Design and Engineering of Computer Systems

Lecture 37: Replication and Consistency

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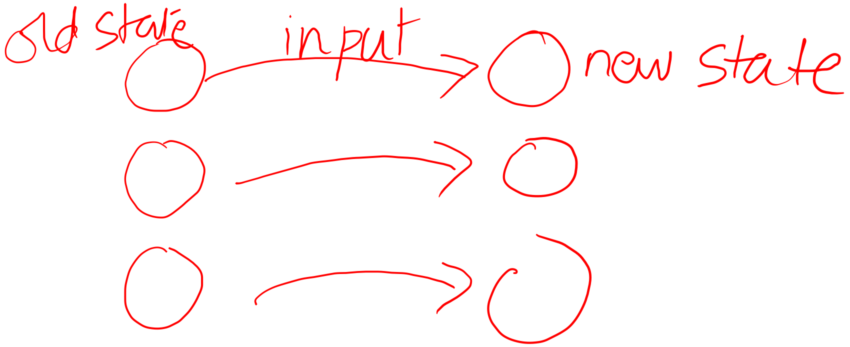
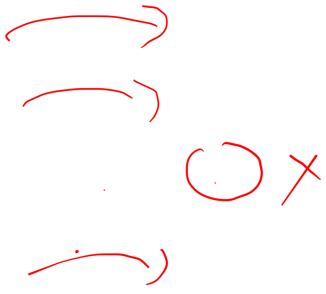


Replication and Consistency

- One way to build fault tolerant systems: replicated state machines
  - Requests from clients (inputs) are processed by all replicas
  - All replicas start with same state, handle same input, so will stay in the same state always (assuming deterministic processing)
  - Used to build active-active replicated systems
  - Used to build reliable distributed data stores for active-passive systems
- Challenge in building replicated state machines: consistency
  - What if a replica was down and didn't receive some input?
  - What if a replica received some inputs in a jumbled order?
  - How to ensure all replicas are always consistent, i.e., in the same state?
- This lecture: mechanisms for replication that guarantee consistency



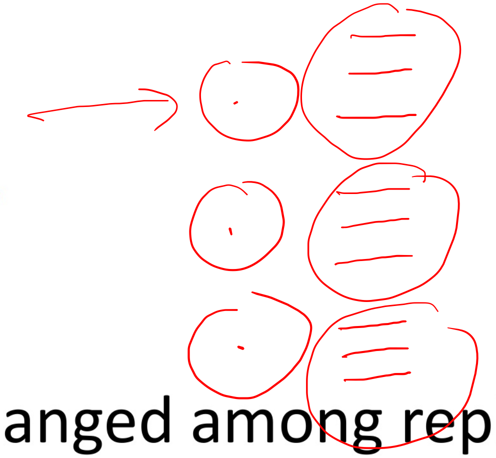
Consistency models

- Many definitions / models of consistency, some strong and some weak
- Atomic consistency is example of strong consistency model
  - All inputs / operations (e.g., add/delete/view items in shopping cart) executed at all replicas in exactly the same order

X: add item
↓
Y: view cart

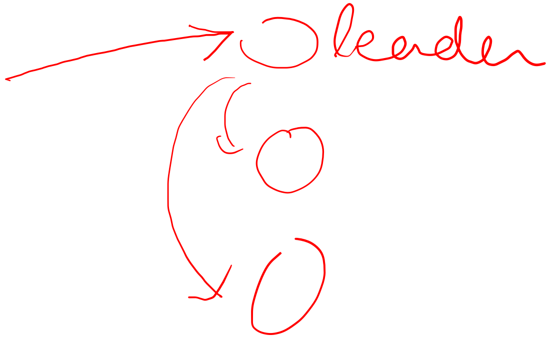
  - If an operation Y (e.g., view shopping cart) starts after operation X (e.g., add item to cart) finishes according to some global clock, then Y should always see the result of X
- Eventual consistency is example of a weak consistency model
  - If an operation Y (e.g., view shopping cart) starts after operation X (e.g., add item to cart) finishes, then Y should see the result of operation X eventually
- Spectrum of consistency models from strong to weak
  - Example: causal consistency model says that same order of operations/inputs maintained only between operations that impact each other (e.g., operations on same shopping cart) and not across all operations

