Données massives et apprentissage profond
Lecture 2 – Distributed and NoSQL databases

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What you will learn

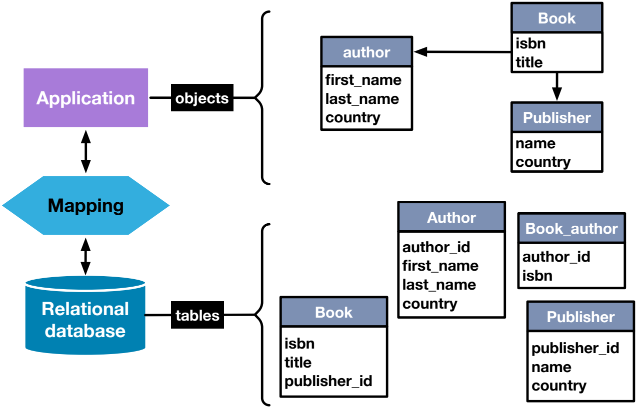
In this lecture you will learn:

- The **limitations** of the **relational data model**.
- What a **distributed database** is.
- How data is **distributed** across different machines.
- The **availability-consistency** trade-off (CAP theorem).
- The main characteristics of **NoSQL databases**.
- The families of NoSQL databases.

Relational data model limitations: impedance mismatch

Definition (Impedance mismatch)

Impedance mismatch refers to the challenges encountered when one needs to map objects used in an application to tables stored in a relational database.



Impedance mismatch: solutions

Object-oriented databases

- Data is stored as **objects**.
- Object-oriented applications save their objects as they are.
- **Examples.** ConceptBase, Db4o, Objectivity/DB.

Disadvantage

- Not as popular as relational database systems.
- Requires familiarity with object-oriented concepts.
- No standard query language.

Impedance mismatch: solutions

Object relational mappers (ORM)

- Use of libraries that map objects to relational tables.
- The application manipulates objects.
- The ORM library translates object operations into SQL queries.
- **Examples.** SQLAlchemy, Hibernate, Sequelize.

Disadvantage

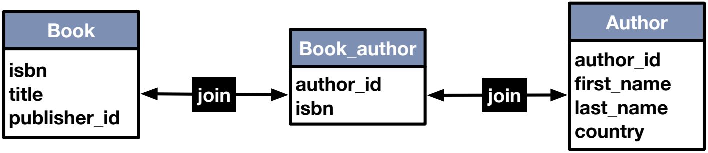
- **Abstraction.** Weak control on how queries are translated.
- **Portability**. Each ORM has a different set of APIs.

Limitations of the relational model: normalization

Normalization

- In a relational database, tables are **normalized**.
- Data on **different entities** are kept in **different tables**.
- This reduces **redundancy** and guarantees **integrity**.

- In a **normalized** relational database, links between entities are expressed with **foreign key constraints**.
- Need to join different tables (**expensive** operation).



Limitations of the relational model: data distribution

Objective of a relational database system

- Privilege data **integrity** and **consistency**.
- Different mechanisms to ensure integrity and consistency.
  - Primary and foreign key constraints.
  - Transactions.

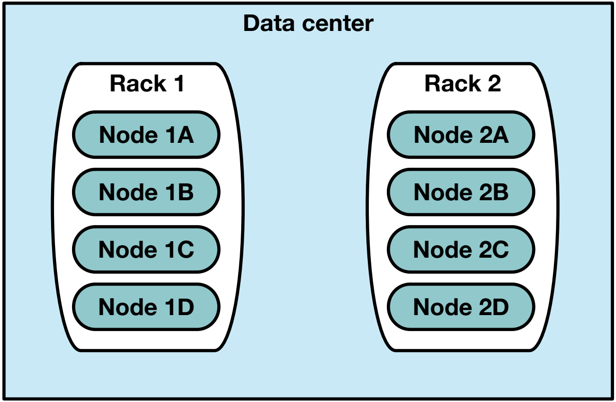
- Mechanisms to enforce data integrity and consistency have a **cost**.
  - Manage transactions.
  - Check that new data complies with the given integrity constraints.

- Things get worse in **distributed databases**.
  - Data is distributed across several machines.
  - Join operations become very expensive.
  - Integrity mechanisms become very expensive.

Distributed databases

Definition (Distributed database)

A **distributed database** is one where data is stored across several **machines**, a.k.a, **nodes**.



Distributed database

Shared-nothing architecture

- Each node has its own CPU, memory and storage.
- Nodes only share the network connection.

Pros/cons of a distributed database

- Allows storage and management of large volumes of data. ☺
- Far more complex than a single-server database. ☹

Distributing data: when? ★

Is it worth distributing data when it is small in size?

Distributing data: when? ★

Small-scale data

- Data distribution is not a good option when the **data scale is small**.
- With **small-scale data**, the performances of a distributed database are **worse** than a single-server database.
  - **Overhead.** We lose more time distributing and managing data than retrieving it.

