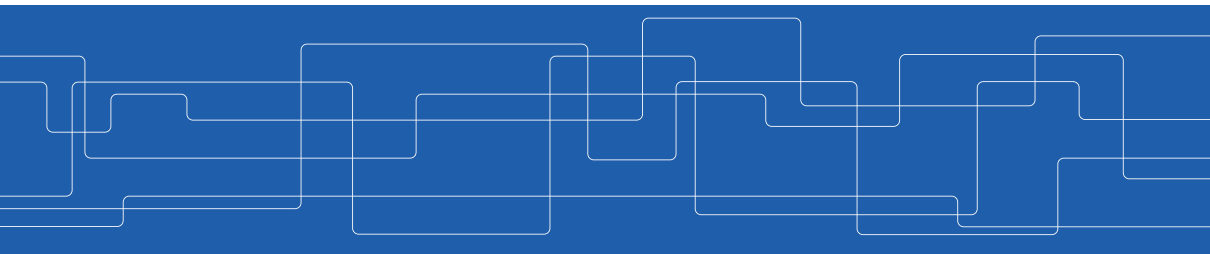




NoSQL Databases

Amir H. Payberah
payberah@kth.se
2022-09-06





The Course Web Page

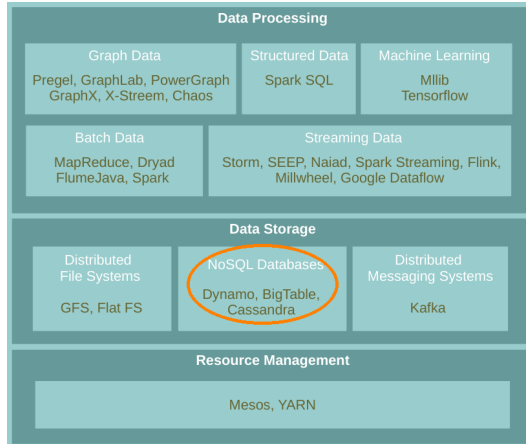
`https://id2221kth.github.io`



The Questions-Answers Page

<https://tinyurl.com/bdenpwc5>

Where Are We?



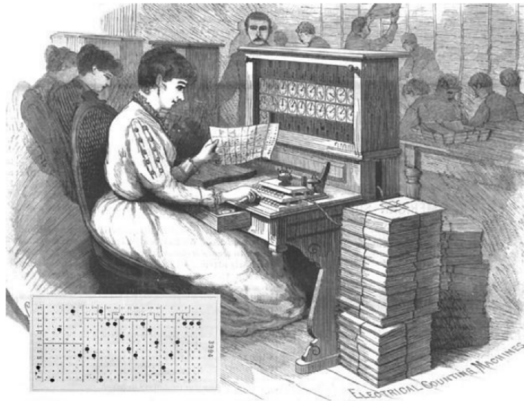
Database and Database Management System

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



Early Database Systems

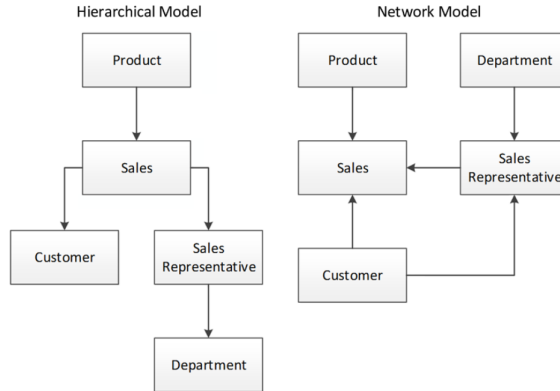
- ▶ There were databases but **no Database Management Systems (DBMS)**.



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

The First Database Revolution

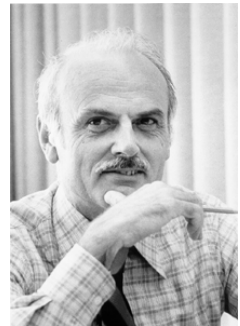
- ▶ Navigational data model: **hierarchical** model (IMS) and **network** model (CODASYL).
- ▶ Disk-aware



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

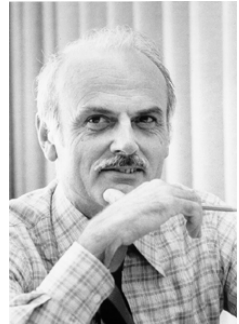
The Second Database Revolution

- ▶ **Relational** data model: Edgar F. **Codd** paper
 - **Logical** data is **disconnected** from **physical** information storage



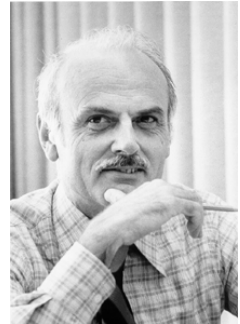
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- ▶ **Relational** data model: Edgar F. **Codd** paper
 - **Logical** data is **disconnected** from **physical** information storage
- ▶ **ACID** transactions
 - Atomic, Consistent, Isolated, Durable



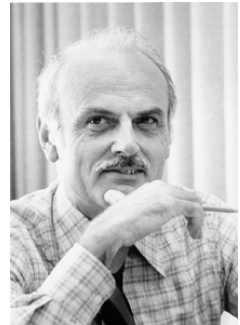
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- ▶ **Relational** data model: Edgar F. **Codd** paper
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 - Atomic, Consistent, Isolated, Durable
- ▶ **SQL** language



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.



