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CS505: Distributed Systems

BigTable. Hbase. Megastore. Spanner

1: BigTable

Acknowledgement

- Slides based on material from course at UMichigan, U Washington, and the authors of BigTable, Megastore, Spanner.

REQUIRED READING

- Bigtable: A Distributed Storage System for Structured Data. 2008. ACM Trans. Comput. Syst. 26, 2 (Jun. 2008), 1-26
- Megastore: Providing Scalable, Highly Available Storage for Interactive Services, CIDR 2011
- Spanner, Google's globally distributed database. OSDI 2012.

BigTable

- Distributed storage system for managing structured data such as:
  - URLs: contents, crawl metadata, links, anchors, pagerank
  - Per-user data: user preference settings, recent queries/search results
  - Geographic locations: physical entities (shops, restaurants, etc.), roads, satellite image data, user annotations, …
- Designed to scale to a very large size: petabytes of data distributed across thousands of servers
- Used for many Google applications
  - Web indexing, Personalized Search, Google Earth, Google Analytics, Google Finance, … and more

Why BigTable?

- Scalability requirements not met by existent commercial systems:
  - Millions of machines
  - Hundreds of millions of users
  - Billions of URLs, many versions/page
  - Thousands or queries/sec
  - 100TB+ of satellite image data
- Low-level storage optimization helps performance significantly

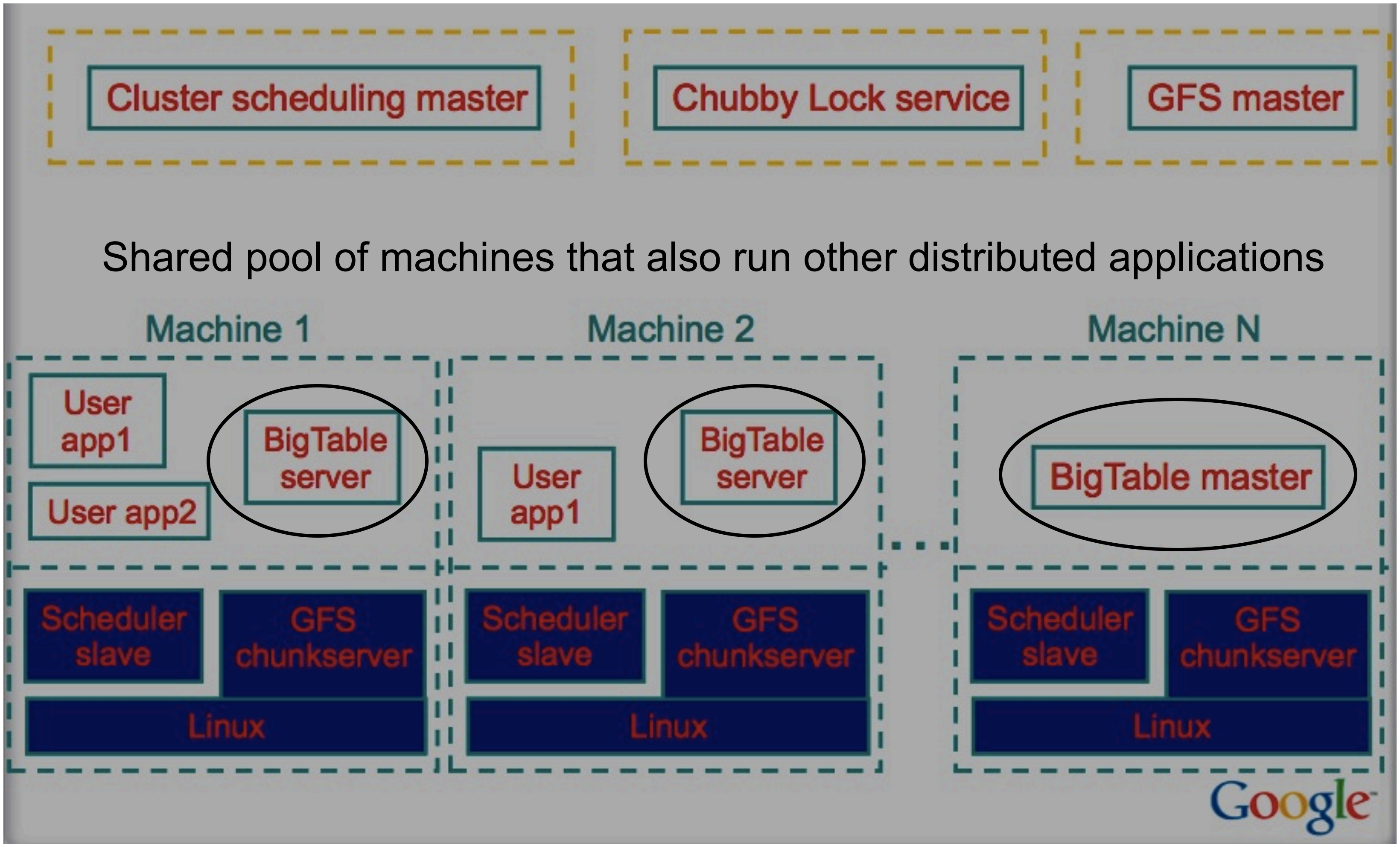
Goals

- Simpler model that supports dynamic control over data and layout format
- Want asynchronous processes to be continuously updating different pieces of data: access to most current data at any time
- Examine data changes over time: e.g. contents of a web page over multiple crawls
- Support for:
  - Very high read/write rates (millions ops per second)
  - Efficient scans over all or subsets of data
  - Efficient joins of large one-to-one and one-to-many datasets

Design Overview

- Distributed multi-level map
- Fault-tolerant, persistent
- Scalable
  - Thousands of servers
  - Terabytes of in-memory data
  - Petabyte of disk-based data
  - Millions of reads/writes per second, efficient scans
- Self-managing
  - Servers can be added/removed dynamically
  - Servers adjust to load imbalance

Typical Google Cluster



Building Blocks

- Google File System (GFS)
  - Stores persistent data (SSTable file format)
- Scheduler
  - Schedules jobs onto machines
- Chubby
  - Lock service: distributed lock manager, master election, location bootstrapping
- MapReduce (optional)
  - Data processing
  - Read/write BigTable data

Chubby

- {lock/file/name} service
- Coarse-grained locks
  - Provides a namespace that consists of directories and small files.
  - Each of the directories or files can be used as a lock.
- Each client has a session with Chubby
  - The session expires if it is unable to renew its session lease within the lease expiration time.
- 5 replicas Paxos, need a majority vote to be active

