Data Management
10 NoSQL Systems

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Last update: May 29, 2021
Announcements/Org

- **#1 Video Recording**
  - Link in TeachCenter & TUbe (lectures will be public)
  - [https://tugraz.webex.com/meet/m.boehm](https://tugraz.webex.com/meet/m.boehm)
  - Corona traffic light RED → May 17: ORANGE (but tests required)

- **#2 Reminder Communication**
  - **Newsgroup:** news://news.tugraz.at/tu-graz.lv.dbase
  - **Office hours:** Mo 12.30-1.30pm ([https://tugraz.webex.com/meet/m.boehm](https://tugraz.webex.com/meet/m.boehm))

- **#3 Exercises/Exams**
  - **Grading:** Exercise 1 - done, Exercise 2 – this/next week
  - **Submission:** Exercise 3: last chance Jun 1, Exercise 4: published May 29
  - **Exams:** Jun 30 5.30pm (i11, i12, i13), Jul 5 3.30pm (i13), 6.30 (i13)

- **#4 Course Evaluation**
  - Please participate; open period: June 1 – July 15
SQL vs NoSQL Motivation

- **#1 Data Models/Schema**
  - **Non-relational**: key-value, graph, doc, time series (logs, social media, documents/media, sensors)
  - Impedance mismatch / complexity
  - Pay-as-you-go/schema-free (flexible/implicit)

- **#2 Scalability**
  - Scale-up vs simple scale-out
  - Horizontal partitioning (sharding) and scaling
  - Commodity hardware, network, disks ($)

- **NoSQL Evolution**
  - Late 2000s: Non-relational, distributed, open source DBMSs
  - Early 2010s: NewSQL: modern, distributed, relational DBMSs
  - Not Only SQL: combination with relational techniques
    - RDBMS and specialized systems (consistency/data models)

Agenda

- Consistency and Data Models
- Key-Value Stores
- Document Stores
- Graph Processing
- Time Series Databases
- Exercise 4: Large-Scale Data Analysis

[Wolfram Wingerath, Felix Gessert, Norbert Ritter: NoSQL & Real-Time Data Management in Research & Practice. BTW 2019]

Lack of standards and imprecise classification

[http://geek-and-poke.com/]
Consistency and Data Models
Recap: ACID Properties

- **Atomicity**
  - A transaction is executed atomically *(completely or not at all)*
  - If the transaction fails/aborts no changes are made to the database *(UNDO)*

- **Consistency**
  - A successful transaction ensures that all *consistency constraints are met*
    (referential integrity, semantic/domain constraints)

- **Isolation**
  - Concurrent transactions are executed in isolation of each other
  - Appearance of serial transaction execution

- **Durability**
  - *Guaranteed persistence* of all changes made by a successful transaction
  - In case of system failures, the database is recoverable *(REDO)*
Two-Phase Commit (2PC) Protocol

- **Distributed TX Processing**
  - N nodes with logically related but physically distributed data (e.g., vertical data partitioning)
  - Distributed TX processing to ensure consistent view (atomicity/durability)

- **Two-Phase Commit** (via 2N msgs)
  - **Phase 1 PREPARE:** check for successful completion, logging
  - **Phase 2 COMMIT:** release locks, and other cleanups
  - **Problem:** Blocking protocol

- **Excursus: Wedding Analogy**
  - Coordinator: marriage registrar
  - **Phase 1:** Ask for willingness
  - **Phase 2:** If all willing, declare marriage
CAP Theorem

- **Consistency**
  - Visibility of updates to distributed data (atomic or linearizable consistency)
  - Different from ACIDs consistency in terms of integrity constraints

- **Availability**
  - Responsiveness of a services (clients reach available service, read/write)

- **Partition Tolerance**
  - Tolerance of temporarily unreachable network partitions
  - System characteristics (e.g., latency) maintained

**CAP Theorem**

"You can have AT MOST TWO of these properties for a networked shared-data systems."

[Eric A. Brewer: Towards robust distributed systems (abstract). PODC 2000]

[Seth Gilbert, Nancy A. Lynch: Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services. SIGACT News 2002]
CAP Theorem, cont.

