Google Cloud

Spanner

A horizontally scalable, highly-available SQL Database

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Google

3 April 2025

What is Spanner?

Spanner is a SQL Database

```
SELECT COUNT(*) AS Count
FROM Artists AS a
WHERE LEFT(a.name,1) = ‘M’;
```

Spanner is Transactional & Consistent

1 Transaction A

2 Transaction D

3 Transaction B

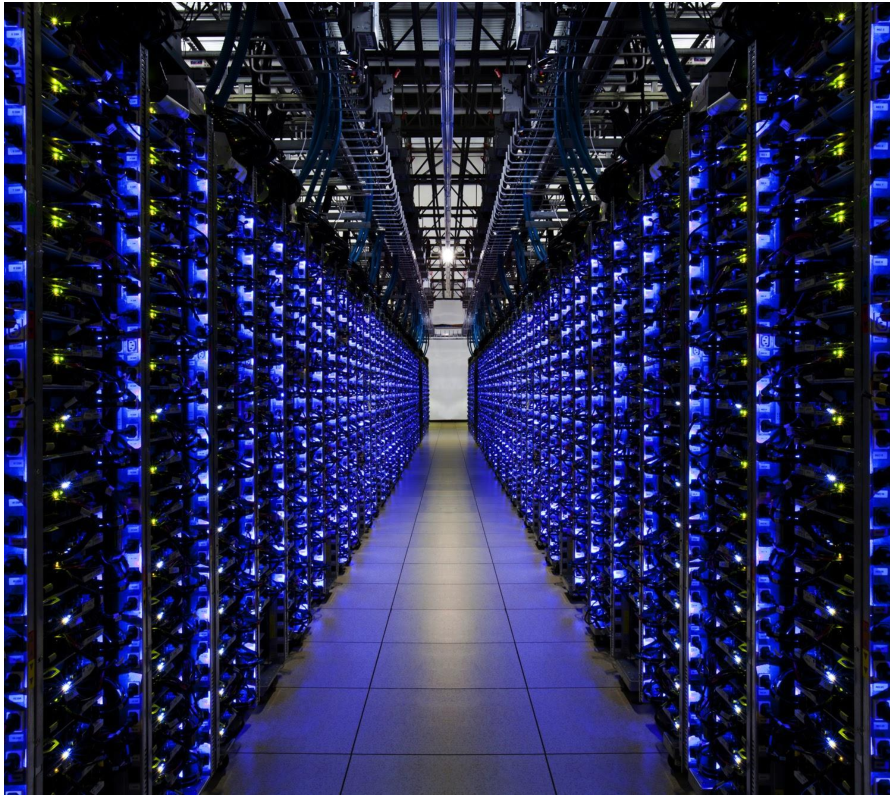
4 Transaction E

External Consistency
(stronger than linearizability and serializability)

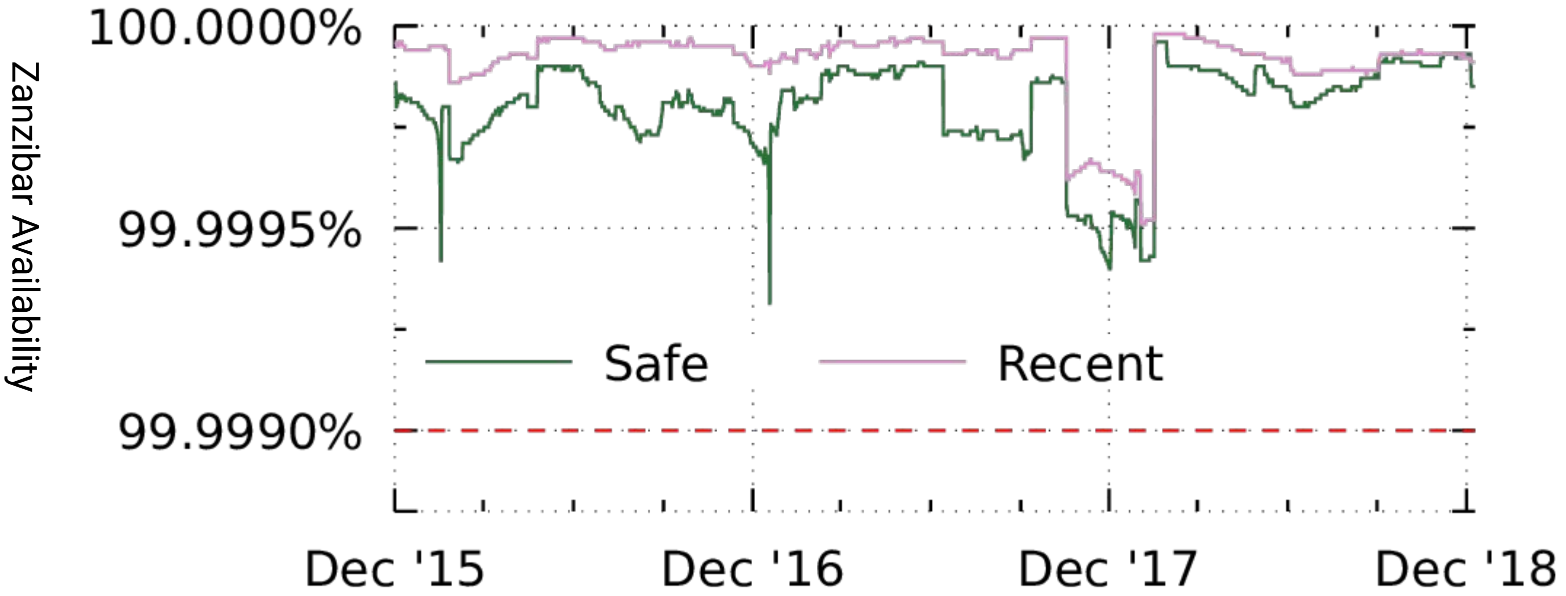
https://cloud.google.com/spanner/docs/true-time-external-consistency

Spanner is Geographically Replicated

Spanner is Horizontally Scalable



Zanzibar Availability on Spanner



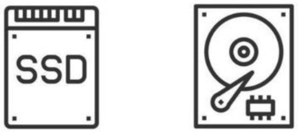
Availability over 3 years remained above 99.999% (“five 9’s”)

99.999% is ~5 minutes of downtime per year.

Pang, Cáceres, et al: [Zanzibar: Google's Consistent, Global Authorization System](), 2019 USENIX Annual Technical Conference

How Big is Spanner?

Spanner’s Scale



15 Exabytes

5 B QPS

What Makes Spanner so Big?

