NoSQL Databases

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Database and Database Management System

- Database: an organized collection of data.

- Database Management System (DBMS): a software that interacts with users, other applications, and the database itself to capture and analyze data.

Relational Databases Management Systems (RDMBSs)

- RDMBSs: the dominant technology for storing structured data in web and business applications.

- SQL is good
  - Rich language and toolset
  - Easy to use and integrate
  - Many vendors

- They promise: ACID

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  - All included statements in a transaction are either executed or the whole transaction is aborted without affecting the database.

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- Consistency
  - A database is in a consistent state before and after a transaction.
- Isolation
  - Transactions can not see uncommitted changes in the database.
- Durability
  - Changes are written to a disk before a database commits a transaction so that committed data cannot be lost through a power failure.

RDBMS Challenges

- Web-based applications caused spikes.
  - Internet-scale data size
  - High read-write rates
  - Frequent schema changes

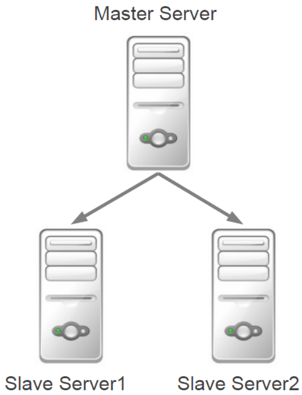
Let's Scale RDBMSs

- RDBMS were not designed to be distributed.

- Possible solutions:
  - Replication
  - Sharding

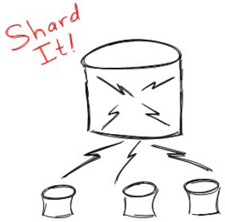
Let's Scale RDBMSs - Replication

- Master/Slave architecture
- Scales read operations

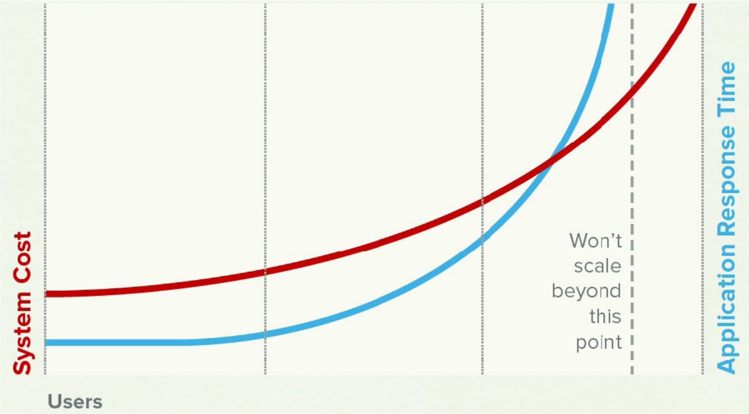


Let's Scale RDBMSs - Sharding

- Dividing the database across many machines.
- It scales read and write operations.
- Cannot execute transactions across shards (partitions).



Scaling RDBMSs is Expensive and Inefficient



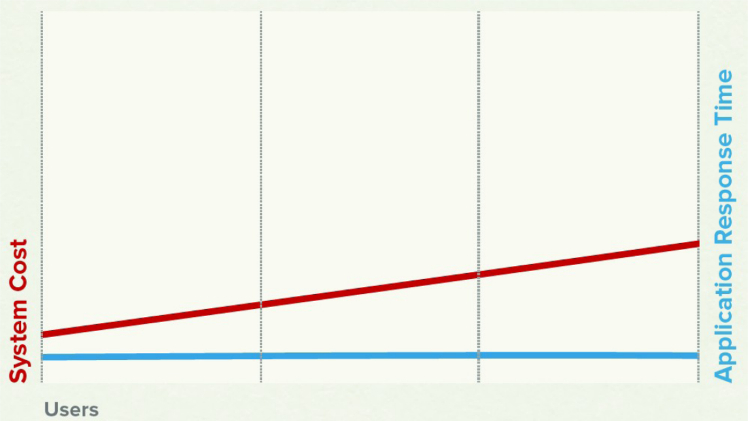
[http://www.couchbase.com/sites/default/files/uploads/all/whitepapers/NoSQLWhitepaper.pdf]

Not Only SQL

NoSQL

- Avoidance of unneeded complexity
- High throughput
- Horizontal scalability and running on commodity hardware
- Compromising reliability for better performance

NoSQL Cost and Performance



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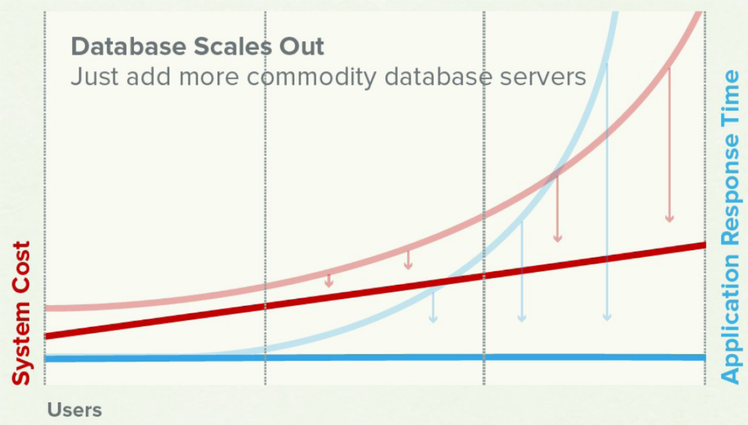
RDBMS vs. NoSQL



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NoSQL Data Models

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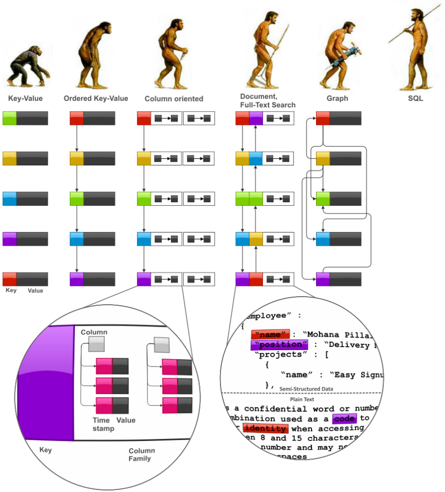


[http://highlyscalable.wordpress.com/2012/03/01/nosql-data-modeling-techniques]

Key-Value Data Model

- Collection of key/value pairs.
- Ordered Key-Value: processing over key ranges.
- Dynamo, Scalaris, Voldemort, Riak, ...

