# Advanced Data Management (CSCI 490/680)

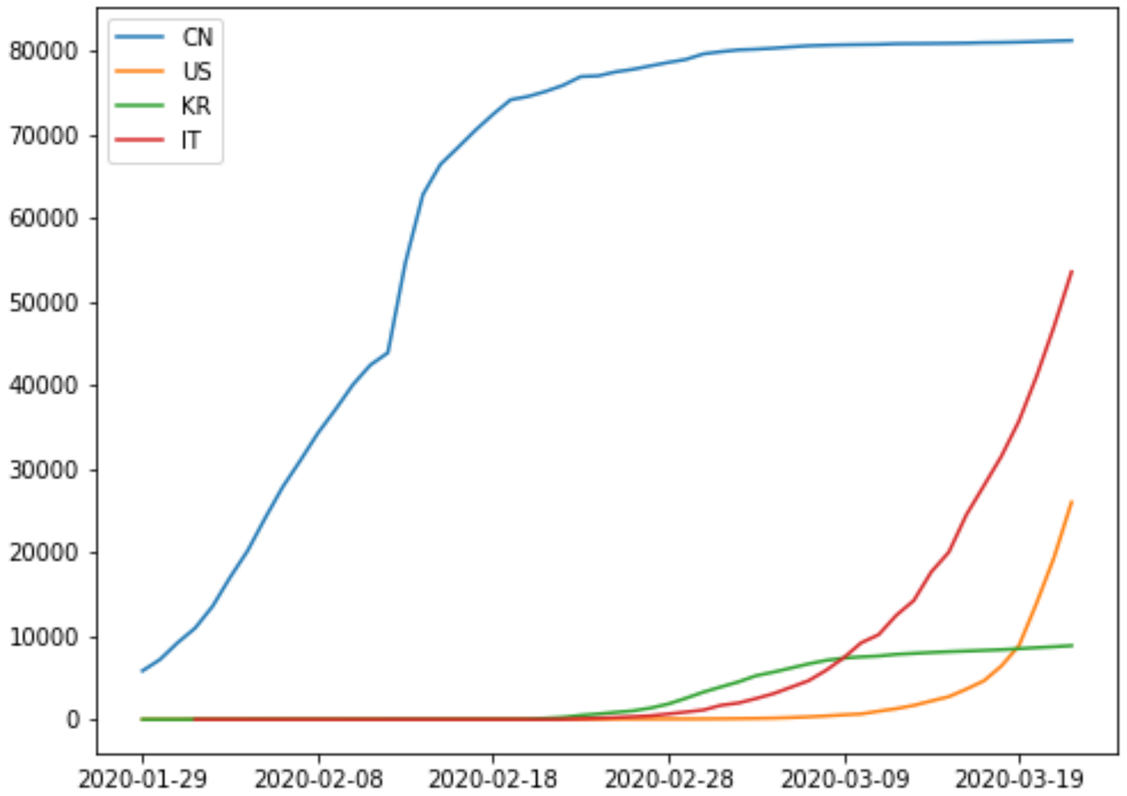
## Scalable Database Systems

Dr. David Koop

# Reading Quiz

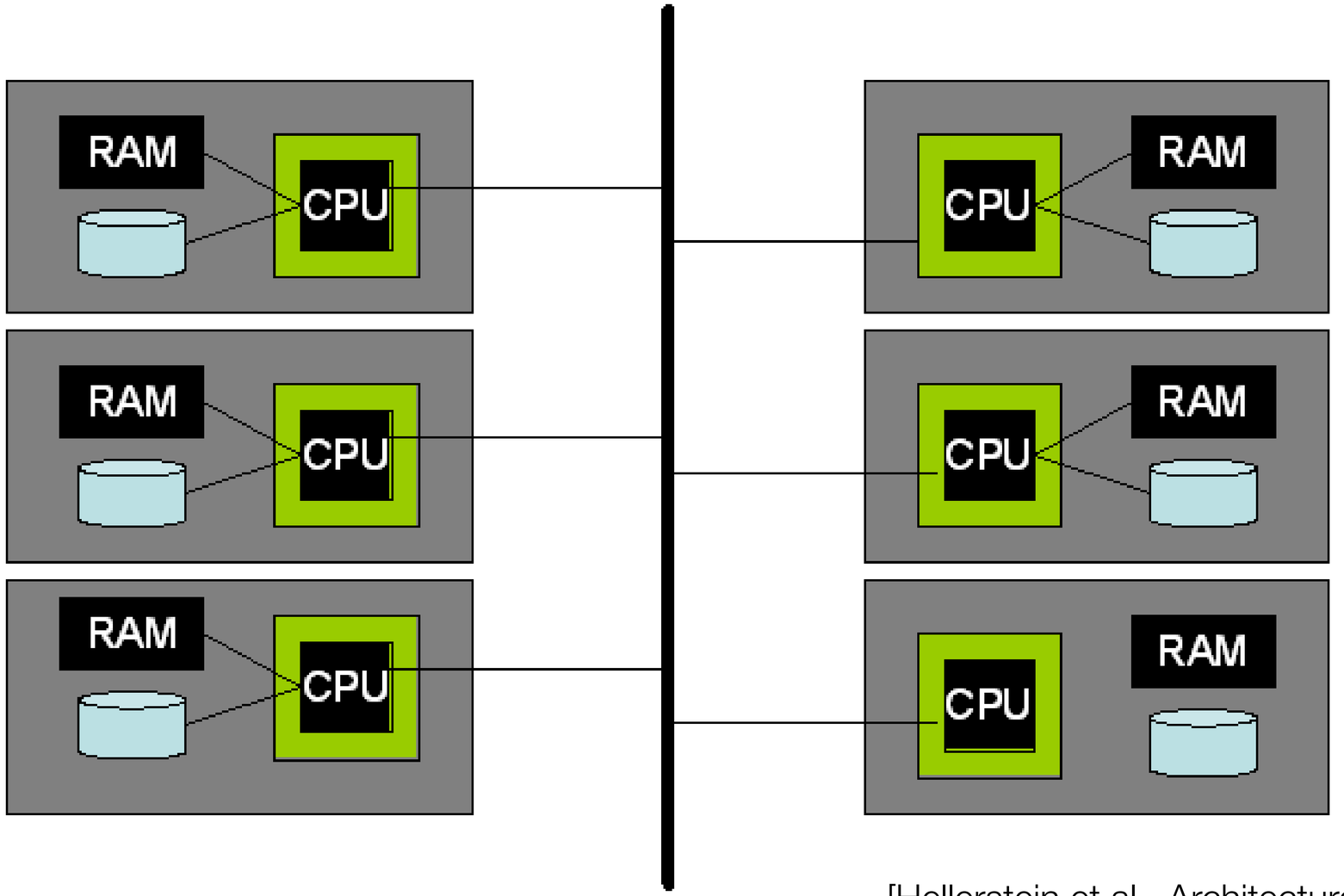
- Before continuing with the lecture
  - Make sure you have read the paper:
    Spanner: Google's Globally-Distributed Database
  - Take the quiz on the reading on Blackboard
  - Quiz will focus on key concepts not the details

# Assignment 4



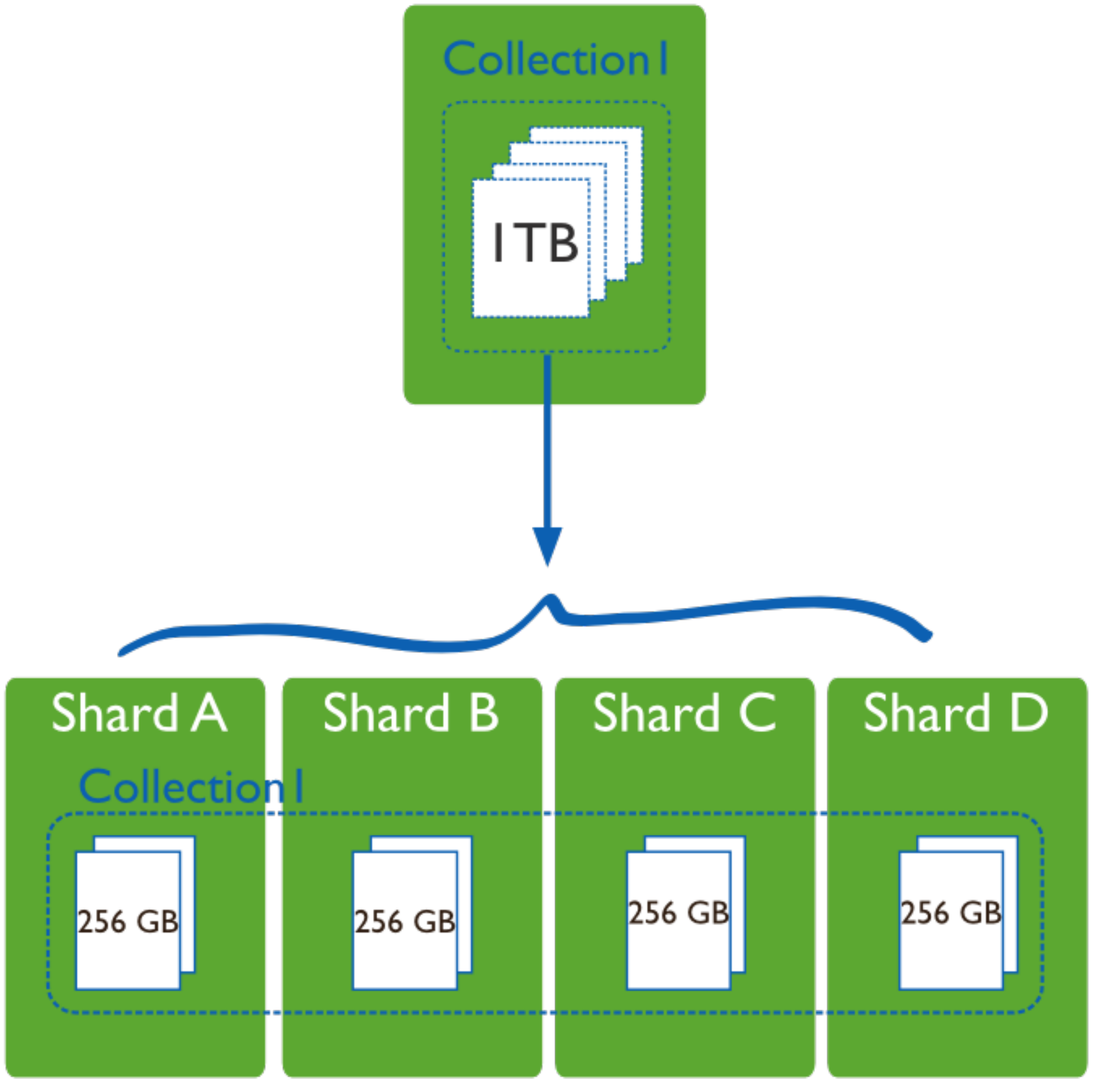

- COVID-19 data
- Data Integration
  - Population
  - Temperature
- Data Fusion:
  - Our World in Data
  - Johns Hopkins
  - Wikipedia
- Questions?