Photos Play Search Maps Ads YouTube Gmail Calendar Drive Docs Meet

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Google Cloud

Cloud Control Plane

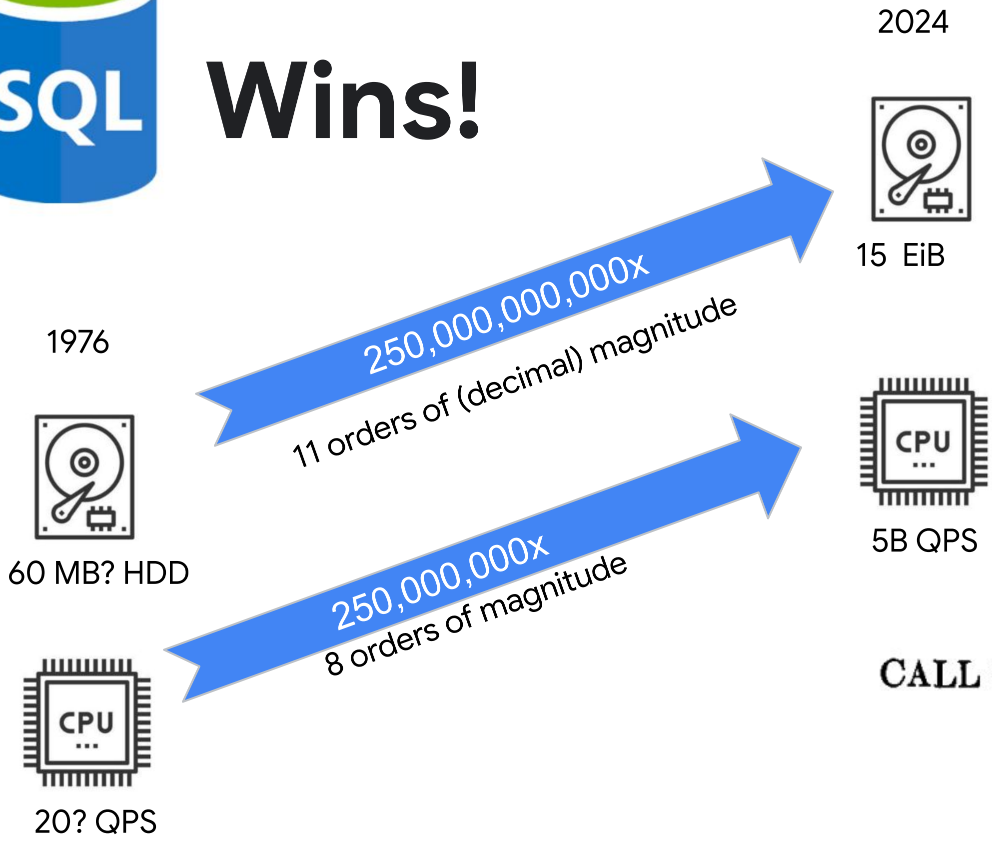
Cloud Spanner

Zanzibar

google3

Google's internal infrastructure

SQL Wins!




```
CALL SEQUEL('UNDERPAID(NAME, SAL) ←
        SELECT   NAME, SAL
        FROM     EMP
        WHERE    JOB = ''PROGRAMMER''
        AND      SAL < 10,000');
```

Astrahan et al: "System R: Relational Approach to Database Management" *ACM TODS 1*, 2 (June 1976)

Programmers Not So Much

```
CALL SEQUEL('UNDERPAID(NAME, SAL) ←
        SELECT   NAME, SAL
        FROM     EMP
        WHERE    JOB = ''PROGRAMMER''
        AND      SAL < 10,000');
```

