CS162
Operating Systems and Systems Programming
Lecture 22

Distributed Decision Making (Finished), TCP/IP Networking, RPC

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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 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: 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!

Recall: 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 machines agree to do something, or not do it, atomically
- Two-Phase Commit protocol:
  – 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
- Persistent stable log on each machine:
  – Help nodes remember what they have said that they would do
    » If a machine crashes, when it wakes up it first checks its log to recover state of world at time of crash
    » Log can be used to complete this process such that all machines either commit or don't commit

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

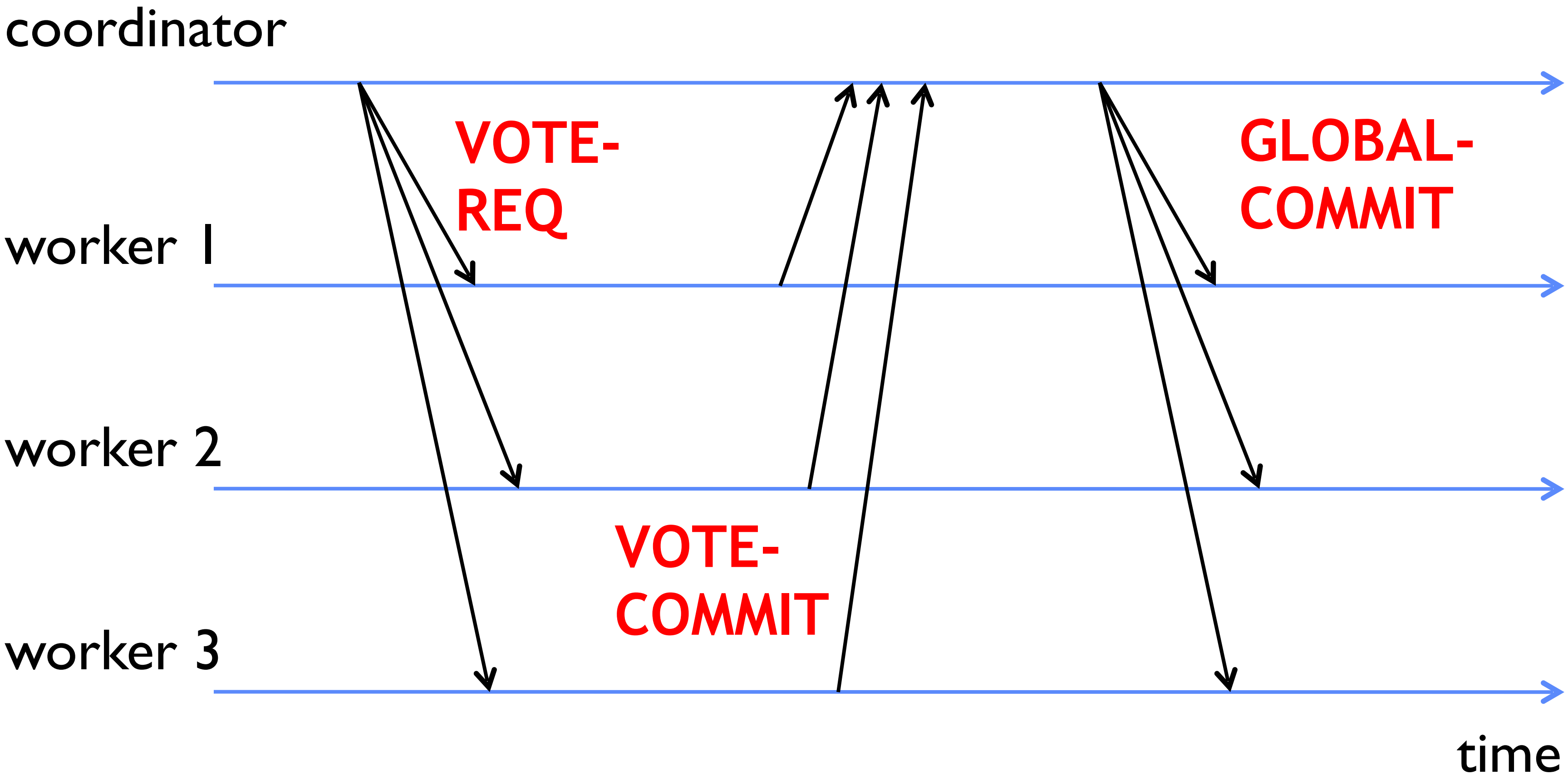
- If receive **VOTE-COMMIT** from all N workers, send **GLOBAL-COMMIT** to all workers
- If don't receive **VOTE-COMMIT** from all N workers, send **GLOBAL-ABORT** to all workers

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

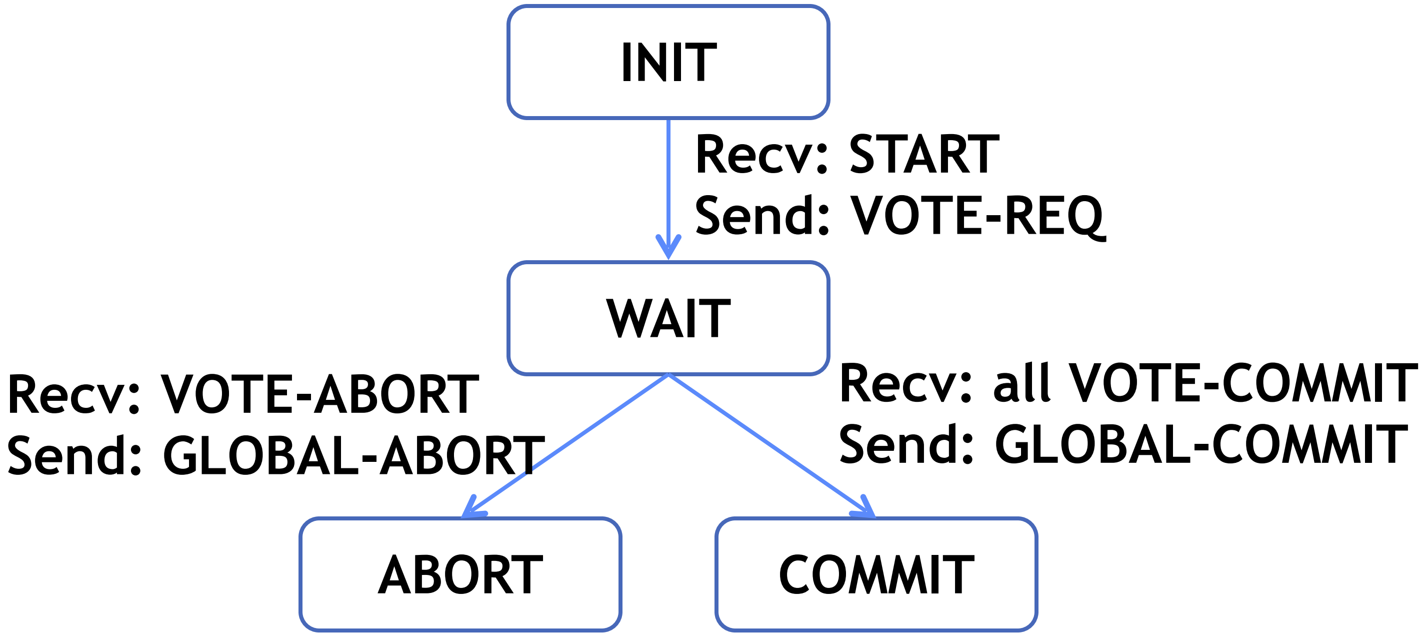
- If receive **GLOBAL-COMMIT** then commit
- If receive **GLOBAL-ABORT** then abort

