Spanner: Google's Globally-Distributed Database

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What is Spanner?

- Google's scalable, multi-version, globally-distributed, and synchronously-replicated database
    - SQL Query Language
    - General-purpose transactions (ACID)
    - Schematized tables
    - Semi-relational data model

Why Spanner?

- Bigtable (OSDI 2006)
  - Difficult to use for complex, evolving schemas and by applications that requires strong consistency guarantees for geo-replicated sites.

- Megastore (CIDR 2011)
  - Layered on top of Bigtable
  - Provides semi-relational data model and similar schema language to Spanner's
  - Bad write throughput (e.g., does not support long-lived leaders)

Linearizability and Serializability

- **Linearizability**: Guarantee for a single operation on a single object
  - Writes should be appear instantaneously ; All later reads as defined by wall-clock time (i.e., real-time) reflect the written value or some latter written value
  - “C” in CAP theorem
- **Serializability**: Guarantee for transactions, or one or more operations on one or more objects
  - A set of transactions over some objects should execute as though each transaction ran in some serial order (doesn’t specify which order)
  - “Isolation” in ACID properties
- **Linearizability + Serializability = Strict Serializability**
  - Transactions have some serial behavior which corresponds to wall-clock time

Consistency Properties

- **Serializable** transaction isolation
- **Linearizable** reads and writes
- Atomic commit of transactions across shards
  - Each shard holds a subset of the data

- Spanner's techniques
  - State machine replication (Paxos) within a shard
  - Two-phase locking (2PL) for serializability
  - Two-phase commit (2PC) for cross-shard atomicity

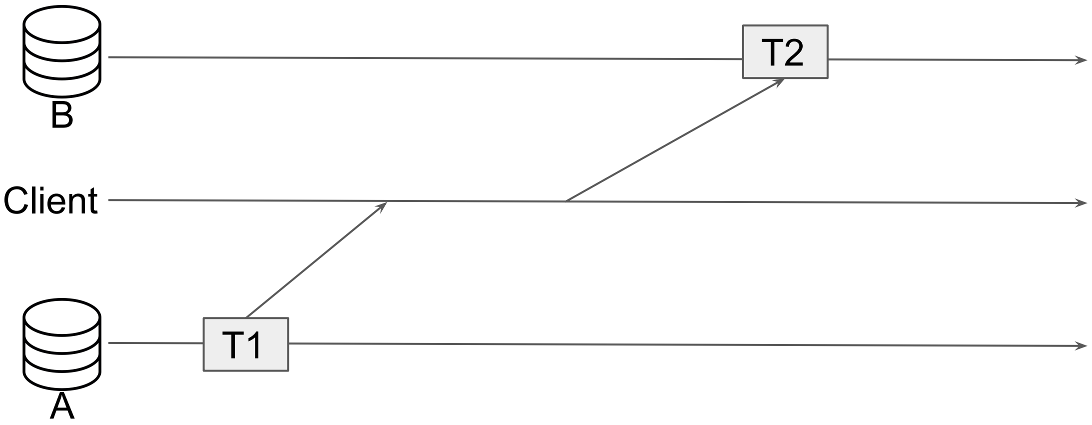
Lock-free read-only transactions

- Spanner guarantees a read-only transactions observes a consistent snapshot:
  - If $T_1 \rightarrow T_2$, snapshot reflects writes by T_2 also reflects writes by T_1 and snapshot that does not reflect writes by T_1 does not reflect writes by T_2
  - Snapshot is **consistent with causality**

- Spanner's approach:
  - Each read-write transaction T_w is assigned a commit timestamp t_w
  - Every value is tagged with the timestamp of corresponding transaction
  - Read-only transaction T_r is assigned a timestamp t_r
  - T_r contains values with $t_w \leq t_r$ but ignores values with $t_w > t_r$

Timestamps

- Can we use physical clocks?
  - No, Inconsistent with causality
- Can we use Lamport clocks?
  - No, Linearizability depends on real-time order, but Lamport clocks may not reflect this



TrueTime API & Implementation

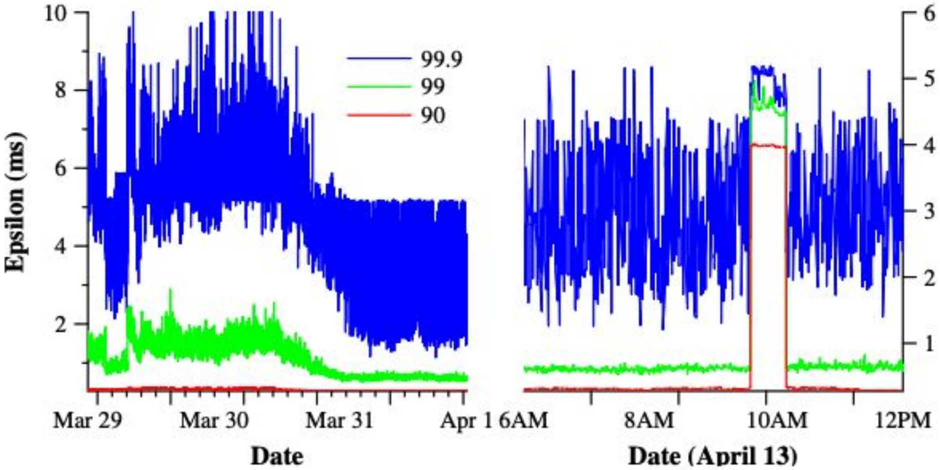
- TrueTime is a global synchronized clock with bounded non-zero error.

Method	Returns
$TT.now()$	$TTinterval$: $[earliest, latest]$
$TT.after(t)$	true if t has definitely passed
$TT.before(t)$	true if t has definitely not arrived

- TrueTime uses GPS and atomic clocks for time references.
    - Each datacenter has a set of **time master** machines:
        - **GPS time master:** physically separated GPS receivers with dedicated antennas.
        - **Armageddon time master:** equipped with atomic clocks.
    - Every machine has a **timeslave daemon**, who polls a variety of time masters to reduce vulnerability from any one master.

TrueTime API & Implementation

- Daemon advertises a slowly increasing time uncertainty ϵ.
  - Reset to 0ms at every poll. Poll happens every 30s.
  - Conservatively applied worst case clock drift (200μs/s).
    - Bad CPUs are 6 times more likely than bad clocks (exceeding 200μs/s).
  - ϵ also depends on time-master uncertainty and communication delay to time masters.