1976

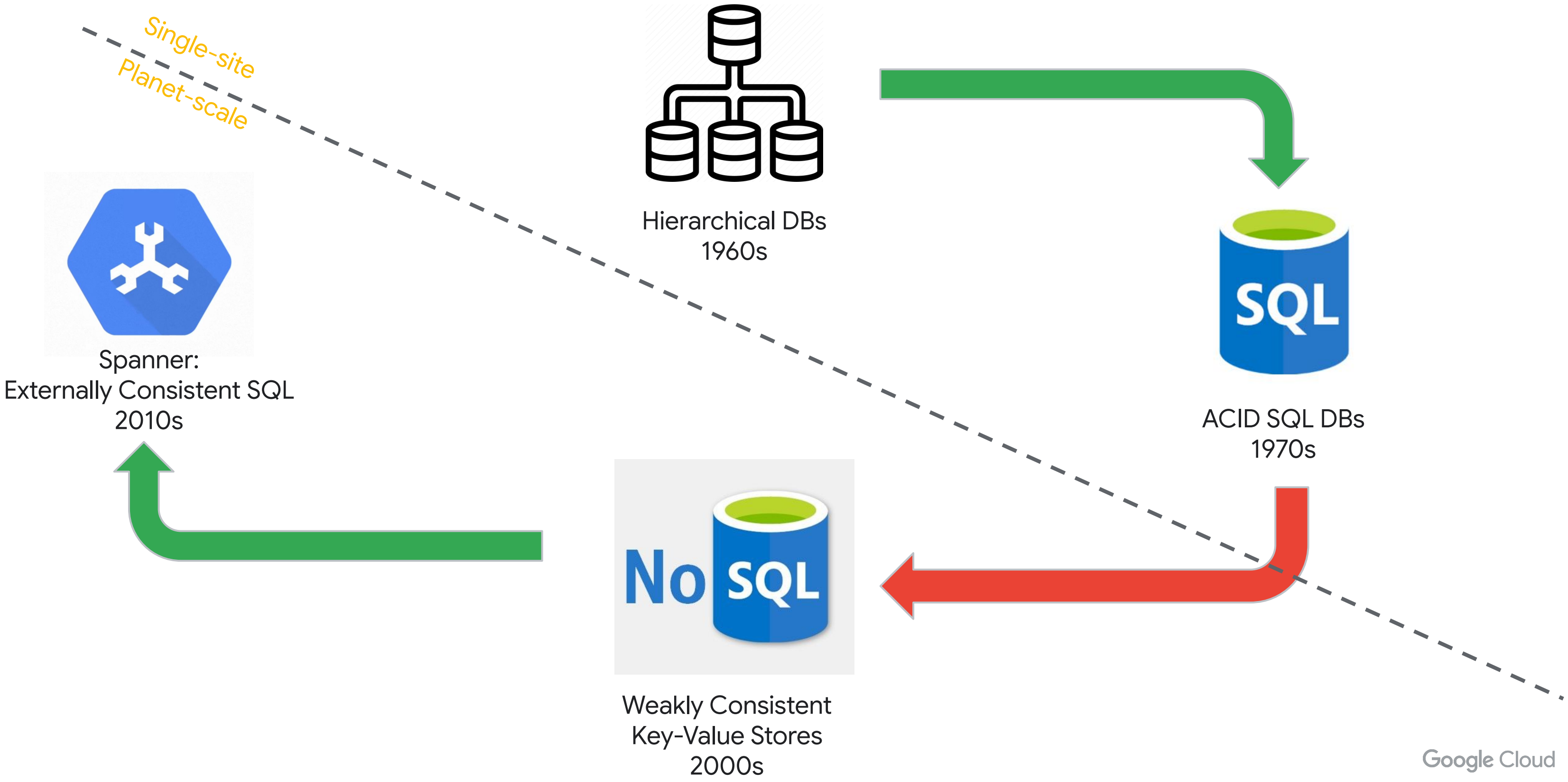
< $10,000

1 order of magnitude

2024

< $100,000

Coming Full Cycle



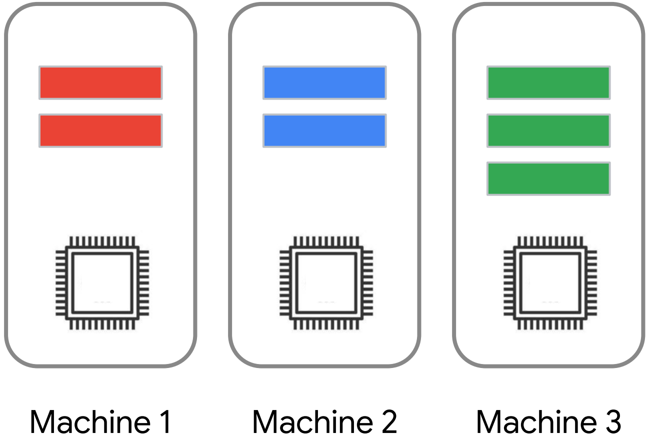
How Does Spanner Scale?

SQL Example (not so unrealistic)

```
CREATE TABLE Songs (
  ArtistId      INT64 NOT NULL,
  AlbumId       INT64 NOT NULL,
  TrackId       INT64 NOT NULL,
  SongName      STRING(MAX),
  ...
) PRIMARY KEY (
  ArtistId, AlbumId, TrackId)
```

ArtistId	AlbumId	TrackId	SongName
1	1	1	A Night in Tunisia
1	2	1	Exuberante
3	1	1	Straight, No Chaser
3	2	1	All Blues
3	2	2	Flamenco Sketches
3	2	3	So What
5	1	1	Gangnam Style

Sharding



ArtistId	AlbumId	TrackId	SongName
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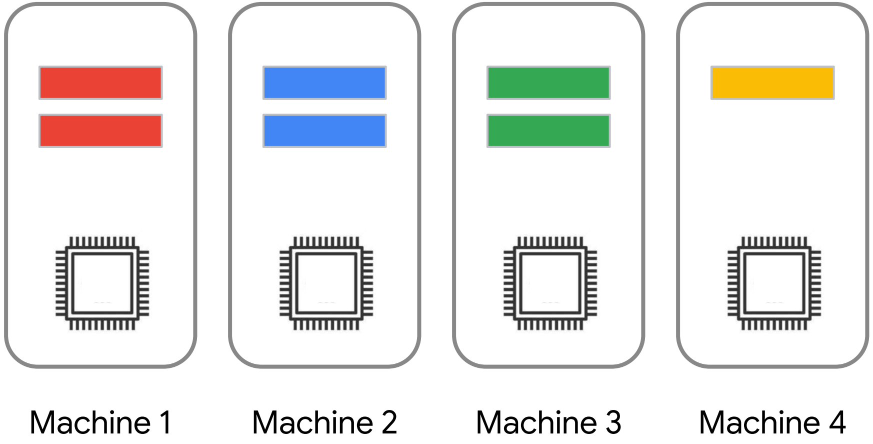
3	2	1	All Blues
3	2	2	Flamenco Sketches
3	2	3	So What
5	1	1	Gangnam Style

Splitting (and Merging)



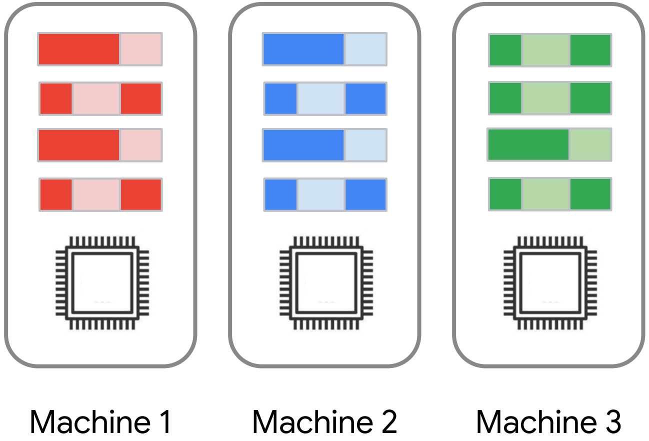
ArtistId	AlbumId	TrackId	SongName
1	1	1	A Night in Tunisia
1	2	1	Exuberante
3	1	1	Straight, No Chaser
3	2	1	All Blues
3	2	2	Flamenco Sketches
3	2	3	So What
5	1	1	Gangnam Style

Interleaving

```
CREATE TABLE Albums (
  ArtistId      INT64 NOT NULL,
  AlbumId       INT64 NOT NULL,
  AlbumName     STRING(MAX),
  ...
) PRIMARY KEY (
  ArtistId, AlbumId);
```

```
CREATE TABLE Songs (
  ArtistId      INT64 NOT NULL,
  AlbumId       INT64 NOT NULL,
  TrackId       INT64 NOT NULL,
  SongName      STRING(MAX),
  ...
) PRIMARY KEY (
  ArtistId, AlbumId, TrackId),
INTERLEAVE IN PARENT Albums;
```

Interleaving



ArtistId	AlbumId	AlbumName	TrackId	SongName
1	1	Best of Dizzy Gillespie		
1	1		1	A Night in Tunisia
1	2	Afro-Cuban Moods		
1	2		1	Exuberante
3	1	Milestones		
3	1		1	Straight, No Chaser
3	2	All Blues		
3	2		1	All Blues
3	2		2	Flamenco Sketches
3	2		3	So What
5	1	Psy 6 (Six Rules)		
5	1		1	Gangnam Style

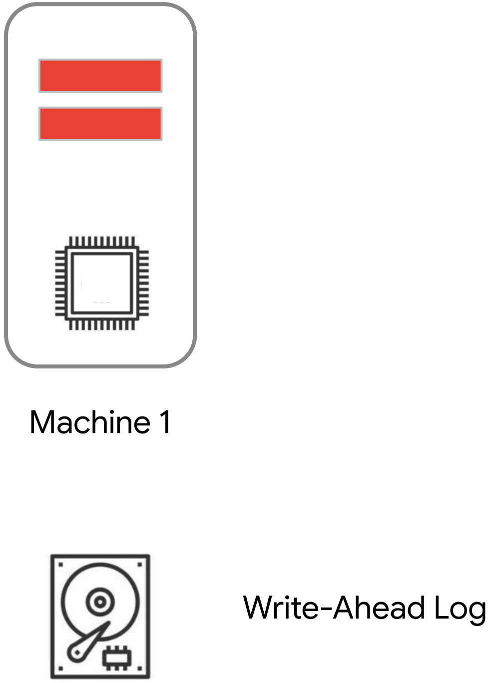
Transactions &
High Availability

Transactions: Single-Shard

Well-understood:

- Transaction Manager with pessimistic locking
- Strict 2-Phase Locking
- Write-Ahead Logging to persistent storage (disk)

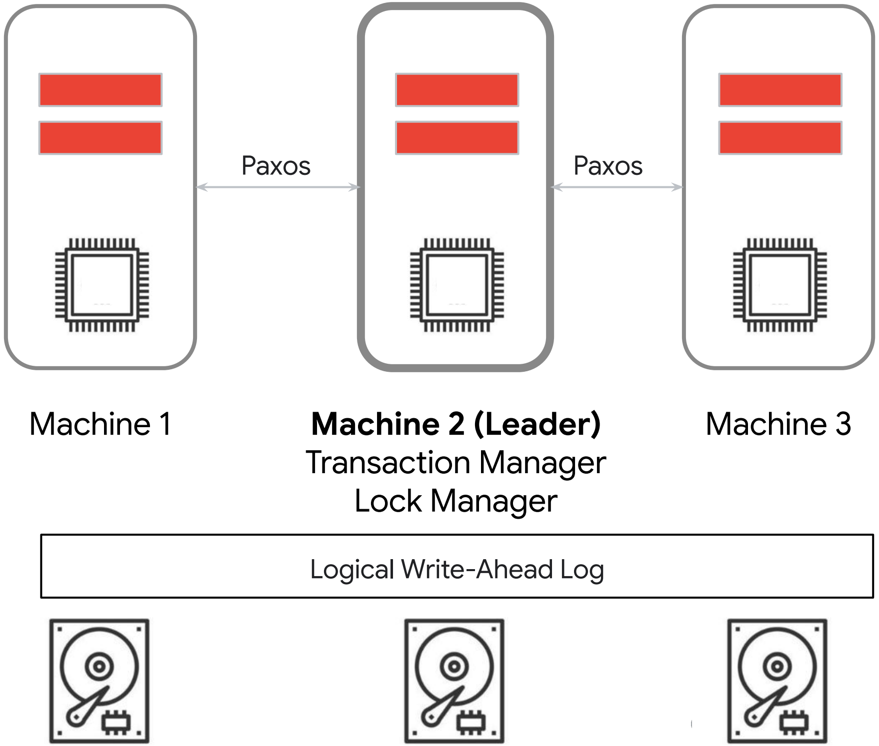
But what about machine failures? Want copies of the data on multiple machines (ideally in different data centers).



Transactions: Paxos

Answer: Paxos (or Raft)

- Synchronous replication protocol
- Gracefully deals with failures
  - Makes progress as long as majority of replicas are alive
- Elects a leader to manage writes
  - Transaction Manager and Lock Manager run here



Paxos in a Nutshell

Manages a shared log of writes. Every replica applies log entries in order.

Consists of N = 2f + 1 nodes

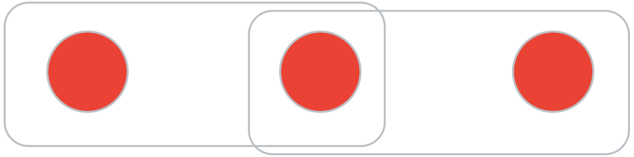
- Can tolerate f failures

Examples:

- N=3 nodes: tolerate 1 failed node
- N=5 nodes: tolerate 2 failed nodes

Quorum: Majority of nodes (f + 1)

Observation: Intersection between any two quorums is at least one node.



Distributed Transactions

What about transactions that span multiple shards?

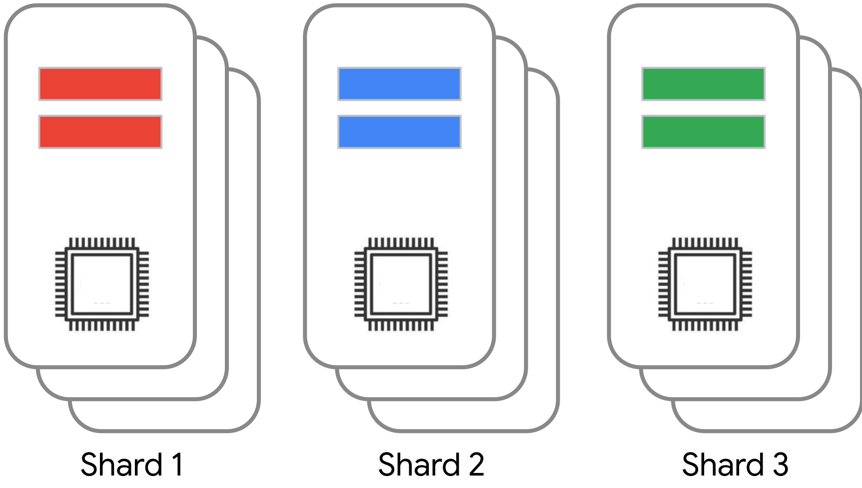
Answer: 2-Phase Commit (2PC)

- Participants are paxos groups (not individual machines)
- One participant picked as Coordinator
- All participants (durably) prepare and notify coordinator
    - Promise not to release locks
- Coordinator commits transaction once all participants have prepared, then notifies participants

Biggest down-side of 2PC:

- Gets stuck if coordinator becomes unavailable

We just made every participants (and coordinator) highly available through Paxos!



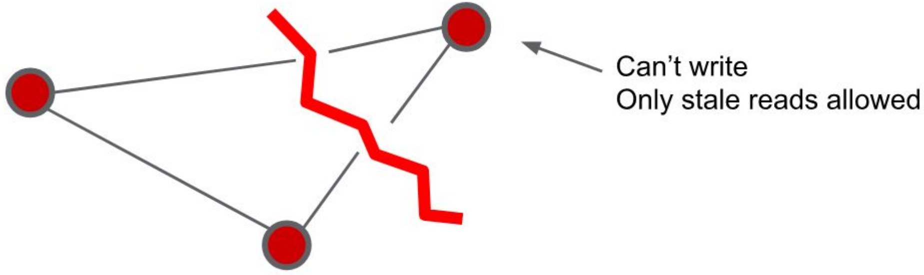
CAP Theorem

C - Consistent
- All nodes have identical data, strong reads

A - Available
- Every request gets a response

P - Partition Tolerant
- Continue to function (correctly) even if a network partition occurs.

Pick 2!



Spanner is a **CP** system.

SQL interface

Common SQL dialect

- Standards-compliant
- Type system aligned with programming languages
  - INT64, FLOAT, STRING (UTF8), TIMESTAMP (nanoseconds)
  - Reduces impedance mismatch
- First-class support for nested data
  - ARRAY and STRUCT types
  - Protocol Buffers: schematized binary objects

    Significant language design work across teams
- Shared with other Google systems: BigQuery, F1, etc.