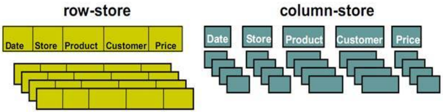
Column-Oriented Data Model

- Similar to a key/value store, but the value can have multiple attributes (Columns).

- Column: a set of data values of a particular type.

- Store and process data by column instead of row.

- BigTable, Hbase, Cassandra, ...



Document Data Model

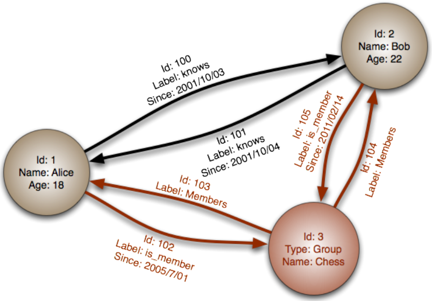
- Similar to a column-oriented store, but values can have complex documents, instead of fixed format.
- Flexible schema.
- XML, YAML, JSON, and BSON.
- CouchDB, MongoDB, ...

```
{
    FirstName: "Bob",
    Address: "5 Oak St.",
    Hobby: "sailing"
 }

 {
   FirstName: "Jonathan",
   Address: "15 Wanamassa Point Road",
   Children: [
        {Name: "Michael", Age: 10},
        {Name: "Jennifer", Age: 8},
   ]
  }
```

Graph Data Model

- Uses graph structures with nodes, edges, and properties to represent and store data.
- Neo4J, InfoGrid, ...

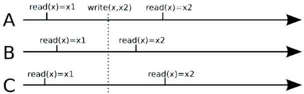


[http://en.wikipedia.org/wiki/Graph_database]

Consistency

Consistency

- Strong consistency
  - After an update completes, any subsequent access will return the updated value.



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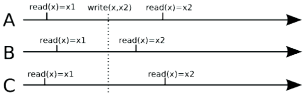
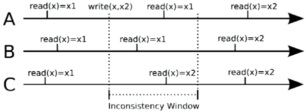


- Eventual consistency
  - Does not guarantee that subsequent accesses will return the updated value.
  - Inconsistency window.
  - If no new updates are made to the object, eventually all accesses will return the last updated value.



Quorum Model

- N: the number of nodes to which a data item is replicated.
- R: the number of nodes a value has to be read from to be accepted.
- W: the number of nodes a new value has to be written to before the write operation is finished.

- To enforce strong consistency: $R + W > N$

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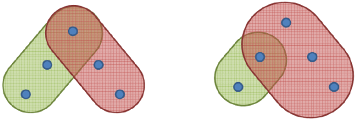


R = 3, W = 3, N = 5　　R = 4, W = 2, N = 5

NRW.

Consistency vs. Availability

- The large-scale applications have to be reliable: availability + redundancy

- These properties are difficult to achieve with ACID properties.

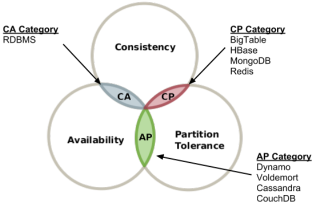
- The BASE approach forfeits the ACID properties of consistency and isolation in favor of availability, graceful degradation, and performance.

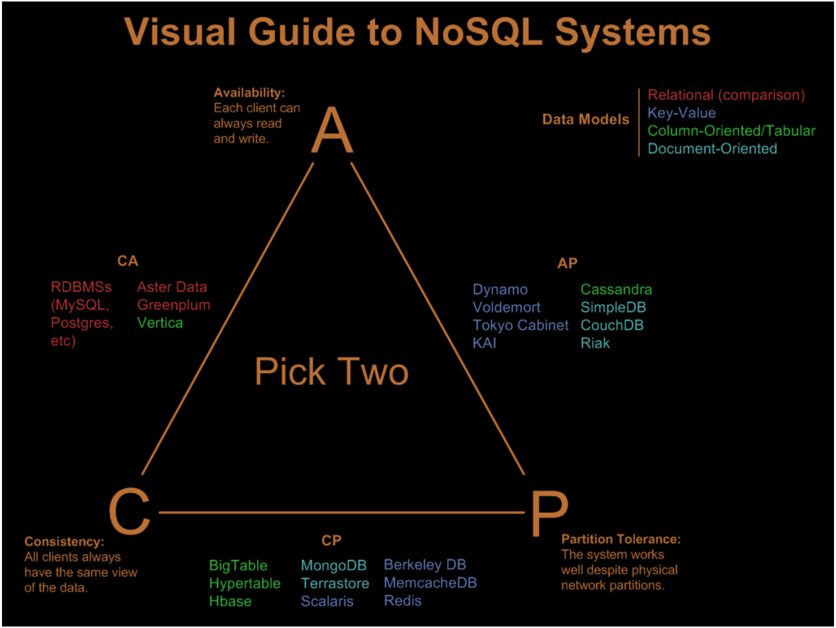
BASE Properties

- Basic Availability
  - Possibilities of faults but not a fault of the whole system.
- Soft-state
  - Copies of a data item may be inconsistent
- Eventually consistent
  - Copies becomes consistent at some later time if there are no more updates to that data item

CAP Theorem

- Consistency
  - Consistent state of data after the execution of an operation.
- Availability
  - Clients can always read and write data.
- Partition Tolerance
  - Continue the operation in the presence of network partitions.
- You can choose only two!