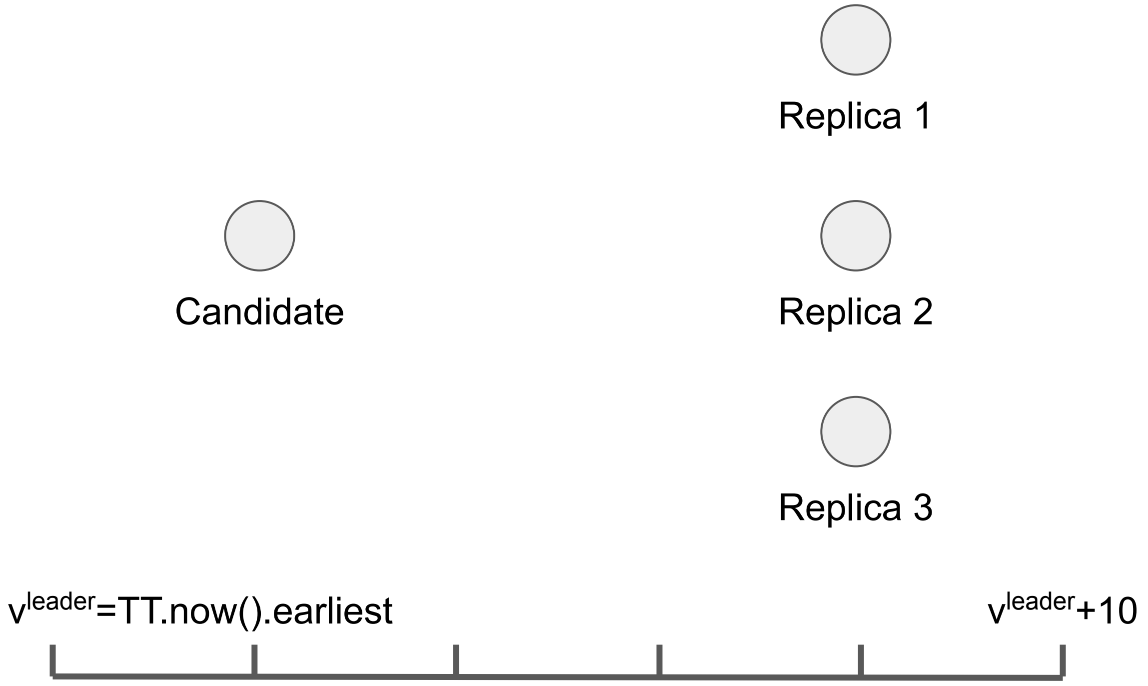


How does Spanner use TrueTime?

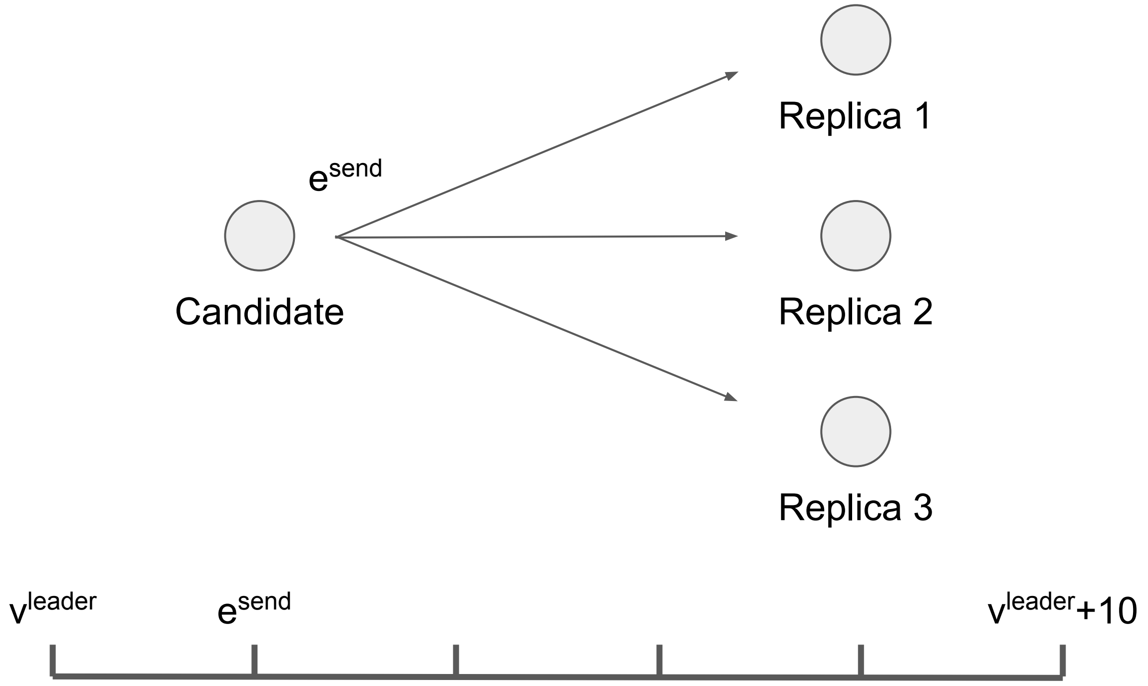
- Paxos Leader Lease Disjointness Invariant
  - For each Paxos group, each Paxos leader's lease interval is disjoint from every other leader's.
- External Consistency Invariant
  - If the start of a transaction *T2* occurs after the commit of a transaction *T1*, then the commit timestamp of *T2* must be greater than the commit timestamp of *T1*.

