Database Systems
10 NoSQL Systems

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Announcements/Org

- **#1 Video Recording**
  - Since lecture 03, video/audio recording
  - Link in TeachCenter & TUBE

- **#2 Exercises**
  - Exercise 1 graded, feedback in TC, office hours
  - Exercise 2 in progress of being graded
  - Exercise 3 published, due Jun 04, 11.59pm

- **#3 Exam Dates**
  - Jun 24, 4pm, HS i13
  - Jun 27, 4pm, HS i13
  - Jun 27, 7.30pm, HS i13
  - Exam starts +10min,
    working time: 90min
    (no lecture materials)
  - Additional dates for repetition
    (beginning of WS19)

77.4%
60.4%
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]
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."

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

- **Proof**

  [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 \(\rightarrow\) **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 other 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
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/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
  - **INCR/DECR**: 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
  - 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 $L_{i+1}$
    - $L_1$
    - $L_2$
    - $L_3$

[Niv Dayan: Log-Structured-Merge Trees, Comp115 guest lecture, 2017]
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
  - **JSONiq**: 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
  
  mdict = {
    "name": "Jane Smith",
    "address": "Inffeldgasse 13, Graz"
  }
  id = cust.insert_one(mdict).inserted_id
  # ids = cust.insert_many(mlist).inserted_ids
  ```

- Inserting into a Collection
  
  ```python
  print(cust.find_one({"_id": id}))
  ```

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

[Credit: https://api.mongodb.com/python/current]
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
- $k1=v1$
- $k2=v2$
- $k2=v3$
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

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**Graph Processing**

- **Tall head**
- **Long tail**
- **e.g., 80-20 rule**
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:
      $$\text{value} = \frac{0.15}{\text{numVertices()}} + 0.85 \times \text{sum(msg)}$$
    - 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 ➔ faster convergence

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

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

**Example Query**

```
SELECT ?person
WHERE {
  ?person rdf:type uri3:Player ;
  uri4:worksFor uri1:"Bayern Munich" .
}
```
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 Özsu: The Ubiquity of Large Graphs and Surprising Challenges of Graph Processing. PVLDB 2017]

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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
  - Attributes (values)
  - Tags

- **System Architecture**
  - Written 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 | ...

Time Series Databases

[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**: 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 → [user, sys, idle]
  - host → [A, B]
  - Region → [west, east]

- cpu → [1, 2, 3, 4, 5, 6]
- 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

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 27]
  - 12 Data-parallel computation (MapReduce, Spark) [May 27]
  - 13 Data stream processing systems [Jun 03]
  - Jun 17: Q&A and exam preparation