# Spanner

COS 418: Distributed Systems
Lecture 17

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Some slides from the Spanner OSDI talk

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## Recap: Distributed Storage Systems

- Concurrency control
  - Order transactions across shards
- State machine replication
  - Replicas of a shard apply transactions in the same order decided by concurrency control

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## Google's Setting

- Dozens of datacenters (zones)
- Per zone, 100-1000s of servers
- Per server, 100-1000 shards (tablets)
- Every shard replicated for fault-tolerance (e.g., 5x)

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## Why Google Built Spanner

2005 – BigTable [OSDI 2006]
- Eventually consistent across datacenters
- Lesson: "don't need distributed transactions"

2008? – MegaStore [CIDR 2011]
- Strongly consistent across datacenters
- Option for distributed transactions
- But performance was not great…

2011 – Spanner [OSDI 2012]
- Strictly Serializable Distributed Transactions
- "We wanted to make it easy for developers to build their applications"

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## Motivation: Performance-consistency tradeoff

- Strict serializability
  - Serializability + linearizability
  - As if coding on a single-threaded, transactionally isolated machine
  - Spanner calls it external consistency
- Strict serializability makes building correct application easier
- Strict serializability is expensive
  - Performance penalty in concurrency control + Repl.
    - OCC/2PL: multiple round trips, locking, etc.

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## Motivation: Read-Only Transactions

- Transactions that only read data
  - Predeclared, i.e., developer uses READ_ONLY flag / interface
- Reads dominate real-world workloads
  - FB's TAO had 500 reads : 1 write [ATC 2013]
  - Google Ads (F1) on Spanner from 1? DC in 24h:
    - 31.2 M single-shard read-write transactions
    - 32.1 M multi-shard read-write transactions
    - 21.5 B read-only (~340 times more)
- Determines system overall performance

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Can we design a strictly serializable, geo-replicated, sharded system with very fast (efficient) read-only transactions?

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## Before we get to Spanner …

- How would you design SS read-only transactions?
- OCC or 2PL: Multiple round trips and locking
- Can always read in local datacenters like COPS?
  - Maybe involved in Paxos agreement
  - Or must contact the leader
- Performance penalties
  - Round trips increase latency, especially in wide area
  - Distributed lock management is costly, e.g., deadlocks

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## Goal is to …

- Make read-only transactions efficient
  - One round trip (as could be wide-area)
  - Lock-free
    - No deadlocks
    - Processing reads do not block writes, e.g., long-lived reads
  - Always succeed (do not abort)
- And strictly serializable

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## Leveraging the Notion of Time

- Strict serializability: a matter of real-time ordering
  - If txn T2 starts after T1 finishes, then T2 must be ordered after T1
  - If T2 is ro-txn, then T2 should see effects of all writes finished before T2 started
- A similar scenario at a restaurant
  - Alice arrives, writes her name and time she arrives (e.g., 5pm) on waiting list
  - Bob then arrives, writes his name and the time (e.g., 5:10PM)
  - Then Bob is ordered after Alice on the waiting list
  - I arrive later at 5:15PM and check how many people are ahead of me by checking the waiting list by time

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## Leveraging the Notion of Time

- Task 1: when committing a write, tag it with the current physical time
- Task 2: when reading the system, check which writes were committed before the time this read started.
- How about the serializable requirement?
  - Physical time naturally gives a total order

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Invariant:

If T2 starts after T1 commits (finishes), then T2 must have a larger timestamp

Trivially provided by perfect clocks

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## (Obvious) Challenges

- Clocks are not perfect
  - Clock skew: some clocks are faster/slower
  - Clock skew may not be bounded
  - Clock skew may not be known a priori
- T2 may be tagged with a smaller timestamp than T1 due to T2's slower clock
- Seems impossible to have perfect clocks in distributed systems. What can we do?

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## Nearly perfect clocks

- Partially synchronized
  - Clock skew is bounded and known a priori
  - My clock shows 1:30PM, then I know the absolute (real) time is in the range of 1:30 PM +/- X.
    - e.g., between 1:20PM and 1:40PM if X = 10 mins
- Clock skew is short (e.g., X = a few milliseconds)
- Enable something special, e.g., Spanner!

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## Spanner: Google's Globally-Distributed Database

**OSDI 2012**

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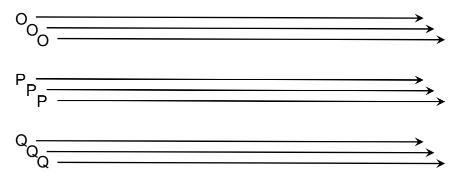
## Scale-out vs. Fault Tolerance




- Every shard replicated via MultiPaxos (akin to RAFT)
- So every "operation" within transactions across tablets actually a replicated operation within Paxos RSM
- Paxos groups can stretch across datacenters!

