Distributed Systems

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Contents

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Big thanks to **Prof. Anna Arpaci-Dusseau**
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at Boston University [1].

All illustration contain original assets.

Disclaimer: These notes are my personal understanding and interpretation of the course material. They are not officially endorsed by the instructor or the university. Please use them as a supplementary resource and refer to the official course materials for accurate information.

Prerequisites

This text assumes the reader has a basic understanding of computer science and programming. It will also assume they are somewhat familiar with computer architecture and operating systems at a high level. The text will review these concepts briefly for completeness, but it will not try to teach them from scratch or provide a full understanding of these topics.

The main focus will be on distributed systems, and will touch on:

- **Concurrency and Parallelism**
  - Concurrency, Parallelism, Threads
- **Consistency and Fault Tolerance**
  - Consistency, Fault-tolerance, Atomicity
- **Distributed Systems and Coordination**
  - Asynchrony, Coordination, Logical Time, Snapshots
- **Consensus Algorithms**
  - Raft, Paxos, Consensus
- **Replication and Data Management**
  - Replication, Sharding, Cluster
- **Protocols and Computing Models**
  - RPC, 2PC, Broadcast
- **Technologies and Tools**
  - MapReduce, Spanner, Dynamo, GFS, TLA+, Golang

Summary

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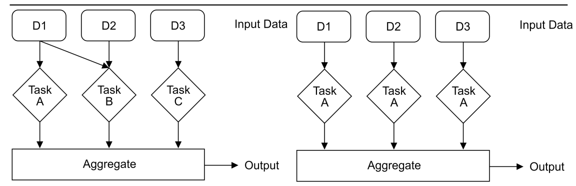
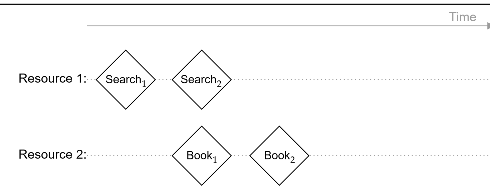
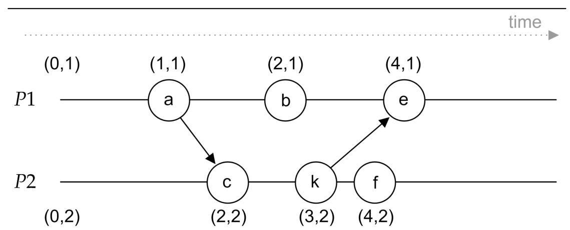
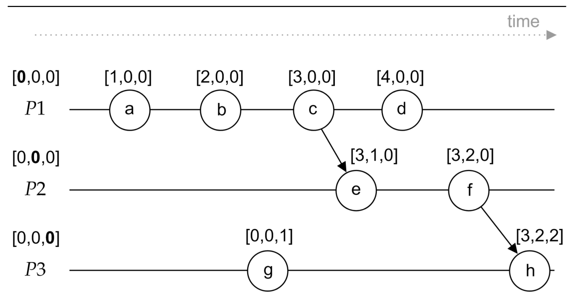
—**System**—**Threads:** Hardware threads (CPU cores) each may run one software thread (program) at a time. Switching, between threads is context switching (overhead). E.g., Go manages internal thread pools, offering it to the OS, reducing overhead. **Thread Comm:** Inter-process communication (IPC), threads communicate via shared memory (e.g., channels, pipes, virtual memory). **Conc. & Parrelism:** Concurrency shuffles tasks, parallelism runs tasks simultaneously (threads). **Dist. Conn:** A client connects to a server (client-server model), a TCP conn. (FIFO) secures the line, the RPC (remote procedure call) abstracts dist. communication. **Races & Deadlocks:** Data race, two threads manipulating shared data (reads-onlys are fine). **Mutexes:** Placing locks around shared data, stopping concurrent access. **RPC Fail Models:** At-least-once, client retries until a response is received. Rads are fine, writes cause race conditions. At-most-once, server handles dupes, clients send unique IDs (cached responses). Exactly-once, both at-least-once and at-most-once. **(a)sync:** Asynchronous, non-blocking, no waiting for a response. Synchronous, blocking, waiting for a response. **(un)buffered-channers:** Unbuffered, sender waits for receiver on some thread to receive message. Buffered, sender sends message(s) to a buffer, takes one at a time. **Task, Data, Pipeline Parallelism:** Task, same data, different tasks. Data, same task, different data. Pipeline, task split into dependent stages, independent stages run in parallel. **Time Accr:** Physical clocks drift due to hardware limitations. Atomic clocks, have insignificant drift. NTP (network time protocol), utilizes GPS satellites to sync time, to a ground truth clocks, which propagates time to other systems. —**Logical Time**—**Lamport Clocks:** Lamport Clocks, (t_p, p), t_p time of process p, monotonically increases for each event/send (Total Ordering). Receivers q resolve time differences, $t_q = max((t_p + 1), t_q)$ (send vs. local time). Given two events a & b, timestamps $t(a)$ & $t(b)$, with r trace: $a \rightarrow_r b \implies t(a) < t(b)$ (causal ordering); $t(a) \geq t(b) \implies a \not\rightarrow_r b$ (concurrent); $(t(a) = t(b) \wedge a \gg b) \implies a \rightarrow_r b$, s.t., $(\gg)$ rep. process order. **Non-causal:** $(a \ll b) := (a \not\rightarrow_r b) \wedge (b \not\rightarrow_r a)$ (concurrent). **Vector Clocks:** Operate as an array of Lamport clocks, index is process p_i, and value is t_{p_i} (time); However, sends do not increment t_{p_i}. Given timestamps a & b, if all indexes in a are larger than b, $a \rightarrow_r b$. If some in a are larger than b, vice versa, $a <> b$ (non-comparable, concurrent, partial ordering).

