NoSQL Databases

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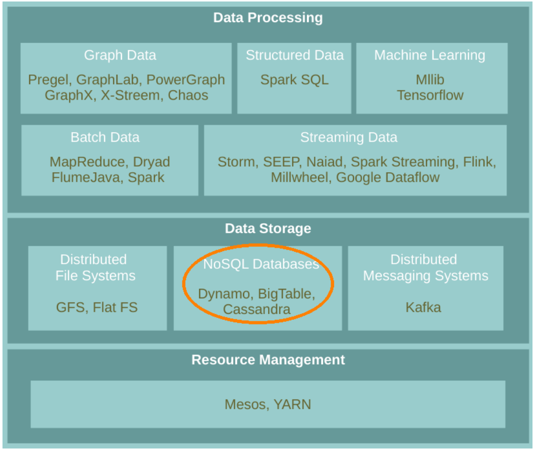
2020-09-01

The Course Web Page

https://id2221kth.github.io

https://tinyurl.com/y4qph82u

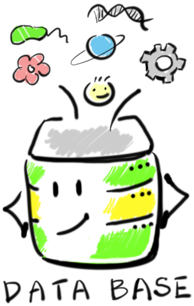
Where Are We?



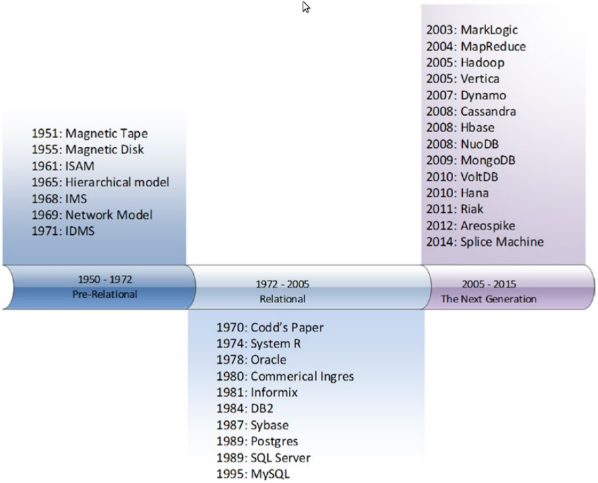
Data Processing
Graph Data
Pregel, GraphLab, PowerGraph
GraphX, X-Streem, Chaos
Structured Data
Spark SQL
Machine Learning
Mllib
Tensorflow
Batch Data
MapReduce, Dryad
FlumeJava, Spark
Streaming Data
Storm, SEEP, Naiad, Spark Streaming, Flink,
Millwheel, Google Dataflow
Data Storage
Distributed
File Systems
GFS, Flat FS
NoSQL Databases
Dynamo, BigTable,
Cassandra
Distributed
Messaging Systems
Kafka
Resource Management
Mesos, YARN

Database and Database Management System

- Database: an organized collection of data.
- Database Management System (DBMS): a software to capture and analyze data.



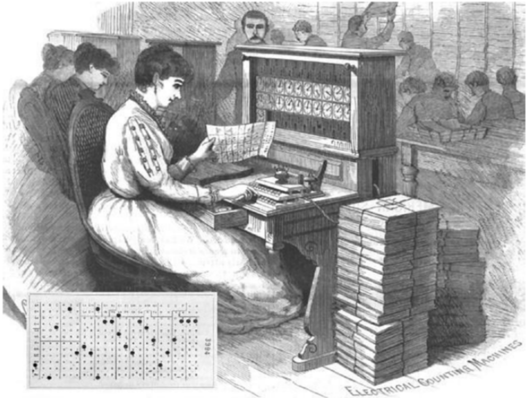
Three Database Revolutions



[Guy Harrison, Next Generation Databases: NoSQLand Big Data, 2015]

Early Database Systems

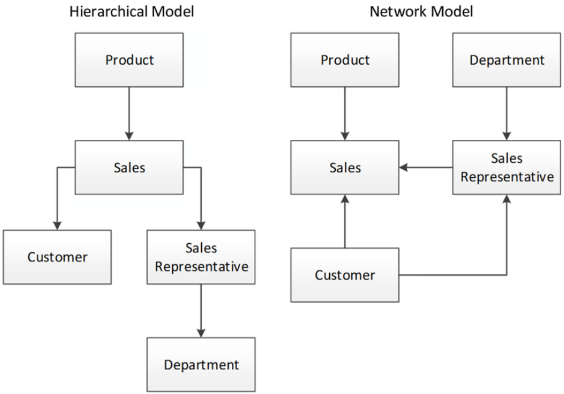
- There were databases but no Database Management Systems (DBMS).



