NoSQL databases II

Francieli ZANON BOITO

This class

- Last week: general motivations and principles for NoSQL
- Today:
  - Amazon's Dynamo (2007)
  - Google's BigTable (2006)
  - Neo4j
- Next week: lab session about Neo4j

Go deeper into the design of storage solutions

Inspired more recent systems

"Dynamo: Amazon's Highly Available Key-Value Store"

Amazon's Dynamo

- Paper from 2007
- Key-value store (key and values are binary objects, values are usually < 1MB)
- Many services only need primary-key access
- High reliability requirements, sacrifice consistency (remember the CAP theorem!)
- Tight latency and throughput requirements
- Example: Shopping Cart System (tens of millions of requests in a single day)
    - Has to be always available, specially for writes
- Some key principles:
    - Incremental scalability
    - Heterogeneity
    - Symmetry and decentralization (no centralized control, all nodes are the same)

Problem	How do they solve it?
Partitioning	Consistent hashing
High availability for writes	Vector clocks with reconciliation during reads
Handling temporary failures	Sloppy quorum and hinted handoff
Recovering from permanent failures	Anti-entropy using Merkle trees
Membership and failure detection	Gossip-based membership protocol and failure detection

Source: G. DeCandia et al. "Dynamo: amazon's highly available key-value store"

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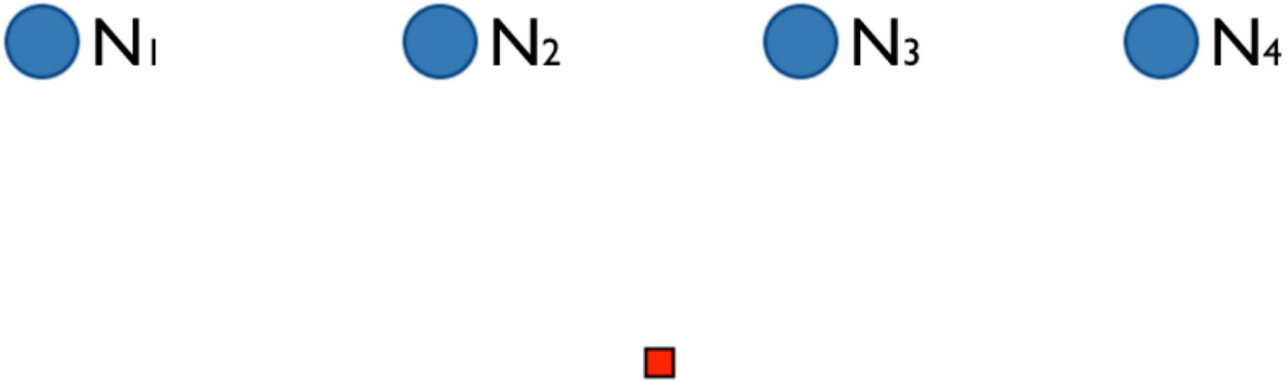
Source: slides by Lorenzo Alberton

Modulo-based Hashing



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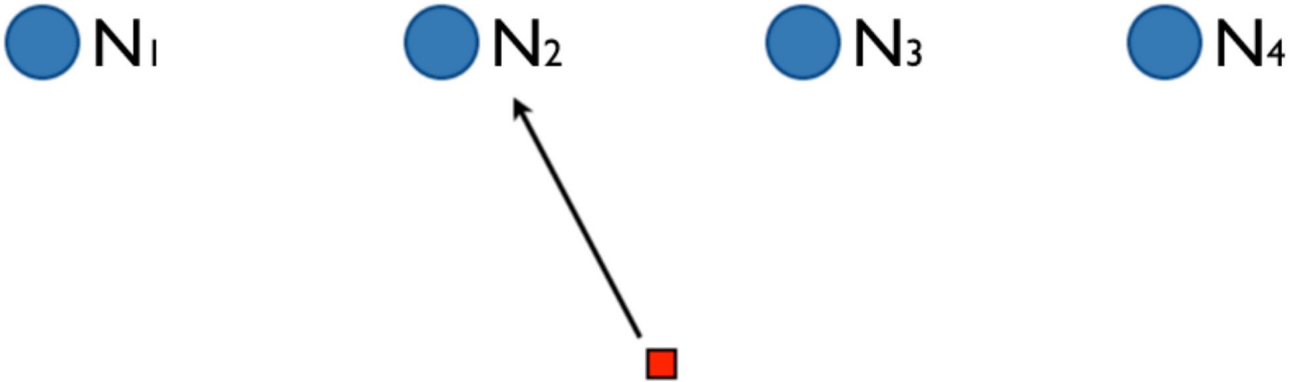
Modulo-based Hashing




```
partition = key % n_servers
```

Source: slides by Lorenzo Alberton

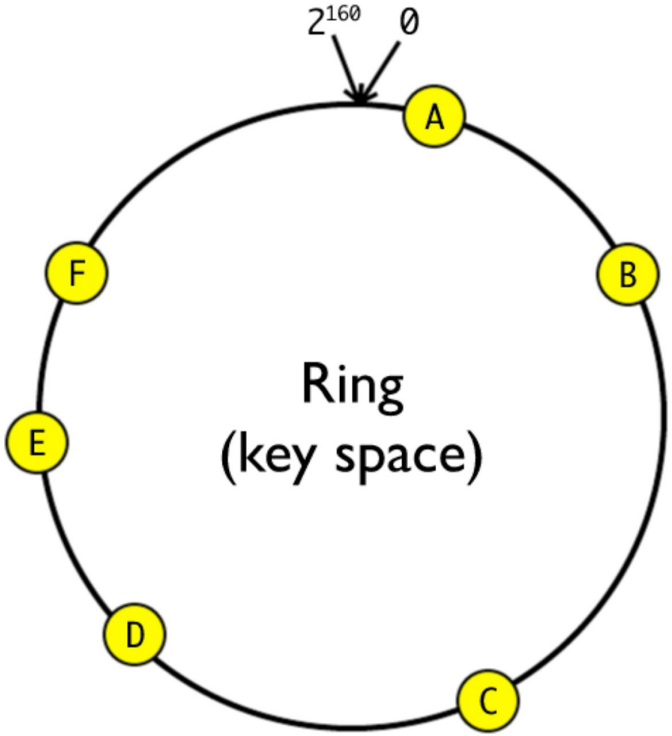
Modulo-based Hashing


```
partition = key % (n_servers - 1)
```

Recalculate the hashes for all entries if n_servers changes
(full data redistribution when adding/removing a node)