# Parallel DB Architecture: Shared Nothing




[Hellerstein et al., Architecture of a Database System]

# Sharding

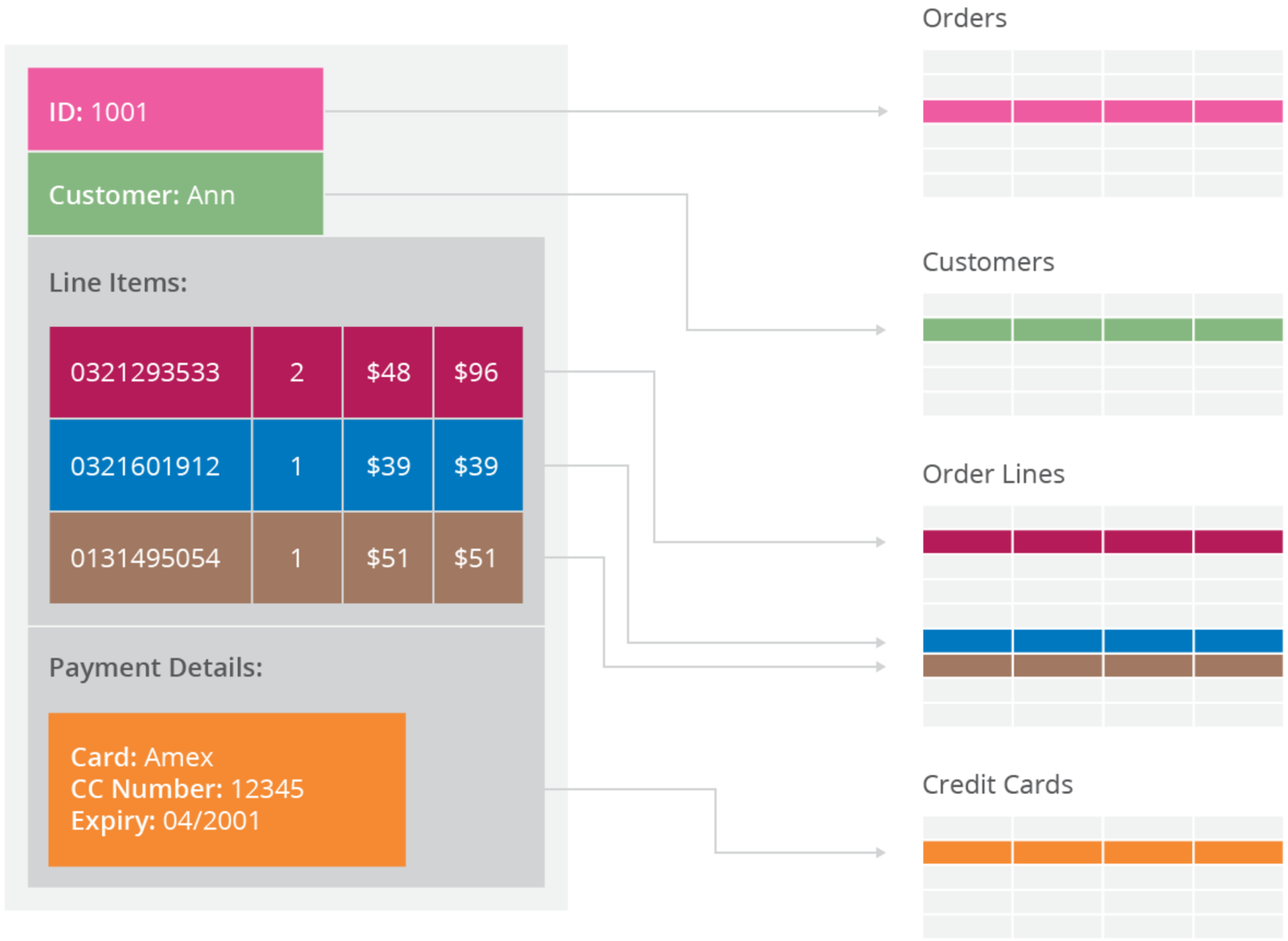



[MongoDB]

# Stonebraker: The End of an Architectural Era

- "RDBMSs were designed for the business data processing market, which is their sweet spot"
- "They can be beaten handily in most any other market of significant enough size to warrant the investment in a specialized engine"
- Changes in markets (science), necessary features (scalability), and technology (amount of memory)
- RDBMS Overhead: Logging, Latching, and Locking
- Relational model is not necessarily the answer
- SQL is not necessarily the answer

# Problems with Relational Databases




[P. Sadalage]

# Horizontal Partitioning vs. Vertical Partitioning

## Vertical Partitions

### VP1

| CUSTOMER ID | FIRST NAME | LAST NAME |
|---|---|---|
| 1 | TAEKO | OHNUKI |
| 2 | O.V. | WRIGHT |
| 3 | SELDA | BAĞCAN |
| 4 | JIM | PEPPER |

### VP2

| CUSTOMER ID | FAVORITE COLOR |
|---|---|
| 1 | BLUE |
| 2 | GREEN |
| 3 | PURPLE |
| 4 | AUBERGINE |

### Original Table

| CUSTOMER ID | FIRST NAME | LAST NAME | FAVORITE COLOR |
|---|---|---|---|
| 1 | TAEKO | OHNUKI | BLUE |
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## Horizontal Partitions

### HP1

| CUSTOMER ID | FIRST NAME | LAST NAME | FAVORITE COLOR |
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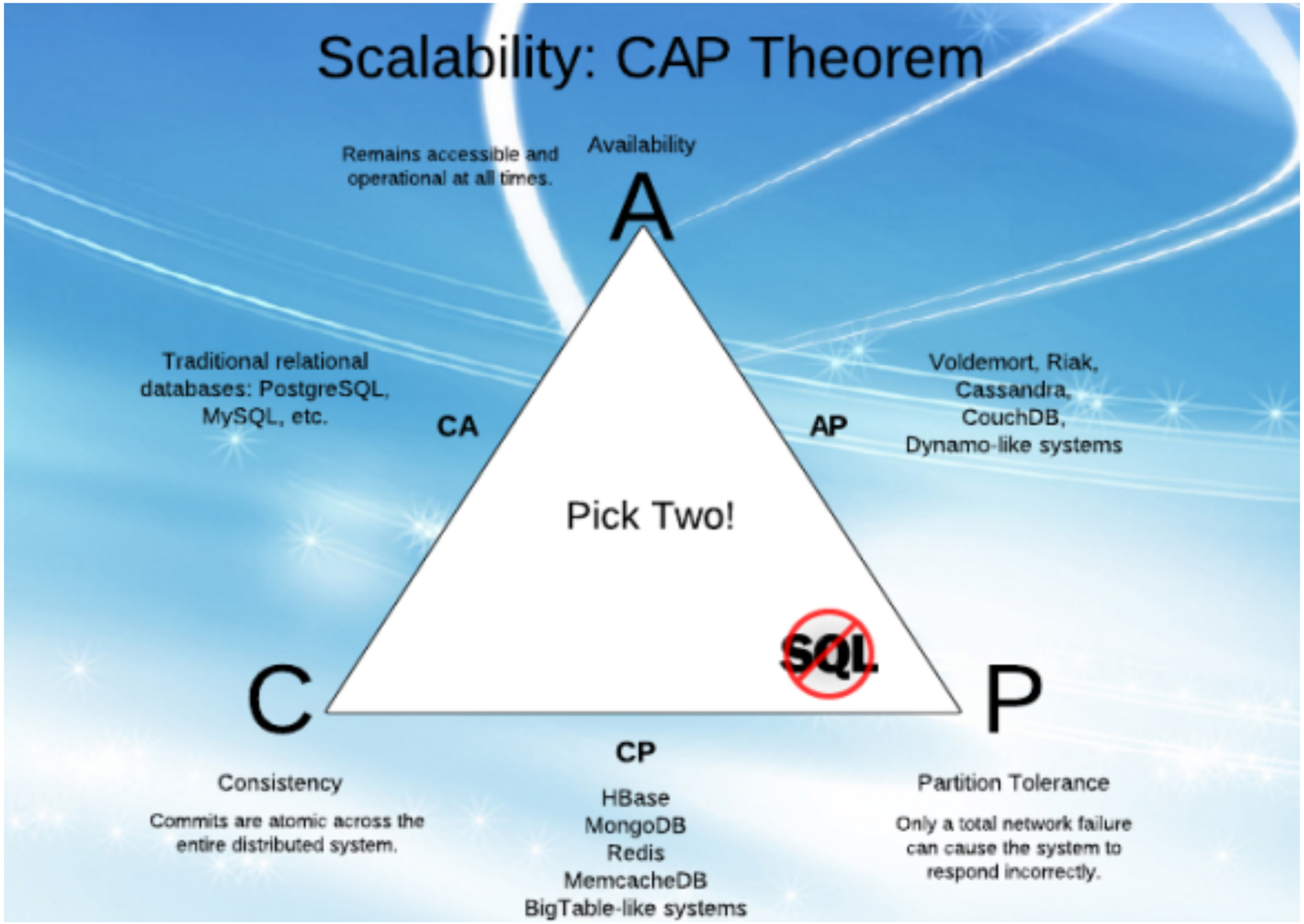
### HP2

| CUSTOMER ID | FIRST NAME | LAST NAME | FAVORITE COLOR |
|---|---|---|---|
| 3 | SELDA | BAĞCAN | PURPLE |
| 4 | JIM | PEPPER | AUBERGINE |