[Guy Harrison, Next Generation Databases: NoSQLand Big Data, 2015]

The First Database Revolution

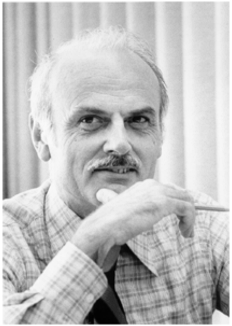
- Navigational data model: hierarchical model (IMS) and network model (CODASYL).
- Disk-aware



[Guy Harrison, Next Generation Databases: NoSQLand Big Data, 2015]

The Second Database Revolution

- Relational data model: Edgar F. Codd paper
  - Logical data is disconnected from physical information storage
- ACID transactions
  - Atomic, Consistent, Isolated, Durable
- SQL language
- Object databases
  - Information is represented in the form of objects

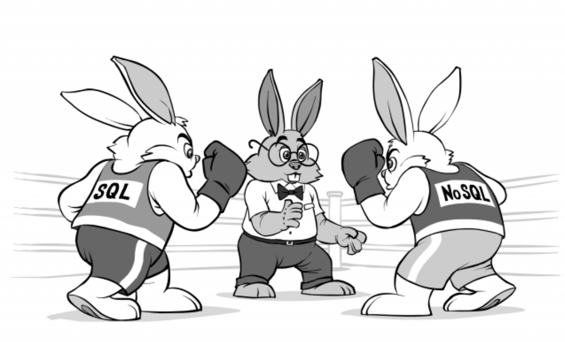


ACID Properties

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

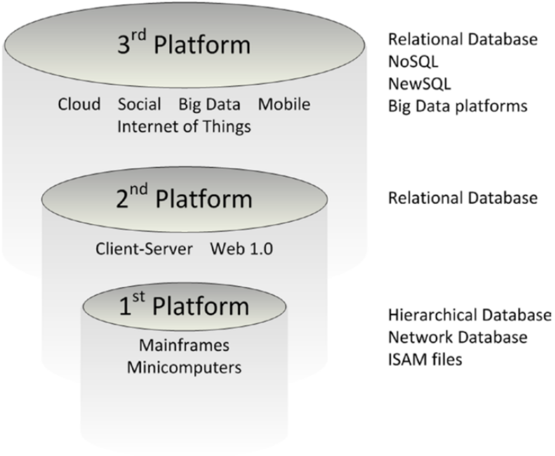
The Third Database Revolution

- NoSQL databases: BASE instead of ACID.
- NewSQL databases: scalable performance of NoSQL + ACID.



[http://ithare.com/nosql-vs-sql-for-mogs]

Three Waves of Database Technology



[Guy Harrison, Next Generation Databases: NoSQLand Big Data, 2015]

SQL vs. NoSQL Databases

Relational SQL Databases

- 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

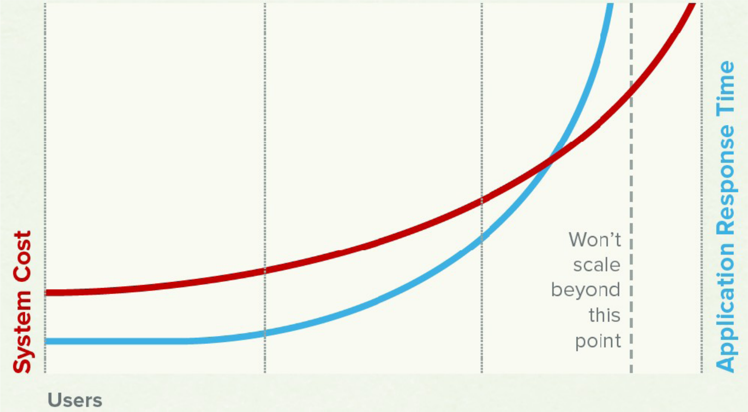
- They promise: ACID

SQL Databases Challenges

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

- RDBMS were not designed to be distributed.

