EECS 262a
Advanced Topics in Computer Systems
Lecture 24

Paxos/Megastore
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Today's Papers

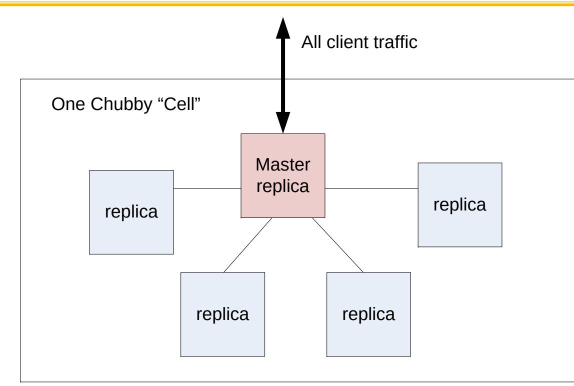
- Paxos Made Live - An Engineering Perspective, Tushar Chandra, Robert Griesemer, and Joshua Redstone. Appears in *Proceedings of the Symposium on Principles of Distributed Computing* (PODC), 2007
- Megastore: Providing Scalable, Highly Available Storage for Interactive Services, Jason Baker, Chris Bond, James C. Corbett, JJ Furman, Andrey Khorlin, James Larson, Jean Michel Léon, Yawei Li, Alexander Lloyd, Vadim Yushprakh. Appears in *Proceedings of the 5th Biennial Conference on Innovative Data Systems Research* (CIDR '11), January 2011

- Thoughts?

Google Chubby

- A *coarse-grained lock and small file storage service*
  – Other (Google) distributed systems can use this to synchronize access to shared resources
- Intended for use by "loosely-coupled distributed systems"
  – GFS: Elect a master
  – Bigtable: master election, client discovery, table service locking
  – Well-known location for bootstrapping larger systems
  – Partitioning workloads
- Goals:
  – High availability
  – Reliability
- Anti-goals:
  – High performance, Throughput, Storage capacity

Distributed Consensus



- Chubby cell is usually 5 replicas
  – 3 must be alive for cell to be viable
- How do replicas in Chubby agree on their own master, official lock values?
  – Distributed commit algorithm

What about Two Phase Commit?

- Commit request/Voting phase
  - Coordinator sends query to commit
  - Cohorts prepare and reply – single abort vote causes complete abort
- Commit/Completion phase
  - Success: Commit and acknowledge
  - Failure: Rollback and acknowledge
- Disadvantage: Blocking protocol
  - Handles coordinator failures really poorly – blocks
  - Handles cohort failure poorly during voting phase – aborts

Basic Paxos (Quorum-based Consensus)

- Prepare and Promise
  - Proposer selects proposal number N and sends promise to acceptors
  - Acceptors accept or deny the promise
- Accept! and Accepted
  - Proposer sends out value
  - Acceptors respond to proposer and learners
- Paxos algorithm properties
  - Family of algorithms (by Leslie Lamport) designed to provide *distributed consensus* in a **network** of several **replicas**
  - Enables reaching consensus on a single binding of variable to value (“fact”)
  - Tolerates delayed or reordered messages and replicas that fail by stopping
  - Tolerates up to N/2 replica failure (*i.e.*, *F* faults with *2F+1* replicas)

