CS162
Operating Systems and Systems Programming
Lecture 23

Distributed Decision Making (Con't), Networking and TCP/IP

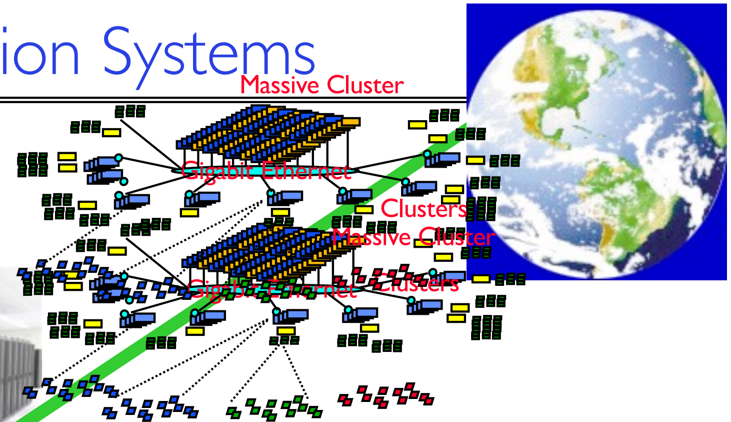
April 19th, 2022

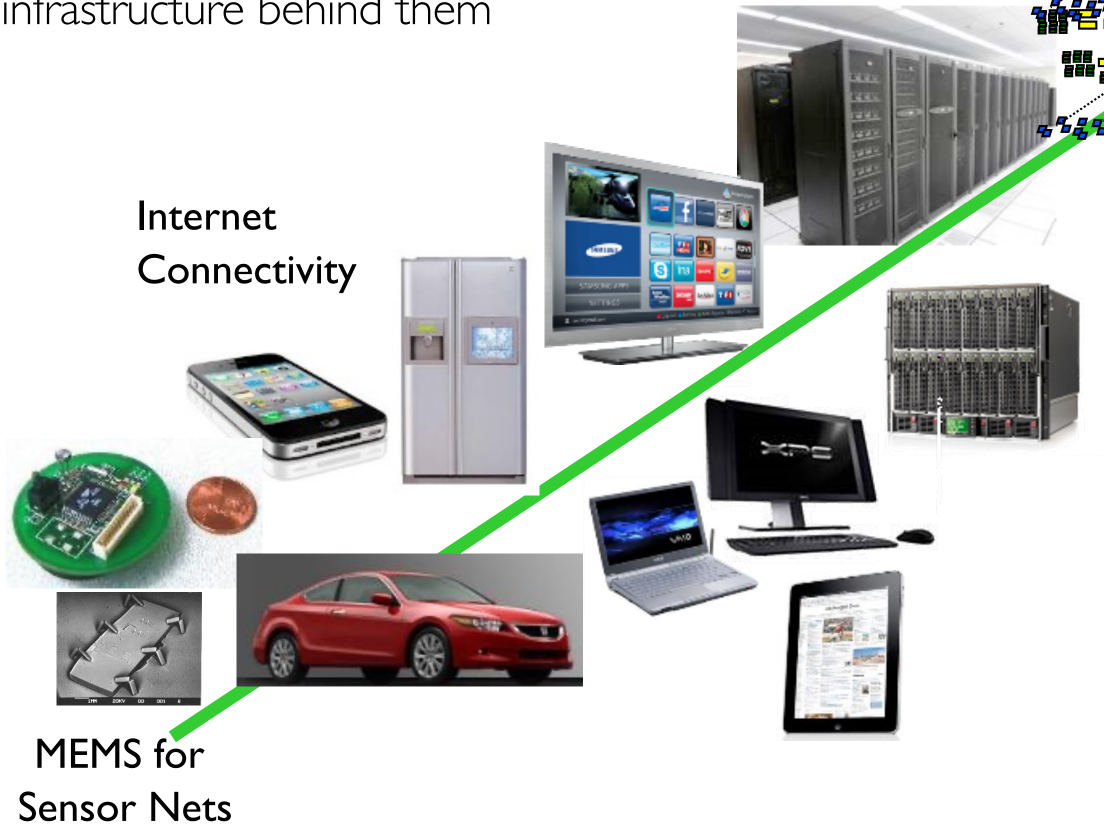
Prof. Anthony Joseph and John Kubiatowicz