Scaling SQL Databases is Expensive and Inefficient

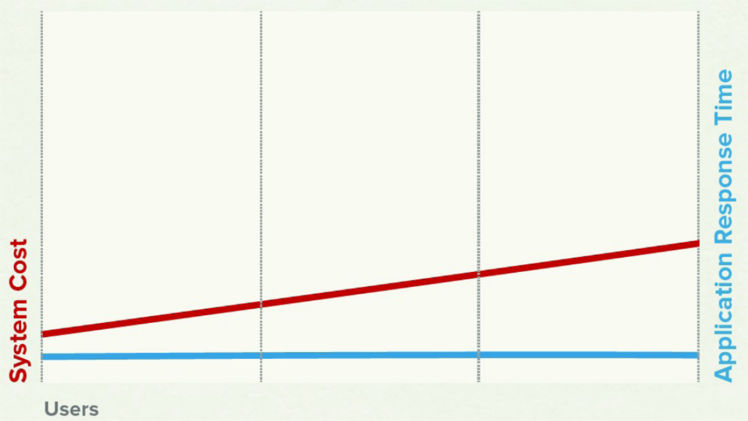


[http://www.couchbase.com/sites/default/files/uploads/all/whitepapers/NoSQLWhitepaper.pdf]

NoSQL

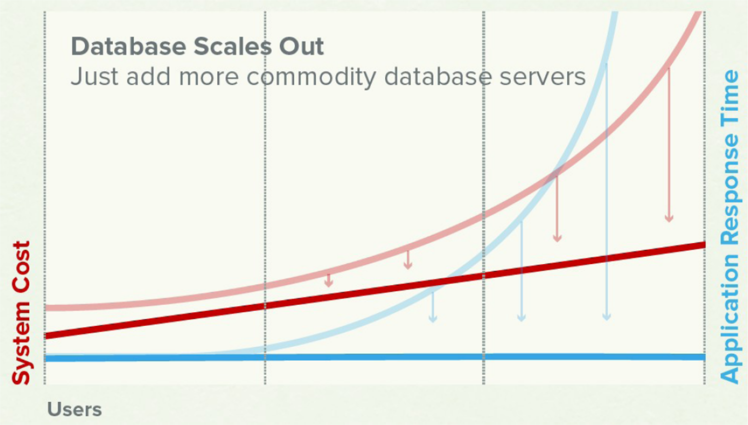
- Avoids:
  - Overhead of ACID properties
  - Complexity of SQL query
- Provides:
  - Scalablity
  - Easy and frequent changes to DB
  - Large data volumes

NoSQL Cost and Performance



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

SQL vs. NoSQL



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

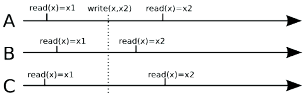
ACID vs. BASE

Availability

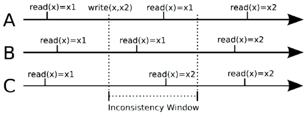
- Replicating data to improve the availability of data.
- Data replication
  - Storing data in more than one site or node

Consistency

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

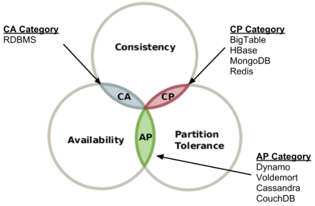


- Eventual consistency
  - Does not guarantee that subsequent accesses will return the updated value.
  - Inconsistency window.
  - If no new updates are made to the object, eventually all accesses will return the last updated value.



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!



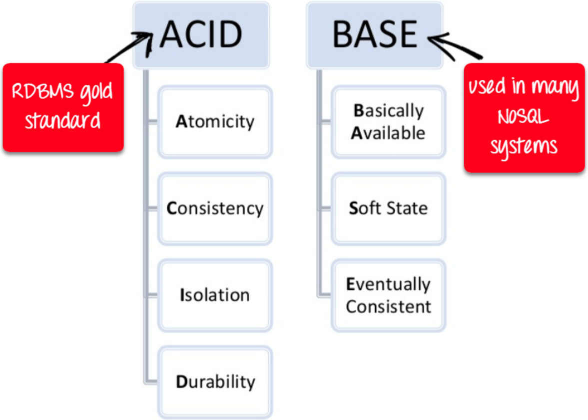
Consistency vs. Availability

- The large-scale applications have to be reliable: availability, consistency, partition tolerance
- Not possible to achieve with ACID properties.
- The BASE approach forfeits the ACID properties of consistency and isolation in favor of availability 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