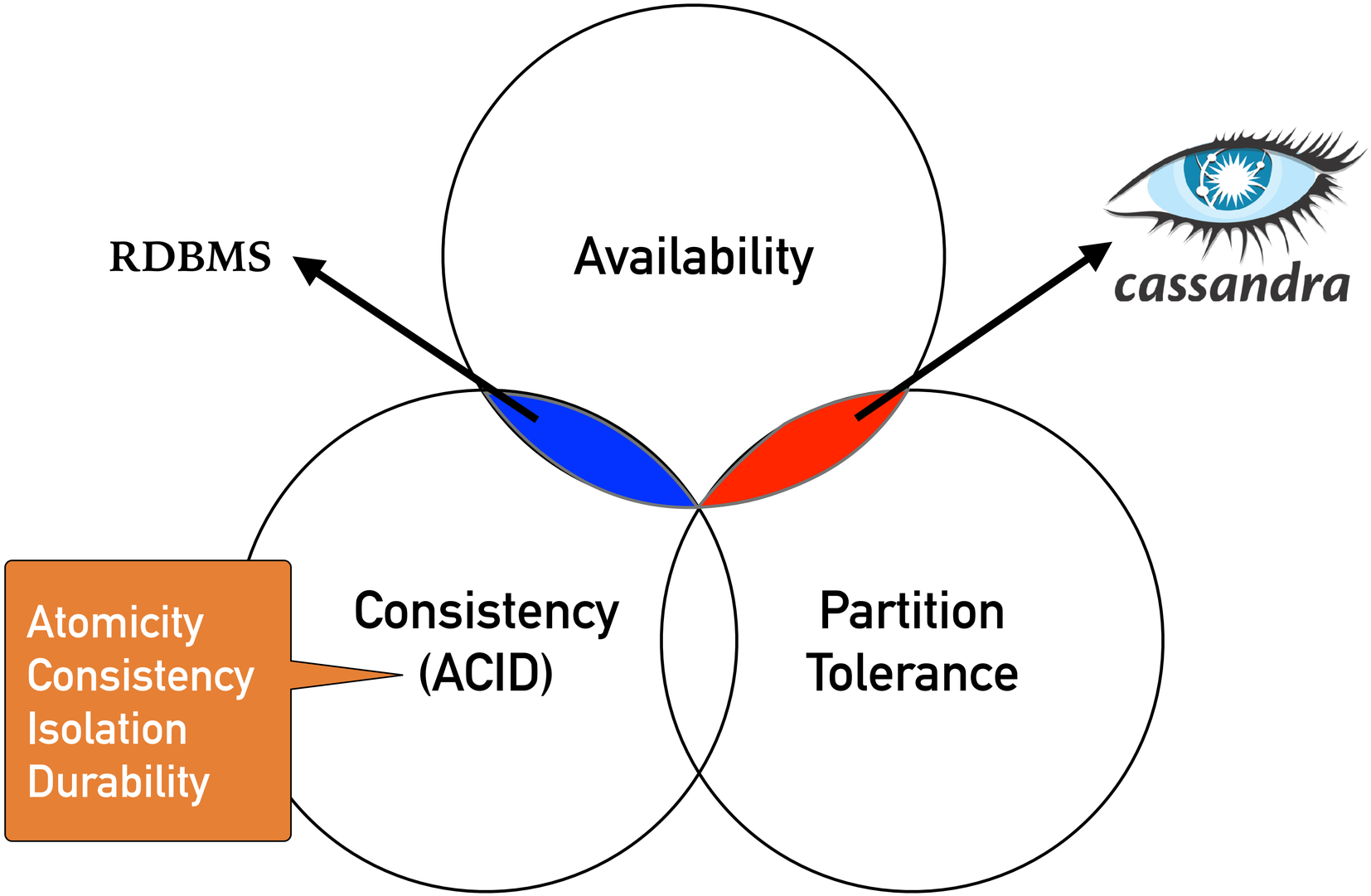
[M. Drake]

# CAP Theorem




[E. Brewer]

# Cassandra and CAP




[G. Atil]

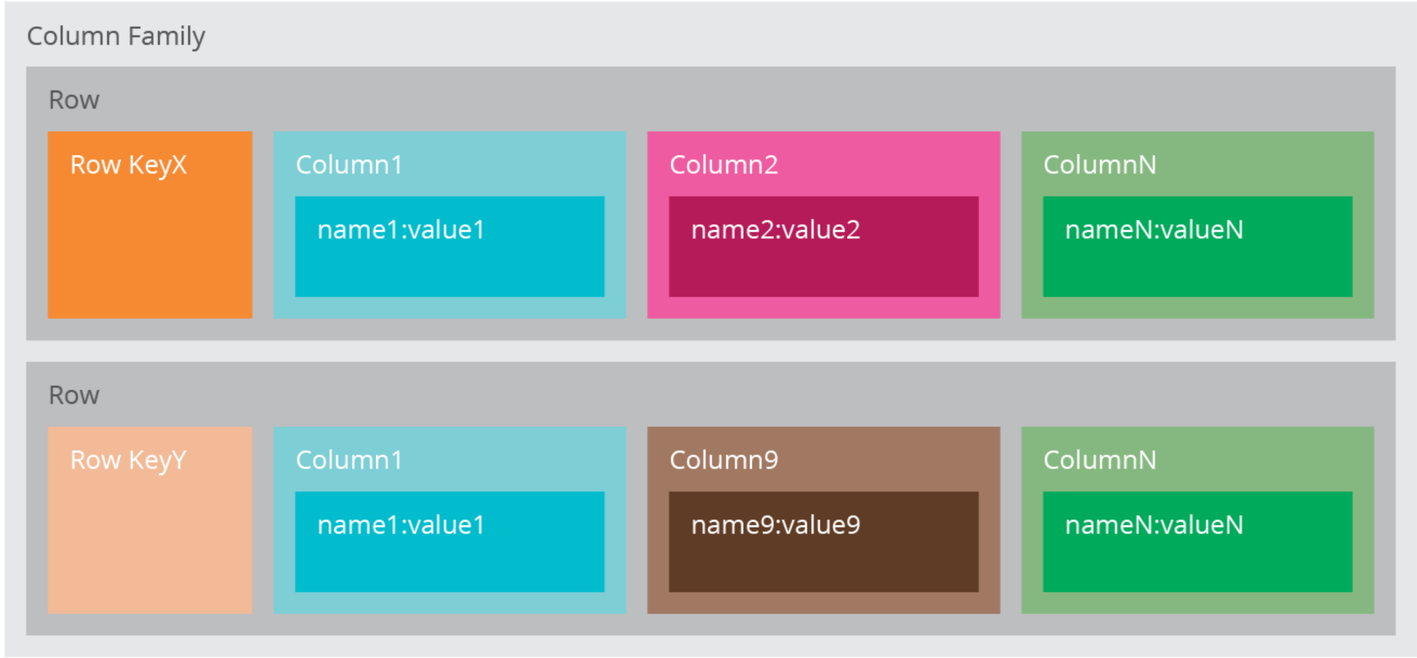
# What is Cassandra?

- Fast Distributed (Column Family NoSQL) Database
  - High availability
  - Linear Scalability
  - High Performance
- Fault tolerant on Commodity Hardware
- Multi-Data Center Support
- Easy to operate
- Proven: CERN, Netflix, eBay, GitHub, Instagram, Reddit

[G. Atil]

# NoSQL: Column Stores

- Instead of having rows grouped/sharded, we group columns
- …or families of columns
- Put similar columns together
- Examples: Cassandra, HBase



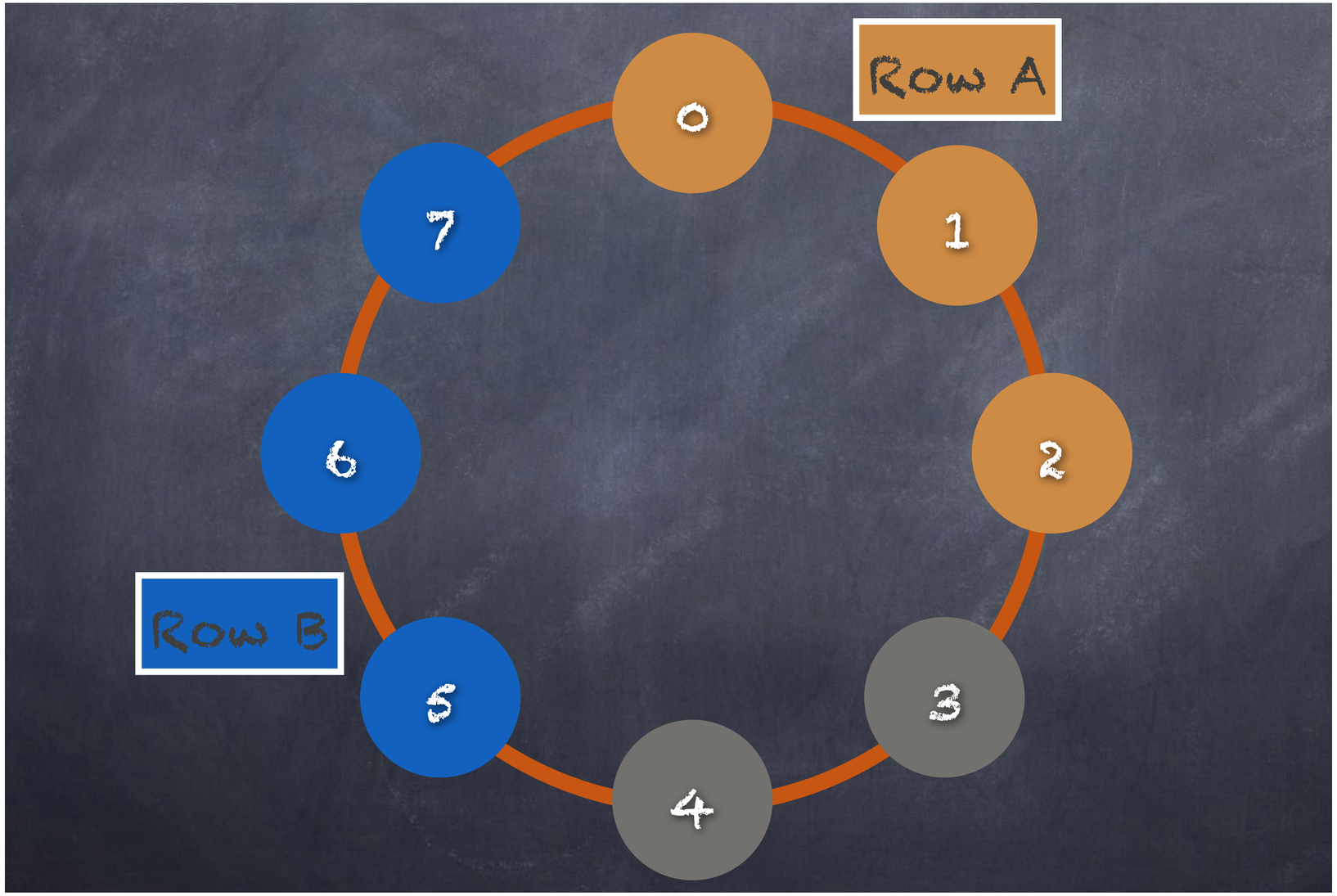

[P. Sadalage]

