Spanner: Google's Globally-Distributed Database

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OSDI 2012

Courtesy

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What is Spanner?

Spanner is Google's scalable, multi-version, globally-distributed, and synchronously-replicated database.

It is the first system to distribute data at global scale and support externally-consistent distributed transactions.

Running in the production:

- Storage for Google's Ad data
- Replaced a sharded MySQL database

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- Distributed multi-version database
  - General-purpose transactions
  - SQL query language
  - Schematized tables
  - Semi-relational data model

- Focus: managing cross-datacenter replication
  - Replication can be controlled by clients for load balancing and failure responses.

Why Spanner ?

- **Bigtable (2008):**
  - Difficult to use for complex, evolving schemas
  - Can’t give strong consistency guarantees for geo-replicated sites
- **NoSQL(2010):**
  - Similar problem as Bigtable.
- **Megastore (2011):**
  - It supports semi-relational data model.
  - synchronous replication
  - But poor write throughput

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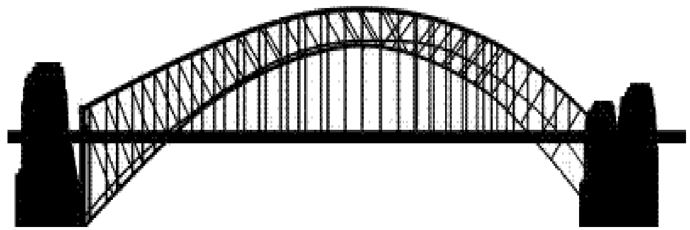
Megastore



Google Bigtable

Solution: Google Spanner

- Bridging the gap between Megastore and Bigtable.
- SQL transactions + high throughput
- lower latency over higher availability

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Spanner Overview

- Bigtable-like versioned key-value store into a temporal multi-version database.
- Data is stored in schematized semi-relational tables.
- data is versioned,
- each version is automatically timestamped with its commit time;
- old versions of data are subject to configurable garbage-collection policies;
- applications can read data at old timestamps.
- supports general-purpose transactions,
- provides a SQL-based query language.

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Features of Spanner

- The replication configurations for data can be dynamically controlled at a fine grain by applications.
- It provides externally consistent reads and writes .
- It provides globally-consistent reads across the database at a timestamp.
  - These features enable Spanner to support consistent backups, consistent MapReduce executions [12], and atomic schema updates, all at global scale, and even in the presence of ongoing transactions.

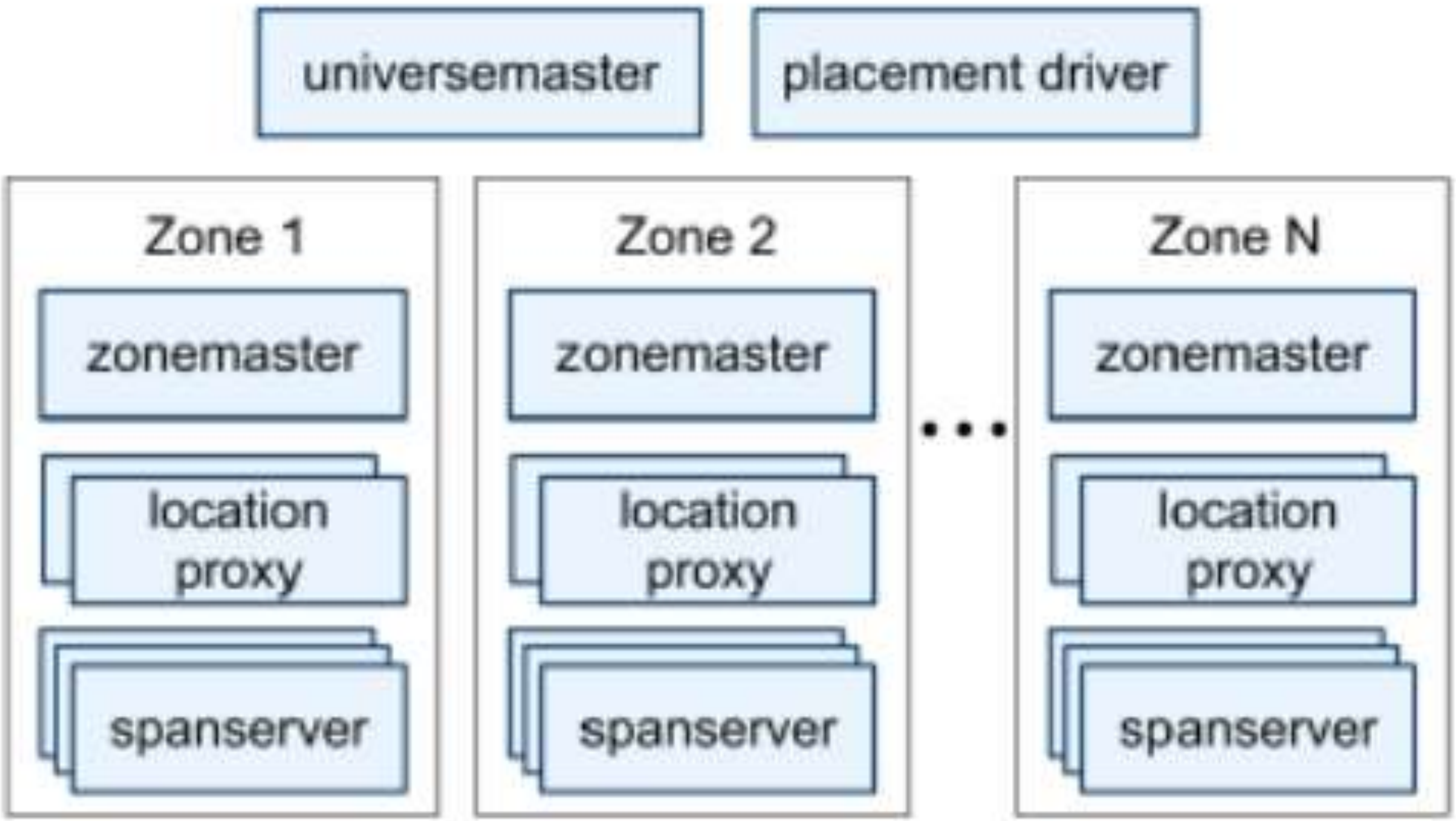
Replication configurations

- dynamically controlled at a fine grain by applications
- control which datacenters contain which data,
- how far data is from its users (to control read latency),
- how far replicas are from each other (to control write latency), and
- how many replicas are maintained (to control durability, availability, and read performance).