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## Strictly Serializable Multi-shard Transactions

- How are clocks made "nearly perfect"?
- How does Spanner leverage these clocks?
  - How are writes done and tagged?
  - How read-only transactions are made efficient?

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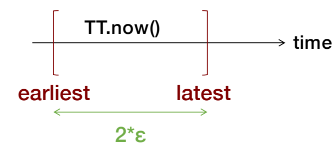
## TrueTime (TT)

- "Global wall-clock time" with bounded uncertainty
  - ε is worst-case clock divergence
  - Spanner's notion of time becomes intervals, not single values
  - ε is 4ms on average,  2 ε is about 10ms




**Consider event $e_{now}$ which invoked tt = TT.now():**

**Guarantee:** tt.earliest <= $t_{abs}(e_{now})$ <= tt.latest

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## TrueTime (TT)

- API (software interface)
  - TT.now() = [earliest, latest]    # latest – earliest = 2*ε
  - TT.after(t) = true if t has passed
    - TT.now().earliest > t   (because $t_{abs}$ >= TT.now().earliest)
  - TT.before(t) = true if t has not arrived
    - TT.now().latest < t   (because $t_{abs}$ <= TT.now().latest)

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## TrueTime (TT)

- Implementation
  - Relies on specialized hardware, e.g., satellite and atomic clocks

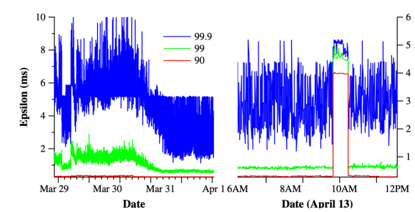


Figure 6: Distribution of TrueTime ε values, sampled right after timeslave daemon polls the time masters. 90th, 99th, and 99.9th percentiles are graphed.

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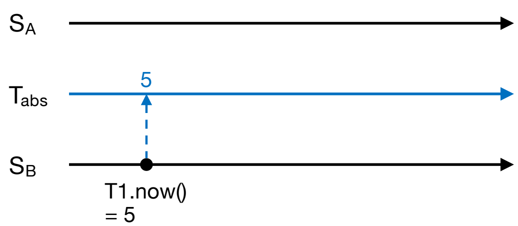
## Enforcing the Invariant

If T2 starts after T1 commits, then T2 must have larger timestamp

Let T1 write $S_B$ and T2 write $S_A$




Perfect Clocks

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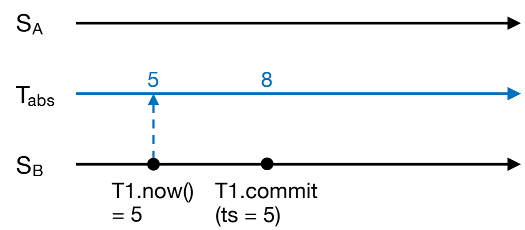


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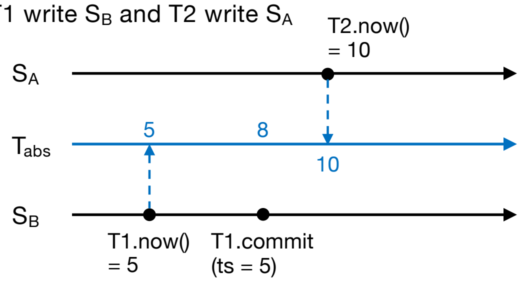


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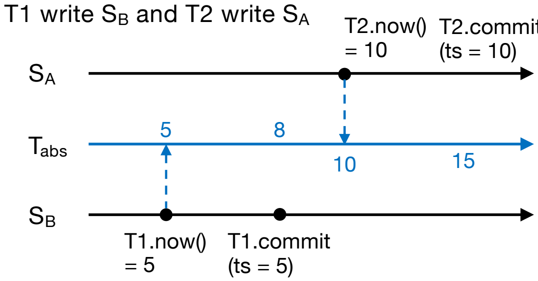


Perfect Clocks

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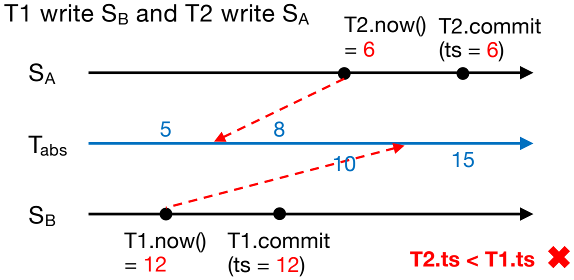


