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

Gianluca Quercini

gianluca.quercini@centralesupelec.fr

Polytech Paris-Saclay, 2023

CentraleSupélec

What you will learn

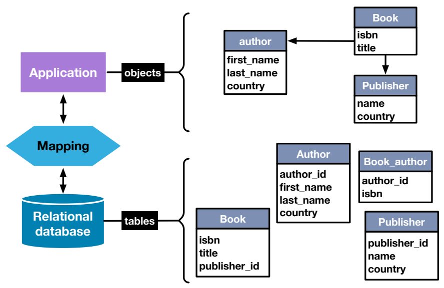
In this lecture you will learn:

- 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

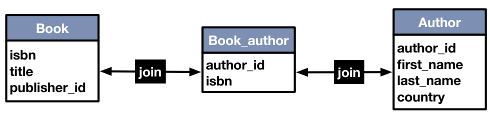
- **Abstraction.** Weak control on how queries are translated.
- **Portability**. Each ORM has a different set of APIs.

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

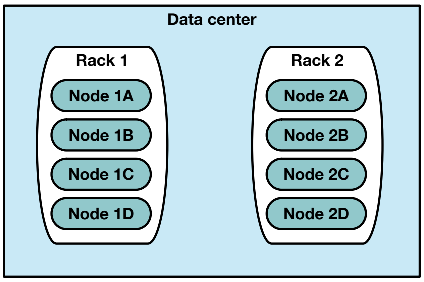
- Privilege data **integrity** and **consistency**.
- Different mechanisms to ensure integrity and consistency.
  - Primary and foreign key constraints.
  - Transactions.

- 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

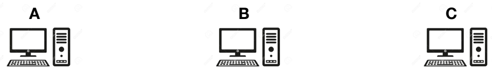
- **Replication.** Multiple copies of the same data stored on different nodes.
- **Sharding.** Data partitions stored on different nodes.
- **Hybrid.** Replication + Sharding.

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.



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

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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.

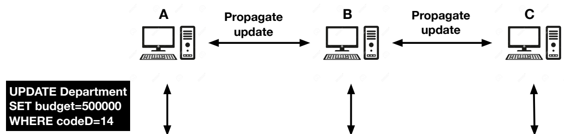
Disadvantages

- **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.



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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. ☹

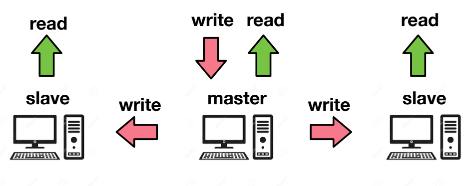
Asynchronous updates

- 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.



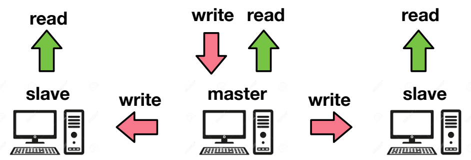
Replication: architecture ★

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. ☹

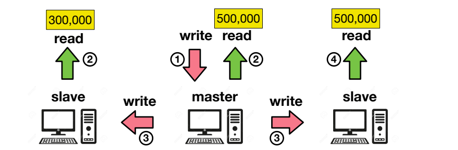


Replication: architecture

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)



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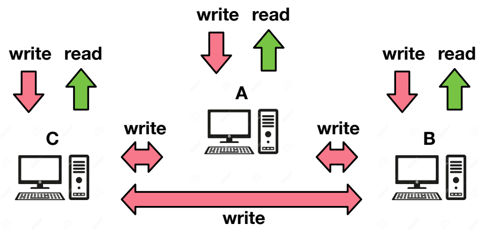
Replication: architecture

Peer-to-peer replication

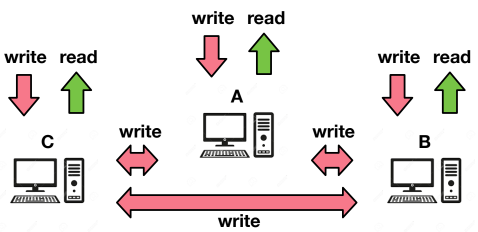
- **Read** and **write** operations are possible on **any node**.



