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Advanced Database Systems

Key-value stores

Strategic project of TBU in Zlín, reg. no. CZ.02.2.69/0.0/0.0/16_015/0002204

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Content

- Principles of key-value databases
- Main techniques
  - Data distribution
  - Data Consistency
  - Availability of data
- Applicability and use
  - Basic and advanced functions

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Basic principles

- A key-value store we can imagine as:
  - Associative array (map)
  - A simple hash table storing arbitrary values according to a unique key
  - That is the principle is **key-value mapping**
- Key - unique data identifier - access to data via the primary key
- Values - stored data - can be divided by type into separate storage (buckets)
  - Repositories can be understood as **namespaces** of keys
- The repository does not examine the contents of the values (any type) - the client application does

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Basic principles

- Advantages of this type of storage:
  - Simple structure
  - Simple operations
  - Allows data to be distributed efficiently (sharding and replication)
  - It works very fast
  - It is used by both **write and reads-intensive** applications (e.g. write every millisecond)

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Basic principles

Basic operations:

- **PUT** – entering / updating the key value
- **GET** - getting the key value
- **DELETE** - delete key and value from storage

- Key - identifier of stored data objects - key role for work
  - Native - The natural primary key
  - Artificial (derived, created) primary key
    - E.g. hash function and timestamp (generated by the system)

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Basic principles

Unsuitable use:

- Relationships between data
  - Relationships between different data sets
- Data queries
  - Search based on data from the value part
- Operations by sets
  - Operations that are limited to one key at a time
- Multi-operational transaction
  - Storing multiple keys

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Basic principles

Typical use:

- Web Application Caching
- Saving information from the so-called session
- Management of shopping cart items (e-shop)
- User Profiles

Comparison with RDBS:

  - A table with two columns:
  - ID column (primary key)
  - DATA column to store the value

A database instance	Riak cluster
table	bucket (namespace)
row	key-value
row id	key

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Basic principles - example

E-shop: storage of user information

- User Profiles
- Web sessions
- Contents of shopping carts

1. Storing all data in one namespace
   - Use: if the application will need all the information at once

namespace User

Key	UserID
Value:	UserProfile Sessions ShoppingList .item1 .item2

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Basic principles - example

2. Storing data in multiple namespaces
   - Use: when part of the application only needs some information
   - All data will require multiple accesses (3)

namespace Sessions

Key	UserID
Value:	Sessions

namespace ShoppingList

Key	UserID
Value:	ShoppingList .item1 .item2

namespace UserProfiles

Key	UserID
Value:	UserProfile

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Representatives

- First - Amazon Dynamo (2007)
- Each representative has a slightly different purpose
- Various techniques were used to complete the tasks
- Other functions may vary - advanced system-specific functions
- The most popular representatives:
  - Persistent distributed systems (Riak, Redis, Infinispan...)
  - Libraries for creating embedded disk storage (BerkeleyDB, LevelDB, RocksDB, MapDB...)
  - Memory caches (Memcached, Ehcache, Hazelcast...)

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DB-Engines Ranking. (2019). Retrieved from https://db-engines.com/en/ranking

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Representatives

redis
MEMCACHED
hazelcast
AEROSPIKE
EHCACHE
riak
ORACLE NOSQL DATABASE
levelDB
ORACLE BERKELEY DB 12c
Infinispan
RocksDB
amazon DynamoDB
MapDB
Project Voldemort

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Selected challenges and solutions

Challenge	Technical solution
Data distribution (sharding)	Consistent hashing
Read scalability & reliability	Data replication
Node detection connection/abandonment/failure	Gossip protocol (no centralized registry of node membership and activity)
Managing Replicas	Version stamps, vector clock
Competition, transactions	Two Phase Confirmation Protocol, MVCC

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Data distribution

- Data can be distributed among multiple nodes of a distributed system
- On which node the key-value pair will be stored determines:
  - Direct key
  - Hash function - hash(key)

Standard hashing - based on the modulo operation

– uniform distribution of values under the condition of a constant number of nodes

node number = hash(key) **mod** (number of nodes)