- **CA**: Consistency & Availability (ACID single node)
  - Network partitions cannot be tolerated
  - Visibility of updates (consistency) in conflict with availability → no distributed systems

- **CP**: Consistency & Partition Tolerance (ACID distributed)
  - Availability cannot be guaranteed
  - On connection failure, unavailable
    (wait for overall system to become consistent)

- **AP**: Availability & Partition Tolerance (BASE)
  - Consistency cannot be guaranteed, use of optimistic strategies
  - Simple to implement, main concern: availability to ensure revenue ($$$)

→ BASE consistency model
BASE Properties

- **Basically Available**
  - *Major focus on availability*, potentially with outdated data
  - No guarantee on global data consistency across entire system

- **Soft State**
  - Even without explicit state updates, the *data might change* due to asynchronous propagation of updates and nodes that become available

- **Eventual Consistency**
  - Updates eventually propagated, system would reach consistent state if no further updates, and network partitions fixed
  - No temporal guarantees on changes are propagated
Eventual Consistency

**Basic Concept**
- Changes made to a copy eventually migrate to all
- If update activity stops, replicas will converge to a logically equivalent state
- **Metric:** time to reach consistency (probabilistic bounded staleness)

**#1 Monotonic Read Consistency**
- After reading data object A, the client never reads an older version

**#2 Monotonic Write Consistency**
- After writing data object A, it will never be replaced with an older version

**#3 Read Your Own Writes / Session Consistency**
- After writing data object A, a client never reads an older version

**#4 Causal Consistency**
- If client 1 communicated to client 2 that data object A has been updated, subsequent reads on client 2 return the new value

---

Consistency and Data Models

Amazon SimpleDB | 500ms
Cassandra | 200ms
Amazon S3 | 12s

Key-Value Stores
Motivation and Terminology

**Motivation**
- **Basic key-value mapping via simple API** (more complex data models can be mapped to key-value representations)
- **Reliability at massive scale on commodity HW** (cloud computing)

**System Architecture**
- **Key**-value maps, where values can be of a variety of data types
- APIs for **CRUD** operations (create, read, update, delete)
- Scalability via sharding (horizontal partitioning)

**Example Systems**
- **Dynamo** (2007, AP) → **Amazon DynamoDB** (2012)
- **Redis** (2009, CP/AP)

[Giuseppe DeCandia et al: Dynamo: amazon's highly available **key-value store.** SOSP 2007]
Example Systems

- **Redis Data Types**
  - Redis is not a plain KV-store, but “data structure server” with persistent log *(appendfsync no/everysec/always)*
  - **Key**: ASCII string (max 512MB, common key schemes: comment:1234:reply.to)
  - **Values**: strings, lists, sets, sorted sets, hashes (map of string-string), etc

- **Redis APIs**
  - **SET/GET/DEL**: insert a key-value pair, lookup value by key, or delete by key
  - **MSET/MGET**: insert or lookup multiple keys at once
  - **INCRBY/DECBY**: increment/decrement counters
  - Others: EXISTS, LPUSH, LPOP, LRANGE, LTRIM, LLEN, etc

- **Other systems**
  - Classic KV stores (AP): Riak, Aerospike, Voldemort, LevelDB, RocksDB, FoundationDB, Memcached
  - Wide-column stores: Google BigTable (CP), Apache HBase (CP), Apache Cassandra (AP)
Log-structured Merge Trees

- **LSM Overview**
  - Many KV-stores rely on LSM-trees as their storage engine (e.g., BigTable, DynamoDB, LevelDB, Riak, RocksDB, Cassandra, HBase)
  - **Approach:** Buffers writes in memory, flushes data as sorted runs to storage, merges runs into larger runs of next level (compaction)

- **System Architecture**
  - Writes in C0
  - Reads against C0 and C1 (w/ buffer for C1)
  - Compaction (rolling merge): sort, merge, including deduplication

Log-structured Merge Trees, cont.

- **LSM Tiering**
  - Keep up to T-1 runs per level L
  - Merge all runs of $L_i$ into 1 run of $L_{i+1}$
    - $L_1$
    - $L_2$
    - $L_3$

- **LSM Leveling**
  - Keep 1 run per level L
  - Merge run of $L_i$ with $L_{i+1}$
    - $L_1$
    - $L_2$
    - $L_3$
Document Stores
Recap: JSON (JavaScript Object Notation)

- **JSON Data Model**
  - Data exchange format for **semi-structured data**
  - **Not as verbose as XML** (especially for arrays)
  - Popular format (e.g., Twitter)

```
{“students”:[
    {“id”: 1, “courses”:[
      {“id”:“INF.01017UF”, “name”:“DM”},
      {“id”:“706.550”, “name”:“AMLS”}]
    },
    {“id”: 5, “courses”:[
      {“id”:“706.520”, “name”:“DIA”}]
    }
  ]}
```