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 ★

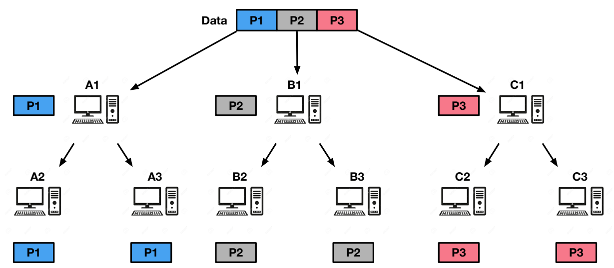
Advantages

- **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

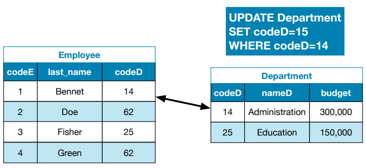
There can be **different definitions** of **consistency** in a distributed database.

- **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.



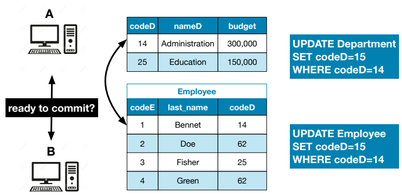
- **Transactions** are used to keep a database consistent.

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.



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.

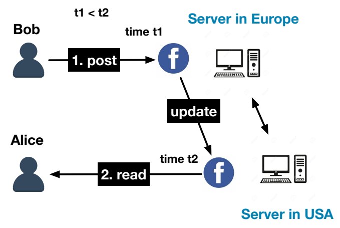
☞ If one of the nodes is not reachable, the write operation cannot be executed!

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

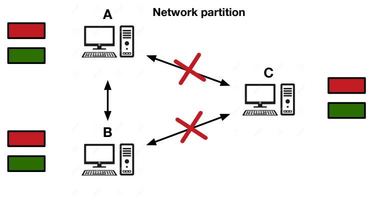
- Traditionally, relational databases favor **consistency** over **availability**.
  - **ACID**-compliant databases.
- NoSQL databases provide more degrees of freedom.
  - **BASE**: **B**asic **A**vailability, **S**oft state, **E**ventually consistent.

☞ 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

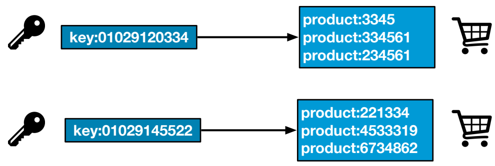
- Aggregates are **schemaless**.
  - No need to adhere to a rigid schema.
  - Flexible evolution of the database.
- Normalization is not required.
  - We accept some **redundancies** in exchange of faster queries.
  - Remember: storage hardware is **cheap** today.
- All data in an aggregate is stored 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**.

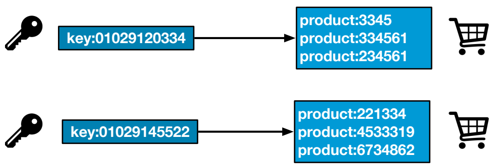
- **Key**: alphanumeric string, usually auto-generated by the database.
- **Value**: an aggregate.
- **Query**: get an aggregate given its key.



Key-value databases

Idea

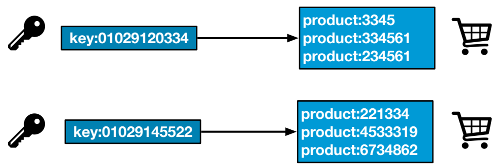
- Data is partitioned based on the key.
- Partitions are distributed across different nodes.
- Little to no checks on integrity constraints.
- **Goal.** High scalability and fast read/write queries.



Key-value databases

Application scenario - Shopping cart

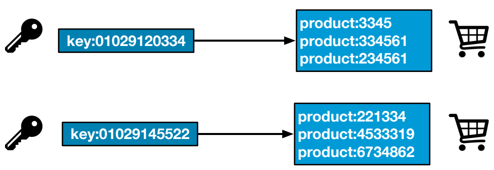
- An e-commerce website may receive billions of orders in seconds.
- Each shopping cart has a **unique identifier** (the key).
- Shopping cart data is only queried by the identifier.
- Shopping cart data can be easily replicated to handle node failures.