Failure Free Example Execution

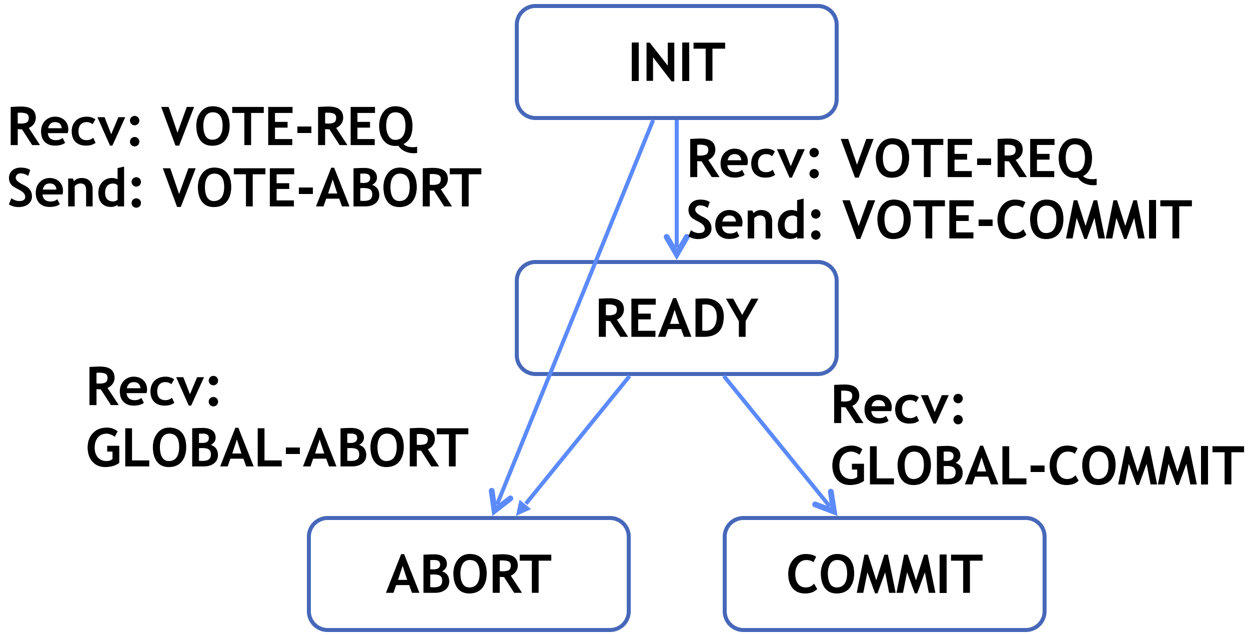


State Machine of Coordinator

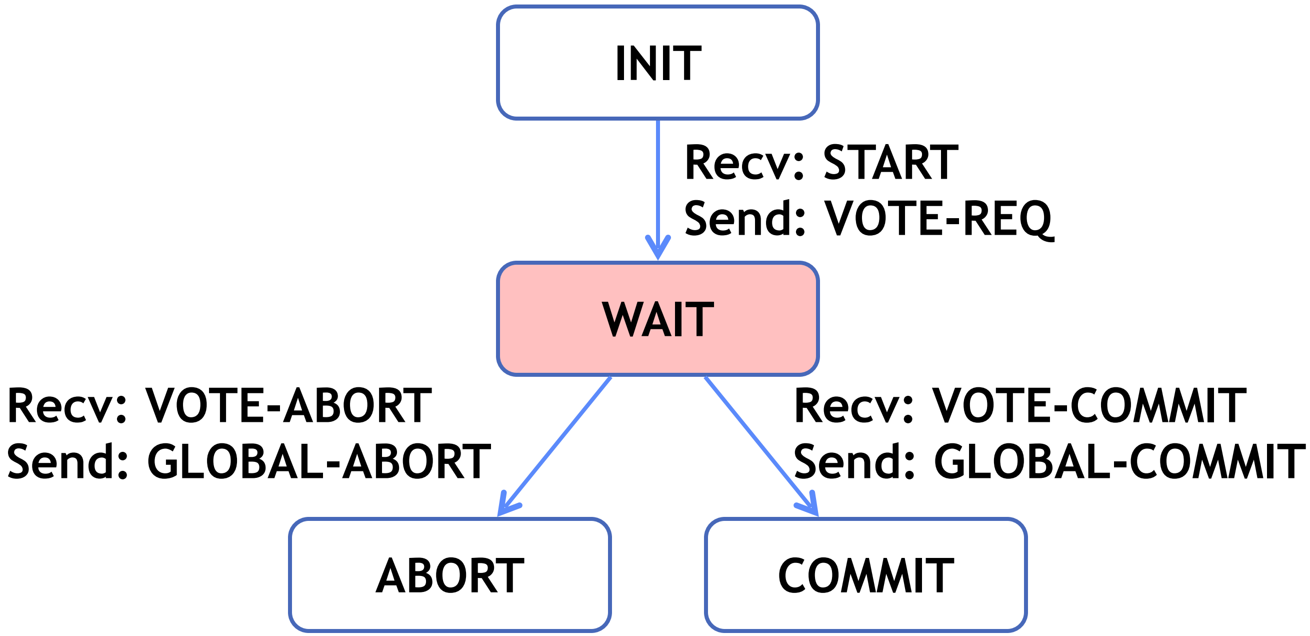
- Coordinator implements simple state machine:



State Machine of Workers

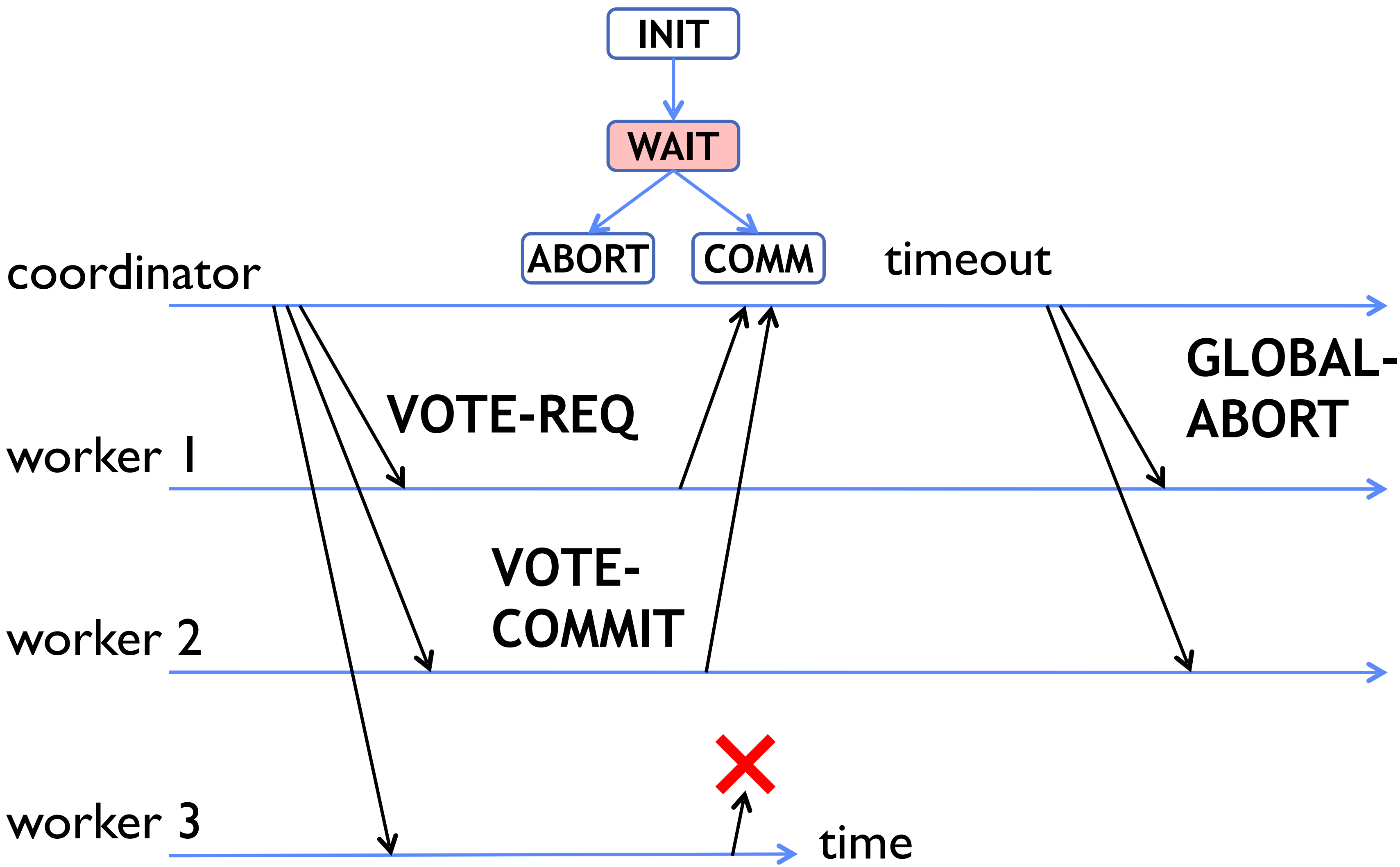


Dealing with Worker Failures

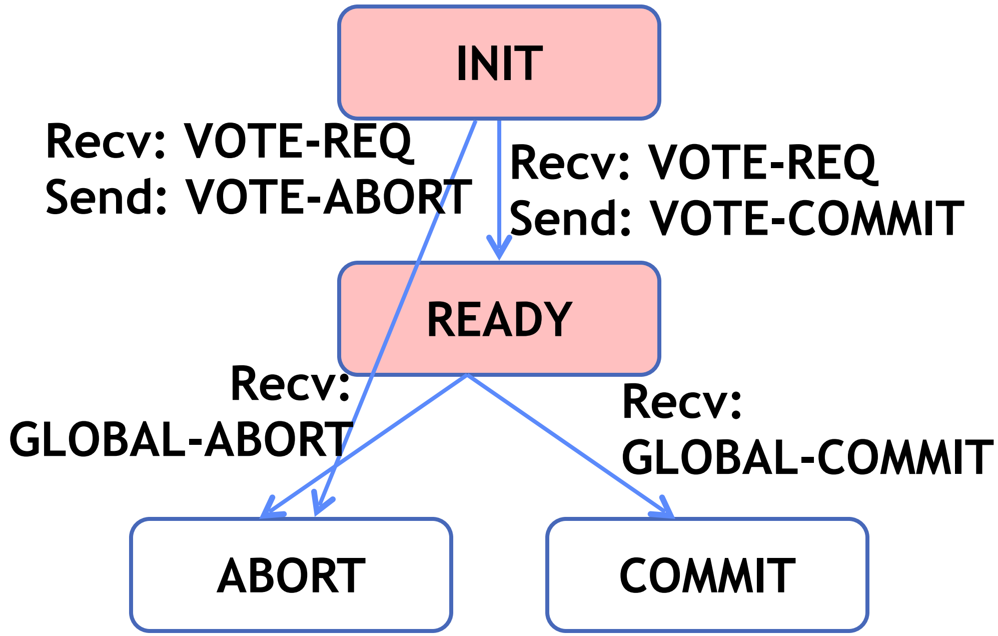


- Failure only affects states in which the coordinator is waiting for messages
- Coordinator only waits for votes in "**WAIT**" state
- In **WAIT**, if doesn't receive N votes, it times out and sends **GLOBAL-ABORT**