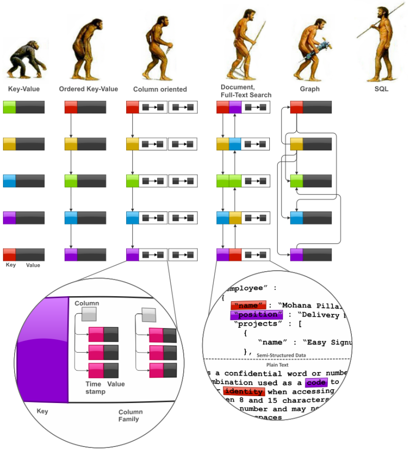
ACID vs. BASE



[https://www.guru99.com/sql-vs-nosql.html]

NoSQL Data Models

NoSQL Data Models



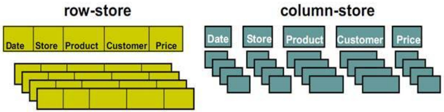
[http://highlyscalable.wordpress.com/2012/03/01/nosql-data-modeling-techniques]

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

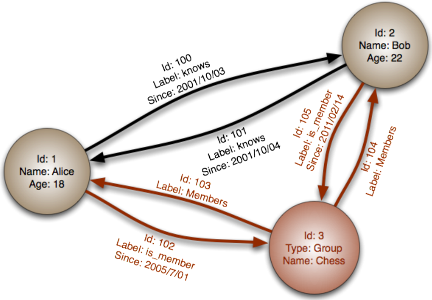
- Similar to a column-oriented store, but values can have complex documents.
- Flexible schema (XML, YAML, JSON, and BSON).
- CouchDB, MongoDB, ...

```
{
    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]

BigTable

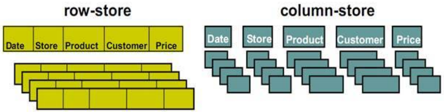
BigTable

- Lots of (semi-)structured data at Google.
  - URLs, per-user data, geographical locations, ...
- Distributed multi-level map
- CAP: strong consistency and partition tolerance

Data Model

Data Model (1/6)

- 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.



Data Model (2/6)

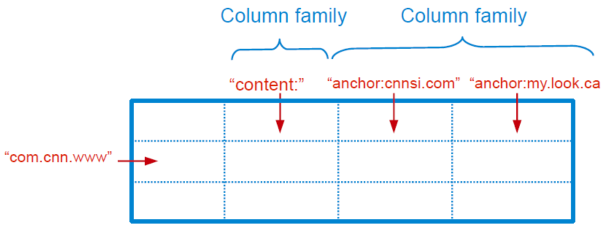
- Table
- Distributed multi-dimensional sparse map

Data Model (3/6)

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

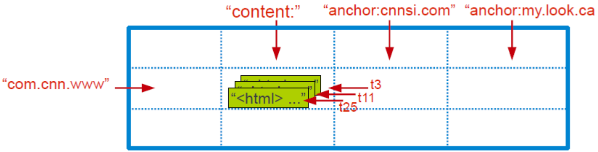
Data Model (4/6)

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



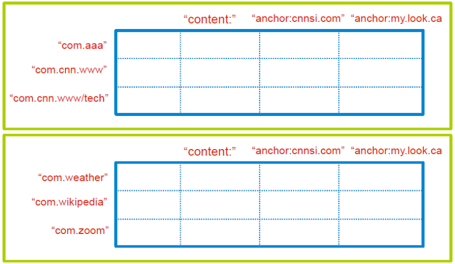
Data Model (5/6)

- Timestamp
- Each column value may contain multiple versions.



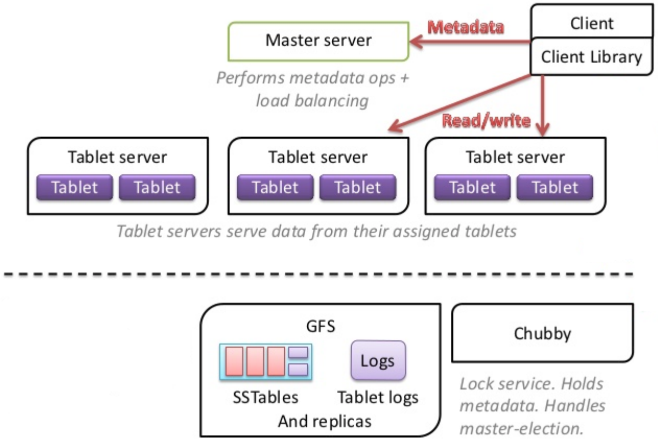
Data Model (6/6)

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



System Architecture

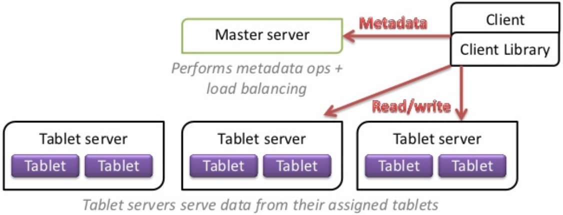
BigTable System Structure



[https://www.slideshare.net/GrishaWeintraub/cap-28353551]

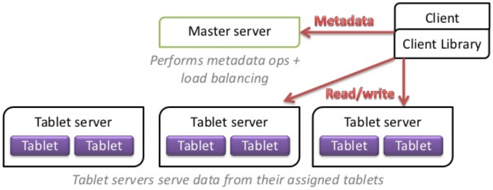
Main Components

- Master
- Tablet server
- Client library



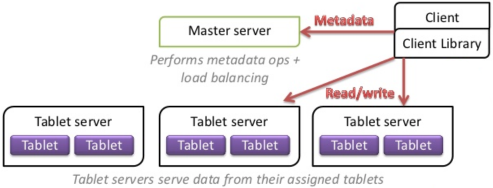
Master

- 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



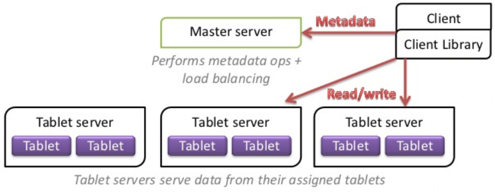
Tablet Server

- 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.



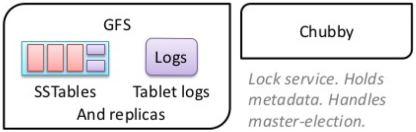
Client Library

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