Visual Guide to NoSQL Systems
Availability:
Each client can always read and write.
A
Data Models
Relational (comparison)
Key-Value
Column-Oriented/Tabular
Document-Oriented
CA
RDBMSs (MySQL, Postgres, etc)
Aster Data
Greenplum
Vertica
AP
Dynamo
Voldemort
Tokyo Cabinet
KAI
Cassandra
SimpleDB
CouchDB
Riak
Pick Two
C
P
Consistency:
All clients always have the same view of the data.
CP
BigTable
Hypertable
Hbase
MongoDB
Terrastore
Scalaris
Berkeley DB
MemcacheDB
Redis
Partition Tolerance:
The system works well despite physical network partitions.

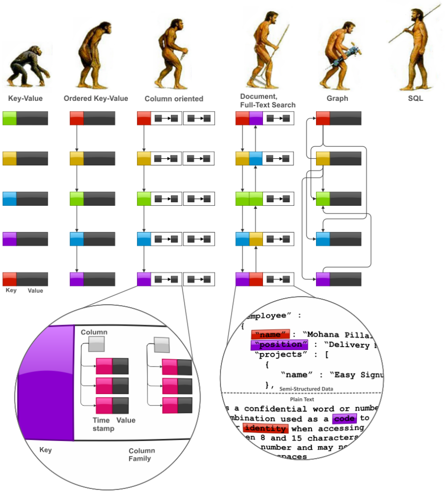
Dyanmo

Dynamo

- Distributed key/value storage system
- Scalable and Highly available
- CAP: it sacrifices strong consistency for availability: always writable

Data Model

Data Model



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Partitioning

- Key/value, where values are stored as objects.
- If size of data exceeds the capacity of a single machine: partitioning

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- If size of data exceeds the capacity of a single machine: partitioning
- Consistent hashing is one form of sharding (partitioning).

Consistent Hashing

- Hash both data and nodes using the same hash function in a same id space.
- `partition = hash(d) mod n`, `d`: data, `n`: number of nodes

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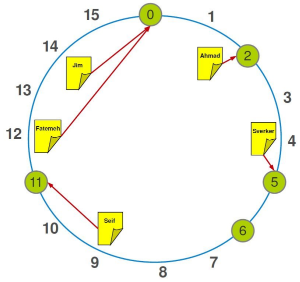
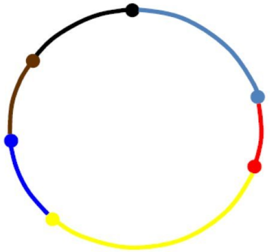
- `partition = hash(d) mod n`, `d`: data, `n`: number of nodes

```
hash("Fatemeh") = 12
hash("Ahmad") = 2
hash("Seif") = 9
hash("Jim") = 14
hash("Sverker") = 4
```



Load Imbalance (1/4)

- Consistent hashing may lead to imbalance.
- Node identifiers may not be balanced.



Load Imbalance (2/4)

- Consistent hashing may lead to imbalance.
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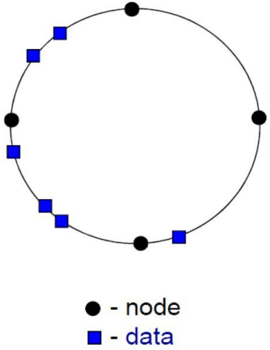
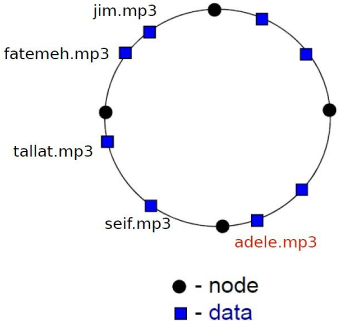


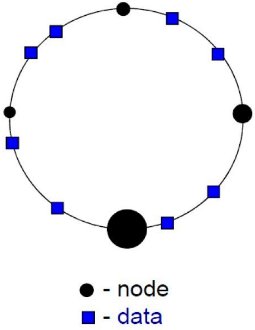
Load Imbalance (3/4)

- Consistent hashing may lead to imbalance.
- Hot spots.



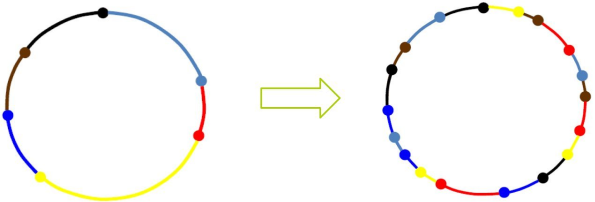
Load Imbalance (4/4)

- Consistent hashing may lead to imbalance.
- Heterogeneous nodes.



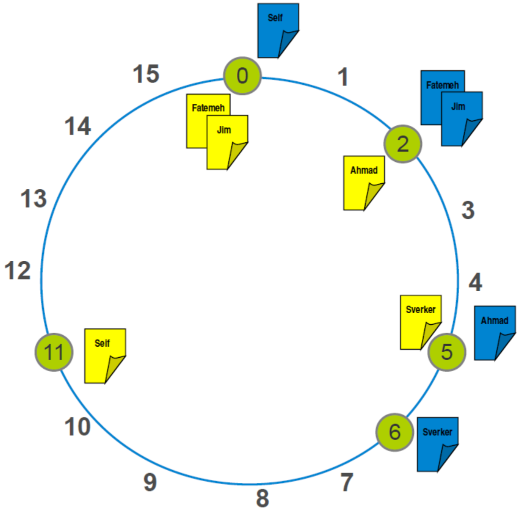
Load Balancing via Virtual Nodes

- Each physical node picks multiple random identifiers.
- Each identifier represents a virtual node.
- Each node runs multiple virtual nodes.