Message Flow: Basic Paxos

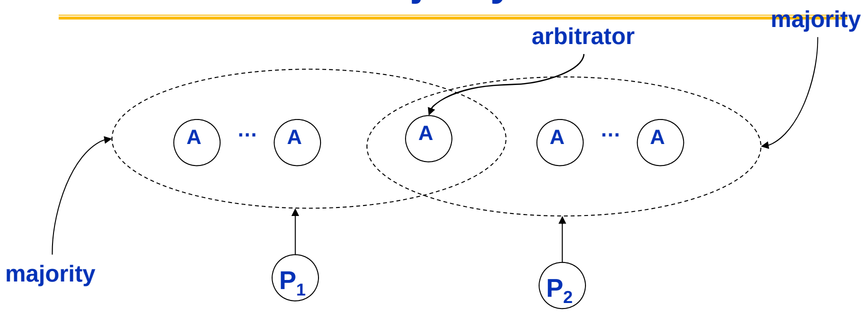
- Proposer – An agent that proposes a fact
- Leader – the authoritative proposer
- Acceptor – holds agreed-upon facts in its memory
- Learner – May retrieve a fact from the system

```
• Client   Proposer      Acceptor     Learner
•    |         |          |  |  |       |  |
•    X-------->|          |  |  |       |  |  Request
•    |         X--------->|->|->|       |  |  Prepare(N)
•    |         |<---------X--X--X       |  |
  Promise(N,{V_a,V_b,V_c})
•    |         X--------->|->|->|       |  |  Accept!(N,V_n)
•    |         |<---------X--X--X------>|->|  Accepted(N,V_n)
•    |<---------------------------------X--X  Response
```


Paxos Assumptions

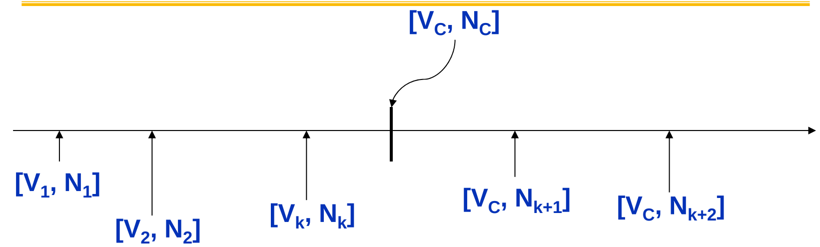
- Replica assumptions
  - Operate at arbitrary speed
  - Independent, random failures
  - Replicas with stable storage may rejoin protocol after failure
  - Do not lie, collude, or attempt to maliciously subvert the protocol
- Network assumptions
  - All processors can communicate with (“see”) one another
  - Messages are sent asynchronously and may take arbitrarily long to deliver
  - Order of messages is not guaranteed: they may be lost, reordered, or duplicated
  - Messages, if delivered, are not corrupted in the process

Basic Paxos – Majority consensus



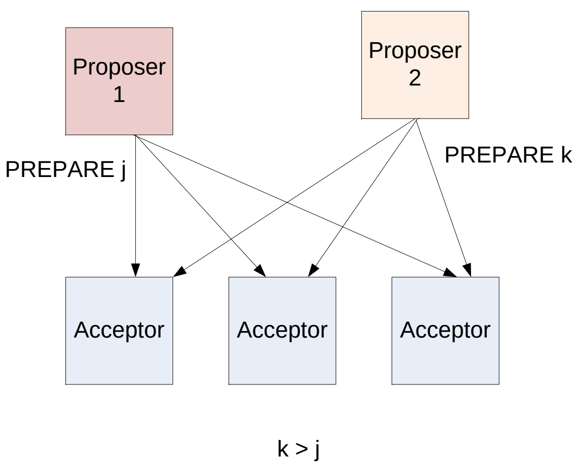
- Determines the authoritative value for a single variable
- Each proposer makes a proposal to some majority (quorum) of the acceptors; acceptors respond with latest value
- A majority (quorum) of acceptors must accept a proposal for the proposed value to be chosen as the consensus value
- If P_1 and P_2 are making different proposals, then there must be at least one acceptor that they share in common – this common acceptor decides which proposal prevails

Choosing a value



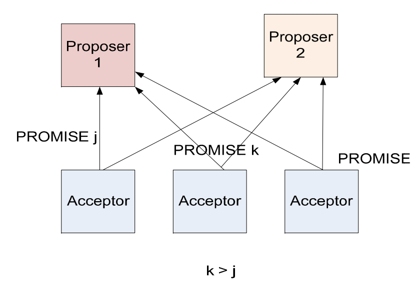
- Since different proposers (leaders) may be proposing at same time, protocol uses disjoint proposal numbers (e.g. put identity in LSB)
- An acceptor will accept proposal with largest proposal number
- A value is chosen once majority (quorum) of acceptors have accepted a proposal with that value
- During failed rounds (not majority acceptance), responding acceptors keep track of their previous “votes” to help protocol converge on single value – even in presence of multiple proposers (leaders)