Example of Worker Failure

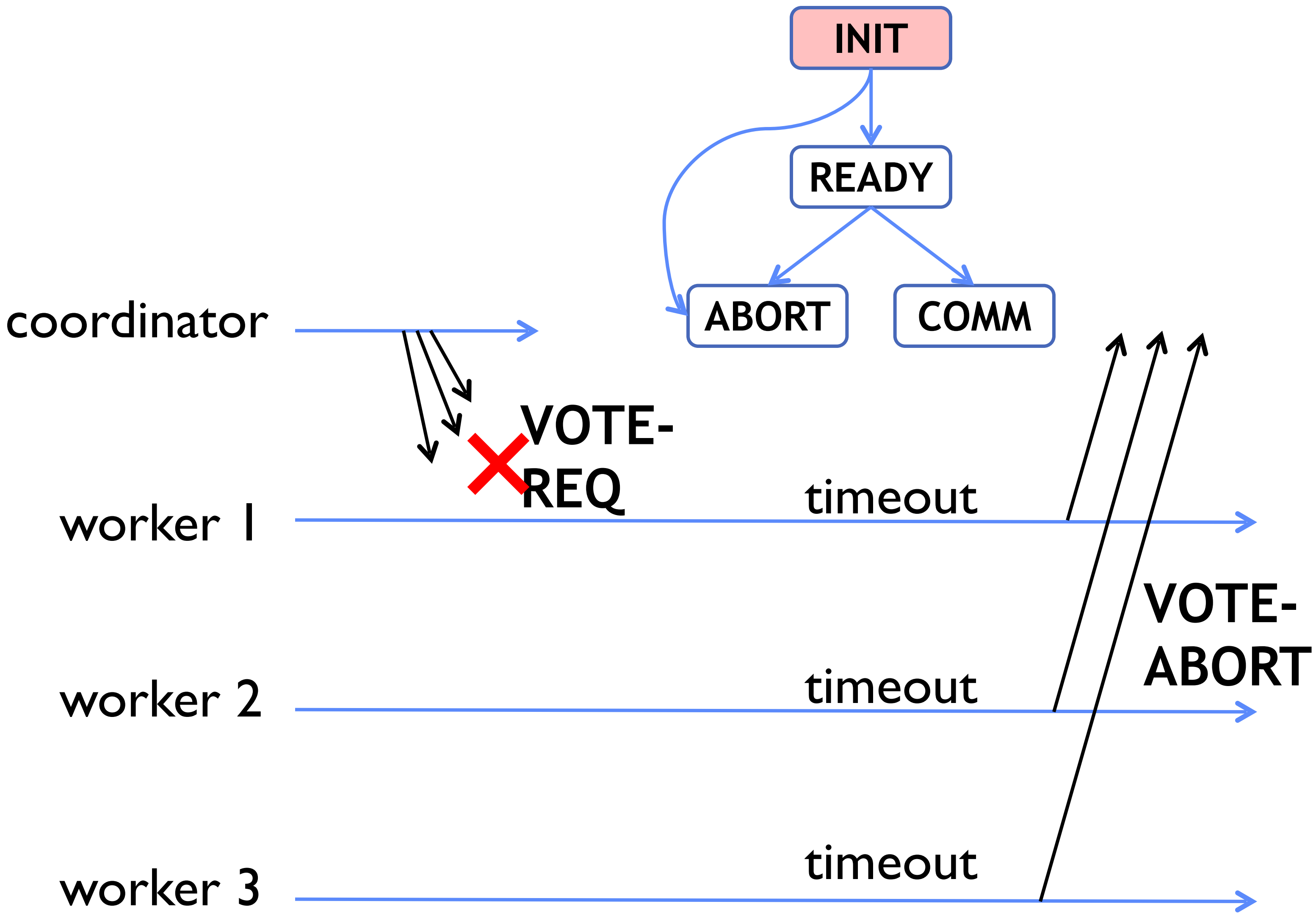


Dealing with Coordinator Failure

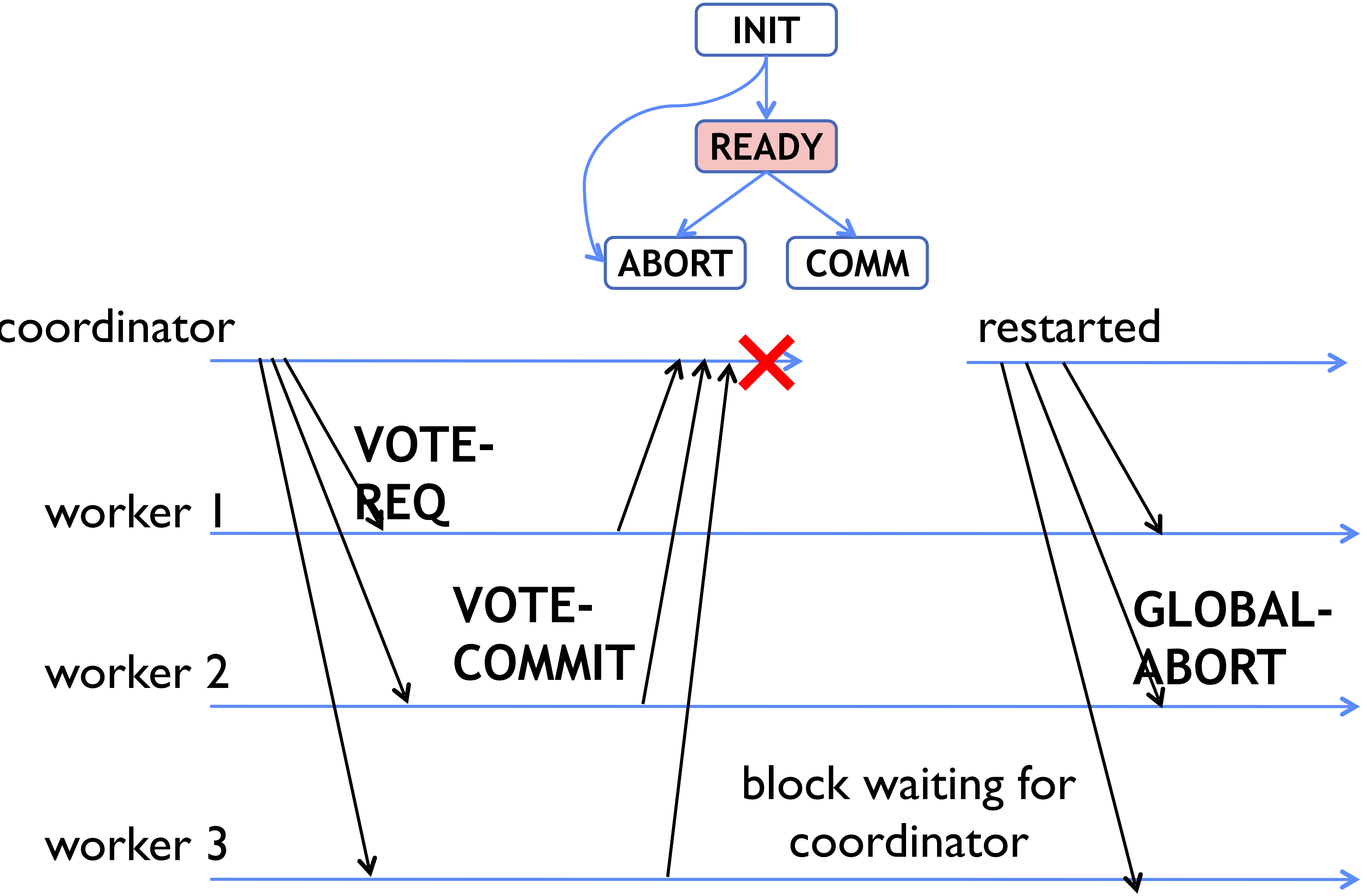


- Worker waits for **VOTE-REQ** in **INIT**
  - Worker can time out and abort (coordinator handles it)
- Worker waits for **GLOBAL-*** message in **READY**
  - If coordinator fails, workers must **BLOCK** waiting for coordinator to recover and send **GLOBAL_*** message

Example of Coordinator Failure #1



Example of Coordinator Failure #2

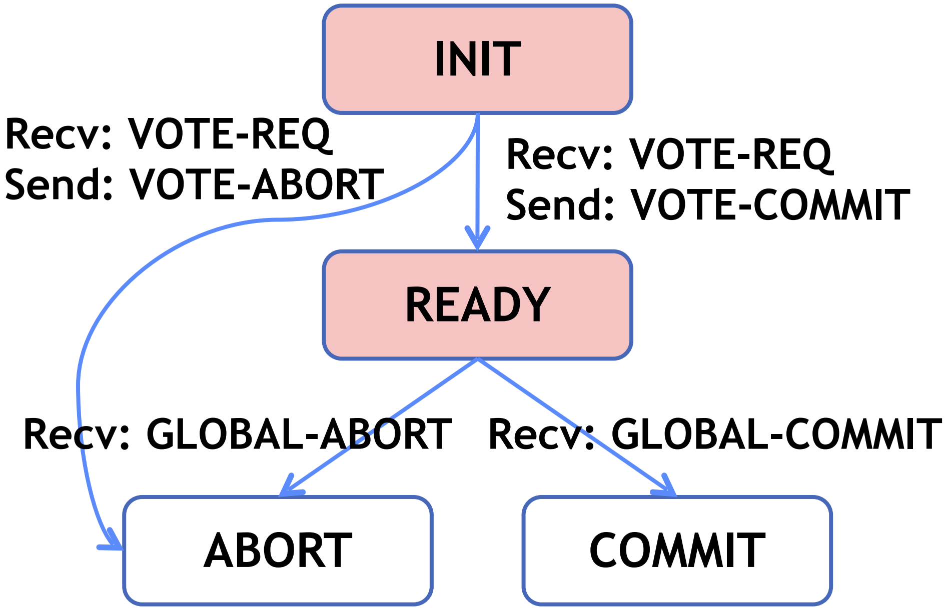


Durability

- 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**

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
  - After decision made, result recorded in multiple places
- Why is 2PC not subject to the 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)

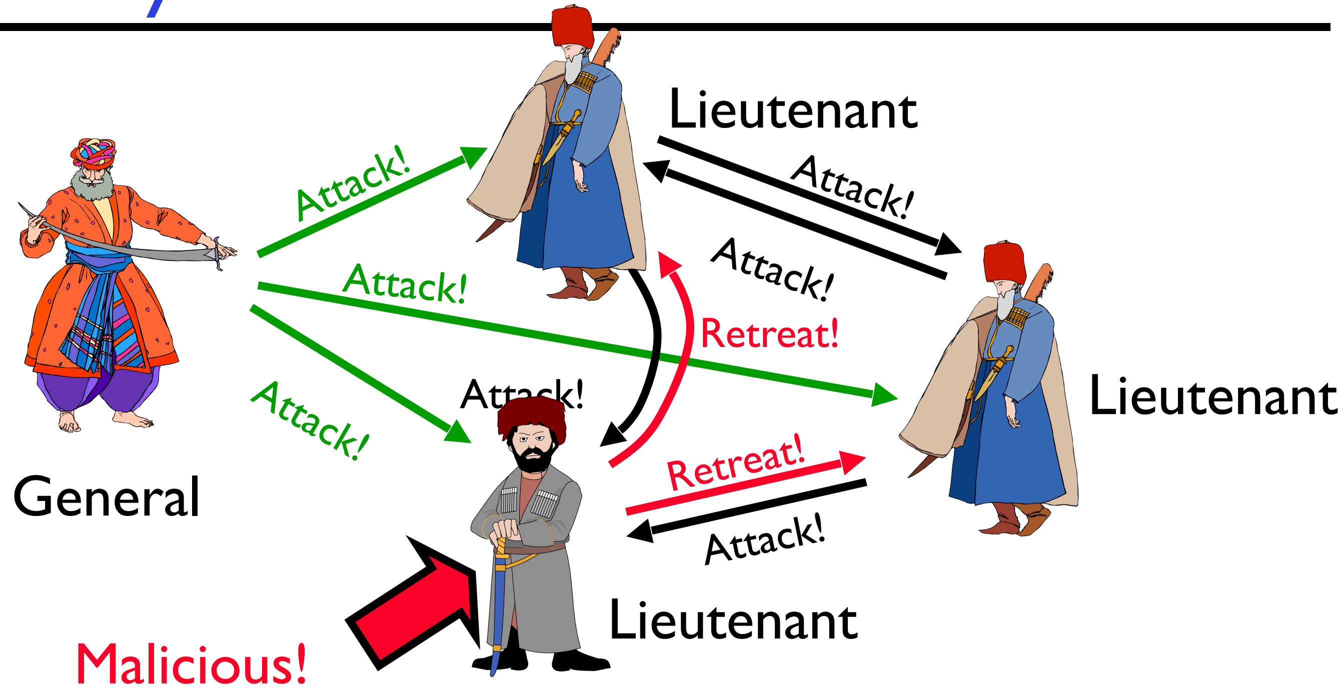
- Undesirable feature of Two-Phase Commit: Blocking
  - One machine can be stalled until another site recovers:
    - » Site B writes "prepared to commit" record to its log, sends a "yes" vote to the coordinator (site A) and crashes
    - » Site A crashes
    - » Site B wakes up, check its log, and realizes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