Replication

- To achieve high availability and durability, data should be replicates on multiple nodes.



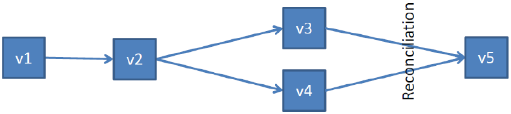
Data Consistency

Data Consistency

- Eventual consistency: updates are propagated asynchronously.
- Each update/modification of an item results in a new and immutable version of the data.
    - Multiple versions of an object may exist.
- Replicas eventually become consistent.

Data Versioning (1/2)

- Use vector clocks for capturing causality, in the form of (node, counter)
  - If causal: older version can be forgotten
  - If concurrent: conflict exists, requiring reconciliation



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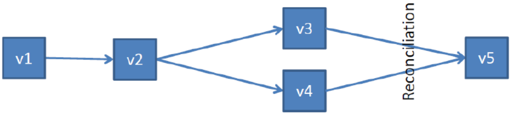
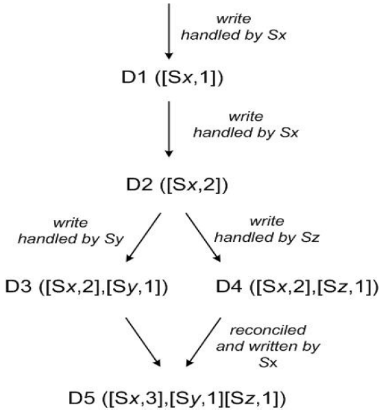
- Version branching can happen due to node/network failures.



Data Versioning (2/2)

- Client C1 writes new object via Sx.



Data Versioning (2/2)

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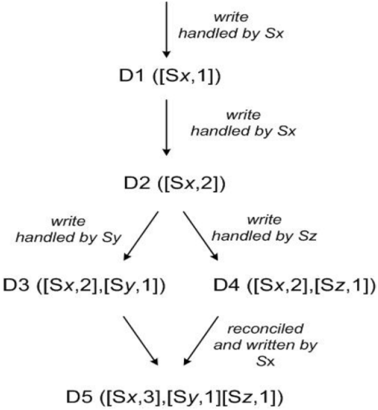

Data Versioning (2/2)

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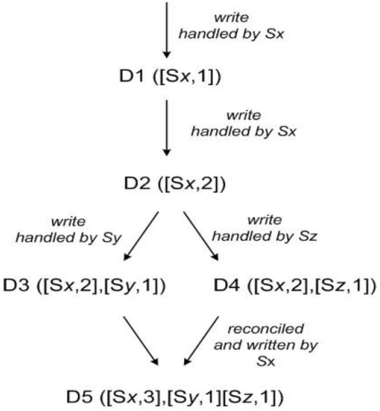
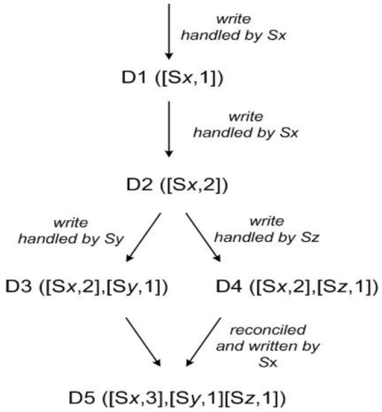
- C1 updates the object via Sy.

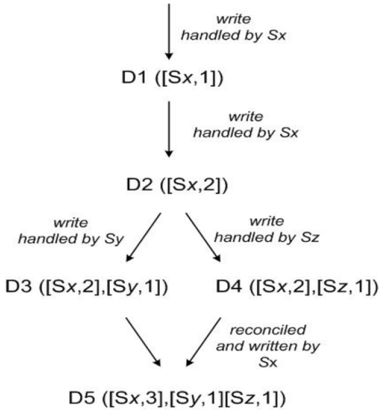


Data Versioning (2/2)

- Client C1 writes new object via Sx.
- C1 updates the object via Sx.
- C1 updates the object via Sy.
- C2 reads D2 and updates the object via Sz.



- Client C1 writes new object via Sx.
- C1 updates the object via Sx.
- C1 updates the object via Sy.
- C2 reads D2 and updates the object via Sz.
- C3 reads D3 and D4 via Sx.
  - The read context is a summary of the clocks of D3 and D4: [(Sx, 2), (Sy, 1), (Sz, 1)].



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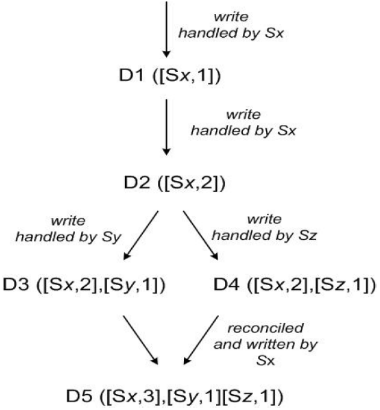
- Reconciliation



Dynamo API

Dynamo API

- `get(key)`
  - Return single object or list of objects with conflicting version and context.
- `put(key, context, object)`
  - Store object and context under key.
  - Context encodes system metadata, e.g., version number.

put Operation

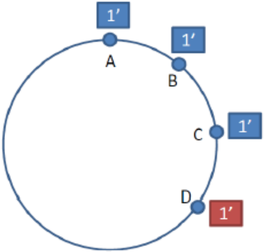
- Coordinator generates new vector clock and writes the new version locally.
- Send to N nodes.
- Wait for response from W nodes.

get Operation

- Coordinator requests existing versions from N.
  - Wait for response from R nodes.
- If multiple versions, return all versions that are causally unrelated.
- Divergent versions are then reconciled.
- Reconciled version written back.