Paxos Leader Leases

Paxos Leader Leases



Paxos Leader Leases



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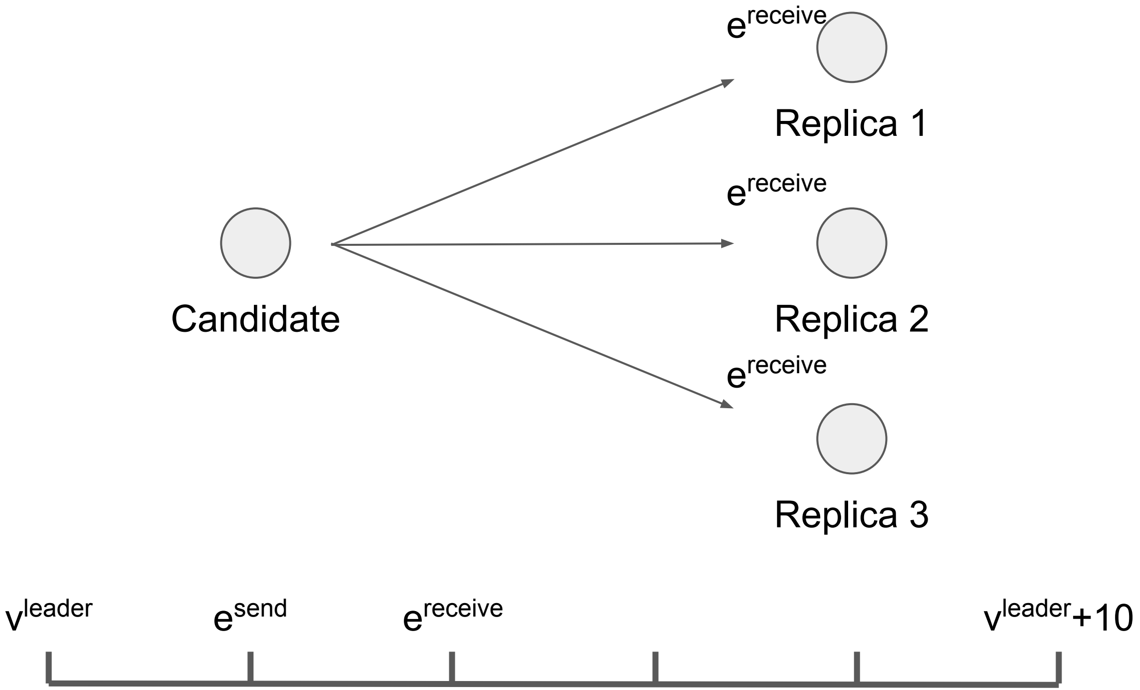

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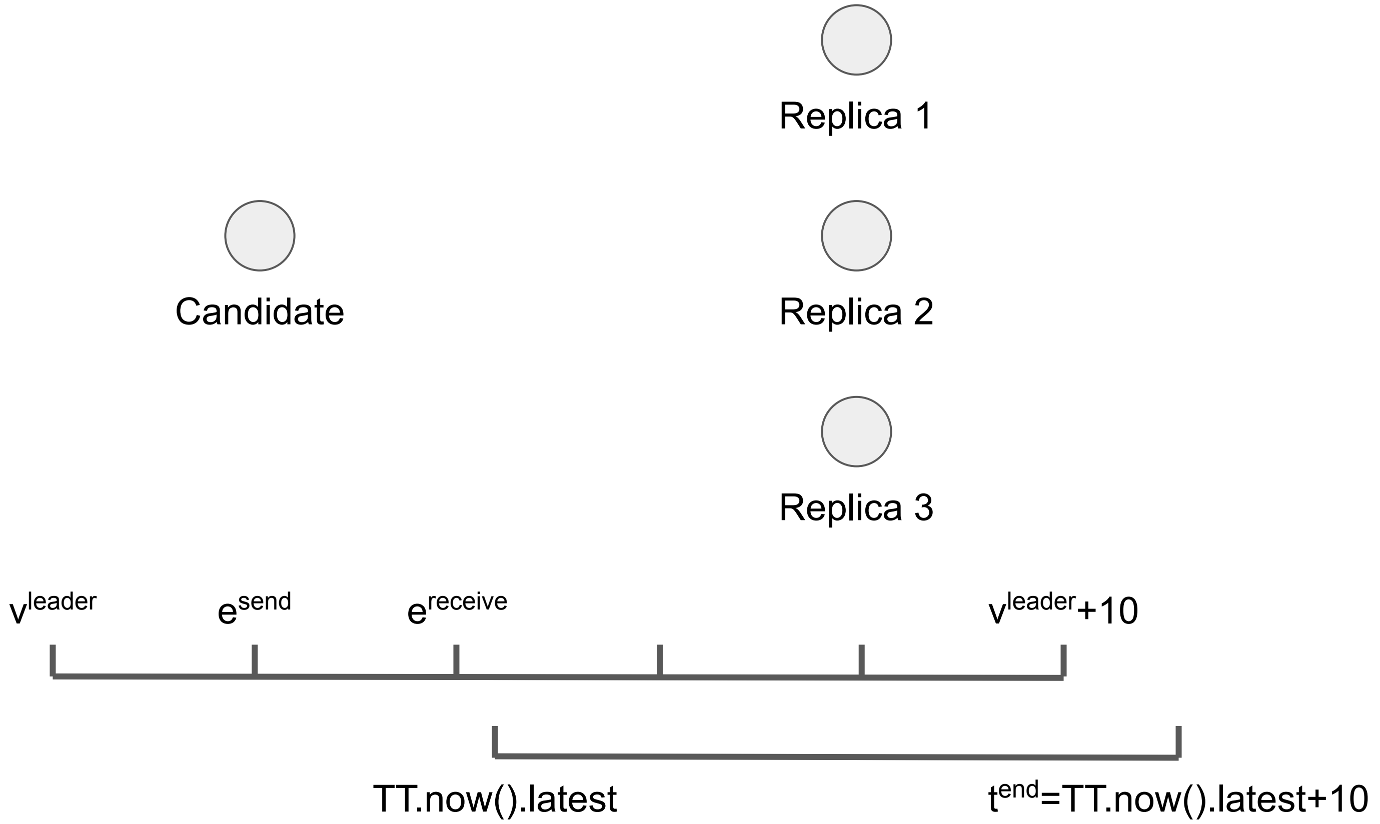