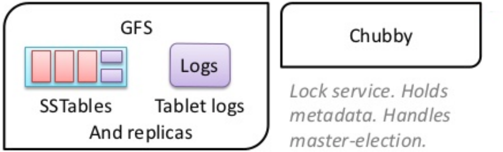
Building Blocks

- The building blocks for the BigTable are:
  - Google File System (GFS)
  - Chubby
  - SSTable



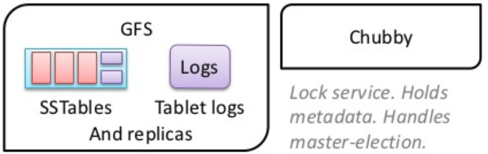
Google File System (GFS)

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



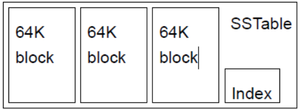
Chubby Lock Service

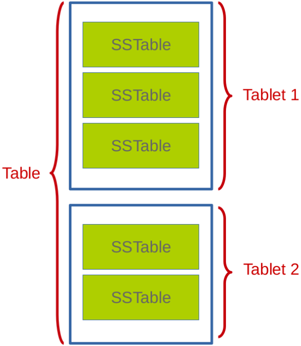
- Ensure there is only one active master.
- Store bootstrap location of BigTable data.
- Discover tablet servers.
- Store BigTable schema information and access control lists.



SSTable

- SSTable file format used internally to store BigTable data.
- Chunks of data plus a block index.
- Immutable, sorted file of key-value pairs.
- Each SSTable is stored in a GFS file.





Tablet Serving

Master Startup

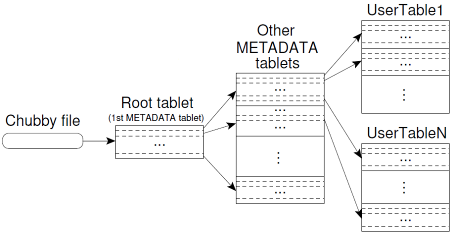
- The master executes the following steps at startup:
  - Grabs a unique master lock in Chubby, which prevents concurrent master instantiations.
  - Scans the servers directory in Chubby to find the live servers.
  - Communicates with every live tablet server to discover what tablets are already assigned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

Tablet Assignment

- 1 tablet $\rightarrow$ 1 tablet server.
- Master uses Chubby to keep tracks of live tablet serves and unassigned tablets.
  - 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.

Finding a Tablet

- Three-level hierarchy.
- The first level is a file stored in Chubby that contains the location of the root tablet.
- 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.

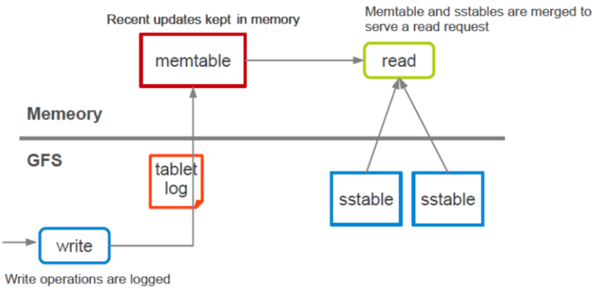


Loading Tablets

- 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.

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.
- Trade-off with availability
  - If a tablet server fails, its portion of data is temporarily unavailable until a new server is assigned.

BigTable vs. HBase

BigTable	HBase
GFS	HDFS
Tablet Server	Region Server
SSTable	StoreFile
Memtable	MemStore
Chubby	ZooKeeper

HBase Example