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Consistent hashing

- It is used for **automatic data sharing** between nodes (automatic sharding) in case of a **change in the number of nodes**
- It is based on standard hashing

It applies: **each node is responsible for a continuous interval of hash keys**

- Each node in the system is assigned a hash key
- We use the same hash function for data and nodes

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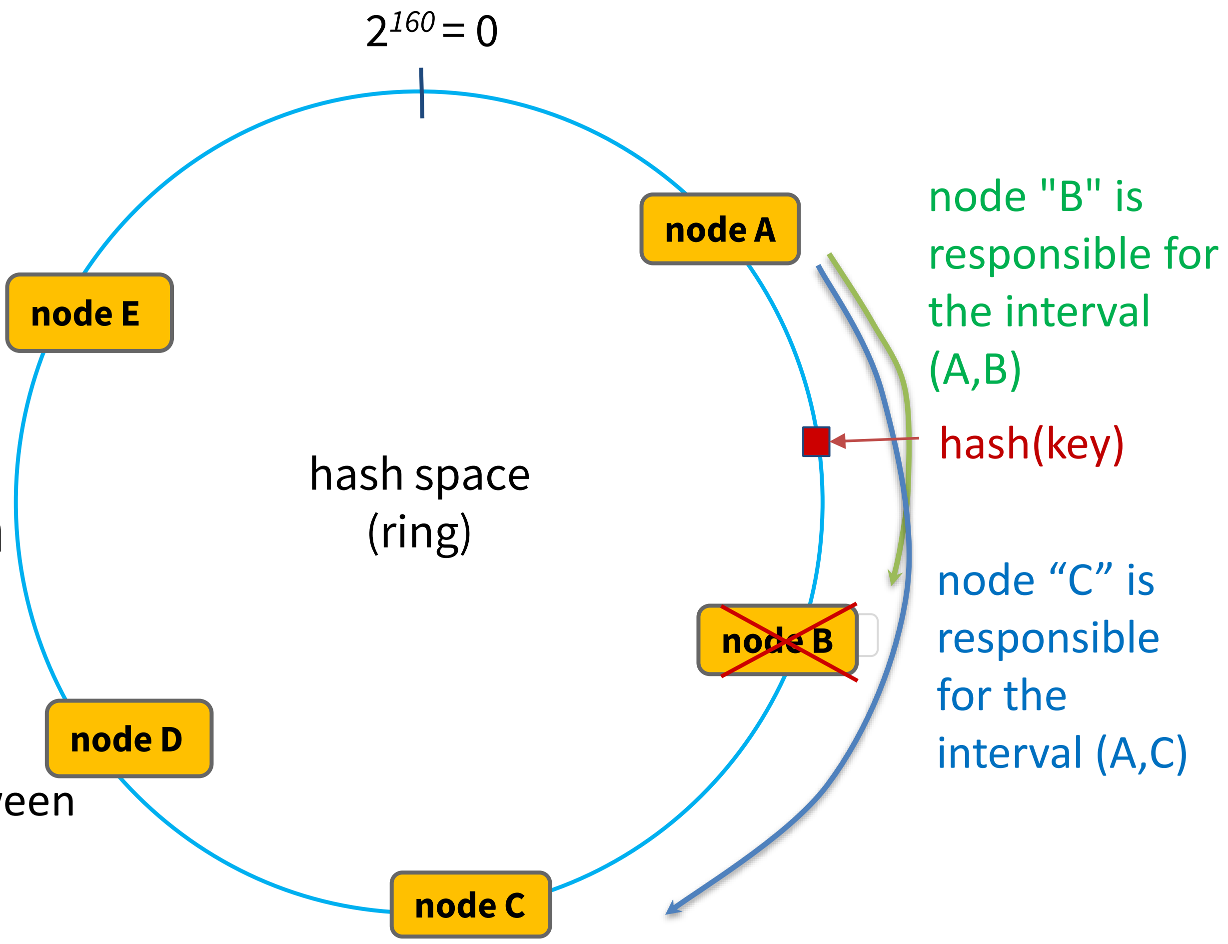
Consistent hashing