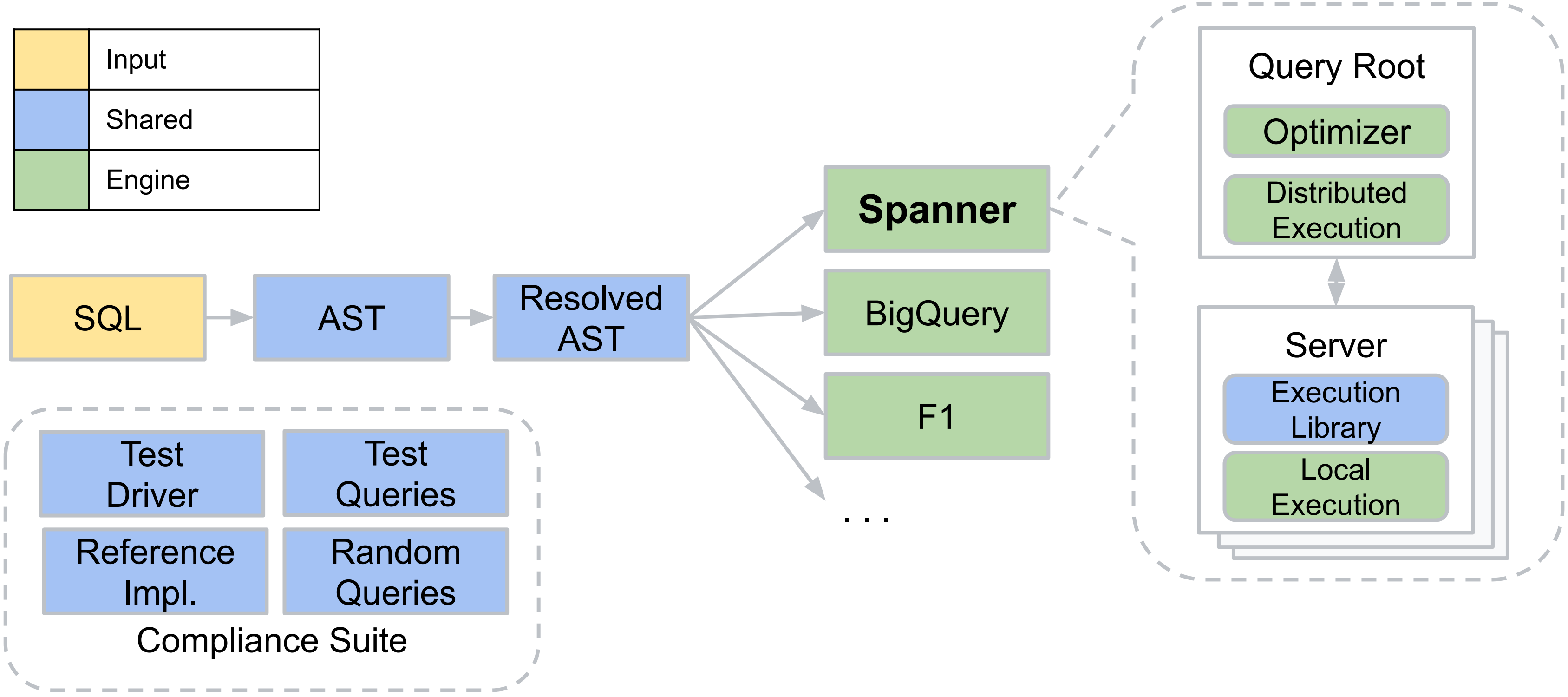
Sample query: name & titles

```
SELECT s.SingerName,
       ARRAY(SELECT a.AlbumTitle
             FROM Albums a
             WHERE a.SingerId = s.SingerId) titles
FROM Singers s
WHERE s.SingerId BETWEEN 1 AND 5
```

SingerName STRING	**titles** ARRAY<STRING>
Beatles	[Help!, Abbey Road]
U2	[ ]
Pink Floyd	[The Wall]

- Easier to use than outer joins or multiple roundtrips

Same query semantics across systems



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Distributed Execution

Distributed query execution

- Tightly coupled architecture
  - Query processor inside the database server
  - Typical design for standalone DBMSes (vs. distributed systems)
- Challenge of scale: data never sits still
  - Continuous resharding (due to load, capacity, config changes, ...)
  - Shard boundaries may change while query is running
  - Shards may become temporarily unavailable during query execution
  - Alternative replicas: near/far, loaded/idle, caught-up/behind
- Mechanisms used in Spanner
  - Query routing: key-range rpcs + range extraction
  - Parallelizing execution: partition work by shards, push it down
  - Dealing with failures: restartable query processing

Query routing: key-range rpcs

- Routes requests to row ranges
  - E.g., `WHERE SingerId BETWEEN @low AND @high`
- Hides complexity of locating data
- Finds nearest, sufficiently up-to-date replica for given concurrency mode
- Retries automatically
  - Unavailability, data movement, schema updates, ...
- Clients cache sharding information
- Clients cache "location hints" for queries
  - Send query to right server without extra hops or query analysis
  - E.g., `Singers/SingerId[@low]`

Query routing: range extraction

```
SELECT * FROM Albums
WHERE (SingerId = 1 AND AlbumId >= 10) OR
      (SingerId IN (2,3) AND AlbumId != 0)
```

- Also used for restricting scan ranges
- Computed at runtime
  - May access data
- Uses efficient data structure
  - Filter tree (in the paper)

SingerId	AlbumId
[1..1]	[10, +INF)
[2..2]	(-INF, 0)
[2..2]	(0, +INF)
[3..3]	(-INF, 0)
[3..3]	(0, +INF)

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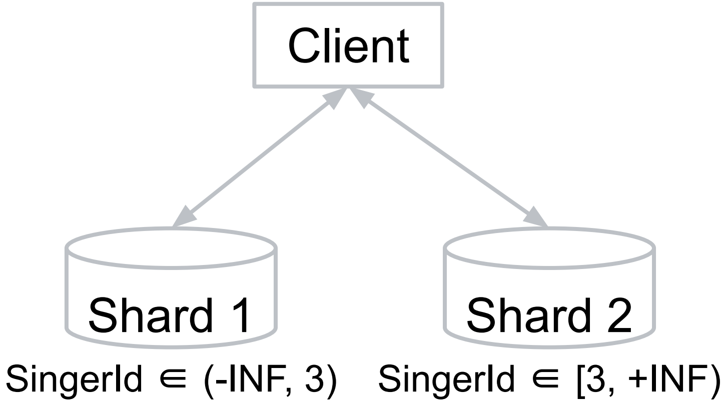
Parallelizing Execution