http://cs162.eecs.Berkeley.edu

Recall: Societal Scale Information Systems

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

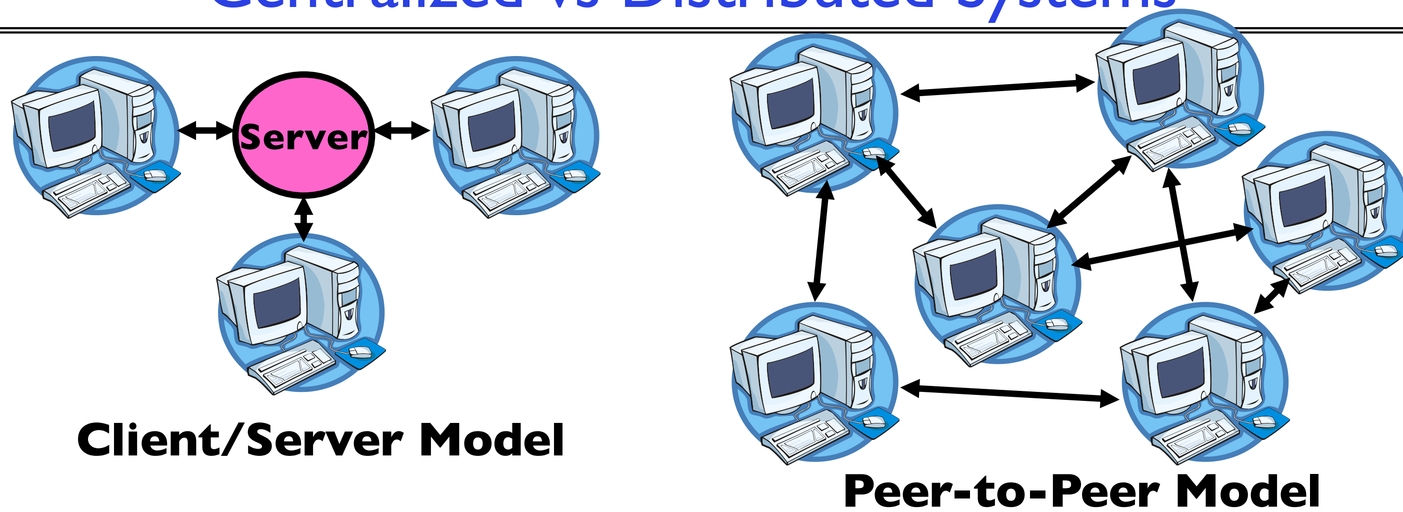




Scalable, Reliable,
Secure Services

Databases
Information Collection
Remote Storage
Online Games
Commerce
…

Centralized vs Distributed Systems



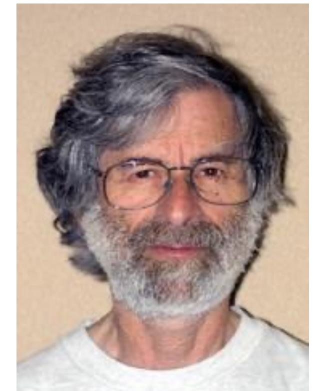
- Centralized System: major functions performed by a single physical computer
  - Originally, everything on single computer
  - Later: client/server model
- Distributed System: physically separate computers working together on task
  - Early model: multiple servers working together
    - » Probably in 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

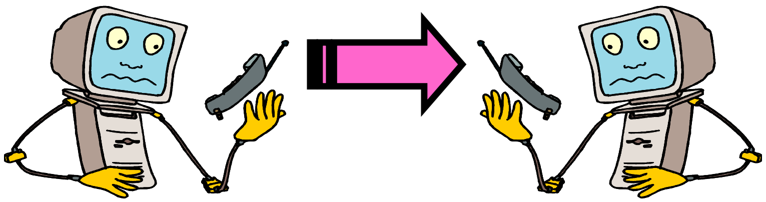


Leslie Lamport

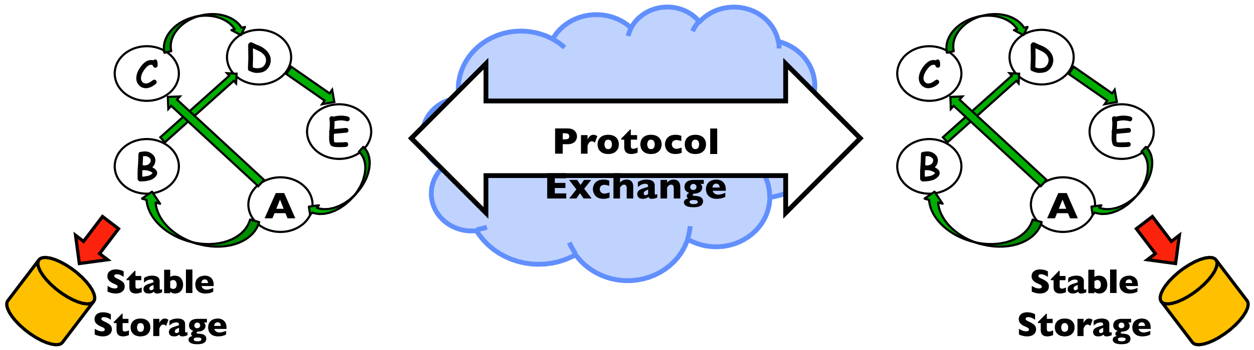
- Reality has been disappointing
  - *Worse availability*: depend on every machine being up
    - » Lamport: "A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable."
  - *Worse reliability*: can lose data if any machine crashes
  - *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!"

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!



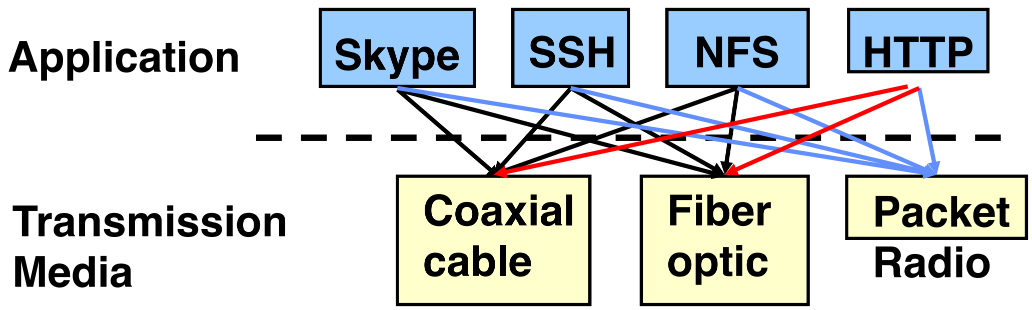
- A protocol is an agreement on how to communicate, including:
  - Syntax: how a communication is specified & structured
    - » Format, order messages are sent and received
  - Semantics: what a communication means
    - » Actions taken when transmitting, receiving, or when a timer expires
- Described 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 Anthony…."
     Or: "Hi, it's me" (← what's *that* about?)
  7. Caller: "Hey, do you think … blah blah blah …" **pause**