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

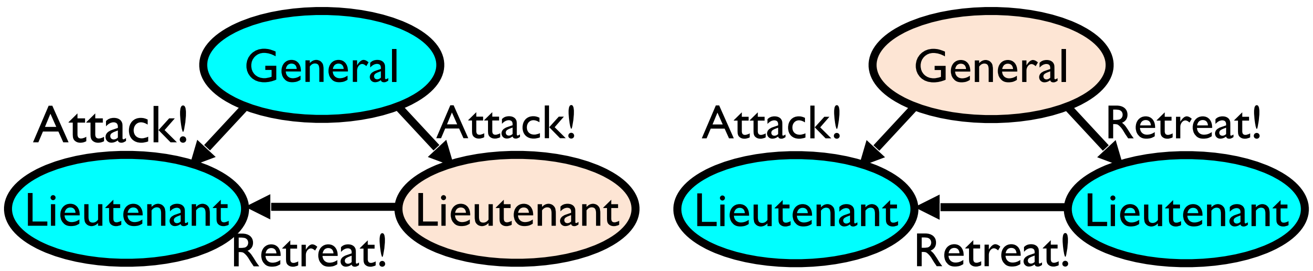
Byzantine General's Problem



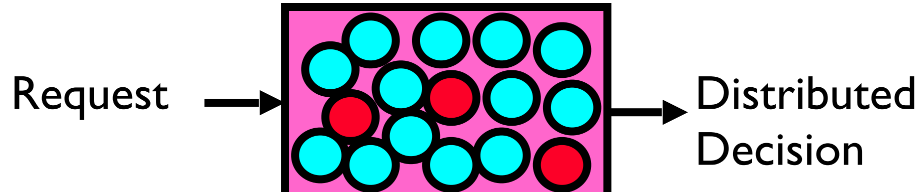
- Byazantine General's Problem (n players):
  - One General and n-1 Lieutenants
  - Some number of these (f) can be insane or malicious
- The commanding general must send an order to his n-1 lieutenants such that the following Integrity Constraints apply:
  - IC1: All loyal lieutenants obey the same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

Byzantine General's Problem (con't)

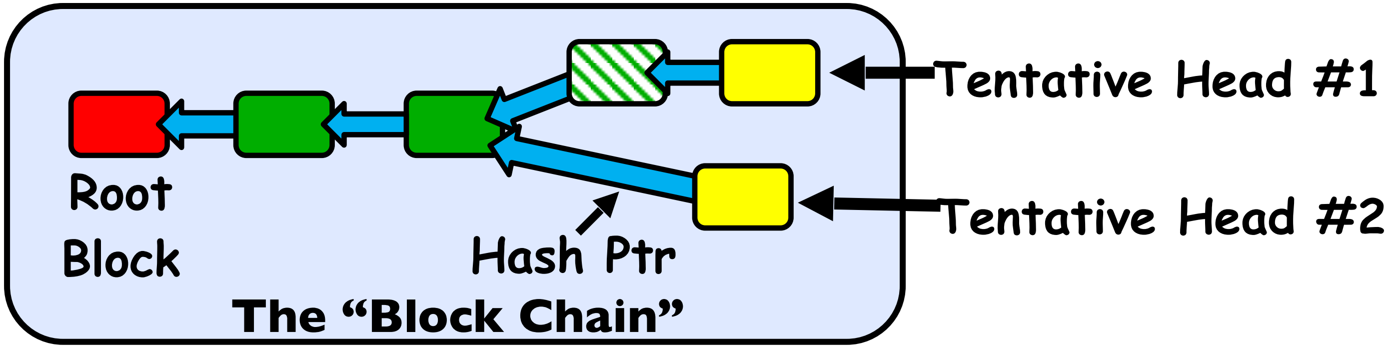
- Impossibility Results:
  - Cannot solve Byzantine General's Problem with n=3 because one malicious player can mess up things



  - 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

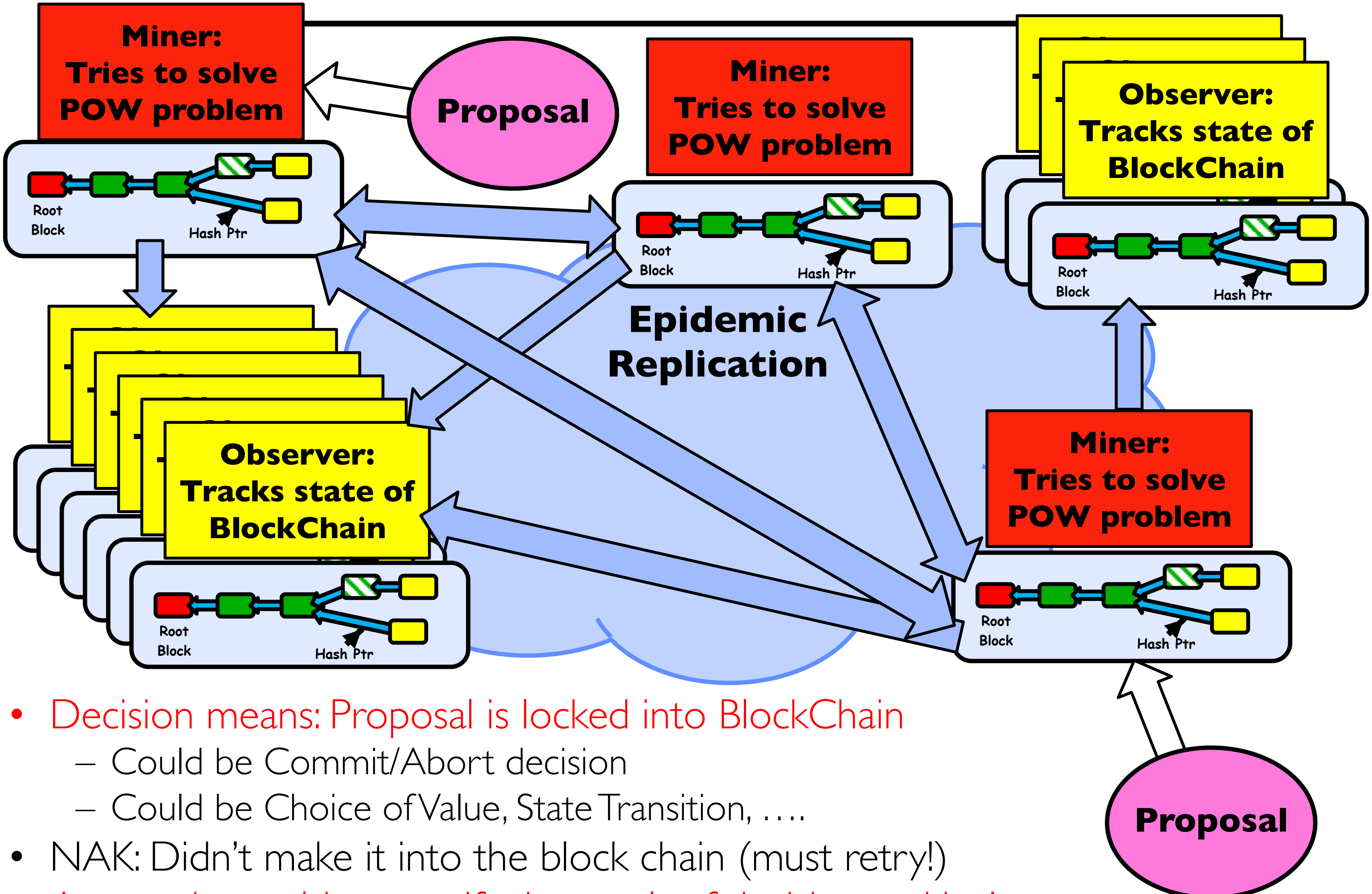


Is a BlockChain a Distributed Decision Making Algorithm?



- 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)