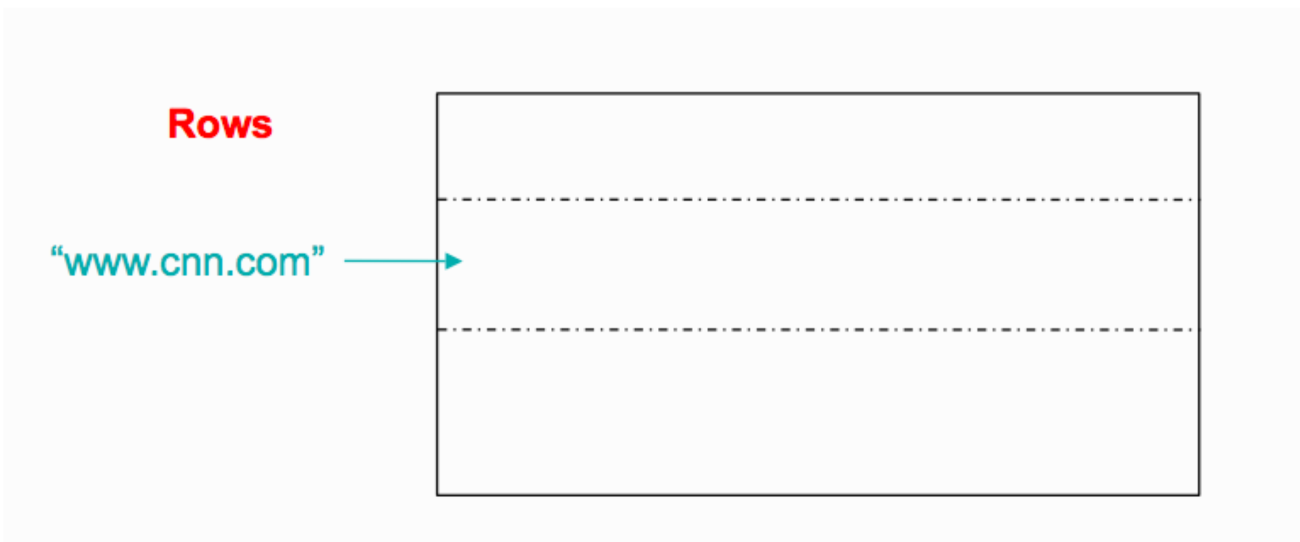
Data Model

- A sparse, distributed persistent multi-dimensional sorted map
- Rows, column are arbitrary strings

- (row, column, timestamp) -> cell contents

Data Model: Rows

- Arbitrary string
- Access to data in a row is atomic
  - Row creation is implicit upon storing data
  - Ordered lexicographically

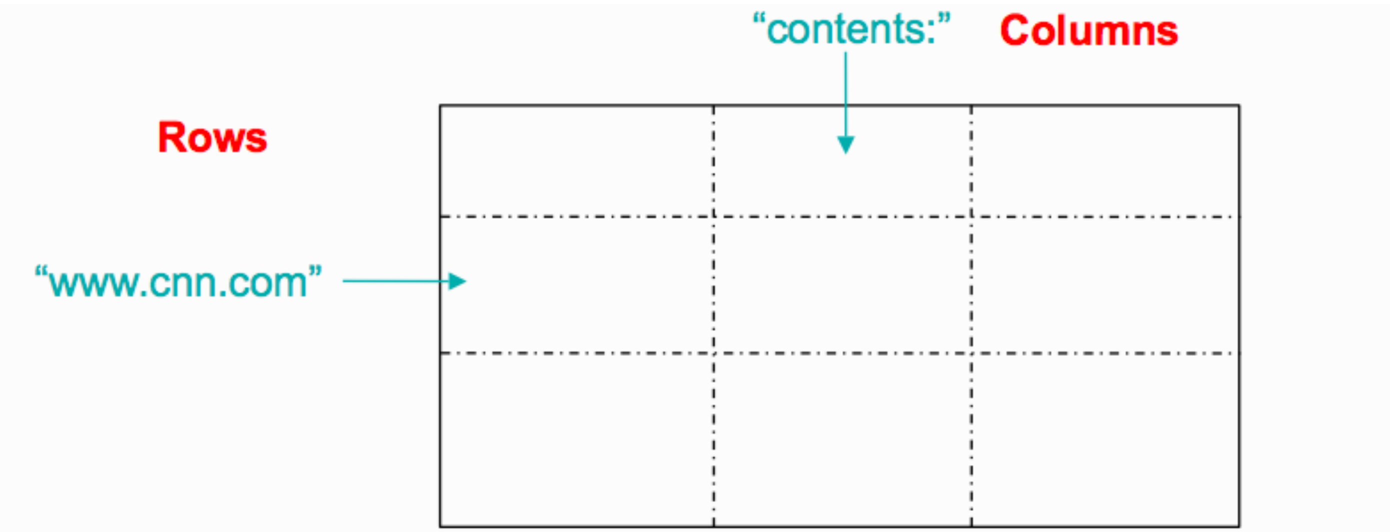


Rows (cont.)

- Rows close together lexicographically usually on one or a small number of machines
- Reads of short row ranges are efficient and typically require communication with a small number of machines
- Can exploit lexicographic order by selecting row keys so they get good locality for data access
- Example:
  - math.gatech.edu, math.uga.edu, phys.gatech.edu, phys.uga.edu
  - VS
  - edu.gatech.math, edu.gatech.phys, edu.uga.math, edu.uga.phys

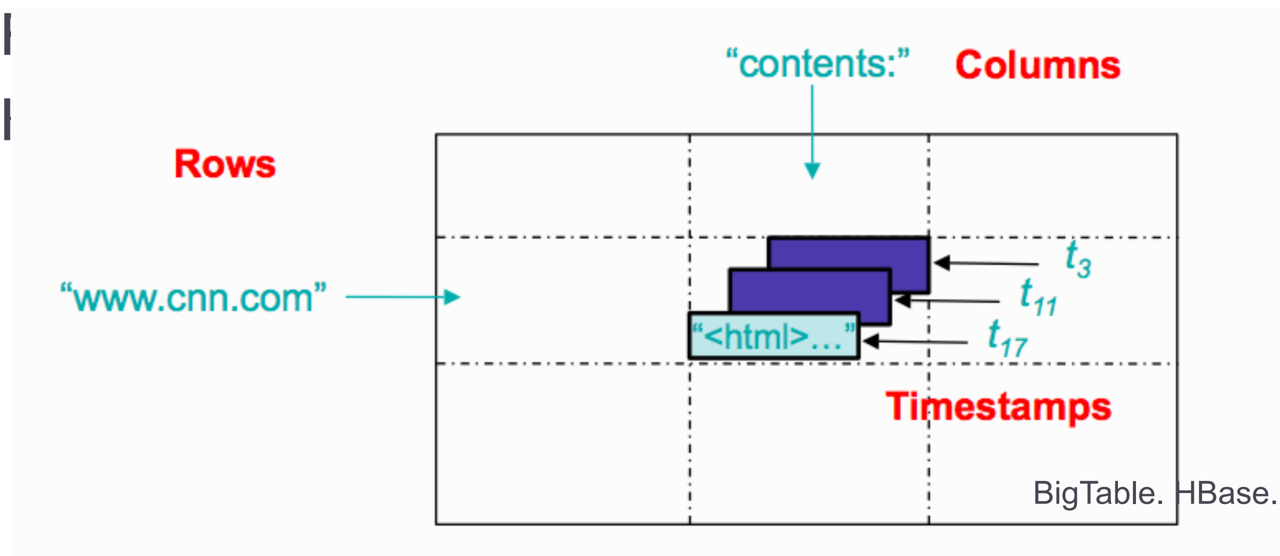
Data Model: Columns

- Two-level name structure: family: qualifier
- Column family:
  - Is the unit of access control
  - Has associated type information
- Qualifier gives unbounded columns
  - Additional levels of indexing, if desired