Sloppy Quorum

- Due to partitions, quorums might not exist.
  - Sloppy quorum.
  - Create transient replicas: N healthy nodes from the preference list.
  - Reconcile after partition heals.



Sloppy Quorum

- Due to partitions, quorums might not exist.
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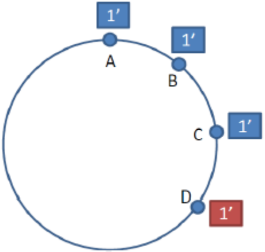
- Say A is unreachable.

- put will use D.

- Later, D detects A is alive.
  - Sends the replica to A
  - Removes the replica.



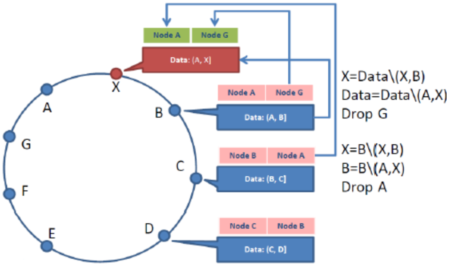
Membership Management

Membership Management

- Administrator explicitly adds and removes nodes.
- Gossiping to propagate membership changes.
  - Eventually consistent view.
  - $O(1)$ hop overlay.

Adding and Removing Nodes

- A new node X added to system.
  - X is assigned key ranges w.r.t. its virtual servers.
  - For each key range, it transfers the data items.



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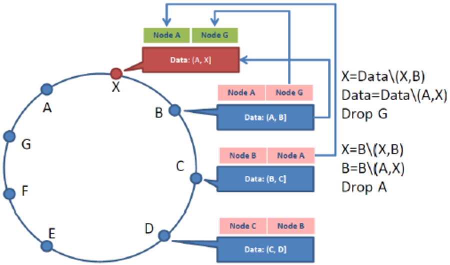


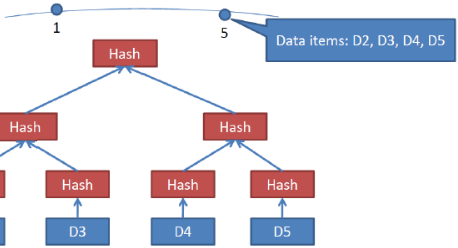
- Removing a node: reallocation of keys is a reverse process of adding nodes.

Failure Detection (1/2)

- Passive failure detection.
  - Use pings only for detection from failed to alive.
- In the absence of client requests, node A doesn't need to know if node B is alive.

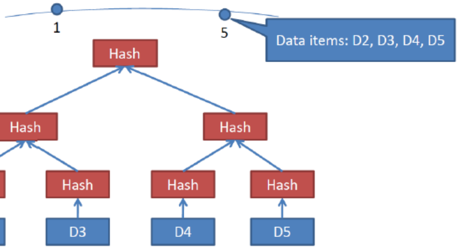
Failure Detection (2/2)

- Anti-entropy for replica synchronization.
- Use Merkle trees for fast inconsistency detection and minimum transfer of data.



Failure Detection (2/2)

- Anti-entropy for replica synchronization.
- Use Merkle trees for fast inconsistency detection and minimum transfer of data.
  - Nodes maintain Merkle tree of each key range.
  - Exchange root of Merkle tree to check if the key ranges are updated.



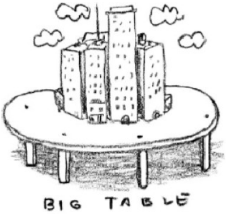
BigTable

Motivation

- Lots of (semi-)structured data at Google.
  - URLs, TextGreenper-user data, geographical locations, ...
- Big data
  - Billions of URLs, hundreds of millions of users, 100+TB of satellite image data, ...

BigTable

- Distributed multi-level map
- Fault-tolerant
- Scalable and self-managing
- CAP: strong consistency and partition tolerance



Data Model

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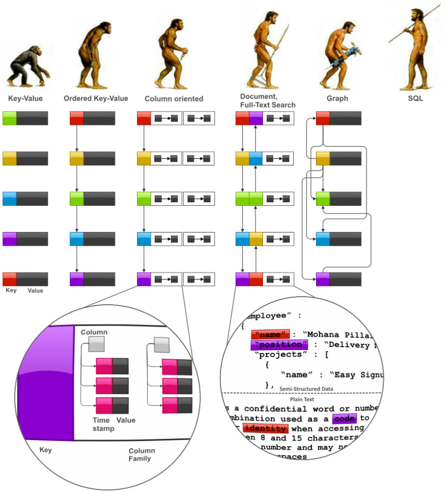

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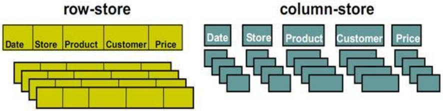
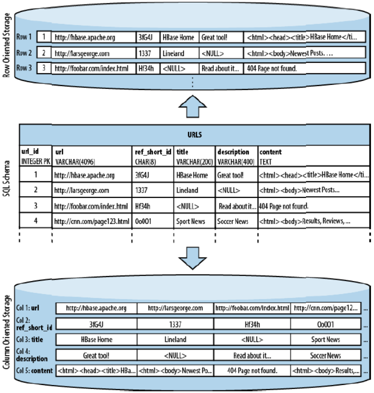


Columns-Oriented Data Model (2/2)

- In many analytical databases queries, few attributes are needed.
- Column values are stored contiguously on disk: reduces I/O.