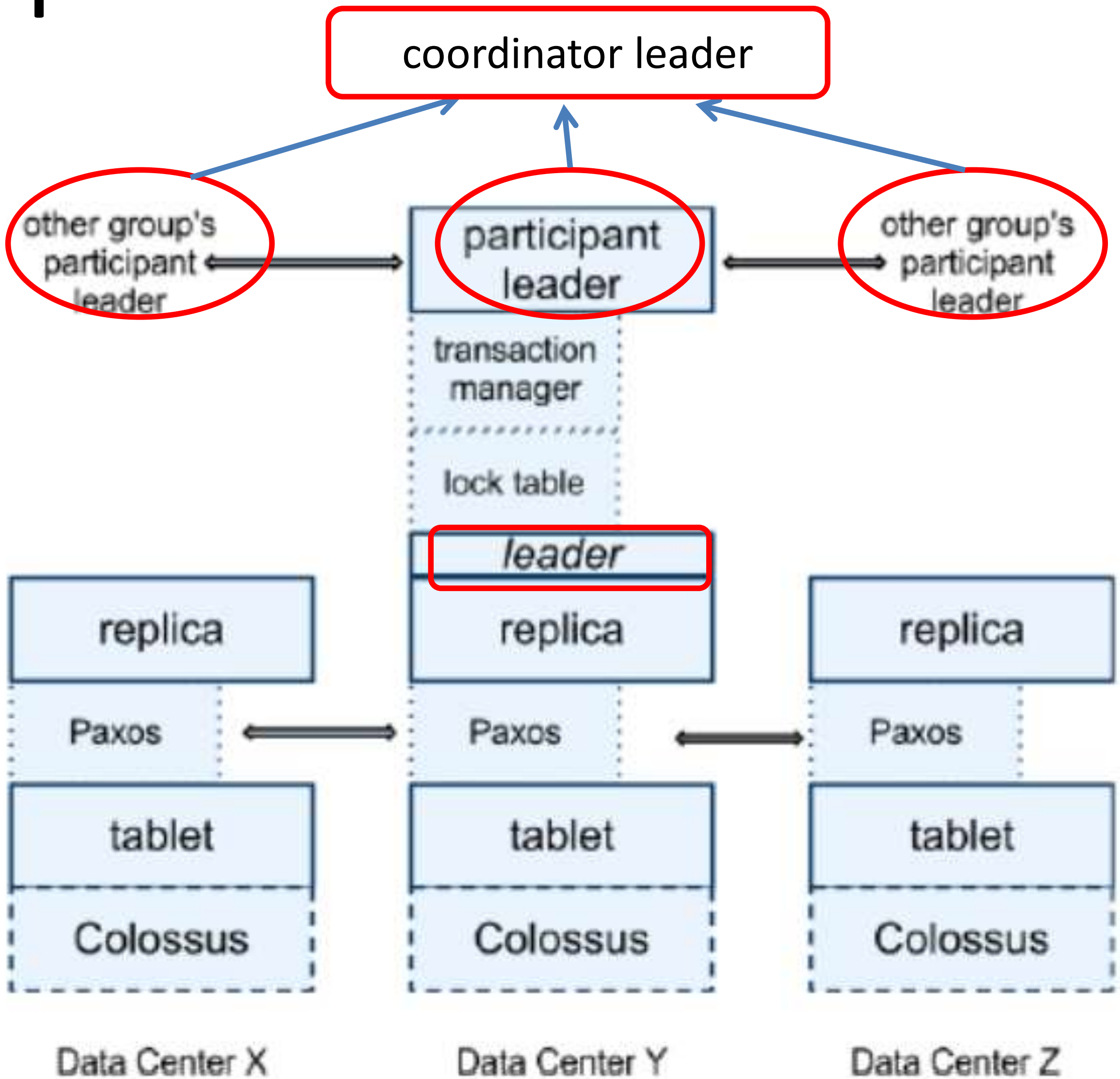
Replication configurations

- Data can also be dynamically and transparently moved between datacenters by the system to balance resource usage across datacenters.

Spanner server organization



Spanserver software stack



Directories and Placement

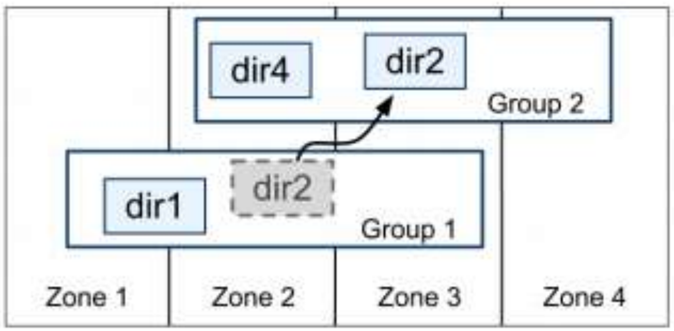


Figure 3: Directories are the unit of data movement between Paxos groups.

- A directory is the unit of data placement.

- Spanner might move a directory to shed load from a Paxos group;
- Put directories that are frequently accessed together into the same group;
- Move a directory into a group that is closer to its accessors;

Data Model

- An application creates one or more *databases* in a universe.
- Each database can contain an unlimited number of schematized *tables*.
- Tables look like relational-database tables, with rows, columns, and versioned values.