# Relational Databases vs. Cassandra

| Relational Database | Cassandra |
|---|---|
| Handles moderate incoming data velocity | Handles high incoming data velocity |
| Data arriving from one/few locations | Data arriving from many locations |
| Manages primarily structured data | Manages all types of data |
| Supports complex/nested transactions | Supports simple transactions |
| Single points of failure with failover | No single points of failure; constant uptime |
| Supports moderate data volumes | Supports very high data volumes |
| Centralized deployments | Decentralized deployments |
| Data written in mostly one location | Data written in many locations |
| Supports read scalability (with consistency sacrifices) | Supports read and write scalability |
| Deployed in vertical scale up fashion | Deployed in horizontal scale out fashion |

[DataStax]

# Cassandra: Replication



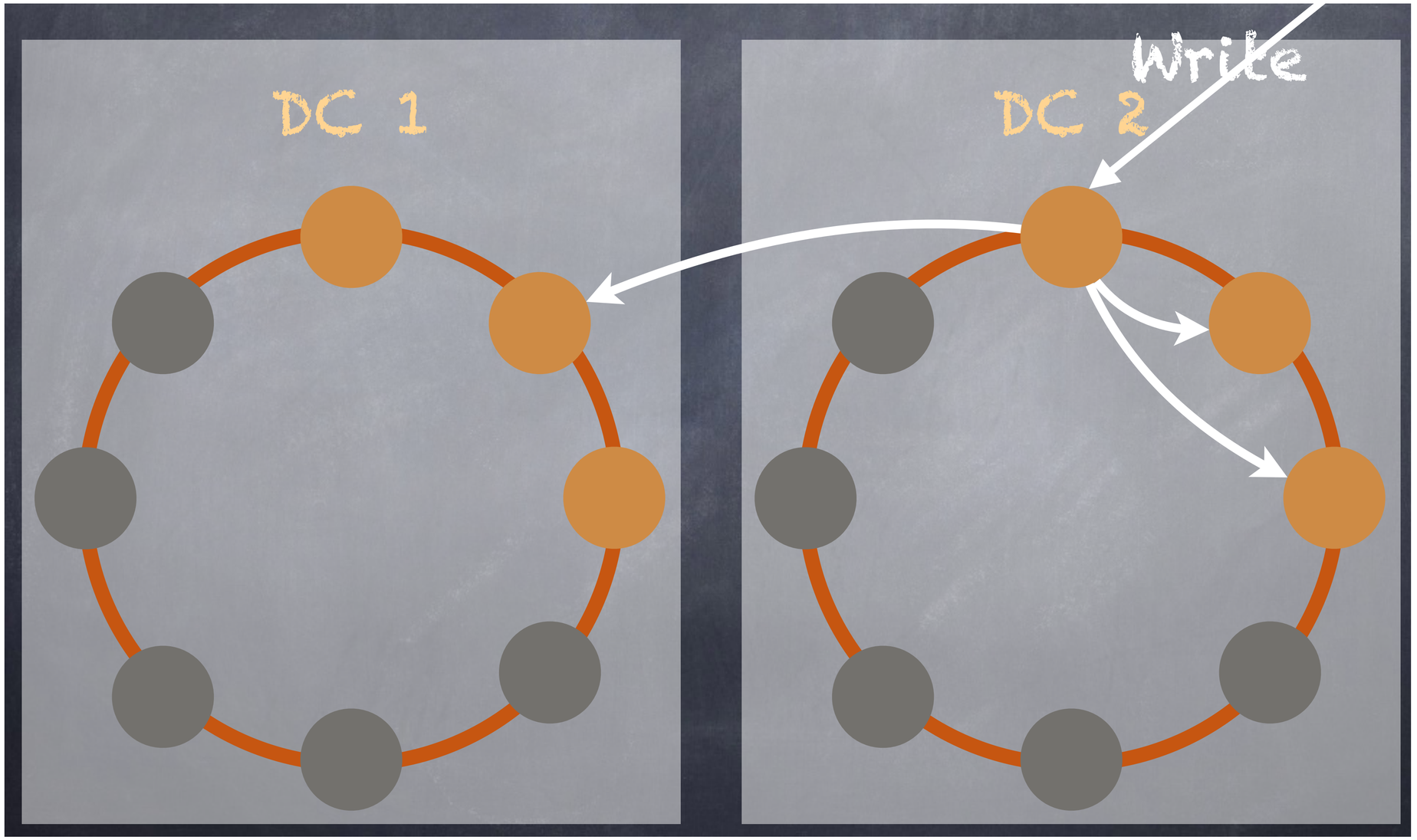

[R. Stupp]

# Cassandra: Consistency Levels

- Data is always replicated according to replication factors
- Consistency Levels: ANY (only writes), ONE, LOCAL_ONE, QUORUM, LOCAL_QUORUM
- Consistency levels defines how many replicas must fulfill the request
- LOCAL_* are local to the data center, others go across data centers
- quorum = (sum-of-replication-factors / 2) + 1
  - Each data center may have its own replication factor
- ANY provides lowest consistency but highest availability
- ALL provides the highest consistency and lowest availability (not recommended)

[R. Stupp]

# Multiple Data Center Replication




[R. Stupp]

# NewSQL

A. Pavlo

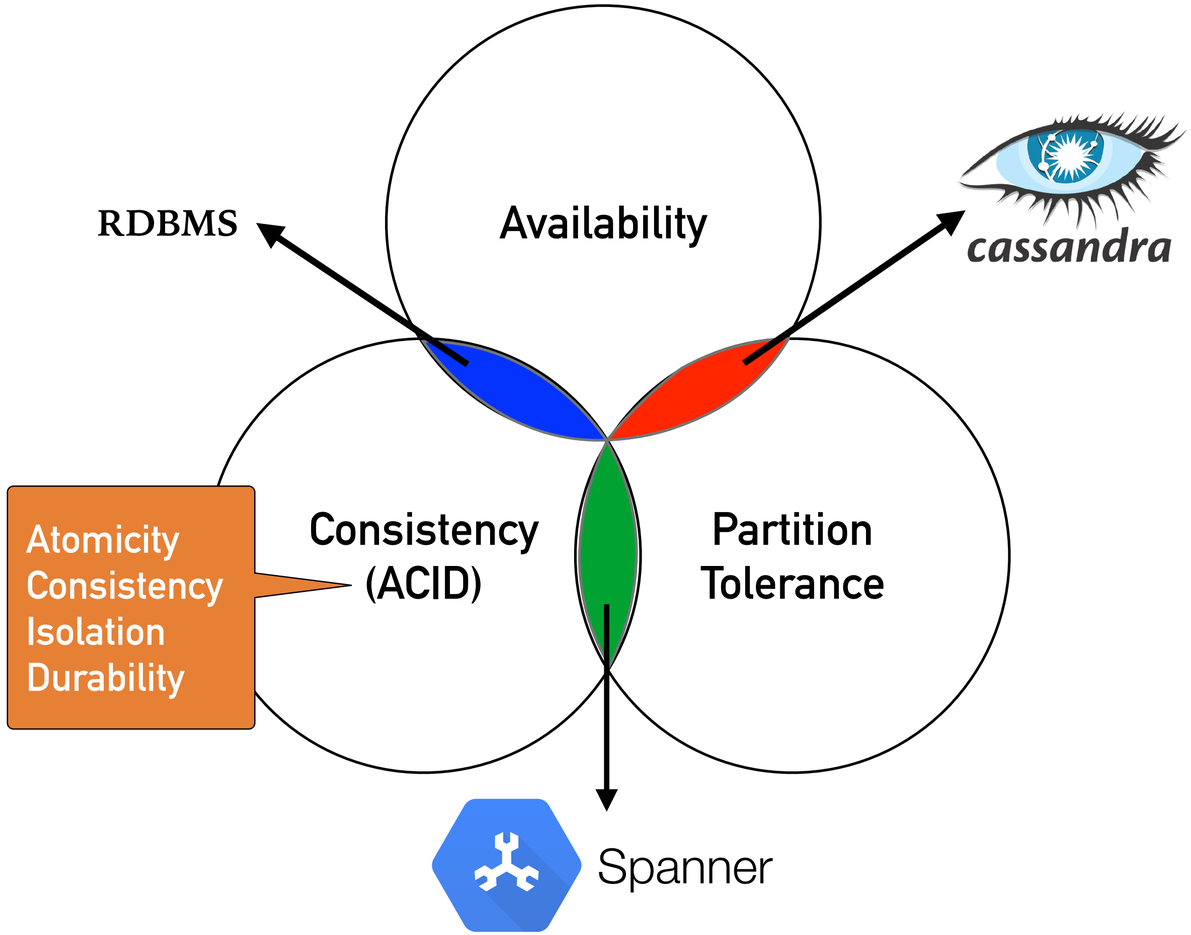
# Spanner:
# Google's Globally-Distributed Database