[Lars George, "Hbase: The Definitive Guide", O'Reilly, 2011]

BigTable Data Model (1/5)

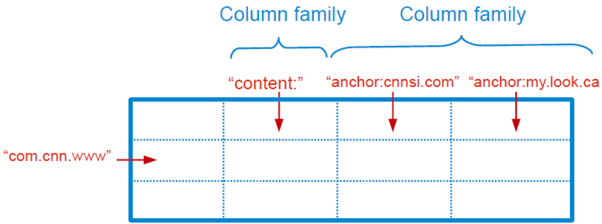
- Table
- Distributed multi-dimensional sparse map

BigTable Data Model (2/5)

- Rows
- Every read or write in a row is atomic.
- Rows sorted in lexicographical order.

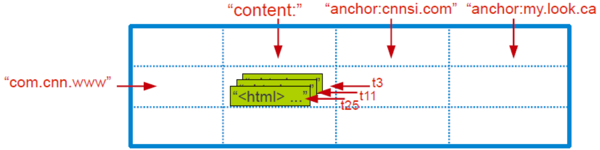
BigTable Data Model (3/5)

- Column
- The basic unit of data access.
- Column families: group of (the same type) column keys.
- Column key naming: family:qualifier



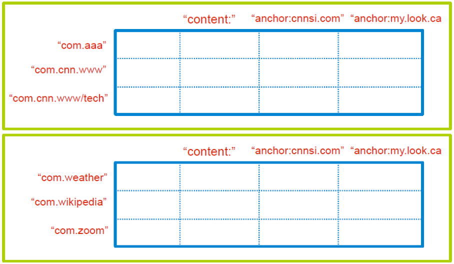
BigTable Data Model (4/5)

- Timestamp
- Each column value may contain multiple versions.



BigTable Data Model (5/5)

- Tablet: contiguous ranges of rows stored together.
- Tables are split by the system when they become too large.
- Auto-Sharding
- Each tablet is served by exactly one tablet server.



Bigtable API

The Bigtable API

- Metadata operations
    - Create/delete tables, column families, change metadata

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The Bigtable API

- Metadata operations
  - Create/delete tables, column families, change metadata
- Writes: single-row, atomic
  - write/delete cells in a row, delete all cells in a row
- Reads: read arbitrary cells in a Bigtable table
  - Each row read is atomic.
  - One row, all or specific columns, certain timestamps, and ...

Writing Example

```
// Open the table
Table *T = OpenOrDie("/bigtable/web/webtable");

// Write a new anchor and delete an old anchor
RowMutation r1(T, "com.cnn.www");
r1.Set("anchor:www.c-span.org", "CNN");
r1.Delete("anchor:www.abc.com");
Operation op;
Apply(&op, &r1);
```

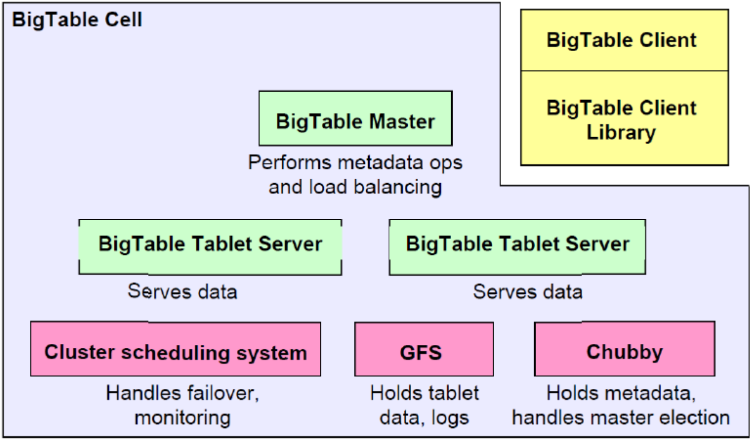
Reading Example

```
Scanner scanner(T);
scanner.Lookup("com.cnn.www");
ScanStream *stream;
stream = scanner.FetchColumnFamily("anchor");
stream->SetReturnAllVersions();

for (; !stream->Done(); stream->Next()) {
  printf("%s %s %lld %s\n",
    scanner.RowName(),
    stream->ColumnName(),
    stream->MicroTimestamp(),
    stream->Value());
}
```

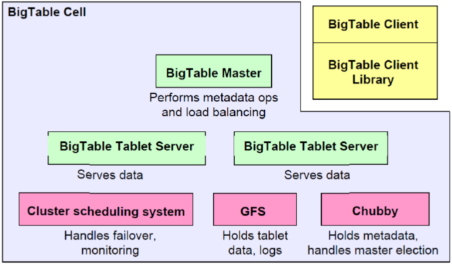
BigTable Architecture

BigTable Cell



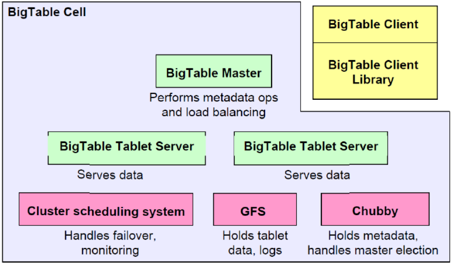
Main Components

- Master server
- Tablet server
- Client library



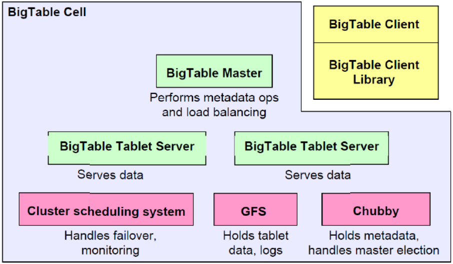
Master Server

- One master server.
- Assigns tablets to tablet server.
- Balances tablet server load.
- Garbage collection of unneeded files in GFS.
- Handles schema changes, e.g., table and column family creations



