CS162
Operating Systems and Systems Programming
Lecture 21

Filesystem Transactions (Con't), End-to-End Argument, Distributed Decision Making

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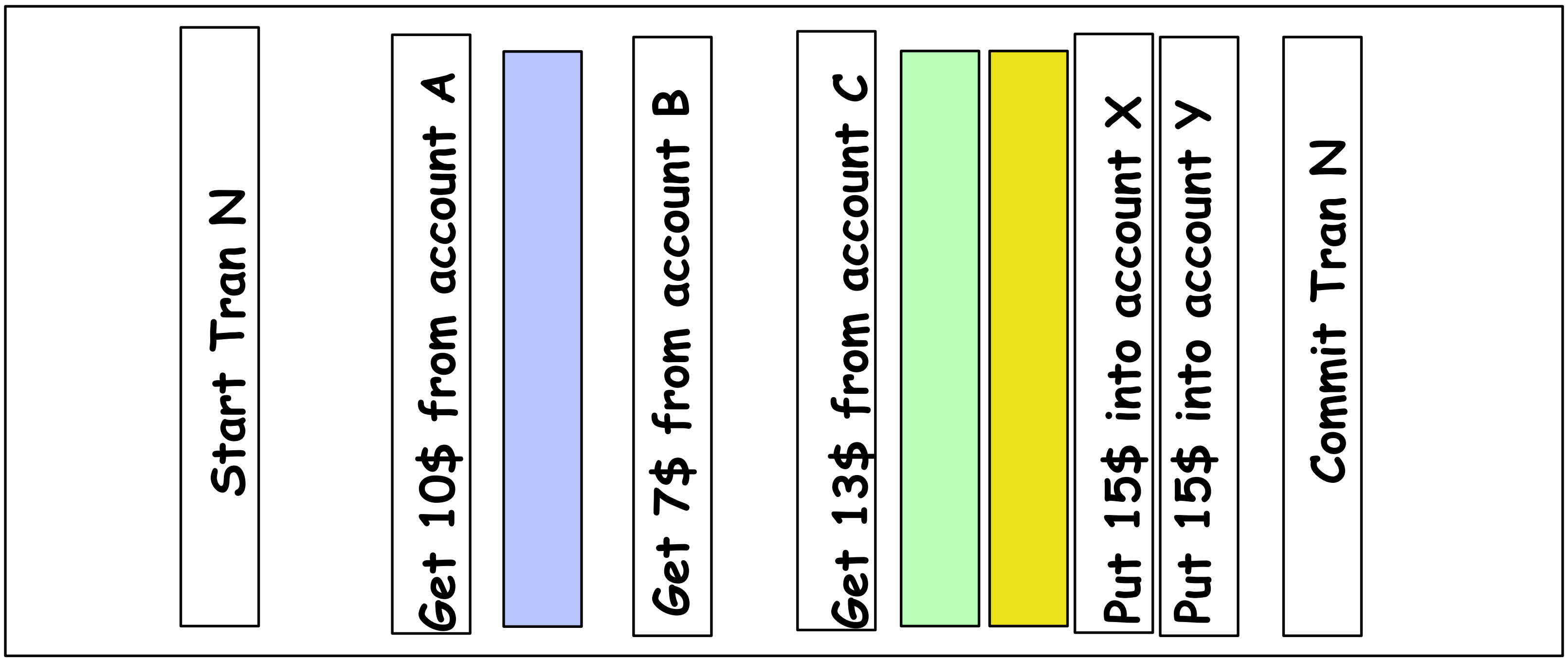
Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes*. When slides are obtained from other sources, a a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the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

Recall: 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

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



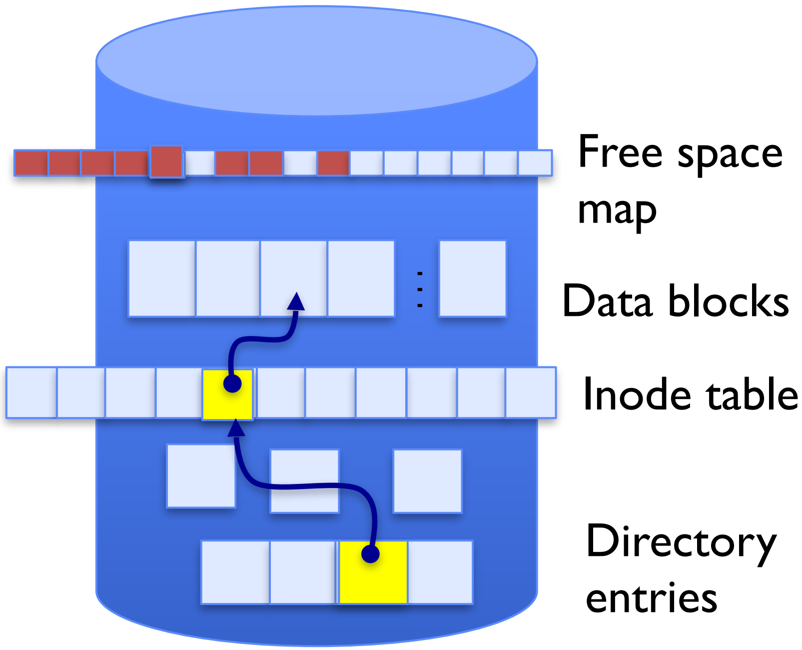
Journaling File Systems

- 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

Example: Creating a File

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

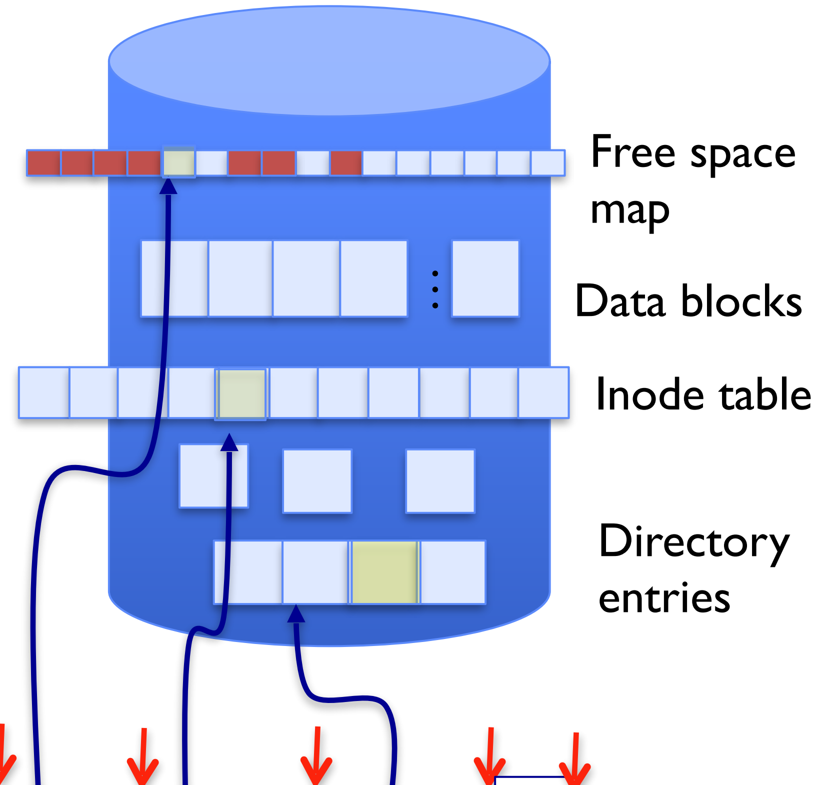
- Write map (i.e., mark used)
- Write inode entry to point to block(s)
- Write dirent to point to inode

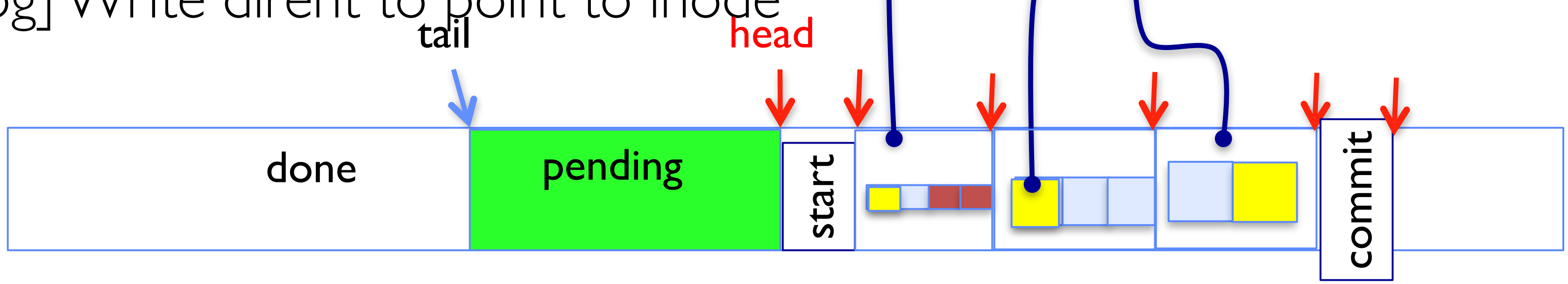


Ex: Creating a file (as a transaction)

- 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

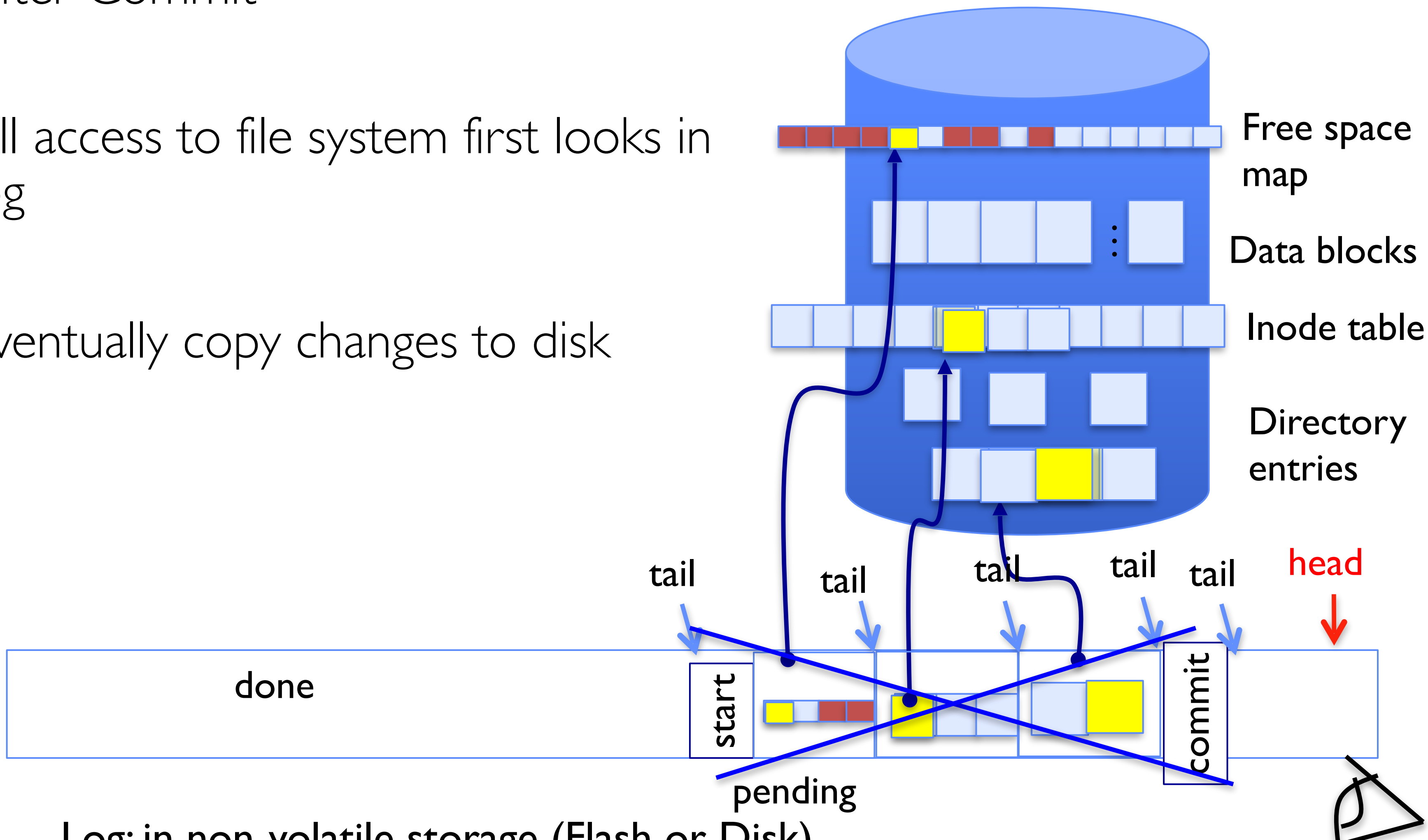




Log: in non-volatile storage (Flash or on Disk)