J. C. Corbett et al.

# Spanner Overview

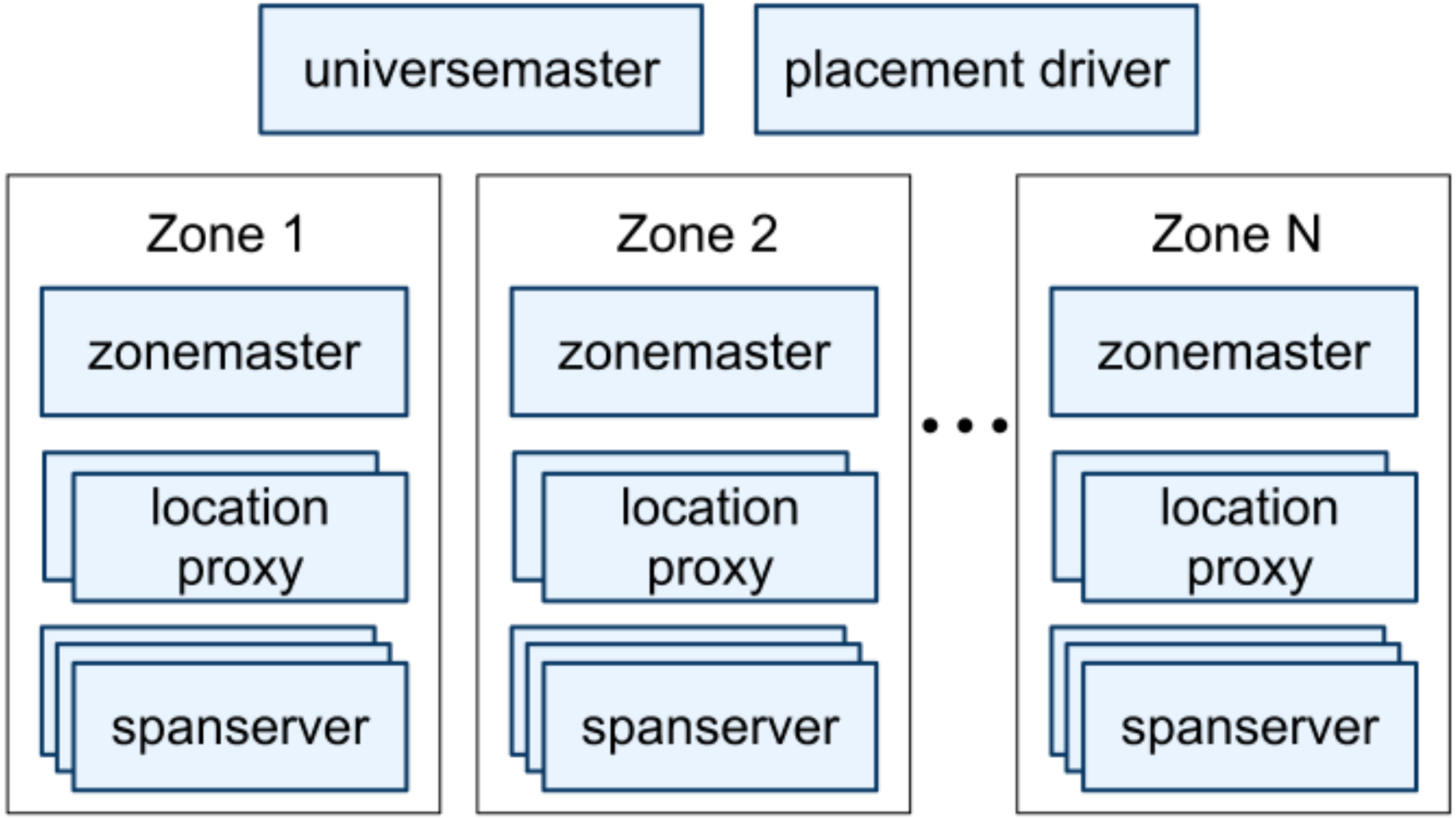
- Focus on scaling databases focused on OLTP (not OLAP)
- Since OLTP, focus is on sharding **rows**
- Tries to satisfy CAP (which is impossible per CAP Theorem) by not worrying about 100% availability
- External consistency using multi-version concurrency control through timestamps
- ACID is important
- Structured: universe with zones with zone masters and then spans with span masters
- SQL-like (updates allow SQL to be used with Spanner)

# Spanner and the CAP Theorem




- Which type of system is Spanner?
  - C: consistency, which implies a single value for shared data
  - A: 100% availability, for both reads and updates
  - P: tolerance to network partitions
- Which two?
  - CA: close, but not totally available
  - So actually **CP**

# Spanner Server Organization

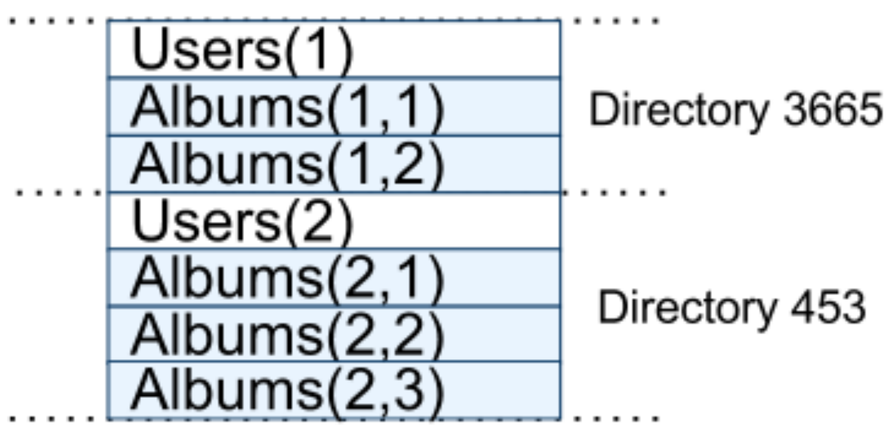



[Corbett et al., 2012]

# Interleaved Schema

```
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;
```




[Corbett et al., 2012]

# External Consistency

- Traditional DB solution: **two-phase locking**—no writes while client reads
- "The system behaves as if all transactions were executed sequentially, even though Spanner actually runs them across multiple servers (and possibly in multiple datacenters) for higher performance and availability" [Google]
- Semantically indistinguishable from a single-machine database
- Uses multi-version concurrency control (MVCC) using **timestamps**
- Spanner uses **TrueTime** to generate monotonically increasing timestamps across all nodes of the system

# TrueTime

- API to try to keep computers on a globally-consistent clock
- Uses GPS and Atomic Clocks!
- Time masters per datacenter (usually with GPS)
- Each machine runs a timeslave daemon
- Armageddon masters have atomic clocks
- 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 |

[Corbett et al., 2012]

# Concurrency Control

- Use TrueTime to implement concurrency control
- Types of reads and writes:

| 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 |

- Use Two-Phase Commits (2PC)

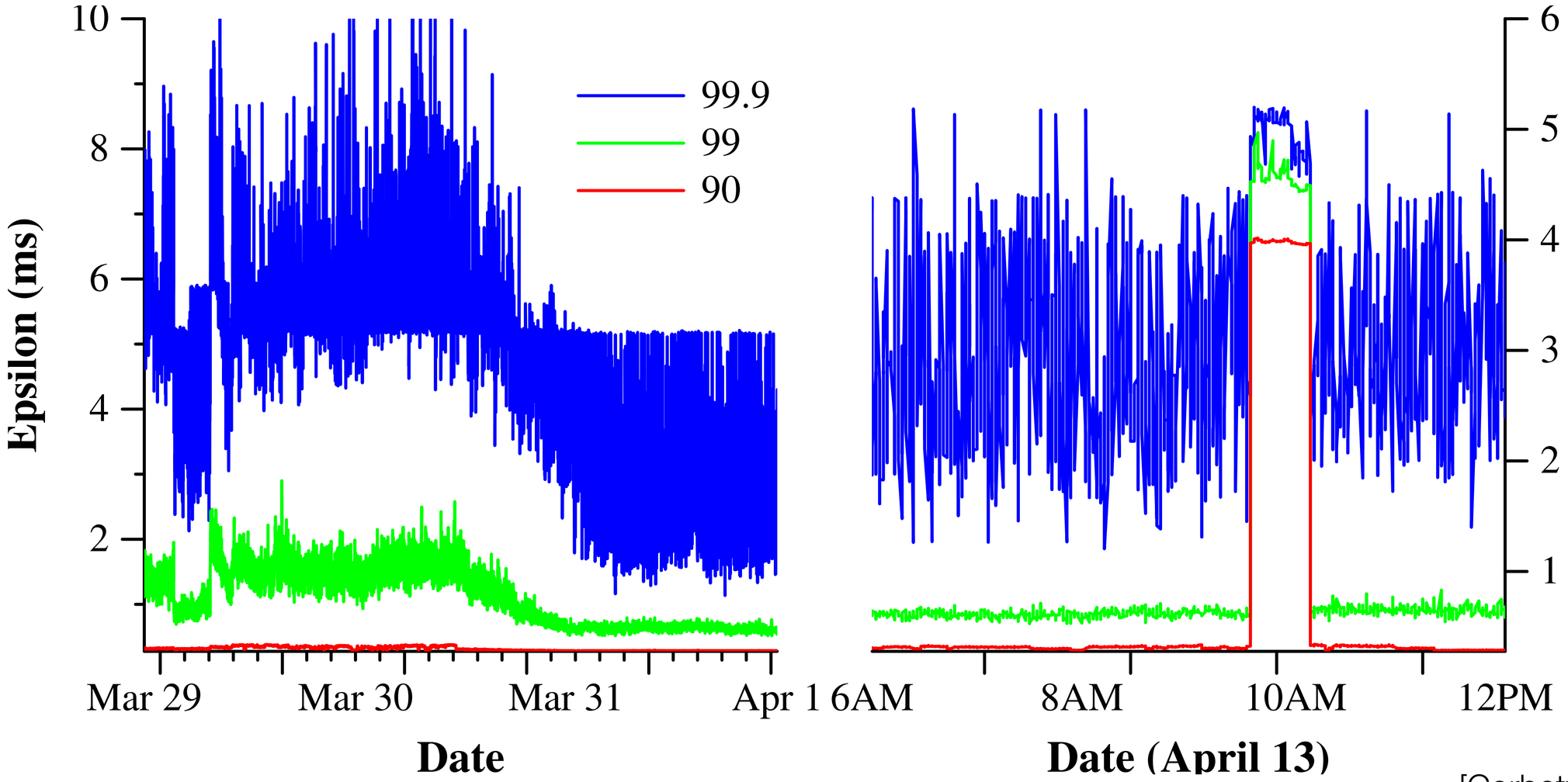
[Corbett et al., 2012]

# Two-Phase Commit Scalability

| 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 |

[Corbett et al., 2012]

# Distribution of TrueTime Epsilons




[Corbett et al., 2012]