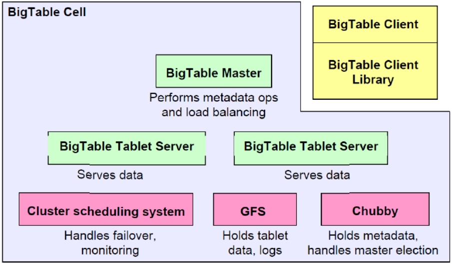
Tablet Server

- Many tablet servers.
- Can be added or removed dynamically.
- Each manages a set of tablets (typically 10-1000 tablets/server).
- Handles read/write requests to tablets.
- Splits tablets when too large.



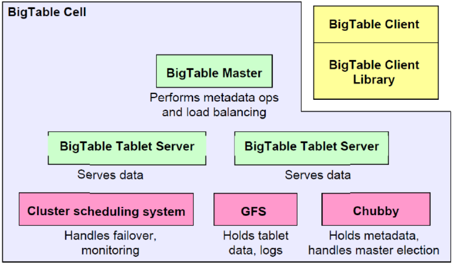
Client Library

- Library that is linked into every client.
- Client data does not move though the master.
- Clients communicate directly with tablet servers for reads/writes.



Building Blocks

- The building blocks for the BigTable are:
  - Google File System (GFS): raw storage
  - Chubby: distributed lock manager
  - Scheduler: schedules jobs onto machines



Google File System (GFS)

- Large-scale distributed file system.
- Store log and data files.

Chubby Lock Service

- Ensure there is only one active master.
- Store bootstrap location of BigTable data.
- Discover tablet servers.
- Store BigTable schema information.
- Store access control lists.

Master Startup

- The master executes the following steps at startup:
  - Grabs a unique master lock in Chubby, which prevents concurrent master instantiations.
  - Scans the servers directory in Chubby to find the live servers.
  - Communicates with every live tablet server to discover what tablets are already assigned to each server.
  - Scans the METADATA table to learn the set of tablets.

Tablet Assignment

- 1 tablet $\rightarrow$ 1 tablet server.

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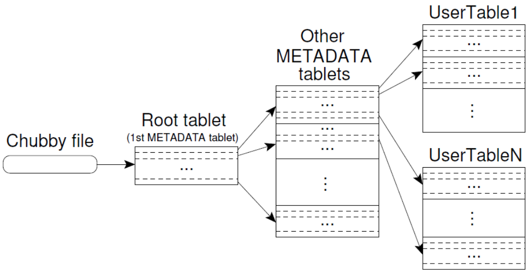
  - When a tablet server starts, it creates and acquires an exclusive lock in Chubby.
- Master detects the status of the lock of each tablet server by checking periodically.
- Master is responsible for finding when tablet server is no longer serving its tablets and reassigning those tablets as soon as possible.

Table Serving

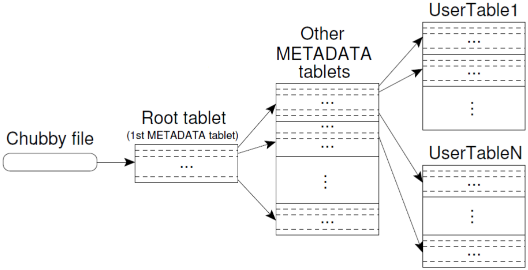
Finding a Tablet

- Three-level hierarchy.



Finding a Tablet

- Three-level hierarchy.
- Root tablet contains location of all tablets in a special METADATA table.



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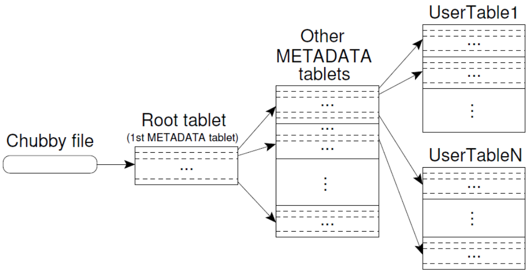
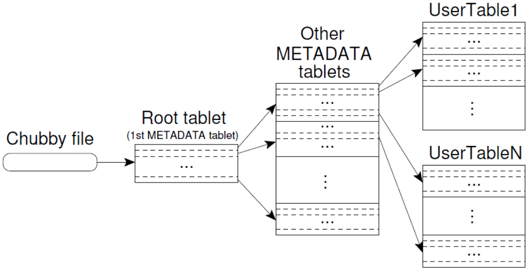


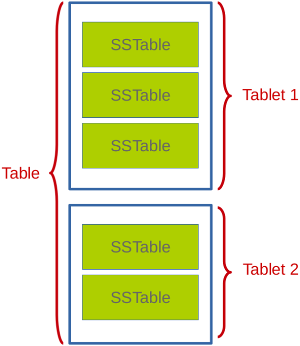
Finding a Tablet

- Three-level hierarchy.
- Root tablet contains location of all tablets in a special METADATA table.
- METADATA table contains location of each tablet under a row.
- The client library caches tablet locations.



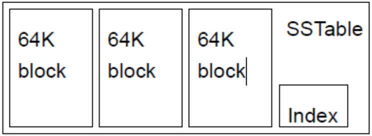
SSTable (1/2)

- SSTable file format used internally to store Bigtable data.
- Immutable, sorted file of key-value pairs.
- Each SSTable is stored in a GFS file.