"Redo Log " – Replay Transactions

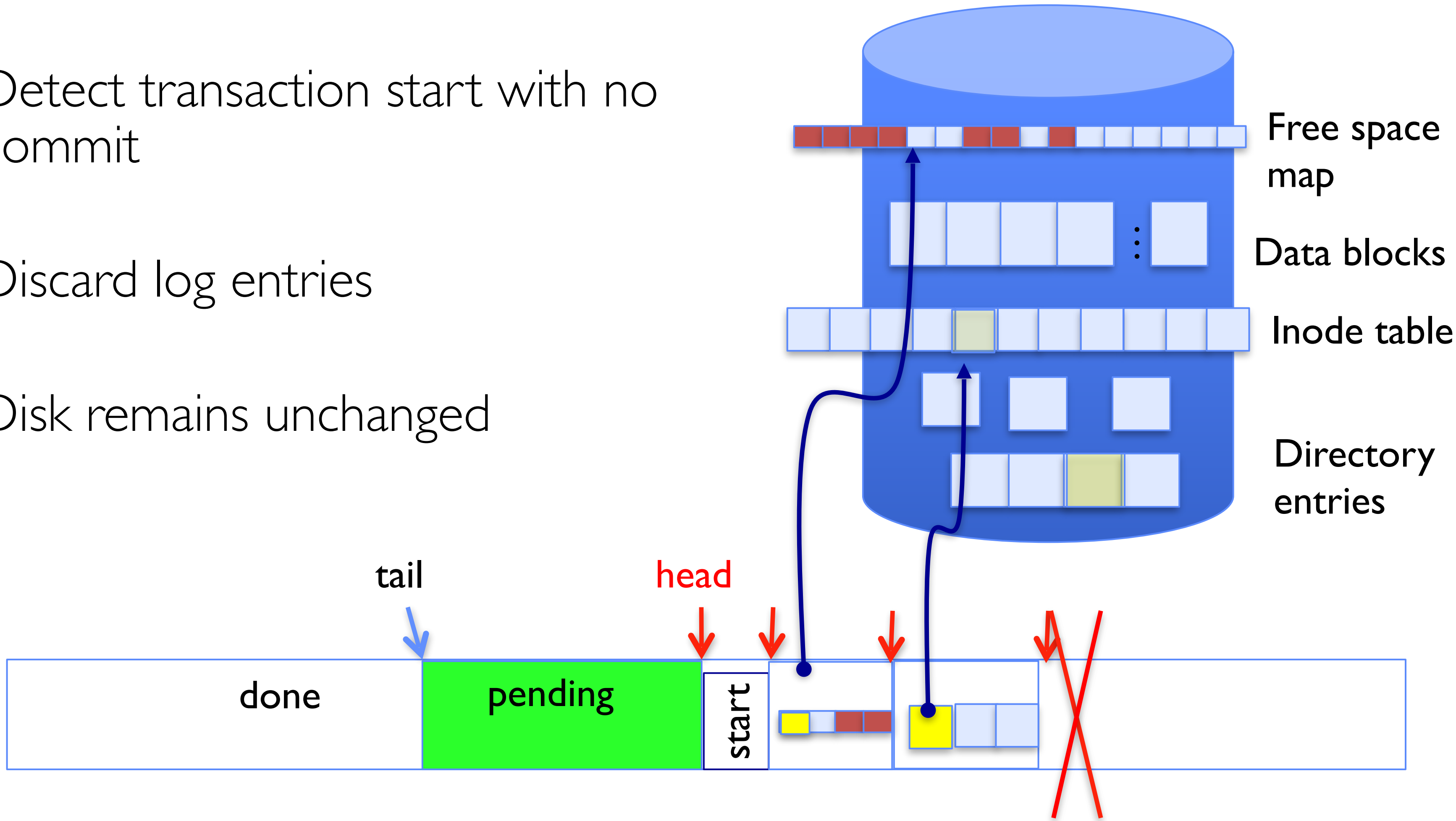
- After Commit
- All access to file system first looks in log
- Eventually copy changes to disk



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

Crash During Logging – Recover

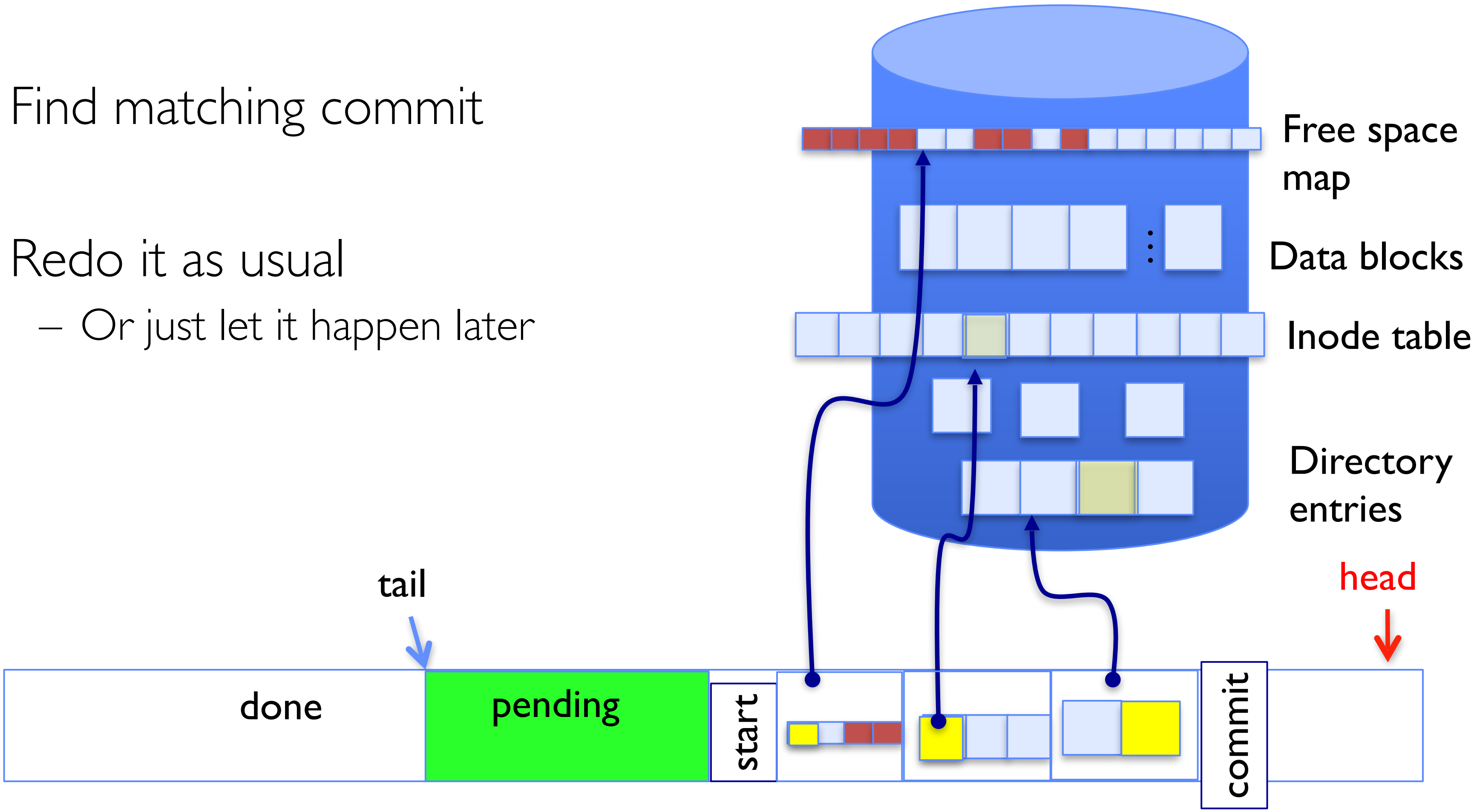
- Upon recovery scan the log
- Detect transaction start with no commit
- Discard log entries
- Disk remains unchanged



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)

Journaling Summary

Why go through all this trouble?

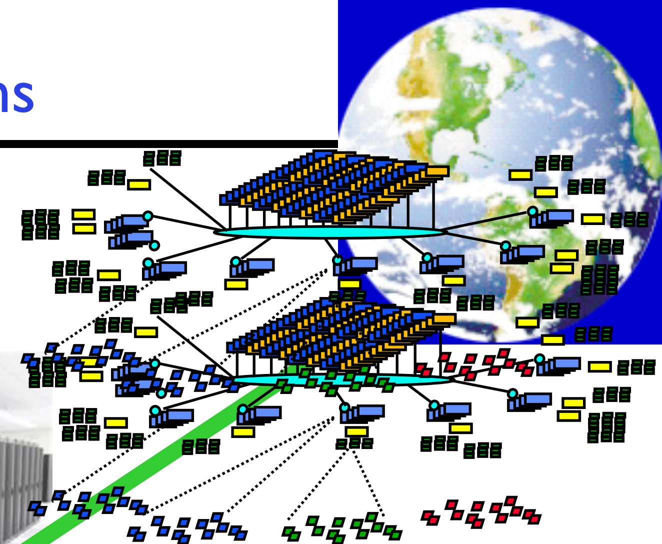
- Updates atomic, even if we crash:
  - Update either gets fully applied or discarded
  - All physical operations *treated as a logical unit*

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 offer an option to journal metadata updates only
  - Record modifications to file system data structures
  - But apply updates to a file's contents directly