Data Model

- Schematized semi-relational tables

BigTable ： (row:string, column:string, time:int64)→string

Spanner ： (key:string, timestamp:int64) → string

- **query language like sql**

```
CREATE TABLE Users {
  uid INT64 NOT NULL, email STRING
} PRIMARY KEY (uid), DIRECTORY;

CREATE TABLE Albums {
  uid INT64 NOT NULL, aid INT64 NOT NULL,
  name STRING
} PRIMARY KEY (uid, aid),
  INTERLEAVE IN PARENT Users ON DELETE CASCADE;
```

TrueTime API

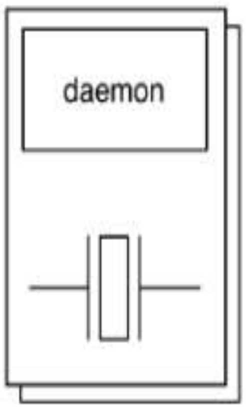
Method	Returns
$TT.now()$	$TTinterval$: $[earliest, latest]$
$TT.after(t)$	true if t has definitely passed
$TT.before(t)$	true if t has definitely not arrived

Table 1: TrueTime API. The argument t is of type *TTstamp*.

- Google’s cluster-management software provides an implementation of the TrueTime API.
- This implementation keeps uncertainty small (generally less than 10ms) by using multiple modern clock references (GPS and atomic clocks).

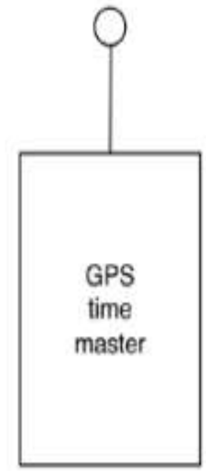
How TrueTime Is Implemented? (1/2)

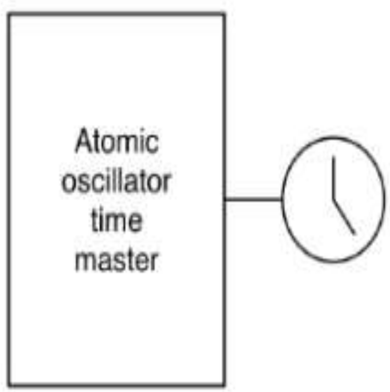
timeslave daemon per **machine**



set of time **master machines per datacenter**

majority of masters have
GPS receivers
with dedicated antennas





The remaining masters (which we refer to as **Armageddon masters**) are equipped with **atomic clocks.**

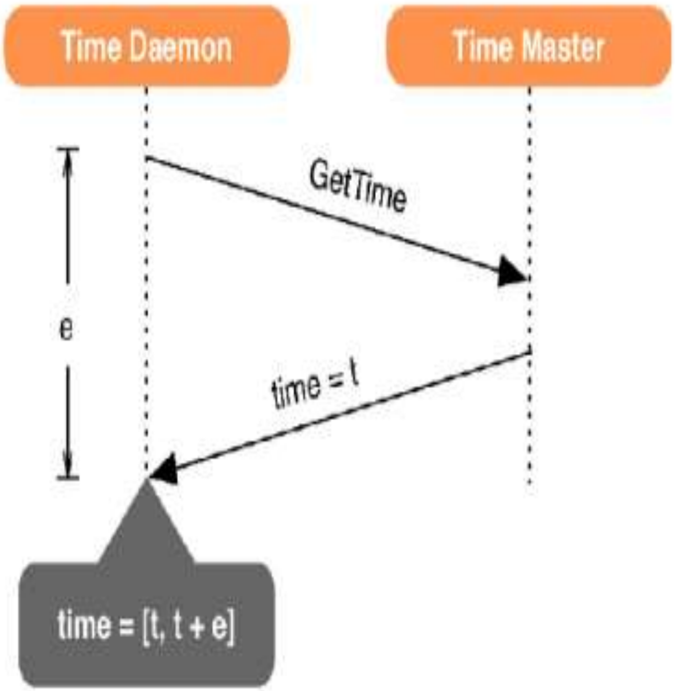
How TrueTime Is Implemented? (2/2)

➢ Daemon polls variety of masters:

• Chosen from nearby datacenters

• From further datacenters

• Armageddon masters



➢ Daemon polls variety of masters and reaches a consensus about correct timestamp.

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Synchronizing Snapshots

Global wall-clock time

==

External Consistency:

Commit order respects global wall-time order

==

Timestamp order respects global wall-time order

given

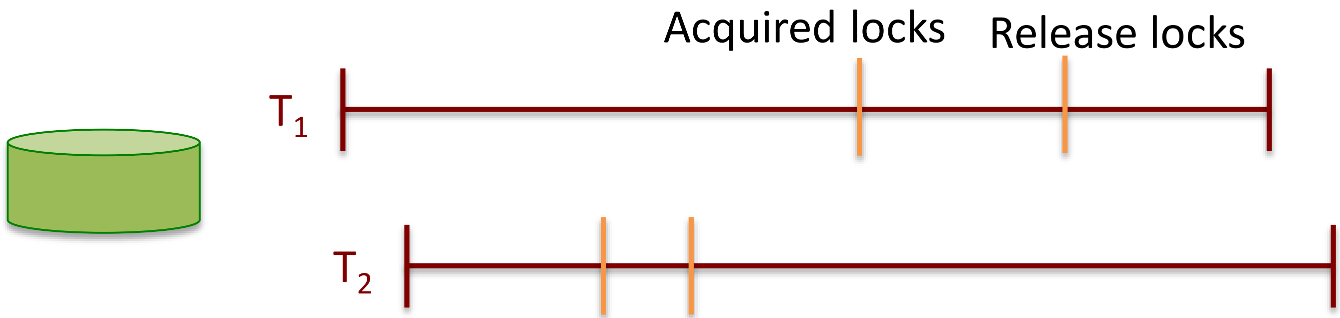
timestamp order == commit order

Timestamps, Global Clock

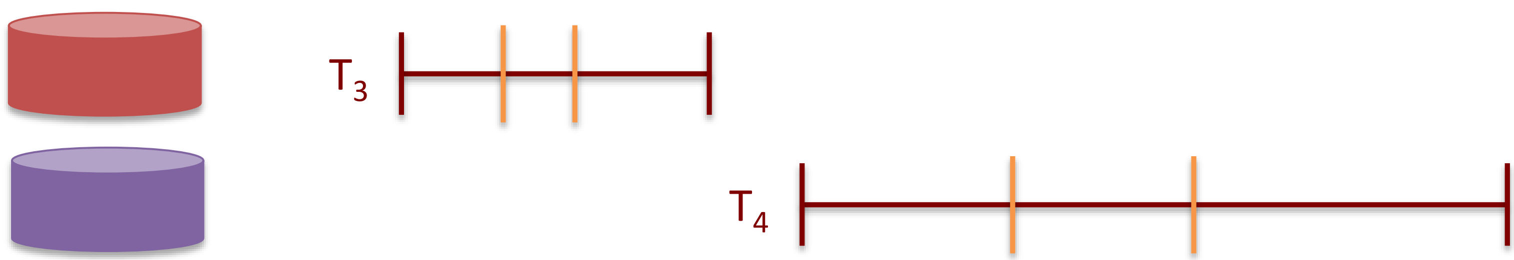
- Strict **two-phase locking** for write transactions
- Assign timestamp while locks are held

Timestamp Invariants

- Timestamp order == commit order



- Timestamp order respects global wall-time order



Types of Reads in Spanner

Operation	Timestamp Discussion	Concurrency Control	Replica Required
Read-Write Transaction	§ 4.1.2	pessimistic	leader
Read-Only Transaction	§ 4.1.4	lock-free	leader for timestamp; any for read, subject to § 4.1.3
Snapshot Read, client-provided timestamp	—	lock-free	any, subject to § 4.1.3
Snapshot Read, client-provided bound	§ 4.1.3	lock-free	any, subject to § 4.1.3

Table 2: Types of reads and writes in Spanner, and how they compare.

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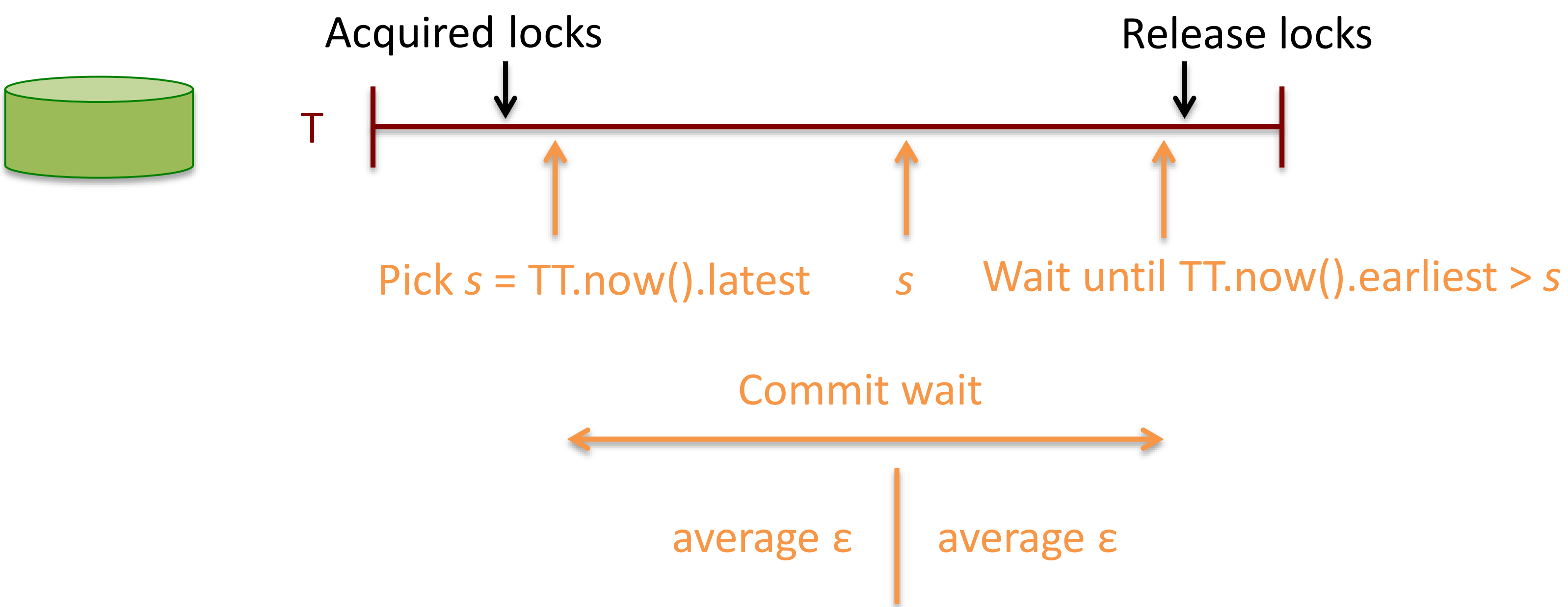
Timestamps and TrueTime

- **Two rules:**

1. **Start:** s_i for T_i > TT.now.latest() computed after e_i^{server} (arrival event at leader)

2. **Commit wait:** Clients should not see data committed by T_i until TT.after(s_i) is true
   $s_i < t_{abs}(e_i^{commit})$



Snapshot reads

– Read in past without locking

– Client can specify timestamp for read or an upper bound of timestamp's staleness

– Each replica tracks a value called safe time t_{safe} which is the maximum timestamp at which a replica is up-to-date.