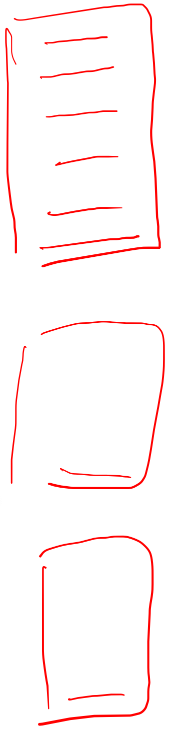
How to achieve strong consistency



- Requires the use of consensus protocols: messages exchanged among replicas to let them agree on certain decisions
- Raft: popular, widely used consensus protocol that lets multiple replicas agree on an consistent ordered log of entries
  - Example: replicas of shopping cart servers agree on a log containing various operations (add/delete/view cart) to be performed on shopping carts
- Building a replicated state machine with Raft
  - All replicas run Raft, agree on a consistent replicated log containing the same operations in the same order at all replicas
  - After an operation replicated in log using Raft, all replicas execute the operation, stay consistent with each other
- Other consensus protocols can be used to build replicated state machines, e.g., Paxos lets all replicas reach agreement on a single value in each round

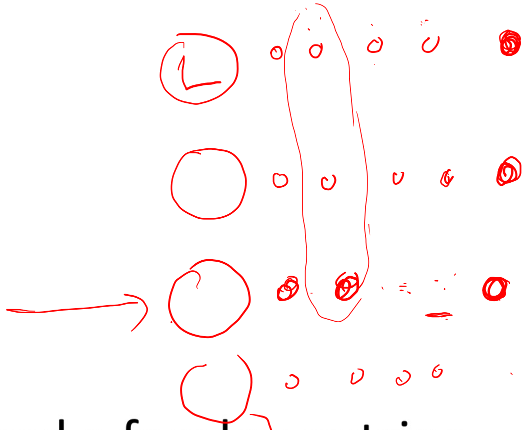
Strong consistency: Raft (1)





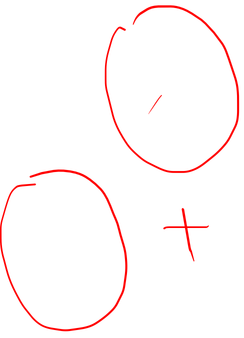
- Basic idea of Raft: replicas exchange messages to maintain a consistent replicated log (same entry at same index in every log)
  - Replicas elect one leader, rest are followers
  - Leader receives inputs from clients, propagates to all replicas in the form of log entries
  - Once leader has replicated entry at majority of nodes, entry considered committed, applied to state machine, confirmation returned to client
  - What if majority of replicas cannot be contacted? No response to client
  - Example of a quorum protocol: contact a quorum before returning response
  - Raft instance with 2f+1 replicas can tolerate up to f failures
  - Leader failure: followers detect via heartbeats, elect new leader, start new term (old leader can come back up and join as follower later)

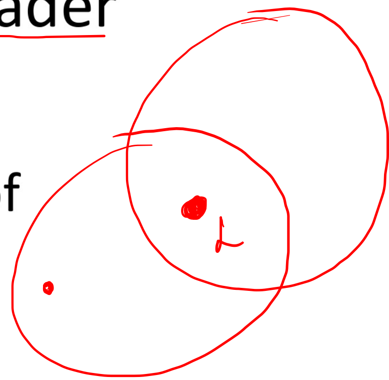
Strong consistency: Raft (2)



- Replica failures can cause logs to diverge
  - Some follower may have briefly crashed and missed a few log entries
  - Old leader of previous term can have some extra uncommitted entries that it did not manage to replicate before it crashed

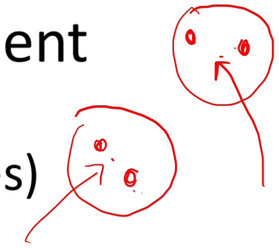
- How does leader reconcile such logs?
  - When leader propagates entry k, it also mentions its entry "k-1". Follower updates entry "k" only if its entry "k-1" matches with that of leader
  - If a follower's previous entry does not match, leader will rollback to the point where logs match and help follower catch up with all previous committed entries
  - Leader tries to sync all follower's logs to its own log
- Leader's log is the authoritative source, so it is crucial to elect good leader
  - All replicas vote for node with most up to date log (with all committed entries)
  - Leader elected successfully only if it gets majority of votes (f+1 out of 2f+1)
  - Any two majorities always intersect, so at least one node with up-to-date log of previous term will be available to be elected as leader in next term