Societal Scale Information Systems

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




Internet Connectivity

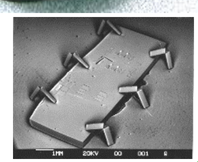


Scalable, Reliable, Secure Services

Databases
Information Collection
Remote Storage
Online Games
Commerce
…

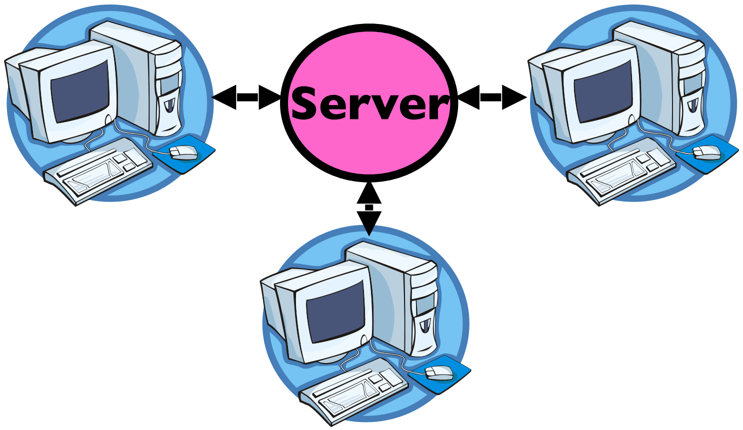




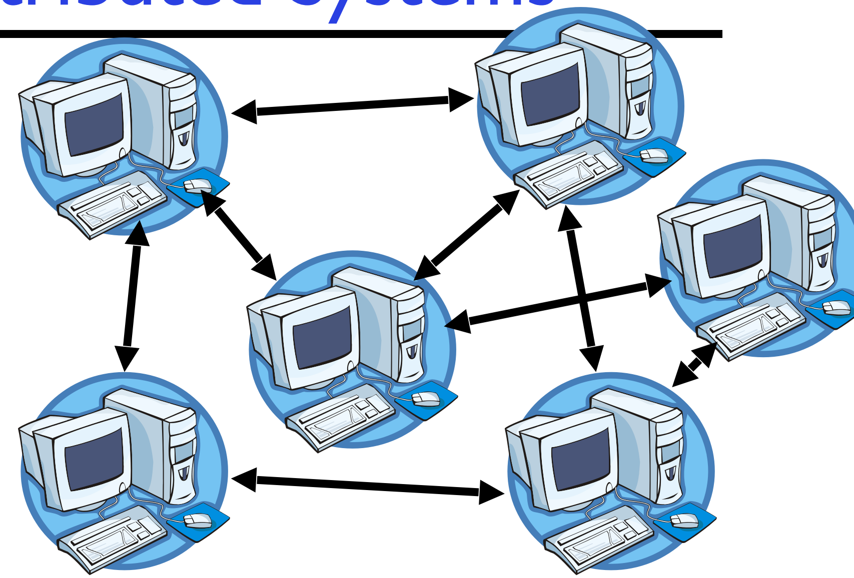



MEMS for Sensor Nets

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
- 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

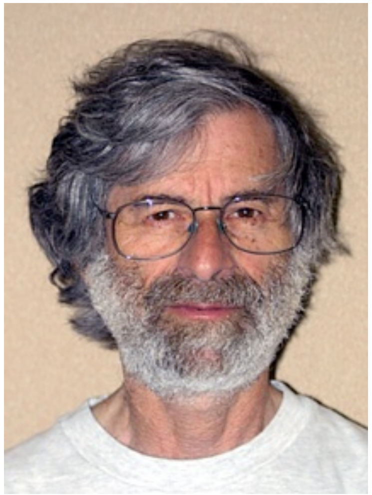
Distributed Systems: Motivation/Issues/Promise

- 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

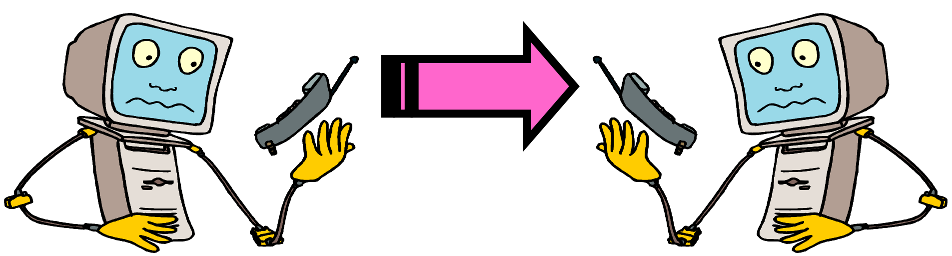
- Reality has been disappointing
  - *Worse availability*: depend on every machine being up
    - » Lamport: "A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable."
  - *Worse reliability*: can lose data if any machine crashes
  - *Worse security*: anyone in world can break into system
- Coordination is more difficult
  - Must coordinate multiple copies of shared state information (using only a network)
  - 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!"



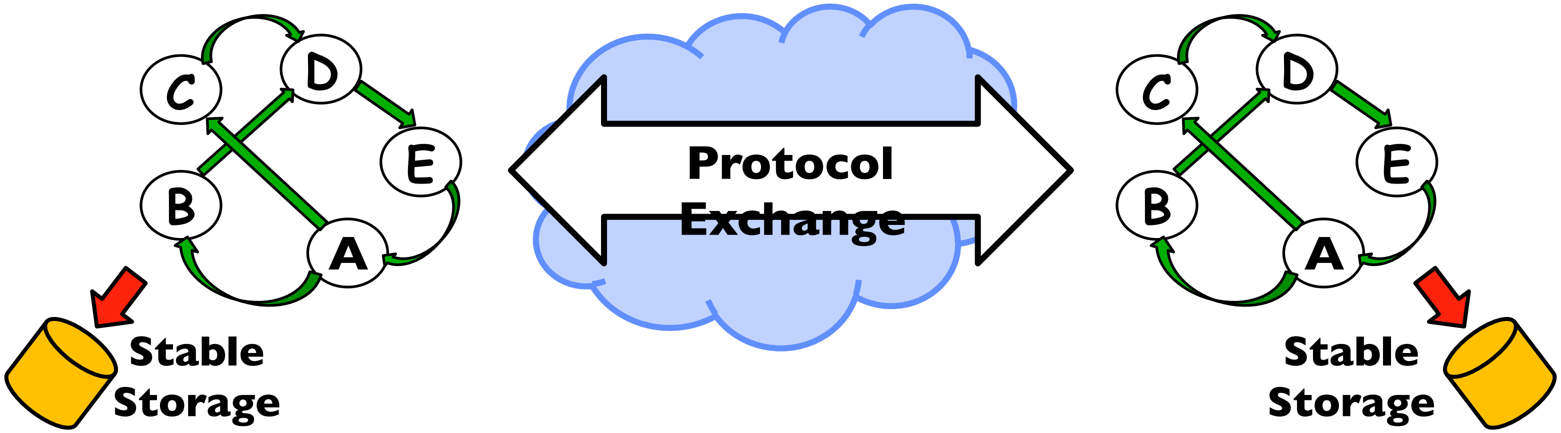
Leslie Lamport

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!



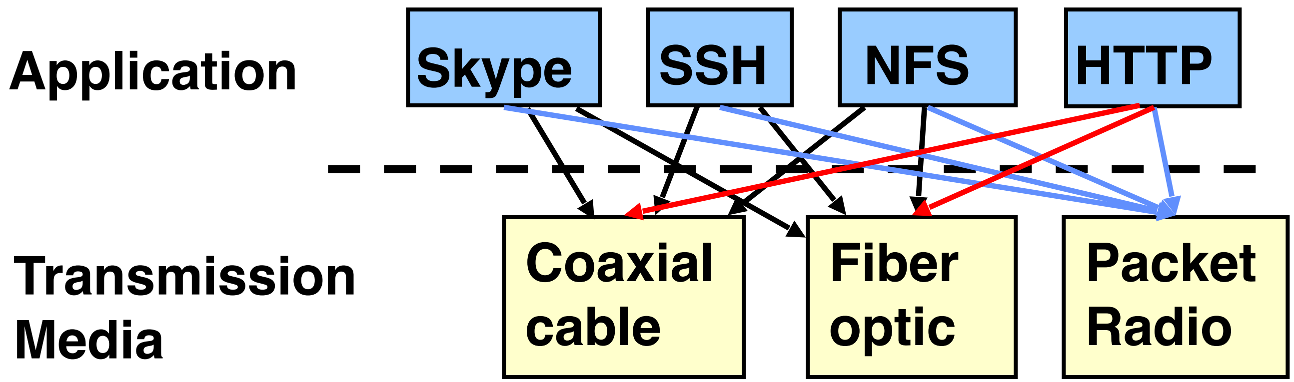
- A protocol is an agreement on how to communicate, including:
  - Syntax: how a communication is specified & structured
    - » Format, order messages are sent and received
  - Semantics: what a communication means
    - » Actions taken when transmitting, receiving, or when a timer expires
- Described 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**

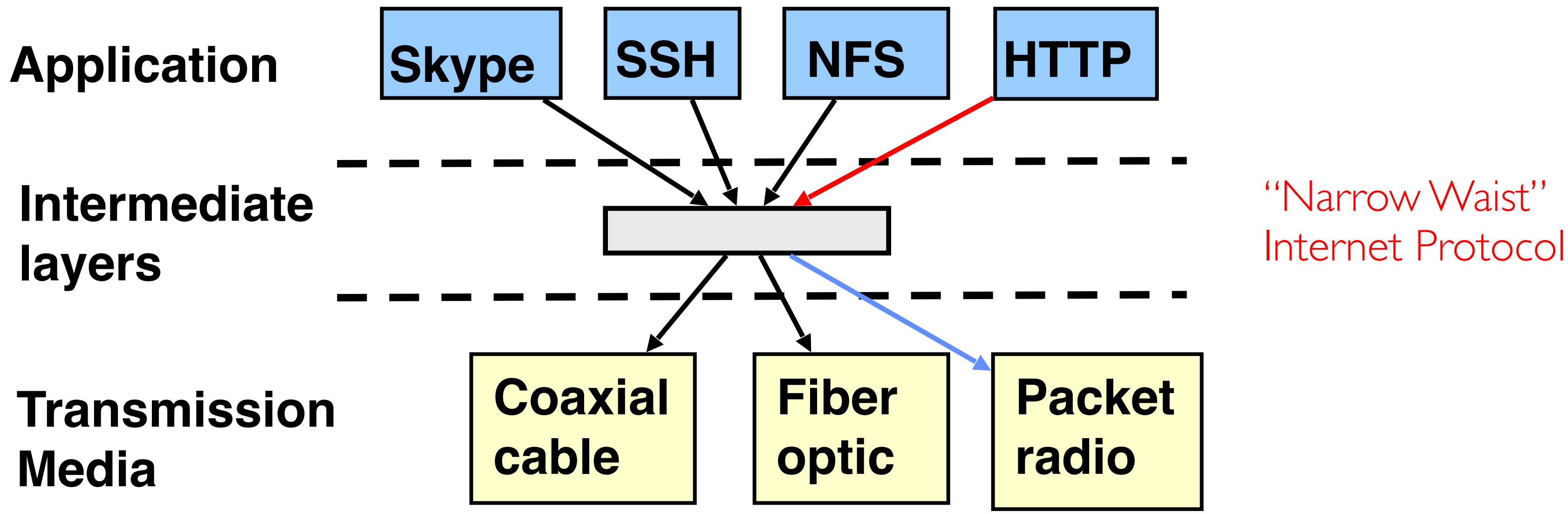
  1. Callee: “Yeah, blah blah blah …” **pause**
  2. Caller: Bye
  3. Callee: Bye
  4. Hang up