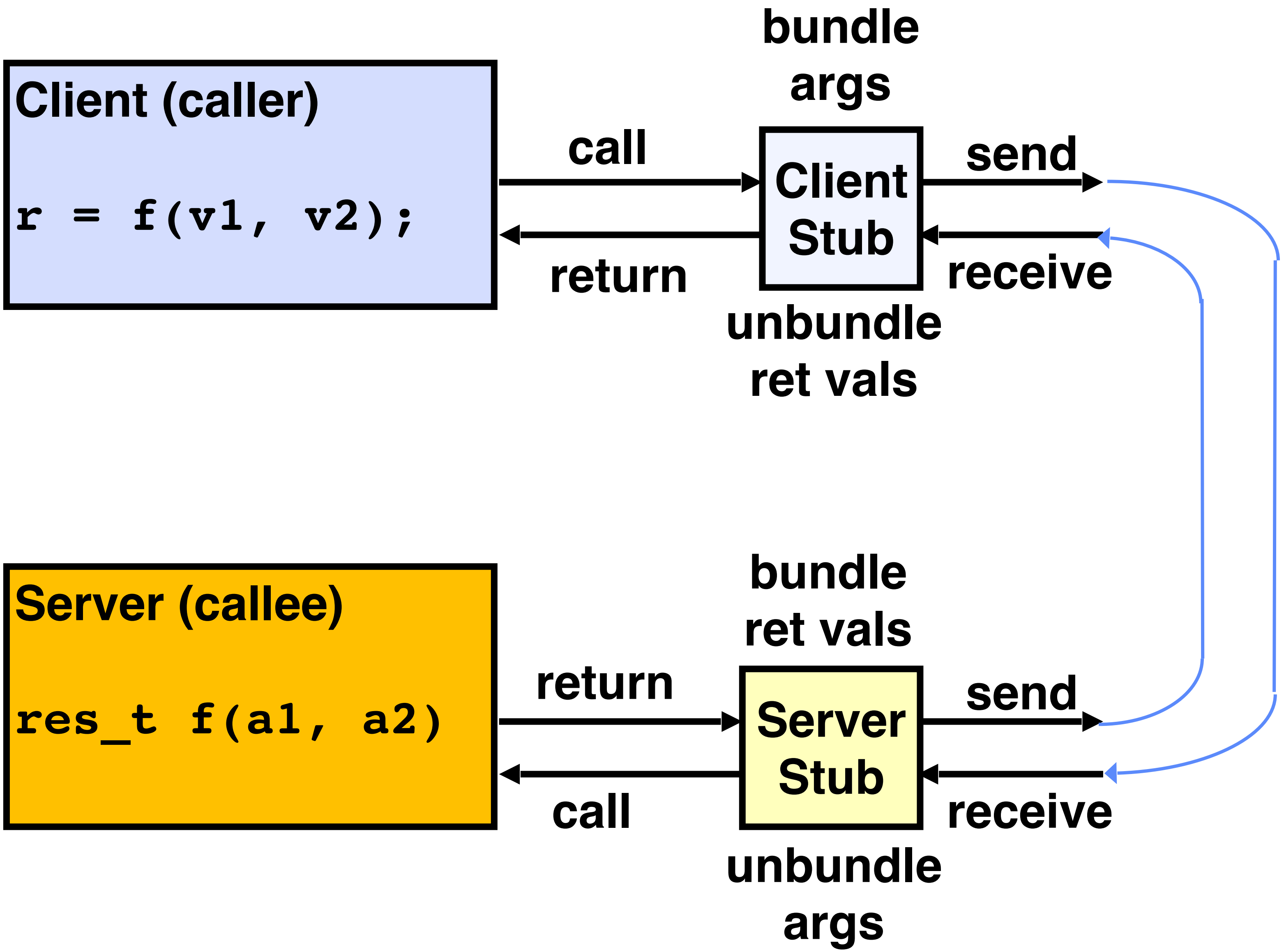


- Decision means: Proposal is locked into BlockChain
  - Could be Commit/Abort decision
  - Could be Choice of Value, State Transition, ….
- NAK: Didn't make it into the block chain (must retry!)
- Anyone in world can verify the result of decision making!

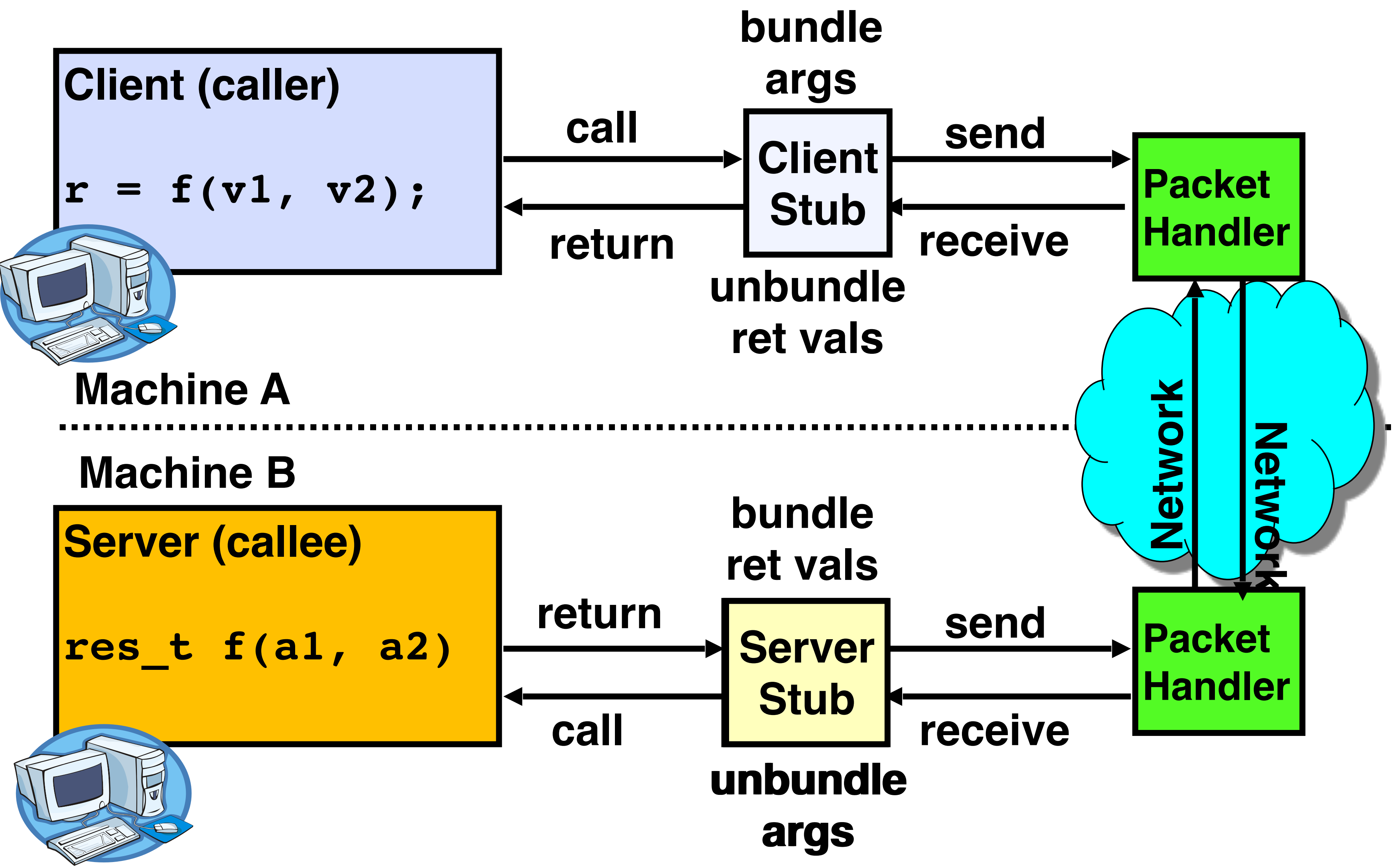
Remote Procedure Call (RPC)

- Raw messaging is a bit too low-level for programming
  - Must wrap up information into message at source
  - Must decide what to do with message at destination
  - May need to sit and wait for multiple messages to arrive
  - And – what about machines with different byte order ("BigEndian" vs "LittleEndian")
- Another option: Remote Procedure Call (RPC)
  - Calls a procedure on a remote machine
  - Client calls:
    ```
    remoteFileSystem→Read("rutabaga");
    ```
  - Translated automatically into call on server:
    ```
    fileSys→Read("rutabaga");
    ```

RPC Concept


Client (caller)
r = f(v1, v2);
call
return
bundle
args
Client
Stub
unbundle
ret vals
send
receive
Server (callee)
res_t f(a1, a2)
return
call
bundle
ret vals
Server
Stub
unbundle
args
send
receive

RPC Information Flow



RPC Implementation

- Request-response message passing (under covers!)
- "Stub" provides glue on client/server
  - Client stub is responsible for "marshalling" arguments and "unmarshalling" the return values
  - Server-side stub is responsible for "unmarshalling" arguments and "marshalling" the return values.

- Marshalling involves (depending on system)
  - Converting values to a canonical form, serializing objects, copying arguments passed by reference, etc.

RPC Details (1/3)

- Equivalence with regular procedure call
  - Parameters ⇔ Request Message
  - Result ⇔ Reply message
  - Name of Procedure: Passed in request message
  - Return Address: mbox2 (client return mail box)

- Stub generator: Compiler that generates stubs
  - Input: interface definitions in an "interface definition language (IDL)"
    - » Contains, among other things, types of arguments/return
  - Output: stub code in the appropriate source language
    - » Code for client to pack message, send it off, wait for result, unpack result and return to caller
    - » Code for server to unpack message, call procedure, pack results, send them off

RPC Details (2/3)

- Cross-platform issues:
  - What if client/server machines are different architectures/ languages?
    - » Convert everything to/from some canonical form
    - » Tag every item with an indication of how it is encoded (avoids unnecessary conversions)
- How does client know which mbox (destination queue) to send to?
  - Need to translate name of remote service into network endpoint (Remote machine, port, possibly other info)
  - Binding: the process of converting a user-visible name into a network endpoint
    - » This is another word for "naming" at network level
    - » Static: fixed at compile time
    - » Dynamic: performed at runtime

RPC Details (3/3)

- Dynamic Binding
  - Most RPC systems use dynamic binding via name service
    - » Name service provides dynamic translation of service → mbox
  - Why dynamic binding?
    - » Access control: check who is permitted to access service
    - » Fail-over: If server fails, use a different one
- What if there are multiple servers?
  - Could give flexibility at binding time
    - » Choose unloaded server for each new client
  - Could provide same mbox (router level redirect)
    - » Choose unloaded server for each new request
    - » Only works if no state carried from one call to next
- What if multiple clients?
  - Pass pointer to client-specific return mbox in request

Problems with RPC: Non-Atomic Failures

- Different failure modes in dist. system than on a single machine
- Consider many different types of failures
  - User-level bug causes address space to crash
  - Machine failure, kernel bug causes all processes on same machine to fail
  - Some machine is compromised by malicious party
- Before RPC: whole system would crash/die
- After RPC: One machine crashes/compromised while others keep working
- Can easily result in inconsistent view of the world
  - Did my cached data get written back or not?
  - Did server do what I requested or not?
- Answer? Distributed transactions/Byzantine Commit

Problems with RPC: Performance

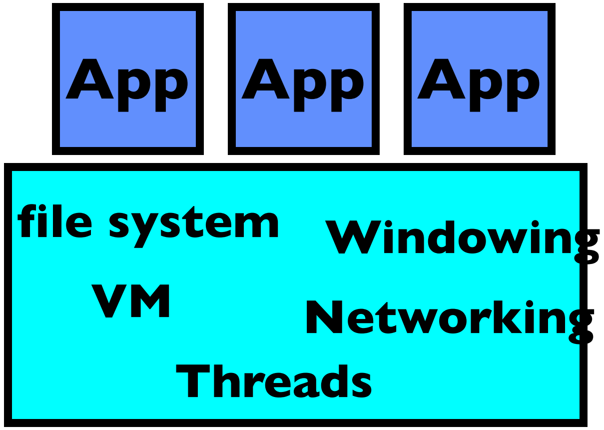
- RPC is *not* performance transparent:
  - Cost of Procedure call « same-machine RPC « network RPC
  - Overheads: Marshalling, Stubs, Kernel-Crossing, Communication
- Programmers must be aware that RPC is not free
  - Caching can help, but may make failure handling complex