Source: slides by Lorenzo Alberton

Consistent Hashing



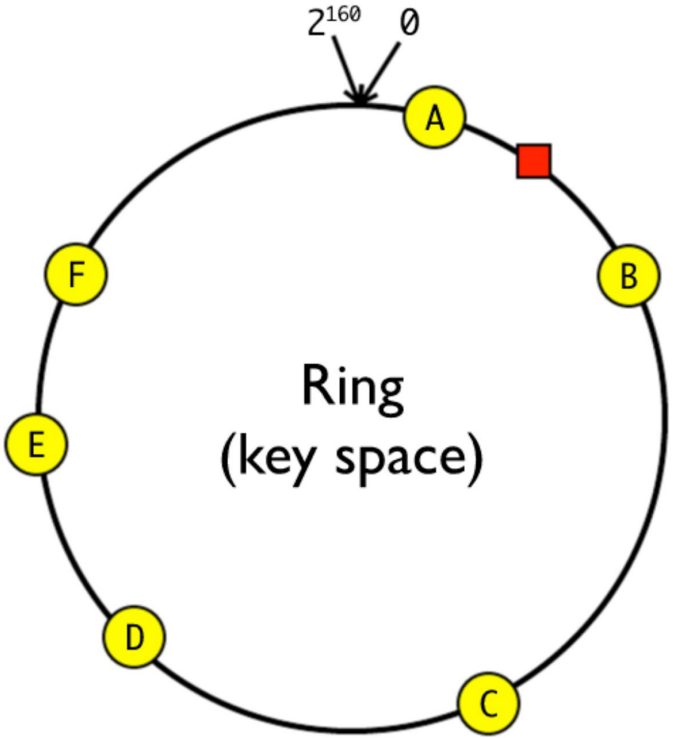
Same hash function for data and nodes

`idx = hash(key)`

Coordinator: next available clockwise node

Source: slides by Lorenzo Alberton

Consistent Hashing



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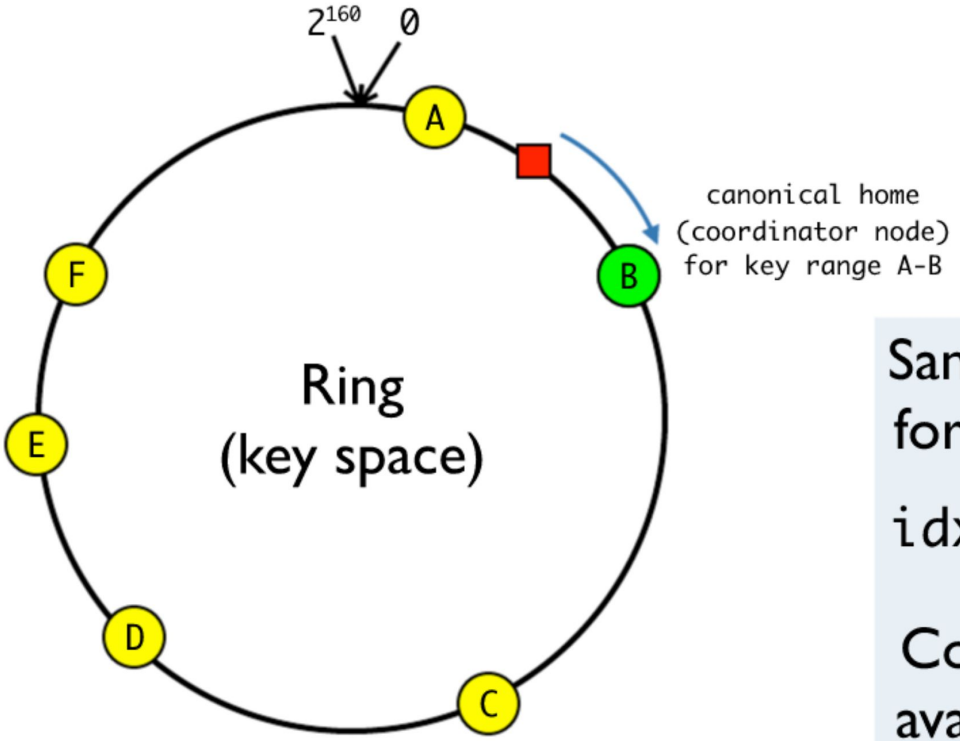

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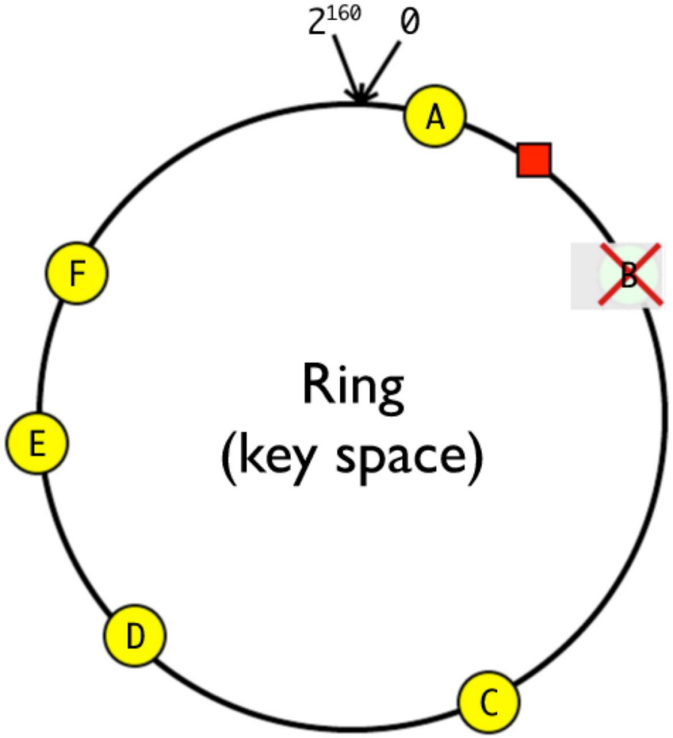

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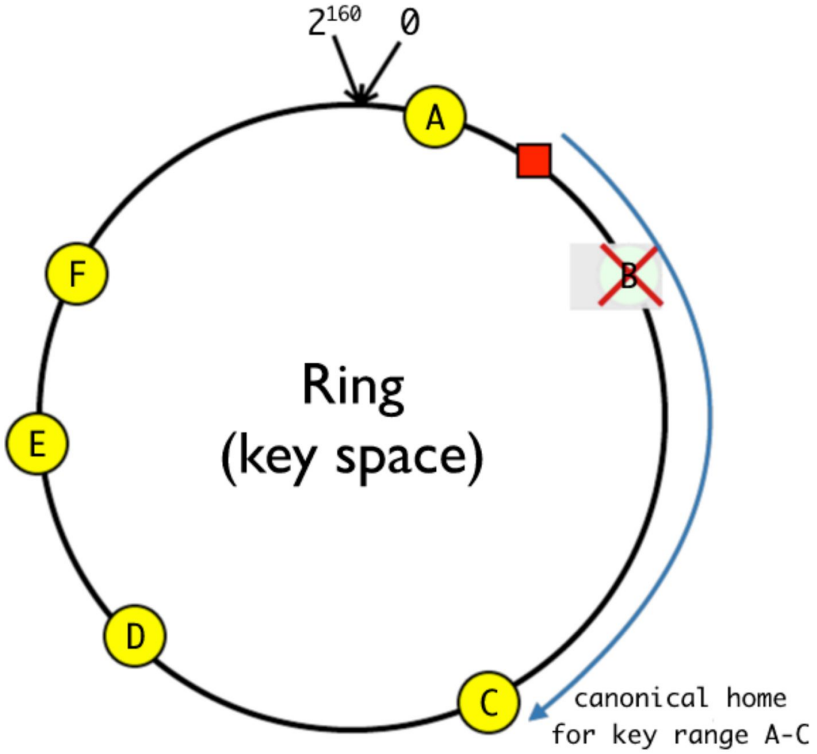