Global Communication: The Problem



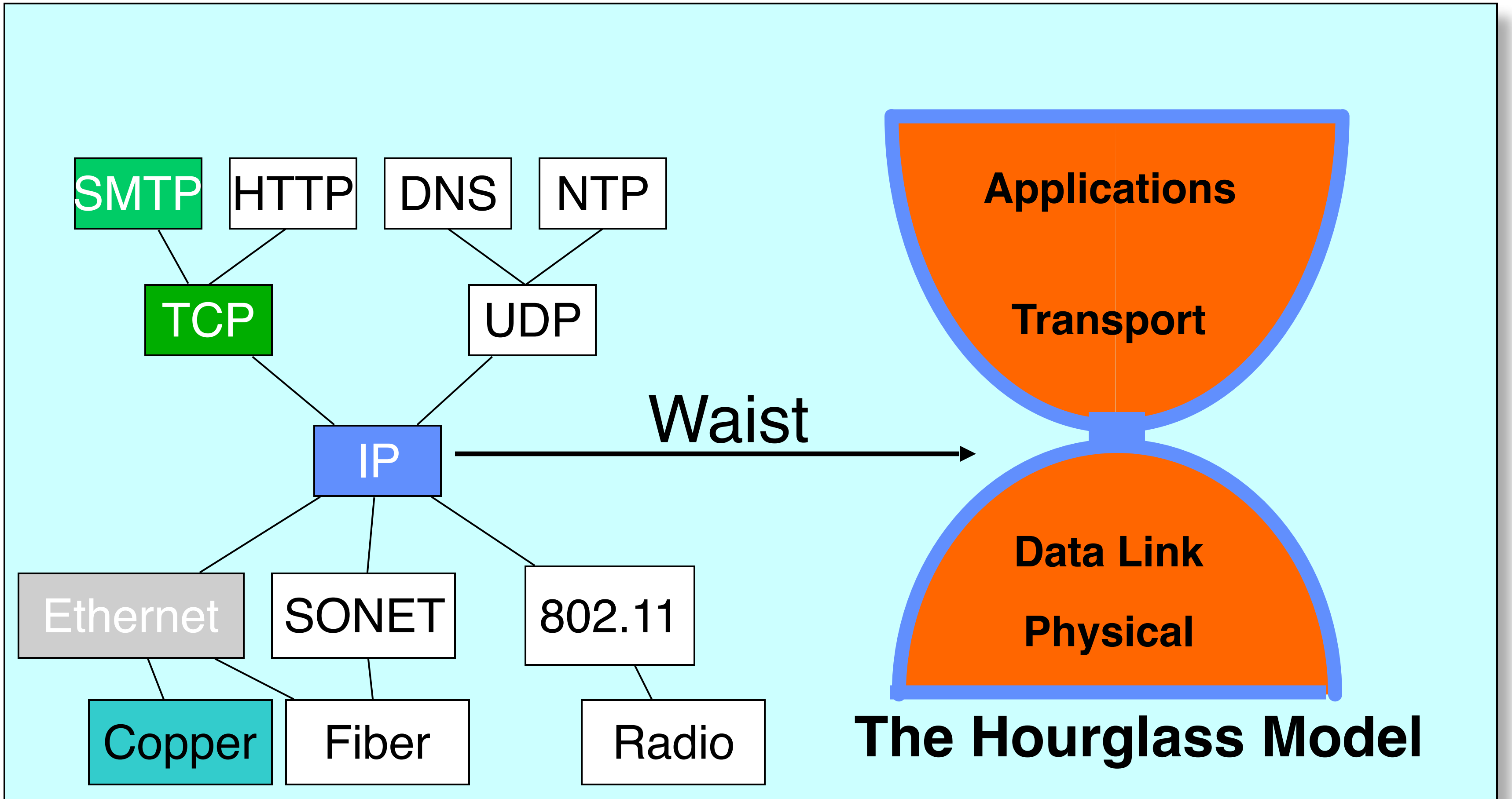
- Many different applications
  - email, web, P2P, etc.
- Many different network styles and technologies
  - Wireless vs. wired vs. optical, etc.
- How do we organize this mess?
  - Re-implement every application for every technology?
- No! But how does the Internet design avoid this?

Solution: Intermediate Layers



- Introduce intermediate layers that provide set of abstractions for various network functionality & technologies
  - A new app/media implemented only once
  - Variation on "add another level of indirection"
- Goal: Reliable communication channels on which to build distributed applications

The Internet *Hourglass*



There is just one network-layer protocol, IP.

The "narrow waist" facilitates interoperability.

Implications of Hourglass

Single Internet-layer module (IP):

- Allows arbitrary networks to interoperate
  - Any network technology that supports IP can exchange packets
- Allows applications to function on all networks
  - Applications that can run on IP can use any network
- Supports simultaneous innovations above and below IP
  - But changing IP itself, i.e., IPv6, very involved

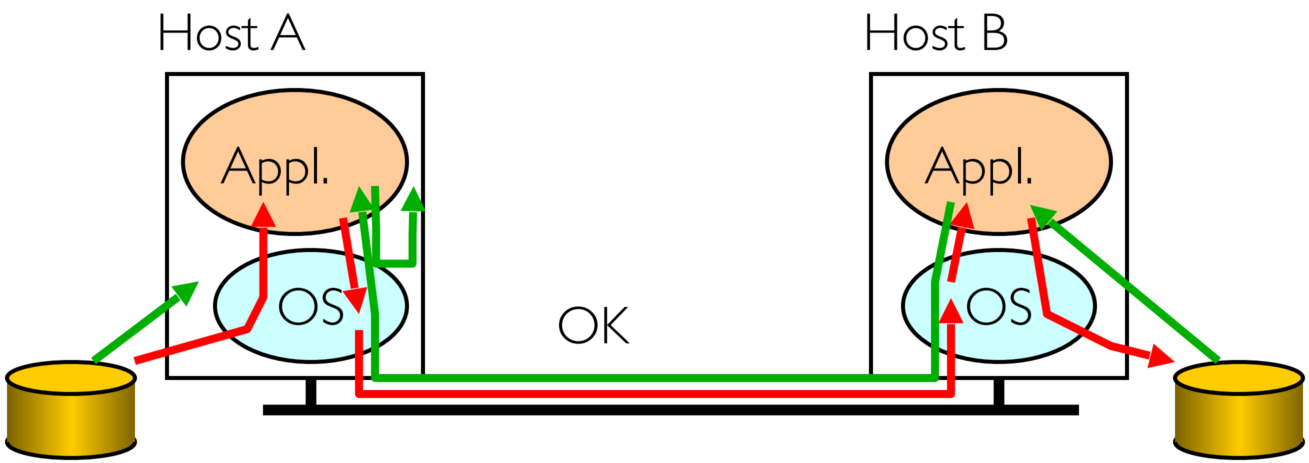
Drawbacks of Layering

- Layer N may duplicate layer N-1 functionality
  - E.g., error recovery to retransmit lost data
- Layers may need same information
  - E.g., timestamps, maximum transmission unit size
- Layering can hurt performance
  - E.g., hiding details about what is really going on
- Some layers are not always cleanly separated
  - Inter-layer dependencies for performance reasons
  - Some dependencies in standards (header checksums)
- Headers start to get really big
  - Sometimes header bytes >> actual content

End-To-End Argument

- Hugely influential paper: "End-to-End Arguments in System Design" by Saltzer, Reed, and Clark ('84)
- "Sacred Text" of the Internet
  - Endless disputes about what it means
  - Everyone cites it as supporting their position
- Simple Message: Some types of network functionality can only be correctly implemented end-to-end
  - Reliability, security, etc.
- Because of this, end hosts:
  - Can satisfy the requirement without network's help
  - Will/must do so, since can't *rely* on network's help
- Therefore don't go out of your way to implement them in the network

Example: Reliable File Transfer



- Solution 1: make each step reliable, and then concatenate them
- Solution 2: end-to-end check and try again if necessary

Discussion

- Solution 1 is incomplete
  – What happens if memory is corrupted?
  – Receiver has to do the check anyway!
- Solution 2 is complete
  – Full functionality can be entirely implemented at application layer with no need for reliability from lower layers
- *Is there any need to implement reliability at lower layers?*
  – Well, it could be more efficient

End-to-End Principle

Implementing complex functionality in the network:

- Doesn't reduce host implementation complexity
- Does increase network complexity
- Probably imposes delay and overhead on all applications, even if they don't need functionality

- However, implementing in network can enhance performance in some cases
  - e.g., very lossy link

Conservative Interpretation of E2E

- Don't implement a function at the lower levels of the system unless it can be completely implemented at this level

- Or: Unless you can relieve the burden from hosts, don't bother

Moderate Interpretation

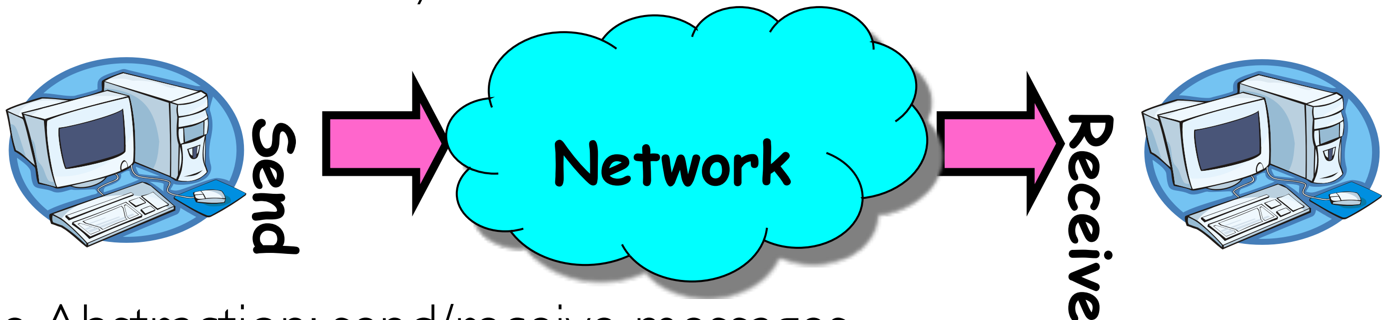
- Think twice before implementing functionality in the network
- If hosts can implement functionality correctly, implement it in a lower layer only as a performance enhancement
- But do so only if it does not impose burden on applications that do not require that functionality
- This is the interpretation we are using

- Is this still valid?
  - What about Denial of Service?
  - What about Privacy against Intrusion?

  - Perhaps there are things that must be in the network???

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

Using Messages: Send/Receive behavior

- When should `send(message,mbox)` return?
  - When receiver gets message? (i.e. ack received)
  - When message is safely buffered on destination?
  - Right away, if message is buffered on source node?
- Actually two questions here:
  - When can the sender be sure that receiver actually received the message?
  - When can sender reuse the memory containing message?
- Mailbox provides 1-way communication from T1→T2
  - T1→buffer→T2
  - Very similar to producer/consumer
    - » Send = V, Receive = P
    - » However, can't tell if sender/receiver is local or not!