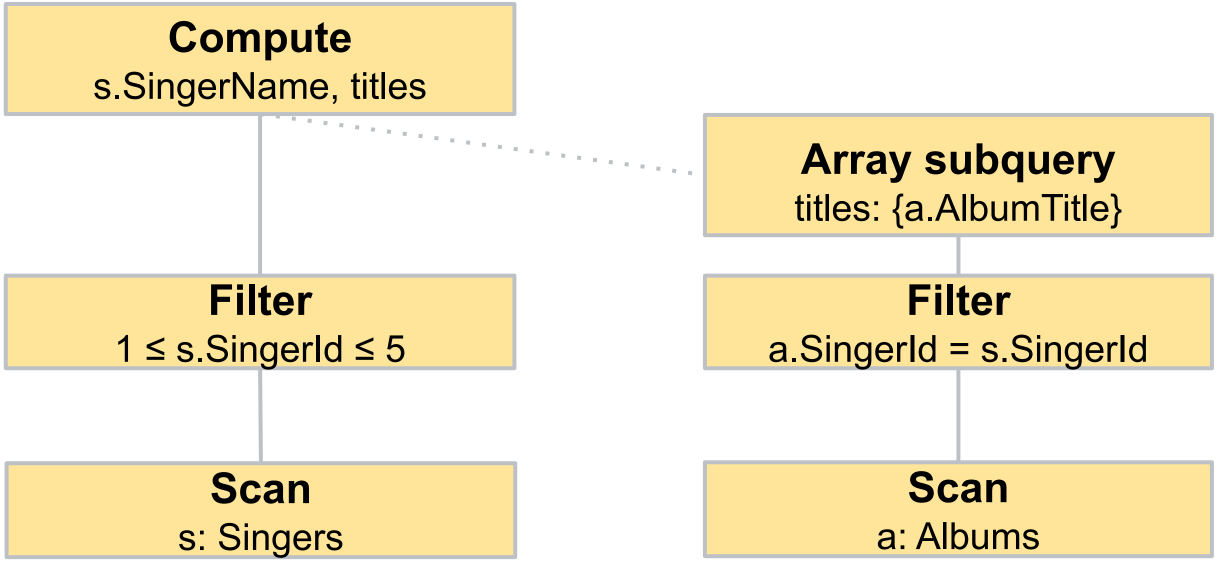
Parallelizing execution

```
SELECT SingerName, ARRAY(SELECT ...) titles
FROM Singers WHERE SingerId BETWEEN 1 AND 5
```