Large-scale data

- If the data does not fit in a single machine, data distribution is the only option left.
- Distributed databases allow **more concurrent database requests** than single-server databases.

Distributing data: how?

Data distribution options

- **Replication.** Multiple copies of the same data stored on different nodes.
- **Sharding.** Data partitions stored on different nodes.
- **Hybrid.** Replication + Sharding.

Properties

- **Location transparency**: applications do not have to be aware of the location of the data.
- **Replication transparency**: applications do not need to be aware that the data is replicated.

Replication

- The same piece of data is replicated across different nodes.
  - Each copy is called a **replica**.
- **Replication factor.** The number of nodes on which the data is replicated.

A

B

C

Department		
codeD	nameD	budget
14	Administration	300,000
25	Education	150,000
62	Finance	600,000
45	Human Resources	150,000

Department		
codeD	nameD	budget
14	Administration	300,000
25	Education	150,000
62	Finance	600,000
45	Human Resources	150,000

Department		
codeD	nameD	budget
14	Administration	300,000
25	Education	150,000
62	Finance	600,000
45	Human Resources	150,000

Replication: pros and cons ★

What are the advantages and the disadvantages of replication?

Replication: pros and cons★

Advantages

- **Scalability.** Multiple nodes can serve queries on the same data.
- **Latency.** Queries can be served by geographically proximate nodes.
- **Fault tolerance.** The database keeps serving queries even if some nodes fail.

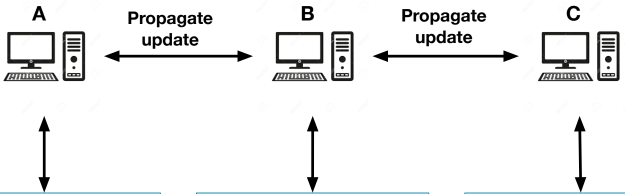
Disadvantages

- **Storage cost.** Storage is used to keep multiple copies of the same data.
- **Consistency.** All replicas must be kept in sync.

Replication: consistency

Replica consistency

When a replica is updated, the other replicas must be updated as well.




```
UPDATE Department
SET budget=500000
WHERE codeD=14
```

Department (A)

codeD	nameD	budget
14	Administration	**500,000**
25	Education	150,000
62	Finance	600,000
45	Human Resources	150,000

Department (B)

codeD	nameD	budget
14	Administration	300,000
25	Education	150,000
62	Finance	600,000
45	Human Resources	150,000

Department (C)

codeD	nameD	budget
14	Administration	300,000
25	Education	150,000
62	Finance	600,000
45	Human Resources	150,000

Replication: consistency

Synchronous updates

- Updates are propagated immediately to the other replicas.
- **Small inconsistency window.** The replicas will be inconsistent for a short interval of time. ☺
- If updates are frequent, the database might be too busy propagating updates than serving queries. ☹

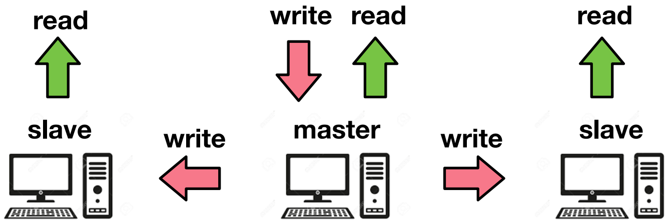
Asynchronous updates

- Updates are propagated at regular intervals.
- More efficient when updates are frequent. ☺
- Long inconsistency window. ☹

Replication: architecture

Master-slave replication

- **Write** operations are only possible on the **master node**.
- The **master node** propagates the updates to the **slave nodes**.
- **Read** operations are served by both the master and the slave nodes.



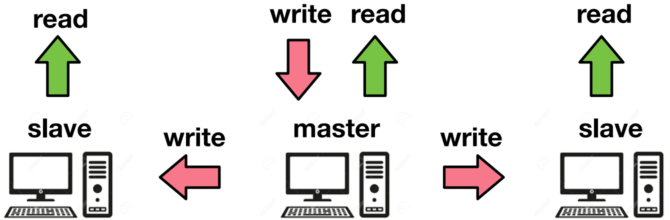
Replication: architecture ★

What are the advantages and disadvantages of master-slave replication?

Replication: architecture ★

Master-slave replication

- Prevents **write conflicts**. ☺
  - Only one replica is written at any given time.
- Single **point of failure**. ☹
  - If the master fails, write operations are unavailable.
  - Algorithms exist to **elect** a new master.
- **Read conflicts** are possible. ☹

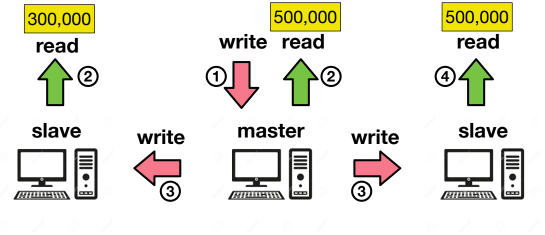


Replication: architecture

Master-slave replication read conflict

Two **read** operations on the **same data** might return **different values**.