Messaging for Producer-Consumer Style

- Using send/receive for producer-consumer style:

```
Producer:
   int msg1[1000];
   while(1) {
      prepare message;
      send(msg1,mbox);
   }
Consumer:
   int buffer[1000];
   while(1) {
      receive(buffer,mbox);
      process message;
   }
```

Send Message

Receive Message

- No need for producer/consumer to keep track of space in mailbox: handled by send/receive
  - Next time: will discuss fact that this is one of the roles the window in TCP: window is size of buffer on far end
  - Restricts sender to forward only what will fit in buffer

Messaging for Request/Response communication

- What about two-way communication?
  - Request/Response
    - » Read a file stored on a remote machine
    - » Request a web page from a remote web server
  - Also called: client-server
    - » Client ≡ requester, Server ≡ responder
    - » Server provides "service" (file storage) to the client
- Example: File service

```
Client: (requesting the file)
   char response[1000];

   send("read rutabaga", server_mbox);
   receive(response, client_mbox);

Server: (responding with the file)
   char command[1000], answer[1000];

   receive(command, server_mbox);
   decode command;
   read file into answer;
   send(answer, client_mbox);
```

Request File

Get Response

Receive Request

Send Response

Distributed Consensus Making

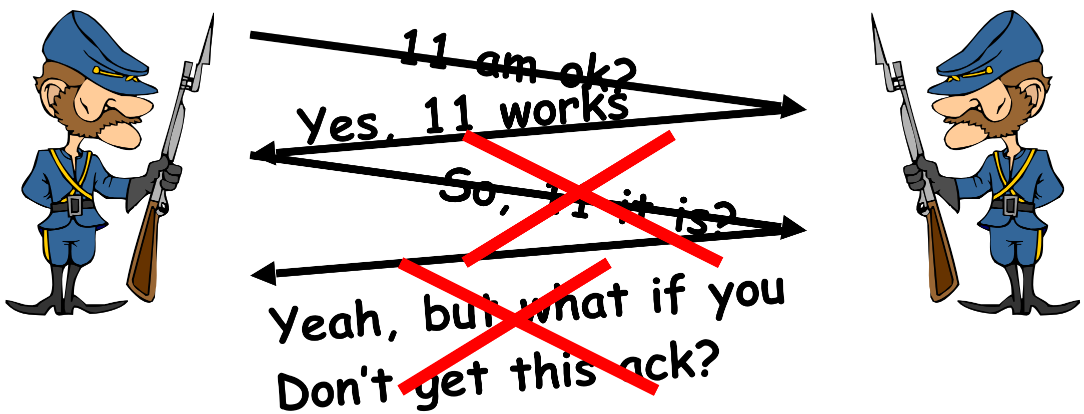
- Consensus problem
  - All nodes propose a value
  - Some nodes might crash and stop responding
  - Eventually, all remaining nodes decide on the same value from set of proposed values
- Distributed Decision Making
  - Choose between "true" and "false"
  - Or Choose between "commit" and "abort"
- Equally 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?
    - » Like BlockChain applications!

General's Paradox

- 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

General's Paradox (con't)

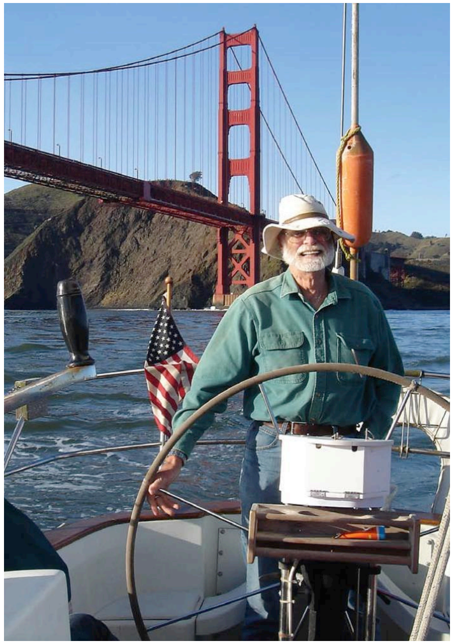
- Can messages over an unreliable network be used to guarantee two entities do something simultaneously?
  - Remarkably, "no", even if all messages get through



  - 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 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

2PC 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

Agree 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

Agree 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 on 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

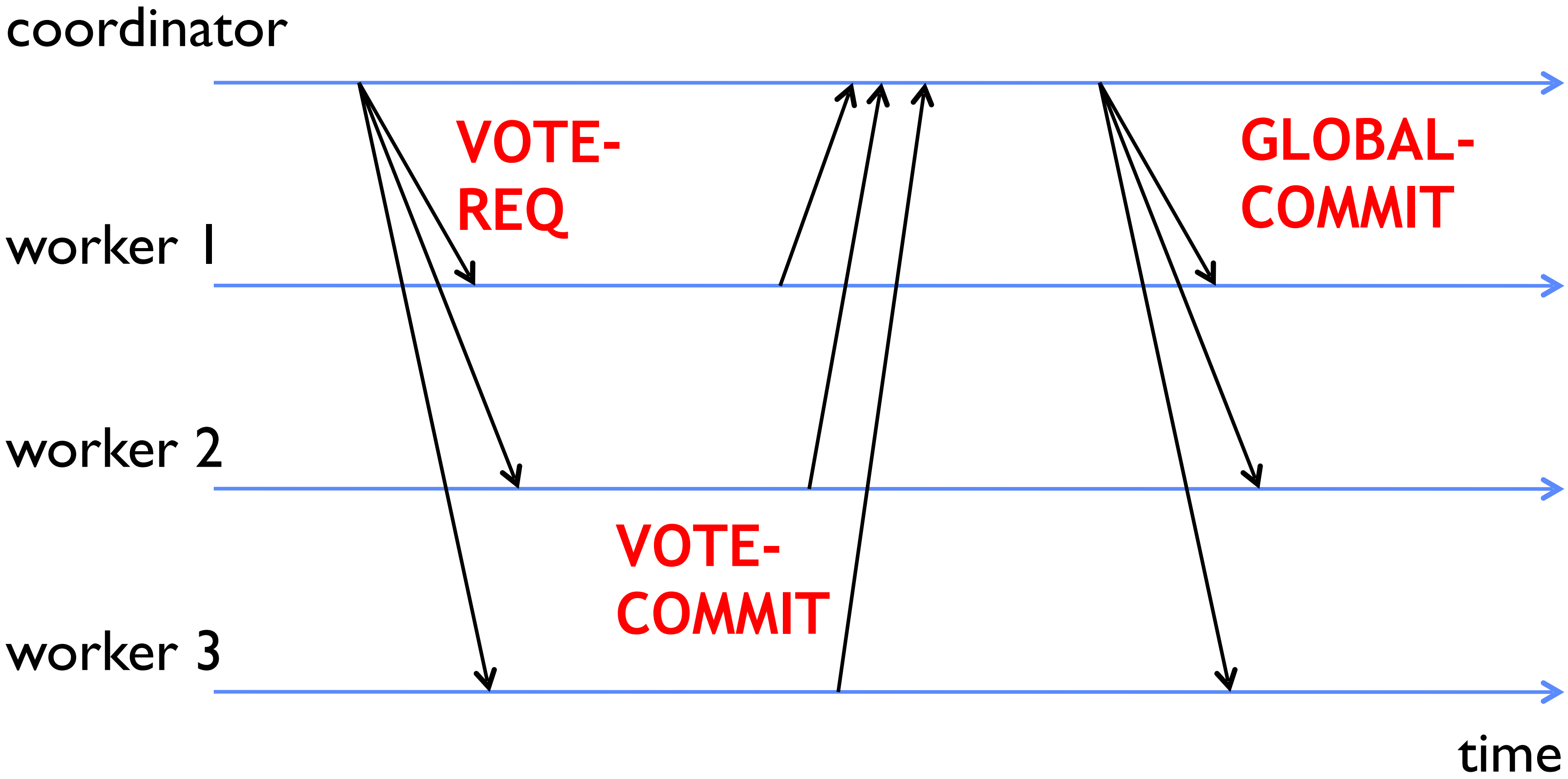
- If receive **VOTE-COMMIT** from all N workers, send **GLOBAL-COMMIT** to all workers
- If doesn't receive **VOTE-COMMIT** from all N workers, send **GLOBAL-ABORT** to all workers

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

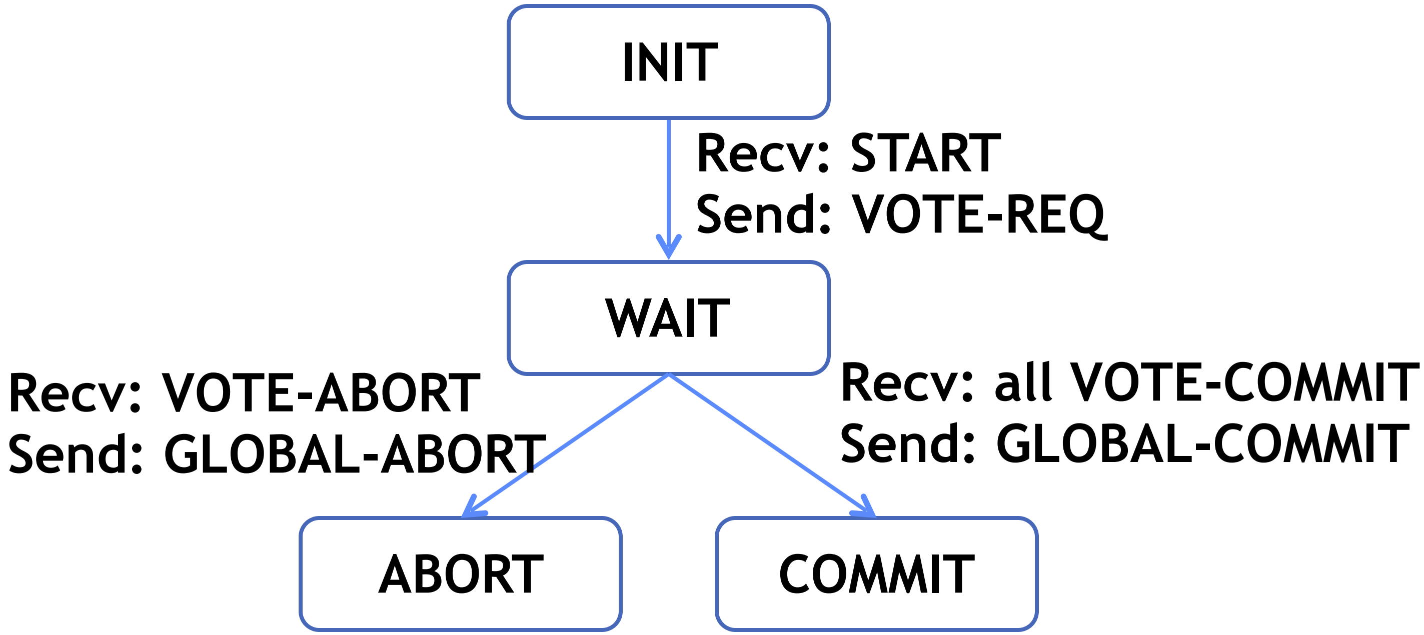
- If receive **GLOBAL-COMMIT** then commit
- If receive **GLOBAL-ABORT** then abort