Step 1: Prepare

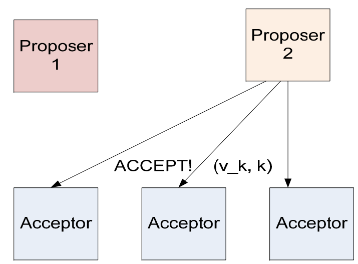


Step 2: Promise

- PROMISE x – Acceptor will accept proposals only numbered *x* or higher
- Proposer 1 is *ineligible* because a quorum has voted for a higher number than *j*

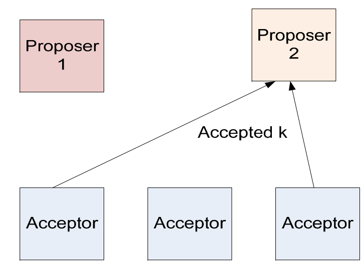


Step 3: Accept!



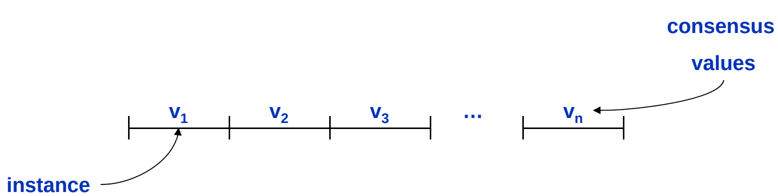
Proposer 1 is disqualified; Proposer 2 offers a value

Step 4: Accepted



A quorum has accepted value v_k; it is now a fact

MultiPaxos

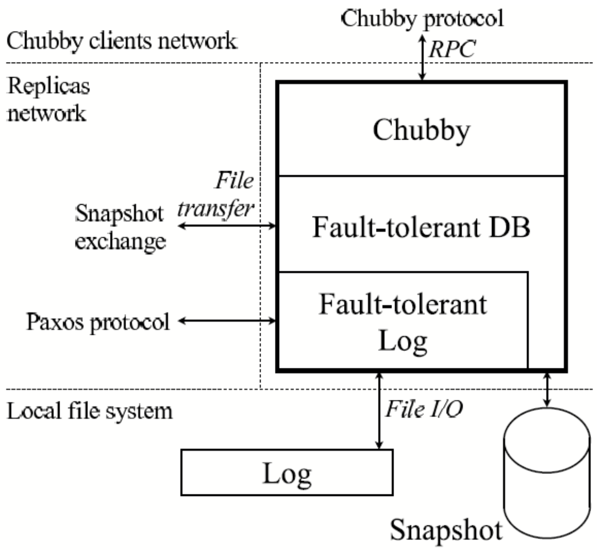


- Within each instance (basic) Praxos is used to arrive at a consensus of the value to be used by all replicas
- The sequence of instances determines a sequence of values accepted by all replicas

Paxos in Chubby

- MultiPaxos:
  - Steps 1 (*prepare*) and 2 (*promise*) done once
  - Steps 3 (*accept!*) and 4 (*accepted*) repeated multiple times by same leader
- Replicas in a cell initially use Paxos to establish the leader
  - Majority of replicas must agree
- Optimization: Master Lease
  - Replicas promise not to try to elect new master for at least a few seconds
  - Master lease is periodically renewed
- Master failure
  - If replicas lose contact with master, they wait for grace period (4-6 secs)
  - On timeout, hold new election

Architecture



From Theory to Practice: Fault-tolerant LOG implement with Paxos

- Disk Corruption
  - Need to recognize and handle subtle corruption in stable state
- Use of Master Leases
  - Grant leadership for fixed period of time
  - Allows clients to read latest value from Master
  - Prevents inefficient oscillation in algorithm
- Use of Epochs
  - Recognize when leader changes
  - Chubby semantics requires abort in these circumstances
- Group membership
  - Use of Paxos protocol to select servers that are members of Paxos group
- Snapshot integration with Paxos
- MultiOp
  - Allows implementation of atomic operations on log
  - If (guard[database]) then {t_op} else {f_op}