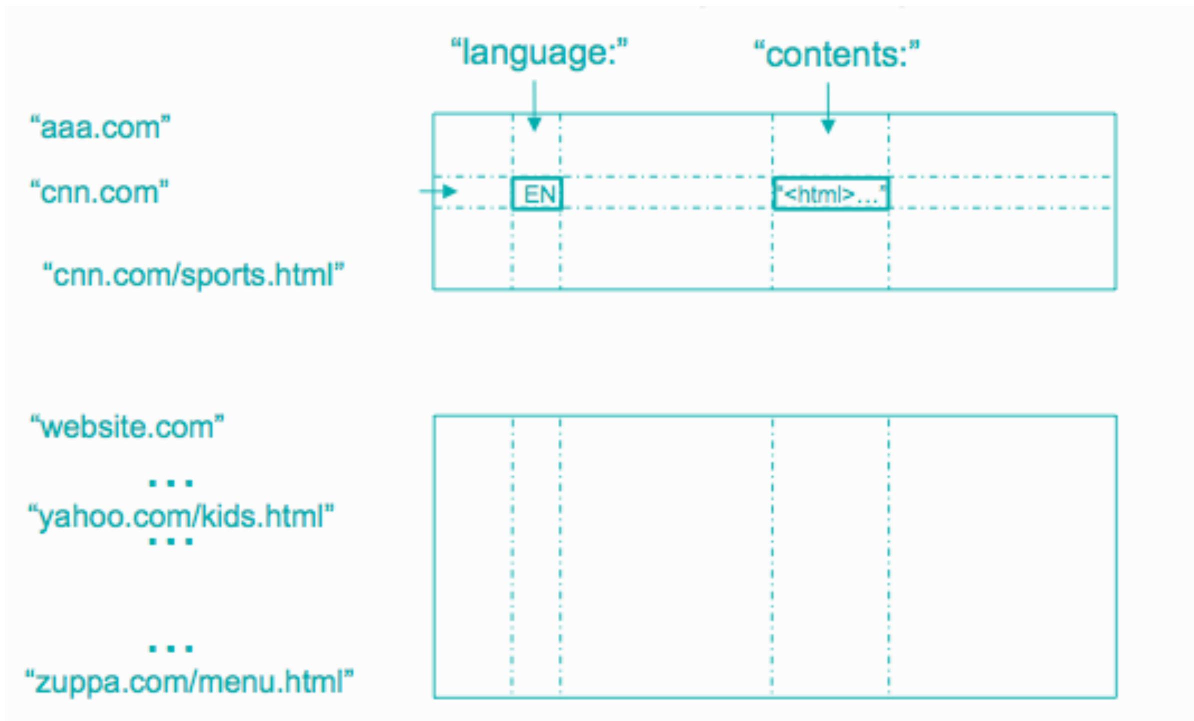
Data Model: Timestamps (64bit integers)

- Store different versions of data in a cell:
  - New writes default to current time, but timestamps for writes can also be set explicitly by clients
- Lookup options
  - Return most recent K values
  - Return all values
- Column families can be marked w/ attributes:



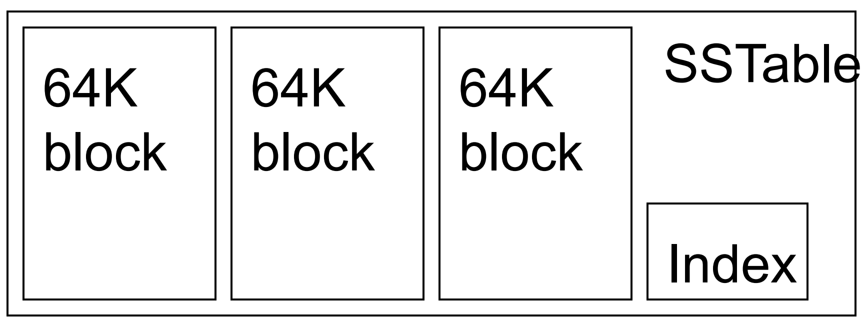
Data Model: Tablet

- The row range for a table is dynamically partitioned
- Each row range is called a tablet (typically 10-100 bytes)
- Tablet is the unit for distribution and load balancing



Storage: SSTable

- Immutable, sorted file of key-value pairs
- Optionally, SSTable can be completely mapped into memory
- Chunks of data plus an index
  - Index is of block ranges, not values
  - Index is loaded into memory when SSTable is open



Tablet vs. SSTable

- Tablet is built out of multiple SSTables

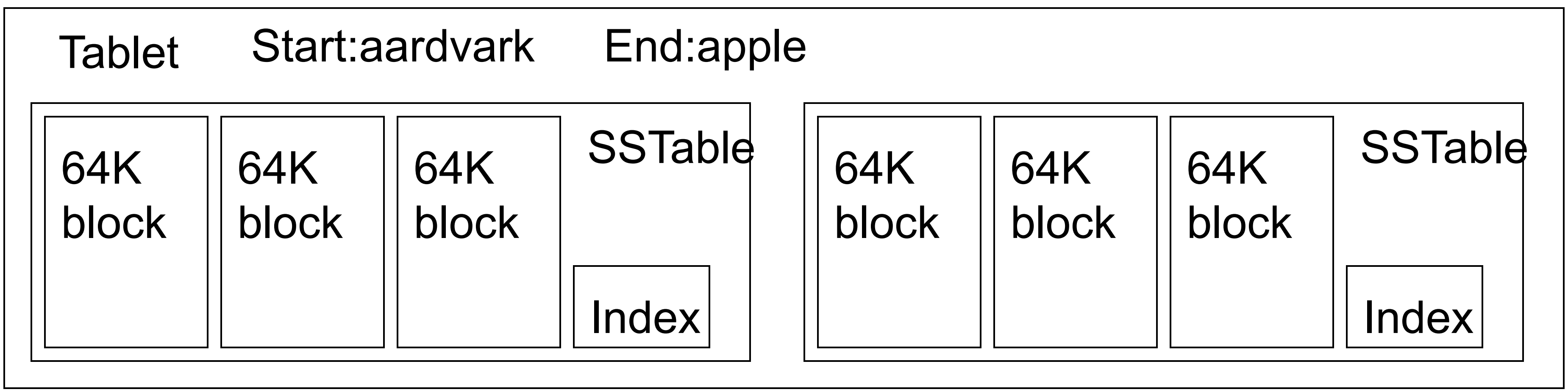
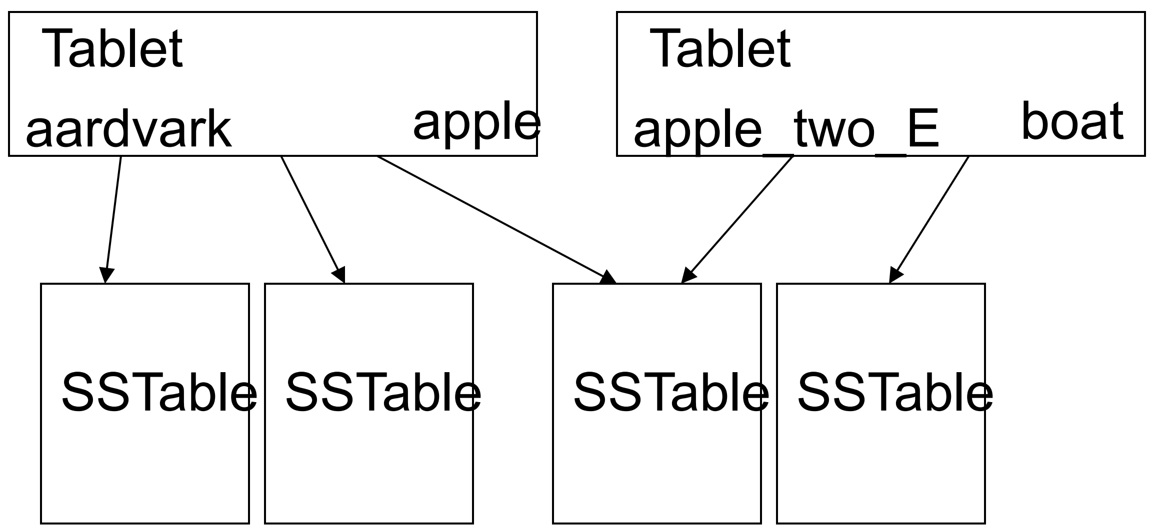
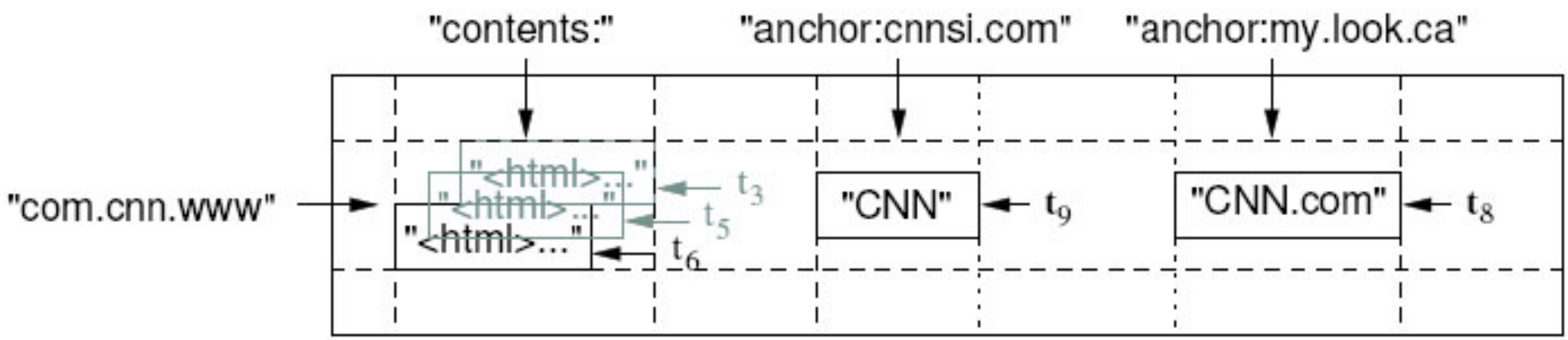


