B4M36DS2, BE4M36DS2: **Database Systems 2**

https://cw.fel.cvut.cz/b231/courses/b4m36ds2/

Lecture 4

Basic Principles

Yuliia Prokop
prokoyul@fel.cvut.cz

16. 10. 2022

Author: Martin Svoboda
(martin.svoboda@matfyz.cuni.cz)

Czech Technical University in Prague, Faculty of Electrical Engineering

Lecture Outline

Different aspects of **data distribution**

- **Scaling**
  - Vertical vs. horizontal
- **Distribution** models
  - **Sharding**
  - **Replication**: master-slave vs. peer-to-peer architectures
- **CAP** properties
  - **Consistency**, **availability** and partition tolerance
  - ACID vs. **BASE guarantees**
- **Consistency**
  - Read and write quora

Scalability

Scalability

What is **scalability**?

- = **capability of a system to handle growing amounts of data and/or queries** without losing performance, or its potential to be enlarged in order to accommodate such a growth

Two general approaches

- Vertical scaling
- Horizontal scaling

Vertical Scalability

Vertical scaling (scaling up/down)

- = **adding resources to a <u>single node</u> in a system**
  - E.g. increasing the number of CPUs, extending system memory, using larger disk arrays, …
  - I.e. **larger and more powerful machines** are involved
- Traditional choice
  - In favor of **strong consistency**
  - Easy to implement and deploy
  - No issues caused by data distribution
  - …

Works well in many cases but …

Vertical Scalability: Drawbacks

Performance limits

- **Even the most powerful machine has a limit**
- Moreover, everything works well…
  at least until we start approaching such limits

Higher costs

- The cost of expansion increases exponentially
  - In particular, it is **higher than the sum of costs of equivalent commodity hardware**

Proactive provisioning

- New projects / applications might evolve rapidly
- **Upfront budget is needed** when deploying new machines
- And so flexibility is seriously suppressed

Vertical Scalability: Drawbacks

Vendor lock-in

- There are **only a few manufacturers** of large machines
- Customer is made dependent on a single vendor
  - Their products, services, but also implementation details, proprietary formats, interfaces, support, …
- I.e. it is difficult or impossible to switch to another vendor

Deployment downtime

- Inevitable downtime is often required when scaling up

Horizontal Scalability

Horizontal scaling (scaling out/in)

- = **adding more nodes to a system**
  - I.e. system is distributed across multiple nodes in a cluster
- Choice of many NoSQL systems

Advantages

- **Commodity hardware, cost effective**
- **Flexible** deployment and maintenance
- Often surpasses the vertical scaling
- Often no single point of failure
- …

Horizontal Scalability: Consequences

Significantly **increases complexity**

- Complexity of management, programming model, …

Introduces **new issues and problems**

  - Data distribution
  - Synchronization of nodes
  - Data consistency
  - Recovery from failures
  - …

And there are also plenty of **false assumptions** …

Horizontal Scalability: Fallacies

False assumptions

- Network is **reliable**
- **Latency** is zero
- **Bandwidth** is infinite
- Network is **secure**
- **Topology** does not change
- There is one **administrator**
- Network is **homogeneous**
- **Transport cost** is zero

Source: https://blogs.oracle.com/jag/resource/Fallacies.html

Horizontal Scalability: Conclusion

⇒ a standalone node still might be a better option in certain cases

- E.g. for graph databases
  - Simply because it is difficult to split and distribute graphs
- In other words
  - **It can make sense to run even a NoSQL database system on a single node**
  - No distribution at all is the most preferred / simple scenario

But in general, horizontal scaling really opens new possibilities

Horizontal Scalability: Architecture

What is a cluster?

- = **a collection of mutually interconnected commodity nodes**
- Based on the **shared-nothing architecture**
  - Nodes do not share their CPUs, memory, hard drives, …
  - Each node runs its own operating system instance
  - **Nodes send messages to interact with each other**
- Nodes of a cluster can be heterogeneous
- Data, queries, calculations, requests, workload, …
  this is all **distributed among the nodes** within a cluster

Distribution Models

Distribution Models

Generic techniques of **data distribution**

- **Sharding**
  - Idea: **different data on different nodes**
  - Motivation: increasing volume of data, increasing performance
- **Replication**
  - Idea: **the same data on different nodes**
  - Motivation: increasing performance, increasing fault tolerance