```
# Create the table "test", with the column family "cf"
create 'test', 'cf'
```

```
# Use describe to get the description of the "test" table
describe 'test'
```

```
# Put data in the "test" table
put 'test', 'row1', 'cf:a', 'value1'
put 'test', 'row2', 'cf:b', 'value2'
put 'test', 'row3', 'cf:c', 'value3'
```

```
# Scan the table for all data at once
scan 'test'
```

```
# To get a single row of data at a time, use the get command
get 'test', 'row1'
```

Cassandra

Cassandra

- A column-oriented database
- It was created for Facebook and was later open sourced
- CAP: availability and partition tolerance

Borrowed From BigTable

- Data model: column oriented
  - Keyspaces (similar to the schema in a relational database), tables, and columns.
- SSTable disk storage
  - Append-only commit log
  - Memtable (buffering and sorting)
  - Immutable sstable files

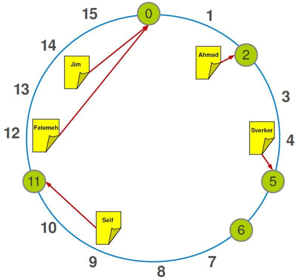
Data Partitioning (1/2)

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

Data Partitioning (2/2)

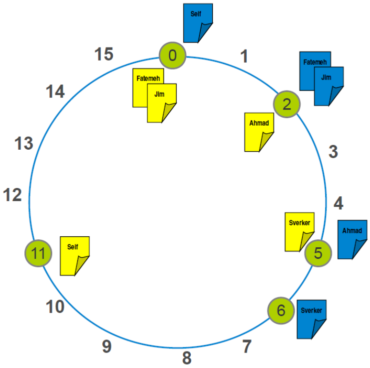
- Consistent hashing.
- Hash both data and node ids using the same hash function in a same id space.
- `partition = hash(d) mod n`, `d`: data, `n`: the size of the id space

```
id space = [0, 15], n = 16
hash("Fatemeh") = 12
hash("Ahmad") = 2
hash("Seif") = 9
hash("Jim") = 14
hash("Sverker") = 4
```



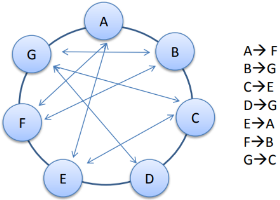
Replication

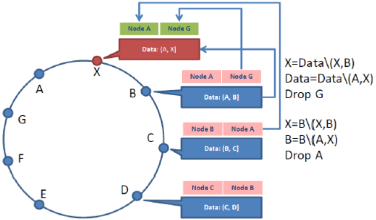
- To achieve high availability and durability, data should be replicated on multiple nodes.



Adding and Removing Nodes

- Gossip-based mechanism: periodically, each node contacts another randomly selected node.





Cassandra Example

```
# Create a keyspace called "test"
create keyspace test
with replication = {'class': 'SimpleStrategy', 'replication_factor': 1};
```