Write: update (Department, budget=500,000) **Read**: select (Department, budget)



Department		
codeD	**nameD**	**budget**
14	Administration	**300,000**
25	Education	150,000
62	Finance	600,000
45	Human Resources	150,000

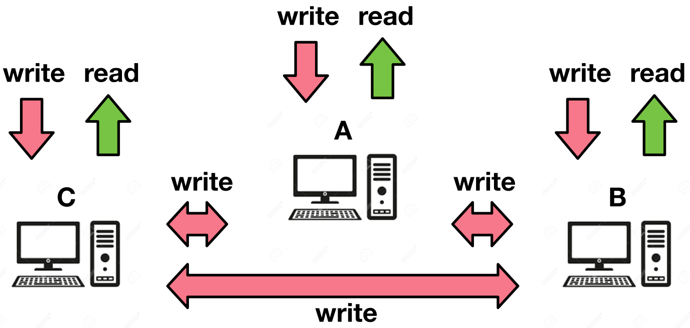
Department		
codeD	**nameD**	**budget**
14	Administration	**500,000**
25	Education	150,000
62	Finance	600,000
45	Human Resources	150,000

Department		
codeD	**nameD**	**budget**
14	Administration	**500,000**
25	Education	150,000
62	Finance	600,000
45	Human Resources	150,000

Replication: architecture

Peer-to-peer replication

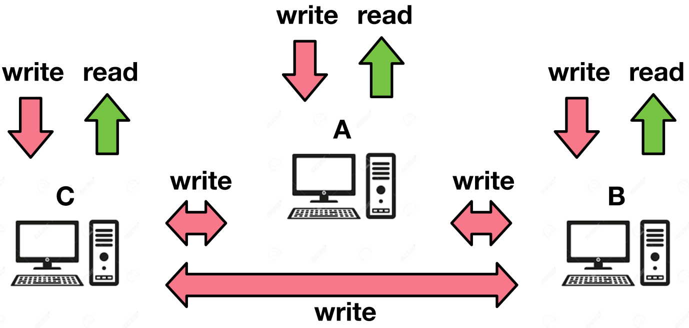
- **Read** and **write** operations are possible on **any node**.



Replication: architecture

Peer-to-peer replication

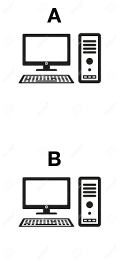
- No single point of failure. ☺
- Write and read conflicts are possible. ☹



Sharding

Sharding

- Data is partitioned into balanced, non-overlapping **shards**.
- Shards are distributed across the nodes.



Department

codeD	nameD	budget
14	Administration	300,000
25	Education	150,000

Employee

codeE	last_name	codeD
1	Bennet	14
2	Doe	62
3	Fisher	25
4	Green	62

Employee

codeE	last_name	codeD
5	Russel	25
6	Smith	62
7	Watson	14
8	Young	45

Department

codeD	nameD	budget
62	Finance	600,000
45	Human Resources	150,000

Sharding: pros and cons ★

What are the advantages and disadvantages of sharding?

Sharding: pros and cons ★

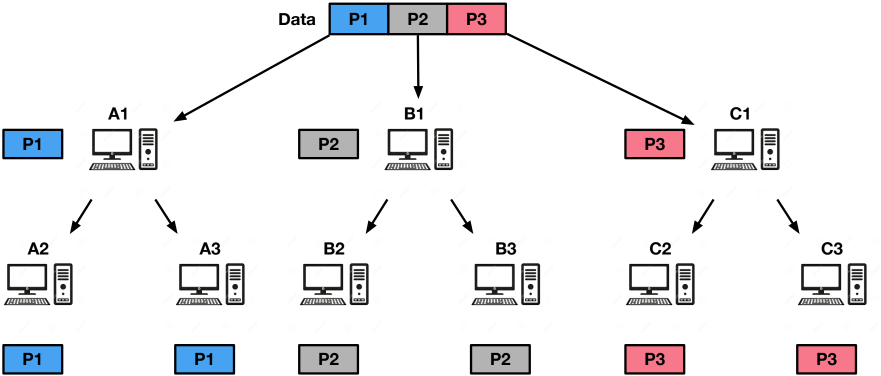
Advantages

- **Load balance.** Data can be uniformly distributed across nodes.
- **Inconsistencies** cannot arise (non-overlapping shards).

Disadvantages

- When a node fails, all its partitions are lost.
- Join operations might need to be performed across nodes.
- When data is added, shards might need to be rebalanced.

Combining replication and sharding



Consistency in distruibuted databases

There can be **different definitions** of **consistency** in a distributed database.