ACID Properties

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- A database is in a **consistent** state before and after a transaction.



ACID Properties

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- Transactions can not see **uncommitted changes** in the database.



ACID Properties

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▶ Isolation

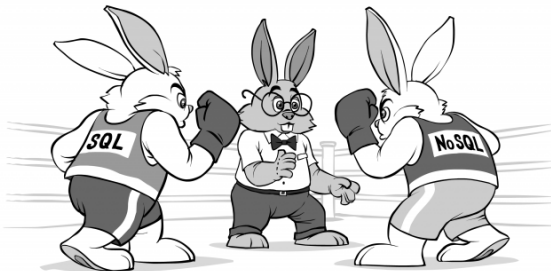
- Transactions can not see **uncommitted changes** in the database.

▶ Durability

- Changes are written to a **disk** before a database commits a transaction so that committed data cannot be lost through a power **failure**.

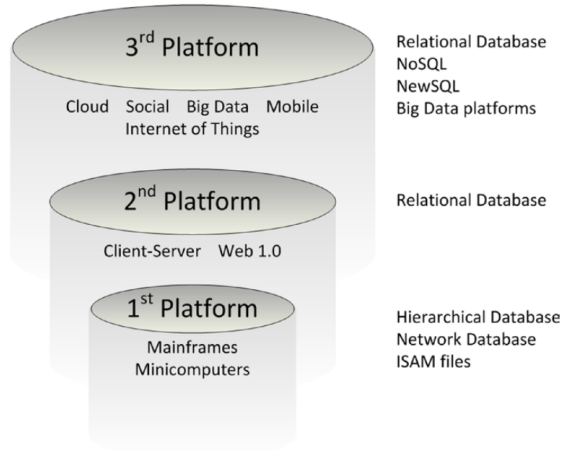
The Third Database Revolution

- ▶ 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

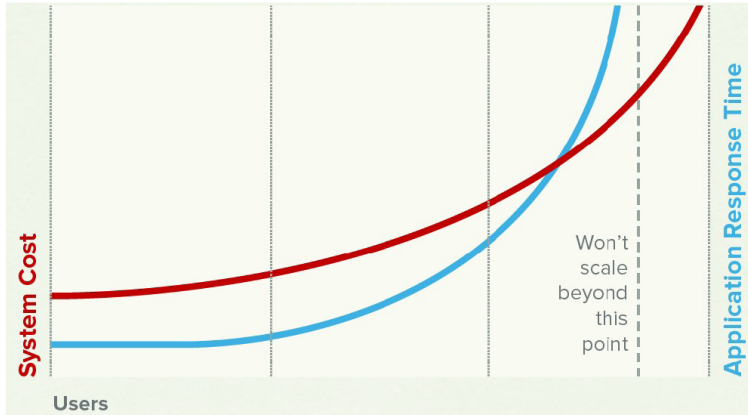


SQL Databases Challenges

- ▶ 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>]

▶ **Avoids:**

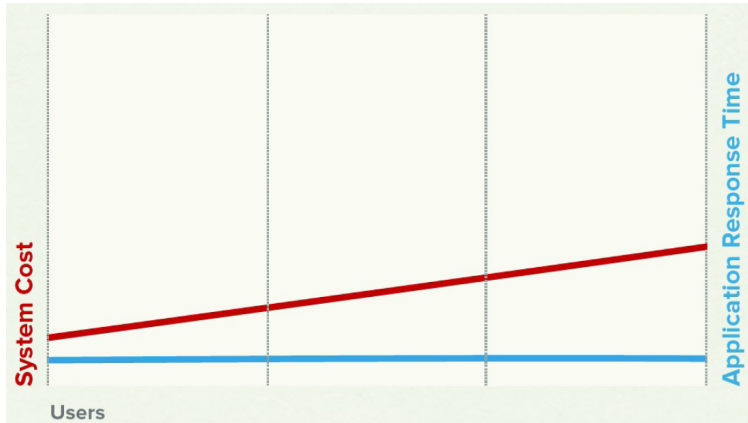
- Overhead of **ACID** properties
- **Complexity** of SQL query