Both the techniques are <u>mutually orthogonal</u>

- I.e. we can use either of them, or combine them both

Distribution model

- = specific way how sharding and replication is implemented

NoSQL systems often offer **automatic sharding and replication**

Sharding

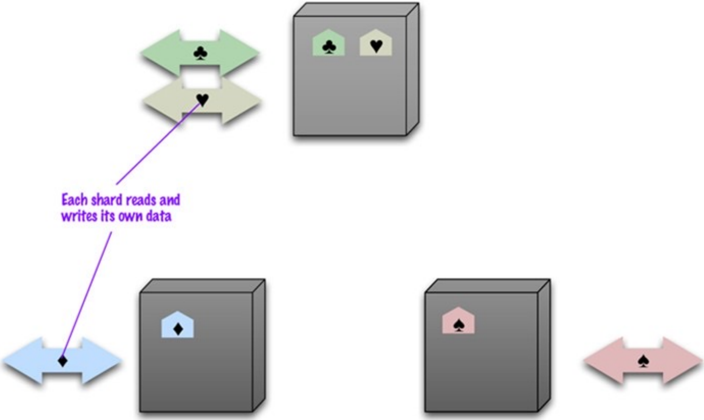
Sharding (horizontal partitioning)

- **Placement of different data on different nodes**
  - What *different data* means? Usually *aggregates*
    - E.g. key-value pairs, documents, …
  - **Related pieces of data that are accessed together should also be kept together**
    - Specifically, operations involving data on multiple shards should be avoided (if possible)

The questions are…

- how to design aggregate structures?
- how to actually distribute these aggregates?

Sharding



Source: Sadalage, Pramod J. - Fowler, Martin: NoSQL Distilled. Pearson Education, Inc., 2013.

Sharding

Objectives

- Achieve **uniform data distribution**
- Achieve **balanced workload** (read and write requests)
- Respect **physical locations**
  - E.g. different data centers for users around the world
- …

Unfortunately, these objectives…

- may **mutually contradict each other**
- may **change in time**

So, how to actually determine shards for aggregates?

Sharding

Sharding strategies

- Based on <u>mapping structures</u>
  - Data is placed on shards in a *random* fashion
    - E.g. round-robin, …
  - Knowledge of the **mapping of individual aggregates to particular shards must then be maintained**
    - Thus usually maintained using a centralized index structures with all the disadvantages
- Based on <u>general rules</u>
  - **Each shard is responsible for storing certain data**
  - Hash partitioning, range partitioning, …

Sharding

Why is sharding difficult?

- Not only we need to be able to determine particular shards during **write requests**
  - I.e. when a new aggregate is about to be inserted
  - So that we can actually make a decision where it should be physically stored
- but also during **read requests**
  - I.e. when existing aggregate/s are about to be retrieved
  - So that we can actually **find and return them efficiently** (or detect they are missing)
  - And all that only based on the **search criteria** provided (e.g. key, id, …) unless all the nodes should be accessed

Sharding

Why is sharding even more **difficult**?

- Structure of the **cluster may be changing**
  - Nodes can be added or removed
- Nodes may have **incomplete / obsolete cluster knowledge**
  - Nodes involved, their responsibilities, sharding rules, …
- Individual **nodes may be failing**
- **Network may be partitioned**
  - Messages may not be delivered even though sent

Replication

Replication

- **Placement of multiple copies of the same data (replicas) on different nodes**

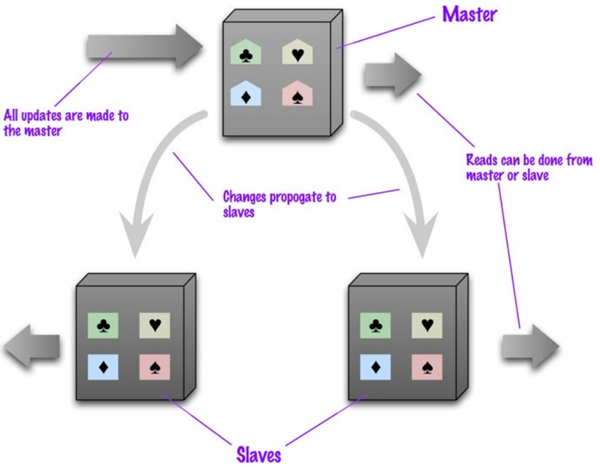
- **Replication factor** = number of such copies

Two approaches

- **Master-slave architecture**
- **Peer-to-peer architecture**

Replication

Master-Slave Architecture



Source: Sadalage, Pramod J. - Fowler, Martin: NoSQL Distilled. Pearson Education, Inc., 2013.