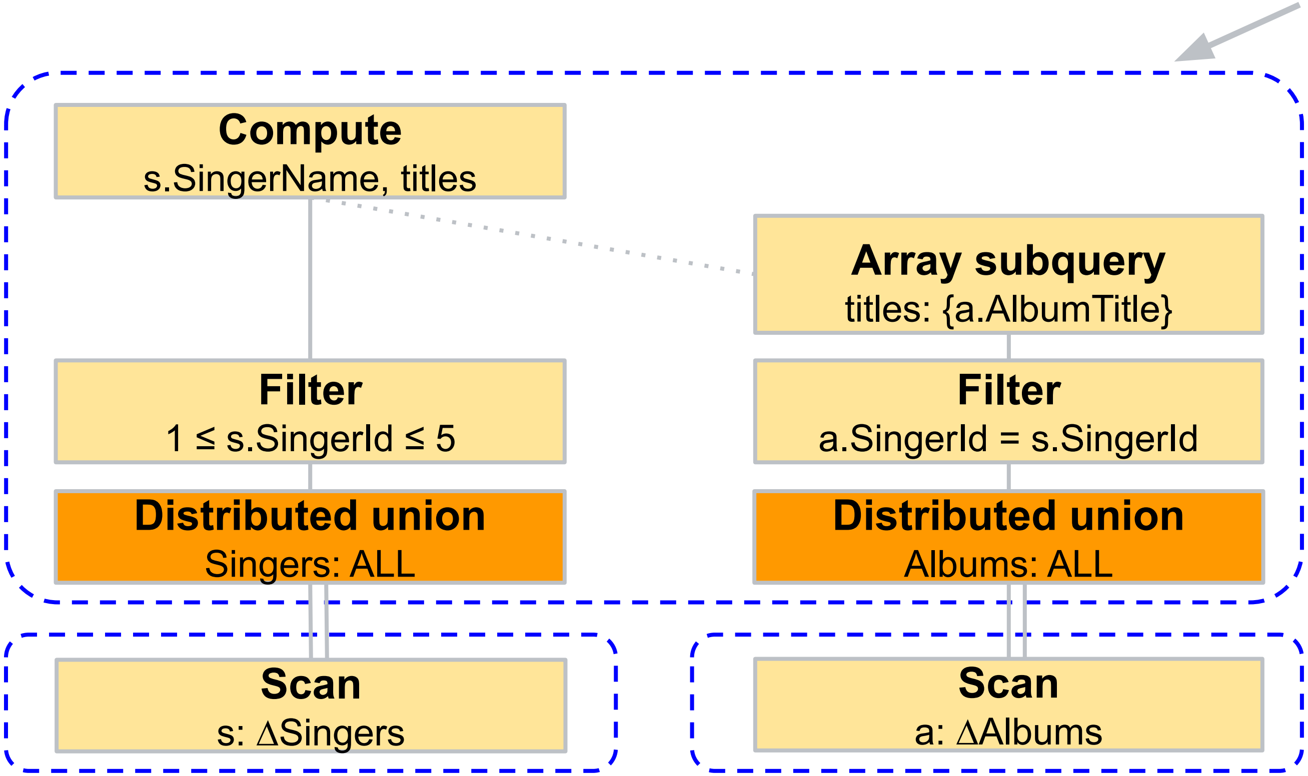


- Assume fixed shard boundaries for now

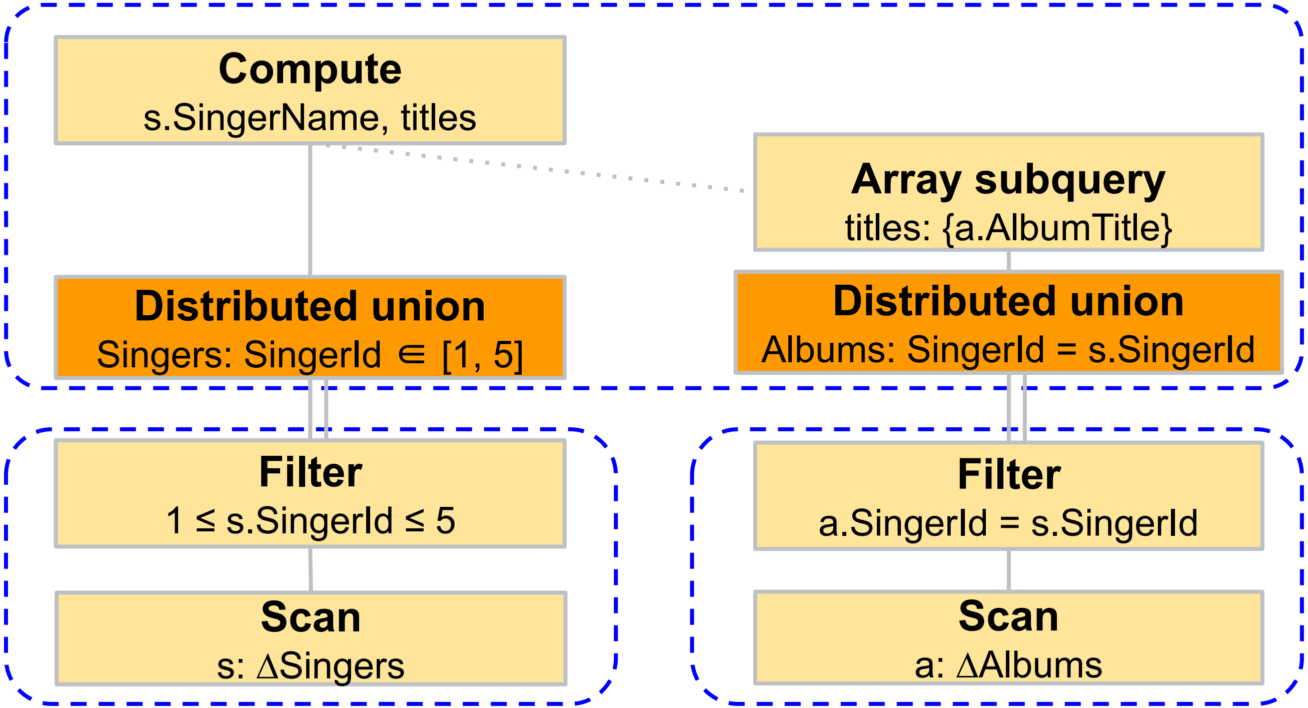
Initial logical plan



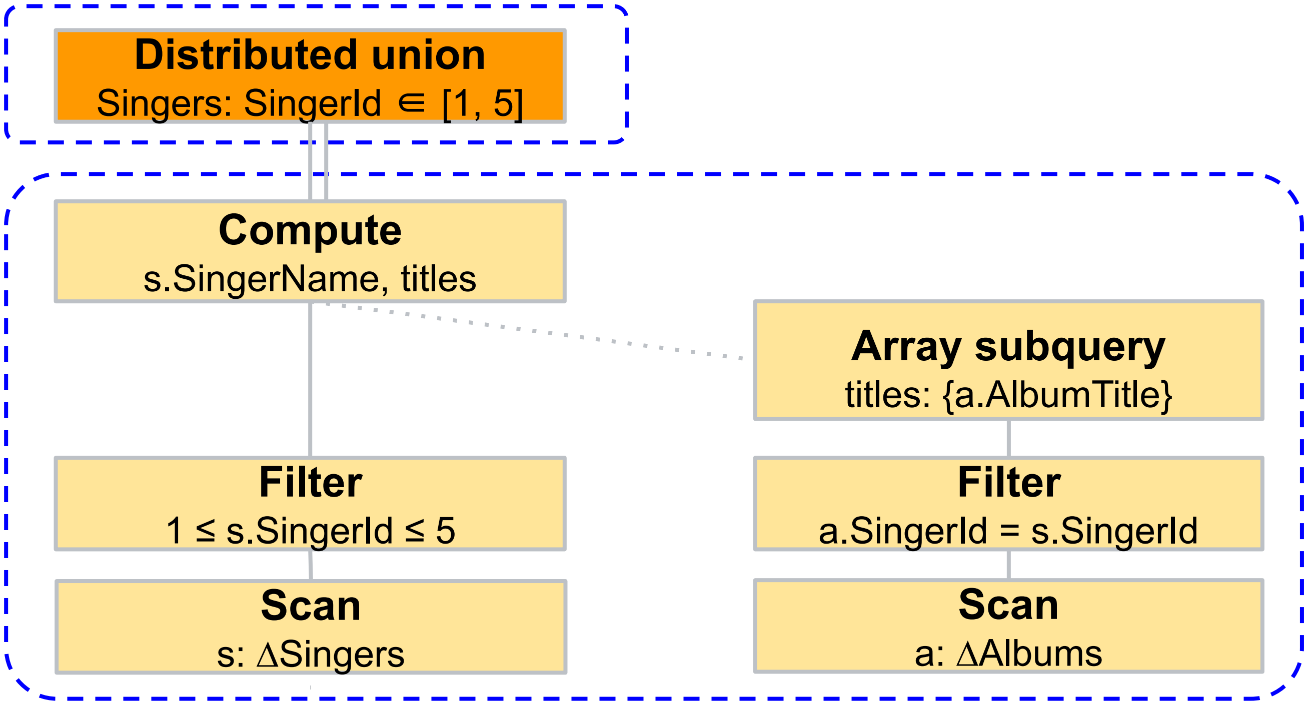
Distributed union operator



Push work to shards, extract distribution ranges



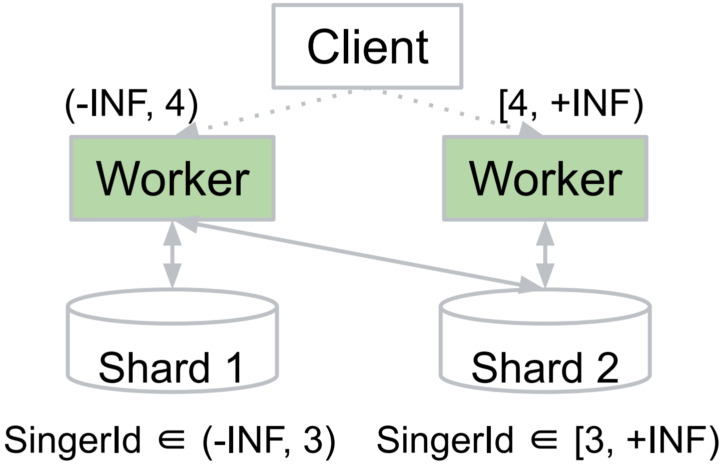
Exploiting co-location



Parallel-consumer API

```
SELECT SingerName, ARRAY(SELECT ...) titles
FROM Singers WHERE SingerId BETWEEN 1 AND 5
```

- Root-partitionable query:
  Q(Union of ΔT) = Union of Q(ΔT)
- Same result up to order of rows
- Another main distribution operator: Distributed Cross Apply



Restartable snapshot queries

Query restarts: overview

- Automatic compensation for failures
- For snapshot queries only
- Server yields "restart token" with each result batch
- Client resumes query execution after consuming partial results
- Contract: omit previously returned rows
  - No repeatability guarantee for subsequent rows

SingerName STRING	**titles** ARRAY<STRING>
Beatles	[Help!, Abbey Road]
U2	[ ]
Pink Floyd	[The Wall]

restart

Query restarts: implementation challenges

- Naive solutions don't work well for "large" queries
  - Buffer final result, persist intermediate results, count rows, etc.
- Instead: efficiently capture distributed state of query execution
- Dynamic resharding
  - May restart on different row range
- Non-determinism
  - Memory size, parallelism, computer architecture, numerics, ...
- Restarts across server versions
  - Query plans, execution algorithms