- **Transactional** consistency. This notion also applies to **single-server databases**.
- **Replication** consistency. This notion only applies to **distributed databases**.

Transactional consistency

Definition (Transactional consistency)

A database is **consistent** if the data respects all the **integrity constraints** imposed by the database administrator.

Employee

codeE	last_name	codeD
1	Bennet	14
2	Doe	62
3	Fisher	25
4	Green	62

```
UPDATE Department
SET codeD=15
WHERE codeD=14
```

Department

codeD	nameD	budget
14	Administration	300,000
25	Education	150,000

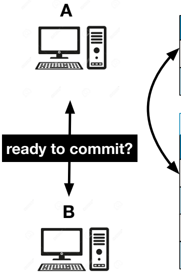
- **Transactions** are used to keep a database consistent.

ACID

Atomicity, **C**onsistency, **I**solation, **D**urability.

Transactional consistency

- **Distributed transactions** are used to keep a distributed database consistent.
- All the data involved in a transaction are **locked** until commit.
    - Write and, possibly, read operations are **not allowed** on locked data.
    - Changes are only visible when (and if) the transaction commits.
    - The database is consistent after the transaction.



codeD	nameD	budget
14	Administration	300,000
25	Education	150,000

Employee

codeE	last_name	codeD
1	Bennet	14
2	Doe	62
3	Fisher	25
4	Green	62

```
UPDATE Department
SET codeD=15
WHERE codeD=14
```

```
UPDATE Employee
SET codeD=15
WHERE codeD=14
```

Transactional consistency

- Managing distributed transactions is **expensive**.
  - **Transaction managers** in all the nodes involved in the transaction need to communicate before committing.
- Distributed transactions guarantee the **consistency** of the database.
- Distributed transactions reduce the **availability** of the database.

☞ Different DBMS make different choices on the trade-off between **consistency** and **availability**.

Replication consistency ★

Definition (Replication consistency)

A (distributed) database is **consistent** if reads and updates behave as if there were a single copy of the data. (▸ Source).

Consider **3 replicas** of some data stored on 3 different nodes A, B and C. The replica stored in A is updated and we let an application read from all the nodes **before** the update is propagated to B and C. What happens?

Replication consistency ★

Definition (Replication consistency)

A (distributed) database is **consistent** if reads and updates behave as if there were a single copy of the data. (Source).

- Two different applications might get two different results while reading that replica.
- The application might read an outdated replica.
- Availability is strong.

Replication consistency ★

Definition (Replication consistency)

A (distributed) database is **consistent** if reads and updates behave as if there were a single copy of the data. (▸ Source).

Consider **3 replicas** of some data stored on 3 different nodes A, B and C. The replica stored in A is updated and we prevent any applications from reading that data **until** the update is propagated to both B and C. What happens?

Replication consistency ★

Definition (Replication consistency)

A (distributed) database is **consistent** if reads and updates behave as if there were a single copy of the data. (▸ Source).

- Consistency is strong.
- Availability is weak.

☞ If one of the nodes is not reachable, the write operation cannot be executed!

Replication consistency ★

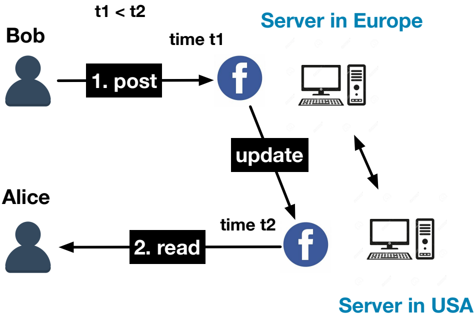
Definition (Replication consistency)

A (distributed) database is **consistent** if reads and updates behave as if there were a single copy of the data. (▸ Source).

Replication with quorum

- Applications cannot read the data until the replica is propagated to a given number of nodes (not necessarily all).
- A way to balance consistency and availability.

Is strong consistency always necessary?



Alice does not see Bob's post between $t1$ and $t2$.
Is it really an issue?

Consistency vs Availability

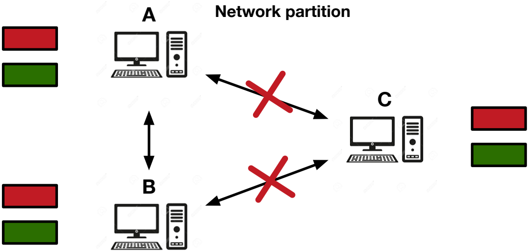
- Traditionally, relational databases favor **consistency** over **availability**.
  - **ACID**-compliant databases.
- NoSQL databases provide more degrees of freedom.
  - **BASE**: **B**asic **A**vailability, **S**oft state, **E**ventually consistent.

☞ What happens in case of a network problem hampering the communication between nodes?

The CAP theorem

Consistency (C), Availability (A), Partition tolerance (P)

- **Consistency.** Any application making a request to the database will get the same view of data.
- **Availability.** A database can still execute read/write operations when some nodes fail.
- **Partition tolerance.** The database can still operate when a **network partition** occurs.