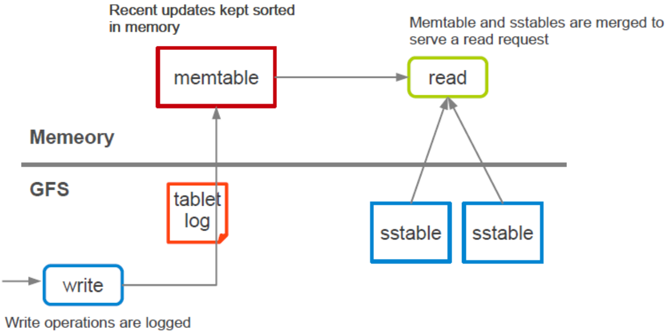
SSTable (2/2)

- Chunks of data plus a block index.
  - A block index is used to locate blocks.
  - The index is loaded into memory when the SSTable is opened.



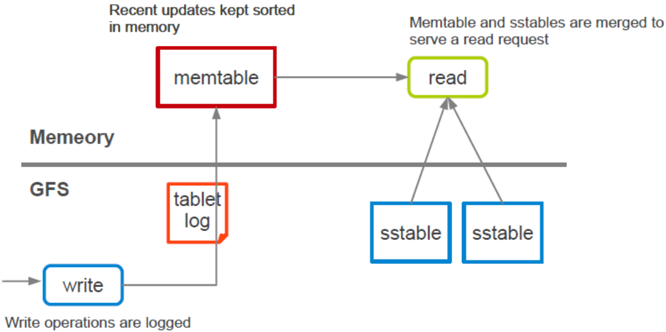
Tablet Serving (1/2)

- Updates committed to a commit log.



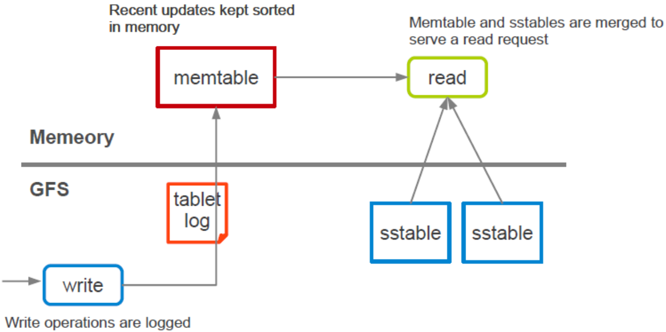
Tablet Serving (1/2)

- Updates committed to a commit log.
- Recently committed updates are stored in memory - memtable



Tablet Serving (1/2)

- Updates committed to a commit log.
- Recently committed updates are stored in memory - memtable
- Older updates are stored in a sequence of SSTables.



Tablet Serving (2/2)

- Strong consistency
  - Only one tablet server is responsible for a given piece of data.
  - Replication is handled on the GFS layer.

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- Strong consistency
  - Only one tablet server is responsible for a given piece of data.
  - Replication is handled on the GFS layer.
- Tradeoff with availability
  - If a tablet server fails, its portion of data is temporarily unavailable until a new server is assigned.

Loading Tablets

- To load a tablet, a tablet server does the following:
- Finds locaton of tablet through its METADATA.
  - Metadata for a tablet includes list of SSTables and set of redo points.
- Read SSTables index blocks into memory.
- Read the commit log since the redo point and reconstructs the memtable.

Compaction

- Minor compaction
  - Convert the memtable into an SSTable.

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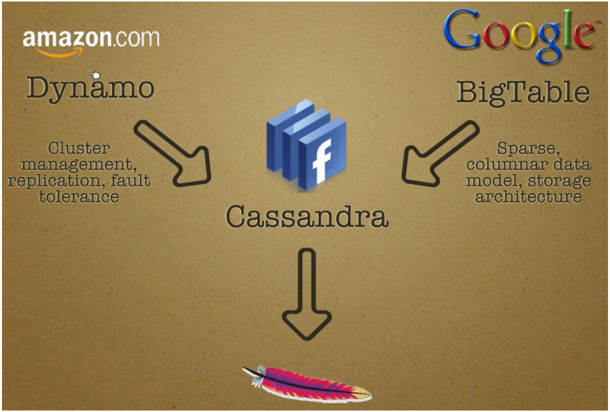
  - Reads the contents of a few SSTables and the memtable, and writes out a new SSTable.

Compaction

- Minor compaction
  - Convert the memtable into an SSTable.
- Merging compaction
  - Reads the contents of a few SSTables and the memtable, and writes out a new SSTable.
- Major compaction
  - Merging compaction that results in only one SSTable.
  - No deleted records, only sensitive live data.

Cassandra

Cassandra


amazon.com
Dynamo
Cluster management, replication, fault tolerance
Google
BigTable
Sparse, columnar data model, storage architecture
Cassandra

From Dynamo

- Symmetric P2P architecture
- Gossip based discovery and error detection
- Distributed key-value store: partitioning and topology discovery
- Eventual consistency

From BigTable

- Sparse Column oriented sparse array
- SSTable disk storage
  - Append-only commit log
  - Memtable (buffering and sorting)
  - Immutable sstable files
  - Compaction

Summary

Summary

- NoSQL data models: key-value, column-oriented, document-oriented, graph-based
- Sharding and consistent hashing
- ACID vs. BASE
- CAP (Consistency vs. Availability)

Summary

- Dynamo: key/value storage: put and get
- Data partitioning: consistent hashing
- Load balancing: virtual server
- Replication: several nodes, preference list
- Data versioning: vector clock, resolve conflict at read time by the application
- Membership management: join/leave by admin, gossip-based to update the nodes' views, ping to detect failure
- Handling transient failure: sloppy quorum
- Handling permanent failure: Merkle tree

Summary

- BigTable
- Column-oriented
- Main components: master, tablet server, client library
- Basic components: GFS, chubby, SSTable

Questions?