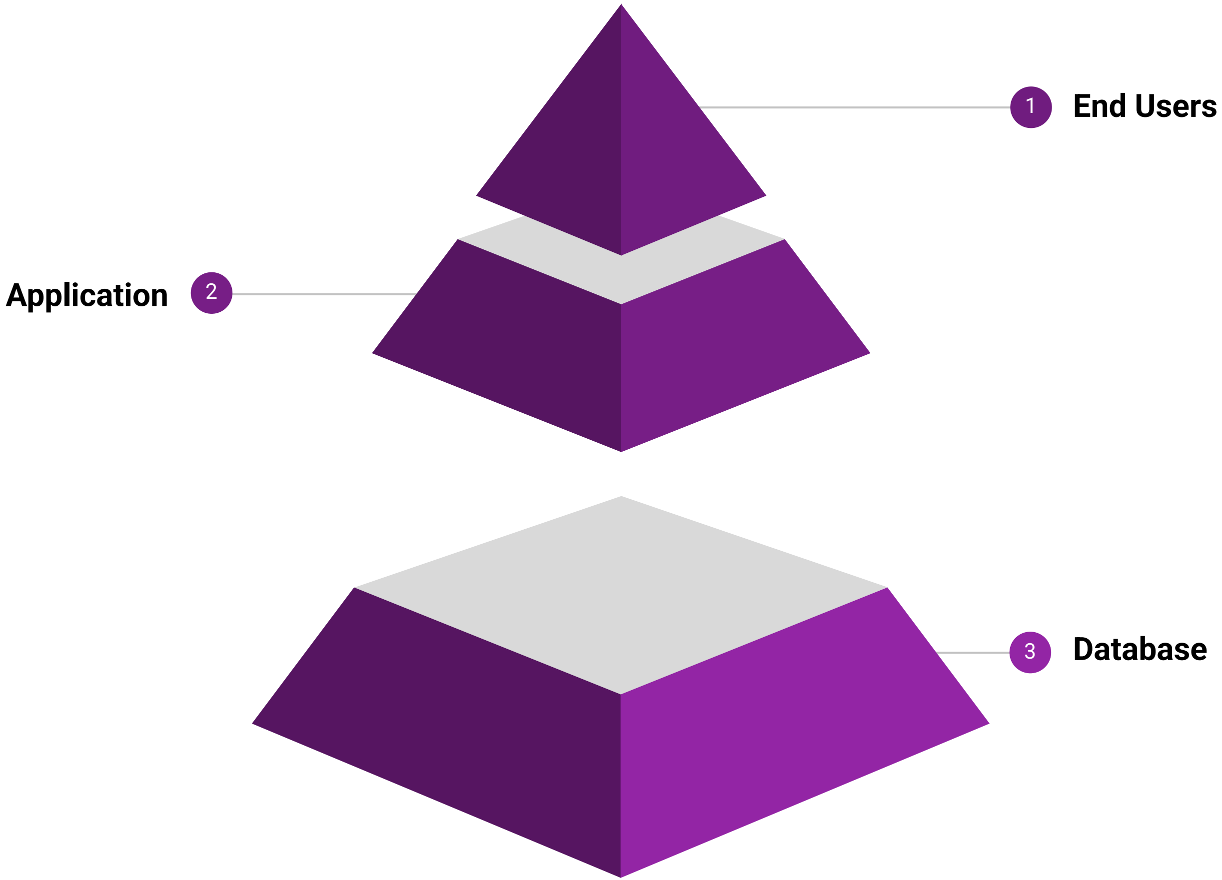
Query restarts: hard but worth it

- Hide transient failures
- No retry loops: simpler programming model
- Streaming pagination
- Ensure forward progress for important class of long-running queries

- Improve tail latency of online requests
- Low-impact rolling server upgrades

Building Database Systems

Location



Database System Contract

Goal: Absorb complexity from application designers

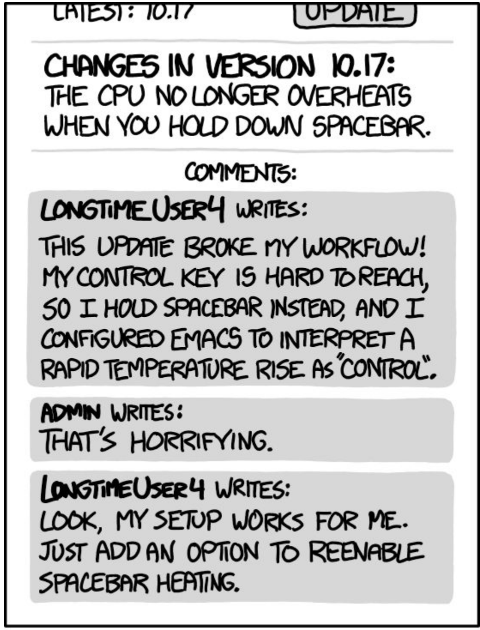
- Failures - Replication, Transactions
- Performance - Efficient data layout, Query Optimization
- Scalability - Sharding, Routing
- Security & Compliance - Regulatory, Fine-grained ACLs

What are we building?

- Operating System + Compiler + Distributed System
- Interface surface area is immense
- SQL is a standard - OK, not really.

Hyrum's Law

With a sufficient number of users of an API,
it does not matter what you promise in the contract:
all observable behaviors of your system
will be depended on by somebody



EVERY CHANGE BREAKS SOMEONE'S WORKFLOW.

[HTTPS://XKCD.COM/1172/](https://xkcd.com/1172/)

Complexity

- Respect Complexity
  - No one person fully understands Spanner. Not even close.
- Spend "complexity budget" where it matters
- Databases are heavily interconnected systems
  - Hard to tightly componentize - "leaky abstractions"
  - Everything breaks Backup/Restore

Tests, Tests, Tests

- Randomized Testing
  - **Random Query, Data, and Schema generators**

    Generate syntactically and semantically valid queries and data

    (eg queries actually return rows)
  - **Inject Faults**

    Anything that can fail or change should
  - **Validate with simpler emulator**

    Check the answers against a much simpler system with the same semantics

For more: "Randomized Testing of Cloud Spanner" Jay Corbett (Medium post)

Tests, Tests, Tests

- Integrity Checks
  - **Validate structures against each other internally**

    Index vs table, generated columns vs expressions, check constraints, foreign keys, etc.
  - **Use disaggregated compute to avoid workload impact**
- Log like crazy
  - It may take a while to notice an issue

Plan Stability: Avoiding Regressions

- *"We have millions of query plans in production,*

  how do we update the optimizer safely?"
- Pin Plans? Pin Optimizer version? Pin feature flags?
- Disaggregation helps:
  - pin plans
  - async validate nothing regresses
  - unpin as you validate

Questions?