– Replica can satisfy read at any $t <= t_{safe}$

Read-only transaction

- Assign timestamp s_{read} and executes read at s_{read}
- $s_{read} = TT.now().latest()$ guarantees external consistency
- For read at single paxos group:
  - Let LastTS() = timestamp of the last committed write at the Paxos group.
  - If there are no prepared transactions, the assignment s_{read} = LastTS() trivially satisfies external consistency: the transaction will see the result of the last write
- For read at multiple paxos group:
  - $s_{read} = TT.now().latest()$ [may wait for safe time to advance]

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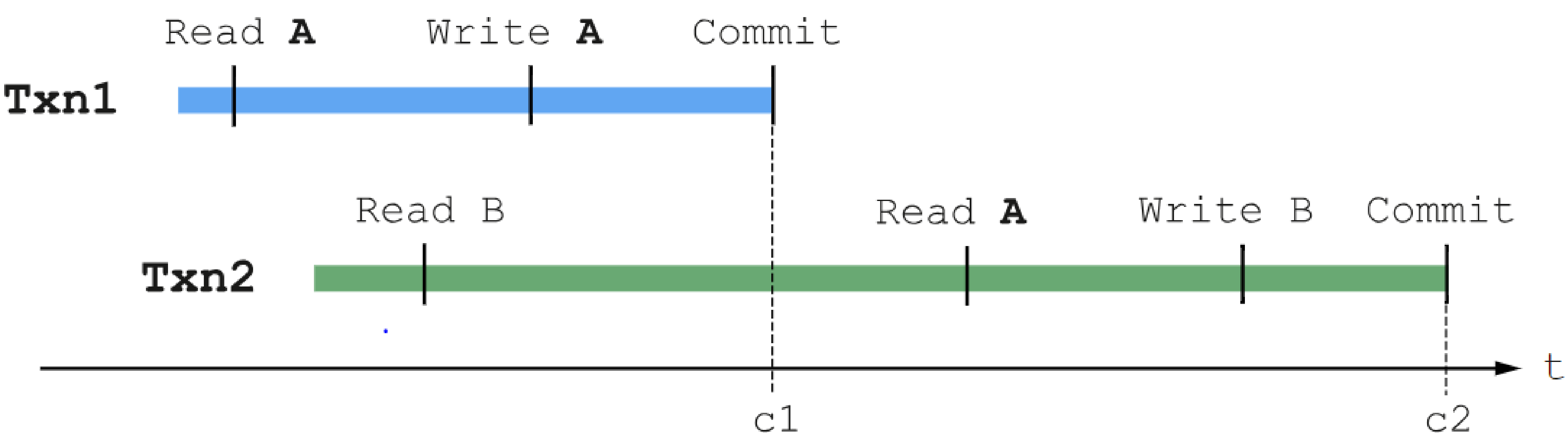
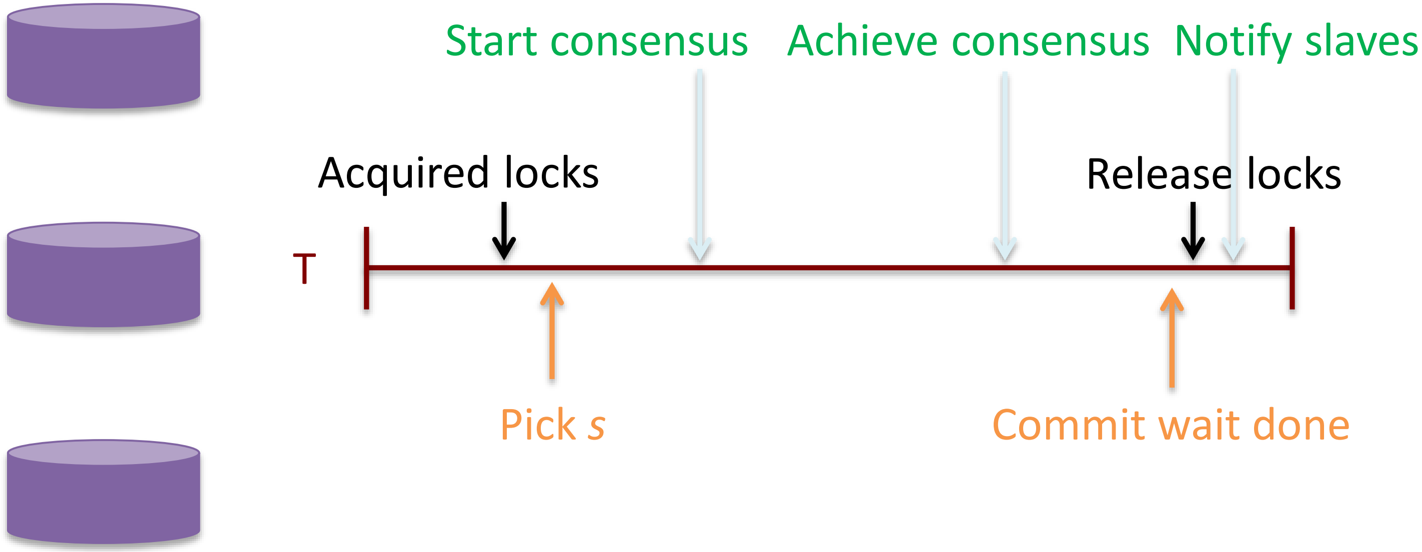
Read Write Transactions

- Leader must only assign timestamps within the interval of its leader lease.
- Timestamps must be assigned in monotonically increasing order.
- Wound-wait protocol to avoid deadlocks