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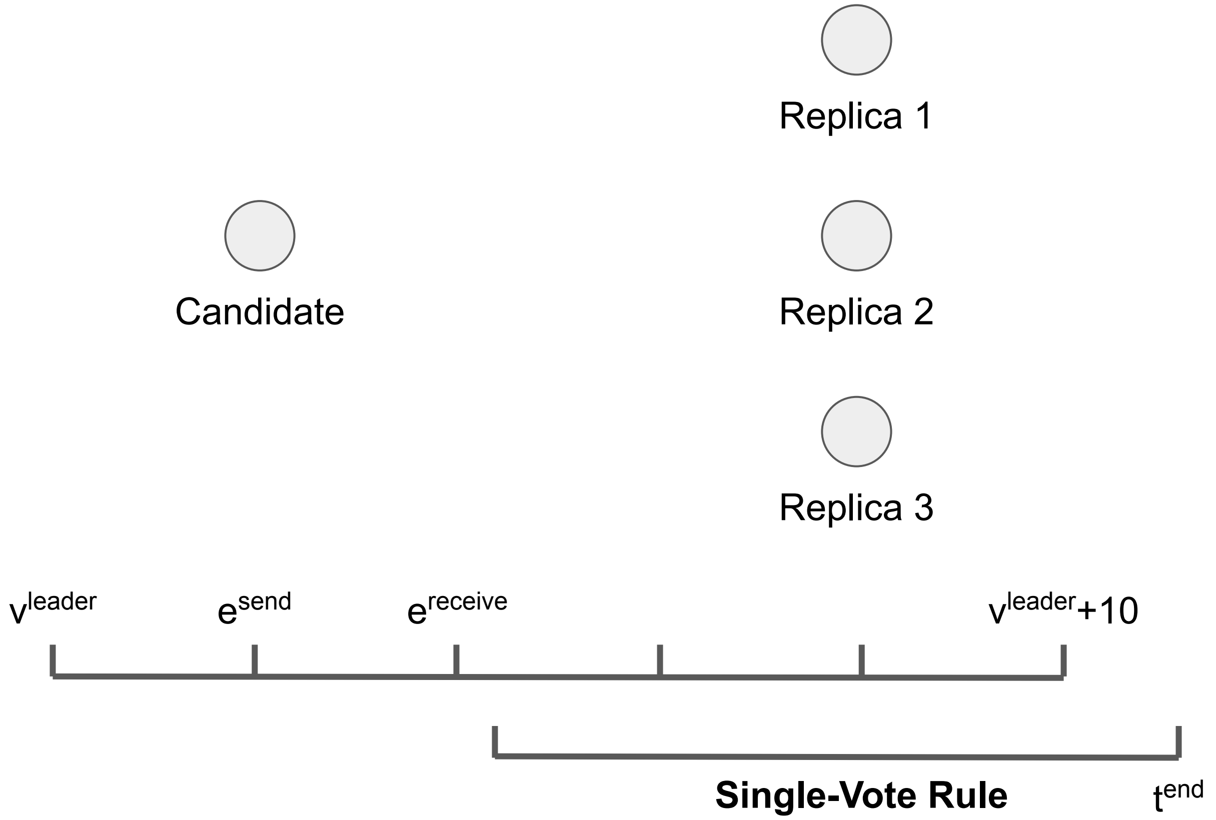

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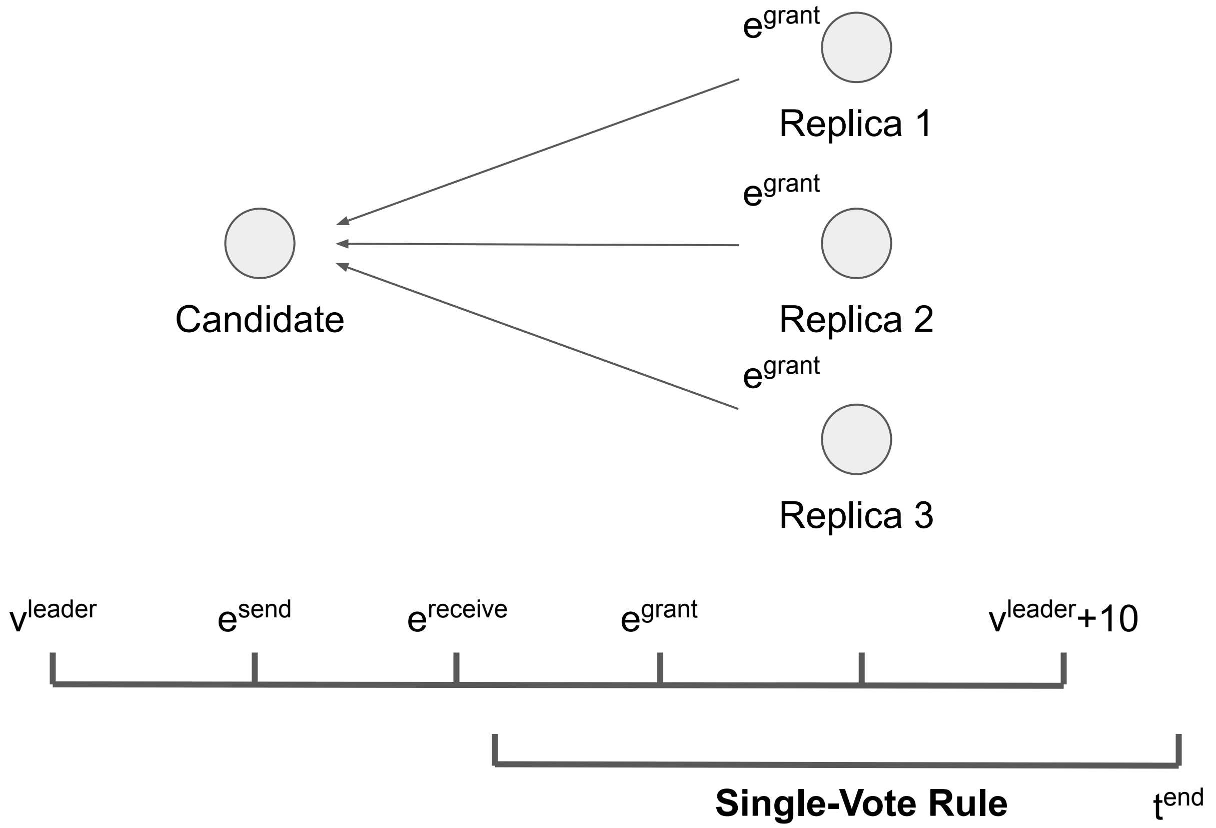