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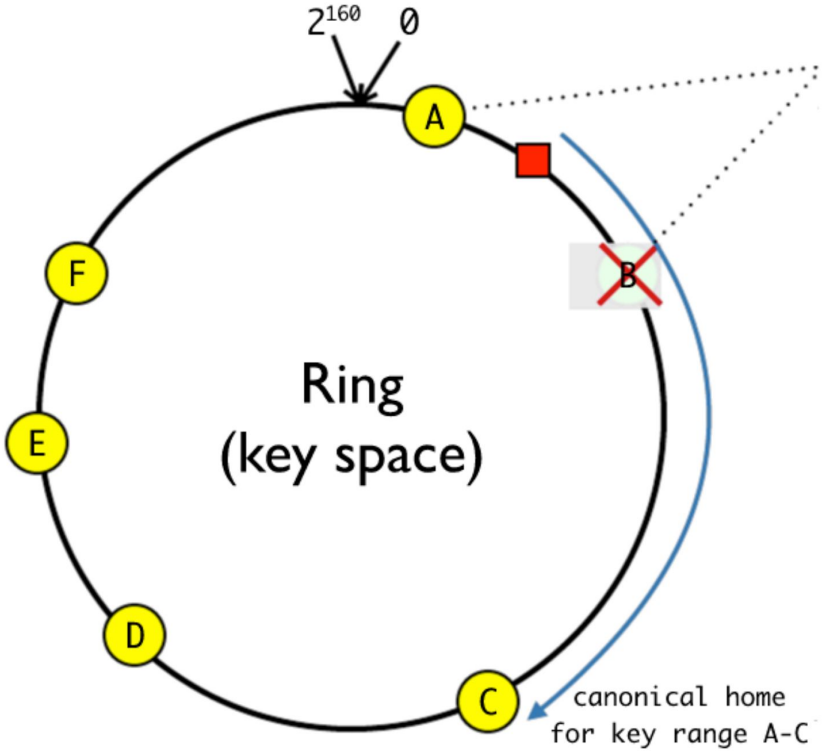

Same hash function for data and nodes

`idx = hash(key)`

Coordinator: next available clockwise node

Virtual nodes variation

- Consistent hashing using virtual nodes (#virtual nodes > #nodes)
- If a node disappears, its load is distributed across remaining nodes
- A new node receives load from all other nodes
- Accounts for heterogeneity

Problem	How do they solve it?
Partitioning	Consistent hashing
High availability for writes	Vector clocks with reconciliation during reads

Source: G. DeCandia et al. "Dynamo: amazon's highly available key-value store"

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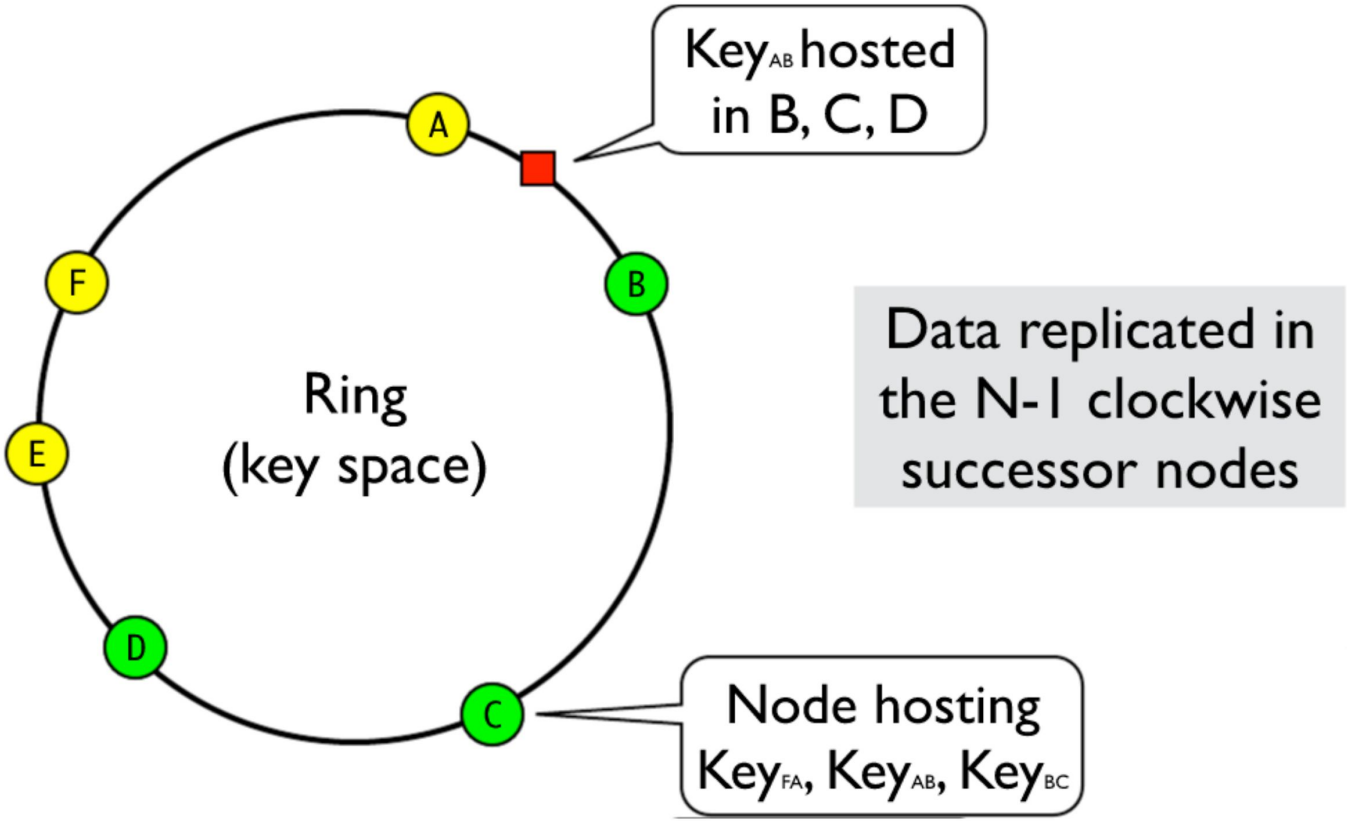
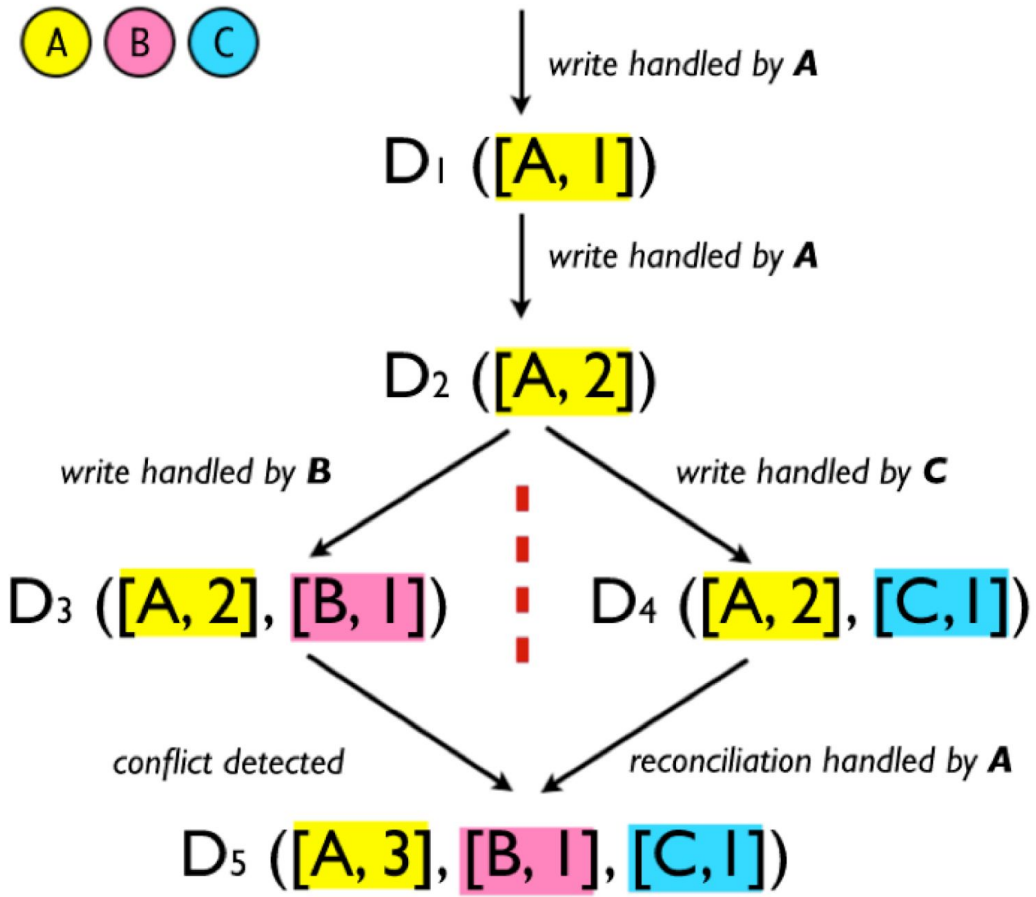
Consistent Hashing - Replication