Transaction within paxos group

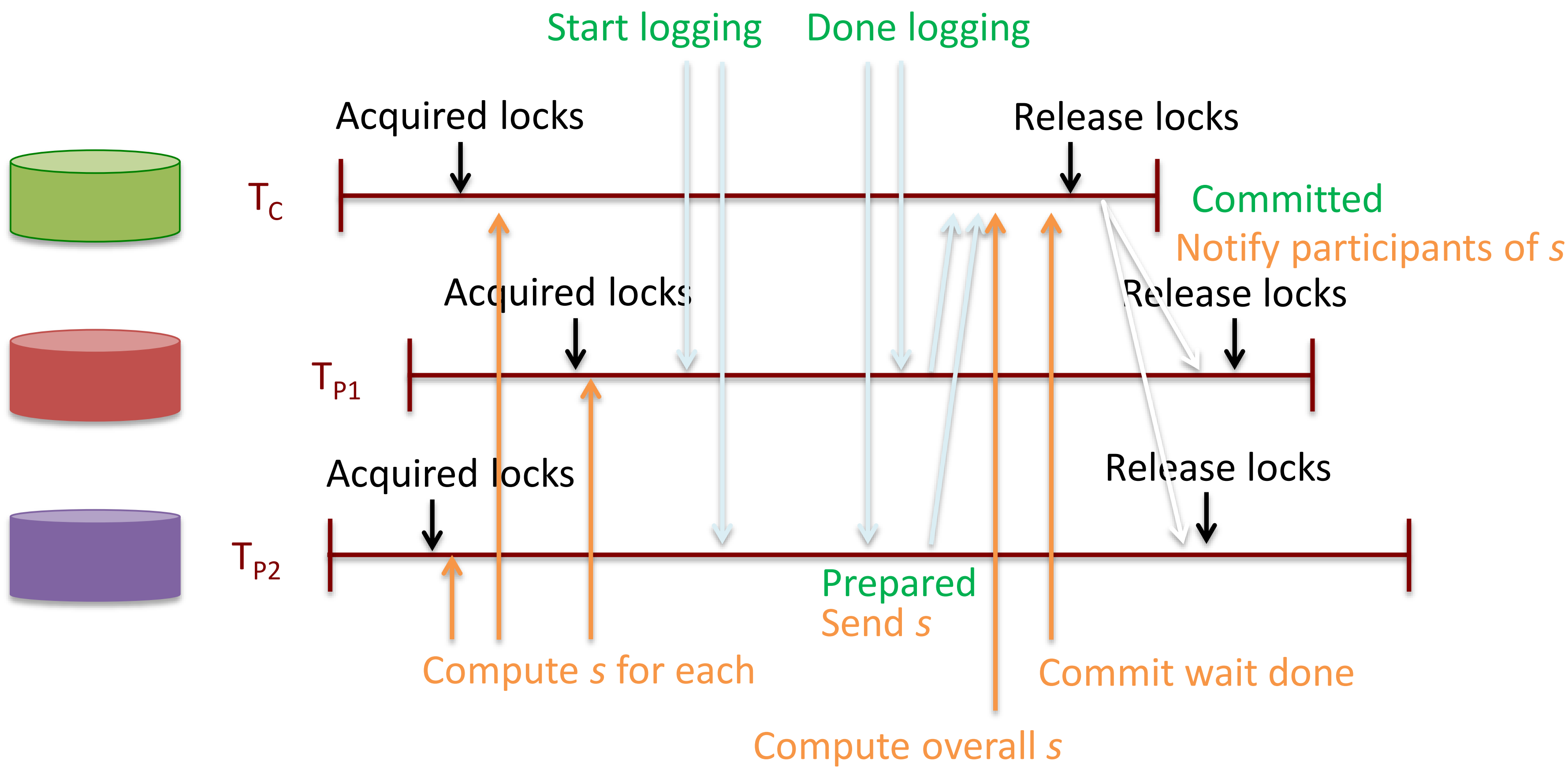


Paxos algorithm is used for consensus

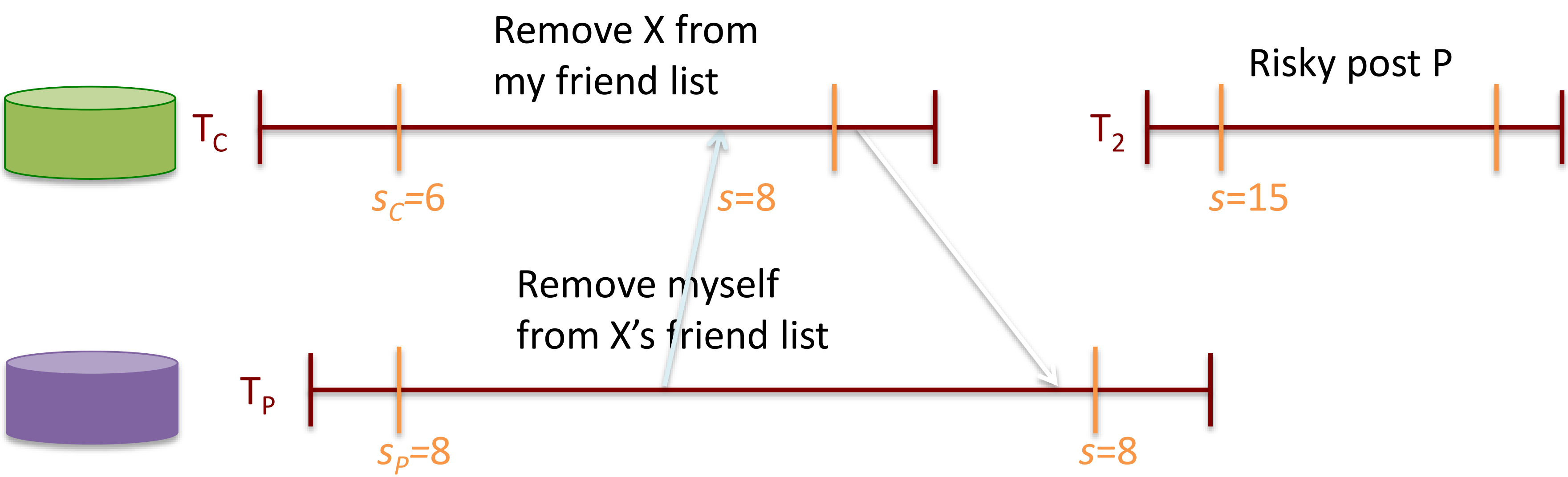
Transactions across Paxos groups

- Client buffer writes
- Client chooses a coordinating group that initiates 2PC
- A non-coordinator-participant leader chooses a prepare timestamp and logs a prepare record through paxos and notifies the coordinator.