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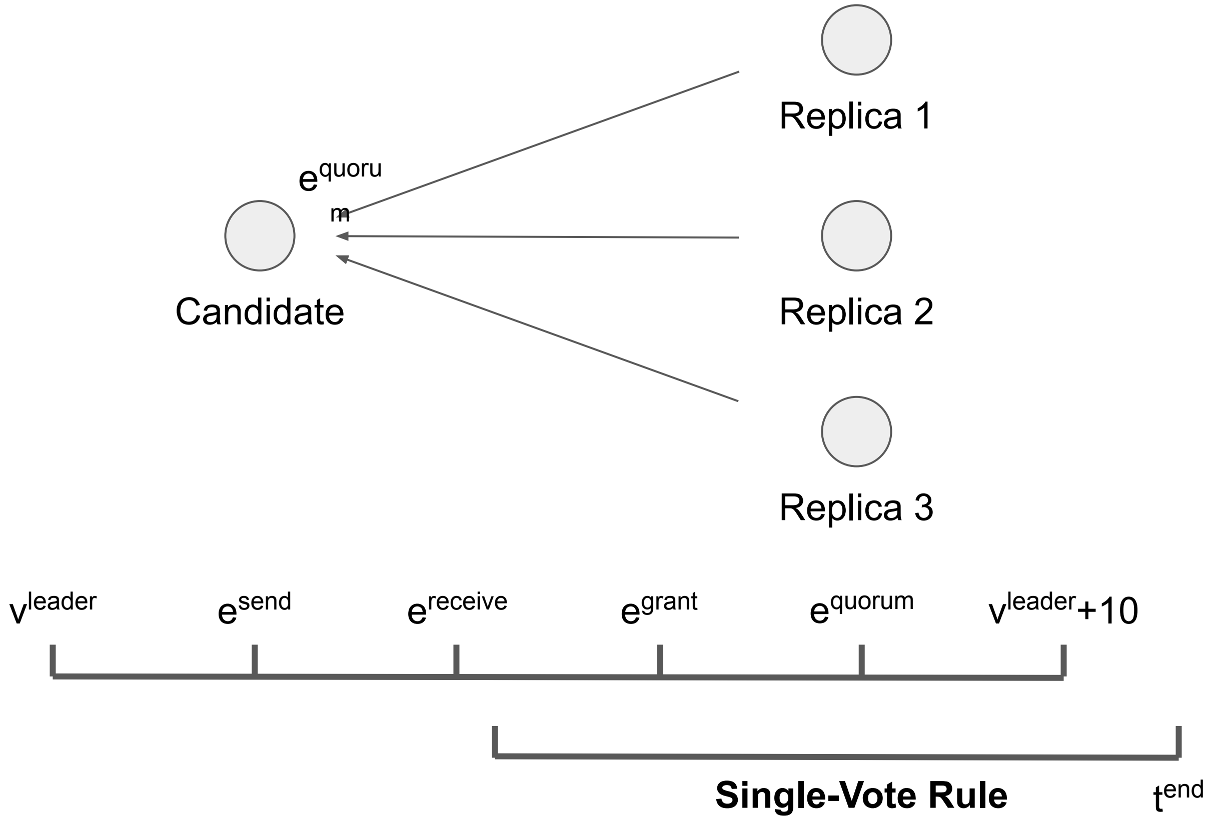
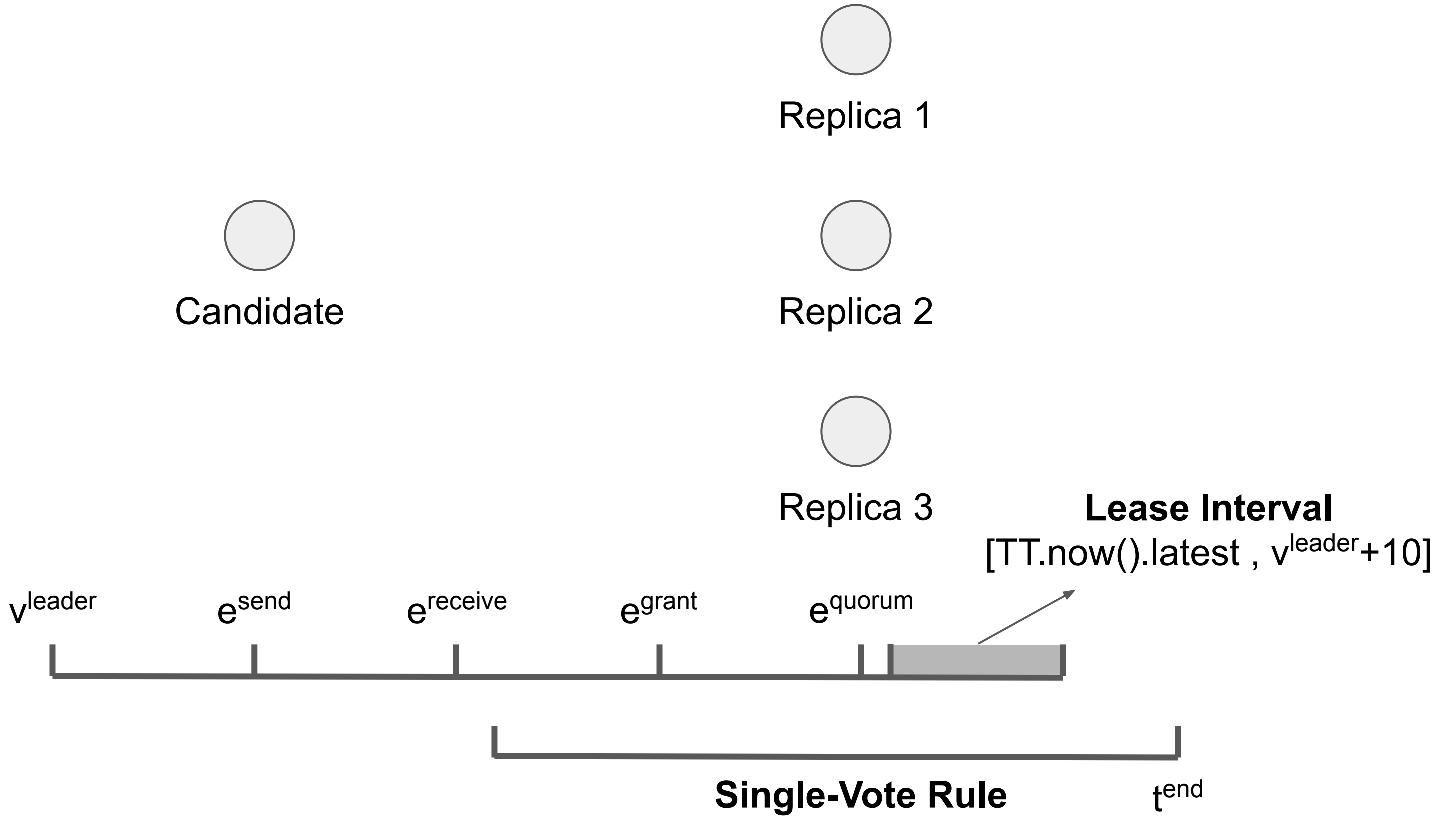
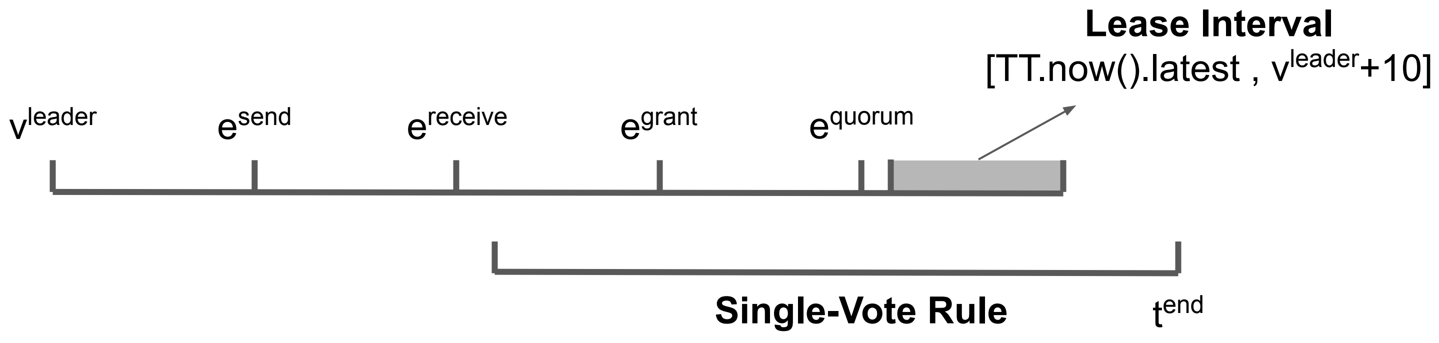