Table vs. Tablet vs. SSTable

- Multiple tablets make up the table
- SSTables can be shared
- Tablets do not overlap, SSTables can overlap



Example: WebTable

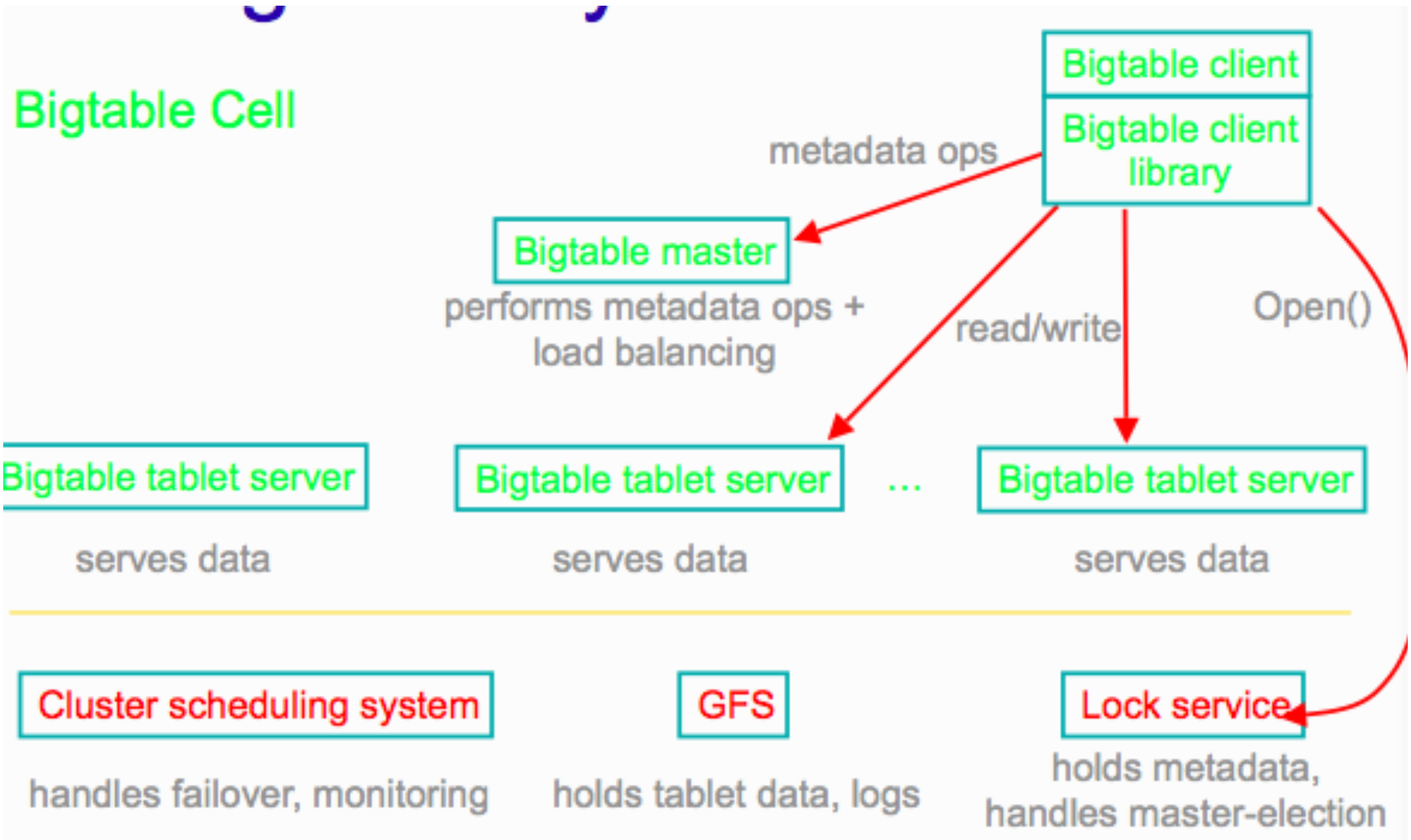


- Want to keep copy of a large collection of web pages and related information
- Use URLs as row keys
- Various aspects of web page as column names
- Store contents of web pages in the contents: column under the timestamps when they were fetched.

Implementation

- Library linked into every client
- One master server responsible for:
  - Assigning tablets to tablet servers
  - Detecting addition and expiration of tablet servers
  - Balancing tablet-server load
  - Garbage collection
  - Handling schema changes such as table and column family creation
- Many tablet servers, each of them:
  - Handles read and write requests to its table
  - Splits tablets that have grown too large
- Clients communicate directly with tablet servers for reads and writes.

Deployment



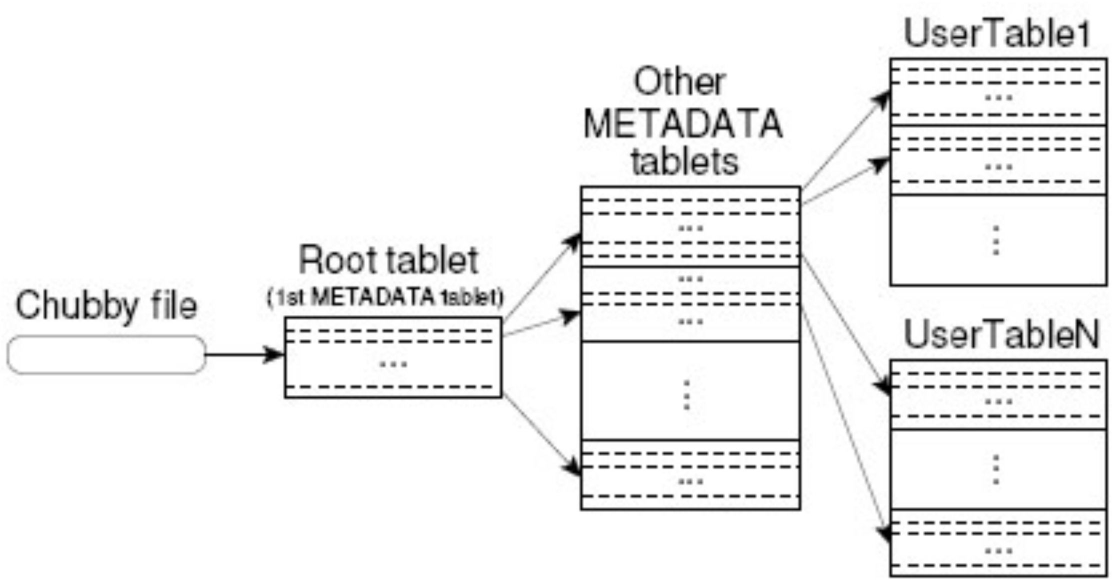
Bigtable Cell
Bigtable client
Bigtable client library
metadata ops
Bigtable master
performs metadata ops + load balancing
read/write
Open()
Bigtable tablet server
serves data
Bigtable tablet server
serves data
...
Bigtable tablet server
serves data
Cluster scheduling system
handles failover, monitoring
GFS
holds tablet data, logs
Lock service
holds metadata, handles master-election