Building a Correct System

- Simple one-page pseudocode for Paxos algorithm == thousands of lines of C++ code
  - Created simple state machine specification language and compiler
  - Resulting code is "Correct by construction"
- Aggressive testing strategy
  - Tests for *safety* (consistent) and *liveness* (consistent and making progress)
  - Added entry points for test harnesses
  - Reproducible simulation environment
    - » Injection of random errors in network and hardware
    - » Use of pseudo-random seed provided reproducibility
- Data structure and database corruption
  - Aggressive, liberal usage of `assert` statements (makes Chubby fail-stop)
  - Added lots of checksum checks
- Upgrades and rollbacks are hard
  - Fix buggy scripts!
  - Recognize differences between developers and operators
- Forced to "add concurrency" as project progressed

Reliability

- Started out using replicated Berkeley DB ("3DB")
  - Ill-defined, unproven, buggy replication protocol
- Replaced with custom write-thru logging DB
- Entire database periodically sent to GFS
  - In a different data center
- Chubby replicas span multiple racks

Summary

- Simple protocols win again
- Reuse of functionality
  - Chubby uses GFS
  - GFS uses Chubby
- Many challenges going from theoretical algorithm to practical implementation
  - No tools for implementing fault-tolerant protocols
  - Test, test, and test again (critical component!)
  - Everything can be corrupted so checksum everything
  - People are fallible (so are scripts!)

Is this a good paper?

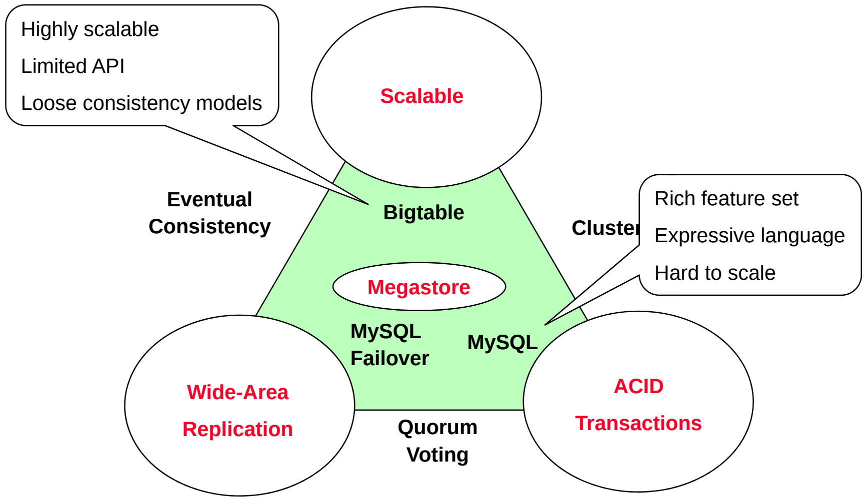
- What were the authors' goals?
- What about the evaluation/metrics?
- Did they convince you that this was a good system/approach?
- Were there any red-flags?
- What mistakes did they make?
- Does the system/approach meet the "Test of Time" challenge?
- How would you review this paper today?

BREAK

Google Megastore – Motivation

- Storage requirements of today's interactive online applications
  - Scalability (a billion internet users)
  - Rapid Development
  - Responsiveness (low latency)
  - Durability and Consistency (never lose data)
  - Fault Tolerant (no unplanned/planned downtime)
  - Easy Operations (minimize confusion, support is expensive)
- These requirements are in conflict!