```
# Print the list of keyspaces
describe keyspaces;
```

```
# Navigate to the "test" keyspace
use test
```

```
# Create the "words" table in the "test" keyspace
create table words (word text, count int, primary key (word));
```

```
# Insert a row
insert into words(word, count) values('hello', 5);
```

```
# Look at the table
select * from words;
```

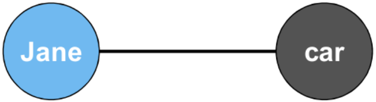
Neo4j

Neo4j

- A graph database
- The relationships between data is equally important as the data itself
- Cypher: a declarative query language similar to SQL, but optimized for graphs
- CAP: strong consistency and availability

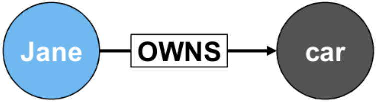
Data Model (1/4)

- Node (Vertex)
  - The main data element from which graphs are constructed.
  - A waypoint along a traversal route



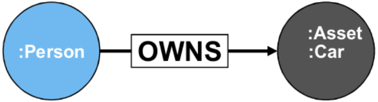
Data Model (2/4)

- Relationship (Edge)
- May contain
  - Direction
  - Metadata, e.g., weight or relationship type



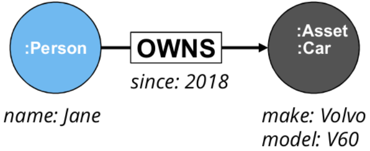
Data Model (3/4)

- Label
  - Define node category (optional)
  - Can have more than one

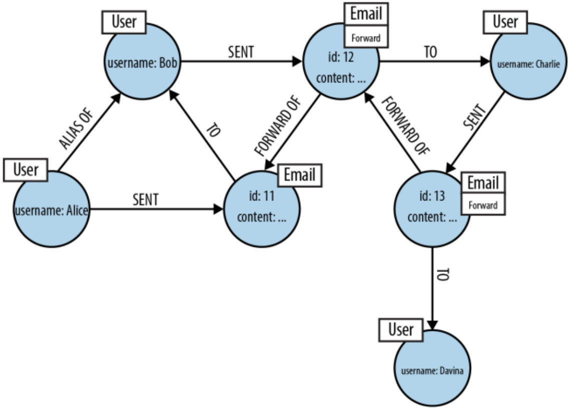


Data Model (4/4)

- Properties
  - Enrich a node or relationship



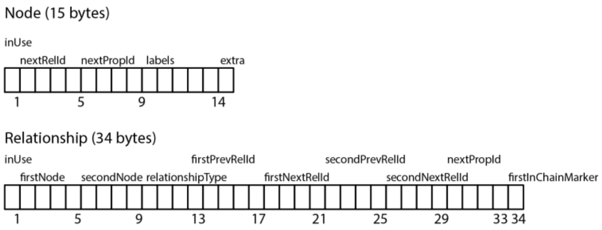
Example



[Ian Robinson et al., Graph Databases, 2015]

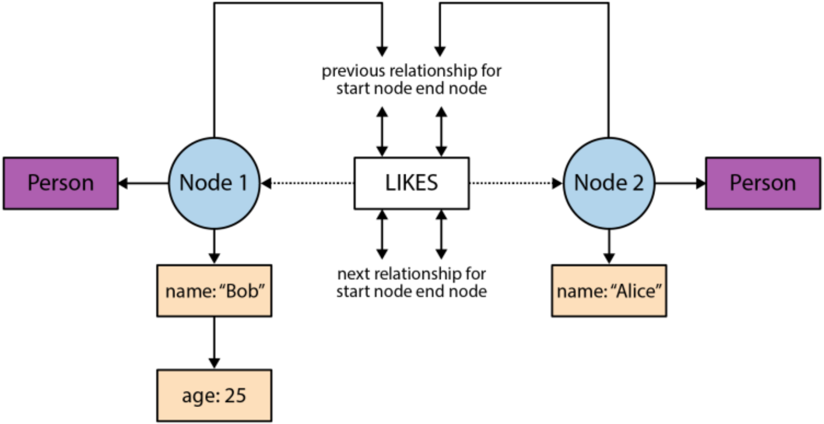
How a Graph is Stored in Neo4j? (1/2)

- Neo4j stores graph data in a number of different store files.
- Each store file contains the data for a specific part of the graph.
  - Separate stores for nodes, relationships, labels, and properties.
- The division of storage responsibilities facilitates performant graph traversals.



[Ian Robinson et al., Graph Databases, 2015]

How a Graph is Stored in Neo4j? (2/2)

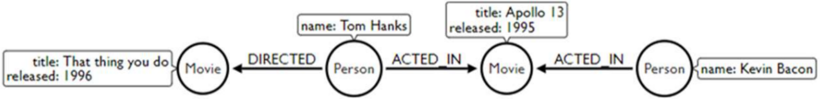


[Ian Robinson et al., Graph Databases, 2015]

What is Cypher?

- Declarative query language
- (): Nodes
- []: Relationships
- {}: Properties

Cypher Example (1/4)

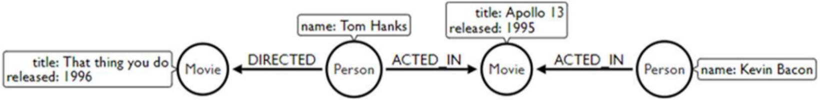