Failure Free Example Execution

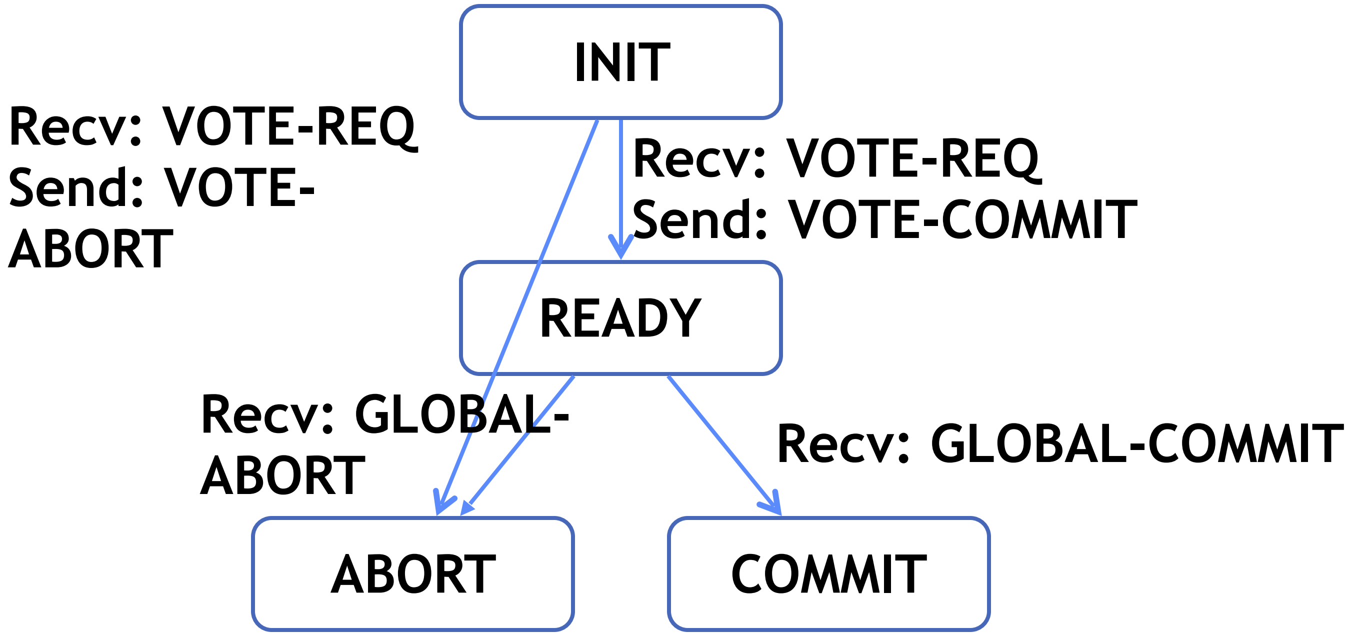


State Machine of Coordinator

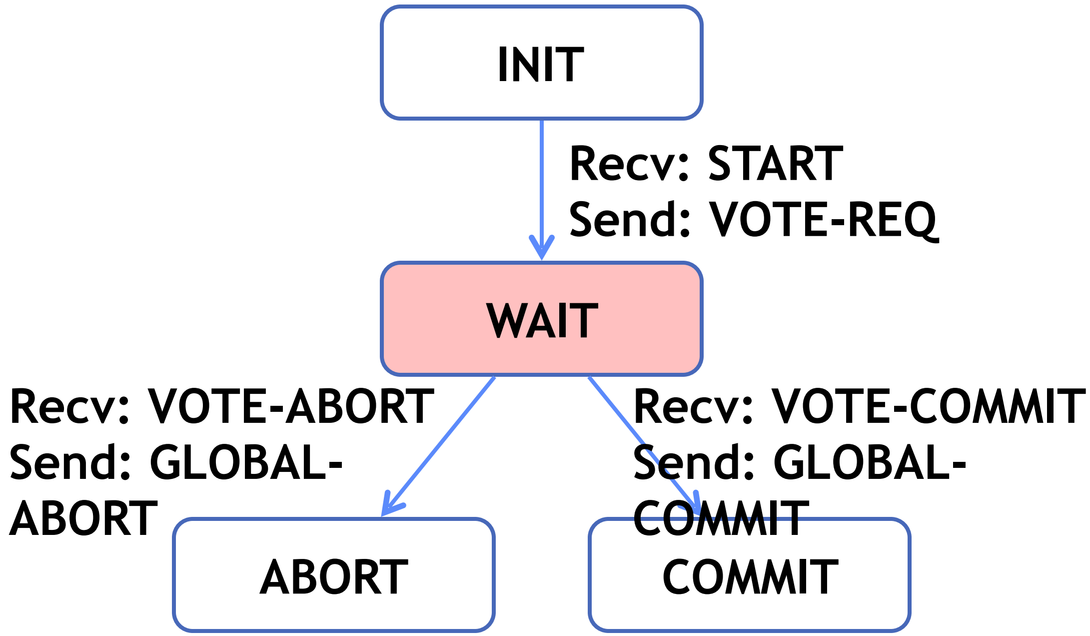
- Coordinator implements simple state machine:



State Machine of Workers

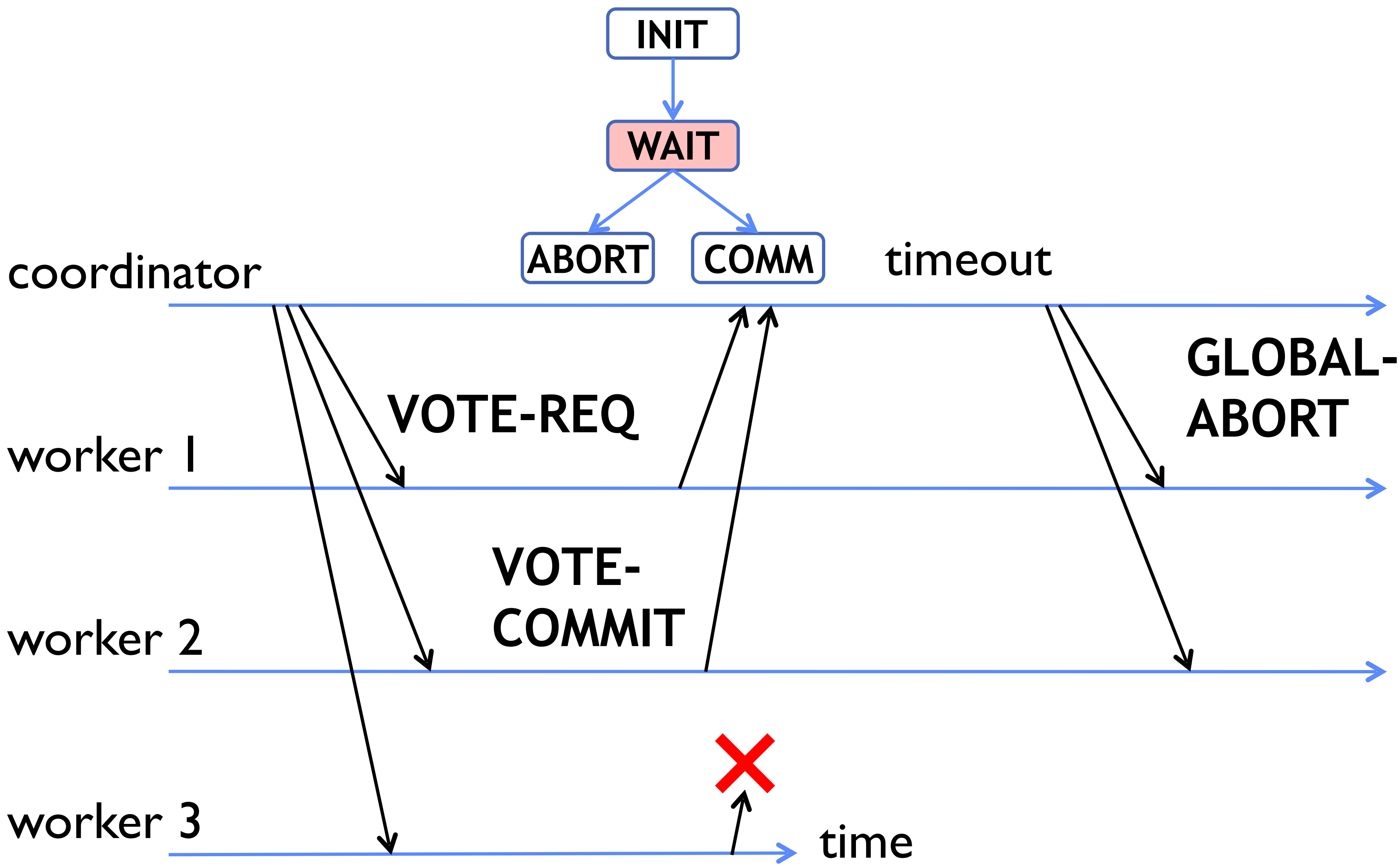


Dealing with Worker Failures

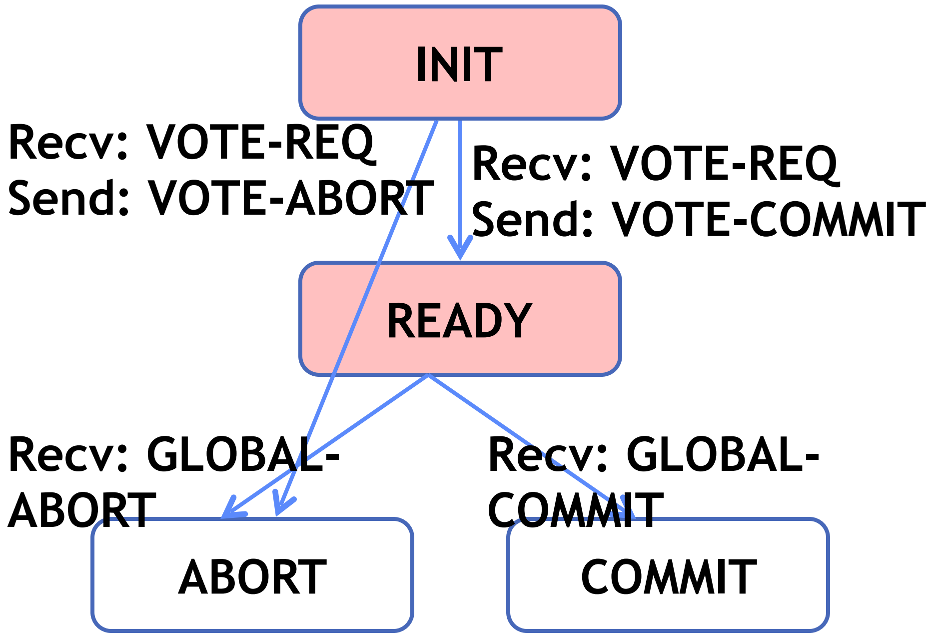


- Failure only affects states in which the coordinator is waiting for messages
- Coordinator only waits for votes in "**WAIT**" state
- In **WAIT**, if doesn't receive N votes, it times out and sends **GLOBAL-ABORT**