Technology Options



Megastore

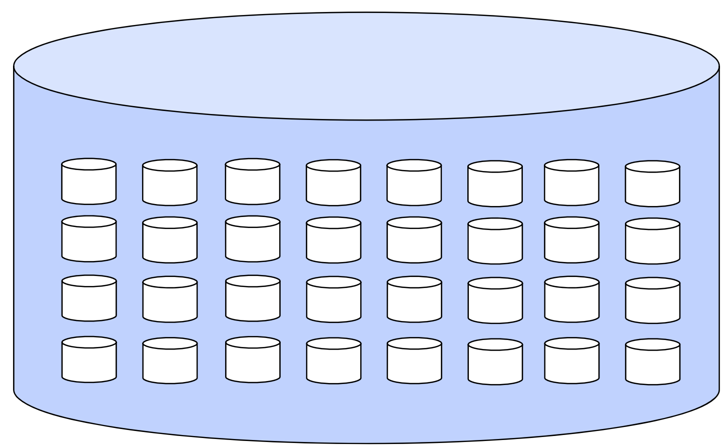
- Started in 2006 for app development at Google
- Service layered on:
  - Bigtable (NoSQL scalable data store per datacenter)
  - Chubby (Config data, config locks)
- Turnkey scaling (apps, users)
- Developer-friendly features
- Wide-area synchronous replication
  - Partition by “Entity Group”

Data Model

- Between abstract tuples of RDBMS and concrete row-column storage of NoSQL
- Tables are *entity group root tables* or *child tables*
- Entity Group – consists of a *root entity* along with all *child entities*
- There can be several root tables – leading to several classes of *Entity Groups*

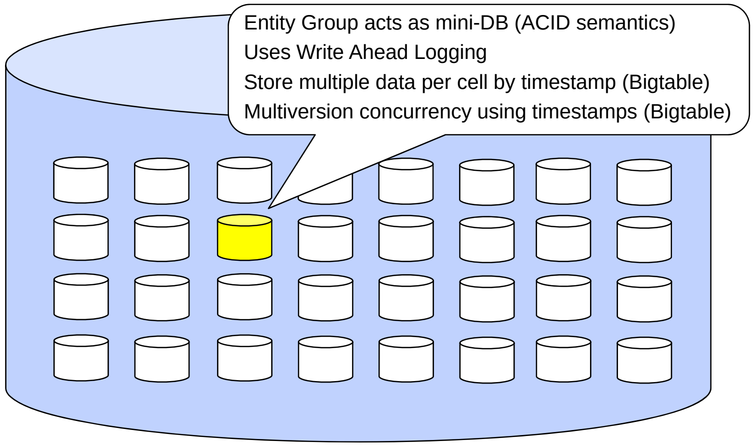
Entity Groups

- Entity groups are sub-databases



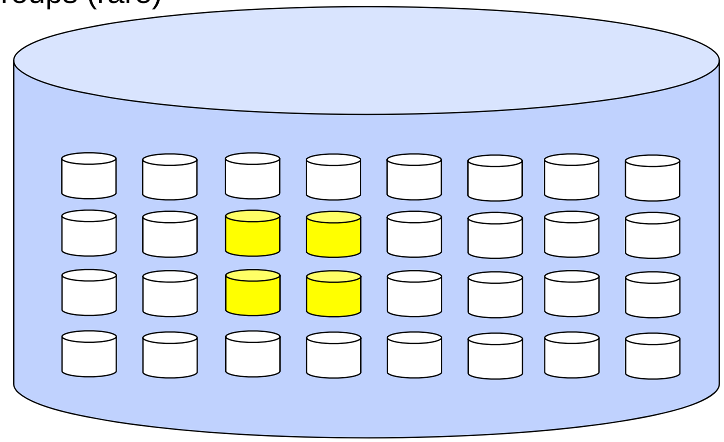
Entity Groups

- Cheap transactions within an entity group (common)



Entity Groups

- Expensive or loosely-consistent operations across Entity Groups (rare)