- Each node is assigned a hash key from the same domain, e.g.

  hash: Keys->$[0,2^{160}-1]$

- Each subsequent node in a clockwise direction is "responsible" for all keys from the interval of the previous one and its own key

- the new node is assigned a hash (key) – 1 key interval between two nodes is split – the data is moved to the new node
- I only need to move the data between nodes A and B



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Consistent Hashing - Node detection

- Information about the change in the number of nodes is "spread" by so-called **gossip protocols**
- Principle:
  - At regular time intervals, each node randomly selects one of its known nodes, contacts it and gives it "news" (up-to-date information about the nodes in the system)

- Disadvantages of consistent hashing:
  - Uneven distribution of data between cooperating nodes
  - The concept of virtual nodes is used for load balancing

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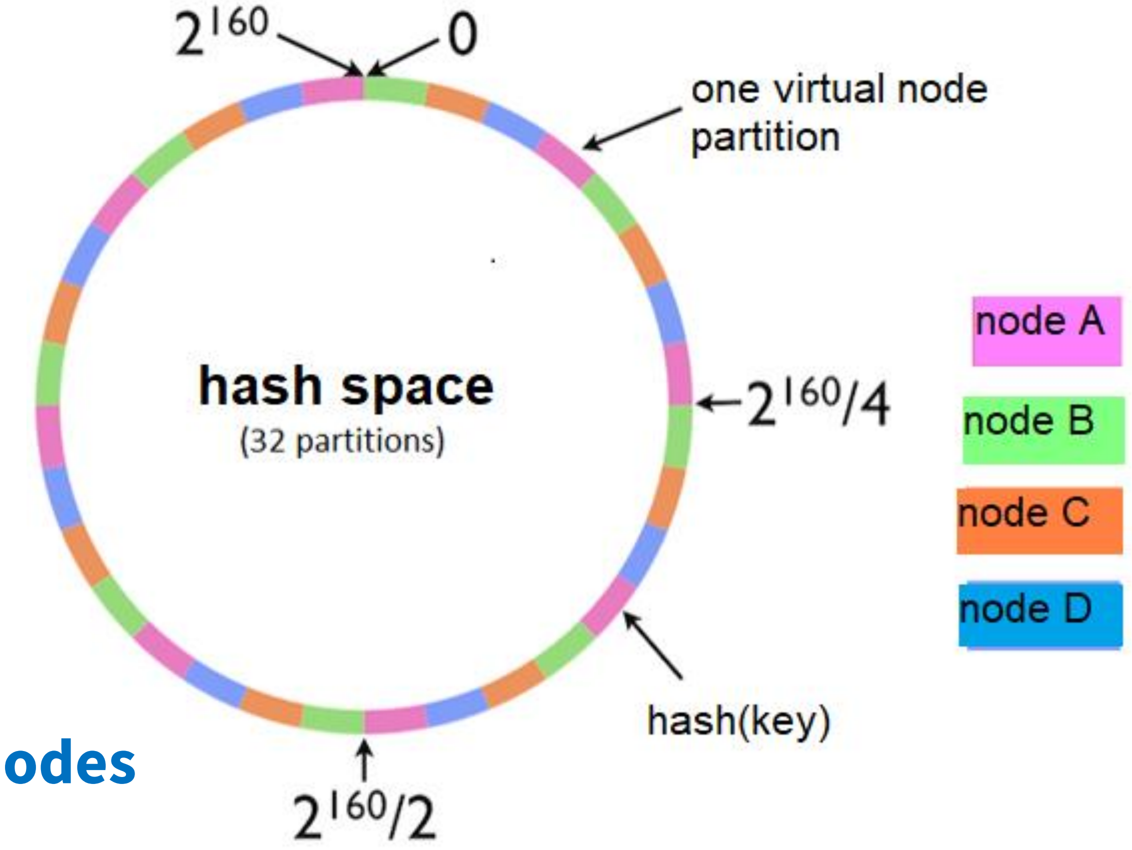
Consistent hashing