Paxos Leader Leases



Paxos Leader Leases

- The lease interval is contained in the single-vote rule interval.
- If another participant wants to be the leader, in order to hit the quorum, it needs the vote of at least one replica who voted for the previous candidate.
- The lease interval of another leader must be disjoint from the single-vote rule interval.
- Lease intervals of different leaders must be disjoint.



External Consistency Invariant

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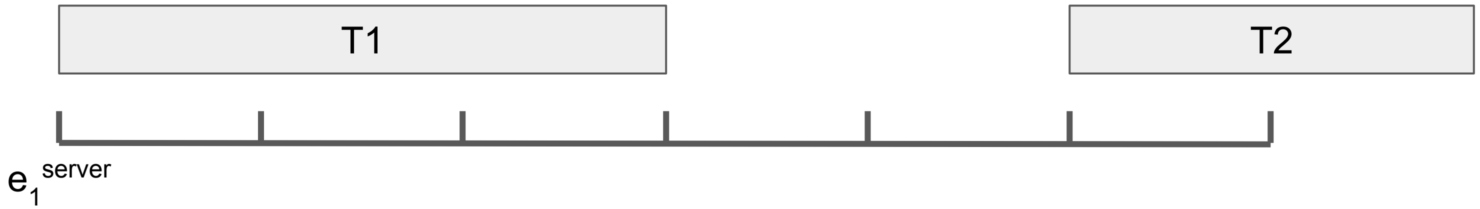

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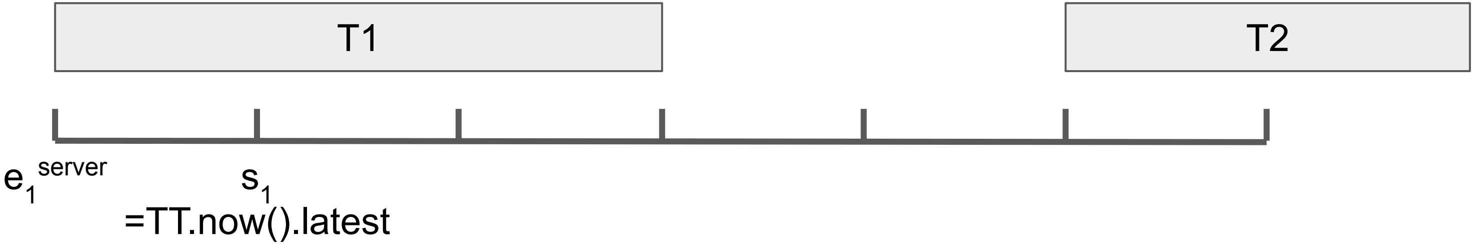

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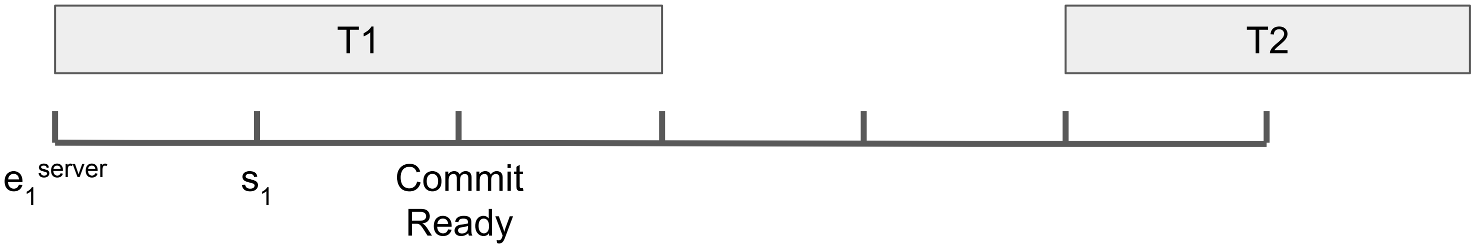

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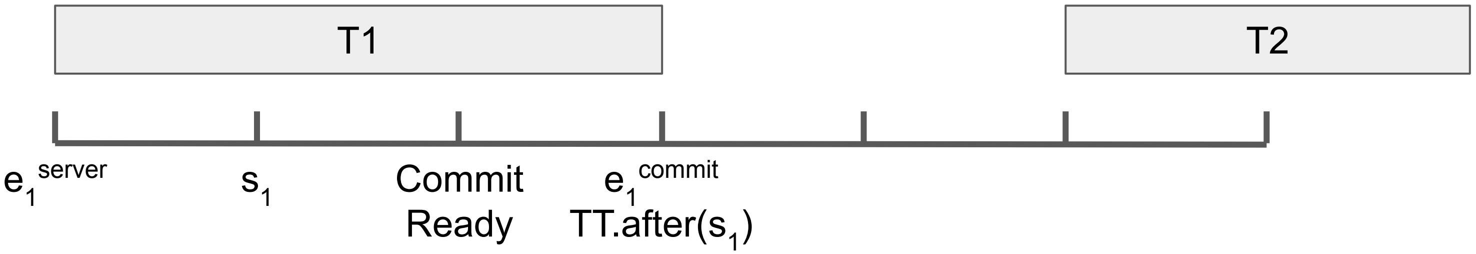