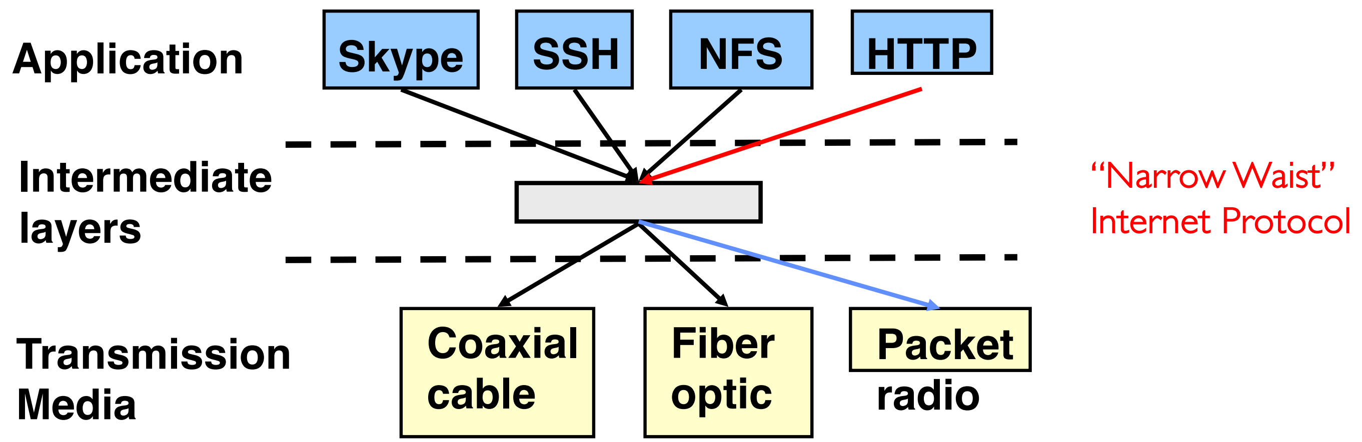
  1. Callee: "Yeah, blah blah blah …" **pause**
  2. Caller: Bye
  3. Callee: Bye
  4. Hang up

Global Communication: The Problem



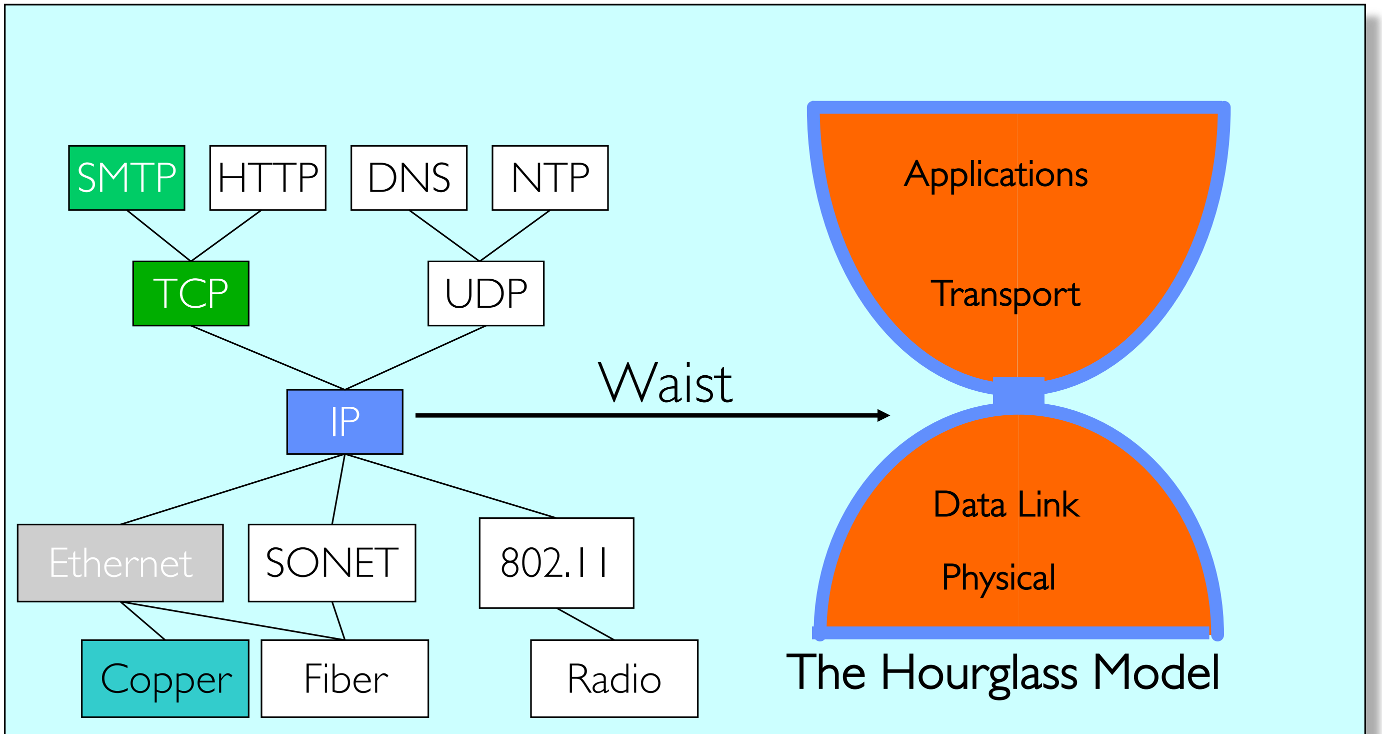
- Many different applications
  - email, web, P2P, etc.
- Many different network styles and technologies
  - Wireless vs. wired vs. optical, etc.
- How do we organize this mess?
  - Re-implement every application for every technology?
- No! But how does the Internet design avoid this?