Cross-Domain Communication / Location Transparency

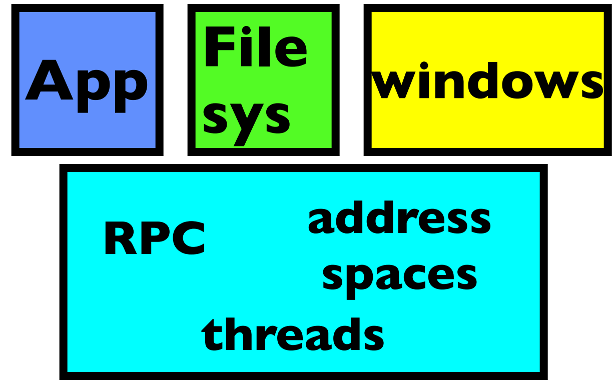
- How do address spaces communicate with one another?
  - Shared Memory with Semaphores, monitors, etc…
  - File System
  - Pipes (1-way communication)
  - "Remote" procedure call (2-way communication)
- RPC's can be used to communicate between address spaces on different machines or the same machine
  - Services can be run wherever it's most appropriate
  - Access to local and remote services looks the same
- Examples of RPC systems:
  - CORBA (Common Object Request Broker Architecture)
  - DCOM (Distributed COM)
  - RMI (Java Remote Method Invocation)

Microkernel operating systems

- Example: split kernel into application-level servers.
  - File system looks remote, even though on same machine



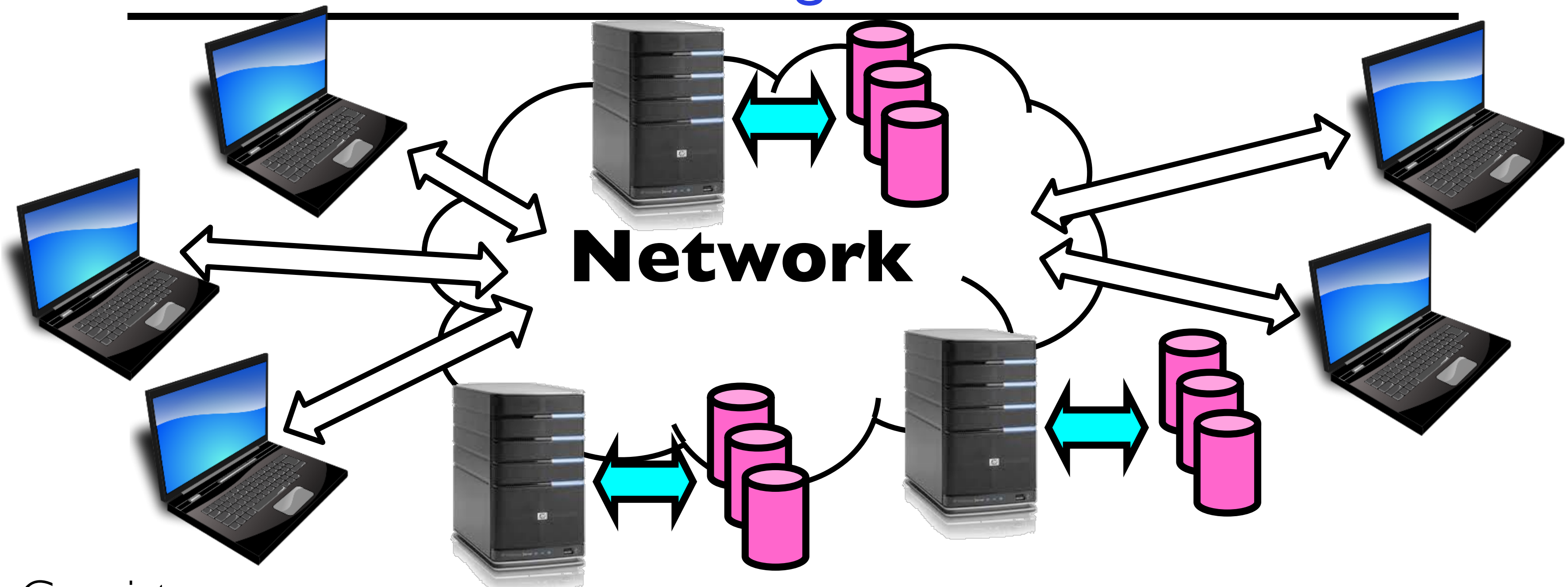
Monolithic Structure



Microkernel Structure

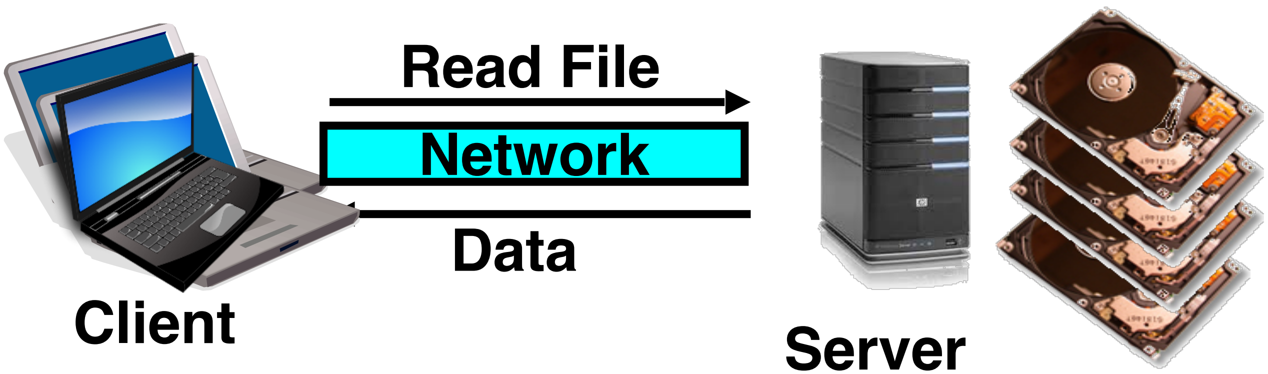
- Why split the OS into separate domains?
  - Fault isolation: bugs are more isolated (build a firewall)
  - Enforces modularity: allows incremental upgrades of pieces of software (client or server)
  - Location transparent: service can be local or remote
    - » For example in the X windowing system: Each X client can be on a separate machine from X server;

Network-Attached Storage and the CAP Theorem



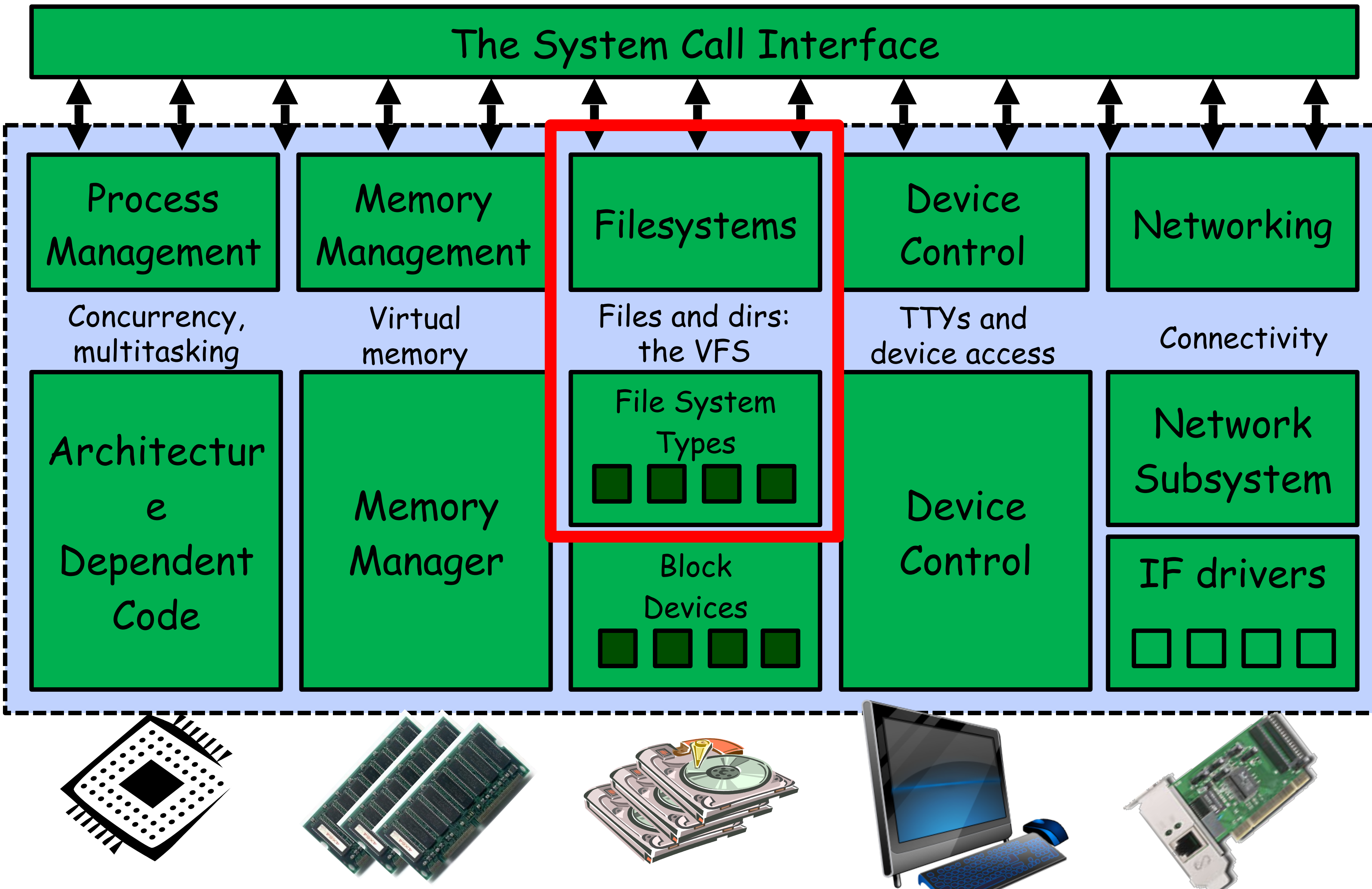
- Consistency:
  - Changes appear to everyone in the same serial order
- Availability:
  - Can get a result at any time
- Partition-Tolerance
  - System continues to work even when network becomes partitioned
- Consistency, Availability, Partition-Tolerance (CAP) Theorem: Cannot have all three at same time
  - Otherwise known as "Brewer's Theorem"