Imperfect Clocks

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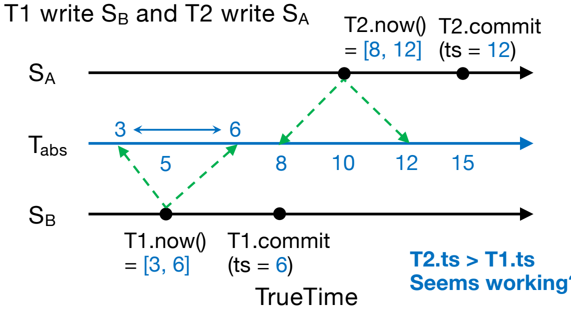


TrueTime

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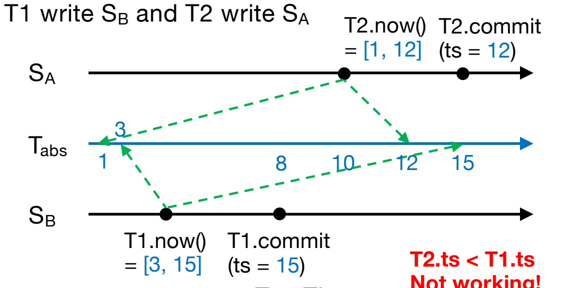
## Enforcing the Invariant (Strawman)

If T2 starts after T1 commits, then T2 must have larger timestamp

Let T1 write $S_B$ and T2 write $S_A$




TrueTime

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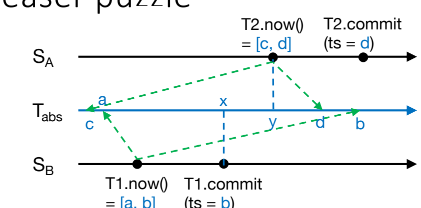
## A brain teaser puzzle




**We know.**

1. **x < y**, because T2 in real-time after T1 (the assumption)
2. **c <= y <= d**, because TrueTime
3. **T1.ts = b, T2.ts = d**, because how ts is assigned

**We want:** it is always true that b < d, how?

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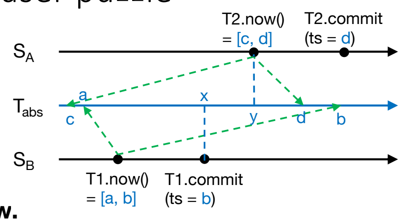
## A brain teaser puzzle

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**We want:** it is always true that b < d, how?

1 and 2 → x < d; we need to ensure b < x; then b < x < d, done.

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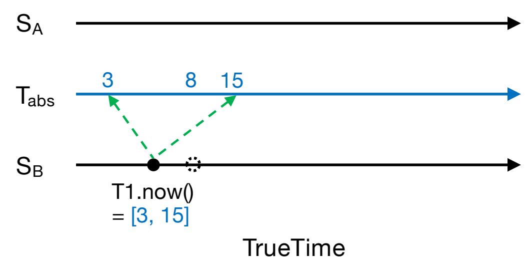


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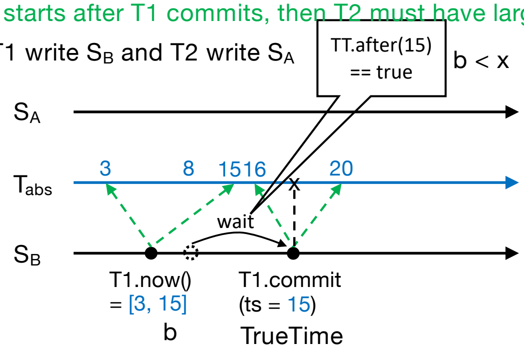


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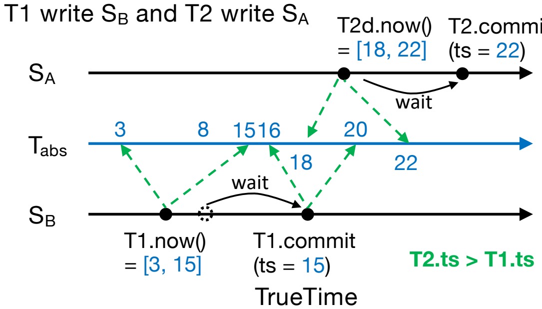


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## Takeaways

- The invariant is always enforced: If T2 starts after T1 commits (finishes), then T2 must have a larger timestamp
- How big/small ε is does not matter for correctness
- Only need to make sure:
  - TT.now().latest is used for ts (in this example)
  - Commit wait, i.e., TT.after(ts) == true
- ε must be known a priori and small so commit wait is doable!

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## After-class Puzzles

- Can we use TT.now().earliest for ts?
- Can we use TT.now().latest – 1 for ts?
- Can we use TT.now().latest + 1 for ts?
- Then what's the rule of thumb for choosing ts?

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