▶ **Provides:**

- **Scalability**
- Easy and frequent **changes** to DB
- **Large** data volumes

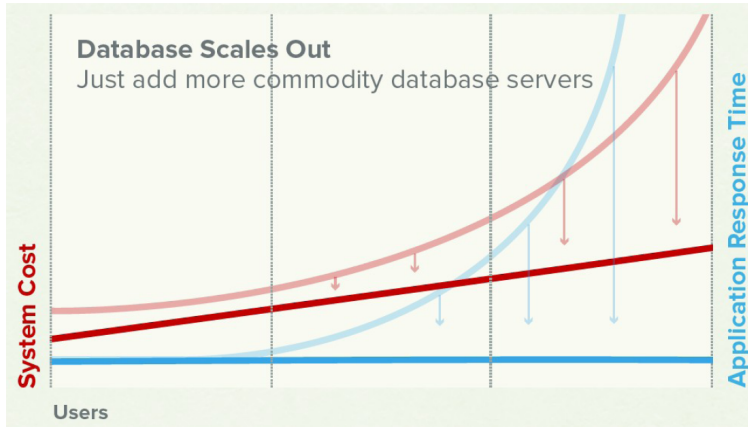


NoSQL Cost and Performance



[<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>]

Availability vs. Consistency

Availability

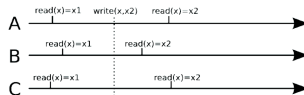
- ▶ **Replicating** data to improve the **availability** of data.
- ▶ **Data replication**
 - Storing data in **more than one** site or node



Consistency

▶ **Strong** consistency

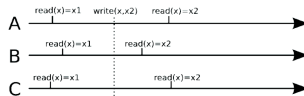
- After an update completes, any subsequent access will return the **updated value**.



Consistency

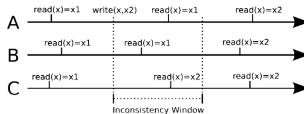
▶ **Strong** consistency

- 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.





Availability vs. Consistency

- ▶ The large-scale applications have to be **reliable**: availability, consistency, partition tolerance



Availability vs. Consistency

- ▶ The large-scale applications have to be **reliable**: **availability**, **consistency**, **partition tolerance**
- ▶ Achieving **ACID** properties on large-scale applications is **challenging**.



Availability vs. Consistency

- ▶ The large-scale applications have to be **reliable**: **availability**, **consistency**, **partition tolerance**
- ▶ Achieving **ACID** properties on large-scale applications is **challenging**.
- ▶ The **BASE** approach forfeits the **consistency** in favor of **availability**.



BASE Properties

- ▶ **Basic Availability**

- Possibilities of faults but not a fault of the whole system.



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



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

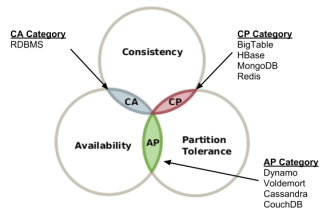
▶ Eventually consistent

- 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.



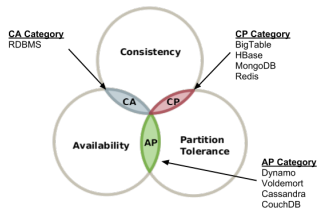
CAP Theorem

▶ Consistency

- Consistent state of data after the execution of an operation.

▶ Availability

- Clients can always read and write data.



CAP Theorem

▶ Consistency

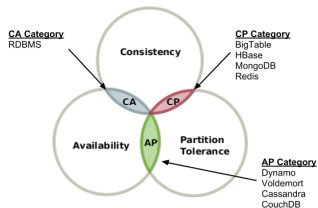
- Consistent state of data after the execution of an operation.

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▶ Partition Tolerance

- Continue the operation in the presence of network partitions.



CAP Theorem

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- Consistent state of data after the execution of an operation.

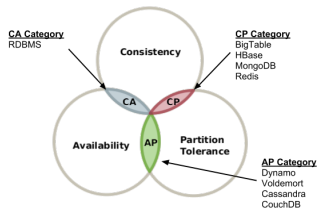
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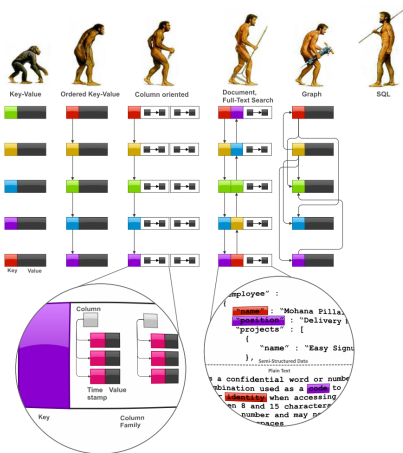
▶ You can choose only two!





