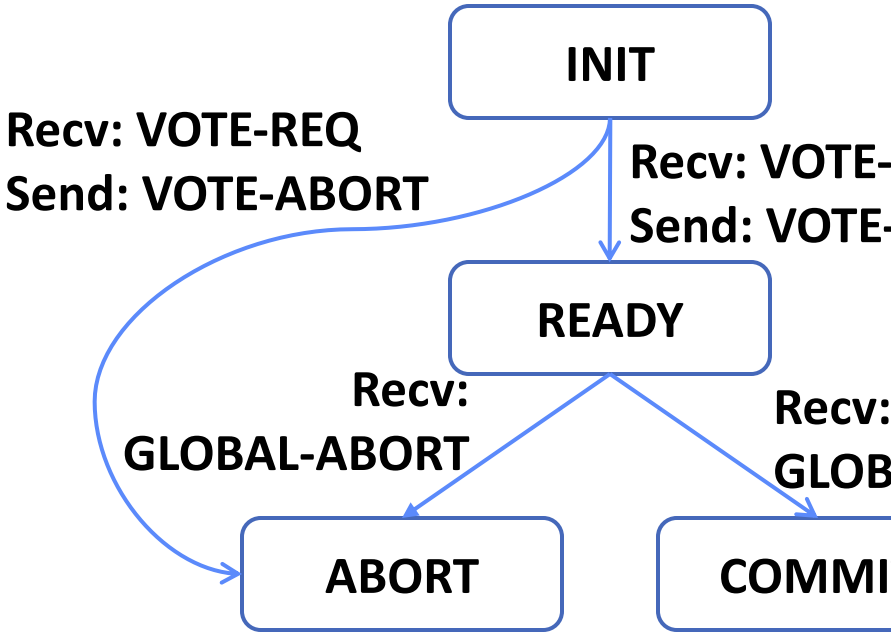


# State Machine of Coordinator

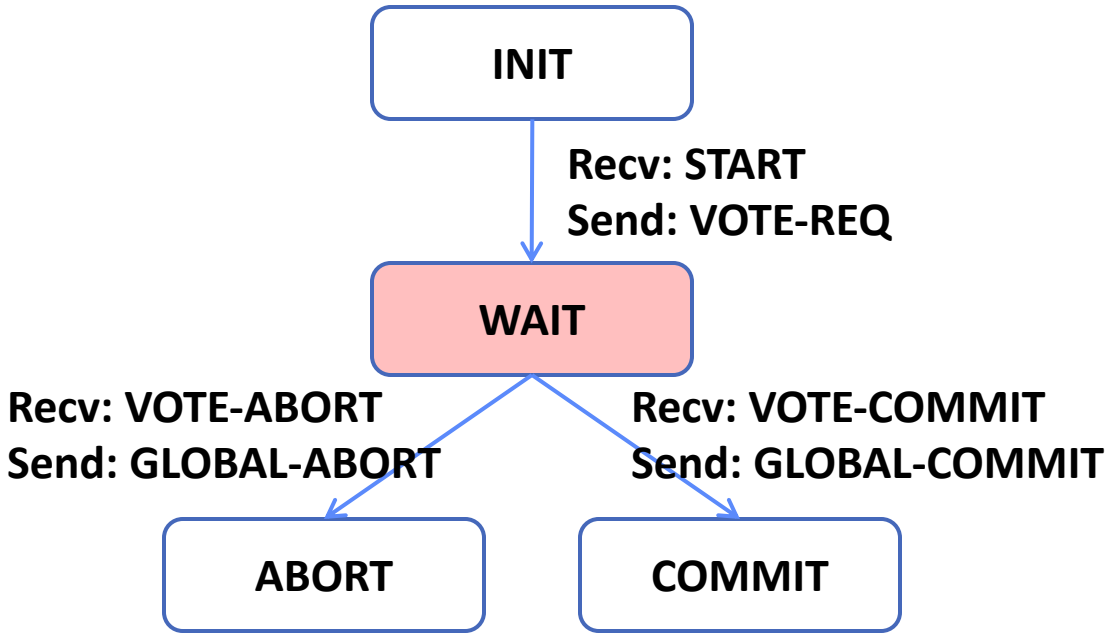
- Coordinator implements simple state machine:



# State Machine of Workers

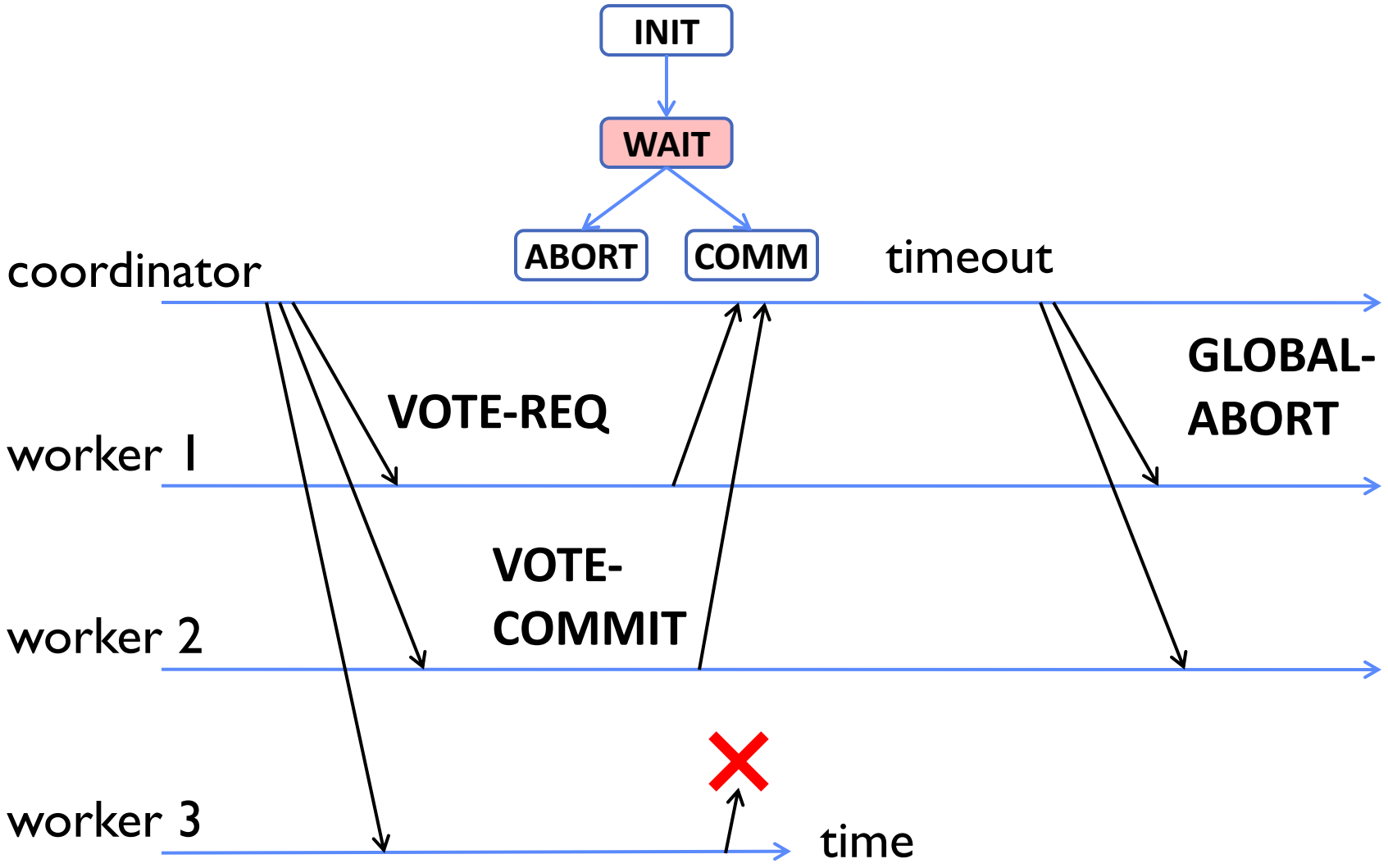


# Dealing with Worker Failures

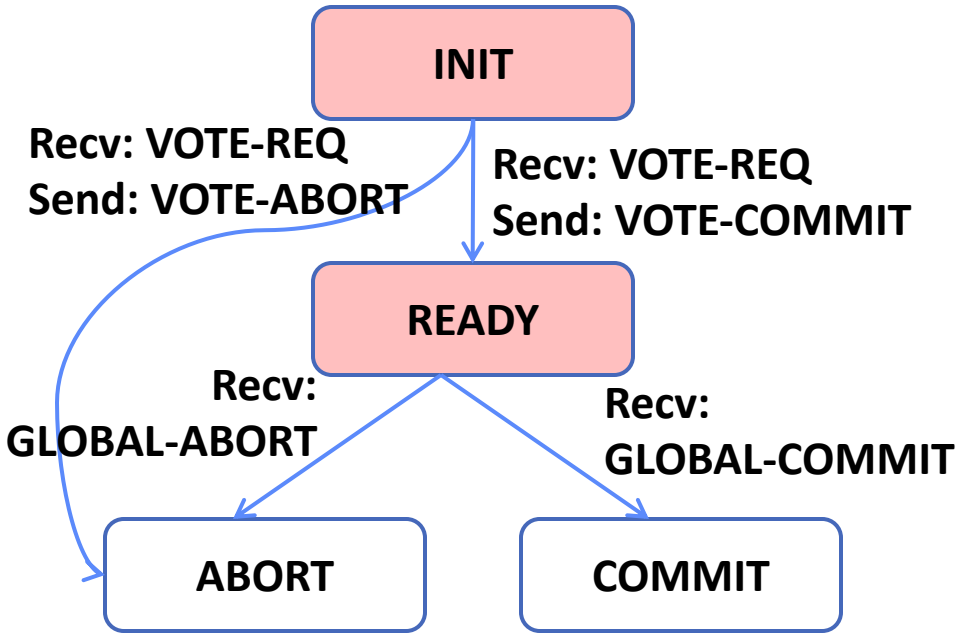



- Failure only affects states in which the coordinator is waiting for messages
- Coordinator only waits for votes in “WAIT” state
- In WAIT, if doesn’t receive N votes, it times out and sends GLOBAL-ABORT

