Data Management
10 NoSQL Systems

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Announcements/Org

- **#1 Video Recording**
  - Link in TeachCenter & TUbe (lectures will be public)
  - **Live Streaming** Mo 4.10pm until end of semester (June 30)
  - **Office hours**: Mo 1pm-2pm [https://tugraz.webex.com/meet/m.boehm](https://tugraz.webex.com/meet/m.boehm)

- **#2 Exercises**
  - **Exercise 1 graded**, feedback in TC (plagiarism, discussion issues)
  - **Exercise 2 in progress of being graded**
  - Exercise 3 due **May 19, 11.59pm** (published data)

- **#3 Exam Dates**
  - Generally approved, but no global scheduling yet (so far, until June 12)
  - June 22, 4pm; June 22, 7pm; July 1, 6pm; July 2, 6pm; July 3, 6pm;
    July 28, 4pm; July 29 4pm
  - Limited **oral exams via Webex** (e.g., for international students)
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)

[Credit: http://nosql-database.org/]
Agenda

- Consistency and Data Models
- Key-Value Stores
- Document Stores
- Graph Processing
- Time Series Databases

Lack of standards and imprecise classification

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

[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 service (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."

- **Proof**
  [Seth Gilbert, Nancy A. Lynch: Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services. SIGACT News 2002]
  [Eric A. Brewer: Towards robust distributed systems (abstract). PODC 2000]

[Image 44x670 to 69x739]
[Image 547x679 to 567x741]
[Image 404x694 to 462x739]
[Image 471x694 to 529x739]
[101x53]8

INF.01017UF Data Management / 706.010 Databases – 10 NoSQL Systems
Matthias Boehm, Graz University of Technology, SS 2020
**CAP Theorem, cont.**

- **CA: Consistency & Availability (ACID single node)**
  - Network partitions cannot be tolerated
  - Visibility of updates (**consistency**) in conflict with **availability** $\Rightarrow$ **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 ($$$$)
  $\Rightarrow$ **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

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Consistency and Data Models


<table>
<thead>
<tr>
<th>Service</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon SimpleDB</td>
<td>500ms</td>
</tr>
<tr>
<td>Cassandra</td>
<td>200ms</td>
</tr>
<tr>
<td>Amazon S3</td>
<td>12s</td>
</tr>
</tbody>
</table>
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**
  - *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/everysync/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/DECRBY**: increment/decrement counters
  - Others: EXISTS, LPUH, 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 $L_{i+1}$
    - $L_1$
    - $L_2$
    - $L_3$

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[Niv Dayan: Log-Structured-Merge Trees, Comp115 guest lecture, 2017]

[Stratos Idreos, Mark Callaghan: Key-Value Storage Engines (Tutorial), SIGMOD 2020]
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)

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

**JSONig Example:**

```json
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"
  }
  id = cust.insert_one(mdict).inserted_id
  # ids = cust.insert_many(mlist).inserted_ids
  ```

- Querying a Collection
  ```python
  print(cust.find_one({"_id": id}))
  ret = cust.find({"name": "Jane Smith"})
  for x in ret:
      print(x)
  ```

[Credit: https://api.mongodb.com/python/current]
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)

```
<table>
<thead>
<tr>
<th>k</th>
<th>v</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Blob1</td>
</tr>
<tr>
<td>2</td>
<td>Blob2</td>
</tr>
<tr>
<td>4</td>
<td>Blob4</td>
</tr>
<tr>
<td>7</td>
<td>Blob7</td>
</tr>
<tr>
<td>15</td>
<td>Blob15</td>
</tr>
<tr>
<td>9</td>
<td>Blob9</td>
</tr>
<tr>
<td>14</td>
<td>Blob14</td>
</tr>
<tr>
<td>8</td>
<td>Blob8</td>
</tr>
</tbody>
</table>
```

- \( R = (R_1 \cup R_2) \cup R_3 \)
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**

Undirected Graph | Directed Graph | Multi Graph | Labeled Graph | Data/Property Graph
---|---|---|---|---
Gene interacts | k1=v1 | k2=v2 | k1=v1 | k2=v3

Gene interacts | k1=v1 | k2=v2 | k1=v1 | 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

\[ \text{in-degree}^3 \quad \text{out-degree}^2 \]

\[ \text{Tall head} \quad \text{e.g., 80-20 rule} \quad \text{Long tail} \]
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
public abstract class Vertex {
    public String getID();
    public long superstep();
    public VertexValue getValue();
    public compute(Iterator<Message> msgs);
    public void sendMsgTo(String v, Message msg);
    public void voteToHalt();
}
```

[Grzegorz Malewicz et al: Pregel: a system for large-scale graph processing. SIGMOD 2010]
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

- **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:
      \[
      \text{value} = 0.15/\text{numVertices()} + 0.85*\text{sum(msg)}
      \]
    - Send to all neighbors:
      \[
      \text{value}/\text{numOutgoingEdges()}
      \]

[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 ➔ faster convergence

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[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

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

- **Selected Example Systems**
  - AWS Neptune
  - AllegroGraph
  - *Sparksee
  - Apache Marmotta
  - Jena
Example Systems

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

[Note: Further details on the use of graph systems in practice could be provided here, including types of graphs used, computations performed, and systems utilized.]

- **Summary of State of the Art**
- **Runtime Techniques**

[Tables and figures illustrating the state of the art in graph processing systems, including technologies, their versions, and user counts.]

[Note: Tables and figures illustrating the runtime techniques used in graph processing, with examples of popular graph processing systems and their user counts.]
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
  - Fields (values)
  - Time

- **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

[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
Example InfluxDB, cont.

- **Compression (of blocks)**
  - Compress up to **1000 values per block** (Type | Len | Timestamps | Values)
  - **Timestamps**: 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
  - **Posting lists:**
    Measurement to fields: cpu → [1,2,3,4,5,6]
    host → [A, B]
    Region → [west, east]
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
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 file systems and object storage [May 25]
  - 12 Data-parallel computation (MapReduce, Spark) [May 25]
  - **June 1:** Whit Monday (Pfingstmontag)
  - 13 Data stream processing systems [Jun 08]
  - **Additional office hours** for Q & A

Incl. Exercise 4