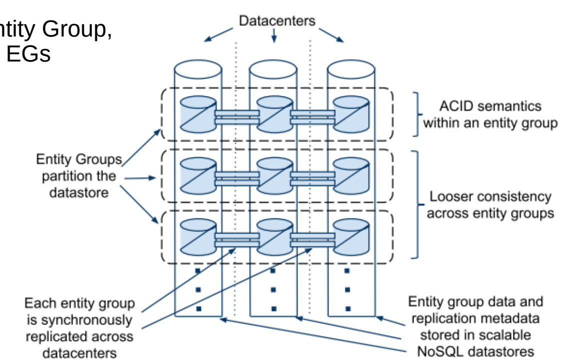


Entity Group Examples

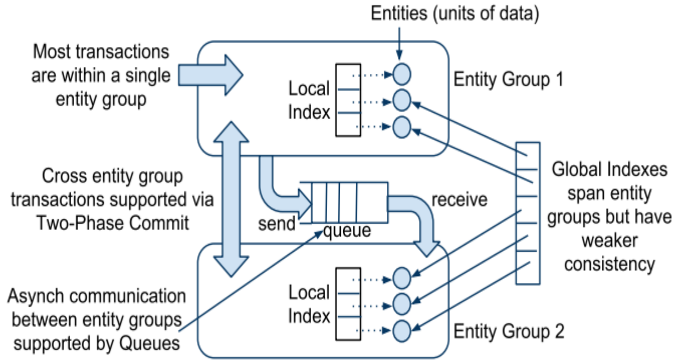
Application	Entity Groups	Cross-EG Ops
Email	User accounts	none
Blogs	Users, Blogs	Access control, notifications, global indexes
Mapping	Local patches	Patch-spanning ops
Social	Users, Groups	Messages, relationships, notifications
Resources	Sites	Shipments

Achieving Technical Goals (I)

- Scalability
  - Bigtable within datacenters – easy to add EGs (storage, throughput)
  - Performance maximized by partitioning based on EGs
  - Transactions within an EG – single phase using Paxos
  - Transactions across entity groups – two phase using Asynchronous Message Queue
  - Indexes – ACID within Entity Group, Looser semantics across EGs
- Availability
  - Fault Tolerance through replication
  - Fault Tolerant log replication of logs (adapted from Paxos)



Achieving Technical Goals (II)



- ACID transactions
  - Write-ahead log per Entity Group
  - 2PC or Queues between Entity Groups
- Wide-Area replication
  - Paxos with tweaks for optimal latency

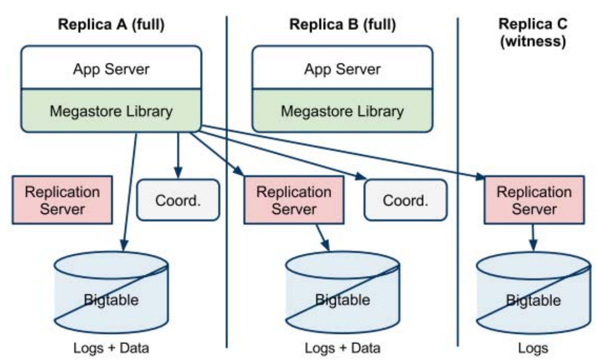
Paxos and Megastore

- Basic Paxos not used (poor match for high-latency links)
  - Writes require at least two inter-replica roundtrips to achieve consensus (prepare round, accept round)
  - Reads require one inter-replica roundtrip (prepare round)
- Approaches using a Master replica
  - Master participates in all writes (state is always up-to-date)
  - Master serves reads (current consensus state) *without additional comm*
  - Writes are single roundtrip – piggyback *prepare* for next write on *accepted*
  - Batch writes for efficiency
- Issues with using a Master
  - Need to place transactions (readers) near master replica to avoid latency
  - Master must have sufficient processing resources (side effect: replicas waste resources since they must be capable of becoming masters)
  - Master failover requires lots of timers and a complex state machine (side effect: user visible outages)