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

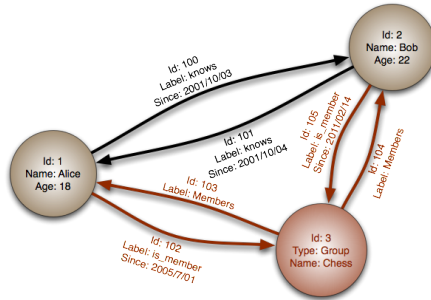
- ▶ Similar to a **column-oriented** store, but values can have **complex documents**.
- ▶ Flexible schema (XML, YAML, JSON, and BSON).
- ▶ **CouchDB, MongoDB, ...**

```
{
  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).

Data Model (1/6)

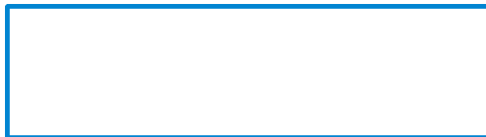
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- ▶ Store and process data by **column** instead of **row**.





Data Model (2/6)

- ▶ Table
- ▶ Distributed multi-dimensional sparse `map`





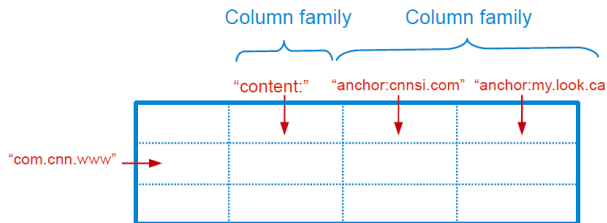
Data Model (3/6)

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



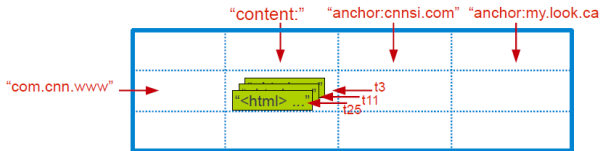
Data Model (4/6)

- ▶ 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)

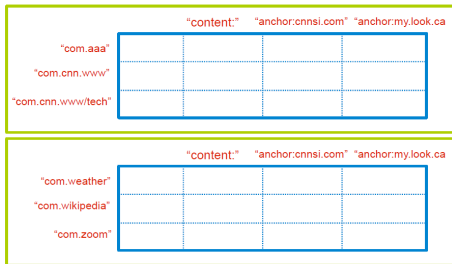
- ▶ Timestamp
- ▶ Each column value may contain multiple **versions**.





Data Model (6/6)

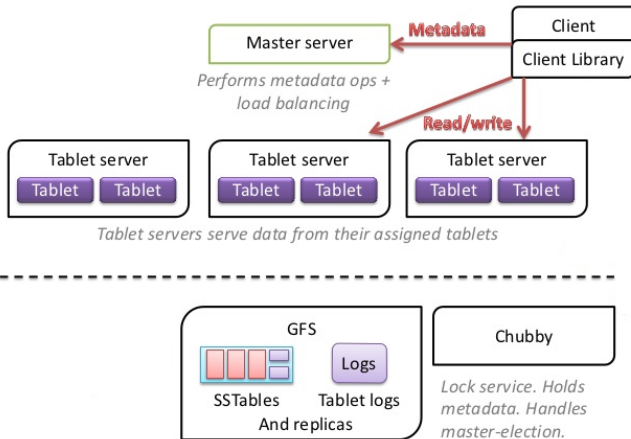
- ▶ **Tablet:** contiguous ranges of rows stored together.
- ▶ Tablets are split by the system when they become too large.
- ▶ Each tablet is served by exactly one tablet server.





System Architecture

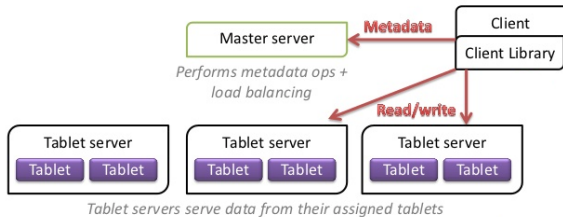
BigTable System Structure



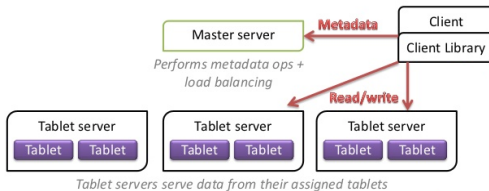
[<https://www.slideshare.net/GrishaWeintraub/cap-28353551>]

Main Components

- ▶ Master
- ▶ Tablet server
- ▶ Client library

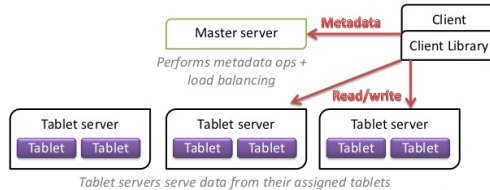


- ▶ Assigns tablets to tablet server.



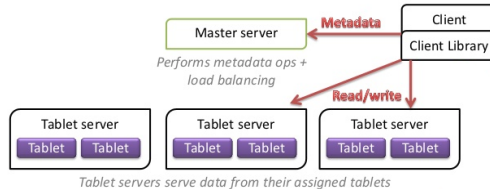
Master

- ▶ Assigns tablets to tablet server.
- ▶ Balances tablet server load.



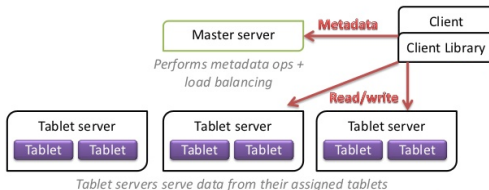
Master

- ▶ Assigns tablets to tablet server.
- ▶ Balances tablet server load.
- ▶ Garbage collection of unneeded files in GFS.



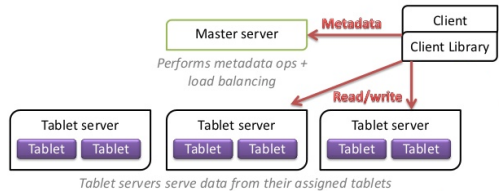
Master

- ▶ 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