More about Tablets

- Serving machine responsible for 10 - 1000
  - Usually about 100 tablets
- Fast recovery:
  - 100 machines each pick up 1 tablet for failed machine
- Fine-grained load balancing:
  - Migrate tablets away from overloaded machine
  - Master makes load-balancing decisions

Tablet Location

- Since tablets move around from server to server, given a row, how do clients find the right machine
  - Find tablet whose row range covers the target row
- METADATA: Key: table id + end row,   Data: location
- Aggressive caching and prefetching at client side



Tablet Assignment

- Each tablet is assigned to one tablet server at a time.
- Master server
  - Keeps track of the set of live tablet servers and current assignments of tablets to servers.
  - Keeps track of unassigned tablets.
- When a tablet is unassigned, master assigns the tablet to a tablet server with sufficient room.
- It uses Chubby to monitor health of tablet servers, and restart/replace failed servers.

Tablet Assignment: Chubby

- Tablet server registers itself with Chubby by getting a lock in a specific directory of Chubby
- Chubby gives "lease" on lock, must be renewed periodically
- Server loses lock if it gets disconnected
- Master monitors this directory to find which servers exist/are alive
  - If server not contactable/has lost lock, master grabs lock and reassigns tablets
  - GFS replicates data. Prefer to start tablet server on same machine that the data is already at

API

- Metadata operations
  - Create/delete tables, column families, change metadata
- Writes (atomic)
  - Set(): write cells in a row
  - DeleteCells(): delete cells in a row
  - DeleteRow(): delete all cells in a row
- Reads
  - Scanner: read arbitrary cells in a bigtable
    - Each row read is atomic
    - Can restrict returned rows to a particular range
    - Can ask for just data from 1 row, all rows, etc.
    - Can ask for all columns, just certain column families, or specific columns

Refinements: Locality Groups

- Can group multiple column families into a locality group
  - Separate SSTable is created for each locality group in each tablet.
- Segregating columns families that are not typically accessed together enables more efficient reads.
  - In WebTable, page metadata can be in one group and contents of the page in another group.

Refinements: Compression

- Many opportunities for compression
  - Similar values in the same row/column at different timestamps
  - Similar values in different columns
  - Similar values across adjacent rows
- Two-pass custom compressions scheme
  - First pass: compress long common strings across a large window
  - Second pass: look for repetitions in small window
- Speed emphasized, but good space reduction (10-to-1)

Refinements: Bloom Filters

- Read operation has to read from disk when desired SSTable is not in memory
- Reduce number of accesses by specifying a Bloom filter:
  - Allows to ask if a SSTable might contain data for a specified row/column pair.
  - Small amount of memory for Bloom filters drastically reduces the number of disk seeks for read operations
  - Results in most lookups for non-existent rows or columns not needing to touch disk

Real Applications

ble size (TB)	Compression ratio	# Cells (billions)	# Column Families	# Locality Groups
800	11%	1000	16	8
50	33%	200	2	2
20	29%	10	1	1
200	14%	80	1	1
2	31%	10	29	3
0.5	64%	8	7	2
70	–	9	8	3
9	–	0.9	8	5
4	47%	6	93	11

Limitations

- No transactions supported
- Does not support full relational data model
- Achieved throughput is limited by GFS

Lessons Learnt

- Large distributed systems vulnerable to many type of failures
  - Memory and network corruption
  - Large clock skew
  - Hung machines
  - Extended and asymmetric network partitions
  - Bugs in other systems
- Proper system-level monitoring critical
- Simple design better
- Do not add new features before they are needed

2: HBase

HBase

- Open-source, distributed, versioned, column-oriented data store, modeled after Google's Bigtable
- Random, real time read/write access to large data:
  - Billions of rows, millions of columns
  - Distributed across clusters of commodity hardware

History

- 2006.11
  - Google releases paper on BigTable
- 2007.2
  - Initial HBase prototype created as Hadoop contrib.
- 2007.10
  - First useable HBase
- 2008.1
  - Hadoop become Apache top-level project and HBase becomes subproject
- Current stable release 0.98.x

HBase Is Not …

- Tables have one primary index, the row key.
- No join operators.
- Scans and queries can select a subset of available columns.
- There are three types of lookups:
  - Fast lookup using row key and optional timestamp.
  - Full table scan
  - Range scan from region start to end.

HBase Is Not …(2)

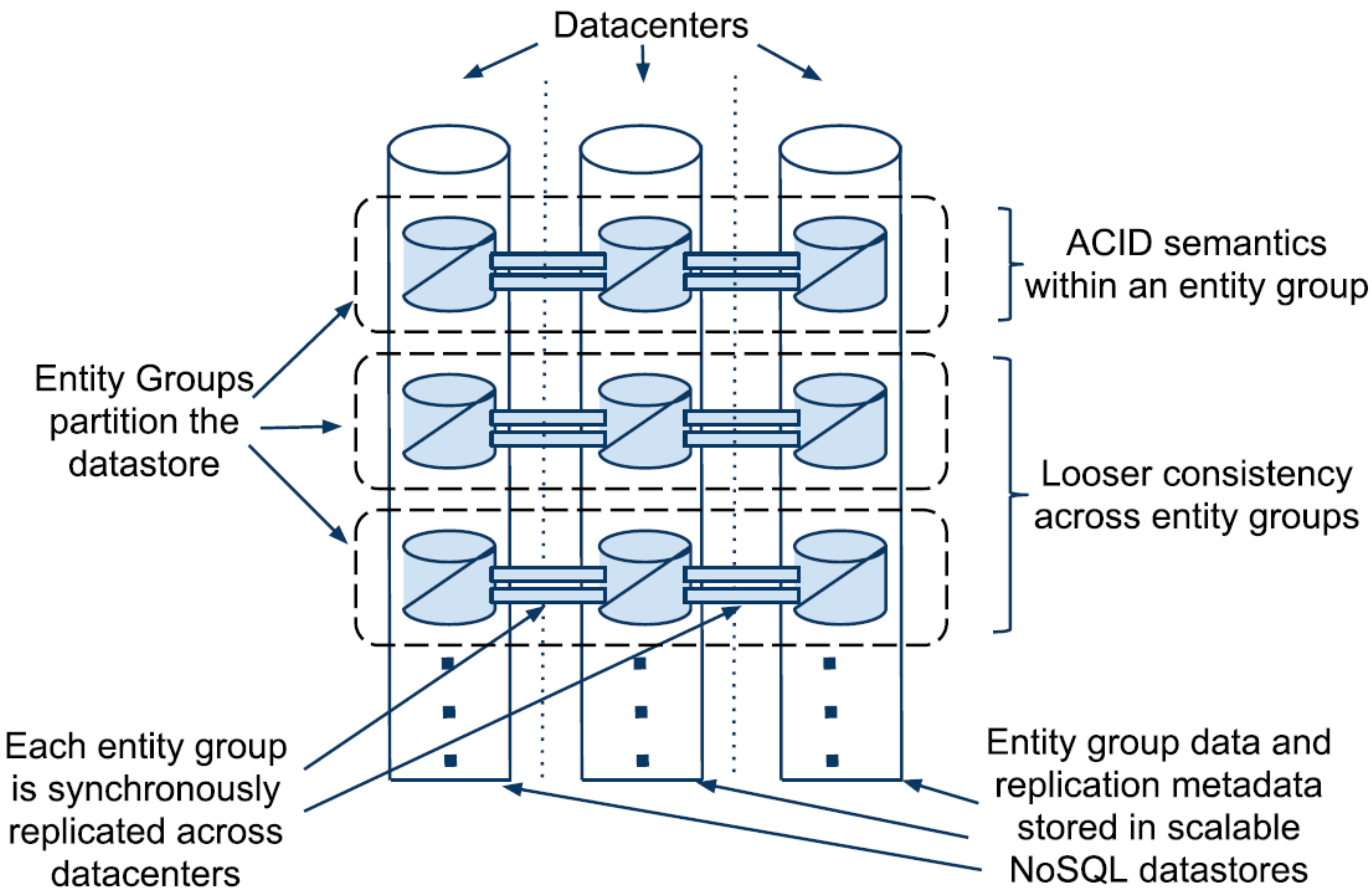
- Limited atomicity and transaction support.
  - HBase supports multiple batched mutations of single rows only.
  - Data is unstructured and untyped.
- No accessed or manipulated via SQL.
  - Programmatic access via Java, REST, or Thrift APIs.
  - Scripting via JRuby.

