Data Management in Large-Scale Distributed Systems

NoSQL Databases

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References

- The lecture notes of V. Leroy
- The lecture notes of F. Zanon Boito
- Designing Data-Intensive Applications by Martin Kleppmann
  - Chapters 2 and 7

In this lecture

- Motivations for NoSQL databases
- ACID properties and CAP Theorem
- A landscape of NoSQL databases

Agenda

Introduction

Why NoSQL?

Transactions, ACID properties and CAP theorem

Data models

NoSQL databases design and implementation

Common patterns of data accesses

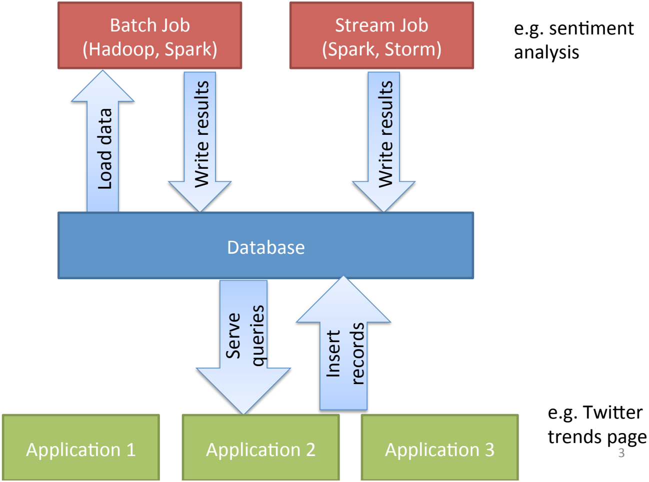
Large-scale data processing

- Batch processing: Hadoop, Spark, etc.
- Perform some computation/transformation over a full dataset
- Process all data

Selective query

- Access a specific part of the dataset
- Manipulate only data needed (1 record among millions)
- Main purpose of a database system

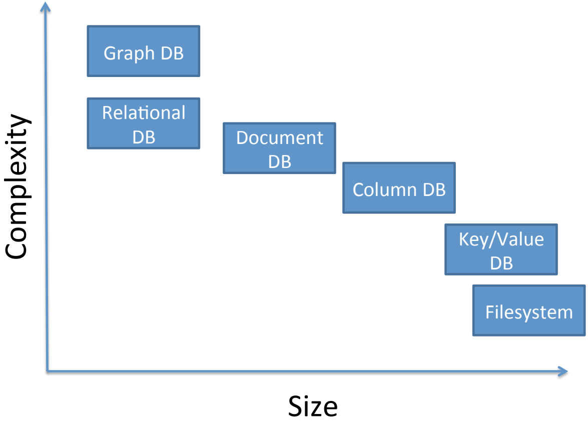
Processing / Database Link



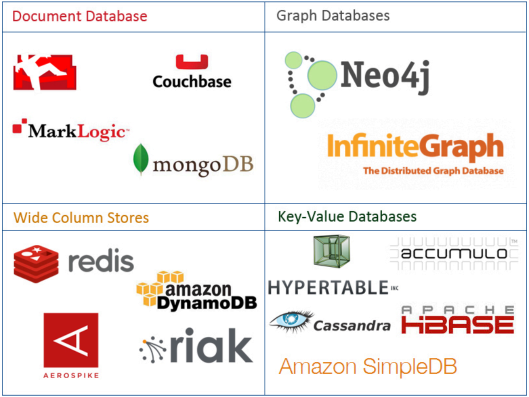
Different types of databases

- So far we used HDFS
  - A file system can be seen as a very basic database
  - Directories / files to organize data
  - Very simple queries (file system path)
  - Very good scalability, fault tolerance …
- Other end of the spectrum: Relational Databases
  - SQL query language, very expressive
  - Limited scalability (generally 1 server)

Size / Complexity



The NoSQL Jungle



@cloudtxt http://www.aryannava.com

Agenda

Relational databases

SQL

- Born in the 70's – Still heavily used
- Data is organized into relations (in SQL: tables)
- Each relation is an unordered collection of tuples (rows)

Students

ID#	Name	Phone	DOB
500	Matt	555-4141	06/03/70
501	Jenny	867-5309	3/15/81
502	Sean	876-9123	10/31/82