Eventual consistency

- Updates are asynchronously propagated to replicas
- Each update makes a new immutable version of data (multiple versions may co-exist)
- Ordering of versions: vector clocks
- Read returns a context structure containing the vector clock
  - Subsequent updates need to specify the version
  - If Dynamo cannot reconcile, read returns a list of versions (the application will handle)



Causality-based partial order over events that happen in the system.

Document version history: a counter for each node that updated the document.

If all update counters in V_1 are smaller or equal to all update counters in V_2, then V_1 precedes V_2.

Source: slides by Lorenzo Alberton

Problem	How do they solve it?
Partitioning	Consistent hashing
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Handling temporary failures	Sloppy quorum and hinted handoff

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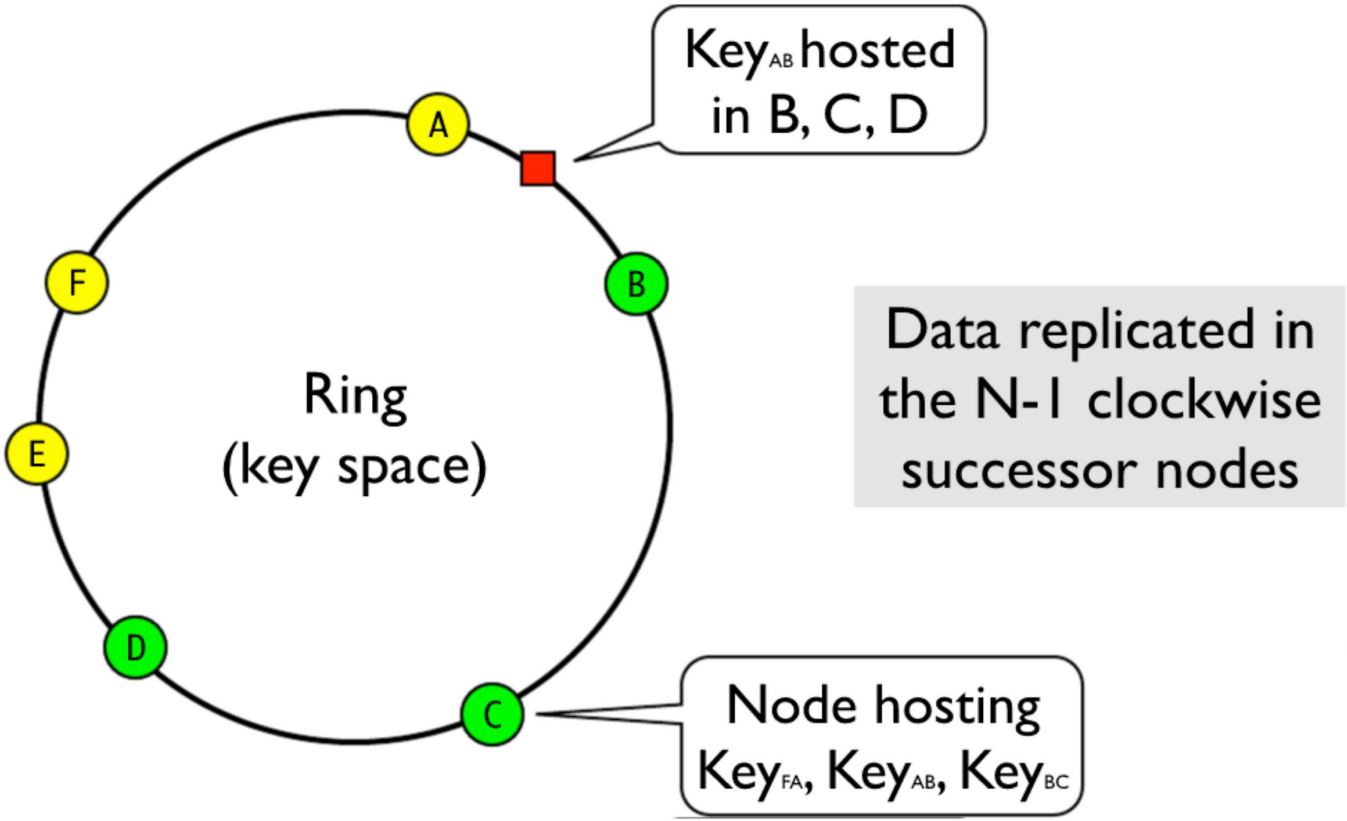

Source: slides by Lorenzo Alberton

Consistency: Server-side (Quorum)

N = number of nodes with a replica of the data
W = number of replicas that must acknowledge the update(*)
R = minimum number of replicas that must participate in a successful read operation

(*) but the data will be written to N nodes no matter what

W + R > N ⟶ Strong consistency (usually N=3, W=R=2)

W = N, R = 1 ⟶ Optimised for reads
W = 1, R = N ⟶ Optimised for writes

(durability not guaranteed in presence of failures)

W + R <= N ⟶ Weak consistency

Sloppy Quorum

- Preference list: list of nodes containing replicas of a piece of data
  - Actually perform more than N replicas
  - Try to ensure replicas on different nodes and different data centers
- All nodes know the preference list! Forward requests to one of the first N
- Reads and writes involve the first N **healthy** replicas
  - “Sloppy quorum”: it might include nodes that are not in the top N (if some have failed)
  - The coordinator writes to local disk and propagates to others
    - Waits for (R-1) or (W-1) acks
    - R+W > N, R < N and W < N
    - R and W are configurable and adjust a trade-off between durability and availability

Hinted handoff

- When a node receives a write but it is not in the top N (preference list)
  - It comes with a “hint” of what node from the top N was supposed to receive that
  - Store that data separately to send to the right node when it comes back

Problem	How do they solve it?
Partitioning	Consistent hashing
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Recovering from permanent failures	Anti-entropy using Merkle trees