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

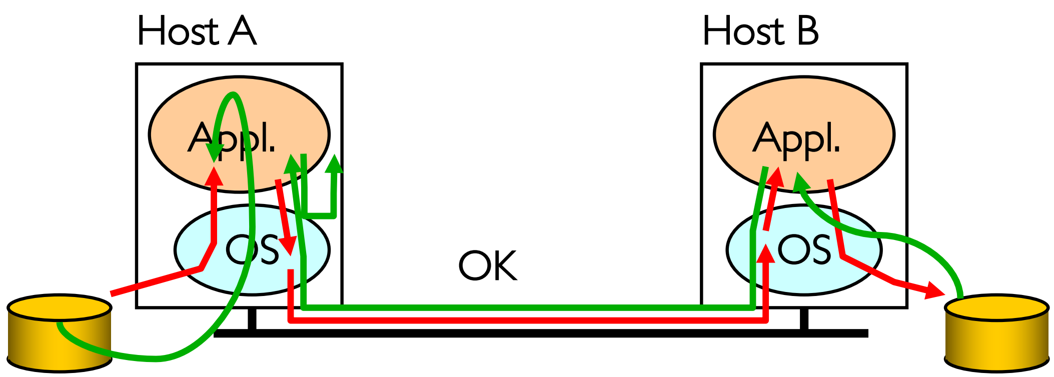
Drawbacks of Layering

- 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

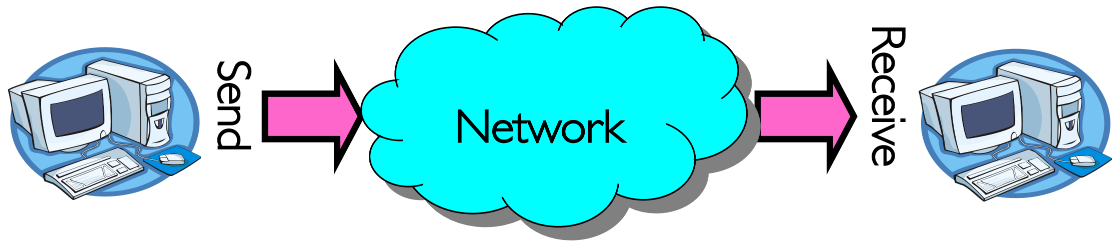
- Think twice before implementing functionality in the network
- If hosts can implement functionality correctly, implement it in a lower layer only as a performance enhancement
- But do so only if it does not impose burden on applications that do not require that functionality
- This is the interpretation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

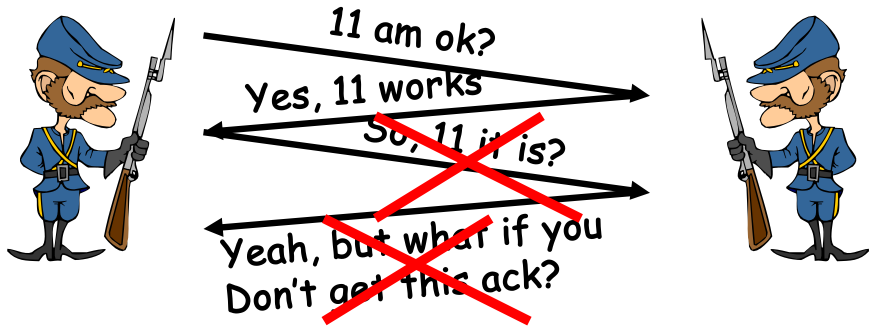
- Consensus problem
  - All nodes propose a value
  - Some nodes might crash and stop responding
  - Eventually, all remaining nodes decide on the same value from set of proposed values
- Distributed Decision Making
  - Choose between "true" and "false"
  - Or Choose between "commit" and "abort"
- Equally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

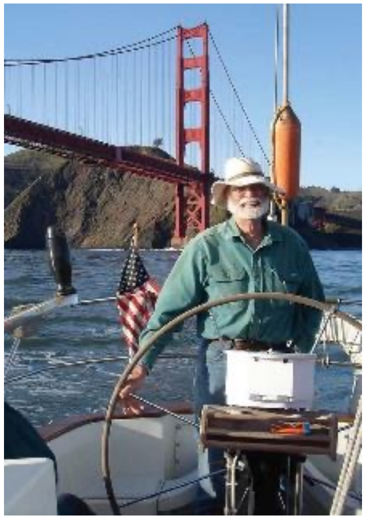
- Can messages over an unreliable network be used to guarantee two entities do something simultaneously?
  - Remarkably, "no", even if all messages get through



  - 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

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

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

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 one 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

Administrivia

- Midterm 3: Thursday 4/28: 7-9PM
  - All course material
  - Review session 4/25