ID#	ClassID	Sem
500	1001	Fall02
501	1002	Fall02
501	1002	Spr03
502	1003	S203

Takes_Course

ClassID	Title	ClassNum
1001	Intro to Informatics	I101
1002	Data Mining	I400
1003	Internet and Society	I400

Courses

About SQL

Advantages

- Separate the data from the code
  - High-level language
  - Space for optimization strategies
- Powerful query language
  - Clean semantics
  - Operations on sets
- Support for transactions

Motivations for alternative models

see https://blog.couchbase.com/nosql-adoption-survey-surprises/

Some limitations of relational databases

- Performance and scalability
  - Difficult to partition the data (in general run on a single server)
  - Need to scale up to improve performance
- Lack of flexibility
  - Will to easily change the schema
  - Need to express different relations
  - Not all data are well structured
- Few open source solutions
- Mismatch between the relational model and object-oriented programming model

Illustration of the object-relational mismatch

Figure by M. Kleppmann

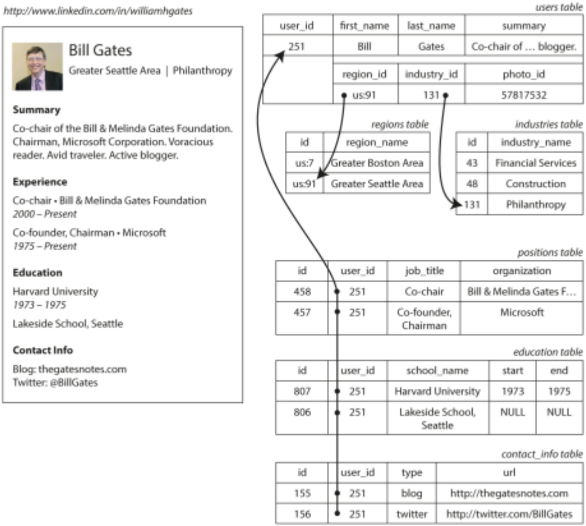


Figure: A CV in a relation database

Illustration of the object-relational mismatch

Figure by M. Kleppmann


```
{
  "user_id":251,
  "first_name": "Bill",
  "last_name": "Gates",
  "summary": "Co−chair of the Bill & Melinda Gates; Active blogger.",
  "region_id": "us:91",
  "industry_id": 131,
  "photo_url": "/p/7/000/253/05b/308dd6e.jpg",
  "positions": [
    {"job_title": "Co−chair", "organization": "Bill & Melinda Gates
          Foundation"},
    {"job_title": "Co−founder, Chairman", "organization": "Microsoft"}
  ],
  "education": [
    {"school_name": "Harvard University", "start": 1973, "end": 1975},
    {"school_name": "Lakeside School, Seattle", "start": null, "end": null}
  ],
  "contact_info": {
    "blog": "http://thegatesnotes.com",
    "twitter": "http://twitter.com/BillGates"
  }
}
```


Figure: A CV in a JSON document

About NoSQL

What is NoSQL?

- A hashtag
  - NoSQL approaches were existing before the name became famous
- No SQL
- New SQL
- Not only SQL
  - Relational databases will continue to exist alongside non-relational datastores

About NoSQL

A variety of NoSQL solutions

- Key-Value (KV) stores
- Wide column stores (Column family stores)
- Document databases
- Graph databases

Difference with relational databases

There are several ways in which they differ from relational databases:

- Properties
- Data models
- Underlying architecture

Agenda

Introduction

Why NoSQL?

Transactions, ACID properties and CAP theorem

Data models

NoSQL databases design and implementation

About transactions

The concept of transaction

- Groups several read and write operations into a logical unit
- A group of reads and writes are executed as one operation:
  - The entire transaction succeeds (commit)
  - or the entire transaction fails (abort, rollback)
- If a transaction fails, the application can safely retry

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Why do we need transactions?

- Crashes may occur at any time
  - On the database side
  - On the application side
  - The network might not be reliable
- Several clients may write to the database at the same time

ACID

ACID describes the set of safety guarantees provided by transactions

- Atomicity
- Consistency
- Isolation
- Durability

Having such properties make the life of developers easy, but:

- ACID properties are not the same in all databases
  - It is not even the same in all SQL databases
- NoSQL solutions tend to provide weaker safety guarantees
  - To have better performance, scalability, etc.