TaskPar. DataPar. PipePar. La&Ve.Clock:

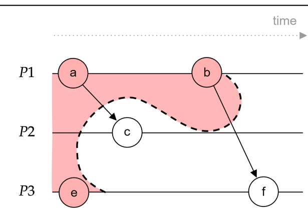


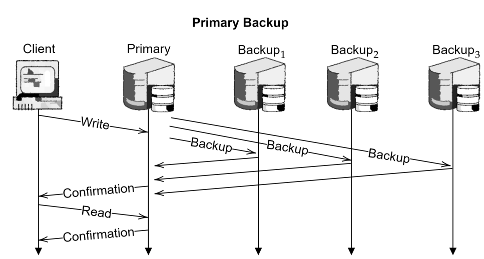


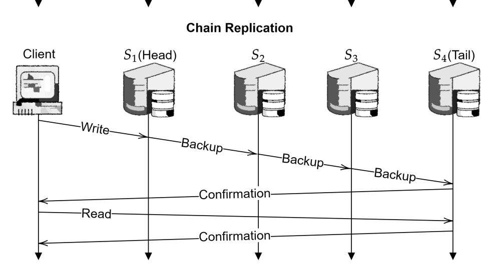




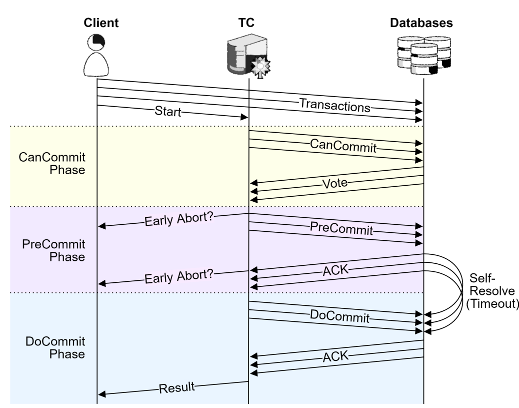
Snapshots: Consistent snap., captures causal dependencies, if $e_1 \rightarrow_r e_2$, and e_2 is in the snap., e_1 must also be present (otherwise it's inconsistent). If in the snap., e_1 sent a message to e_2, and e_2 is not in the snap., replay the message on snap. recovery. **Chandy-Lamp.Snap:** Alg. for capturing consistent snaps. Reqs: No failures, FIFO channels, Strongly conn. graph, Single initiator. (1) Marker sent to all out-chans., record local state. (2) On marker retrieval, block (empty) the chan. from which it came. Record local state, except for empty chans. Send marker to all out-chans. (3) Completion, When all processes have received and sent a marker, the snapshot is complete. (every processes' incoming channel is empty). —**Replication**— **Def:** Maintaining multiple copies of the same data across distinct nodes (machines), providing fault-tolerance, load-balancing, and availability. **Active vs. Passive Rep:** Active, client sends reqs. to all replicas, must process in FIFO order. Passive, client sends reqs. to one replica (primary), which propagates to others (backups). **State vs. Req. Rep:** State Rep., forwards the entire state to backups. Request Rep., forwards individual reqs. to backups. **Primary Commit:** Client→Primary→Backups→Primary→Client (Commit Point). **Arbitrary Serv. (CFG):** The Configuration Service Provider (CFG) ensures a controlled **failover** (switching to backups) in the event of a primary failure. **Chain Rep:** An ordered chain of s_n replicas, writes propagate from s_1 to s_n, where s_n reports back to the client. Reads speak directly with s_n. For any failover, the next adjacent successor takes over. —**Consensus**—**State Machine:** Processes a seq. of inputs from a log, saving them in state. **Rep. State Machine:** Replicated logs across multiple machines, the processing of which is deterministic, generating the same state.**Consensus Model:** facilitates agreement of replicated logs between replicas. **Raft:** A consensus algorithm, with a central leader elected by the cluster in monotonically increasing terms. Liveliness is measured by periodic heartbeats, if the leader isn't reachable, followers, run for election. Split votes are dealt with the current candidates by timing out again (new timeout). Log Matching Property: Same index and term implies, same command and previous indexes are identical. Log Correction: The leader will find the index of the first mismatch, then overwrite the followers entries with its own. Leader Completeness: All proceeding leaders must have all committed entries of the previous leader. Leaders may only commit entries from their term. Candidates are rejected if they have a lower term, shorter log. Timings: $heartbeatReceipt \ll electionTimeout \ll failRate$. Cluster Reconfiguration: A joint consensus reconfiguration follows two phases: (1) propagate mix config of old and new, (2) propagate new config, which includes new servers or deletions. New servers enter with empty logs. Log Compaction/Snapshotting: Servers independently take snapshots, which truncates all committed logs, storing the last committed log index, term, and state (key-value pairs). Clients are always redirected to the leader. 2ReplaysSnap. Primary & Chain Rep.