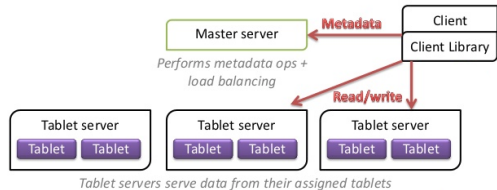
Tablet Server

- ▶ Can be added or removed dynamically.



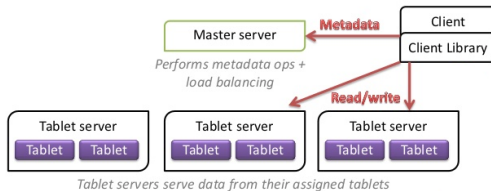
Tablet Server

- ▶ Can be **added** or **removed** **dynamically**.
- ▶ Each **manages** a set of tablets (typically 10-1000 tablets/server).



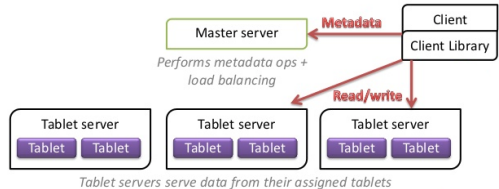
Tablet Server

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- ▶ Handles **read/write** requests to tablets.



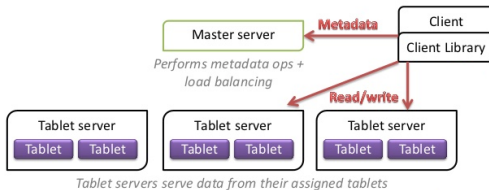
Tablet Server

- ▶ Can be added or removed dynamically.
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- ▶ Splits tablets when too large.



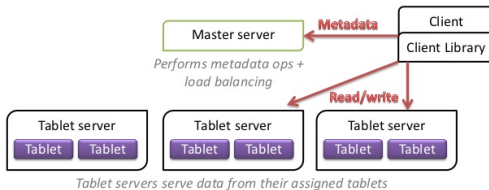
Client Library

- ▶ Library that is linked into every client.



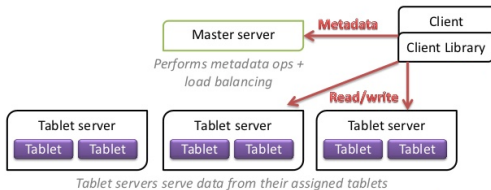
Client Library

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- ▶ Client **data** does not move through the **master**.



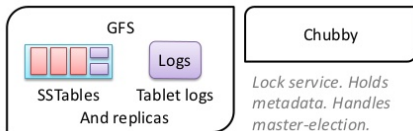
Client Library

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



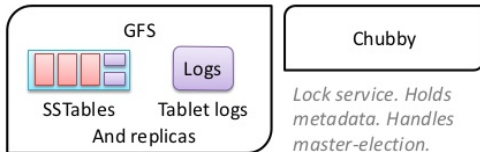
Building Blocks

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



Google File System (GFS)

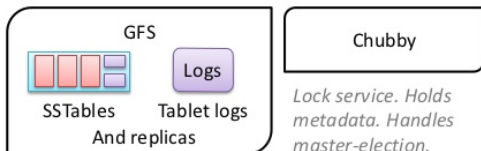
- ▶ Large-scale distributed file system.
- ▶ Store log and data files.





Chubby Lock Service

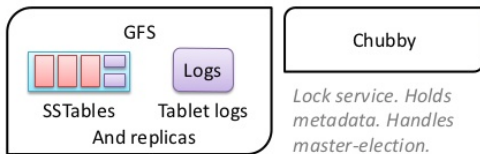
- ▶ Ensure there is only **one active master**.





Chubby Lock Service

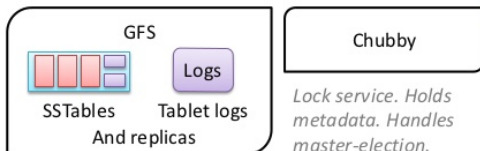
- ▶ Ensure there is only **one active master**.
- ▶ Store **bootstrap location** of BigTable data.





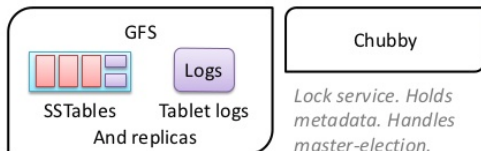
Chubby Lock Service

- ▶ Ensure there is only **one active master**.
- ▶ Store **bootstrap location** of BigTable data.
- ▶ **Discover** tablet servers.



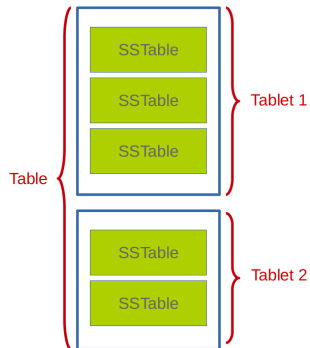
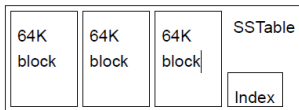
Chubby Lock Service

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



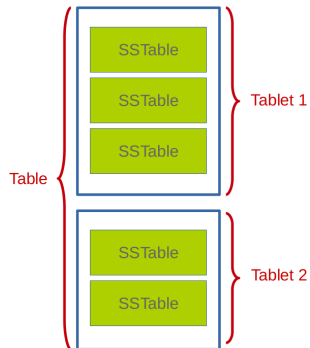