ACID: Atomicity

Description

- A transactions succeeds completely or fails completely
  - If a single operation in a transaction fails, the whole transaction should fail
  - If a transaction fails, the database is left unchanged
- It should be able to deal with any faults *in the middle* of a transaction
- If a transaction fails, a client can safely retry

In the NoSQL context:

- Atomicity is still ensured

ACID: Consistency

Description

- Ensures that the transaction brings the database from a valid state to another valid state
  - Example: Credits and debits over all accounts must always be balanced
- It is a property of the application, not of the database
  - The application cannot enforce application-specific invariants
  - The database can check some specific invariants
    - A foreign key must be valid

In the NoSQL context:

- Consistency is (often) not discussed

ACID: Durability

Description

- Ensures that once a transaction has committed successfully, data will not be lost
  - Even if a server crashes (flush to a storage device, replication)

In the NoSQL context:

- Durability is also ensured

ACID: Isolation

Description

- Concurrently executed transactions are isolated from each other
  - We need to deal with concurrent transactions that access the same data
- Serializability
  - High level of isolation where each transaction executes as if it was the only transaction applied on the database
    - As if the transactions are applied *serially*, one after the other
  - Many SQL solutions provide a lower level of isolation

In the NoSQL context:

- **What about the CAP theorem?**

The CAP theorem

3 properties of databases

- Consistency
  - What guarantees do we have on the value returned by a read operation?
  - It strongly relates to Isolation in ACID (and not to consistency)
- Availability
  - The system should always accept updates
- Partition tolerance
  - The system should be able to deal with a partitioning of the network

Comments on CAP theorem

- Was introduced by E. Brewer in its lectures (beginning of years 2000)
- Goal: discussing trade-offs in database design

What does the CAP theorem says?

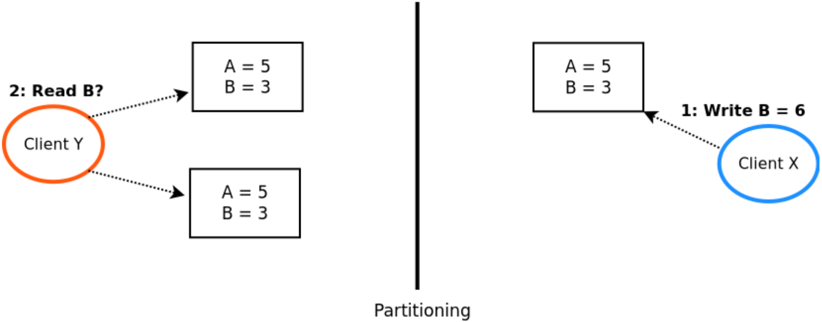
The theorem

It is impossible to have a system that provides Consistency, Availability, and partition tolerance.

How it should be understood:

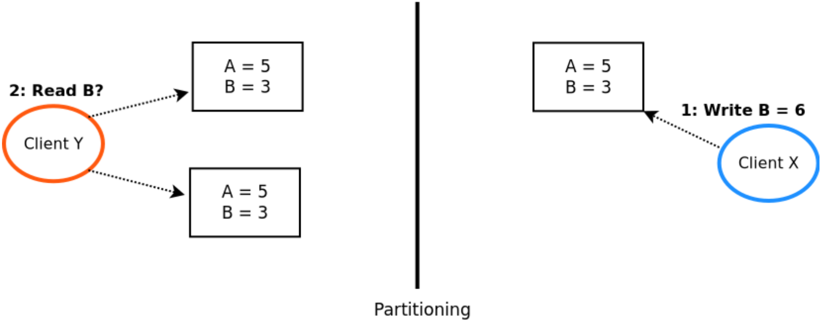
- Partitions are unavoidable
  - It is a fault, we have no control on it
- We need to choose between availability and consistency
  - In the CAP theorem:
    - Consistency is meant as *linearizability* (the strongest consistency guarantee)
    - Availability is meant as *total availability*
  - In practice, different trade-offs can be provided

The intuition behind CAP



- Let inconsistencies occur? (No C)
- Stop executing transactions? (No A)

The intuition behind CAP



- Let inconsistencies occur? (No C)
- Stop executing transactions? (No A)

Note that in a centralized system (non-partitioned relational database), no need for Partition tolerance