Example of Worker Failure

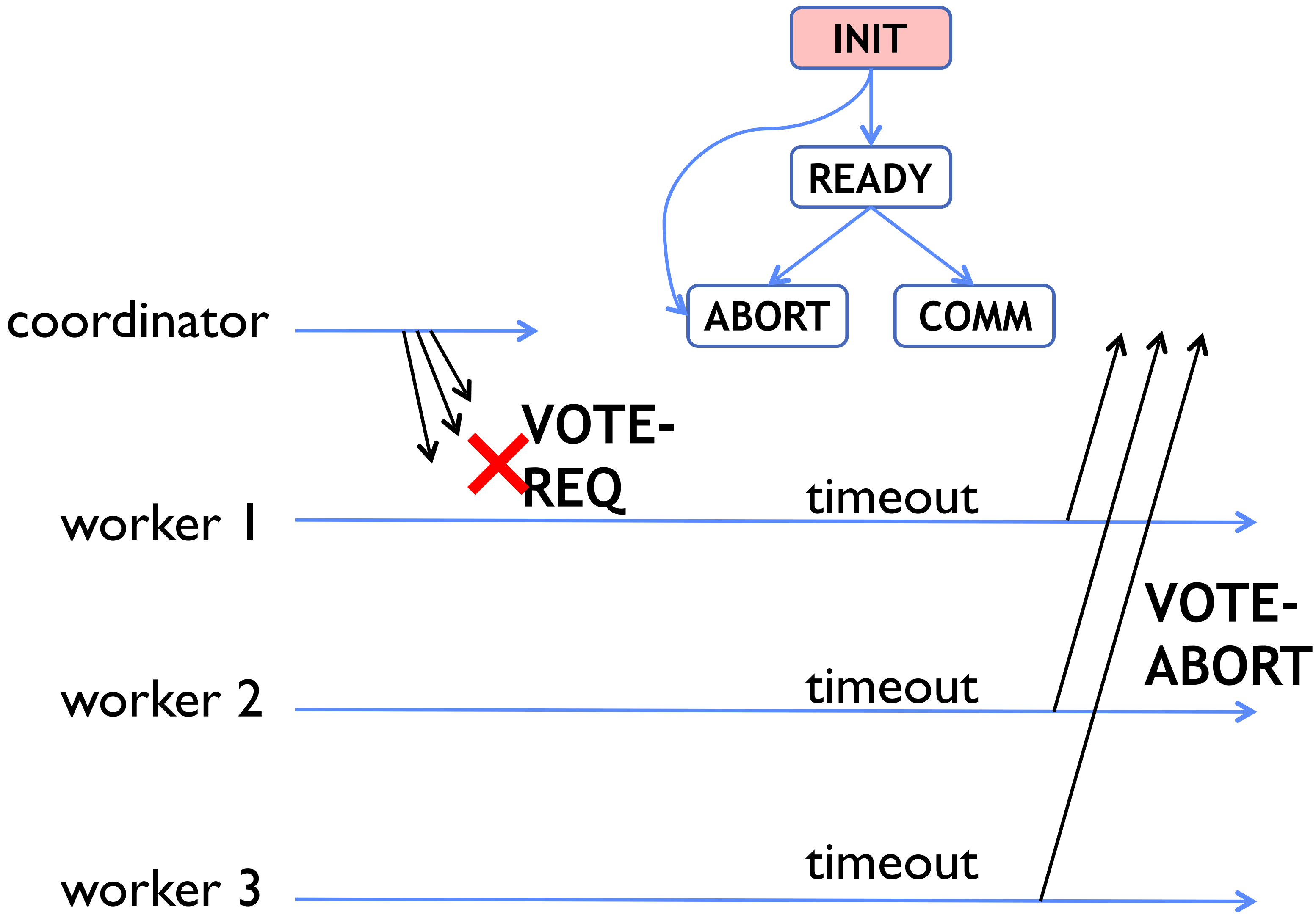


Dealing with Coordinator Failure

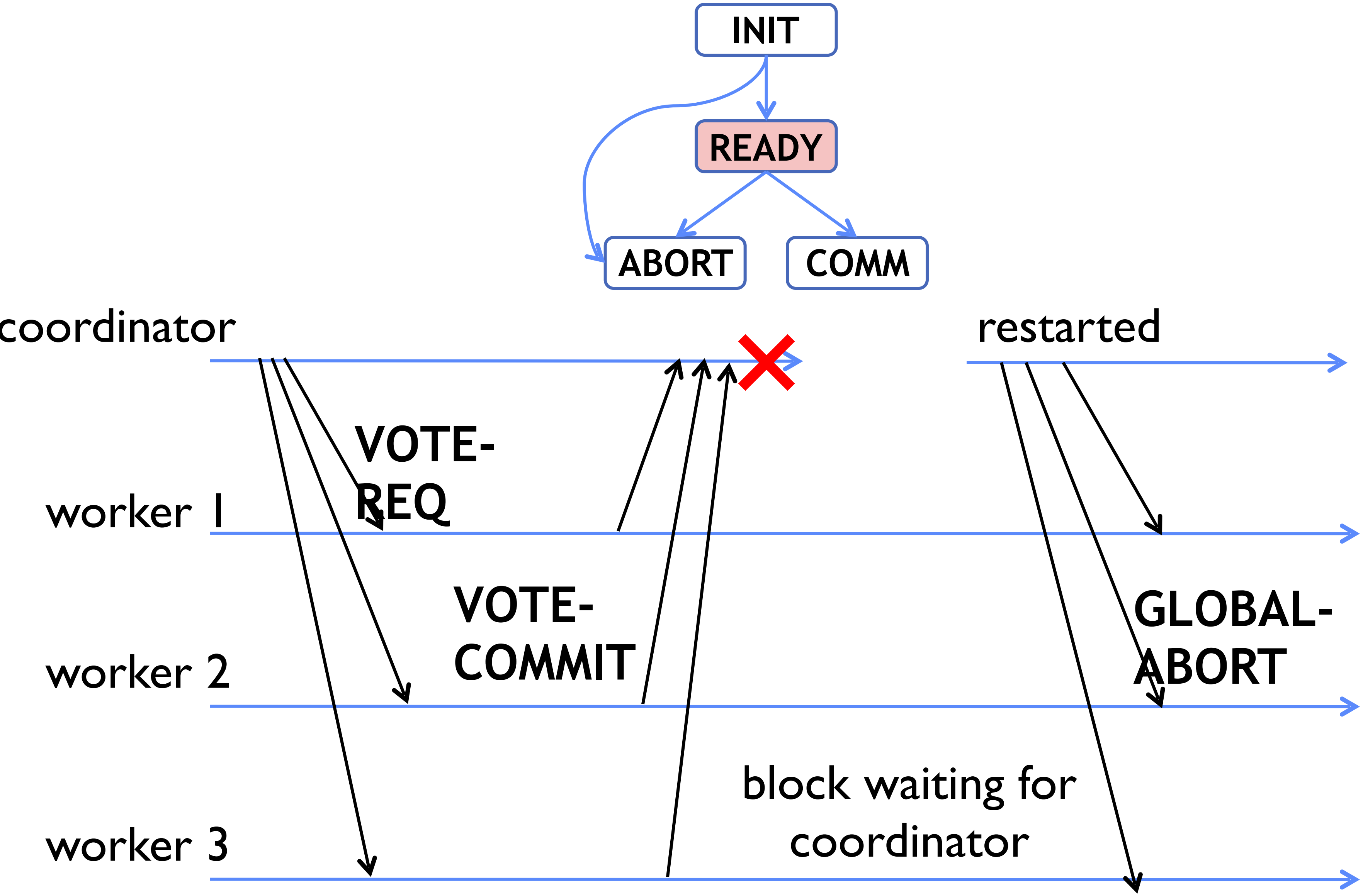


- Worker waits for **VOTE-REQ** in **INIT**
  - Worker can time out and abort (coordinator handles it)
- Worker waits for **GLOBAL-*** message in **READY**
  - If coordinator fails, workers must **BLOCK** waiting for coordinator to recover and send **GLOBAL_*** message

Example of Coordinator Failure #1



Example of Coordinator Failure #2

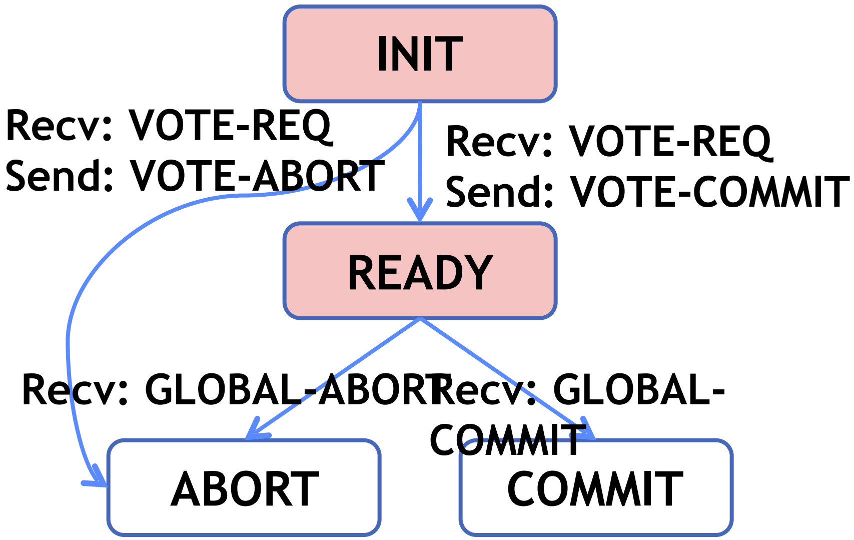


Durability

- 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, it 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**

Blocking for Coordinator to Recover

- A worker waiting for global decision can ask fellow workers about their state
  - If another worker is in ABORT or COMMIT state then coordinator must have sent GLOBAL-*
    - » Thus, worker can safely abort or commit, respectively
  - If another worker is still in INIT state then both workers can decide to abort
  - If all workers are in ready, need to BLOCK (don't know if coordinator wanted to abort or commit)



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" (different modes later)
  - After decision made, result recorded in multiple places

Distributed Decision Making Discussion (2/2)

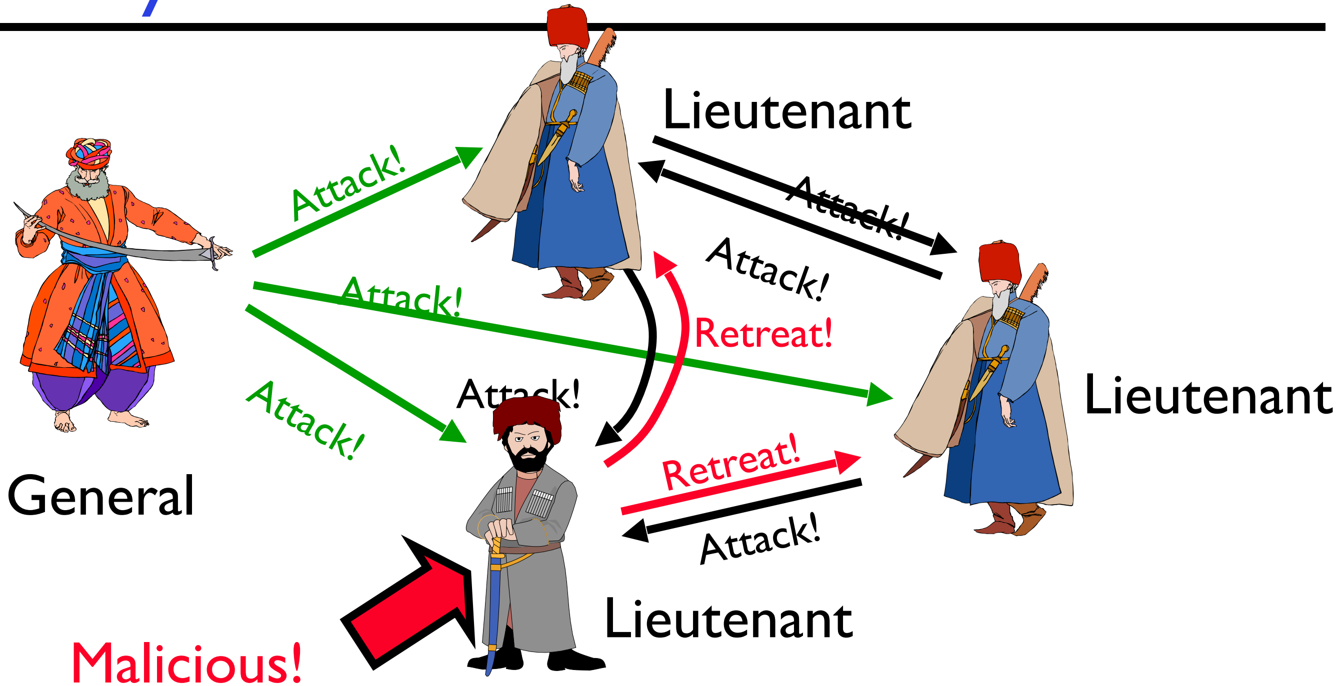
- Undesirable feature of Two-Phase Commit: Blocking
  - One machine can be stalled until another site recovers:
    - » Site B writes "prepared to commit" record to its log, sends a "yes" vote to the coordinator (site A) and crashes
    - » Site A crashes
    - » Site B wakes up, check its log, and realizes 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