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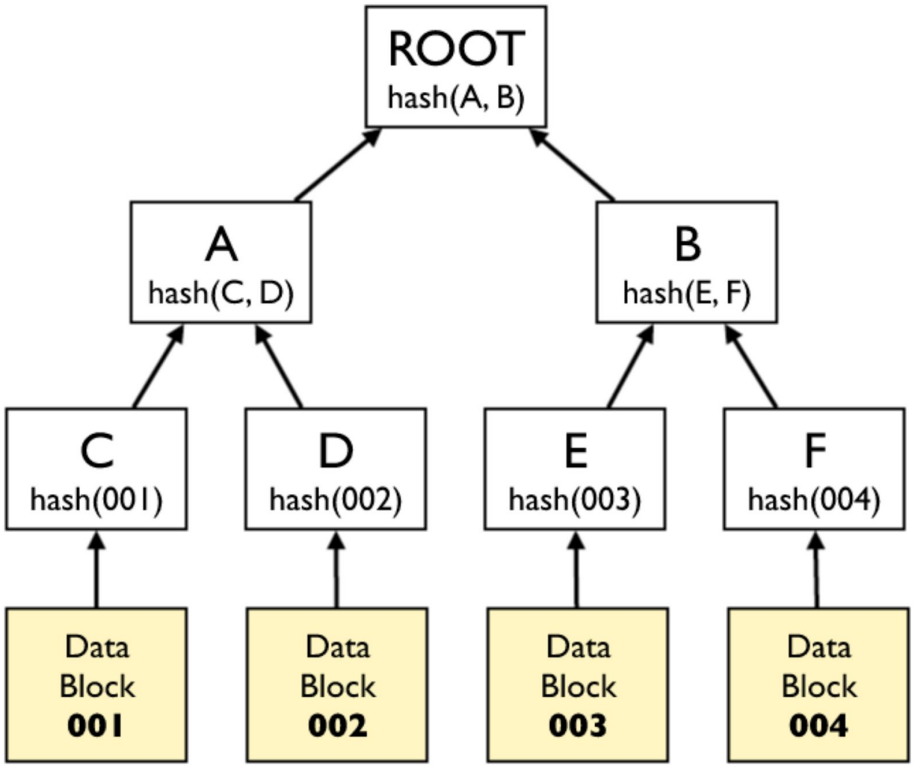
Anti-entropy (replica synchronization)

- Improve durability (for more permanent failures)
- A Merkle tree has stored entries as leaves (the hash of the value)
  - Each node has a hash of its children
  - To compare trees: if two nodes have the same hash, no need to check the sub-trees
    - No need to send the whole tree through the network
- Each node keeps a Merkle tree per key range it stores

Source: slides by Lorenzo Alberton

Merkle Trees (Hash Trees)



Leaves: hashes of data blocks.
Nodes: hashes of their children.

Used to detect inconsistencies between replicas (anti-entropy) and to minimise the amount of transferred data

Problem	How do they solve it?
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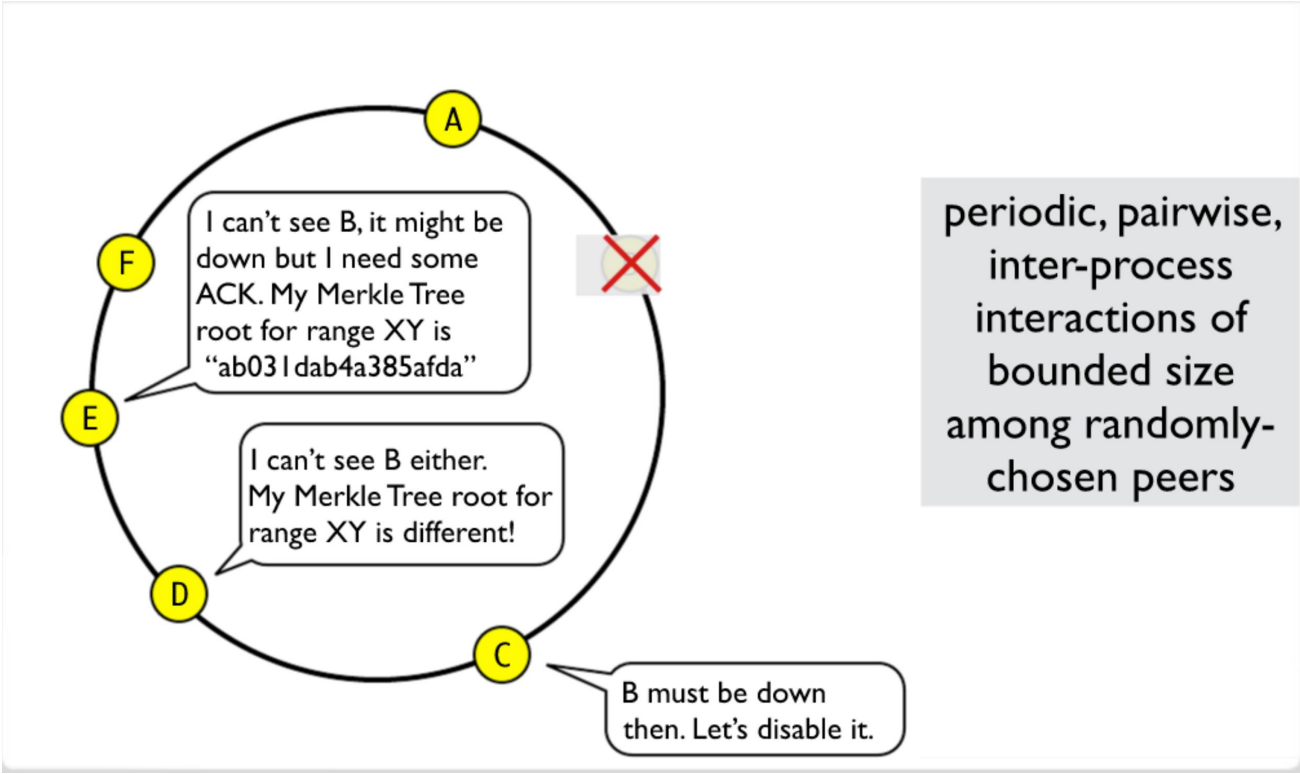
Gossip strategy

- When adding or removing a node, contact any node already in the system
  - The node stores this information locally
  - The new node decides its ring locations and stores it locally
  - Some nodes can be discovered by an external mechanism (seeds)
- Periodic random exchanges between nodes to share information (gossip)
  - Nodes in the system
  - Ring formation
  - Merkle tree root
  - (that is how everybody knows the preference list for all keys)

Source: slides by Lorenzo Alberton



Impact

- The implementation was never released
- But inspired other implementations
  - Voldemort (powered Linkedin until August 2018)
- Evolution: DynamoDB (key-value and documents) announced in 2012