- We can have Consistency and Availability

The impact of CAP on ACID for NoSQL

source: E. Brewer

The main consequence

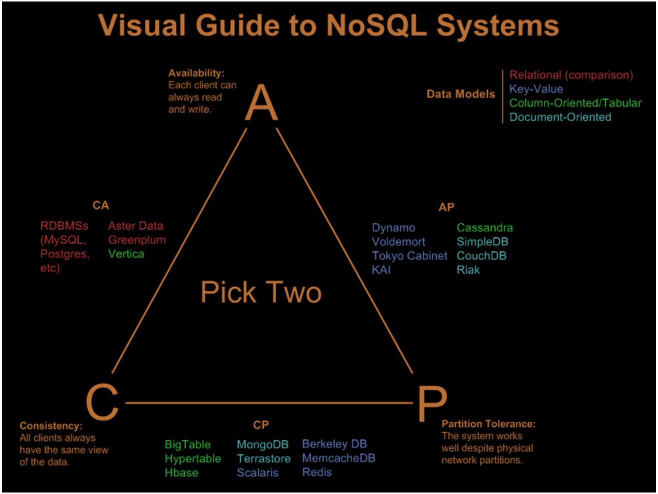
- No NoSQL database with strong Isolation

Discussion about other ACID properties

- Atomicity
  - Each side should ensure atomicity
- Durability
  - Should never be compromised

A vision of the NoSQL landscape

Source: https://blog.nahurst.com/visual-guide-to-nosql-systems



To be read with care:

- Solutions often provide a trade-off between CP and AP
- A single solution may often a different trade-off depending on how is is configured.
- **We don't pick two !**

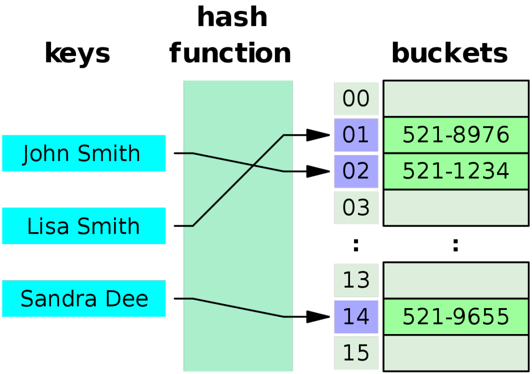
Agenda

Key-Value store

- Data are stored as key-value pairs
  - The value can be a data structure (eg, a list)
- In general, only support single-object transactions
  - In this case, key-value pairs
- Examples:
  - Redis
  - Voldemort
- Use case:
  - Scalable cache for data
  - Note that some solutions ensure durability by writing data to disk

Key-value store

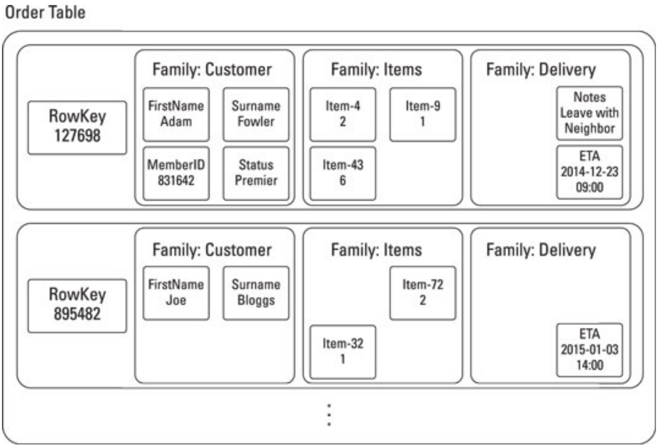
Image by J. Stolfi



Column family stores

- Data are organized in rows and columns (Tabular data store)
  - The data are arranged based on the rows
  - Column families are defined by users to improve performance
    - Group related columns together
- Only support single-object transactions
  - In this case, a row
- Examples:
  - BigTable/HBase
  - Cassandra
- Use case:
  - Data with some structure with the goal of achieving scalability and high throughput
  - Provide more complex lookup operations than KV stores

Column family stores



Note that not a row does not need to have an entry for all columns

Document databases

- Data are organized in Key-Document pairs
  - A document is a nested structure with embedded metadata
  - No definition of a global schema
  - Popular formats: XML, JSON
- Only support single-object transactions
  - In this case, a document or a field inside a document
- Examples:
  - MongoDB
  - CouchDB
- Use case:
  - An alternative to relational databases for structured data
  - Offer a richer set of operations compared to KV stores: Update, Find, etc.