Replication

Master-Slave Architecture

Architecture

- **One node is primary** (master), **all the other secondary** (slave)
- Master node bears all the management responsibility
- All the nodes contain identical data

Read requests can be handled by both the master or slaves

- Suitable for read-intensive applications
  - More read requests to deal with → more slaves to deploy
- When the master fails, read operations can still be handled

Replication

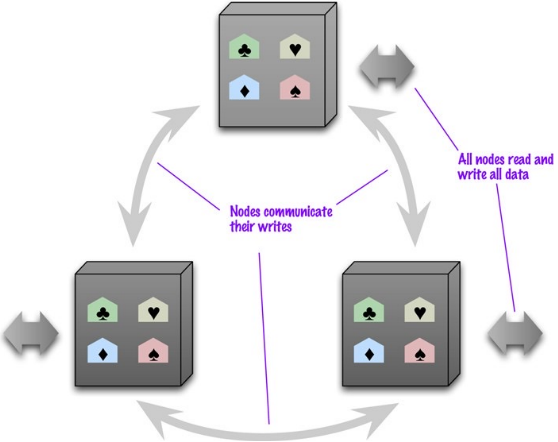
Master-Slave Architecture

Write **requests can only be handled by the master**

- **Newly written replicas are propagated to all the slaves**
- Consistency issue
  - Luckily enough, **at most one write request is handled at a time**
  - But the propagation still takes some time during which obsolete reads might happen
  - Hence certain **synchronization is required to avoid conflicts**
- In case of **master failure**, a new one needs to be appointed
  - **Manually** (user-defined) or **automatically** (cluster-elected)
  - Since the nodes are identical, appointment can be fast
- Master might therefore represent a **bottleneck** (because of the performance or failures)

Replication

Peer-to-Peer Architecture



Source: Sadalage, Pramod J. - Fowler, Martin: NoSQL Distilled. Pearson Education, Inc., 2013.

Replication

Peer-to-Peer Architecture

Architecture

- All the nodes have **equal roles and responsibilities**
- All the nodes contain identical data once again

Both read and write requests can be handled by any node

- No bottleneck, no single point of failure
- Both the operations scale well
  - More requests to deal with → more nodes to deploy
- Consistency issues
  - Unfortunately, **multiple write requests can be initiated independently and being executed at the same time**
  - Hence **synchronization is required to avoid conflicts**

Sharding and Replication

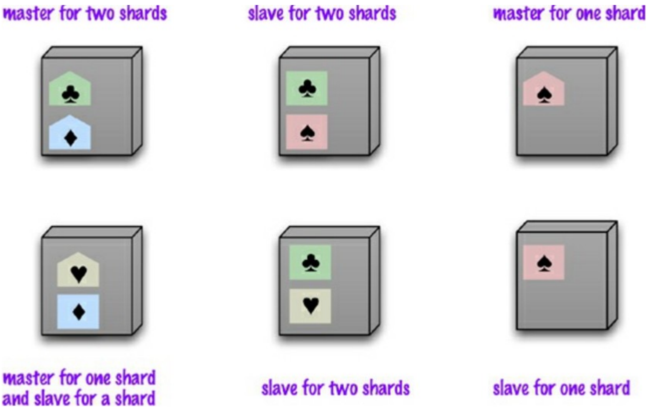
Observations with respect to the **replication**:

- **Does the replication factor really need to correspond to the number of nodes**?
  - No, replication factor of 3 will often be the right choice
  - Consequences
    - Nodes will no longer contain identical data
    - **Replica placement strategy** will be needed
- **Do all the replicas really need to be successfully written** when write requests are handled?
  - No, but consistency issues have to be tackled carefully

Sharding and replication can be combined… but how?

Sharding and Replication

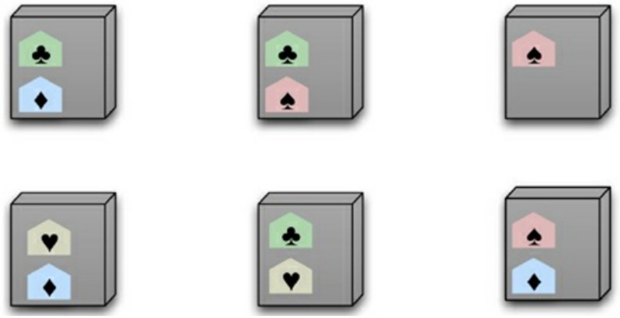
Sharding and Master-Slave Replication



Source: Sadalage, Pramod J. - Fowler, Martin: NoSQL Distilled. Pearson Education, Inc., 2013.

Sharding and Replication

Sharding and Peer-to-Peer Replication



Source: Sadalage, Pramod J. - Fowler, Martin: NoSQL Distilled. Pearson Education, Inc., 2013.