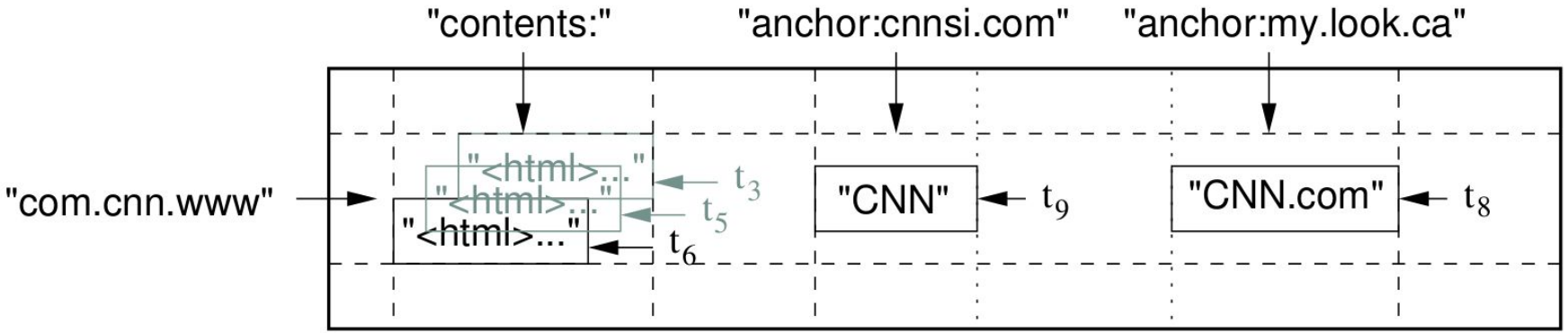
"Bigtable: A Distributed Storage System for Structured Data"

Bigtable

- At the time: over 60 products and projects (Orkut, Google Analytics, Google Earth, …)
  - Integrated with Google's MapReduce implementation
- Big table: a sparse, distributed, persistent, multidimensional sorted map
  - Indexed by row key, column key, and a timestamp (to identify a version)
  - All fields are uninterpreted arrays of bytes

Data model

- Data is stored in lexicographic order by row key
  - Dynamically partitioned in "tablets"
  - Users can plan their keys so they will be stored together
  - Example: Webtable has reversed URLs as keys ("com.google.maps" instead of "maps.google.com")
- Column families need to be created before receiving data
  - Each family has an unbounded number of column keys
  - Access control, data locality, and garbage collection setting are decided per column family
- Versions are stored in decreasing timestamp order (finding the most recent is faster)
- Operations over a row are atomic



Source: F. Chang et al. "BigTable: a Distributed Storage System for Structured Data"

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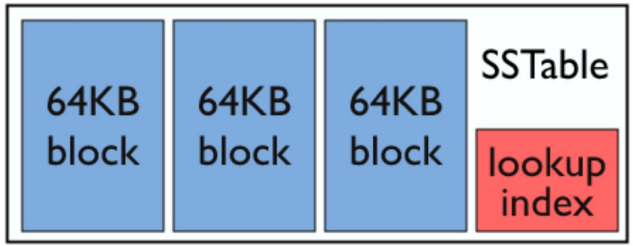
Google BigTable: Data Structure

SSTable

Smallest building block

Persistent immutable Map[k,v]

Operations: lookup by key / key range scan

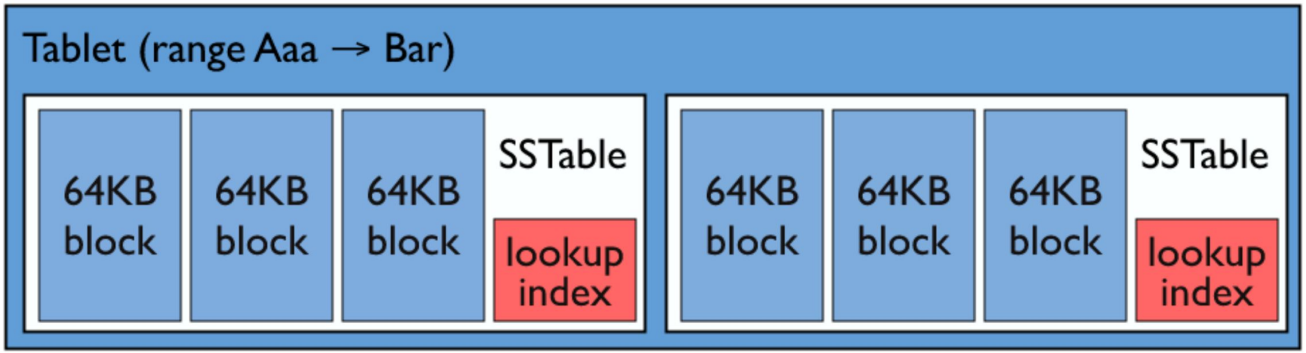


Source: slides by Lorenzo Alberton

Google BigTable: Data Structure

Tablet

Dynamically partitioned range of rows
Built from multiple SSTables
Unit of distribution and load balancing