Document DB

A document can have one or more documents inside.

```
{
    {
        "_id": ObjectId ("51c4218"),
        "name": "Claudia",
        "NumberKids": 3,
        "isActive": true,
        "interests": ["swimming", "tennis"]
        "favoriteCountries":
            [
              {
                    "name": "France",
                    "capital" : ”Paris"
              },
              {
                    "name": "Japan"
              }
            ]
    },
    {
        "_id": 2,
        "name": "Rubby"
        "friends": 354,
        "favorite Country":
        {
            "name": "Italy",
            "capital": "Rome"
        }
    }
}
```

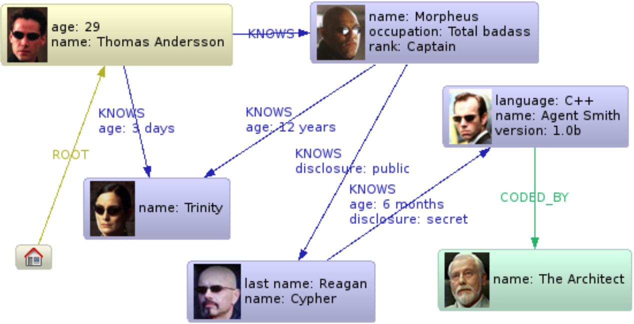
Embedded document

Embedded document

Embedded document

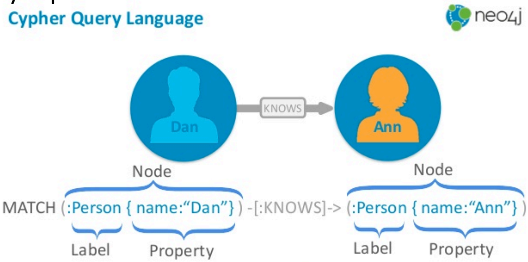
Graph DB

- Represent data as graphs
  - Nodes / relationships with properties as K/V pairs



Graph DB: Neo4j

- Rich data format
  - Query language as pattern matching
  - Limited scalability
    - Replication to scale reads, writes need to be done to every replica



On the Many-to-one relationship

Many-to-one relationship

- Many items may refer to the same item
- Example: Many people went to the same university

Relational vs Document DB

On the Many-to-one relationship

Many-to-one relationship

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- Example: Many people went to the same university

Relational vs Document DB

- Relational databases use a foreign key
  - Consistency and low memory footprint (normalization)
  - Easy updates and support for joins
  - Difficult to scale
- Document databases duplicate data
  - Efficient read operations
  - Easy to scale
  - Higher memory footprint and updates are more difficult (risk of consistency issues)
    - Transactions on multiple objects could be very useful in this case
  - Join operations have to be implement by the application

More on relations

One-to-many relationship

- An item may have several entries of the same kind
- Example: One person may have had several positions during her career.
- Document DB allow storing such information easily and allow simple read operations

Many-to-many relationship

- An item may have several entries of the same kind that are referred by multiple items
- Example: Several persons may have worked in the same company.
- Document DB may not have good support for such relationships

Agenda

Google BigTable

- Column family data store
  - Data storage system used by many Google services: Youtube, Google maps, Gmail, etc.
- Paper published by Google in 2006 (F. Chang et al)
  - Now available as a service on Google Cloud
- Many ideas reused in other NoSQL databases

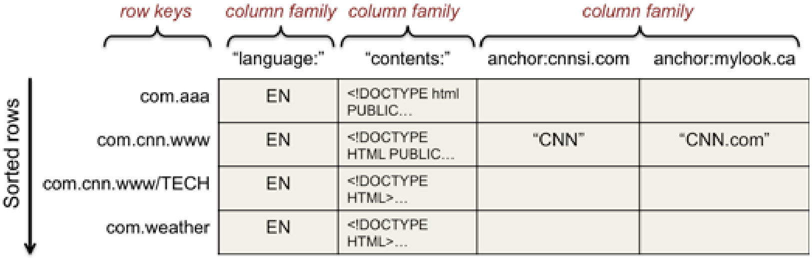
Motivations

- A system that can stores very large amount of data
  - TB or PB of data
  - A very large number of entries
  - Small entries (each entry is an array of bytes)
- A simple data model
  - Key-value pairs (A key identifies a row)
  - Multi-dimensional data
  - Sparse data
  - Data are associated with timestamps
- Works at very large scale
  - Thousands of machines
  - Millions of users