3: Megastore

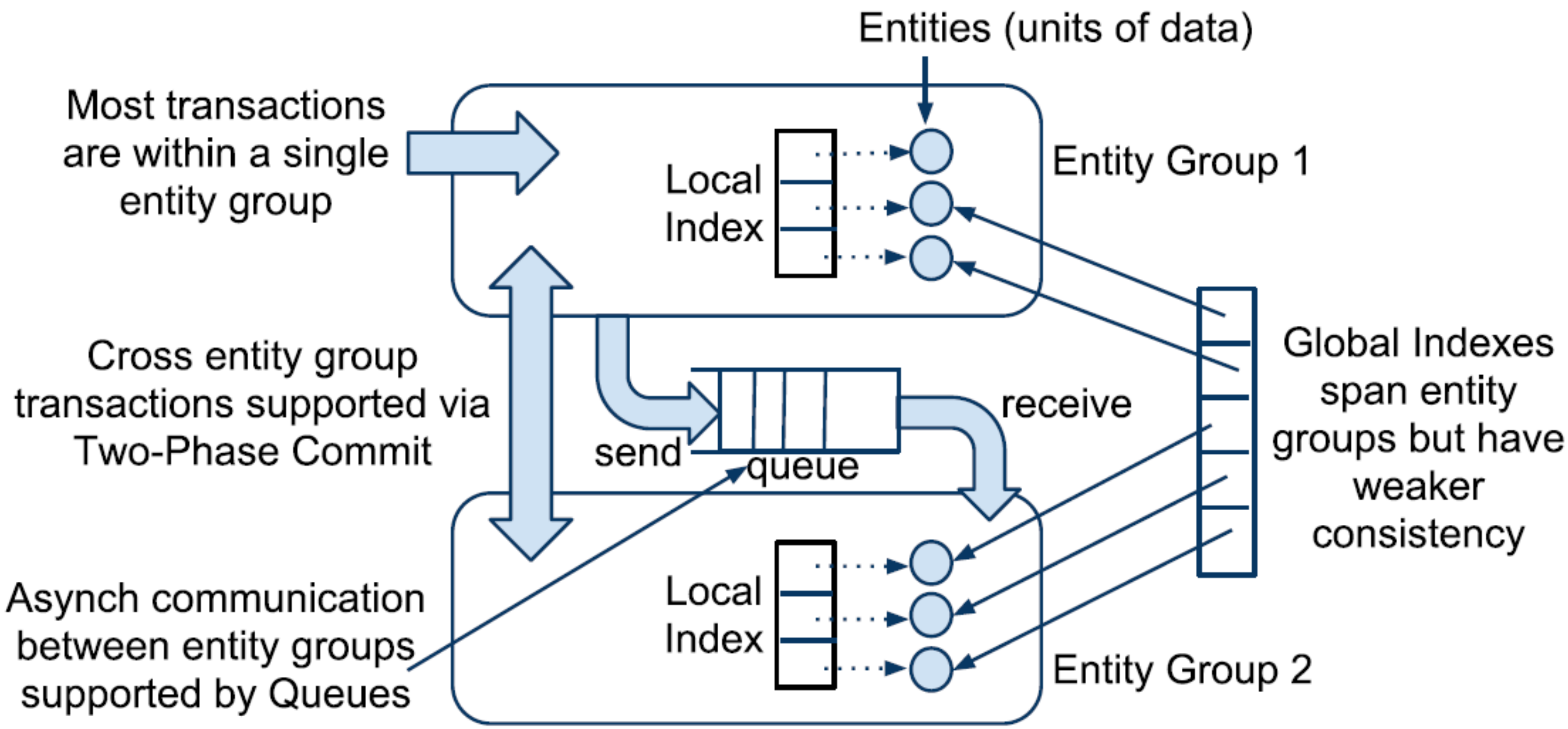
Megastore

- Designed to meet following requirements
  - Highly scalable (MySQL is not enough)
  - Rapid development (fast time-to-market)
  - Low latency (service must be responsive)
  - Consistent view of data (update result)
  - Highly available (24/7 internet service)
- Scales and provides consistent view of the data
  - Scales by using NoSQL (BigTable)
  - Partitions data
  - Uses Paxos to provide consistent view within a partition

Partitioning and Locality



Partitioning and Locality (cont.)



Entity Group Examples

Application	Entity Groups	Cross-EG Ops
Email	User accounts	none
Blogs	Users, Blogs	Access control, notifications, global indexes
Mapping	Local patches	Patch-spanning ops
Social	Users, Groups	Messages, relationships, notifications
Resources	Sites	Shipments

Bigtable

• Bigtable (e.g. key-value store) is straightforward to store and query hierarchical data
• Runs on Google File System and using Chubby, a distributed lock service based on Paxos (5 servers)

Row key	User. name	Photo. time	Photo. tag	Photo. _url
101	John			
101,500		12:30:01	Dinner, Paris	...
101,502		12:15:22	Betty, Paris	...
102	Mary			

Figure 4: Sample Data Layout in Bigtable

Data Model

- Abstract tuples of an RDBMS + row-column storage of NoSQL
- RDBMS features
  - Data model is declared in a schema
  - Tables per schema / entities per table / properties per entity
  - Sequence of properties is used for primary key of entity
  - Hierarchy (foreign key)
    - Tables are either entity group root or child tables
    - Child table points to root table
    - Root table and child table are stored in the same entity group

Example

```
CREATE SCHEMA PhotoApp;

CREATE TABLE User {
 required int64 user_id;
 required string name;
} PRIMARY KEY(user_id), ENTITY GROUP ROOT;

CREATE TABLE Photo {
 required int64 user_id;
 required int32 photo_id;
 required int64 time;
 required string full_url;
 optional string thumbnail_url;
 repeated string tag;
} PRIMARY KEY(user_id, photo_id),
  IN TABLE User,
  ENTITY GROUP KEY(user_id) REFERENCES User;

CREATE LOCAL INDEX PhotosByTime
  ON Photo(user_id, time);

CREATE GLOBAL INDEX PhotosByTag
  ON Photo(tag) STORING (thumbnail_url);
```

Figure 3: Sample Schema for Photo Sharing Service

Secondary Indexes

- Local index: separate indexed for each entity group (e.g. PhotosByTime)
- Global index: spans entity groups, indexed index across entity groups (e.g. PhotosByTag)
- Repeated index: Supports indexing repeated values (e.g. PhotosByTag
- Inline index: Provide a way to de-normalized data from source entities
  - A virtual repeated column in the target entry (e.g. PhotosByTime)