2-Phase Commit



Example

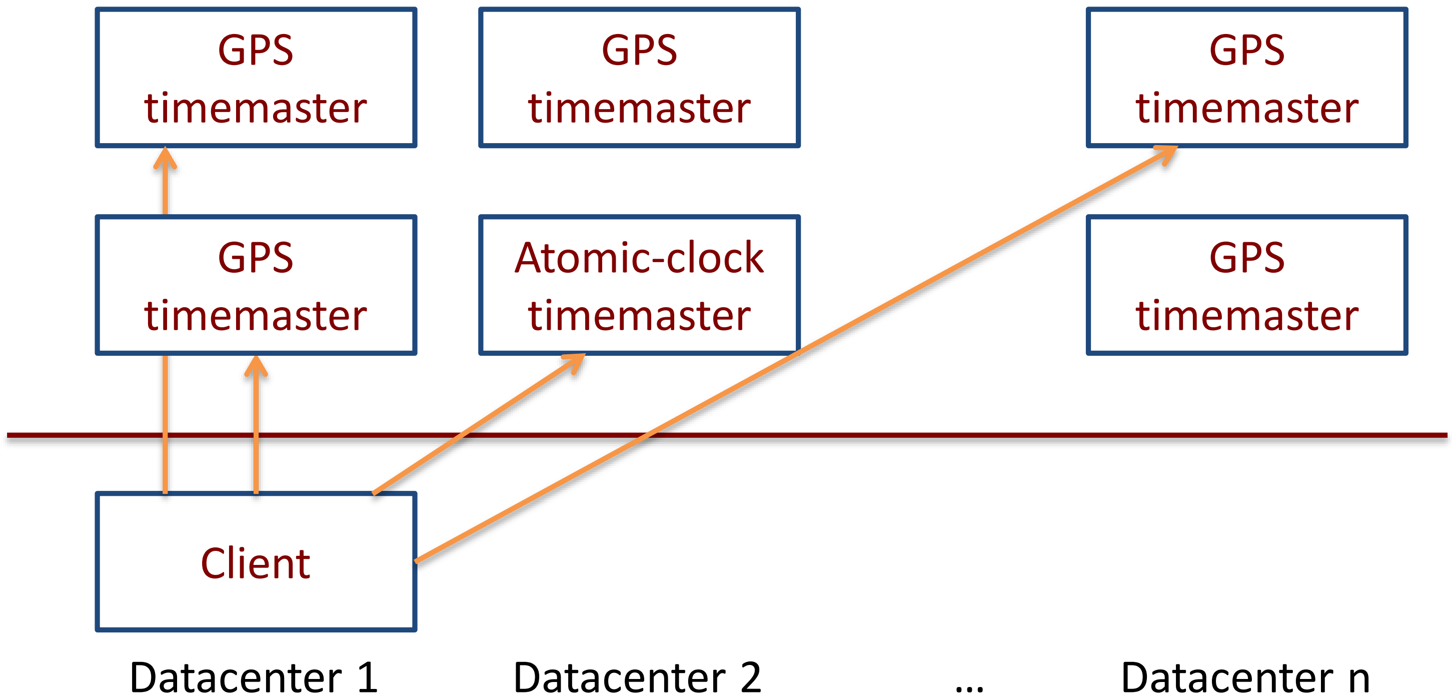


Time	<8	8	15
My friends	[X]	[]	
My posts			[P]
X's friends	[me]	[]	

Schema-change transaction

- How do you make an atomic schema change?
- BigTable only supports changes in one data center, but locks everything
- Spanner has a Non-blocking variant of standard transaction
- Assign a timestamp in the future
- Reads and Writes synchronize with any registered schema at the future timestamp, but not before