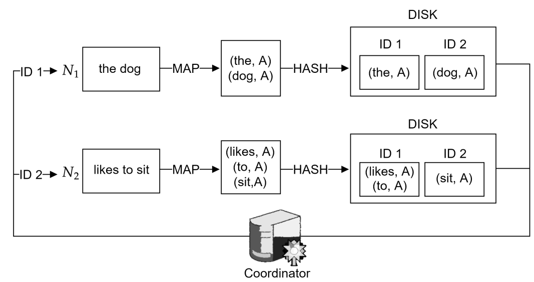


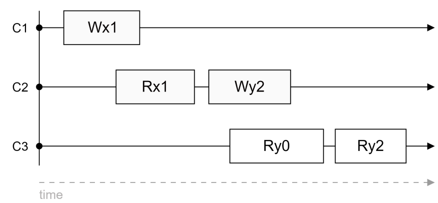


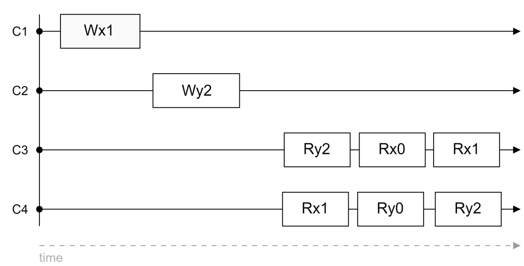
—**Failure Model Hierarchy**—Crash-Stop: Process halts, cannot resume (undetectable) $\subset$ Omission: Process fails to properly communicate $\subset$ Crash-Recovery: Process halts, but can recover $\subset$ Byzantine: Process exhibits arbitrary or malicious behavior. —**Consistency Models**—**Def:** A distributed system's method on validating operation orderings on shared data. **Global Total Order:** Order of observable events agreed upon by all clients. **Strong Consistency (Str):** The client observes nodes agree on order execution (all node reads appear to be identical). **Weak Consistency (Wck):** The client temporarily observes that nodes disagree on shared data values. **Linearizability (Str):** Global Total Order with respect to real-time ordering (operation time intervals unmovable, but execution choice within them are). E.g., Raft leader-commit (happy-path) and Chain Replication. **Sequential (Str):** There is some Global Total Order found when shifting operation time intervals. **Causal Consistency (Wck):** Same as Sequential; However, clients may observe their own view on a Global Total Order. **Eventual Consistency (Wck):** Given no new writes, replicas will eventually agree on the same value after some time. **Causal Implications:** Linearizability $\implies$ Sequential $\implies$ Causal $\implies$ [First-In-First-Out (FIFO)/ Read-Your-Writes (RYW)]. **Release Consistency (Wck):** Push updates to all nodes after releasing the lock. **Lazy-release Consistency (Wck):** Push updates to the next node who acquires the same lock. —**Transactions**—**ACID:** Atomicity, no partial effects, all or nothing. Consistency, A transaction takes the database from one valid state to another. Isolation, no interleaving of transactions. Durability, transactions once committed, are permanent even after system failure. **Serializability (Str):** Ensures the outcome of concurrent transactions is the same as if they executed in some serial (sequential) order. Differs from linearizability, which deals with real-time ordering of single tasks, as opposed to whole jobs. **Strict-Serializability (Str):** Serializability with real-time ordering; In particular, Serializability $\Longleftarrow$ Strict-Serializability $\Longrightarrow$ Linearizability. **Optimistic Concurrency Control (OCC):** Assumes conflicts are rare, proceeds without locking. (1) Prepare the transaction on all nodes, (2) Tell the coordinator to execute, validate the outcome, (3) Commit if Serializable, abort otherwise (isolation). **Timestamping OCC:** Helps with distributed OCC agreement on separated data, but aborts unnecessarily. **Two-Phase Commit (2PC):** Ensures **atomicity**, (1) Prepare Phase: After client's request is received on all nodes, the Transaction Coordinator (TC) sends a prepare message to all nodes, awaiting YES votes. (2) Commit Phase: If all nodes reply