Transactions and Concurrency Control

- Each entity group is a mini-database that provides serializable ACID Semantics
- A transaction writes its update into the entity group's write-ahead log, then the update is applied to the data
- MVCC: multiversion concurrency control
  - Read consistency
    - Current: last committed value
    - Snapshot: value as a start of the read transaction
    - Inconsistent reads: ignore the state of log and read the last values directly
  - Write consistency
    - Always begins with a current read to determine the next available log
    - Commit operation assigns updates of write-ahead log a timestamp higher than any previous one
    - Paxos uses optimistic concurrency with write operations

Transactions in Megastore

- Read: Obtain the timestamp and log position of the last committed transaction
- Application logic: Read from Bigtable and gather writes into a log entry
- Commit: Use Paxos to achieve consensus for appending that entry to the log
- Apply: Write changes to the entities and indexes in Bigtable
- Clean up: Delete data that is no longer required

Replication

- Single, consistent view of the data stored in its underlying replicas
- Reads and writes can be initiated from any replicas
- ACID semantics are preserved regardless of what replica a client starts from
- Replication is done per entity group by synchronously replicating the group's transaction log
- Writes require one round of inter-datacenter communication

Replication Architecture

Replica type
- Full: contain all the entity and index data, able to service current reads
- Witness: storing the write-ahead log (for write transaction)
- Read-only: inverse of witness (storing full snapshot of the data)

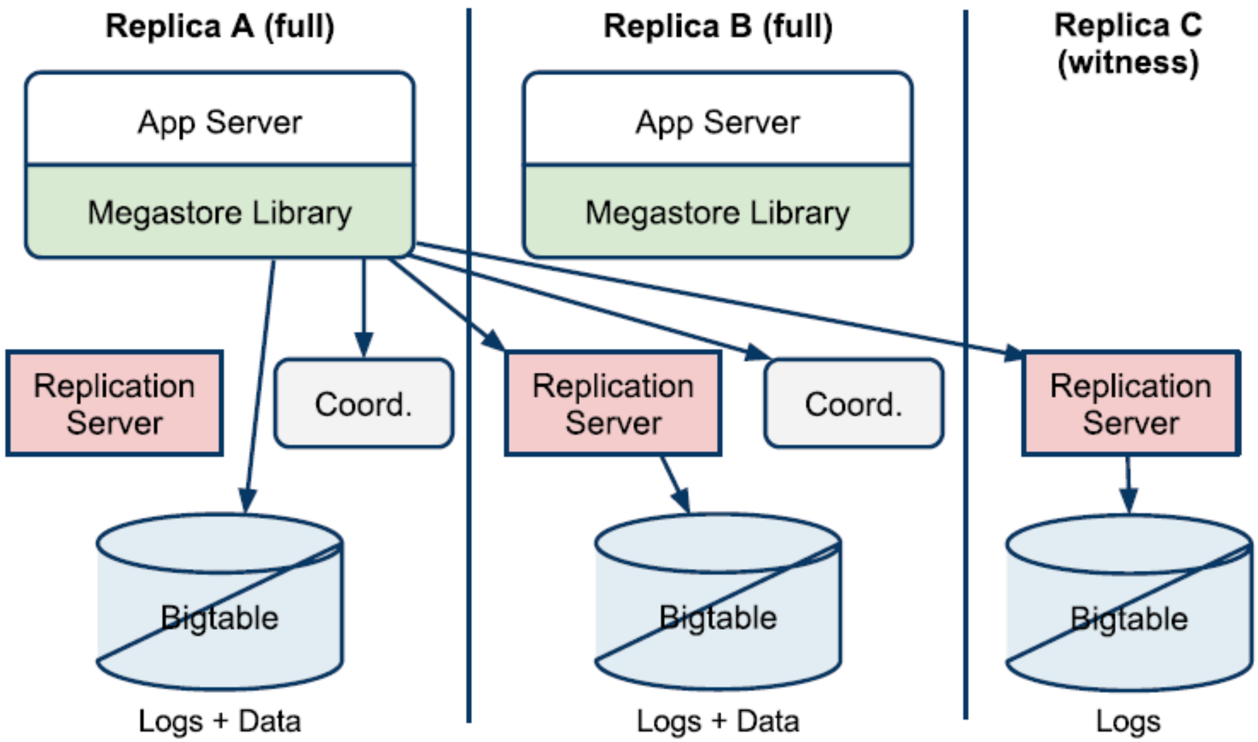


Figure 5: Megastore Architecture Example

3: Spanner

Limitations of BigTable

- Difficult to use for applications that
  - have complex, evolving schemas,
  - want strong consistency in the presence of wide-area replication

What is Spanner

- Scalable, multi-version, globally- distributed, and synchronously-replicated database
- Distribute data at global scale and support externally-consistent distributed transactions.
- Features:
  - non- blocking reads in the past
  - lock-free read-only transactions,
  - atomic schema changes
- Scale up to
  - millions of machines
  - hundreds of datacenters
  - trillions of database rows

What is Spanner

- Applications can control replication configurations for data
- Applications can specify constraints
  - to 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)
  - how many replicas are maintained (to control durability, availability, and read performance).
- Data can also be dynamically and transparently moved between datacenters by the system to balance resource usage across datacenters

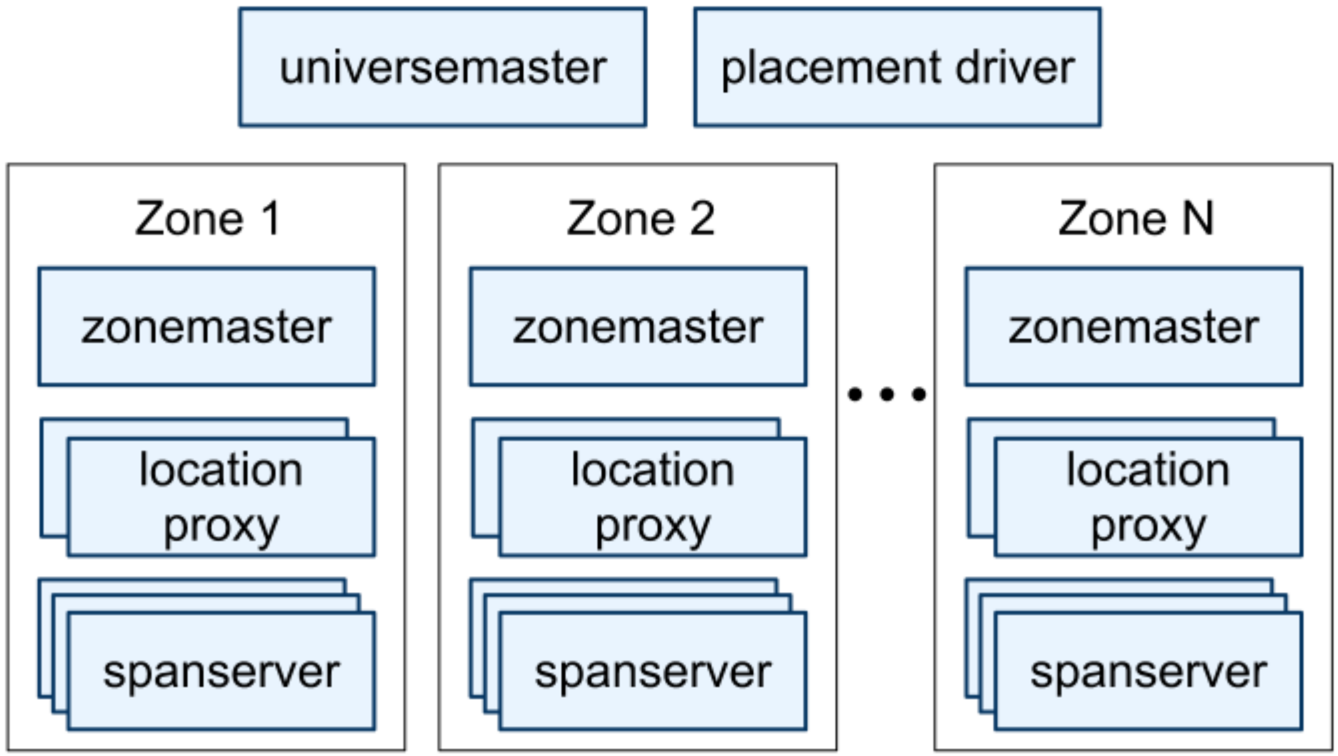
Spanner – key idea

- Consistent reads and writes
- How:
  - use global commit timestamps to transactions, even though transactions may be distributed.
  - timestamps represent serialization order.
  - provide such guarantees at global scale
- How to get the global timestamps: TrueTime
- Relies on existing algorithms as Paxos and 2PC