# Discussion

# Google Cloud Spanner

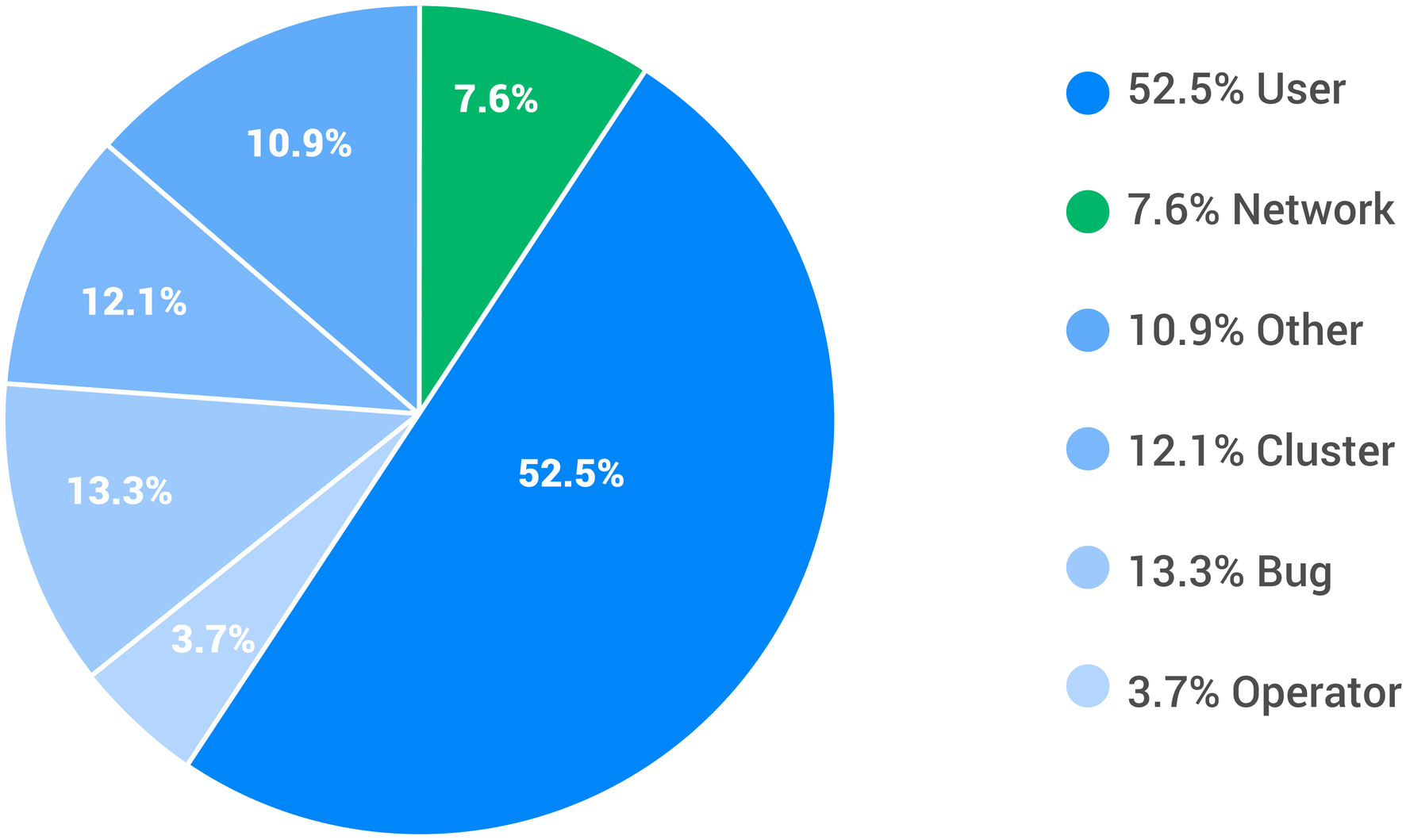
- https://cloud.google.com/spanner/
- Features:
  - Global Scale: thousands of nodes across regions / data centers
  - Fully Managed: replication and maintenance are automatic
  - Transactional Consistency: global transaction consistency
  - Relational Support: Schemas, ACID Transactions, SQL Queries
  - Security
  - Highly Available

# Google Cloud Spanner: NewSQL

| | 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 |

[https://cloud.google.com/spanner/]

# Causes of Spanner Availability Incidents




[E. Brewer, 2017]

# Causes of Spanner Incidents

- User: overload or misconfiguration (specific to one user)
- Cluster: non-network problems, e.g. servers and power
- Operator: misconfiguration by people
- Bug: software error that caused some problem
- Other: most are one-offs
- Network: individual data centers/regions cut off and under-provisioned bandwidth, uni-directional traffic

[E. Brewer, 2017]

# Spanner as "Effectively CA"

- Criteria for being "effectively CA"
  1. At a minimum it must have very high availability in practice (so that users can ignore exceptions), and
  2. As this is about partitions it should also have a low fraction of those outages due to partitions.
- Spanner meets both of these criteria
- Spanner relies on Google's **network** (private links between data centers)
- TrueTime helps create **consistent snapshots**, sometimes have a commit wait

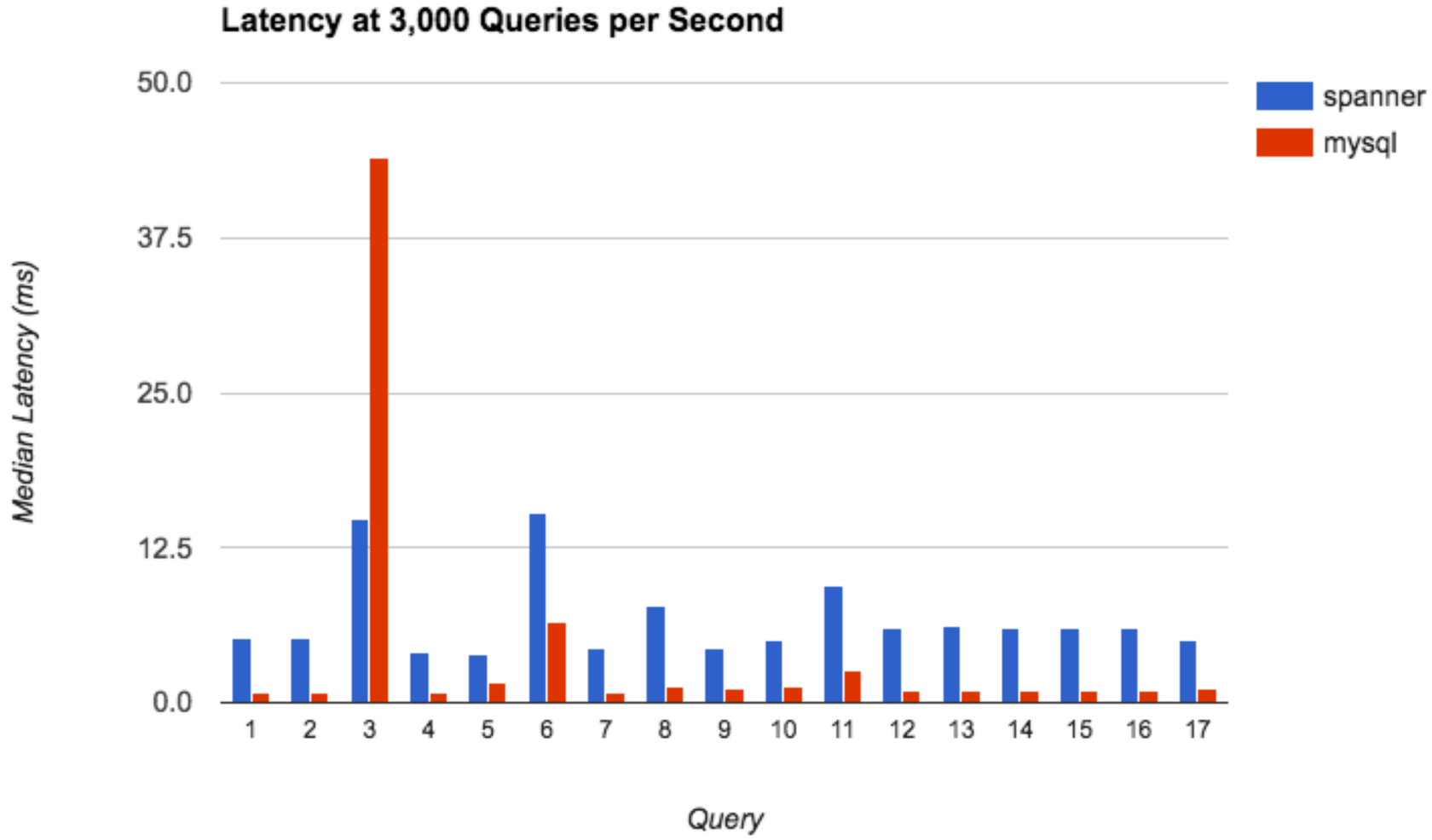
[E. Brewer, 2017]

# More Recent Tests: Spanner vs. MySQL

| | Frequency | Query |
|---|---|---|
| 1 | 0.30% | INSERT INTO `terms` (`term`, `rank`, `set_id`, `last_modified`) VALUES (?,?,?,?),(?,?,?,?) |
| 2 | 0.25% | INSERT INTO `terms` (`term`, `rank`, `set_id`, `last_modified`, `definition`) VALUES (?,?,?,?,?),(?,?,?,?,?),(?,?,?,?,?),... |
| 3 | 4.22% | INSERT INTO `terms` (`term`,`rank`,`set_id`,`last_modified`) VALUES (?,?,?,?) |
| 4 | 1.88% | INSERT INTO `terms` (`term`,`rank`,`set_id`,`last_modified`,`definition`) VALUES (?,?,?,?,?) |
| 5 | 3.28% | SELECT * FROM `terms` WHERE (`is_deleted` = 0) AND (`set_id` IN (??)) AND (`rank` IN (0,1,2,3)) AND (`term` != '') |
| 6 | 14.13% | SELECT `set_id`, COUNT(*) FROM `terms` WHERE (`is_deleted` = 0) AND (`set_id` = ?) GROUP BY `set_id` |
| 7 | 12.56% | SELECT * FROM `terms` WHERE (`id` = ?) |
| 8 | 0.49% | SELECT * FROM `terms` WHERE (`id` IN (??) AND `set_id` IN (??)) |
| 9 | 4.11% | SELECT `id`, `set_id` FROM `terms` WHERE (`set_id` = ?) LIMIT 20000 |
| 10 | 0.43% | SELECT `id`, `set_id` FROM `terms` WHERE (`set_id` IN (??)) LIMIT 20000 |
| 11 | 0.59% | SELECT * FROM `terms` WHERE (`id` IN (??)) |
| 12 | 36.76% | SELECT * FROM `terms` WHERE (`set_id` = ?) |
| 13 | 0.61% | SELECT * FROM `terms` WHERE (`set_id` IN (??)) |
| 14 | 6.10% | UPDATE `terms` SET `definition`=?, `last_modified`=? WHERE `id`=? AND `set_id`=? |
| 15 | 0.33% | UPDATE `terms` SET `is_deleted`=?, `last_modified`=? WHERE `id` IN (??) AND `set_id`=?? |
| 16 | 12.56% | UPDATE `terms` SET `rank`=?, `last_modified`=? WHERE `id`=? AND `set_id`=? |
| 17 | 1.06% | UPDATE `terms` SET `word`=?, `last_modified`=? WHERE `id`=? AND `set_id`=? |
| 18 | 0.32% | UPDATE `terms` SET `definition`=?, `word`=?, `last_modified`=? WHERE `id`=? AND `set_id`=? |