YES, the TC requests for all nodes to commit. If any fail to reply, the TC is blocked, sending the commit request to that node indefinitely (can't abort after this point). **3PC:** 2PC with an additional phase before the commit phase, ensuring people can commit (PreCommit Phase). If any nos or failure to respond in PreCommit, abort. If not partitioned, if the TC fails in the PreCommit phase, servers may attempt to reconcile with themselves about how to continue. **Pessimistic Concurrency Control (PCC):** Assumes conflicts are likely and prevents them by ac- quiring locks before any data access. It then preforms actions directly on shared data, ensuring serializability and isolation. The locks are released after the transaction is completed. 3PC.

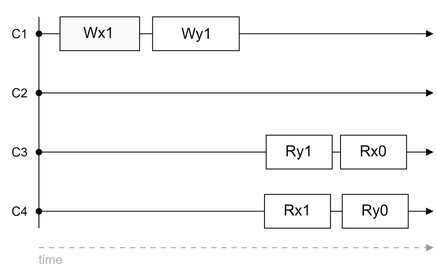


—**Distributed Shared Memory (DSM)**— **Def (str):** A cluster which gives the illusion of a single shared memory space on a single machine, enabling multithreaded programs in a distributed setting. DSMs abstract away consensus and communication, opting to mimic virtual memory page primitives to communicate between nodes. **Sending Pages (Naive) (str):** Sending entire pages over the network is costly on bandwidth, but ensures consistency. **Sending Page Diffs (TreadMark) (Wck):** Keep a versioning history of every change, upon request, send the diffs to the page, avoiding false sharing (unnecessary updates). Versioning control is managed via vector clocks, which identify who made the changes (causal consistency). (1) Pages start as read-only (RO), which many may access. (2) When one claims read-write (RW) access, it invalidates all other copies. (3) Upon request, a page diff is sent over the network, the page now reverts to RO (at most one writeable copy). Weak consistency as per lazy-release style of data sharing. —**Virtualizing**—**Sharding:** Splitting a dataset into smaller chunks, called shards stored on multiple nodes. Multiple copies increases safety. **Consistent Hashing:** Creates a hash ring of 2^m entries with keys of m-bit values. Servers are placed uniformly in multiple locations on a ring, serving for a range of keys. —**MapReduce:**—**Def:** Map: Takes a set of input key-value pairs and produces a set of intermediate key-value pairs. Shuffle: this phase sorts the keys or hashes them (more efficient) into key bins that will be assigned to workers to reduce. Reduce: Takes an intermediate key and a set of values for that key, and merges them into a smaller set of values. Given W workers, M mapping tasks, and R reducing tasks, $W \gg N$ and $R \gg N$. Data is split up and given to workers in partitions. Map failure: Reassign the chunk, first one done is propagated. Reduce failure: Reassign the partition, they write to the same location (e.g., "/filepath/final_data/id"). Coordinator failure: Restart the entire MapReduce job. Failures are not recoverable, and are assumed to be rare. Slow workers (stragglers), will always be a bottleneck. MapRed. Lin. Even. ¬Caus.