Detailed Algorithm

Coordinator Algorithm

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

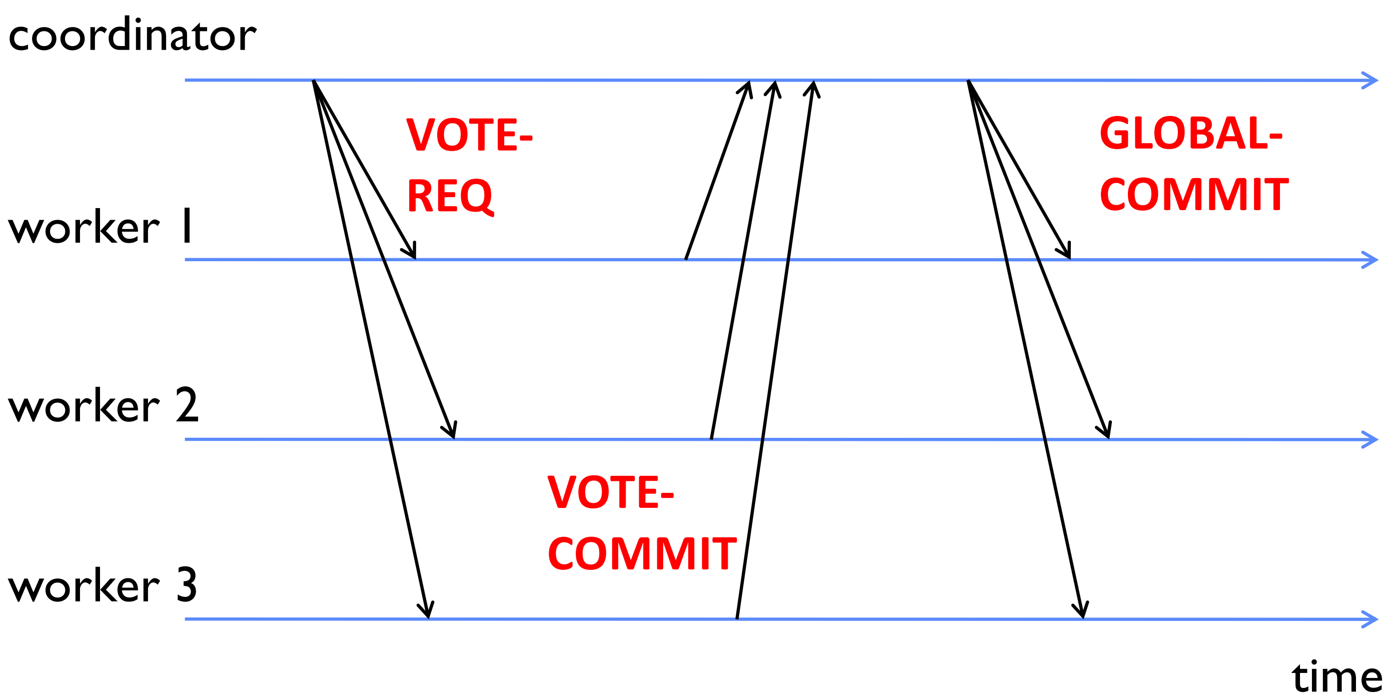
- If receive **VOTE-COMMIT** from all N workers, send **GLOBAL-COMMIT** to all workers
- If don't receive **VOTE-COMMIT** from all N workers, send **GLOBAL-ABORT** to all workers

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

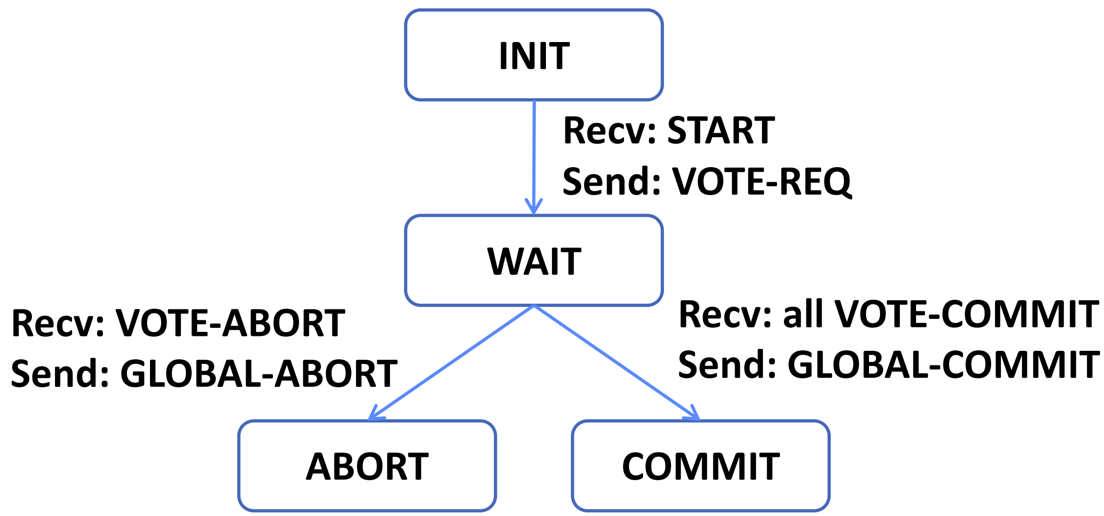
- If receive **GLOBAL-COMMIT** then commit
- If receive **GLOBAL-ABORT** then abort