The CAP theorem

Theorem (CAP, Brewer 1999)

Given the three properties of **consistency**, **availability** *and* **partition tolerance**, *a networked shared-data system can have at most two of these properties.*

Proof

Suppose that the system is **partition tolerant (P)**. When a network partition occurs, we have two options.

1. **Allow write operations**. This makes the database **available (A)**, but **not consistent (C)**.
    - Some of the replicas might not be synced due to the network partition.
2. **Disable write operations**. This makes the database **consistent (C)** but **not available (A).**

The CAP theorem

Theorem (CAP, Brewer 1999)

Given the three properties of **consistency**, **availability** *and* **partition tolerance**, *a networked shared-data system can have at most two of these properties.*

Proof

- The only way that we can have a **consistent (C)** and **available (A)** database is when network partitions do not occur.
- But if we assume that network partitions never occur, the system is **not partition tolerant (P)**.

Interpretation of the CAP theorem

- When there isn't any network partition, the CAP theorem **does not** impose constraints on availability or consistency.
- In case a network partition occurs, the database must trade consistency with availability or viceversa.
- Different databases take different approaches.

CP Databases

- Relational databases.
- Some NoSQL databases: MongoDB, CouchDB, Redis, HBse.

AP databases

- Some NoSQL databases: Cassandra, DynamoDB.

NoSQL databases

NoSQL: interpretations of the acronym

- *Non SQL*: strong opposition to SQL.
- *Not only SQL*: NoSQL and SQL coexistence.

Goals

- Address the **object-relational impedance mismatch**.
- Provide better scalability for **distributed databases**.
- Provide a better modeling of **semi-structured data**.

NoSQL databases

Families

- **Key-value** databases.
- **Document-oriented** databases.
- **Column-oriented** databases.
- **Graph** databases.

- The first three families use the notion of **aggregate** to model the data.
  - They differ in how the aggregates are organized.
- Graph databases are somewhat **outliers**.
  - They were not conceived for data distribution in mind.
  - They were born ACID-compliant.

☞ There is not a single NoSQL database and there is not a “NoSQL” query language.

Aggregate

- An **aggregate** is a data structure used to store the data of a specific entity.
  - In that, it is similar to a row in a relational table.
- We can **nest** an aggregate into another aggregate.
  - This is a huge difference from a row in a relational table.
- An aggregate is a **unit of data** for **replication** and **sharding**.
  - All data in an aggregate will never be split across two shards.
  - All data in an aggregate will always be available on one node.
  - Unlike a relational database, we can control how data is distributed.

A step back: relational databases ★

What's the problem with this database when it is distributed across several nodes?

article

article_id	name	producer
234543	Bamboo utensil spoon	KitchenMaster

article_category

article_id	category_id
234543	1
234543	2
234543	3

category

category_id	name
1	kitchen
2	home
3	spatulas

A step back: relational databases ★

Join operations might need to move data across the network.

A step back: relational databases ★

A possible solution to this problem would be to **denormalize** the table.

article_id	name	producer	categories
234543	Bamboo utensil spoon	KitchenMaster	home, kitchen, spatulas

Queries such as "Give me all articles in category home" are not well-supported in SQL (column `categories` contains list of values).

Aggregate vs relational row

In an **aggregate**, queries against list of values are well-supported.

```
{
  article_id: 234543,
  name: "Bamboo utensil spoon",
  producer: "KitchenMaster",
  categories: ["home", "kitchen", "spatulas"]
}
```

☞ All data in an aggregate is **never** split across different nodes.

- **Denormalization** is allowed in the aggregate.
- Data that are queried together are stored in the same aggregate.

```
{
  code_employee: 12353,
  first_name: "John",
  last_name: "Smith",
  salary: 50000,
  position: "Assistant director",
  department: {
      dept_code: 12,
      dept_name: "Accounting",
      budget: 120000
    }
}
```

- Aggregates are **schemaless**.
- Aggregates might not have the same attributes.

```
{
  code_employee: 12353,
  first_name: "John",
  last_name: "Smith",
  salary: 50000,
  position: "Assistant director",
  department: {
      dept_code: 12,
      dept_name: "Accounting",
      budget: 120000
    }
}
```

```
{
  code: 345321,
  first_name: "Jennifer",
  last_name: "Green",
}
```

☞ We don't need to fix a rigid schema. NULL values are avoided.

```
{
  code_employee: 12353,
  first_name: "John",
  last_name: "Smith",
  salary: 50000,
  position: "Assistant director",
  departments: [
    {
      dept_code: 12,
      dept_name: "Accounting",
      budget: 120000
    },
    {
      dept_code: 145,
      dept_name: "HR",
      budget: 250000
    }
  ]
}
```

```
{
  code_employee: 12353,
  first_name: "John",
  last_name: "Smith",
  salary: 50000,
  position: "Assistant director",
  departments: [
    {
      dept_code: 12,
      dept_name: "Accounting",
      budget: 120000
    },
    {
      dept_code: 145,
      dept_name: "HR",
      budget: 250000
    }
  ]
}
```

☞ We can update **atomically** the salary of an employee. How would we represent the same in a relational database?