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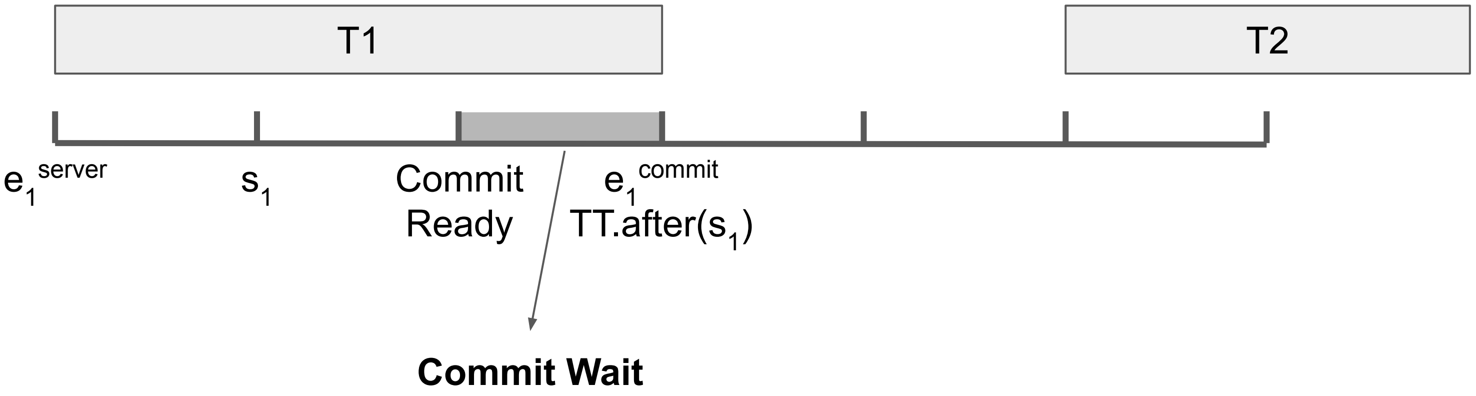

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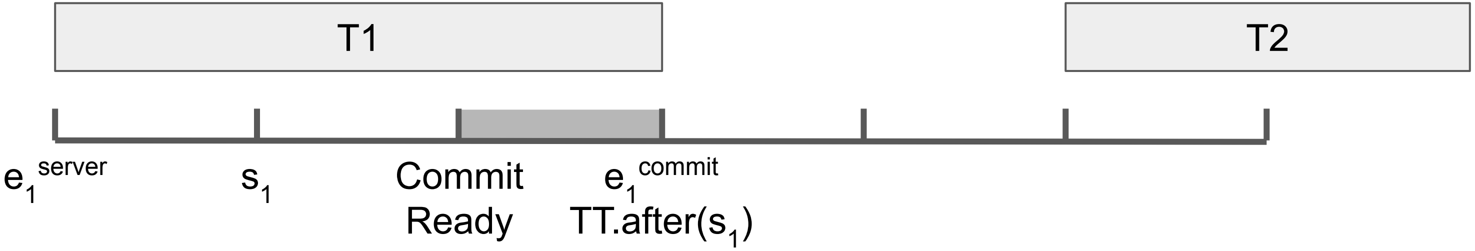
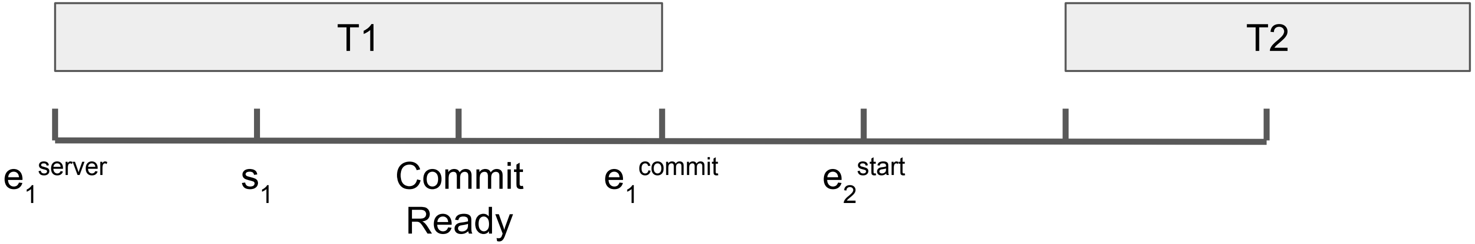


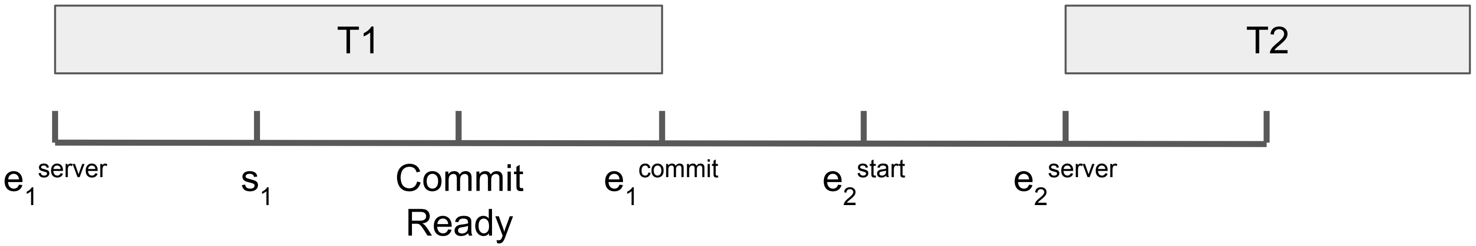
$s_1 < e_1^{commit}$

External Consistency Invariant



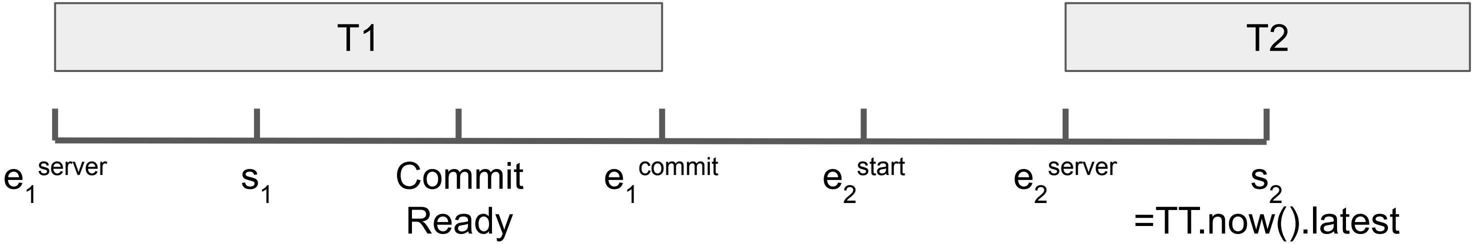
$$s_1 < e_1^{commit} < e_2^{start}$$

External Consistency Invariant



$$s_1 < e_1^{commit} < e_2^{start} < e_2^{server}$$

External Consistency Invariant



$$s_1 < e_1^{commit} < e_2^{start} < e_2^{server} < s_2$$

Discussion

- Why is Paxos leader lease disjointness invariant necessary?
  - Invariant: *for each Paxos group, each Paxos leader's lease interval is disjoint from every other leader's.*
- How does external consistency invariant guarantee external consistency?
  - Invariant: *if the start of a transaction T2 occurs after the commit of a transaction T1, then the commit timestamp of T2 must be greater than the commit timestamp of T1.*
- What are the benefits and drawbacks of TrueTime?