Failure Free Example Execution

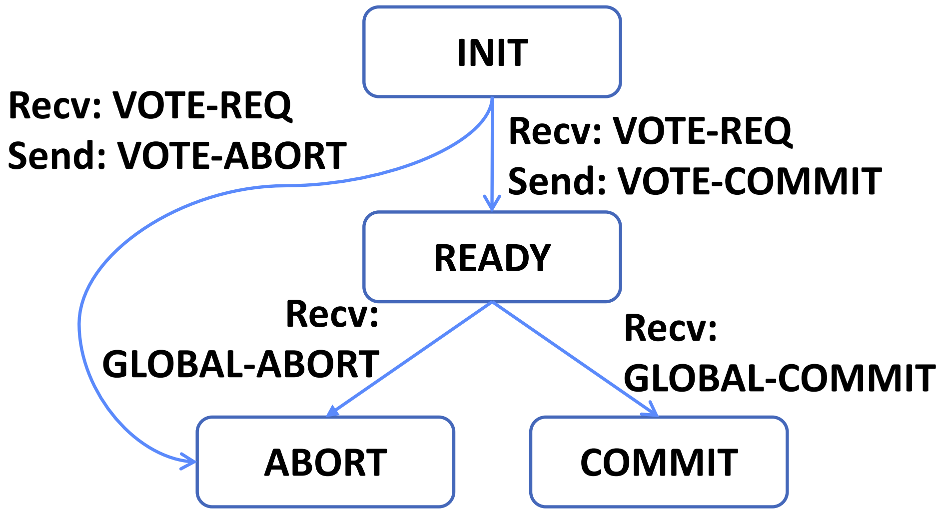


State Machine of Coordinator

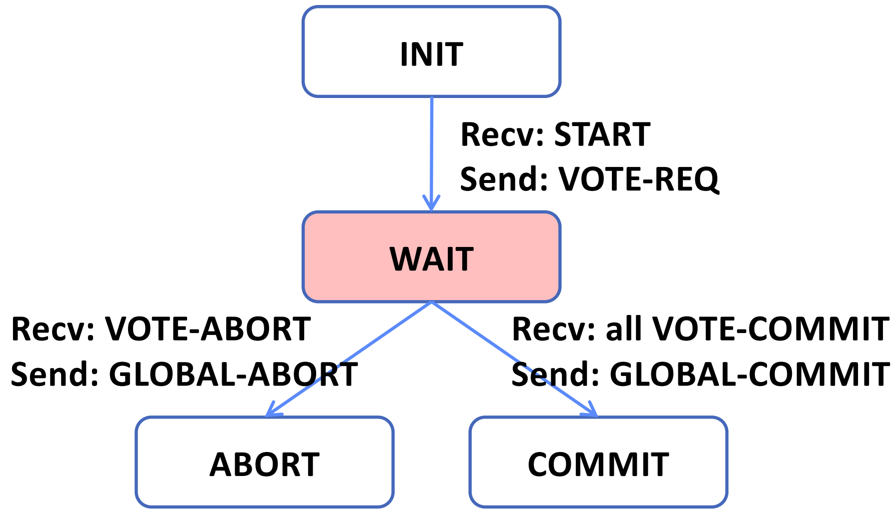
- Coordinator implements simple state machine:



State Machine of Workers

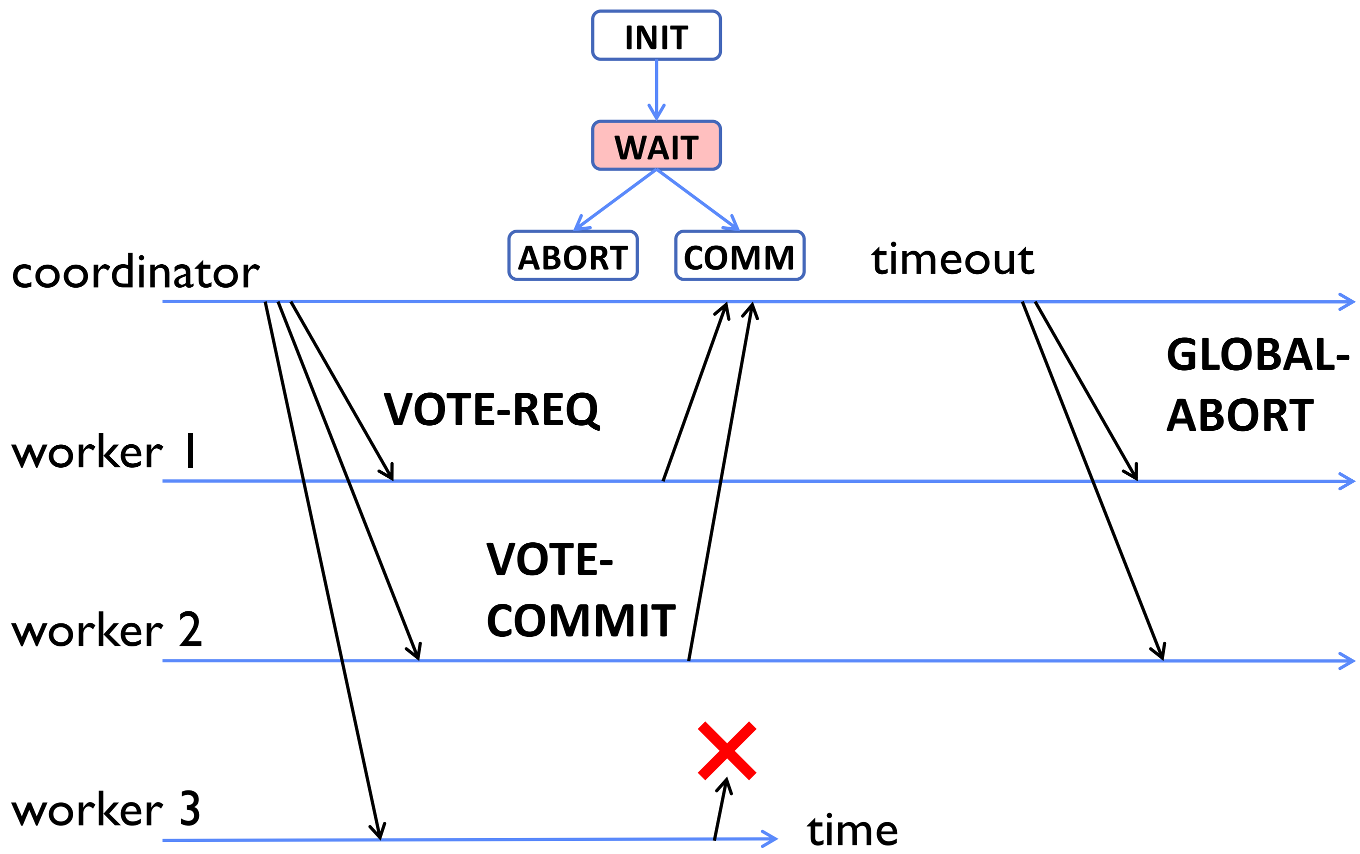


Dealing with Worker Failures

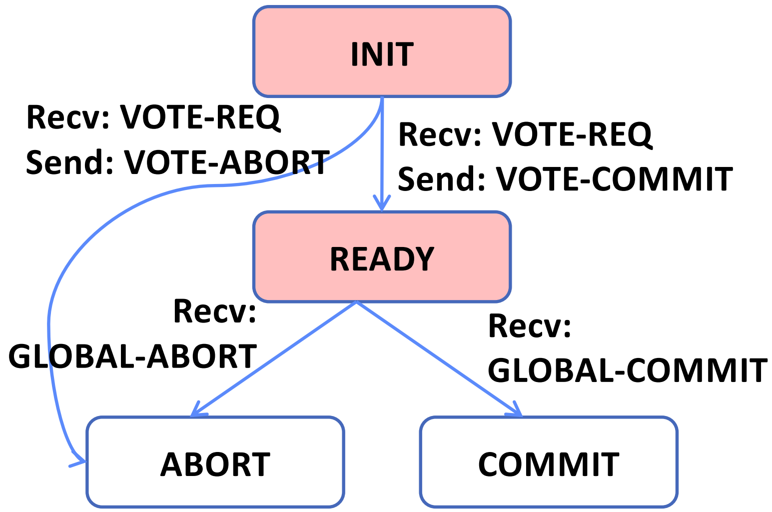


- Failure only affects states in which the coordinator is waiting for messages
- Coordinator only waits for votes in "**WAIT**" state
- In **WAIT**, if doesn't receive N votes, it times out and sends **GLOBAL-ABORT**