# Example of Worker Failure

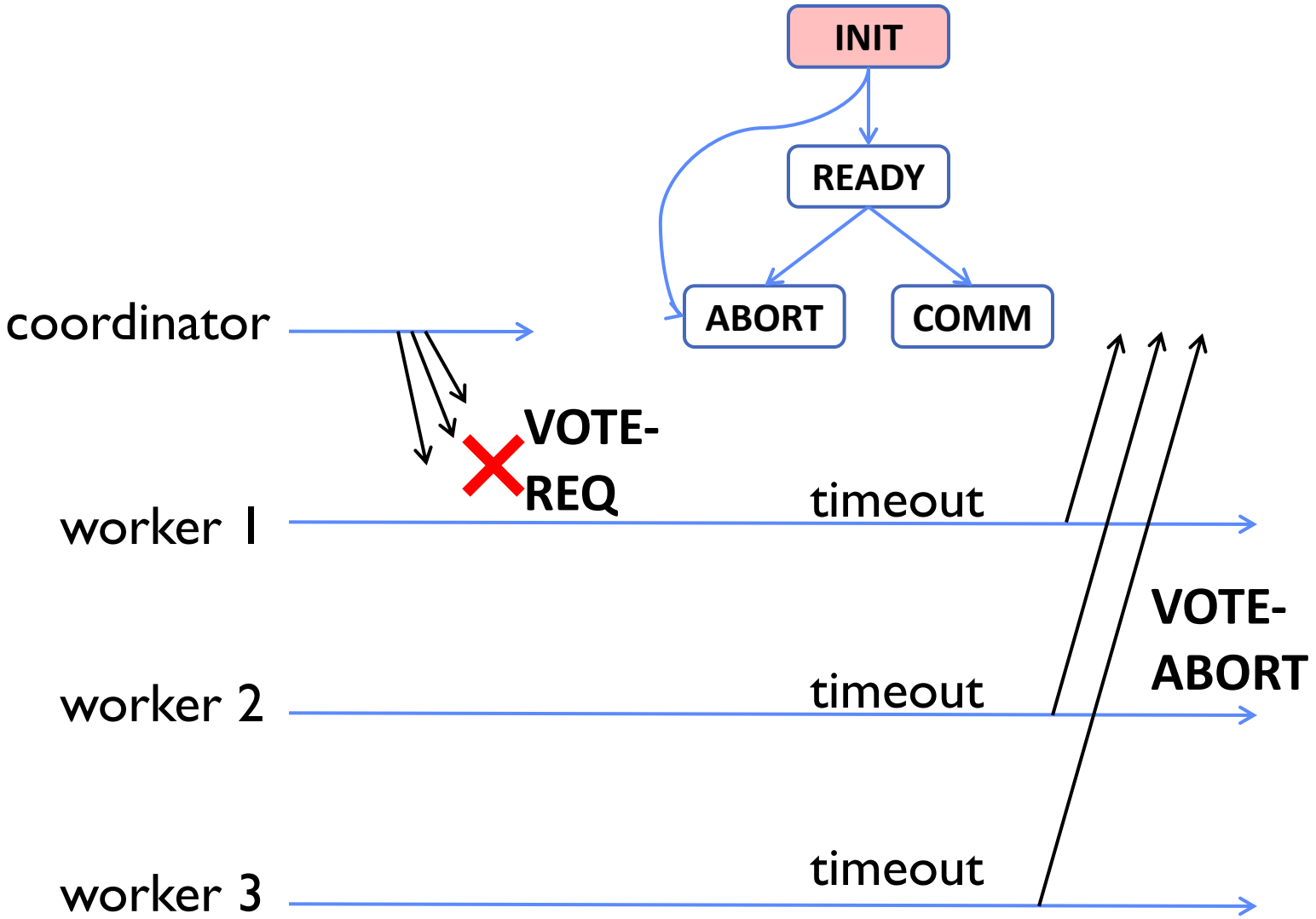


# Dealing with Coordinator Failure

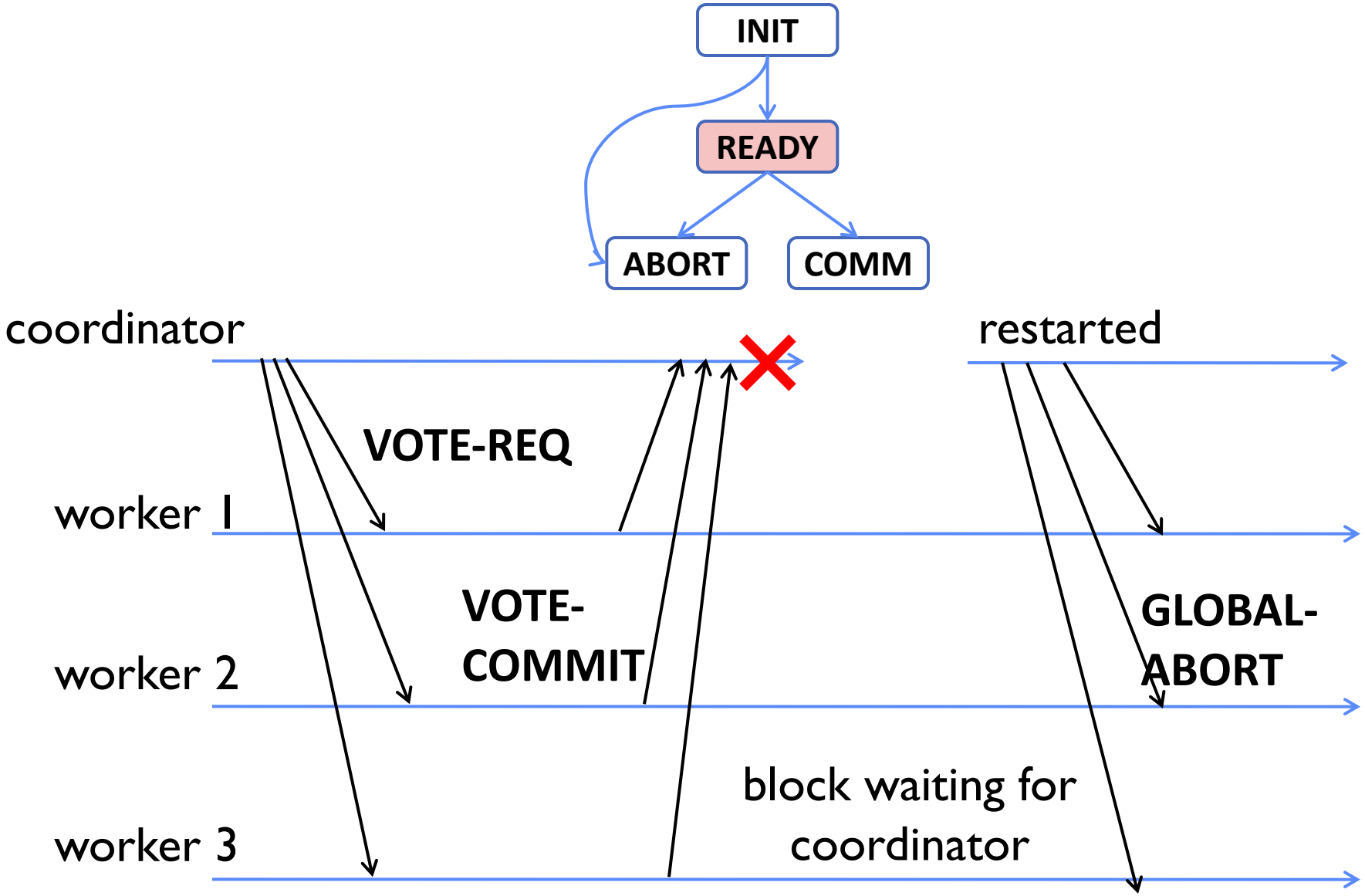



- Worker waits for VOTE-REQ in INIT
  - Worker can time out and abort (coordinator handles it)
- Worker waits for GLOBAL-* message in READY
  - If coordinator fails, workers must **BLOCK** waiting for coordinator to recover and send GLOBAL_* message

# Example of Coordinator Failure #1



# Example of Coordinator Failure #2



# Durability

- All nodes use stable storage to store current state
  - stable storage is non-volatile storage (e.g. backed by disk) that guarantees atomic writes.
  - E.g.: SSD, NVRAM
- Upon recovery, nodes can restore state and resume:
  - Coordinator aborts in INIT, WAIT, or ABORT
  - Coordinator commits in COMMIT
  - Worker aborts in INIT, ABORT
  - Worker commits in COMMIT
  - Worker "asks" Coordinator in READY

# Distributed Decision Making Discussion (1/2)

- Why is distributed decision making desirable?
