NDBI040: **Modern Database Concepts**

http://www.ksi.mff.cuni.cz/~svoboda/courses/191-NDBI040/

Lecture 6

Basic Principles

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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 single node 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

$\Rightarrow$ 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 mutually orthogonal

- 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

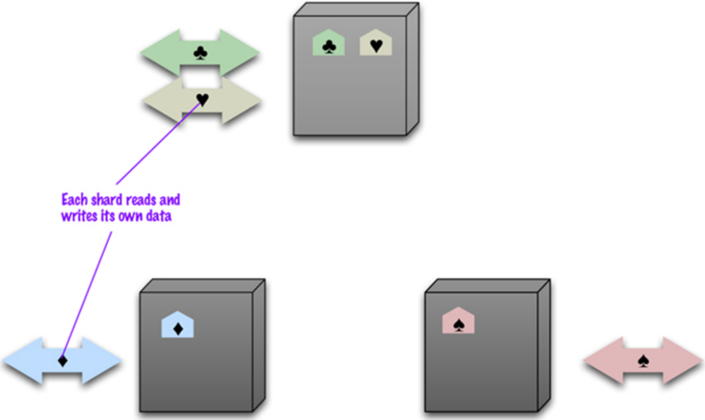
Sharding (horizontal partitioning)

- **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 mapping structures
  - 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 general rules
  - **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

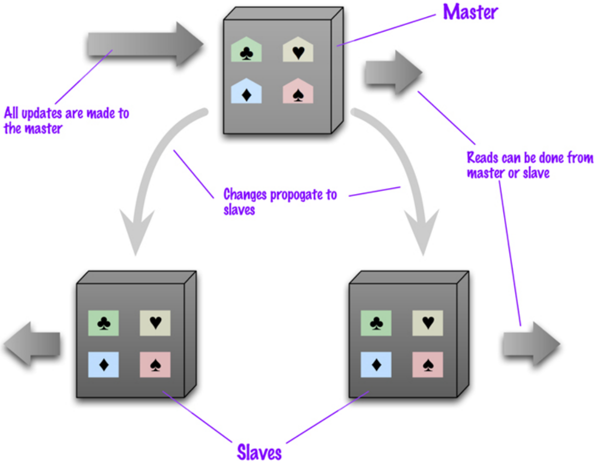
- **Placement of multiple copies of the same data (replicas) on different nodes**
- **Replication factor** = number of such copies

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 $\rightarrow$ more slaves to deploy
- When the master fails, read operations can still be handled

Replication

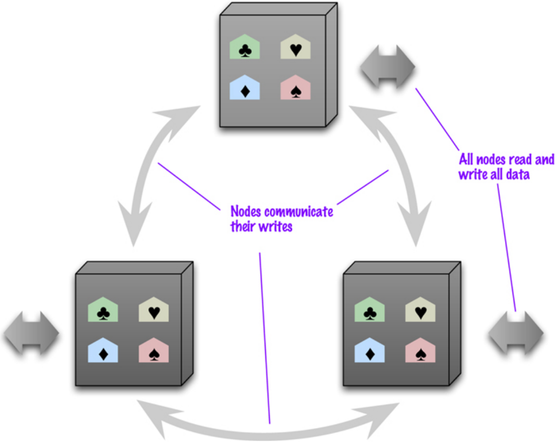
Master-Slave Architecture

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



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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 $\rightarrow$ 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

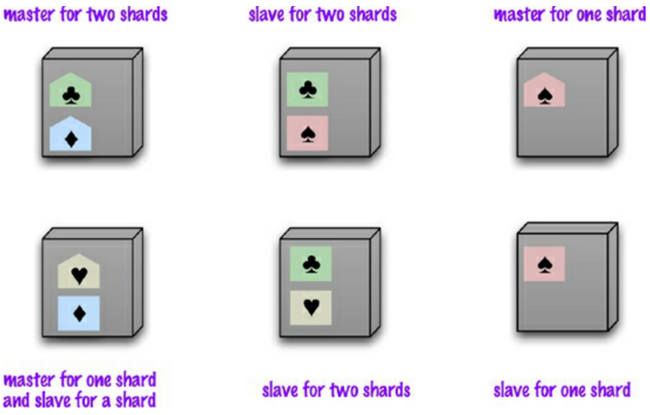
Observations with respect to the **replication**:

- **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



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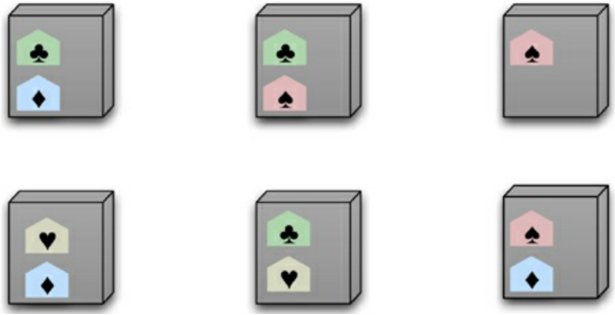
Sharding and Replication

Sharding and Peer-to-Peer Replication



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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 $\rightarrow$ **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
- …

Consistency

Write consistency (update consistency)

- Problem: **write-write** conflict
  - Two or more write requests on the same aggregate are initiated concurrently
- Context: **peer-to-peer architecture only**
- Issue: lost update
- Solution:
  - **Pessimistic** strategies
    - **Preventing conflicts from occurring**
    - Write locks, …
  - **Optimistic** strategies
    - **Conflicts may occur, but are detected and resolved later on**
    - Version stamps, vector clocks, …

Consistency

Read consistency (replication consistency)

- Problem: **read-write** conflict
  - Write and read requests on the same aggregate are initiated concurrently
- Context: **both master-slave and peer-to-peer architectures**
- Issue: inconsistent read
- When not treated, **inconsistency window** will exist
  - **Propagation of changes to all the replicas takes some time**
  - Until this process is finished, inconsistent reads may happen
  - Even the initiator of the write request may read wrong data!
    - Session consistency / read-your-writes / sticky session

Strong Consistency

How many nodes need to be involved to get strong consistency?

- **Write quorum**: $W > N/2$
  - Idea: **only one write request can get the majority**
  - W = number of nodes successfully participating in the write
  - N = number of nodes involved in replication (replication factor)
- **Read quorum**: $R > N - W$
  - Idea: **concurrent write requests cannot happen**
  - R = number of nodes participating in the read
  - Should the retrieved replicas be mutually different, **the newest version is resolved** and then returned

When a quorum is not attained $\rightarrow$ the request cannot be handled

Strong Consistency

Examples

Examples for replication factor $N = 3$

- Write quorum $W = 3$ and read quorum $R = 1$
  - All the replicas are always updated
  - $\Rightarrow$ we can read any one of them
- **Write quorum $W = 2$ and read quorum $R = 2$**
  - *Typical configuration, reasonable trade-off*

Consequence

- **Quora can be configured to balance read and write workload**
  - The higher the write quorum is required,
    the lower the read quorum can then be required

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