Alternatives to 2PC

- Three-Phase Commit: One more phase, allows nodes to fail or block and still make progress.
- PAXOS: An alternative used by Google and others that does not have 2PC blocking problem
  - Develop by Leslie Lamport (Turing Award Winner)
  - No fixed leader, can choose new leader on fly, deal with failure
  - Some think this is extremely complex!
- RAFT: PAXOS alternative from John Osterhout (Stanford)
  - Simpler to describe complete protocol

- What happens if one or more of the nodes is malicious?
  - Malicious: attempting to compromise the decision making

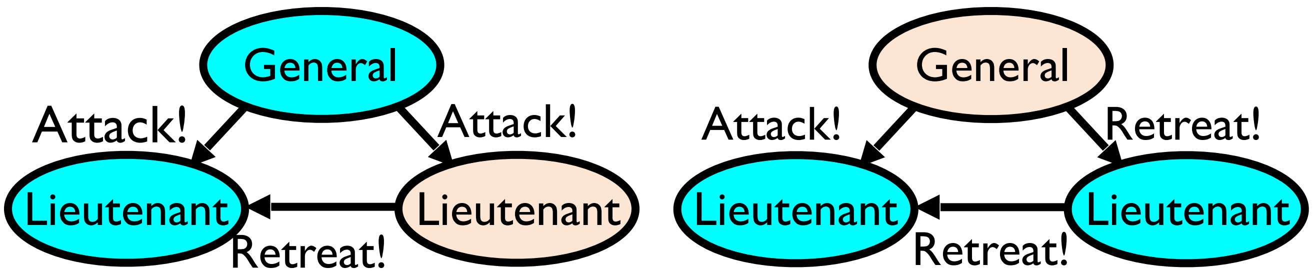
Byzantine General's Problem



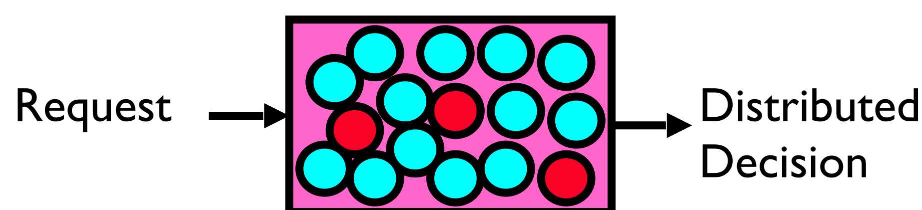
- Byazantine General's Problem (n players):
  - One General and n-1 Lieutenants
  - Some number of these (f) can be insane or malicious
- The commanding general must send an order to his n-1 lieutenants such that the following Integrity Constraints apply:
  - IC1: All loyal lieutenants obey the same order
  - IC2: If the commanding general is loyal, then all loyal lieutenants obey the order he sends

Byzantine General's Problem (con't)

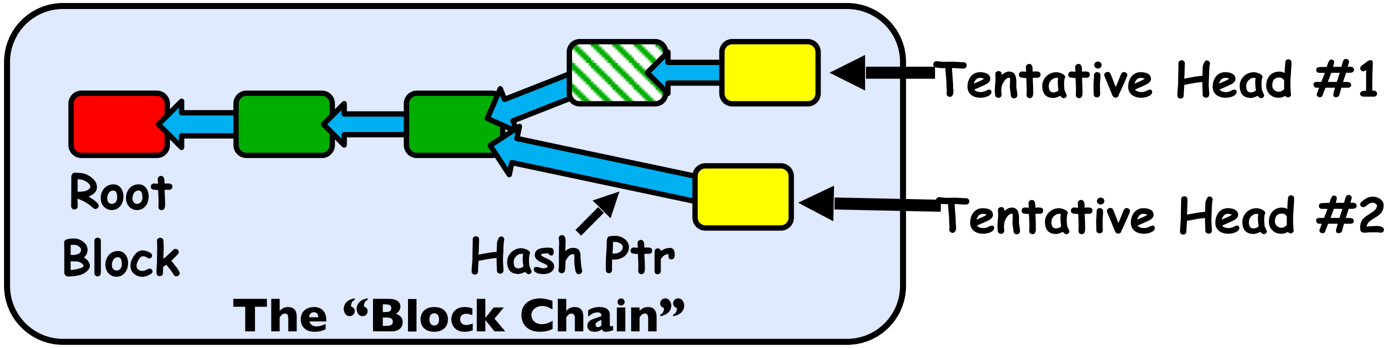
- Impossibility Results:
  - Cannot solve Byzantine General's Problem with n=3 because one malicious player can mess up things



  - With f faults, need n > 3f to solve problem
- Various algorithms exist to solve problem
  - Original algorithm has #messages exponential in n
  - Newer algorithms have message complexity O(n2)
    - » One from MIT, for instance (Castro and Liskov, 1999)
- Use of BFT (Byzantine Fault Tolerance) algorithm
  - Allow multiple machines to make a coordinated decision even if some subset of them (< n/3) are malicious

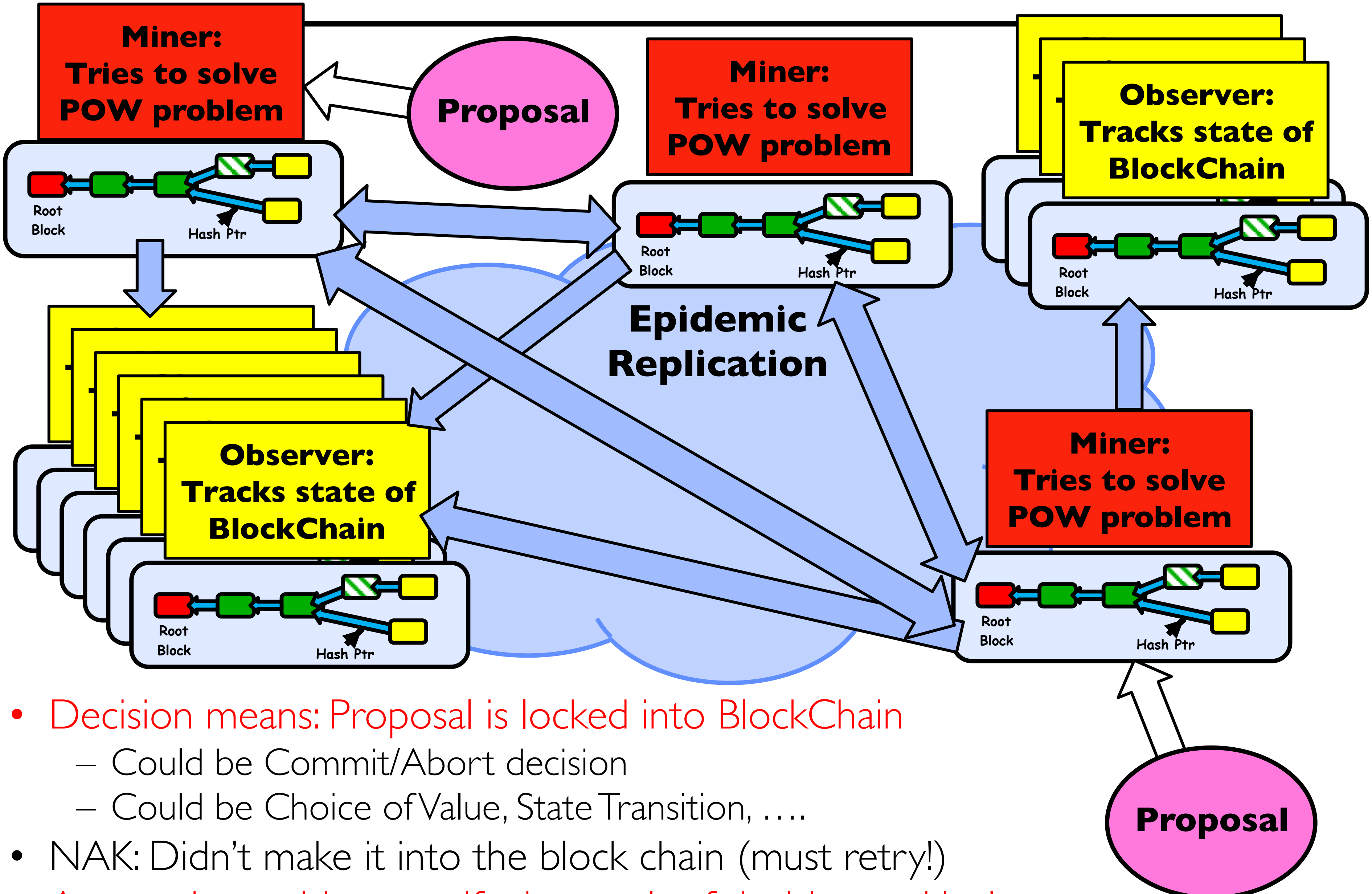


Is a BlockChain a Distributed Decision Making Algorithm?



- BlockChain: a chain of blocks connected by hashes to root block
  - The Hash Pointers are unforgeable (assumption)
  - The Chain has no branches except perhaps for heads
  - Blocks are considered "authentic" part of chain when they have authenticity info in them
- How is the head chosen?
  - Some consensus algorithm
  - In many BlockChain algorithms (e.g. BitCoin, Ethereum), the head is chosen by solving hard problem
    - » This is the job of "miners" who try to find "nonce" info that makes hash over block have specified number of zero bits in it
    - » The result is a "Proof of Work" (POW)
    - » Selected blocks above (green) have POW in them and can be included in chains
  - Longest chain wins

Is a Blockchain a Distributed Decision Making Algorithm? (Con't)



- Decision means: Proposal is locked into BlockChain
  – Could be Commit/Abort decision
  – Could be Choice of Value, State Transition, ….
- NAK: Didn't make it into the block chain (must retry!)
- Anyone in world can verify the result of decision making!

Summary (1/2)

- Protocol: Agreement between two parties as to how information is to be transmitted
- E2E argument encourages us to keep Internet communication simple
  - If higher layer can implement functionality correctly, implement it in a lower layer only if:
    - » it improves the performance significantly for application that need that functionality, and
    - » it does not impose burden on applications that do not require that functionality
- Two-phase commit: distributed decision making
  - First, make sure everyone guarantees that they will commit if asked (prepare)
  - Next, ask everyone to commit

Summary (2/2)

- Byzantine General's Problem: distributed decision making with malicious failures
  – One general, n-1 lieutenants: some number of them may be malicious (often "f" of them)
  – All non-malicious lieutenants must come to same decision
  – If general not malicious, lieutenants must follow general
  – Only solvable if $n \geq 3f+1$
- BlockChain protocols
  – Could be used for distributed decision making