Key-value databases

Existing key-value databases

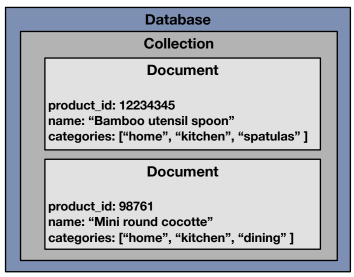
- **Amazon DynamoDB**. One of the first NoSQL databases.
- **Riak**.
- **Redis**. Possibility of tuning data persistence.
- **Voldemort**.



Document-oriented databases

Idea

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

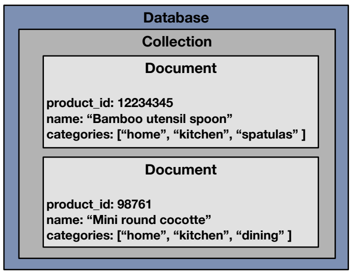


It is possible to search for all products in category *kitchen.*

Document-oriented databases

Existing document-oriented databases

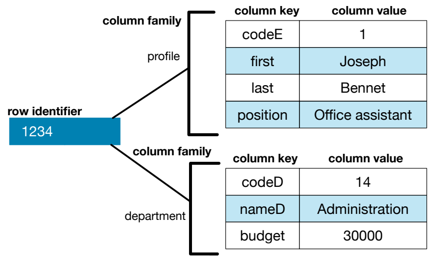
- **MongoDB**, **CouchDB**, **OrientDB**.



Column-oriented databases

Idea

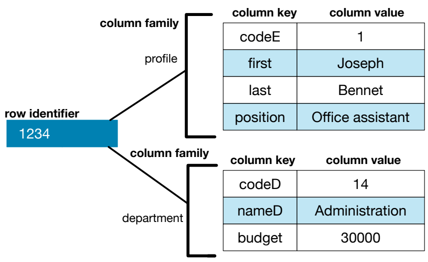
- Similar to document-oriented database but an aggregate can be broken into smaller data units called **columns**.



Column-oriented databases

Idea

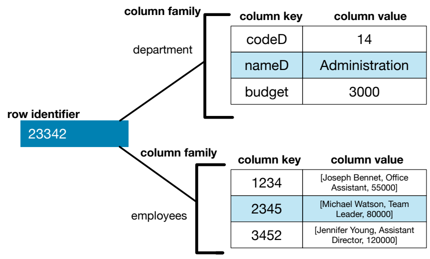
- Columns can be organized into **column families**.
- Columns in the same family are accessed together.



Column-oriented databases

Idea

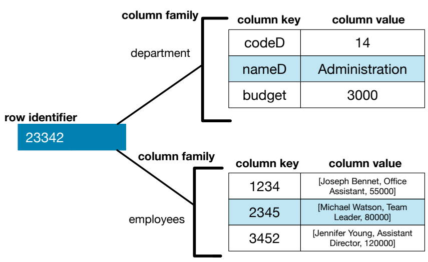
- The value of a column can be an aggregate (**wide column**).



Column-oriented databases

Existing column-oriented databases

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



Graph databases

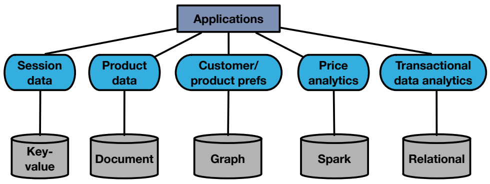
Idea

- 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**.

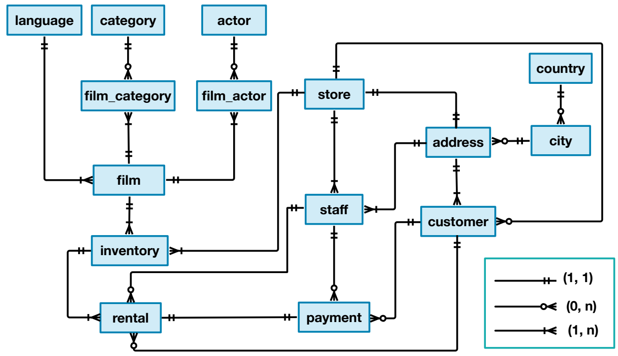
NoSQL databases: conclusions

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