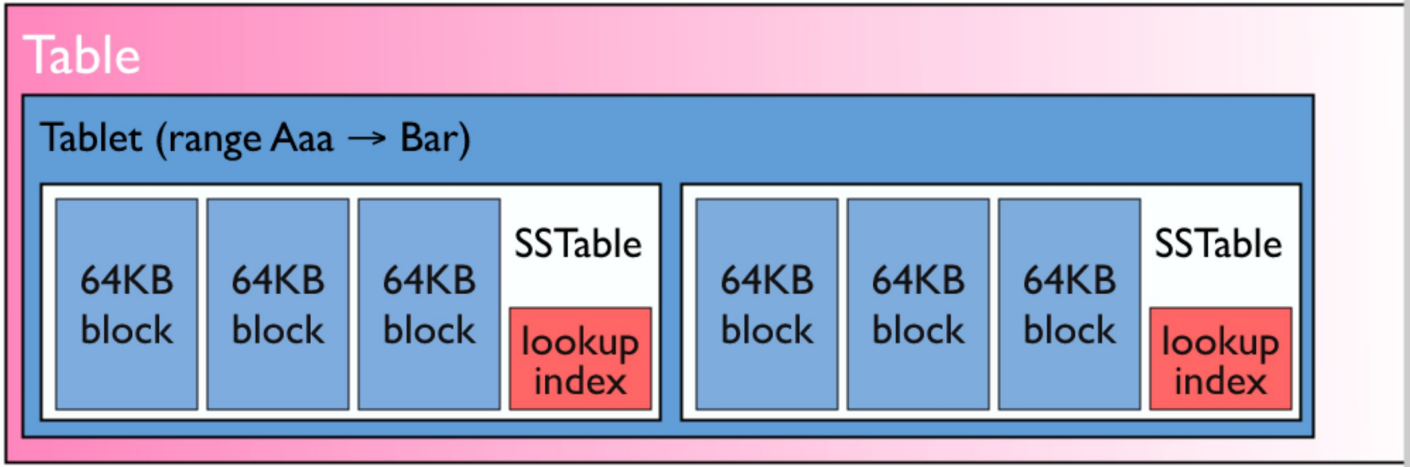


Source: slides by Lorenzo Alberton

Google BigTable: Data Structure

Table

Multiple Tablets (table segments) make up a table



Architecture

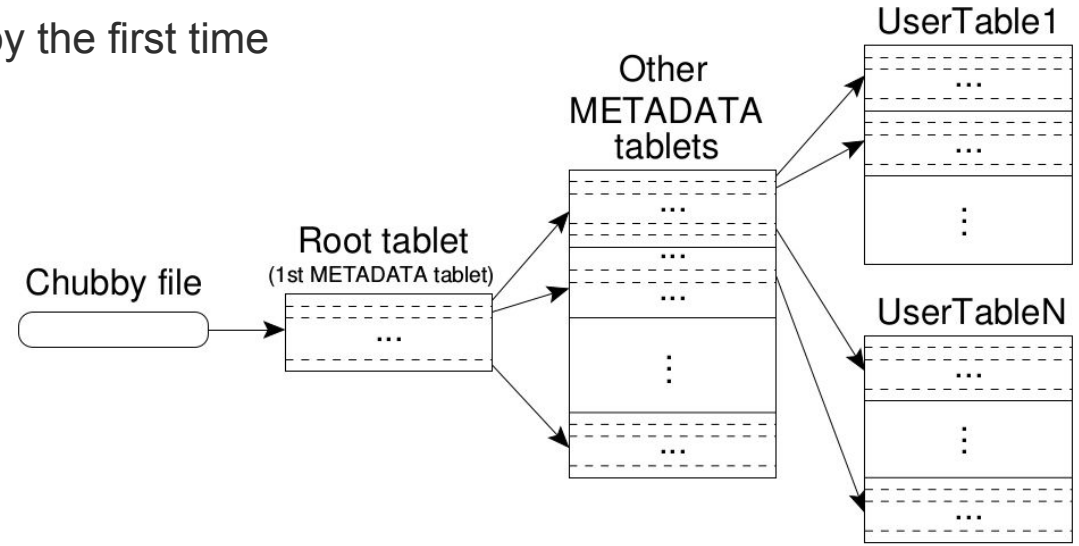
- Single master and multiple tablet servers
  - Tablet servers are added and remove to accomodate to the workload
- The master:
  - Assigns tablets to servers, load balancing
  - Detects addition or removal of servers
  - Garbage collection, table and column family creations
- Read and write DO NOT go through the master
  - Most clients never access the master

Implementation

- Relies on Chubby: a distributed lock manager
  - A limited distributed file system for small files
  - Intended use: locks that will be kept for hours to days, not for seconds (low performance)
- Master keeps a master lock on Chubby
  - Finds existing tablet servers (then periodically contacts them)

Metadata management

- How to know where are all the tablets?
  - A metadata table!
- The root tablet is never split to keep the hierarchy into three levels
- Clients have to access chubby the first time
  - Cache and prefetch



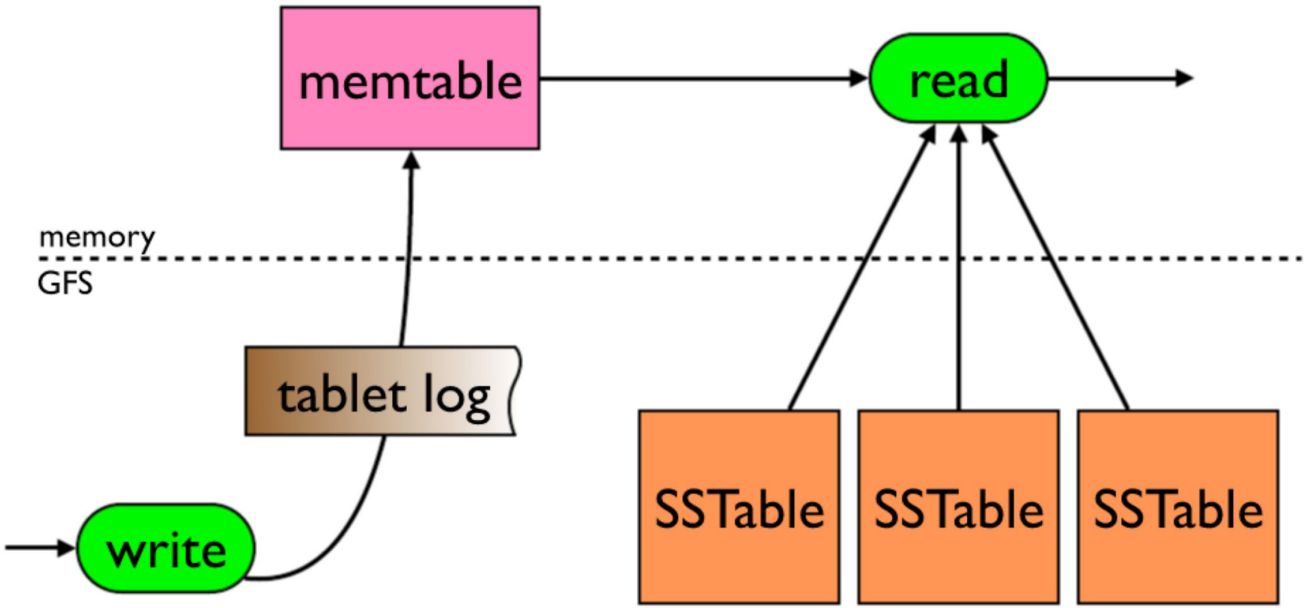
Source: F. Chang et al. "BigTable: a Distributed Storage System for Structured Data"

Persistency

- SSTables are written to the Google File System (GFS)
  - Fault tolerance is provided by the GFS
  - Cached in the tablet server
- Keep a log of performed modifications (also in the GFS)
  - Tablet metadata includes pointers to these logs
  - Recent writes in memory (memtable), older ones in new SSTables

Source: slides by Lorenzo Alberton

Google BigTable: I/O



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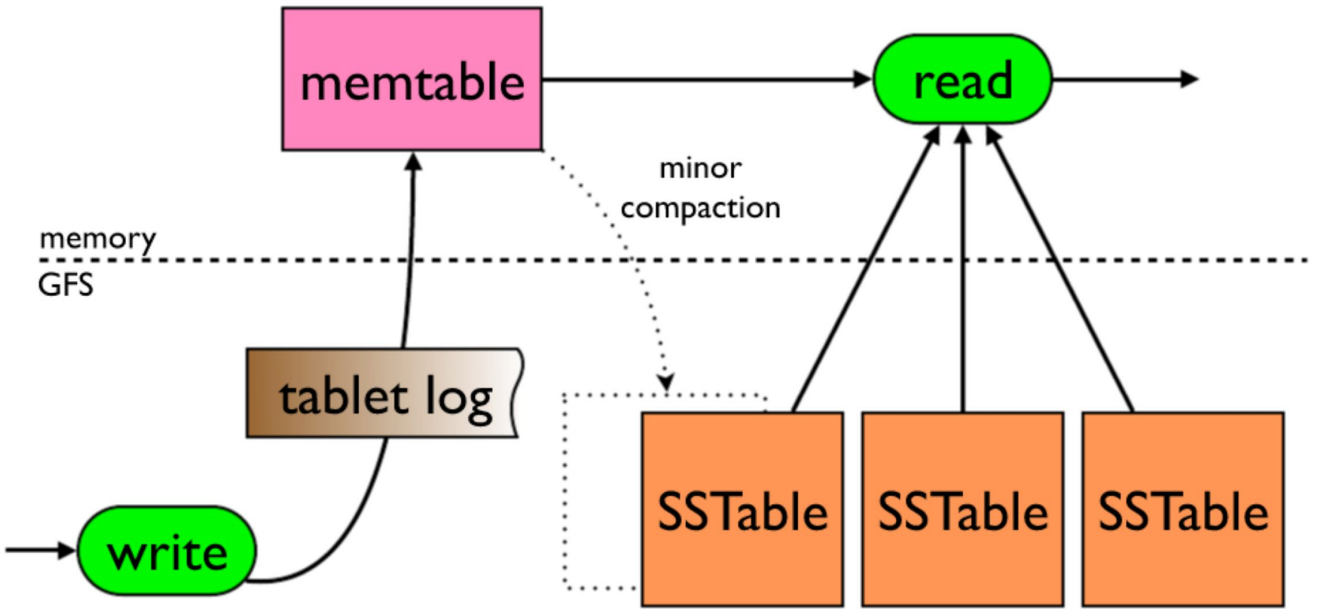