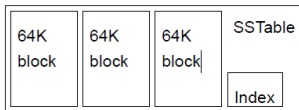
SSTable

- ▶ **SSTable** file format used internally to store BigTable data.



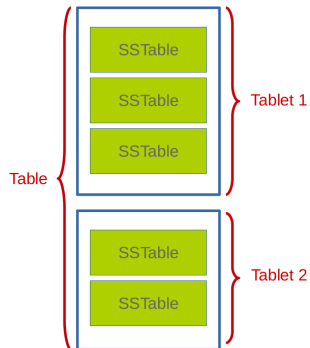
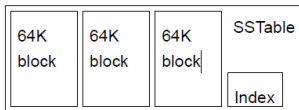
SSTable

- ▶ **SSTable** file format used internally to store **BigTable** data.
- ▶ Chunks of **data** plus a **block index**.



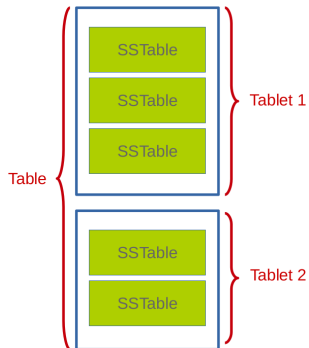
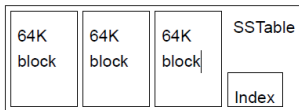
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- ▶ **SSTable** file format used internally to store BigTable data.
- ▶ Chunks of **data** plus a **block index**.
- ▶ **Immutable**, sorted file of **key-value** pairs.



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- ▶ Each SSTable is stored in a **GFS file**.



Tablet Serving



Master Startup

- ▶ The **master** executes the following steps at **startup**:



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 - **Scans the METADATA** table to learn the set of tablets.



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- ▶ 1 tablet → 1 tablet server.



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- ▶ Master uses **Chubby** to keep tracks of **live** tablet serves and **unassigned** tablets.
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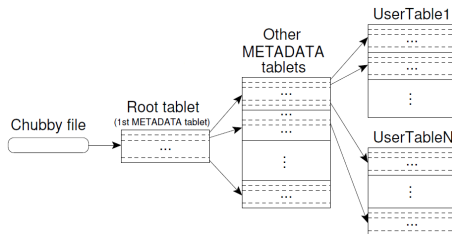


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- ▶ Master detects the **status of the lock of each tablet server** by checking periodically.
- ▶ Master is responsible for finding when tablet server is **no longer serving its tablets** and **reassigning** those tablets as soon as possible.

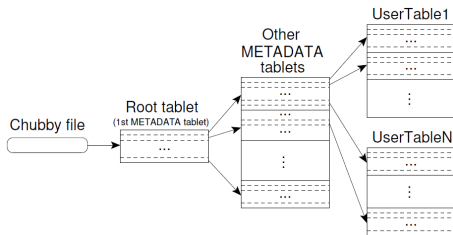
Finding a Tablet

- ▶ Three-level hierarchy.



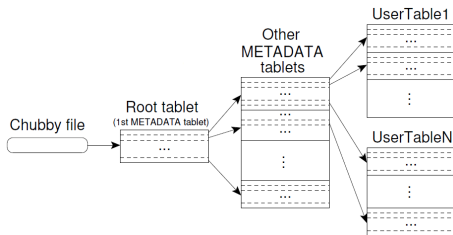
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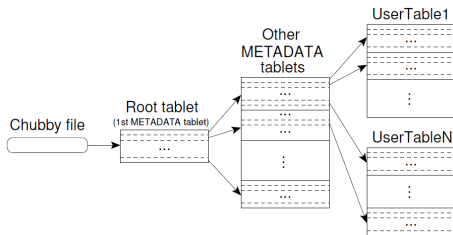
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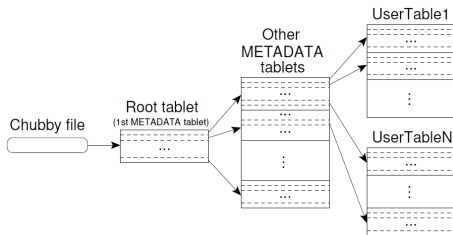