- We use a **denormalized table** (same as aggregate).
- **However**, we have no guarantees that the rows relative to the employee John Smith will be stored in the same node.

code_emp	first_name	last_name	salary	position	dept_code	dept_name	budget
234543	John	Smith	50000	Assistant director	12	Accounting	120000
234543	John	Smith	50000	Assistant director	145	HR	250000

☞ The update of the salary of a single employee might be a **cross-node operation**.

Aggregate-based NoSQL databases

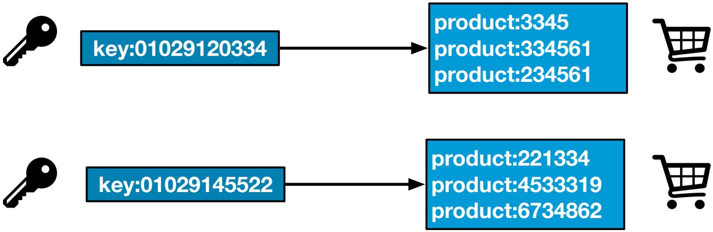
- Aggregates are **schemaless**.
  - No need to adhere to a rigid schema.
  - Flexible evolution of the database.
- Normalization is not required.
  - We accept some **redundancies** in exchange of faster queries.
  - Remember: storage hardware is **cheap** today.
- All data in an aggregate is stored in a **single node**.
  - With aggregates, we are in control of how the data is distributed.
- In general, updates on an aggregate are **atomic operations**.
  - If an update entails many write operations, either all are executed or none.
- Cross-aggregate updates are **not guaranteed** to be atomic.
  - Multi-aggregate transactions might be supported and used if necessary.

Key-value databases

Idea

Data are modeled as **key-value pairs**.

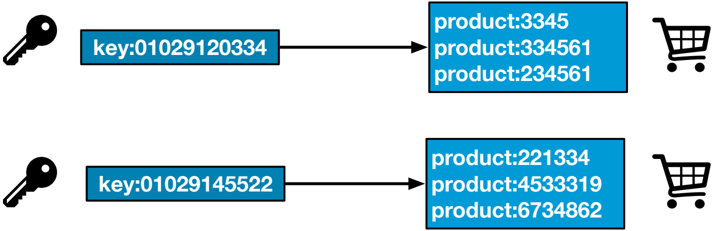
- **Key**: alphanumeric string, usually auto-generated by the database.
- **Value**: an aggregate.
- **Query**: get an aggregate given its key.



Key-value databases

Idea

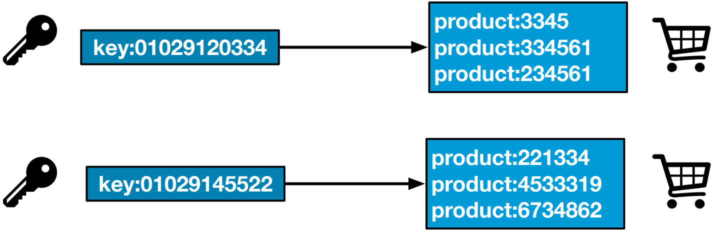
- Data is partitioned based on the key.
- Partitions are distributed across different nodes.
- Little to no checks on integrity constraints.
- **Goal.** High scalability and fast read/write queries.



Key-value databases

Application scenario - Shopping cart

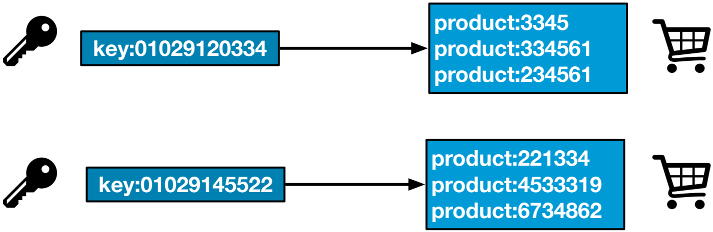
- An e-commerce website may receive billions of orders in seconds.
- Each shopping cart has a **unique identifier** (the key).
- Shopping cart data is only queried by the identifier.
- Shopping cart data can be easily replicated to handle node failures.