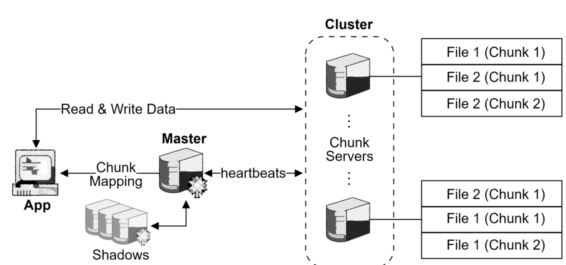






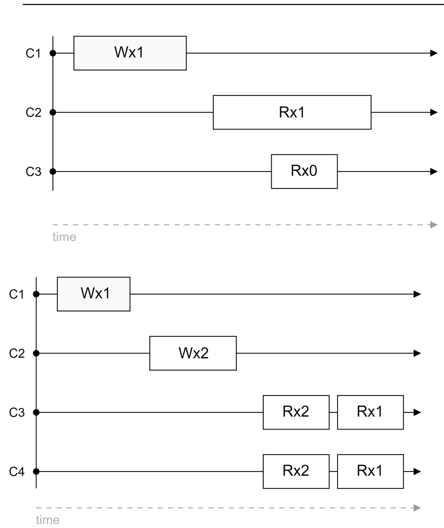


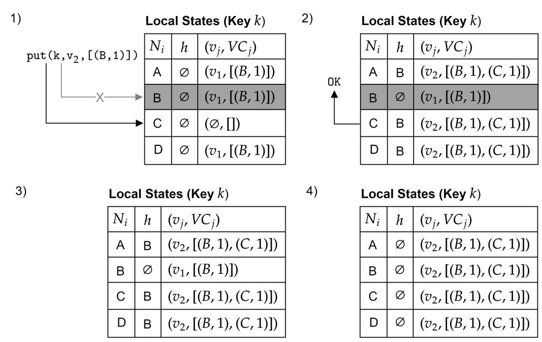
—**Google File System (GFS)**—**Def (Wck):** Dist. file system, Scalable on cheap hardware, High availability on frequent failures (rep. need), High throughput of seq. reads and append-only writes. Files are split into 64MB chunks, given a 64 bit ID chunk handle. Chunks must be replicated N times (Typically $N = 3$). There is one TC, the master, which manages the file→chunk mappings and access control information. The client queries the master with (file name, chunk index), and receives the replica location. It caches this information to speak with the server directly. Clients may directly read from any chunk server (stale reads allowed). For writes, the client sends data to the closest replica, which then forwards it to the next closest replica. After all is done, the client orders the primary replica (picked by the master with a timed lease) to commit the data. The primary eagerly commits their own state and replies success, while the others lazily commit their state. The master will periodically check for stale chunks in case of failures (garbage collection through heartbeats). There are also background master replicas (shadows) that locally replay the master state in case of failure. The master has checkpoints, which are snapshots that truncates the log. Shadows also serve as read-only replicas to reduce load on the master. Shadows exhibit eventual consistency, slightly lagging behind the master. There is non-atomicity and non-serializability across chunks, but there is within a single chunk, due to the order of accepted writes from a primary on any given chunk. If a write is rejected as per full chunk, the client must refresh (find the new chunk server) from the master. Having a single master simplifies the design of the system. —**Dynamo: Key-Value store**—**Def (Wck):** Always writeable (high availability), scalable, decentralized, low-latency performance (SLA: Service Level Agreement of 300ms on 99.9% of requests), Eventual consistency. Utilizes consistent hashing on 128-bit ordered list of N virtual nodes. Writes: client sends put(key, value), which is hashed to N_j, which serves as the coordinator/owner of the key. Such coordinator propagates in parallel to the next $N - 1$ healthy nodes (preferred list). After W servers respond, the coordinator sends a success to the client. Reads: client sends get(key), which is hashed to N_j, who waits for R responses from the preferred list. Quorum Condition: $W + R > N$, ensures sufficient overlap, mitigating stale reads. Failure: If k hashes to A's segment, we retry the next healthy node. We hint (notify) the next node B that A is down. B then stands in as the coordinator, with the addition of hinting A to the cluster. During runtime, all N nodes gossip with each other, sending heartbeats at random. During this phase, if A recovers, a random server C may notice this, and preform a hinted-handoff, passing along the operations A missed. Diverging data is resolved via a versioning vector clock for each object (key, value), where each cell is a node, and the value is a monotonically increasing counter of its participation. During reads, the coordinator attempts to resolve the vector clock, if it can't, it returns all versions to the client. The client must decide how to merge the data (often unioning them in case of two carts). Then sends the merged data back as a put operation. In the background, nodes will try to resolve stale data via merkle trees (hash trees). Merkle trees, first hash a range of keys (leaves), then combines two hashes into a parent (intermediate nodes), until they reach the root node (summarizes the entire tree). Nodes use this to efficiently find divergent data. GFS.