About the data model

- Rows are identified by keys (arbitrary strings)
  - Modifications on one row are atomic
  - Rows are maintained in lexicographic order
- Columns are grouped in columns families
  - Columns can be sparse
  - Clients can ask to retrieve a column family for one row
- Each cell can contain multiple versions indexed by a timestamp
  - Assigned by BigTable or by the client
  - Most recent versions are accessed first
  - GC politics:
    - Keep last n versions
    - Keep all new-enough versions

About the data model



Partitioning and performance

see https://cloud.google.com/bigtable/docs/schema-design

Partitioning

- Partitioning on the rows
- Rows with close keys are in the same partition

Recommendations about the schema for performance

- Accesses can be made based on key, key-prefix or key-range
  - Choose keys appropriately to make sequential accesses to a single host
  - Example: Reverse domain name, timestamps
  - To avoid: Domain name, hash values
  - Take advantage of the concept of key prefix
- Group related columns in a column family
  - Avoids retrieving all data from a single row when not needed
- Creating plenty of tables is not a good pattern
  - Use column families instead

Sparse columns

see `https://cloud.google.com/bigtable/docs/overview`

"follows" column family

	Follows			
Row Key	gwashington	jadams	tjefferson	wmckinley
gwashington		1		
jadams	1		1	
tjefferson	1	1		1
wmckinley			1	

Multiple versions

Building blocks of BigTable

A master

- Assign tablets to severs
- With the help of a locking service

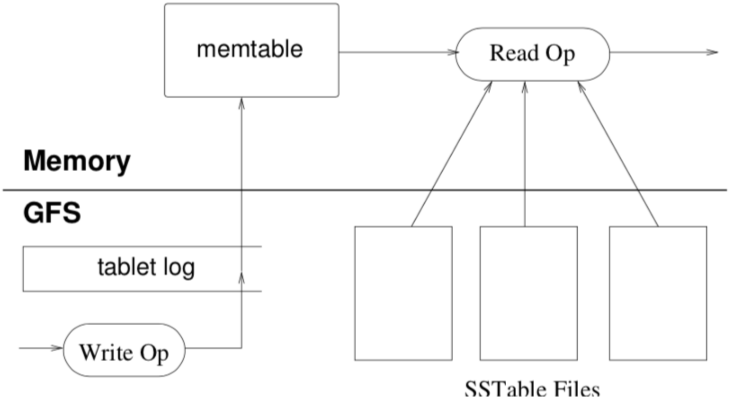
Tablet servers

- Store the tables (divided in tablets)
- Process client requests

Tablets

- Stored as SSTables (Sorted string tables)
- Stored in the Google File System for durability

Implementation of tablets



Implementation of tablets

Write operations

- Data stored in memory (Memtable)
- Any update is written to a commit log on GFS for durability
  - The log is shared between all hosted tablets

Periodic writes to disk

- When the Memtable becomes too big:
  - Copied as a new SSTable to GFS
    - Multiple SSTables are created if locality groups are defined (based on column families)
  - Reduces the memory footprint and reduces the amount of work to do during recovery
  - SSTables are immutable (no problem of concurrency control)
- Operation called minor compaction

Implementation of tablets

Read operations

- The state of the tablet = the Memtable + all SSTables
  - A merged view needs to be created
  - The Memtable and the SSTables may contain delete operations
- Locality groups help improving the performance of read operations

Major compaction

- When the number of SSTables becomes too big, merge them into a single SSTable
  - Allow reclaiming resources for deleted data
  - Improve the performance of read operations

Improving the performance of read operations

- During a read operation, potentially several SSTables need to be read
- How to avoid reading all SSTables when not needed?
  - Use of Bloom filters
  - Data structure that allows us to know if a SStable contains an entry for a given key-column pair

Improving the performance of read operations

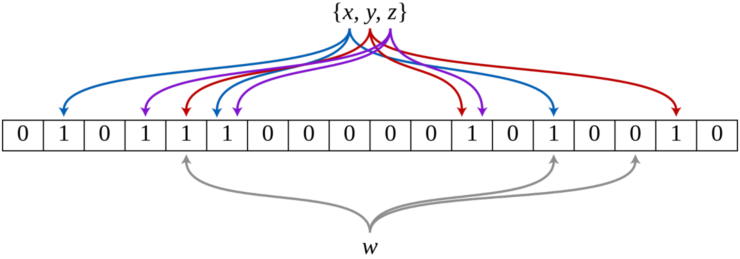
- During a read operation, potentially several SSTables need to be read
- How to avoid reading all SSTables when not needed?
  - Use of Bloom filters
  - Data structure that allows us to know if a SStable contains an entry for a given key-column pair