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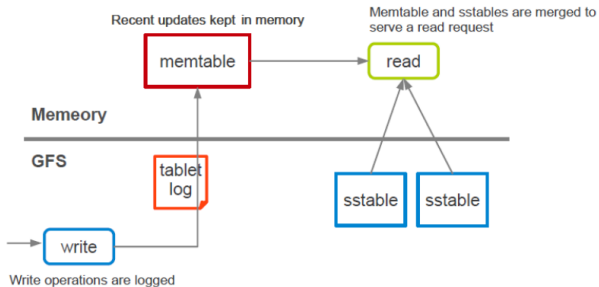
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- ▶ Root tablet contains location of all tablets in a special METADATA table.
- ▶ METADATA table contains location of each tablet under a row.
- ▶ The client library caches tablet locations.



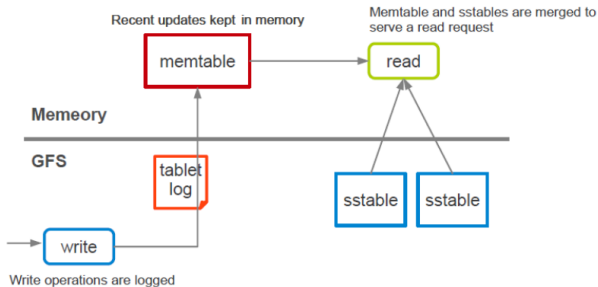
Tablet Serving (1/2)

- ▶ Updates committed to a **commit log**.



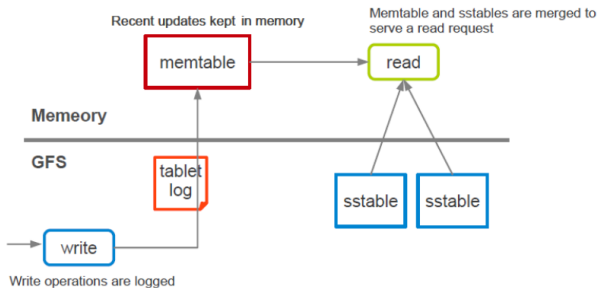
Tablet Serving (1/2)

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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.



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



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**



Data Partitioning (1/2)

- ▶ **Key/value**, where values are stored as **objects**.
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- ▶ **Consistent hashing** for partitioning.





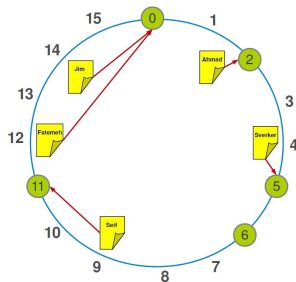
Data Partitioning (2/2)

- ▶ Consistent hashing.
- ▶ Hash both data and node ids using the same hash function in a same id space.
- ▶ $\text{partition} = \text{hash}(d) \bmod n$, d : data, n : the size of the id space

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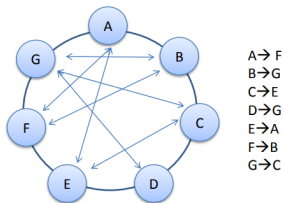
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- ▶ $\text{partition} = \text{hash}(d) \bmod n$, d : data, n : the size of the id space

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



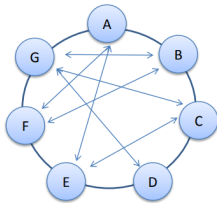
Adding and Removing Nodes

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

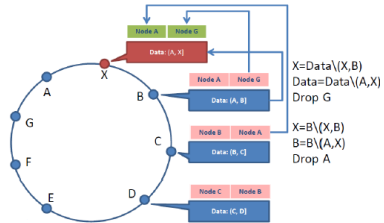


Adding and Removing Nodes

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



$A \rightarrow F$
 $B \rightarrow G$
 $C \rightarrow E$
 $D \rightarrow G$
 $E \rightarrow A$
 $F \rightarrow B$
 $G \rightarrow C$





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

Neo4j



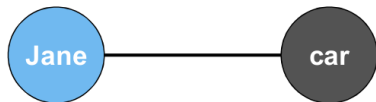
Neo4j