Key-value databases

Existing key-value databases

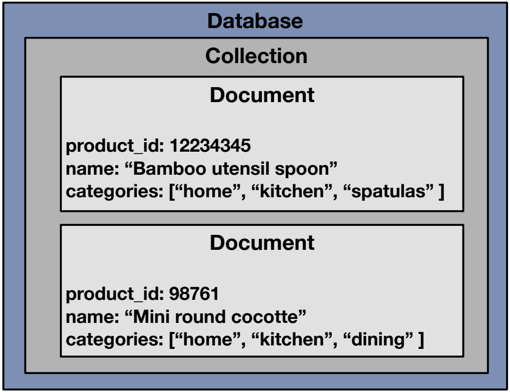
- **Amazon DynamoDB**. One of the first NoSQL databases.
- **Riak**.
- **Redis**. Possibility of tuning data persistence.
- **Voldemort**.



Document-oriented databases

Idea

- Data is modeled as **key-value pairs**, and searching aggregates based on their **attribute values** is supported.

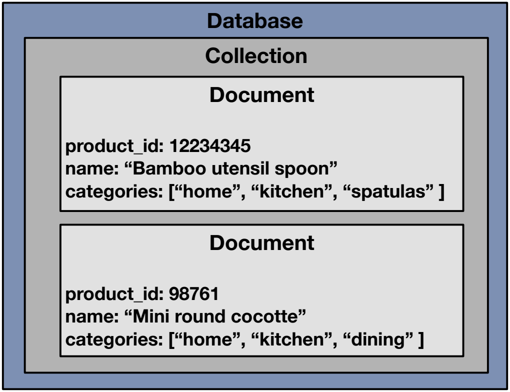


It is possible to search for all products in category *kitchen*.

Document-oriented databases

Existing document-oriented databases

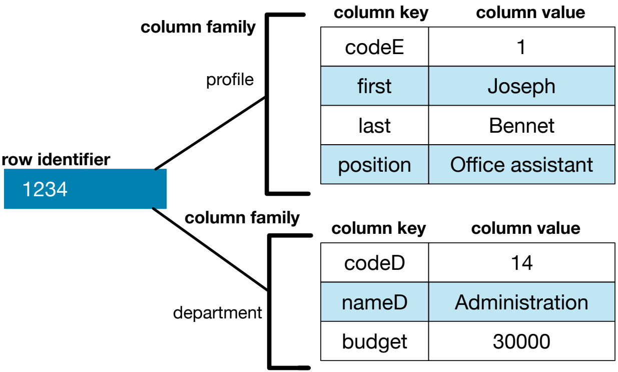
- **MongoDB**, **CouchDB**, **OrientDB**.



Column-oriented databases

Idea

- Similar to document-oriented database but an aggregate can be broken into smaller data units called **columns**.



Column-oriented databases

Idea

- Columns can be organized into **column families**.
- Columns in the same family are accessed together.

row identifier: 1234

column family: profile

column key	column value
codeE	1
first	Joseph
last	Bennet
position	Office assistant

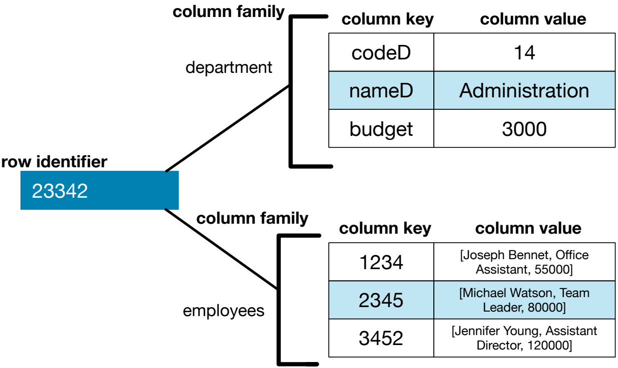
column family: department

column key	column value
codeD	14
nameD	Administration
budget	30000

Column-oriented databases

Idea

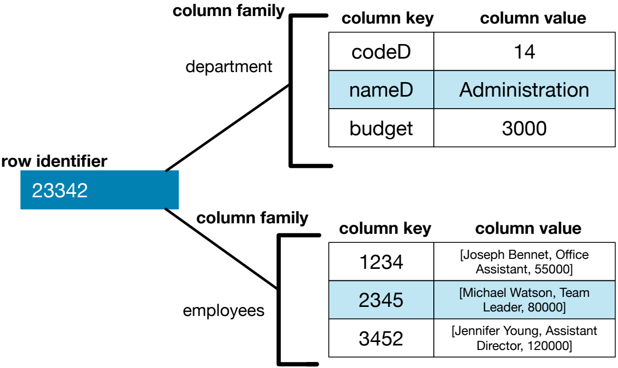
- The value of a column can be an aggregate (**wide column**).



Column-oriented databases

Existing column-oriented databases

- **Cassandra**, **HBase**, **BigTable** (Google).