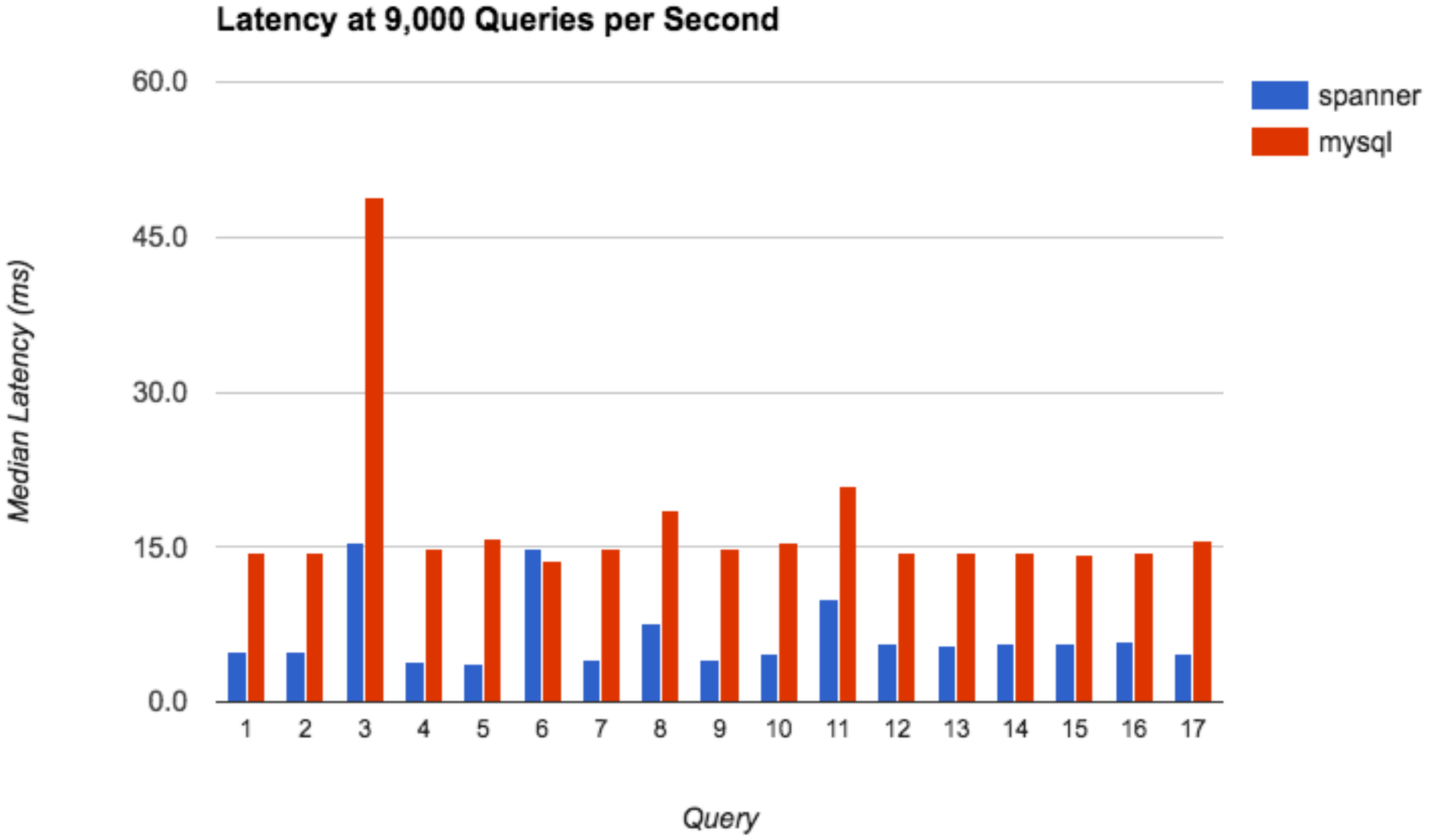
[P. Bakkum and D. Cepeda, 2017]

# Latency: Spanner vs. MySQL



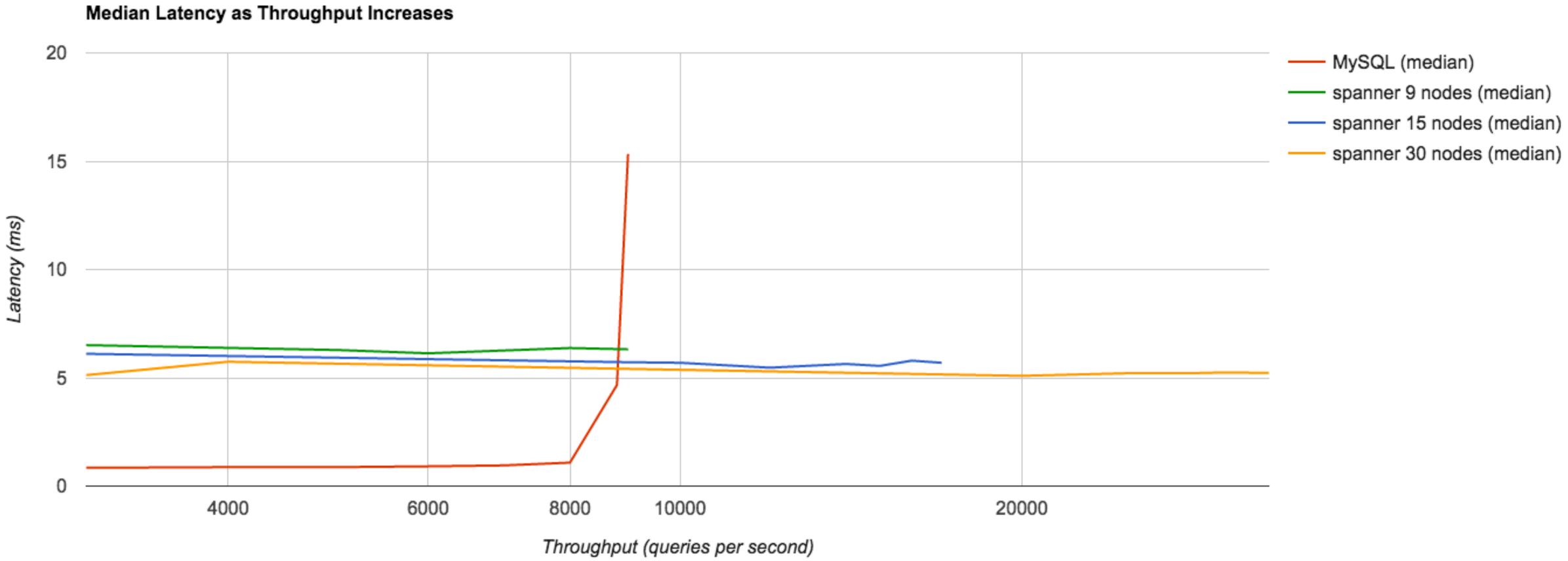

[P. Bakkum and D. Cepeda, 2017]

# Latency: Spanner vs. MySQL



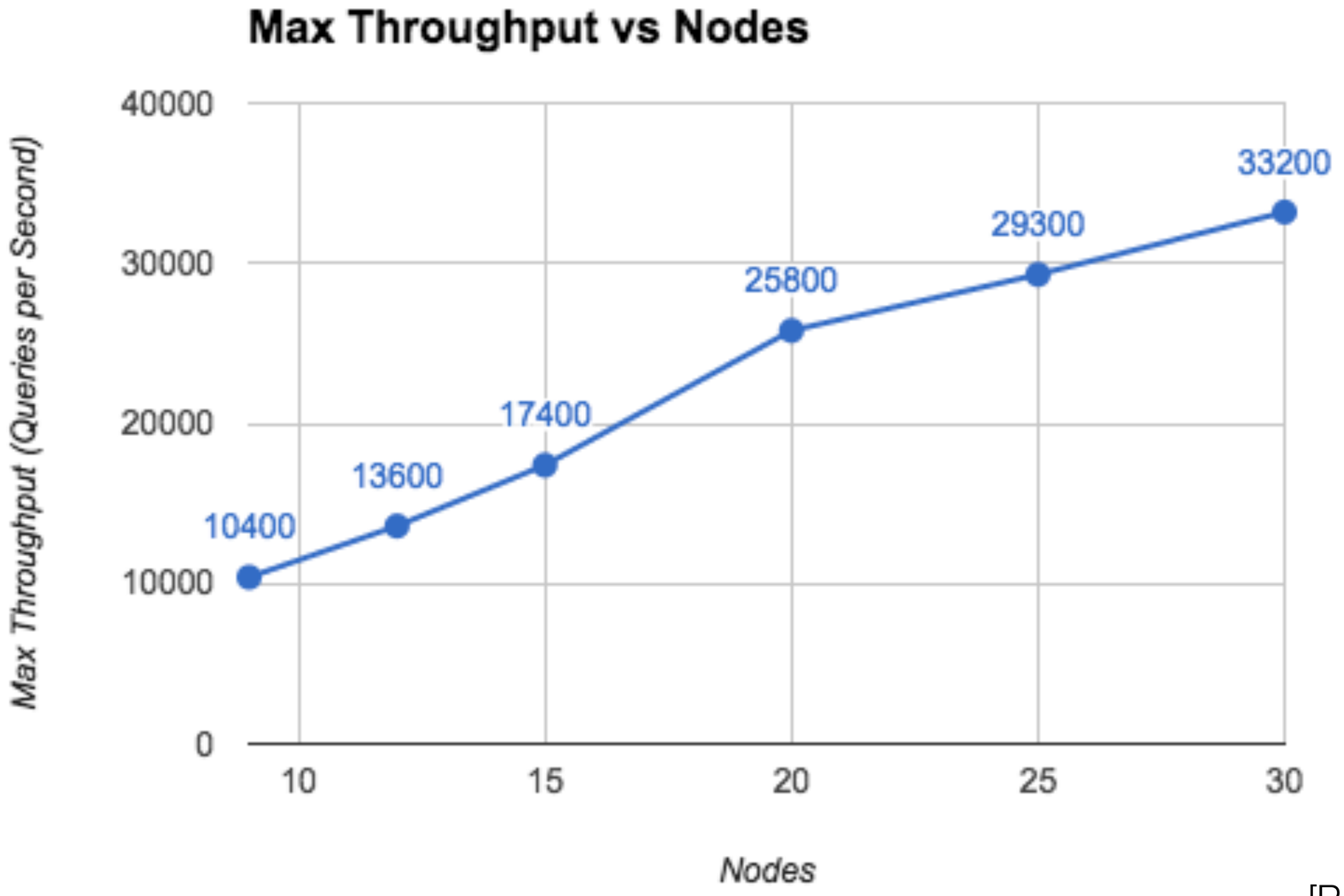

[P. Bakkum and D. Cepeda, 2017]