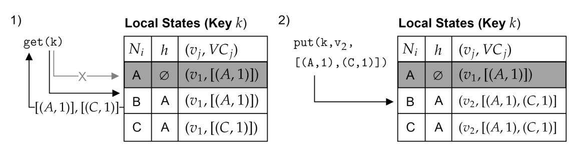


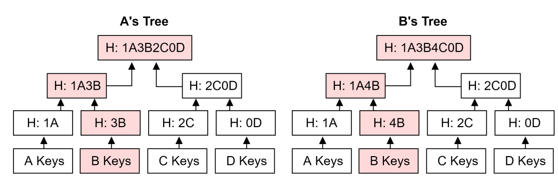
—**Spanner**—**Def (Str):** A globally distributed database, linearizeble reads and writes across shards (globaly agreed timestamp), High availability, low-latency, lock-free read-only transactions, strict serializability, with atomic transactions. Utilizes Multi-Version Concurrency Control (MVCC): Each write transaction assigned a uniquely increasing timestamp with every key-value pair. Safe Time Rule: Before transaction T reads key k, it must see a timestamp greater than the last write to k (if any). Atomic clocks are used to mitigate clock drift, and are synchronized via GPS satellites. The TrueTime API, provides a `TT.now()`, which returns a $[t_{earliest}, t_{latest}]$ interval, where the real time must be between the two (inclusive). The difference of the two intervals is the uncertainty δ, which is the time it must wait before reads or writes can be performed. The protocol uses paxos (consensus model like raft) to ensure fault-tolerance and availability of replicas. Read-write Transactions: two-phase locking (2PL) and two-phase commit (2PC) are used to ensure isolation and atomicity respectively. The first phase acquires locks on needed keys and reads the values, then 2PC commences with one of the shard paxos leaders as the TC. After the commit, the locks are released.—**TLA+**—is a high-level specification language based on temporal logic that lets you model distributed algorithms, exhaustively explore all possible states, and prove safety and liveness properties. While it excels at uncovering subtle bugs and proving correctness, TLA+ specifications do not translate directly into production code—implementing a verified design remains a substantial engineering effort.

Caus. Seq. HintOff. DynCliRec. Merkle.









δ-time. 2PL2PC.