- **Query Languages**
  - **Most common: libraries** for tree traversal and data extraction
  - **JSONig**: XQuery-like query language
  - **JSONPath**: XPath-like query language

**JSONiq Example:**
```
declare option jsoniq-version “…”;
for $x in collection(“students”)
  where $x.id lt 10
  let $c := count($x.courses)
return {“sid”:$x.id, “count”:$c}
```

Motivation and Terminology

**Motivation**
- Application-oriented management of **structured, semi-structured, and unstructured information** (pay-as-you-go, schema evolution)
- Scalability via parallelization on commodity HW (cloud computing)

**System Architecture**
- Collections of *(key, document)*
- Scalability via sharding (horizontal partitioning)
- Custom SQL-like or functional query languages

**Example Systems**
- **MongoDB** (C++, 2007, CP) → RethinkDB, Espresso, Amazon DocumentDB (Jan 2019)
- **CouchDB** (Erlang, 2005, AP) → CouchBase
Example MongoDB

- **Creating a Collection**

```python
import pymongo as m
conn = m.MongoClient("mongodb://localhost:123/")
db = conn["dbs19"]  # database dbs19
cust = db["customers"]  # collection customers
```

- **Inserting into a Collection**

```python
mdict = {
    "name": "Jane Smith",
    "address": "Inffeldgasse 13, Graz"
}
```

```python
id = cust.insert_one(mdict).inserted_id  
# ids = cust.insert_many(mlist).inserted_ids
```

- **Querying a Collection**

```python
print(cust.find_one({"_id": id}))
```

```python
ret = cust.find({"name": "Jane Smith"})
for x in ret:
    print(x)
```
BREAK (and Test Yourself)

- **NoSQL Systems** (10/100 points)
  - Describe the concept and system architecture of a **key-value store**, including techniques for achieving **high write throughput**, and **scale-out** in distributed environments. [...]

- **Solution**
  - Key-value store system architecture [4]
  - Write-throughput via **LSM** (log-structured merge tree) [3]
  - **Horizontal partitioning** [3] (see 07 Physical Design)

\[
\begin{align*}
R1 &= \sigma_{k<=5}(R) \\
R2 &= \sigma_{k>5 \land k<=10}(R) \\
R3 &= \sigma_{k>10 \land k<=15}(R) \\
R &= (R1 \cup R2) \cup R3
\end{align*}
\]
Graph Processing
Motivation and Terminology

- **Ubiquitous Graphs**
  - **Domains:** social networks, open/linked data, knowledge bases, bioinformatics
  - **Applications:** influencer analysis, ranking, topology analysis

- **Terminology**
  - **Graph** \( G = (V, E) \) of vertices \( V \) (set of nodes) and edges \( E \) (set of links between nodes)
  - **Different types of graphs**

**Graph Processing**

- Undirected Graph
- Directed Graph
- Multi Graph
- Labeled Graph
- Data/Property Graph

- Gene interacts
  - \( k_1 = v_1 \)
  - \( k_2 = v_2 \)
- k2=v3
Terminology and Graph Characteristics

- **Terminology, cont.**
  - **Path**: Sequence of edges and vertices (**walk**: allows repeated edges/vertices)
  - **Cycle**: Closed walk, i.e., a walk that starts and ends at the same vertex
  - **Clique**: Subgraph of vertices where every two distinct vertices are adjacent

- **Metrics**
  - **Degree** (in/out-degree): number of incoming/outgoing edges of that vertex
  - **Diameter**: Maximum distance of pairs of vertices (longest shortest-path)

- **Power Law Distribution**
  - Degree of most real graphs follows a power law distribution

![Graph Processing diagram](image)
Vertex-Centric Processing

- **Google Pregel**
  - Name: Seven Bridges of Koenigsberg (Euler 1736)
  - “Think-like-a-vertex” computation model
  - Iterative processing in super steps, comm.: message passing

- **Programming Model**
  - Represent graph as collection of vertices w/ edge (adjacency) lists
  - Implement algorithms via Vertex API
  - Terminate if all vertices halted / no more msgs

```java
class Vertex {
    public String getID();
    public long superstep();
    public VertexValue getValue();
    public void compute(Iterator<Message> msgs);
    public void sendMessageTo(String v, Message msg);
    public void voteToHalt();
}
```

[Grzegorz Malewicz et al: Pregel: a system for large-scale graph processing. SIGMOD 2010 SIGMOD 2020 Test of Time Award]
**Vertex-Centric Processing, cont.**