# Throughput: Spanner vs. MySQL



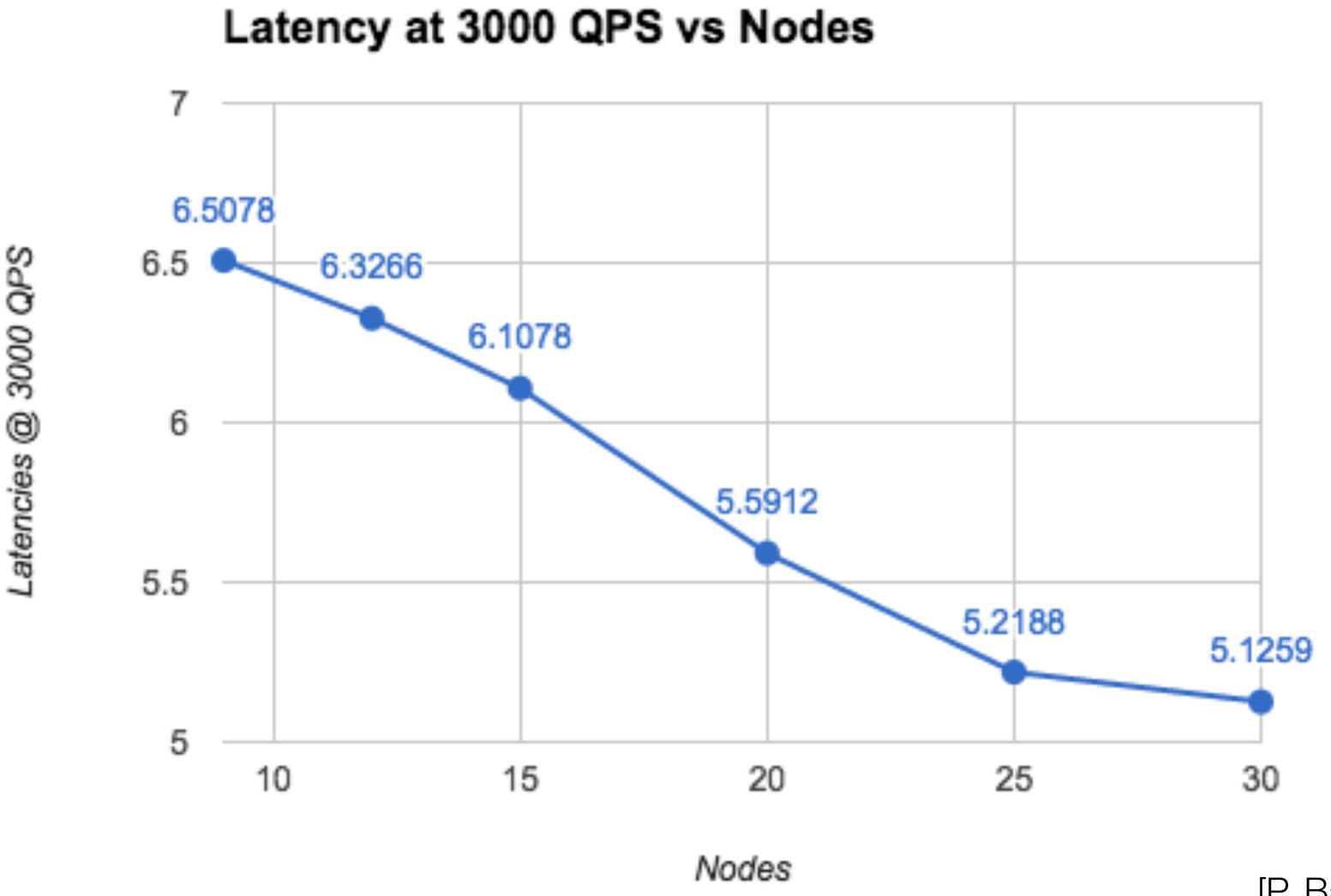

[P. Bakkum and D. Cepeda, 2017]

# Max Throughput vs. Nodes




[P. Bakkum and D. Cepeda, 2017]

# Spanner: Latency vs. Nodes




[P. Bakkum and D. Cepeda, 2017]

# Discussion

# F1: A Distributed SQL Database That Scales

J. Shute, R. Vingralek, B. Samwel, B. Handy, C. Whipkey,
E. Rollins, M. Oancea, K. Littlefield, D. Menestrina, S. Ellner,
J. Cieslewicz, I. Rae, T. Stancescu, and H. Apte

# F1: OLTP and OLAP Together

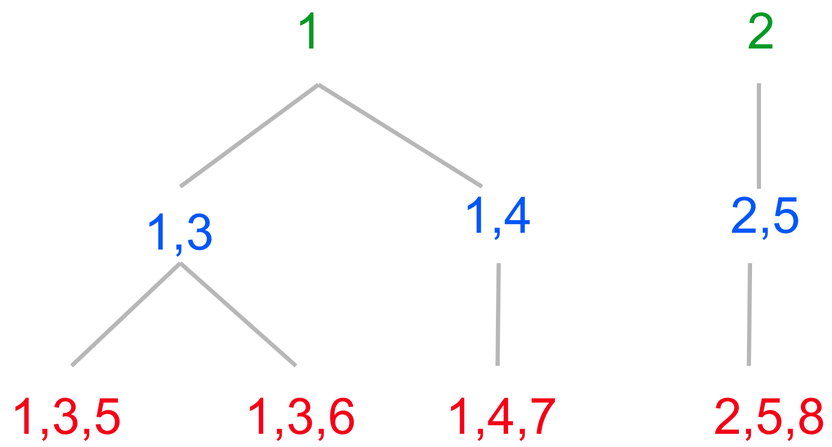
- Distributed data storage: data is not stored at one central location
- Need to keep data and schemas in sync
- Hierarchical schemas keep data that is likely to be accessed at the same time together
- Optimistic Transactions: Long reads that keep track of timestamps and don't lock the database until the write happens
- Change History: Keep track of history with database, also helps with caching
- DIY Object-Relational Mapping: don't automatically join or implicitly traverse relationships
- Protocol buffers as a way to store application data without translation + support for queries

# Hierarchical Schema

Explicit table hierarchies. Example:

- Customer (root table): PK (CustomerId)
- Campaign (child): PK (CustomerId, CampaignId)
- AdGroup (child): PK (CustomerId, CampaignId, AdGroupId)

**Rows and PKs**




**Storage Layout**

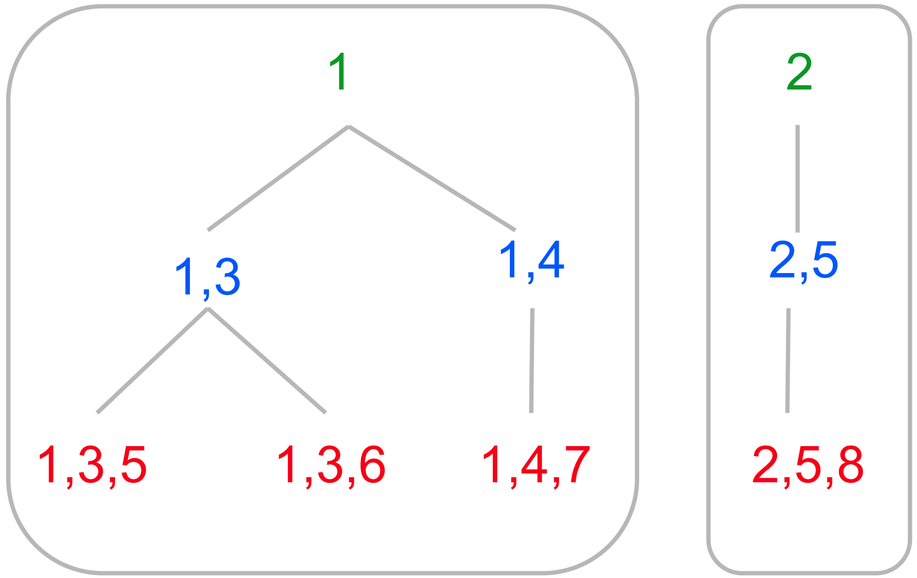
```
Customer  (1)
Campaign  (1,3)
AdGroup   (1,3,5)
AdGroup   (1,3,6)
Campaign  (1,4)
AdGroup   (1,4,7)
Customer  (2)
Campaign  (2,5)
AdGroup   (2,5,8)
```

[Shute et al., 2012]

# Clustered Storage

- Child rows under one root row form a **cluster**
- Cluster stored on one machine (unless huge)
- Transactions within one cluster are most efficient
- Very efficient joins inside clusters (can merge with no sorting)

**Rows and PKs**




**Storage Layout**

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Customer (1)
Campaign (1,3)
AdGroup  (1,3,5)
AdGroup  (1,3,6)
Campaign (1,4)
AdGroup  (1,4,7)
Customer (2)
Campaign (2,5)
AdGroup  (2,5,8)
```

[Shute et al., 2012]

# F1 Notes

- Schema changes: allow two different schemas
- Transaction types: Snapshot, Pessimistic, Optimistic
- Change History and application to caching
- Disk latency or network latency?