Sharding and Replication

Combinations of sharding and replication

- **Sharding + master-slave replication**
  - Multiple masters, each for different data
  - Roles of the nodes can overlap
    - Each node can be master for some data and/or slave for other
- **Sharding + peer-to-peer replication**
  - Basically placement of anything anywhere
    (although certain rules can still be applied)

Sharding and Replication

Questions to figure out for any distribution model

- Can all the nodes serve both **read and write requests**?
- Which **replica placement strategy** is used?
- How the **mapping of replicas** is maintained?
- What level of **consistency and availability** is provided?
- What extent of **infrastructure knowledge** do the nodes have?
- …

CAP Theorem

CAP Theorem

Assumptions

- Distributed system with **sharding and replication**
- Read and write **operations on a single aggregate** only

CAP properties

- Properties of a distributed system

- Consistency, Availability, and Partition tolerance

CAP theorem

> It is not possible to have a distributed system that would guarantee **consistency**, **availability**, and **partition tolerance** at the same time. Only 2 of these 3 properties can be enforced.

But, what these properties actually mean?

CAP Properties

Consistency

- **Read and write operations must be executed atomically**
  - *A bit more formally…*
    There must exist a total order on all operations such that each operation looks as if it was completed at a single instant,
    i.e. as if all the operations were executed sequentially one by one on a single standalone node
- Practical consequence:
  after a write operation, all readers see the same data
  - Since any node can be used for handling of read requests, **atomicity of write operations means that changes must be propagated to all the replicas**
    - *As we will see later on, other ways for such a strong consistency exist as well*

CAP Properties

Availability

- **If a node is working, it must respond to user requests**
  - *A bit more formally…*
    Every read or write request successfully received by a non-failing node in the system must result in a response, i.e. their execution must not be rejected

Partition tolerance

- **System continues to operate even when two or more sets of nodes get isolated**
  - *A bit more formally…*
    The network is allowed to lose arbitrarily many messages sent from one node to another
- I.e. a connection failure must not shut the whole system down

CAP Theorem Consequences

If **at most two properties** can be guaranteed…

- **CA** = **consistency + availability**
  - Traditional **ACID properties** are easy to achieve
  - Examples: RDBMS, Google BigTable
  - Any single-node system, but even clusters (at least in theory)
    - However, should the network partition happen, all the nodes must be forced to stop accepting user requests
- **CP** = **consistency + partition tolerance**
  - Other examples: distributed locking
- **AP** = **availability + partition tolerance**
  - New concept of **BASE properties**
  - Examples: Apache Cassandra, Apache CouchDB
  - Other examples: web caching, DNS

CAP Theorem Consequences

Partition tolerance is necessary in clusters

- Why?
  - Because <u>it is difficult to detect network failures</u>
- Does it mean that only purely CP and AP systems are possible?
- No…

The real meaning of the CAP theorem:

- *The real-world does not need to be just black and white*
- **Partition tolerance** is a must,
  but we can **trade off consistency versus availability**
  - Just a little bit relaxed consistency can bring a lot of availability
  - Such trade-offs are not only possible,
    but often work very well in practice

ACID Properties

Traditional **ACID** properties

- **Atomicity**
  - Partial execution of transactions is not allowed (all or nothing)
- **Consistency**
  - Transactions bring the database from one consistent (valid) state to another
- **Isolation**
  - Transactions executed in parallel do not see uncommitted effects of each other
- **Durability**
  - Effects of committed transactions must remain durable

BASE Properties

New concept of **BASE** properties

- **Basically Available**
  - The system works basically all the time
  - Partial failures can occur, but there are no total system failures
- **Soft State**
  - The system is in flux (unstable), non-deterministic state
  - Changes occur all the time
- **Eventual Consistency**
  - Sooner or later the system will be in some consistent state

BASE is just a vague term, no formal definition was provided

- **Proposed to illustrate design philosophies at the opposite ends of the consistency-availability spectrum**

ACID and BASE

ACID

- Choose consistency over availability
- Pessimistic approach
- Implemented by traditional **relational databases**

BASE

- Choose availability over consistency
- Optimistic approach
- Common in **NoSQL databases**
- **Allows levels of scalability that cannot be acquired with ACID**

Current trend in NoSQL:
strong consistency → **eventual consistency**

Consistency

Consistency

Consistency in general…

- **Consistency is the lack of contradiction** in the database
- However, it has many facets…
  - For example, we only assume atomic operations always manipulating just a single aggregate,
    but set operations could also be considered etc.

Strong consistency is achievable even in clusters,
but **eventual consistency** might often be sufficient

- One minute obsolete article on a news portal does not matter
- Even when an already unavailable hotel room is booked once again, the situation can still be figured out in the real world
- …

Lecture Conclusion

There is a wide range of options influencing…

- **Scalability** – how well the entire system scales?
- **Availability** – when nodes may refuse to handle user requests?
- **Consistency** – what level of consistency is required?
- **Latency** – how long does it take to handle user requests?
- **Durability** – is the committed data written reliably?
- **Resilience** – can the data be recovered in case of failures?

$\Rightarrow$ it's good to know these properties and choose the right trade-off

Xpath & XQuery