- **Example 1: Connected Components**
  - Determine connected components of a graph (subgraphs of connected nodes)
  - Propagate max(current, msgs) if != current to neighbors, terminate if no msgs

![Graph Processing Diagram](Image)

- **Example 2: Page Rank**
  - Ranking of webpages by importance / impact
  - **#1**: Initialize vertices to 1/numVertices()
  - **#2**: In each super step
    - Compute current vertex value:
      \[\text{value} = 0.15/\text{numVertices()} + 0.85 \times \text{sum(msg)}\]
    - Send to all neighbors:
      \[\text{value/numOutgoingEdges()}\]

[Credit: https://en.wikipedia.org/wiki/PageRank]
Graph-Centric Processing

- **Motivation**
  - Exploit graph structure for algorithm-specific optimizations (number of network messages, scheduling overhead for super steps)
  - **Large diameter / average vertex degree**

- **Programming Model**
  - **Partition graph into subgraphs** (block/graph)
  - Implement algorithm directly against subgraphs (internal and boundary nodes)
  - Exchange messages in super steps only between boundary nodes \(\rightarrow\) **faster convergence**

[Da Yan, James Cheng, Yi Lu, Wilfred Ng: Blogel: A Block-Centric Framework for Distributed Computation on Real-World Graphs. **PVLDB 2014**]

[Yuanyuan Tian, Andrey Balmin, Severin Andreas Corsten, Shirish Tatikonda, John McPherson: From "Think Like a Vertex" to "Think Like a Graph". **PVLDB 2013**]
Resource Description Framework (RDF)

- **RDF Data**
  - Data and meta data description via triples
  - **Triple**: (subject, predicate, object)
  - Triple components can be URIs or literals
  - Formats: e.g., RDF/XML, RDF/JSON, Turtle
  - RDF graph is a directed, labeled multigraph

- **Querying RDF Data**
  - **SPARQL** (SPARQL Protocol And RDF Query Language)
  - Subgraph matching

```sql
SELECT ?person
WHERE {
  ?person rdf:type uri3:Player ;
  uri4:worksFor uri1:”Bayern Munich” .
}
```

- **Selected Example Systems**
  - Amazon Neptune
  - AllegroGraph
  - Sparksee
  - Jena
  - Apache Marmotta
### Example Systems

- **Understanding Use in Practice**
  - Types of graphs user have
  - Graph computations run
  - Types of graph systems used

[Siddhartha Sahu, Amine Mhedhbi, Semih Salihoglu, Jimmy Lin, M. Tamer Öztu: The Ubiquity of Large Graphs and Surprising Challenges of Graph Processing. *PVLDB 2017*]

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<th>Technology</th>
<th>Software</th>
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- **Summary of State of the Art Runtime Techniques**

[Da Yan, Yingyi Bu, Yuanyuan Tian, Amol Deshpande, James Cheng: Big Graph Analytics Systems. *SIGMOD 2016*]
Time Series Databases
Motivation and Terminology

- **Ubiquitous Time Series**
  - **Domains**: Internet-of-Things (IoT), sensor networks, smart production/planet, telemetry, stock trading, server/application metrics, event/log streams
  - **Applications**: monitoring, anomaly detection, time series forecasting
  - Dedicated storage and analysis techniques ➔ Specialized systems

- **Terminology**
  - Time series $X$ is a sequence of data points $x_i$ for a specific measurement identity (e.g., sensor) and time granularity
  - **Regular** (equidistant) time series $(x_i)$ vs **irregular** time series $(t_i, x_i)$
Example InfluxDB

- **Input Data**
  - `cpu, region=west, host=A`
  - `user=85, sys=2, idle=10`
  - `1443782126`

- **System Architecture**
  - Written in Go, originally *key-value store*, now *dedicated storage engine*
  - *Time Structured Merge Tree (TSM)*, similar to LSM
  - Organized in shards, TSM indexes and inverted index for reads

- **WAL**
  - append-only
  - fsync

- **In-Mem Index**
  - periodic flushes

- **TSM Indexes**
  - compaction & compression

**Index per TSM file:**
- Header |
- Blocks | Index | Footer
- KeyLen | Key | Type | Min T | Max T | Off | ...

Periodic drop of shards (files) according to retention policy

[Paul Dix: InfluxDB Storage Engine Internals, CMU Seminar, 09/2017]
Example InfluxDB, cont.