QR Code to Discussion Doc

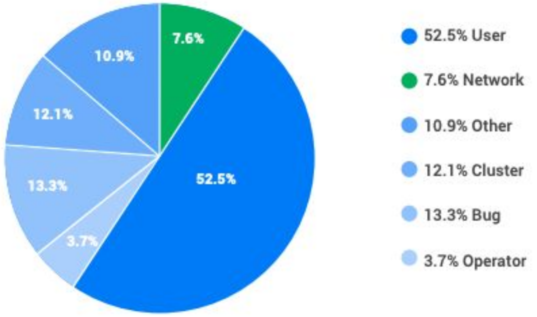
Spanner and CAP Theorem

- CAP Theorem
  - Consistency, 100% availability, partition tolerance

- Is Spanner a CP system or a AP system?
  - Answer: CP - during partitions, Spanner chooses C and forfeits A.
- What design choices make Spanner a CP system?
  - Use of Paxos group to achieve consensus on update - if the leader cannot maintain a quorum due to a partition, updates are stalled and the system is not available
  - Use of two-phase commit for cross-group transactions means partition can prevent commits

Availability of Spanner

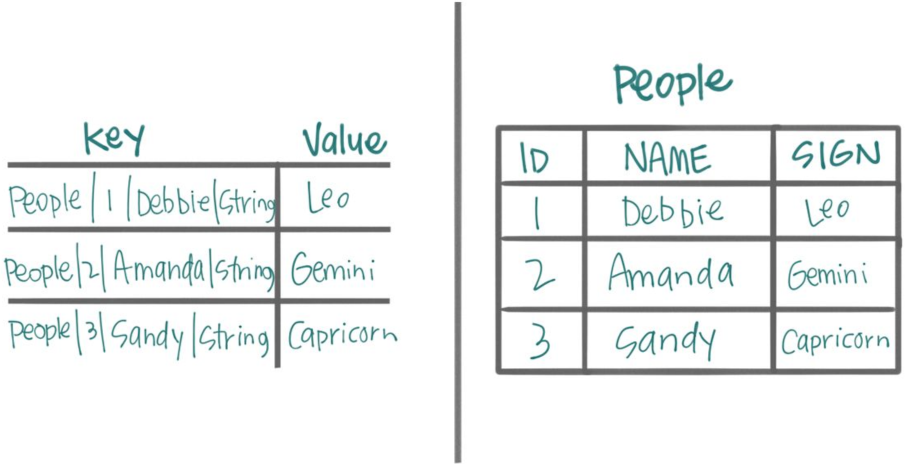
- Spanner provides 99.999% availability (five "9"s)
  - Chubby paper reports 9 outages of 30 seconds in 700 days[1]
- Spanner runs on Google's own private global network
  - Every Spanner packet flows only over Google-controlled routers and links
  - Each data center has at least three independent fibers
  - Redundancy of equipment and paths within a datacenter



[1]The Chubby lock service for loosely-coupled distributed systems - Burrows, OSDI '06

Dynamo: Amazon's Highly Available Key-value Store

- Query Model: simple read and write operations to a data item (uniquely identified by a key)



Credit: Jowanza Joseph

Dynamo: Amazon’s Highly Available Key-value Store

- Query Model: simple read and write operations to a data item (uniquely identified by a key)
- ACID Properties:
  - Provide weaker consistency guarantees - Eventual Consistency
  - No Isolation guarantees and permits only single key updates
- Choose “A” over “C”

Dynamo's Techniques

Problem	Technique	Advantage
Partitioning	Consistent Hashing	Incremental Scalability
High Availability for writes	Vector clocks with reconciliation during reads	Version size is decoupled from update rates.
Handling temporary failures	Sloppy Quorum and hinted handoff	Provides high availability and durability guarantee when some of the replicas are not available.
Recovering from permanent failures	Anti-entropy using Merkle trees	Synchronizes divergent replicas in the background.
Membership and failure detection	Gossip-based membership protocol and failure detection.	Preserves symmetry and avoids having a centralized registry for storing membership and node liveness information.

Table 1 presents a summary of the list of techniques Dynamo uses and their respective advantages.

Hybrid Logical Clocks(HLC)

- Motivation:
  - No perfectly synchronized physical clock (NTP can introduce 100-250ms clock drift)
  - Logical Clocks does not capture relationship between events in real-time
  - TrueTime requires special hardware and tight clock synchronization protocol

Hybrid Logical Clocks(HLC)

- HLC: combines the benefits of logical clock and physical time
  - One-way causality detection
  - Linear space representation
  - Bounded difference from physical time

Initially $l.j := 0; c.j := 0$

Send or local event

$l'.j := l.j;$
$l.j := max(l'.j, pt.j);$
If $(l.j = l'.j)$ then $c.j := c.j + 1$
Else $c.j := 0;$
Timestamp with $l.j, c.j$

Receive event of message m

$l'.j := l.j;$
$l.j := max(l'.j, l.m, pt.j);$
If $(l.j = l'j = l.m)$ then $c.j := max(c.j, c.m) + 1$
Elseif $(l.j = l'.j)$ then $c.j := c.j + 1$
Elseif $(l.j = l.m)$ then $c.j := c.m + 1$
Else $c.j := 0$
Timestamp with $l.j, c.j$

Figure 5: HLC algorithm for node j

pt.j denotes the physical time at node j

Hybrid Logical Clocks(HLC)

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References

- The Chubby lock service for loosely-coupled distributed systems (OSDI '06)
- Bigtable: A Distributed Storage System for Structured Data (OSDI '06)
- Dynamo: Amazon's Highly Available Key-value Store (SOSP '07)
- Logical Physical Clocks and Consistent Snapshots in Globally Distributed Databases
- Spanner, TrueTime & The CAP Theorem by Eric Brewer
- Cloud Spanner: TrueTime and external consistency