TrueTime Architecture

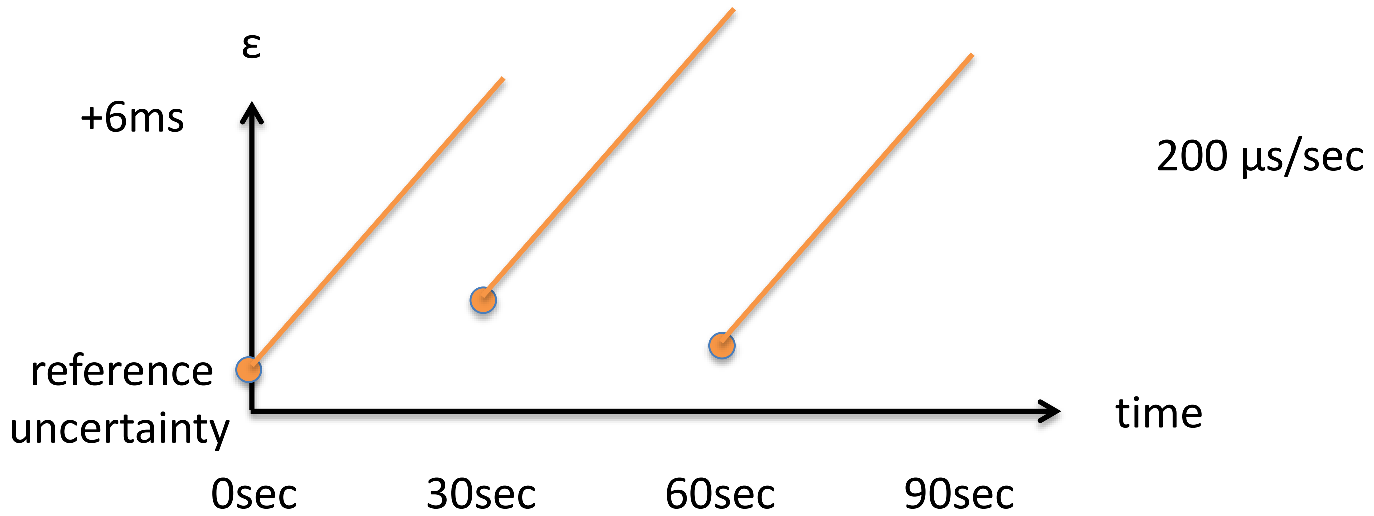


Compute reference [earliest, latest] = now ± ε

TrueTime implementation

now = reference now + local-clock offset

ε = reference ε + worst-case local-clock drift



What If a Clock Goes Rogue?

- Timestamp assignment would violate external consistency
- Empirically unlikely based on 1 year of data
  - Bad CPUs 6 times more likely than bad clocks

Evaluation

replicas	latency (ms)			throughput (Kops/sec)		
	write	read-only transaction	snapshot read	write	read-only transaction	snapshot read
1D	9.4±.6	—	—	4.0±.3	—	—
1	14.4±1.0	1.4±.1	1.3±.1	4.1±.05	10.9±.4	13.5±.1
3	13.9±.6	1.3±.1	1.2±.1	2.2±.5	13.8±3.2	38.5±.3
5	14.4±.4	1.4±.05	1.3±.04	2.8±.3	25.3±5.2	50.0±1.1

Table 3: Operation microbenchmarks. Mean and standard deviation over 10 runs. 1D means one replica with commit wait disabled.

participants	latency (ms)	
	mean	99th percentile
1	17.0 ±1.4	75.0 ±34.9
2	24.5 ±2.5	87.6 ±35.9
5	31.5 ±6.2	104.5 ±52.2
10	30.0 ±3.7	95.6 ±25.4
25	35.5 ±5.6	100.4 ±42.7
50	42.7 ±4.1	93.7 ±22.9
100	71.4 ±7.6	131.2 ±17.6
200	150.5 ±11.0	320.3 ±35.1

Table 4: Two-phase commit scalability. Mean and standard deviations over 10 runs.

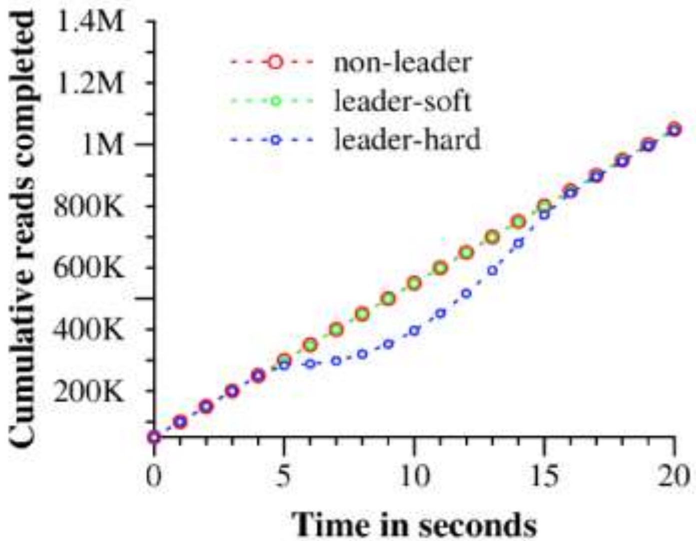


Figure 5: Effect of killing servers on throughput.

F1 Case Study

- Spanner experimentally evaluated under production workloads; rewrite of Google's advertising backend called F1.
- Replaced a MySQL database that was manually sharded.
- The uncompressed dataset is tens of terabytes.
- Spanner removes need to manually reshard
- Spanner provides synchronous replication and auto failover
- F1 requires strong transactional semantics

Future Work

- Improving TrueTime
  - Lower $\varepsilon < 1$ ms
- Building out database features
  - Finish implementing basic features
  - Efficiently support rich query patterns

Advancements

- Spanner claims to be consistent and available
  (A white paper published by Eric Brewer, Google)

- Spanner: Becoming a SQL System
  (SIGMOD'17, May 14–19, 2017, Chicago, IL, USA)
  – Distributed query execution in the presence of resharding
  – query restarts upon transient failures
  – range extraction that drives query routing and index seeks
  – OLTP data management system

Cloud Spanner

	CLOUD SPANNER	TRADITIONAL RELATIONAL	TRADITIONAL NON-RELATIONAL
Schema	✓ **Yes**	✓ Yes	✗ No
SQL	✓ **Yes**	✓ Yes	✗ No
Consistency	✓ **Strong**	✓ Strong	✗ Eventual
Availability	✓ **High**	✗ Failover	✓ High
Scalability	✓ **Horizontal**	✗ Vertical	✓ Horizontal
Replication	✓ **Automatic**	Configurable	Configurable

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Conclusions

- The first service to provide global externally consistent multi-version database
- Relies on novel time API (TrueTime)
  - Known unknowns are better than unknown unknowns
  - Rethink algorithms to make use of uncertainty
- Stronger semantics are achievable
  - Greater scale != weaker semantics

Thanks

- Reference:
  - Spanner: Google’s Globally-Distributed Database
  - Slides on spanner by Google in OSDI 2012 talk
  - http://research.google.com/archive/spanner.html

- Questions?