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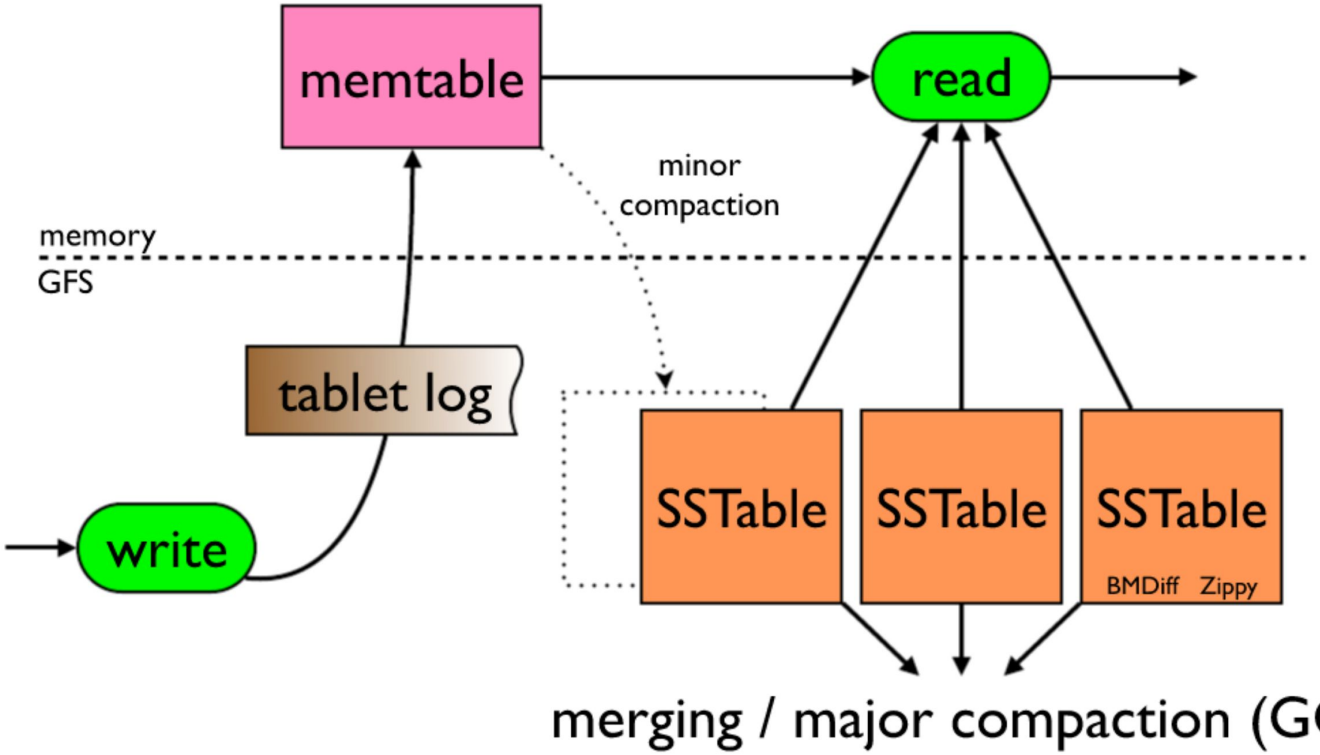

Performance refinements

- Locality groups
  - Store column families in separate SSTables
  - Example: separate information about the webpage from its content
  - Keep it in memory (as done with the location column of the metadata table)

Impact

- Open source implementation: Apache HBase
  - HDFS instead of GFS, Zookeeper instead of Chubby
- Apache Cassandra: data model of Bigtable, infrastructure of Dynamo

An Introduction to Neo4j

Neo4j

- Graph database
- Nodes, relationships, attributes of nodes and relationships
- Relationships are directional
- Example of use: recommendation systems (Walmart and Lufthansa*)
- Cypher Query Language
- HTTP API, Bindings for .net, Java, JavaScript, and Python

* https://www.youtube.com/watch?v=Yzbk6VaavoM

Now we'll see a demo

Cypher Query Language

Query statement with multiple clauses

```
MATCH (m:Movie)<-[:RATED]-(u:User)
WHERE m.title CONTAINS "Matrix"
WITH m.title AS movie, COUNT(*) AS reviews
RETURN movie, reviews
ORDER BY reviews DESC
LIMIT 5;
```

Cypher Query Language

MATCH = find

```
MATCH (m:Movie)<-[:RATED]-(u:User)
WHERE m.title CONTAINS "Matrix"
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LIMIT 5;
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Cypher Query Language

( ) denote a node
":Name" is the type of node

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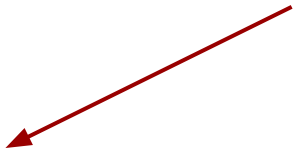
"m" is an alias to use it later in the statement, like here

Cypher Query Language

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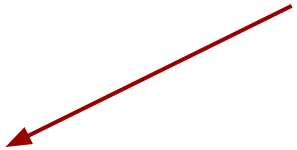

Find relationships of type "RATED" to nodes of type "movie" and from nodes of type "user"

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MATCH (m:Movie)<-[:RATED]-(u:User)
WHERE m.title CONTAINS "Matrix"
WITH m.title AS movie, COUNT(*) AS reviews
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LIMIT 5;
```
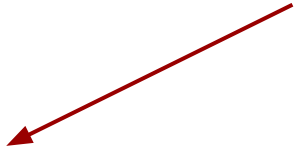

Cypher Query Language

Filter results regarding an attribute of the movie node



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WHERE m.title CONTAINS "Matrix"
WITH m.title AS movie, COUNT(*) AS reviews
RETURN movie, reviews
ORDER BY reviews DESC
LIMIT 5;
```

Cypher Query Language

COUNT(*) is an aggregation, it counts the number of found results

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WHERE m.title CONTAINS "Matrix"
WITH m.title AS movie, COUNT(*) AS reviews
RETURN movie, reviews
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Cypher Query Language

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WHERE m.title CONTAINS "Matrix"
WITH m.title AS movie, COUNT(*) AS reviews
RETURN movie, reviews
ORDER BY reviews DESC
LIMIT 5;
```

The result is a list of movie titles with the number of reviews they have in the database

Cypher Query Language

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WHERE m.title CONTAINS "Matrix"
WITH m.title AS movie, COUNT(*) AS reviews
RETURN movie, reviews
ORDER BY reviews DESC
LIMIT 5;
```

Ordered by the number of reviews in descending order (DESC)

Cypher Query Language

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WHERE m.title CONTAINS "Matrix"
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RETURN movie, reviews
ORDER BY reviews DESC
LIMIT 5;
```

Only show up to 5 results

Extra materials

Paper: Burrows et al., "The Chubby lock service for loosely-coupled distributed systems" (2006)

A tutorial by Neo4j: https://www.youtube.com/watch?v=Yzbk6VaavoM

Neo4j online sandbox: https://neo4j.com/sandbox/

Neo4j example with Pokémon: https://neo4j.com/graphgist/pokemon-amp-neo4j