Bloom filter

- Implements a membership function (is X in the set?)
- If the bloom filter answers no: it is guaranteed that X is not present
- If the bloom filter answers yes: the element is in the set with a high probability
- Good trade-off between accuracy and memory footprint

About bloom filters

- A vector of n bits and k hash functions
- On insert:
  - Compute the k hash values
  - Set the corresponding bits to 1 in the vector
- On lookup:
  - Compute the k hash values
  - Test whether all bits are set to 1



About the logs

On one node, a single commit log is created even if it hosts multiple tablets.

Advantages

Drawbacks

About the logs

On one node, a single commit log is created even if it hosts multiple tablets.

Advantages

- Write a single append-only file on disk
  - Improves performance by avoiding long seeks

Drawbacks

- Recovery is more complex since the log includes data associated with different tablets
- The tablets might be distributed over multiple nodes

Apache Cassandra

- Column family data store
- Paper published by Facebook in 2010 (A. Lakshman and P. Malik)
  - Used for implementing search functionalities
  - Released as open source
- Build on top of several ideas introduced by BigTable
  - Warning: Many changes in the design have been made since the first version of Cassandra

Warning

About the information provided in this lecture:

- Not necessarily up-to-date with to the most recent version of Cassandra
- The goal is to understand some generally applicable ideas
- We are not going to describe all parts of Cassandra:
  - Focus on partitioning and consistency

The design principles of Cassandra are mostly inspired from other systems:

- Google BigTable
- Amazon Dynamo

Suggested reading: Facebook's Cassandra paper, annotated and compared to Apache Cassandra 2.0

Partitioning in Cassandra

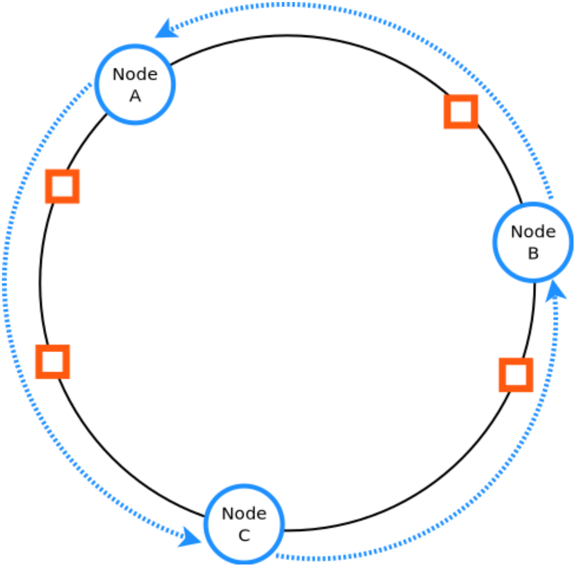
Partitioning based on a hashed name space

- Data items are identified by keys
- Data are assigned to nodes based on a hash of the key
  - Tries to avoid hot spots

Namespace represented as a ring

- Allows increasing incrementally the size of the system
- Each node is assigned a random identifier
  - Defines the position of a node in the ring
- The nodes is responsible for all the keys in the range between its identifier and the one of the previous node.

Partitioning in Cassandra



Better version of the partitioning

Limits of the current approach:

Better version of the partitioning

Limits of the current approach: High risk of imbalance

- Some nodes may store more keys than others
  - Nodes are not necessarily well distributed on the ring
  - Especially true with a low number of nodes
- Issues when nodes join or leave the system
  - When a node joins, it gets part of the load of its successor
  - When a node leaves, all the corresponding keys are assigned to the successor

Better version of the partitioning

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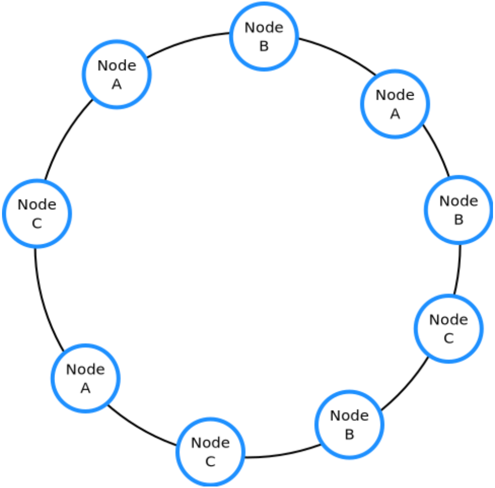
Concept of virtual nodes