Example of Worker Failure

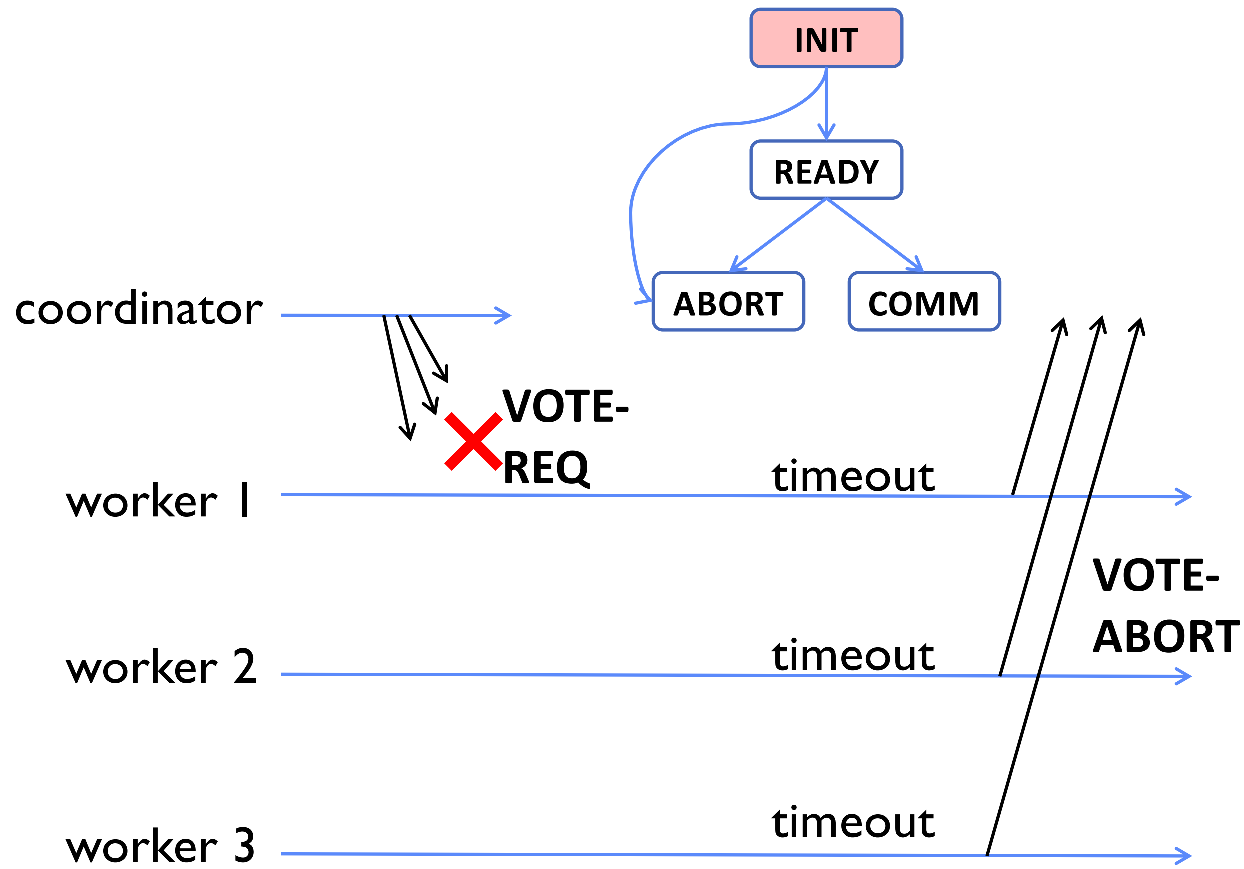


Dealing with Coordinator Failure

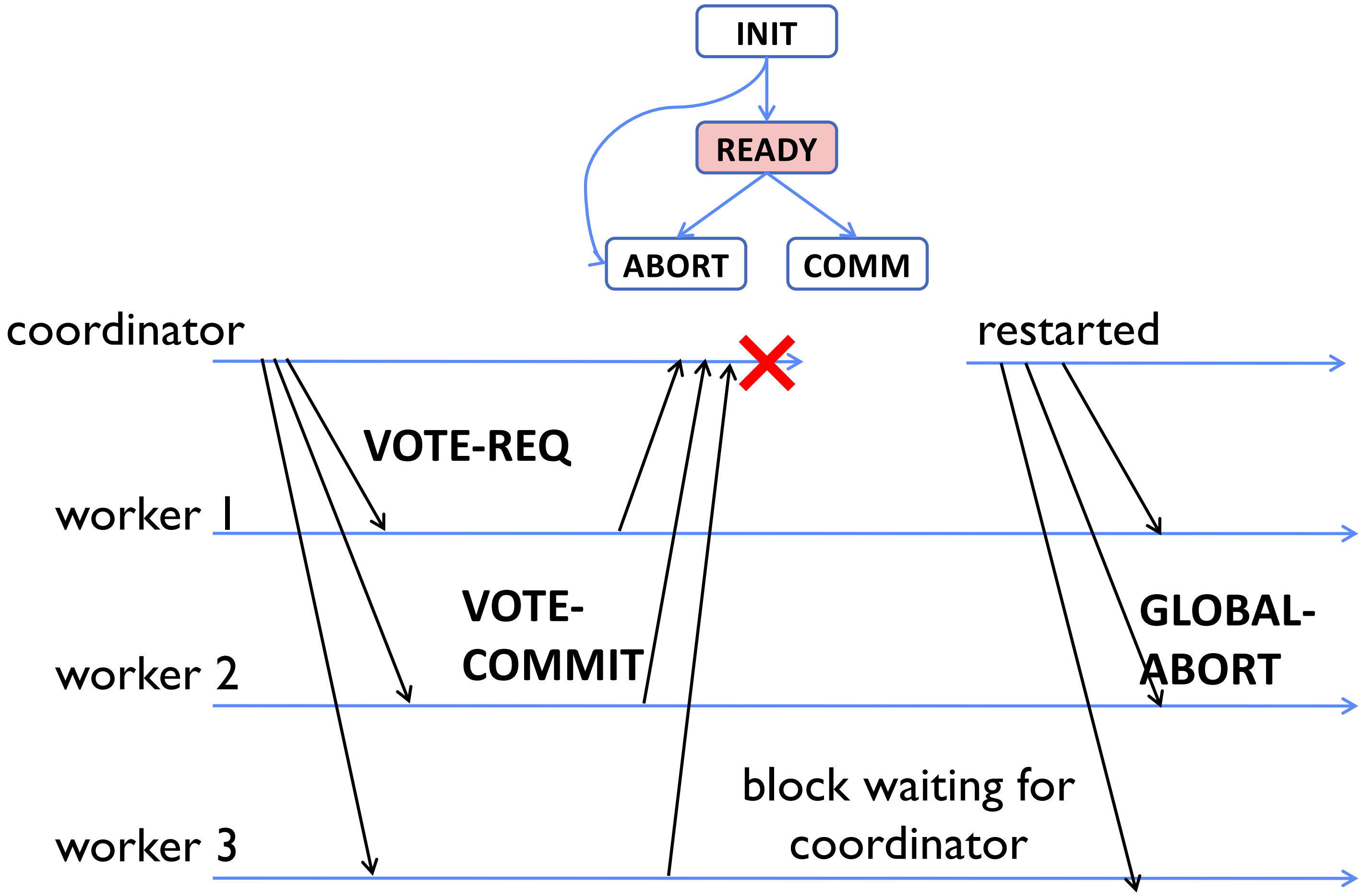


- Worker waits for **VOTE-REQ** in **INIT**
  – Worker can time out and abort (coordinator handles it)
- Worker waits for **GLOBAL-*** message in **READY**
  – If coordinator fails, workers must **BLOCK** waiting for coordinator to recover and send **GLOBAL_*** message

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**