- ▶ 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



► Node (Vertex)

- The **main data element** from which graphs are constructed.
- A waypoint along a **traversal route**



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



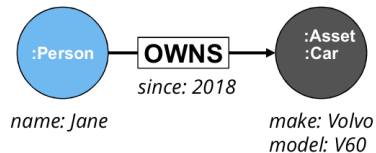
► Label

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

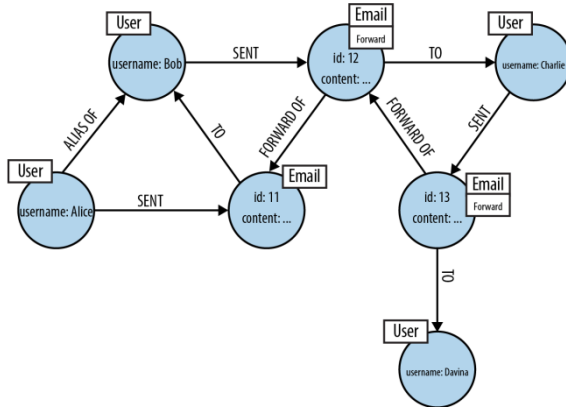


► Properties

- **Enrich** a node or relationship



Example



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

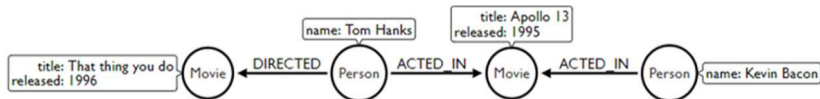




What is Cypher?

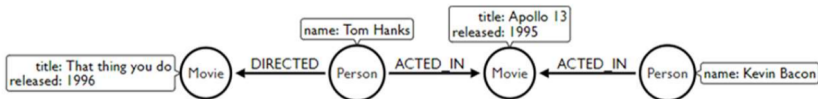
- ▶ Declarative query language
- ▶ `()`: Nodes
- ▶ `[]`: Relationships
- ▶ `{}`: Properties

Cypher Example (1/2)



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

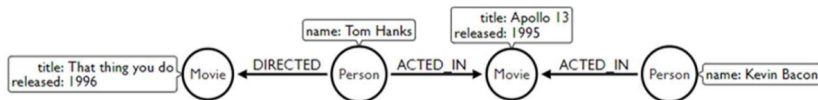
Cypher Example (1/2)



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

Cypher Example (1/2)

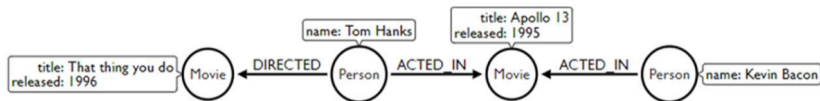


```
// Match all nodes
MATCH (n)
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```

```
// 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;
```

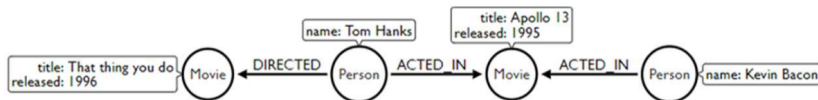
Cypher Example (2/2)



```

// Return nodes with label Person and name property equals 'Tom Hanks'
MATCH (p:Person)
WHERE p.name = 'Tom Hanks'
RETURN p;
  
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Cypher Example (2/2)



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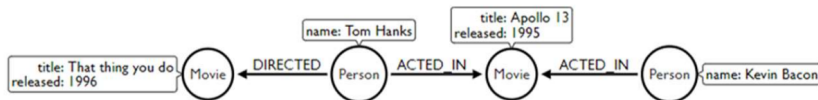
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// Return nodes with label Movie, released property is between 1991 and 1999
MATCH (m:Movie)
WHERE m.released > 1990 AND m.released < 2000
RETURN m;

```


Cypher Example (2/2)



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

Summary



Summary

- ▶ NoSQL data models: key-value, column-oriented, document-oriented, graph-based
- ▶ 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.