  - Fault Tolerance!
  - A group of machines can come to a decision even if one or more of them fail during the process
    - » Simple failure mode called “failstop”
  - After decision made, result recorded in multiple places
- Why is 2PC not subject to the Two General’s paradox?
  - Because 2PC is about *all nodes eventually coming to the same decision – not necessarily at the same time!*
  - Allowing us to reboot and continue allows time for collecting and collating decisions

# Distributed Decision Making Discussion (2/2)

- Undesirable feature of Two-Phase Commit: Blocking
  - One machine can be stalled until another site recovers:
    - » Site B writes "prepared to commit" record to its log, sends a "yes" vote to the coordinator (site A) and crashes
    - » Site A crashes
    - » Site B wakes up, check its log, and realizes that it has voted "yes" on the update. It sends a message to site A asking what happened. At this point, B cannot decide to abort, because update may have committed
    - » B is blocked until A comes back
  - A blocked site holds resources (locks on updated items, pages pinned in memory, etc) until learns fate of update

# Summary (1/2)

- 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
- Copy-on-write provides richer function (versions) with much simpler recovery
  - Little performance impact since sequential write to storage device is nearly free
- Use of Log to improve Reliability
  - Journaled file systems such as ext3, NTFS

# Summary (2/2)

- Transactions over a log provide a general solution
  - Commit sequence to durable log, then update the disk
  - Log takes precedence over disk
  - Replay committed transactions, discard partials
- Protocol: Agreement between two parties as to how information is to be transmitted
- Two-phase commit: distributed decision making
  - First, make sure everyone guarantees they will commit if asked (prepare)
  - Next, ask everyone to commit