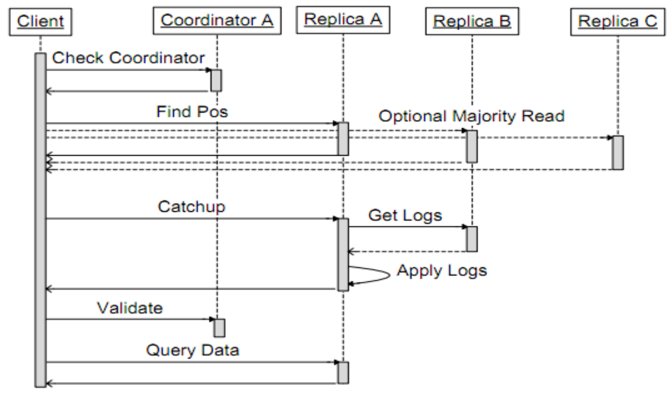
Megastore's Tweaks

- Coordinators
  - Tracks set of entity groups for which its replica has observed all Paxos writes
- Fast Reads
  - Local reads from *any* replica avoid inter-replica RPCs
  - Yield better utilization, low latencies in all regions, fine-grained read failover, simpler programming experience
- Fast Writes
  - Uses same pre-preparing optimization as Master approaches (*accepted* implies next *prepare*)
  - Uses leaders (*coordinators*) instead of masters and runs a Paxos instance for each log position – leader arbitrates which writer succeeds
- Replica Types
  - *Witness Replicas*: participate in voting (tie-breakers) and store log entries (no data)
  - *Read-only Replicas*: non-voting replicas containing snapshots

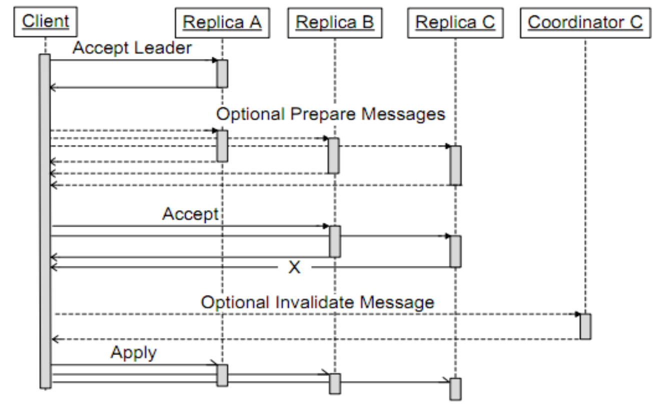
Megastore Architecture



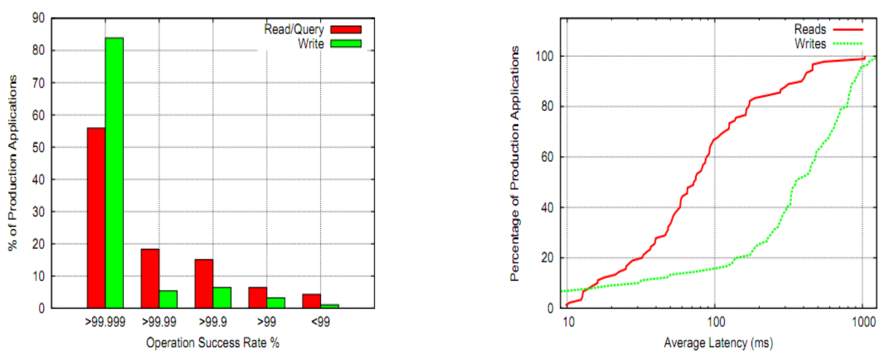
Megastore Reads



Megastore Writes



Availability and Performance



Benefits

- For admins
  - Linear scaling, transparent rebalancing (Bigtable)
  - Instant transparent failover
  - Symmetric deployment
- For developers
  - ACID transactions (read-modify-write)
  - Many features (indexes, backup, encryption, scaling)
  - Single-system image makes code simple
  - Little need to handle failures
- For end Users
  - Fast up-to-date reads, acceptable write latency
  - Consistency

Summary

- Constraints acceptable for most apps
  - Entity Group partitioning
  - High write latency
  - Limited per-EG throughput
- In production use for over 4 years
- No current query language
  - Apps must implement query plans
  - Apps have fine-grained control of physical placement
- Available on Google App Engine as HRD (High Replication Datastore)

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