Distributed File Systems

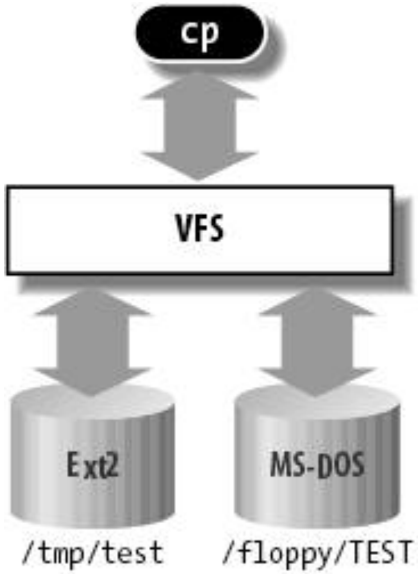


- Transparent access to files stored on a remote disk
- *Mount* remote files into your local file system
  - Directory in local file system refers to remote files
  - e.g., `/home/oksi/162/` on laptop actually refers to `/users/oski` on campus file server

Enabling Design: VFS



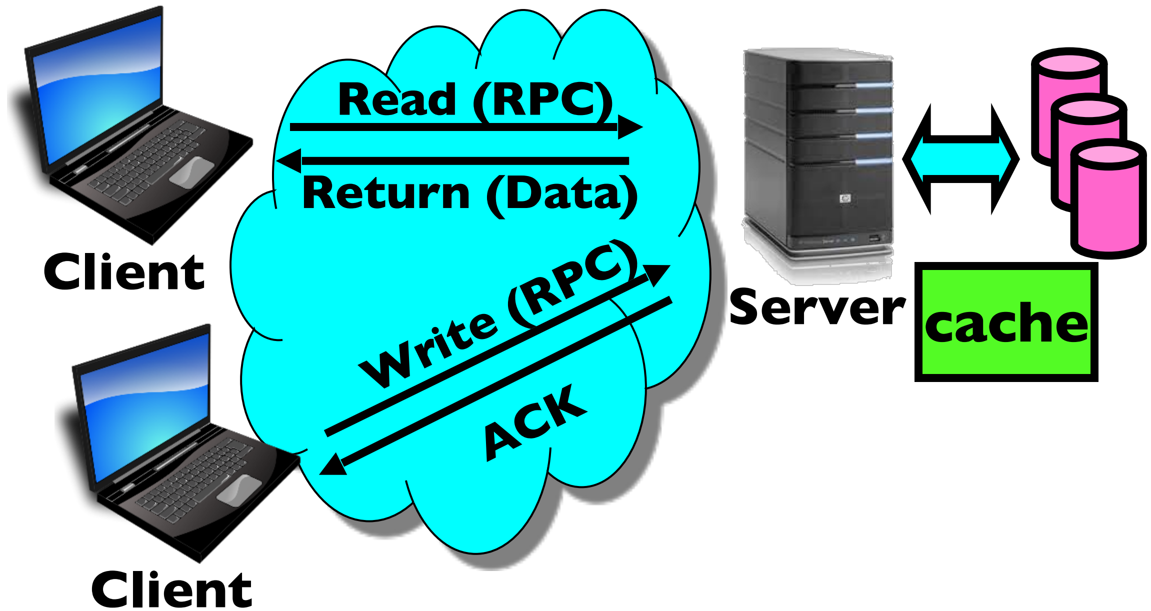
Virtual Filesystem Switch (Con't)




```
inf = open("/floppy/TEST", O_RDONLY, 0);
outf = open("/tmp/test",
       O_WRONLY|O_CREAT|O_TRUNC, 0600);
do {
    i = read(inf, buf, 4096);
    write(outf, buf, i);
} while (i);
close(outf);
close(inf);
```

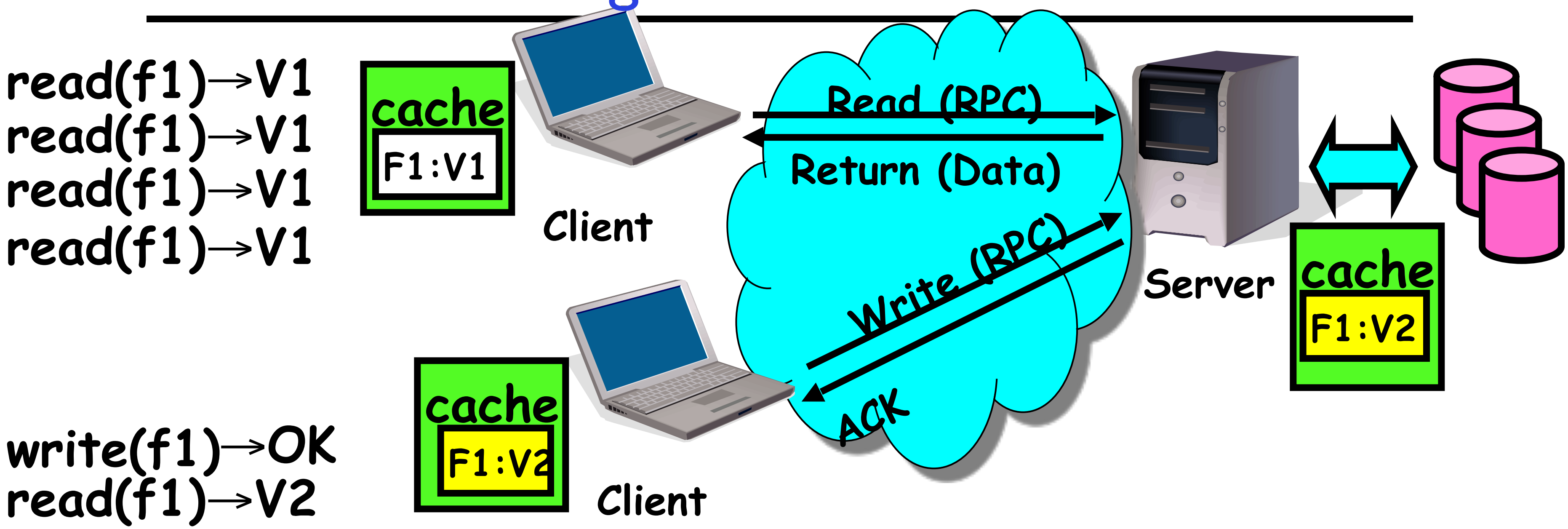
- VFS: Virtual abstraction similar to local file system
  - Provides virtual superblocks, inodes, files, etc
  - Compatible with a variety of local and remote file systems
    - » provides object-oriented way of implementing file systems
- VFS allows the same system call interface (the API) to be used for different types of file systems
  - The API is to the VFS interface, rather than any specific type of file system

Simple Distributed File System



- Remote Disk: Reads and writes forwarded to server
  – Use Remote Procedure Calls (RPC) to translate file system calls into remote requests
  – No local caching/can be caching at server-side
- Advantage: Server provides completely consistent view of file system to multiple clients
- Problems? Performance!
  – Going over network is slower than going to local memory
  – Lots of network traffic
  – Server can be a bottleneck

Use of caching to reduce network load



- Idea: Use caching to reduce network load
  - In practice: use buffer cache at source and destination
- Advantage: if open/read/write/close can be done locally, don't need to do any network traffic…fast!
- Problems:
  - Failure:
    - » Client caches have data not committed at server
  - Cache consistency!
    - » Client caches not consistent with server/each other

Dealing with Failures

- What if server crashes? Can client wait until it comes back and just continue making requests?
  – Changes in server's cache but not in disk are lost
- What if there is shared state across RPC's?
  – Client opens file, then does a seek
  – Server crashes
  – What if client wants to do another read?
- Similar problem: What if client removes a file but server crashes before acknowledgement?

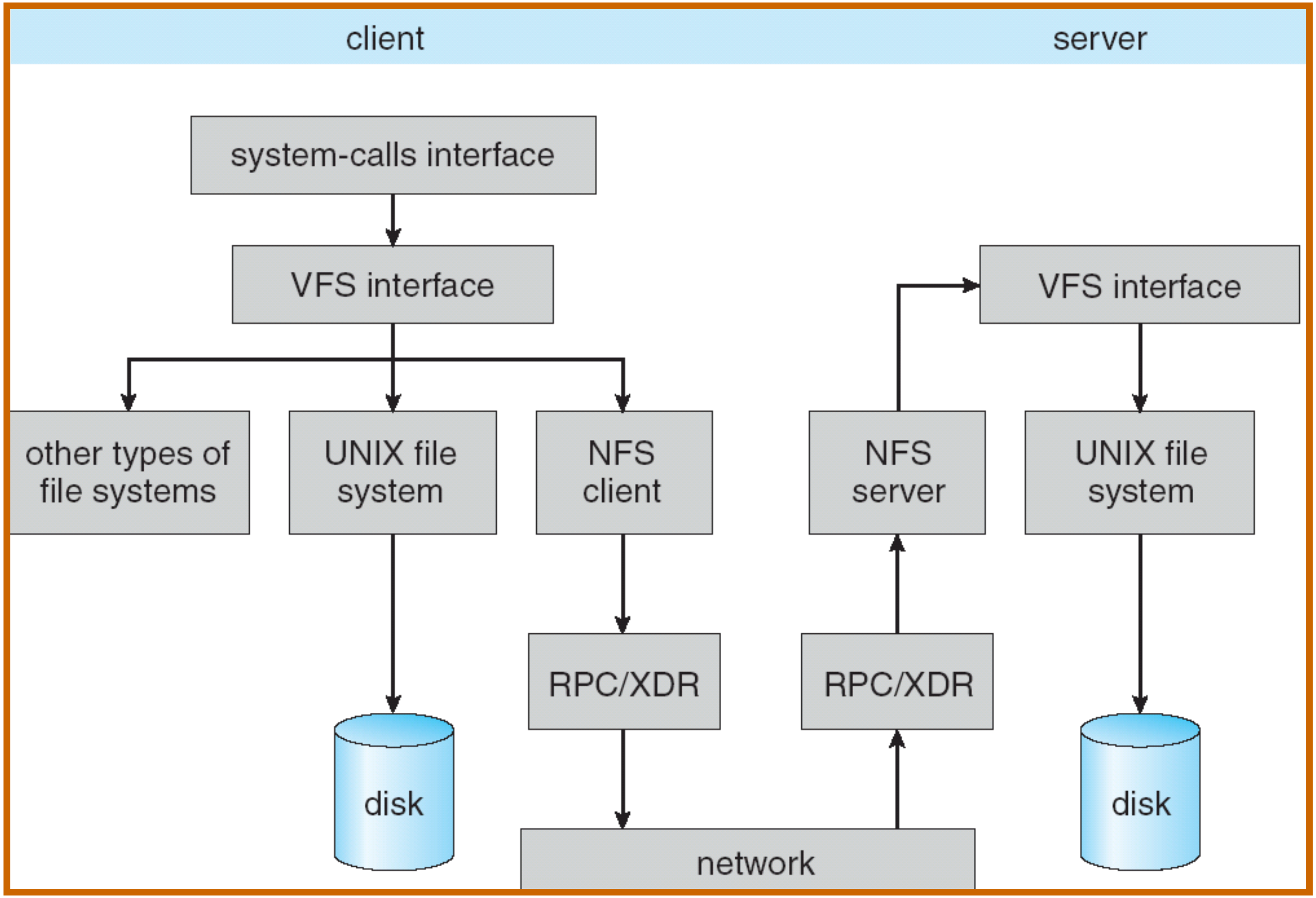
Stateless Protocol

- A protocol in which all information required to service a request is included with the request
- Even better: Idempotent Operations – repeating an operation multiple times is same as executing it just once (e.g., storing to a mem addr.)
- Client: timeout expires without reply, just run the operation again (safe regardless of first attempt)
- Recall HTTP: Also a stateless protocol
  – Include cookies with request to simulate a session