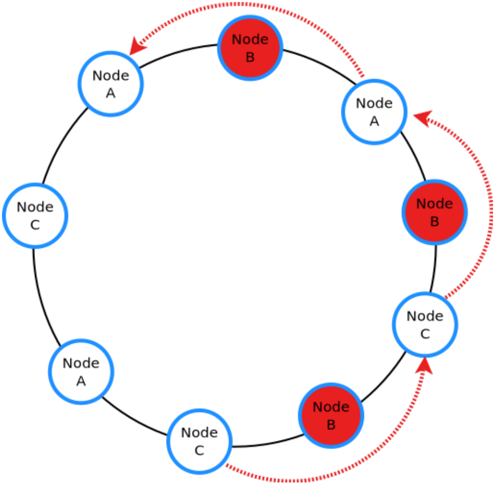
- Assign multiple random positions to each node

Partitioning and virtual nodes



The key space is better distributed between the nodes

Partitioning and virtual nodes



If a node crashes, the load is redistributed between multiple nodes

Partitioning and replication

Items are replicated for fault tolerance.

Strategies for replica placement

- Simple strategy
- Topology-aware placement

Partitioning and replication

Items are replicated for fault tolerance.

Strategies for replica placement

- Simple strategy
  - Place replicas on the next R nodes in the ring
- Topology-aware placement
  - Iterate through the nodes clockwise until finding a node meeting the required condition
  - For example a node in a different rack

Replication in Cassandra

Replication is based on quorums

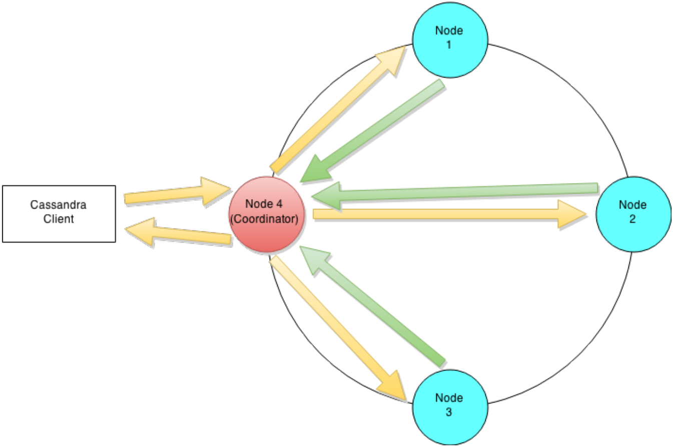
- A read/write request might be sent to a subset of the replicas
  - To tolerate f faults, it has to be sent to $f + 1$ replicas

Consistency

- The user can choose the level of consistency
  - Trade-off between consistency and performance (and availability)
- Eventual consistency
  - If an item is modified, readers will *eventually* see the new value

A Read/Write request

Figure from `https://dzone.com/articles/introduction-apache-cassandras`



- A client can contact any node in the system
- The coordinator contacts all replicas
- The coordinator waits for a specified number of responses before sending an answer to the client

Consistency levels

ONE (default level)

- The coordinator waits for one ack on write before answering the client
- The coordinator waits for one answer on read before answering the client
- Lowest level of consistency
  - Reads might return stale values
  - We will still read the most recent values in most cases

QUORUM

- The coordinator waits for a majority of acks on write before answering the client
- The coordinator waits for a majority of answers on read before answering the client
- High level of consistency
  - At least one replica will return the most recent value

Additional references

Mandatory reading

- *Bigtable: A Distributed Storage System for Structured Data.*, F. Chang et al., OSDI, 2006.
- *Cassandra: a decentralized structured storage system* ., A. Lakshman et al., SIGOPS OS review, 2010.

Suggested reading

- `http://martin.kleppmann.com/2015/05/11/please-stop-calling-databases-cp-or-ap.html`, M. Kleppmann, 2015.
- `https://jvns.ca/blog/2016/11/19/a-critique-of-the-cap-theorem/`, J. Evans, 2016.