Architecture

- Instance – it's called universe; examples: test, deployment, production
  - Universe master
  - Placement master
    - handles automated movement of data across zones on the timescale of minutes
    - periodically communicates with the spanservers to find data that needs to be moved, either to meet updated replication constraints or to balance load.
  - Universe consists of zones
    - Denotes physical isolation
    - Several zones can be in a datacenter

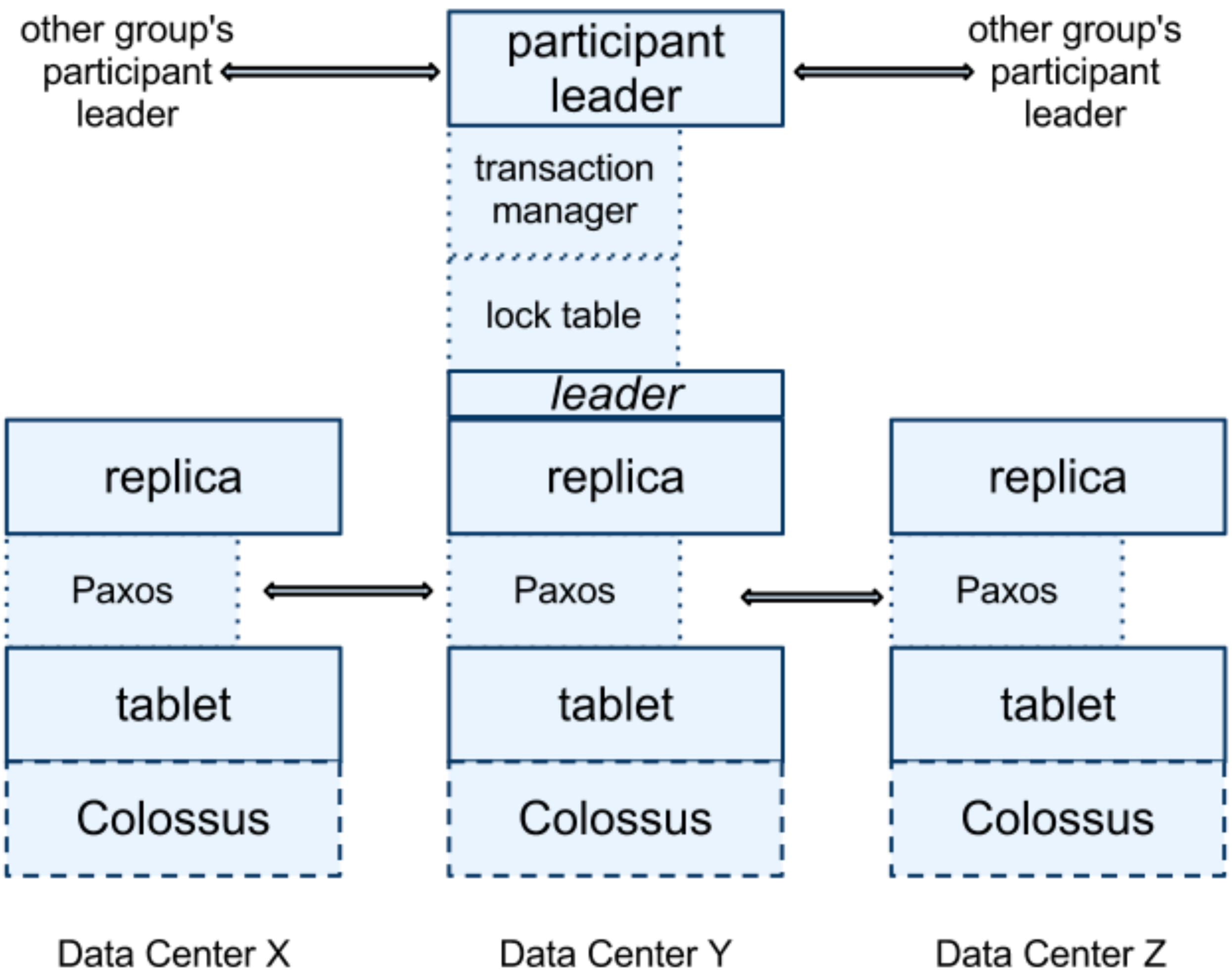
Architecture



Zones

- Zonemaster
  - assigns the data to span servers
- Spanservers
  - hundreds to thousands
  - store data
  - responsible for between 100 and 1000 instances of a data structure called a *tablet* (different from the BigTable tablet)
  - each data has a timestamp
- Location proxies
  - used by clients to locate the spanservers assigned to serve their data

Replication



More about replication

- Directory – analogous to bucket in BigTable
  - Smallest unit of data placement
  - Smallest unit to define replication properties
- 2PC and Paxos-based replication
- Back End: Colossus (successor to GFS)
- Paxos State Machine on top of each tablet stores meta data and logs of the tablet.
- Leader among replicas in a Paxos group is chosen and all write requests for replicas in that group initiate at leader.
- Transaction Leader
  - Is Paxos Leader if transaction involves one Paxos group

TrueTime

- Leverages hardware features like GPS and Atomic Clocks
- Implemented via TrueTime API
  - Key method being now() which not only returns current system time but also another value (ε) which tells the maximum uncertainty in the time returned
- Set of time master server per datacenters and time slave daemon per machines
- Majority of time masters are GPS fitted and few others are atomic clock fitted (Armageddon masters)
- Daemon polls variety of masters and reaches a consensus about correct timestamp

TrueTime

- TrueTime uses both GPS and Atomic clocks since they are different failure rates and scenarios

- Two other boolean methods in API are
  - After(t) – returns TRUE if t is definitely passed
  - Before(t) – returns TRUE if t is definitely not arrived
- TrueTime uses these methods in concurrency control and t serialize transactions

TrueTime

- After() is used for Paxos Leader Leases
  - Uses after(Smax) to check if Smax is passed so that Paxos Leader can abdicate its slaves.
- Paxos Leaders can not assign timestamps(Si) greater than Smax for transactions(Ti) and clients can not see the data commited by transaction Ti till after(Si) is true.
  - After(t) – returns TRUE if t is definitely passed
  - Before(t) – returns TRUE if t is definitely not arrived
- Replicas maintain a timestamp tsafe which is the maximum timestamp at which that replica is up to date.

TrueTime

- Read-Write – requires lock.
- Read-Only – lock free.
  - Requires declaration before start of transaction.
  - Reads information that is up to date
- Snapshot Read – Read information from past by specifying a timestamp or bound
  - Use specifies specific timestamp from past or timestamp bound so that data till that point will be read.

Applications

- Google advertising backend application – F1
- Replicated across 5 datacenters spread across US