Network File System (Sun)

- Defines an RPC protocol for clients to interact with a file server
  - E.g., read/write files, traverse directories, …
  - Stateless to simplify failure cases
- Keeps most operations idempotent
  - Even removing a file: Return advisory error second time
- Don't buffer writes on server side cache
  - Reply with acknowledgement only when modifications reflected on disk

NFS Architecture



Network File System (NFS)

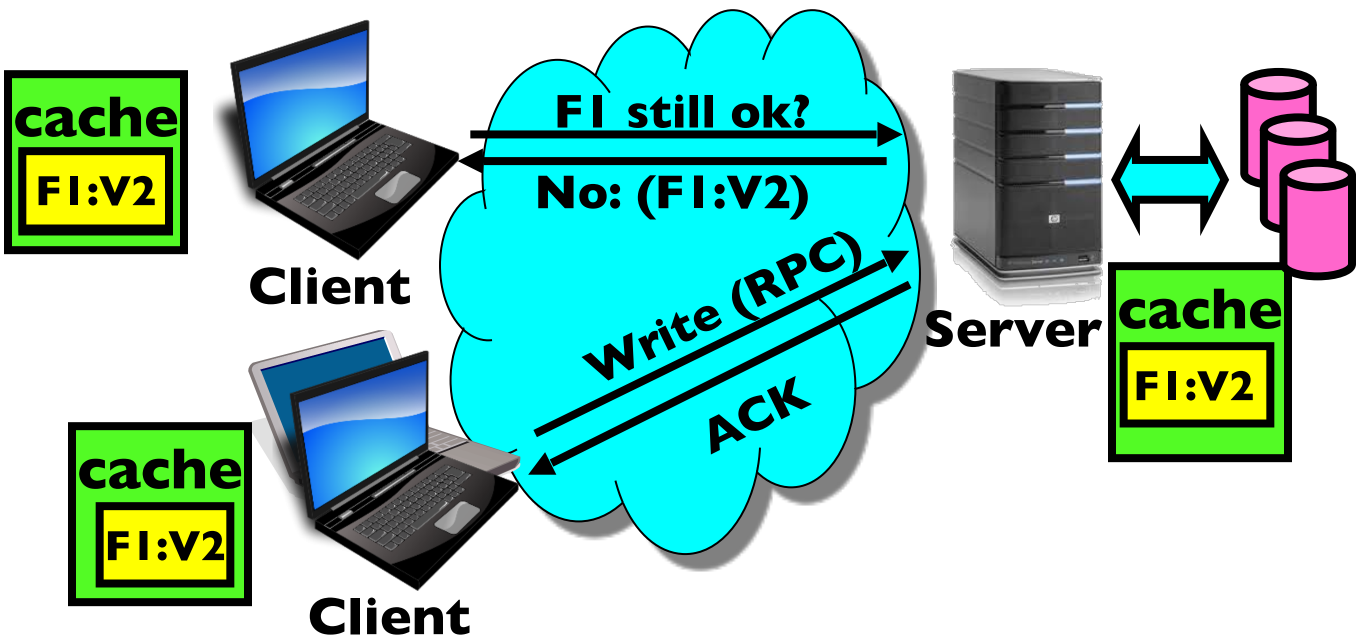
- Three Layers for NFS system
  - UNIX file-system interface: open, read, write, close calls + file descriptors
  - VFS layer: distinguishes local from remote files
    - » Calls the NFS protocol procedures for remote requests
  - NFS service layer: bottom layer of the architecture
    - » Implements the NFS protocol
- NFS Protocol: RPC for file operations on server
  - Reading/searching a directory
  - manipulating links and directories
  - accessing file attributes/reading and writing files
- Write-through caching: Modified data committed to server's disk before results are returned to the client
  - lose some of the advantages of caching
  - time to perform write() can be long
  - Need some mechanism for readers to eventually notice changes! (more on this later)

NFS Continued

- NFS servers are stateless; each request provides all arguments require for execution
  - E.g. reads include information for entire operation, such as **`ReadAt(inumber,position)`**, not **`Read(openfile)`**
  - No need to perform network open() or close() on file – each operation stands on its own
- Idempotent: Performing requests multiple times has same effect as performing it exactly once
  - Example: Server crashes between disk I/O and message send, client resend read, server does operation again
  - Example: Read and write file blocks: just re-read or re-write file block – no side effects
  - Example: What about "remove"? NFS does operation twice and second time returns an advisory error
- Failure Model: Transparent to client system
  - Is this a good idea? What if you are in the middle of reading a file and server crashes?
  - Options (NFS Provides both):
    - » Hang until server comes back up (next week?)
    - » Return an error. (Of course, most applications don't know they are talking over network)

NFS Cache consistency

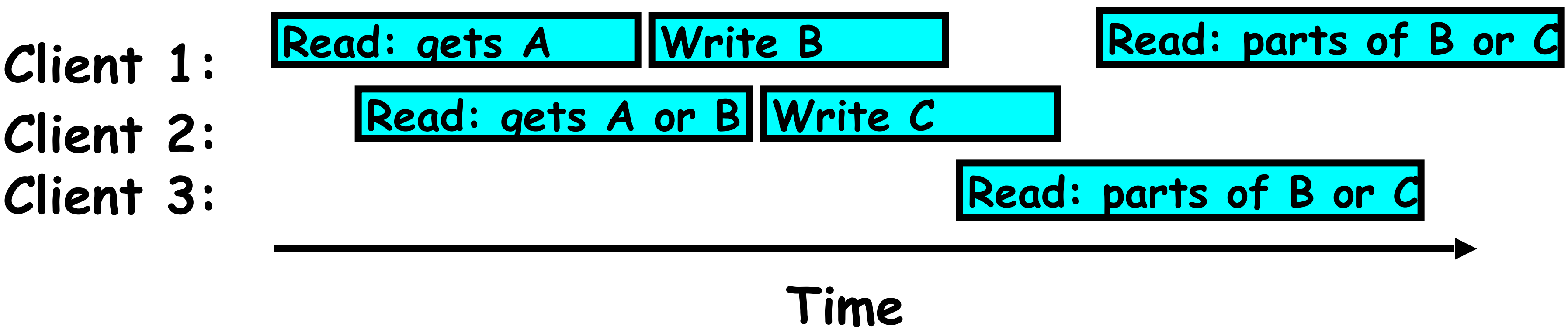
- NFS protocol: weak consistency
  - Client polls server periodically to check for changes
    - » Polls server if data hasn't been checked in last 3-30 seconds (exact timeout it tunable parameter).
    - » Thus, when file is changed on one client, server is notified, but other clients use old version of file until timeout.



  - What if multiple clients write to same file?
    - » In NFS, can get either version (or parts of both)
    - » Completely arbitrary!

Sequential Ordering Constraints

- What sort of cache coherence might we expect?
  – i.e. what if one CPU changes file, and before it's done, another CPU reads file?
- Example: Start with file contents = "A"



- What would we actually want?
  – Assume we want distributed system to behave exactly the same as if all processes are running on single system
    » If read finishes before write starts, get old copy
    » If read starts after write finishes, get new copy
    » Otherwise, get either new or old copy
  – For NFS:
    » If read starts more than 30 seconds after write, get new copy; otherwise, could get partial update

Andrew File System

- Andrew File System (AFS, late 80's) → DCE DFS (commercial product)
- Callbacks: Server records who has copy of file
  - On changes, server immediately tells all with old copy
  - No polling bandwidth (continuous checking) needed
- Write through on close
  - Changes not propagated to server until close()
  - Session semantics: updates visible to other clients only after the file is closed
    - » As a result, do not get partial writes: all or nothing!
    - » Although, for processes on local machine, updates visible immediately to other programs who have file open
- In AFS, everyone who has file open sees old version
  - Don't get newer versions until reopen file

Summary (1/3)

- TCP: Reliable byte stream between two processes on different machines over Internet (read, write, flush)
  - Uses window-based acknowledgement protocol
  - Congestion-avoidance dynamically adapts sender window to account for congestion in network
- Remote Procedure Call (RPC): Call procedure on remote machine or in remote domain
  - Provides same interface as procedure
  - Automatic packing and unpacking of arguments without user programming (in stub)
  - Adapts automatically to different hardware and software architectures at remote end

Summary (2/3)

- Distributed File System:
  - Transparent access to files stored on a remote disk
  - Caching for performance
- VFS: Virtual File System layer
  - Provides mechanism which gives same system call interface for different types of file systems
- Cache Consistency: Keeping client caches consistent with one another
  - If multiple clients, some reading and some writing, how do stale cached copies get updated?
  - NFS: check periodically for changes
  - AFS: clients register callbacks to be notified by server of changes

Summary (3/3)

- Key-Value Store:
  - Two operations
    - » put(key, value)
    - » value = get(key)
  - Challenges
    - » Scalability → serve get()'s in parallel; replicate/cache hot tuples
    - » Fault Tolerance → replication
    - » Consistency → quorum consensus to improve put() performance