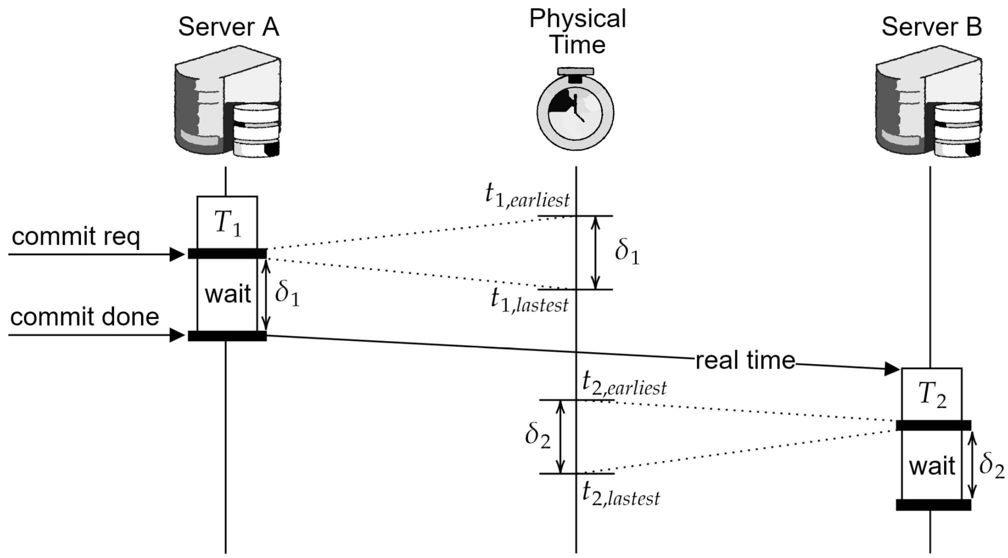


Figure 1.1: Upon receiving a commit request, each coordinator (e.g. A) calls `TT.now()` and obtains an uncertainty interval $[t_{1,\text{earliest}},\ t_{1,\text{latest}}]$. It then delays for $\delta_1 = t_{1,\text{latest}} - t_{1,\text{earliest}}$ before finalizing its commit timestamp.

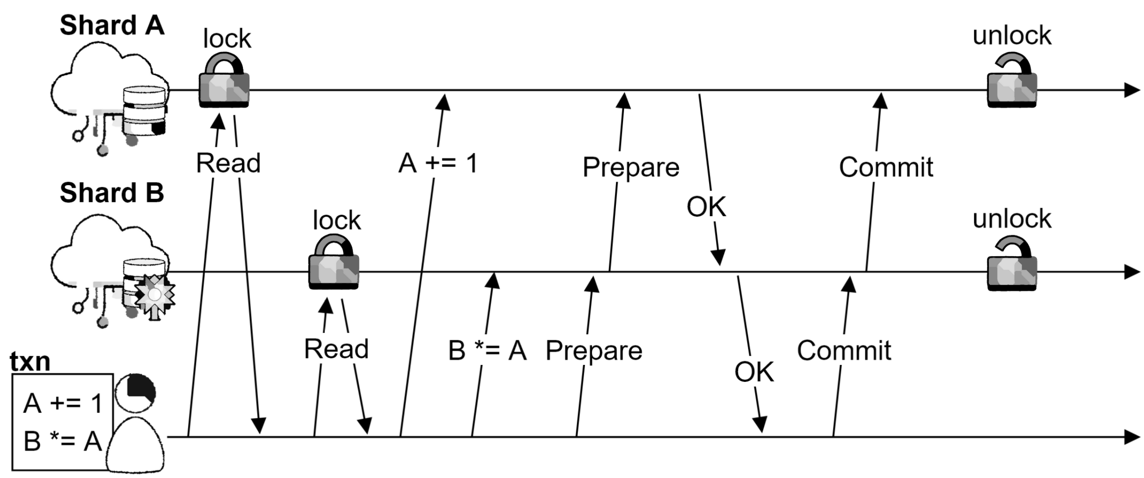


Figure 1.2: A Read-Write Transaction 2PC Commit in Spanner, where txn is the transaction, B's Paxos leader is the coordinator, and A another participant. First, reads acquire locks, then 2PC begins. Commands are sent, and then the `PREPARE` and `COMMIT` phases begin, ending with the release of locks.

Bibliography

[1] Ioannis Liagouris. Cs351: Distributed systems. Lecture notes, Boston University, Spring Semester, 2025. Boston University, CS Department.