Virtual nodes

- The domain of the hashing function is divided into a *fixed number of equally sized intervals* – virtual nodes (partitions) – Q
- These are gradually assigned to physical nodes (servers) – S
- Q/S – partitions per 1 node
- It is assumed: Q >> S



Balanced distribution of data to physical nodes

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Consistent Hashing - Replication

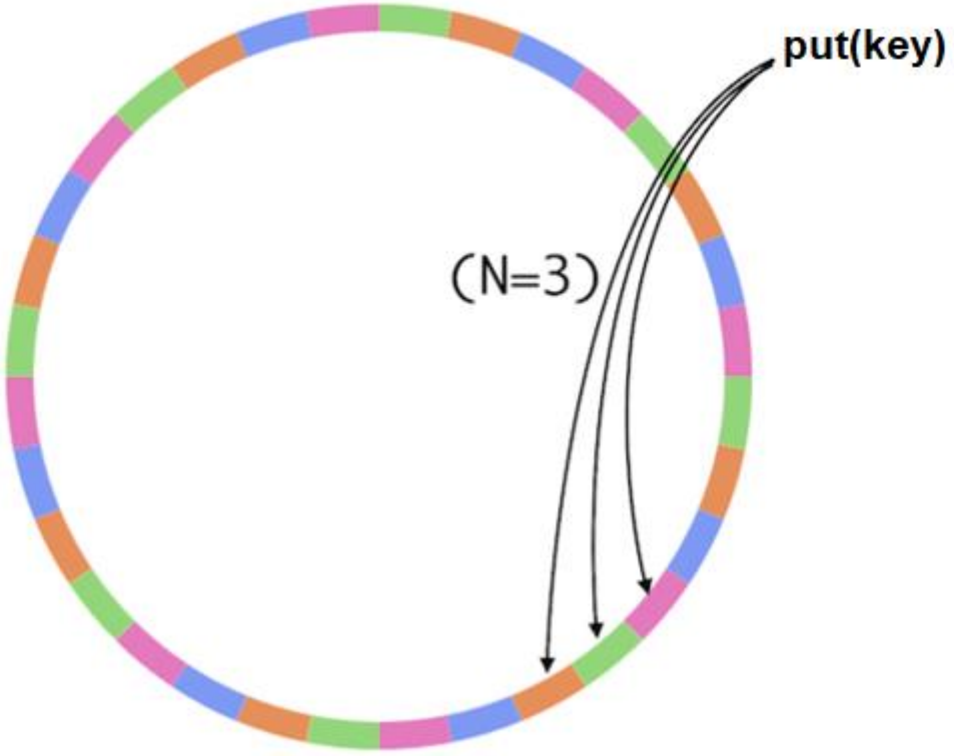
Data replication – ensures reliability

Performance boost - read/write operations

Increased availability - tolerance of the system to outages

Each object stored on N (replication factor) consecutive nodes

Both master-slave and peer-to-peer replication are possible



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Consistency and availability

Manage replicas

- Using the concept of quora
  - N = replication factor (each pair (key, value) is replicated on 3 nodes by default, i.e. N = 3)
  - W = data must be written to at least W nodes
  - R = data must be found on at least R nodes

$$\boxed{W > N/2}$$

$$\boxed{R + W > N}$$

- R/W values:
  - Can be set by the user for each individual operation
  - all / one / quorum / default / integer value

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Version stamps

- Mechanisms for: avoiding / detecting conflicts
  - On one data record
  - Write-write conflicts
- Version stamp in general:
  - A helper attribute stored with a key that changes each time the value for that key changes
- Basic use (also in centralized system):
  - The client reads the stamp along with the record
  - When the record is updated later, the stamp is sent back along with the new value and checked
  - If the stamp is different from the actual stamp => conflict

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Version stamps

Stamps can be created in several ways:

- Counter – changes after each record update
  - Advantages - it is clear which version is newer
  - Disadvantages - Duplications must be avoided
- GUID(globally unique identifier) – generated large unique random number
  - Advantages - anyone (client) can generate
  - Disadvantages - you can't check up-to-date
- Hash from the data
  - Advantages - anyone can generate it, it is deterministic
  - Disadvantages - you can't check up-to-date