Graph databases

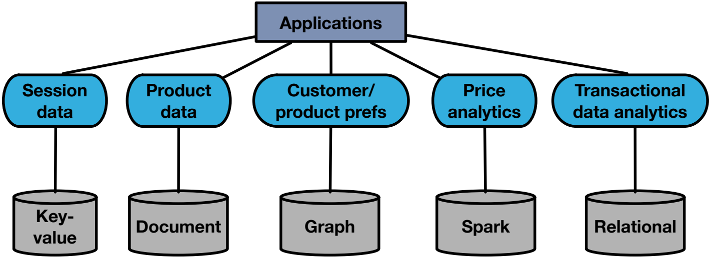
Idea

- Their data model is optimized for storing and retrieving **graph data**.
- Relationships are **first-class citizens**.
  - In relational databases they are implicit in **foreign key constraints**.
  - In aggregate-based NoSQL stores, they are represented with nested aggregates or references.
- Existing graph databases: **Neo4j**, **InfiniteGraph**, **AllegroGraph**.

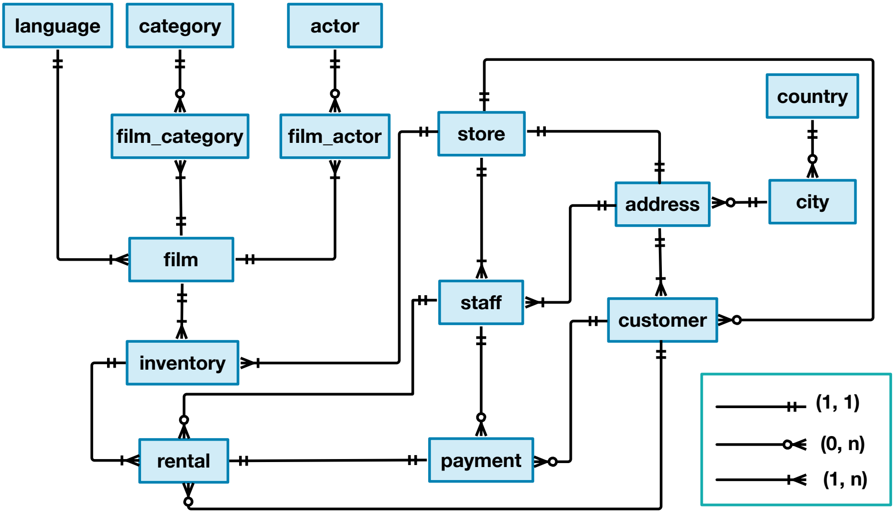
NoSQL databases: conclusions

Polyglot persistence

- NoSQL databases are **not** going to replace relational databases.
- Use of different data storage technologies based on the data type.
- This is called **polyglot persistence**.



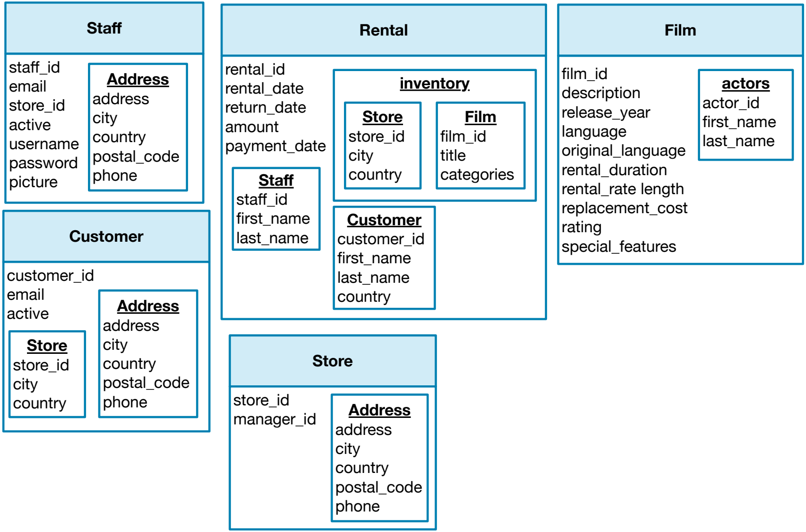
Exercise: model this database in MongoDB



Exercise: details on the database

- Table `customer`: customer_id, store_id, first_name, last_name, email, address_id, active, create_date.
- Table `inventory`: inventory_id, film_id, store_id.
- Table `payment`: payment_id, customer_id, staff_id, rental_id, amount, payment_date.
- Table `rental`: rental_id, rental_date, inventory_id, customer_id, return_date, staff_id
- Table `staff`: store_id, manager_staff_id, address_id

Solution


Staff
staff_id
email
store_id
active
username
password
picture
Address
address
city
country
postal_code
phone
Customer
customer_id
email
active
Store
store_id
city
country
Address
address
city
country
postal_code
phone
Rental
rental_id
rental_date
return_date
amount
payment_date
inventory
Store
store_id
city
country
Film
film_id
title
categories
Staff
staff_id
first_name
last_name
Customer
customer_id
first_name
last_name
country
Store
store_id
manager_id
Address
address
city
country
postal_code
phone
Film
film_id
description
release_year
language
original_language
rental_duration
rental_rate length
replacement_cost
rating
special_features
actors
actor_id
first_name
last_name