```
// Match all nodes
MATCH (n)
RETURN n;
```

```
// Match all nodes with a Person label
MATCH (n:Person)
RETURN n;
```

```
// Match all nodes with a Person label and property name is 'Tom Hanks'
MATCH (n:Person {name: 'Tom Hanks'})
RETURN n;
```

Cypher Example (2/4)

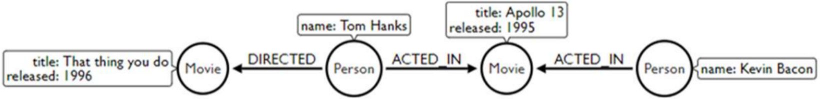



```
// Return nodes with label Person and name property equals 'Tom Hanks'
MATCH (p:Person)
WHERE p.name = 'Tom Hanks'
RETURN p;
```

```
// Return nodes with label Movie, released property is between 1991 and 1999
MATCH (m:Movie)
WHERE m.released > 1990 AND m.released < 2000
RETURN m;
```

```
// Find all the movies Tom Hanks acted in
MATCH (:Person {name:'Tom Hanks'})-[:ACTED_IN]->(m:Movie)
RETURN m.title;
```

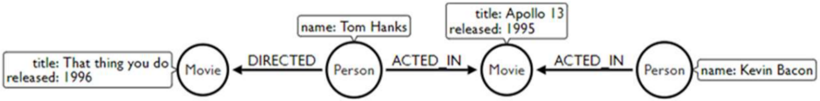
Cypher Example (3/4)




```
// Find all the movies Tom Hanks directed and order by latest movie
MATCH (:Person {name:'Tom Hanks'})-[:DIRECTED]->(m:Movie)
RETURN m.title, m.release ORDER BY m.release DESC;
```

```
// Find all of the co-actors Tom Hanks has ever worked with
MATCH (:Person {name:'Tom Hanks'})-->(:Movie)<-[:ACTED_IN]-(coActor:Person)
RETURN coActor.name;
```

Cypher Example (4/4)




```
// Find nodes with an ACTED_IN relationship
MATCH (p)-[:ACTED_IN]->()
RETURN p
```

```
// Find Person nodes with an ACTED_IN or DIRECTED_IN relationship
MATCH (p:Person)-[:ACTED_IN|DIRECTED]->()
RETURN p
```

```
// Find Person nodes who do not have an ACTED_IN relationship
MATCH (p:Person)
WHERE NOT (p)-[:ACTED_IN]->()
RETURN p
```

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

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

Summary

- Cassandra
- Column-oriented (similar to BigTable)
- Consistency hashing
- Gossip-based membership
- AP

Summary

- Neo4j
- Graph-based
- Cypher
- CA

References

- F. Chang et al., Bigtable: A distributed storage system for structured data, ACM Transactions on Computer Systems (TOCS) 26.2, 2008.
- A. Lakshman et al., Cassandra: a decentralized structured storage system, ACM SIGOPS Operating Systems Review 44.2, 2010.
- I. Robinson et al., Graph Databases (2nd ed.), O'Reilly Media, 2015.

Questions?

Acknowledgements

Some content of the Neo4j slides were derived from Ljubica Lazarevic's slides.