- **Compression (of blocks)**
  - **Compress up to 1000 values per block** (Type | Len | Timestamps | Values)
  - **Timestamps**: Delta + Run-length encoding for regular time series; Simple8B or uncompressed for irregular
  - **Values**: double delta for FP64, bits for Bool, double delta + zig zag for INT64, Snappy for strings

- **Query Processing**
  - SQL-like and functional APIs for filtering (e.g., range) and aggregation
  - Inverted indexes

```
SELECT percentile(90, user) FROM cpu WHERE time>now()-12h AND “region”=‘west’ GROUP BY time(10m), host
```

**Posting lists:**

- Measurement to fields:  
  - cpu → [1,2,3,4,5,6]  
  - cpu → [user,sys,idle]  
  - host → [A, B]  
  - Region → [west, east]

- host=A → [1,2,3]  
  - host=B → [4,5,6]  
  - region=west → [1,2,3]
Other Systems

- **Prometheus**
  - Metrics, high-dim data model, sharding and federation
  - Custom storage and query engine, implemented in Go

- **OpenTSDB**
  - TSDB on top of HBase or Google BigTable, Hadoop

- **TimescaleDB**
  - TSDB on top of PostgreSQL, standard SQL and reliability

- **Druid**
  - Column-oriented storage for time series, OLAP, and search

- **IBM Event Store**
  - HTAP system for high data ingest rates, and data-parallel analytics via Spark
  - Shard-local logs → groomed data


[Christian Garcia-Arellano et al: Db2 Event Store: A Purpose-Built IoT Database Engine. PVLDB 13(12) 2020]
Exercise 4:
Large-Scale Data Analysis

Published: May 29
Deadline: June 22

Entire Exercise is Extra Credit
Task 4.1 Apache Spark Setup

#1 Pick your Spark Language Binding
- Java, Scala, Python

#2 Install Dependencies
- Java: Maven
  - spark-core, spark-sql
- Python:
  - pip install pyspark

(#3 Win Environment)
- Create environment variable HADOOP_HOME="<some-path>/hadoop"
Task 4.2 Query Processing via Spark RDDs

- **#1 Spark Context Creation**
  - Create a spark context `sc` w/ local master (`local[*]`)

- **#2 Implement Q07 via RDD Operations**
  - Implement Q07 in self-contained `executeQ07RDD()`
  - All reads should use `sc.textFile(fname)`
  - RDD operations only → stdout

- **Appendix A.1**

  -- Determine the top-10 athletes that participated
  -- between 1948 and 2016 in the most event occurrences
  -- but never won a single medal.

  ```sql
  SELECT A.AKey, A.Name, A.DoB, count(*)
  FROM Athletes A, Results R
  WHERE A.AKey = R.AKey
  AND A.AKey NOT IN ( -- not in medal winners
      SELECT DISTINCT A2.AKey FROM Athletes A2, Results R2
      WHERE A2.AKey = R2.AKey AND R2.Medal IS NOT NULL)
  AND R.Year BETWEEN 1948 AND 2016
  GROUP BY A.AKey
  ORDER BY count(*) DESC, A.Name ASC
  LIMIT 10
  ```

Task 4.3 Query Processing via Spark SQL

#1 Spark Session Creation
- Create a spark session via a spark session builder and w/ local master (local[*])

#2 Implement Q07 via Dataset Operations
- Implement Q07 self-contained in executeQ07Dataset()
- All reads should use sc.read().format("csv")
- SQL or Dataset operations only ➔ out07.json

WebUI
- INFO Utils: Successfully started service 'SparkUI' on port 4040.
Task 4.4: Medal Prediction

- **Regression Model** (or Classification Model)
  - Training data Summer Olympics 1896-2012
  - Test data Summer Olympics Rio 2016
  - Predict # meals won by individual athletes at a specific instance of the games
  - Data preparation and training pipeline in Spark

- **Example Data**
  - Country?
  - One-Hot Encoding?
  - (Year - DoB)?
  - Other Features?

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<th>gender character (1)</th>
<th>dob date</th>
<th>height integer</th>
<th>weight integer</th>
<th>year integer</th>
<th>count bigint</th>
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<td>Michael Friedrich Mllenbeck</td>
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Conclusions and Q&A

- **Summary 10 NoSQL Systems**
  - Consistency and Data Models
  - Key-Value and Document Stores
  - Graph and Time Series Databases

- **Next Lectures** *(Part B: Modern Data Management)*
  - 11 Distributed Storage and Data Analysis [Jun 07]
  - 12 Data stream processing systems, Q&A [Jun 14]