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Version stamps

Time stamps

- Advantages - Timeliness is clear
- Disadvantages - clock synchronization required, sufficient granularity required

Combination:

- Counter + Hash:
  - Counter - comparison of actuality
  - Hash - if two updates appear simultaneously on two servers (with the same counter), the hash identifies the conflict

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Version stamps on multiple nodes

- Master-slave replication: one "master", everything works fine
- Peer-to-peer replication:
  - Any node can handle the update (multiple masters)
  - When contacted for an update, the node must respond to the client immediately after saving the new value
    - It cannot wait for all partners to confirm the update (two-phase confirmation protocol)
- Goal: A distributed algorithm that would
  - Reliably detect write-write conflict
  - Algorithm struck a balance between doing the write-up and avoiding conflicts
    - Allows user settings

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Version stamps on multiple nodes

Possible solutions:

1. Using counters - remembering the history of counters
    - If the counters on 2 nodes do not match and one of the counters is not in the history of the other=>conflict
    - Space intensive (not used in NoSQL databases)

2. Time stamps
    - Clock synchronization problems
    - A write-write conflict is not detectable for multiple masters

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Version stamps on multiple nodes

3. Vector stamps

- Algorithms for generating partial ordering of events in a distributed system and detecting "conflicts"
- Each node has its own counter
    - For each data item
- A node's counter is incremented when a node updates the value for a given key
- Each node maintains information about the counter values of all nodes
- Nodes exchange information about the state of counters and values, in order to find out
    - Which value is new
    - Whether it is a conflict

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Example: Vector stamps

We have three nodes A, B, C

- At the beginning, the nodes share the same value - the counters on the nodes [A: 1, B: 1, C: 1]
- Node C updates its value - the value of the counter increases[A: 1, B: 1, C: 2]

A (key, value1) [A:1, B:1, C:1]

B (key, value1) [A:1, B:1, C:1]

C (key, value2) [A:1, B:1, **C:2**]

If synchronization occurs
-
The C:2 value is propagated to all nodes

A (key, value2) [A:1, B:1, C:2]

B (key, value2) [A:1, B:1, C:2]

C (key, value2) [A:1, B:1, C:2]

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Example: Vector stamps

- Node A updates its value to value3 and at the same time node B updates its value to value4 – values of vectors [A: 2, B: 1, C: 2] and [A: 1, B: 2, C: 2] are incomparable – write conflict

A (key, value3)
[**A:2**, B:1, C:2]

B (key, value4)
[A:1, **B:2**, C:2]

C (key, value2)
[A:1, B:1, C:2]

A conflict occurs
during
synchronization
-
Which value is
newer?
A or B?

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Vector stamps - conflict resolution

Specific techniques - differ in the way of communication

The most frequently used techniques (and their variants):

- Vector clock (used by dynamo, etc.)
- Lamport's Time Stamps (1987)
  - Counters updated whenever nodes communicate
  - The last value can only be retrieved during a read
- Matrix Clock
- …

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Conflict solving

There are three general ways to resolve write conflicts

- Differences between copies of distributed data need to be reconciled

1. Read correction - (Optimistic Strategy)
   - A correction is made when a read detects a mismatch
   - The read operation is slow
2. Write correction
   - The correction takes place during the write operation - deceleration
3. Asynchronous correction
   - Correction is performed independently of reading and writing - separate operations

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Gossip protocols

It is a set of distributed protocols for:

- Each node periodically sends its current information
  - To a randomly selected partner
- Dissemination of information about the current status
  - Input / output / failed nodes
  - Asynchronous conflict reconciliation (anti-entropy)
  - Other properties

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Transactions

- Some key-value stores allow full transactional processing
- The most used techniques:
  - Two-phase commit protocol (2PC – two-phase commit)
  - Multi-version concurrency control (MVCC -Multi-version concurrency control)
  - Transaction isolation levels

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Questions?

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