Weak consistency: Dynamo (1)

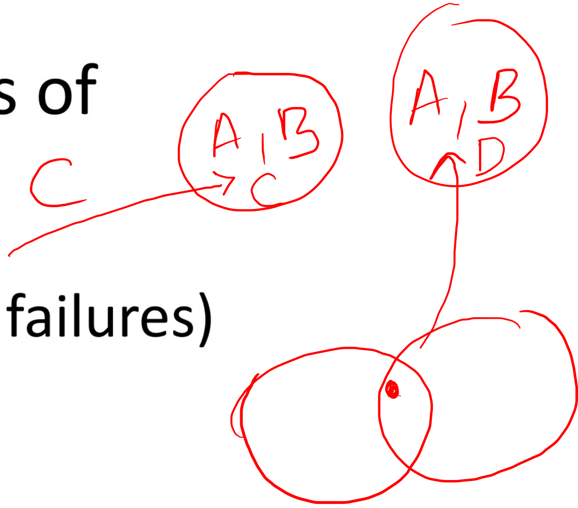
- Raft and other strong consistency protocols: if majority cannot be contacted, no response returned to client, system is unavailable sometimes
- What if we want high availability? What if we return a response back even if client request is not replicated at a majority of nodes?
  - One client request (add item to cart) replicated only at a minority of nodes (due to failures)
  - Another request (view cart) executed at another minority of nodes
  - It is possible to have two minority sets with no intersection, so viewing cart may not reflect latest item added to cart
  - Inconsistent values can be returned by the system, but service always available



- Some systems accept weak consistency in return for high availability, e.g., Dynamo NoSQL key-value store (Amazon) has high availability, only eventual consistency
  - Sloppy quorum protocol, response returned to client even if replication not successful at all desired replicas due to replica failures
  - Systems eventually tries to catch up the missing replicas, but no guarantees on timelines

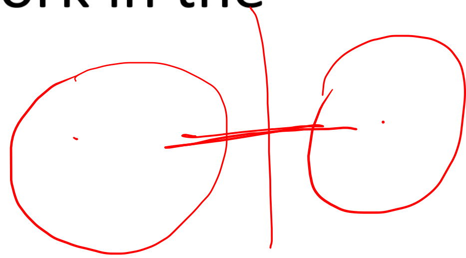
Weak consistency: Dynamo (2)

- Systems with weak consistency can have conflicting values of application state
  - Shopping cart of user has items A, B
  - User adds item C, replicated only at a minority of nodes (due to failures)
  - User adds item D, replicated at a different minority of nodes
  - When user views cart, can get back “A, B, C” or “A, B, D” or both
  - Note that this can never happen with Raft: at least one node will have seen both updates, as any two majorities will intersect
- Application can decide how to handle inconsistent values
  - Merge shopping carts to have superset of all items “A, B, C, D”
  - Trickier to merge two different versions of bank accounts



Which replication / consistency model to use?

- How to replicate, how much consistency depends on application needs
  - Online banking server may prefer a strong consistency model
  - Shopping cart server may be okay with a weaker consistency model
- In general, providing stronger consistency models requires more work in the application, and higher performance overheads
- Tradeoff between consistency and availability
  - Providing strong consistency requires contacting majority of replicas
  - What if some replicas cannot be reached, say due to network partition/failure?
  - Systems providing strong consistency will become unavailable at such times
  - Systems with weak consistency will be available but may return inconsistent results



- CAP theorem: you can get only two but not all out of (strong) Consistency, (high) Availability, (network) Partition tolerance

Summary

- In this lecture:
  - Strong and weak consistency models
  - Different ways of replication to achieve strong/weak consistency
  - Tradeoff between consistency and availability, CAP theorem
- Refer to the original papers on Raft and Dynamo:
  - "In Search of an Understandable Consensus Algorithm", Ongaro and Ousterhout.
  - "Dynamo: Amazon's Highly Available Key-value Store", DeCandia et al.