20.10.2021: Workshop together with DIMA-Group
TU Berlin

Luposdate3000:
Towards (Semantic) Hybrid Multi-model Multi-platform ((S)HM3P) Databases

Professor Dr. rer. nat. habil. Sven Groppe
https://www.ifis.uni-luebeck.de/index.php?id=groppe
Stations of my academic life

1. Paderborn
   - Study of CS ‘96–’02
   - Dr. rer. nat. ‘05
2. Lübeck
   - PD habil. ‘11
   - Prof. ‘19
3. Innsbruck
   - Postdoc ‘05–’07
Trying to impress (not sure if it's working)...

- > 120 publications
  - 94 co-authors
  - 42 publications (33%) are co-authored by bachelor/master students (being students at time of writing)
- 2 supervised dissertations, 3 current PhD students
- ≈ 85 bachelor/master/ diploma thesis/student projects
- ≈ 60 contributors to LUPOSDATE
- > 37 lectures, in the areas of
  - Semantic Web
  - Cloud- and Web-Technologies
  - Mobile and Distributed Databases
  - Databases
  - Algorithms and Datastructures
  - Compiler
Trying to impress *(not sure if it's working)*...

- **7 third-party fundings** *(≈ € 1.3M)*
- **Scientific Services**
  - **Workshop Chairs**
    - Semantic Big Data (SBD) @ SIGMOD (2016 - 2020)
    - Big Data in Emergent Distributed Environments (BiDEDE) @ SIGMOD (2021 - 2021)
    - Very Large Internet of Things (VLIoT) @ VLDB (2017 - 2021)
    - Web Data Processing and Reasoning (WDPAR) @ KI 2018
  - **General Chair**
    - International Semantic Intelligence Conference (ISIC) 2021 - 2022
  - **many other scientific services**
    - ≈ 92 PC memberships
    - reviewer of ≈ 30 journals
    - editor of 3 journals
Trying to impress (not sure if it's working)...

Detailed Information available at

HTTPS://WWW.IFIS.UNI-LUEBECK.DE/~GROPPE
Agenda: Types of Database Management Systems (DBMS)

- Cloud DBMS
- Hardware-Accelerated DBMS (GPU, FPGA, Quantum)
- IoT DBMS
- Mobile DBMS
- Federated DBMS
- Multi-Model DBMS
  - relational, XML, JSON, graph, Semantic Web, unstructured
- Multi-Platform DBMS
  - Examples
  - Multi-Platform Development
- Hybrid Multi-Model Multi-Platform (HM3P) DBMS
  - Challenges
Zoo of **Data Formats**, for example:

- *relational data*
  - in relational databases
- *XML*
  - for exchange
- *JSON*
  - web data
- *Resource Descr. Framework (RDF)*
  - Semantic Web
- *graph data*
  - from social networks
- *unstructured data*
  - of social media like wikis

⇒ Parallel use of different **Data Models** for storing and processing

<table>
<thead>
<tr>
<th>Relational:</th>
<th>XML:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Secondary</td>
</tr>
<tr>
<td>&lt;root&gt;</td>
<td>{root:</td>
</tr>
<tr>
<td>&lt;child&gt;</td>
<td>child:</td>
</tr>
<tr>
<td>&lt;first&gt;hello&lt;/first&gt;</td>
<td>first:hello,</td>
</tr>
<tr>
<td>&lt;sibling&gt;sibling&lt;/sibling&gt;</td>
<td>sibling:sibling</td>
</tr>
<tr>
<td>&lt;child&gt;</td>
<td>}</td>
</tr>
<tr>
<td>&lt;/child&gt;</td>
<td></td>
</tr>
<tr>
<td>&lt;/root&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RDF/Graph Data:</th>
<th>Ontology of Semantic Web</th>
</tr>
</thead>
<tbody>
<tr>
<td>:article rdfs:subclassOf bench:doc</td>
<td></td>
</tr>
<tr>
<td>:article1 rdf:type :article .</td>
<td></td>
</tr>
<tr>
<td>:article1 dc:creator :person1 .</td>
<td></td>
</tr>
<tr>
<td>:person1 foaf:name 'Martin' .</td>
<td></td>
</tr>
<tr>
<td>:person2 foaf:name 'Jennifer' .</td>
<td></td>
</tr>
</tbody>
</table>

**Unstructured Data:**

# Title #
The following issues are important:
1. Very Important Persons (VIPs)
2. Very Important Data (VID)
Every data model (here Semantic Web) has its own set of languages (data, query, rule, ...)

Semantic Web (Core) "Standards"

Query: SPARQL

Ontology:
- RDFS
- OWL (2)

Rule: RIF

Data Format: RDF
Semantic Web: **Ontology**

- **Ontology as additional abstraction layer**
  - More than schema descriptions:
    - Specification of background knowledge (based on which new facts can be derived)
      - avoids storing of redundant data
      - supports re-use of data
      - supports data integration
      - increases computational complexity
Special Concepts 1/2: Open world assumption (OWA)

- **Closed World Assumption (CWA)** in Databases:
  
  "The database contains all and anything not contained in the database is presumed to be false/not existent!"

- **Open Context** like Web
  
  ➡️ CWA is false!
Special Concepts 1/2: **Open world assumption (OWA): Example**

- Data source 1 contains:
  
  "There exists a flight at 2pm"
  "There exists a flight at 3pm"

- My query:
  
  "Is there a flight at 5pm?"

- **CWA Result:** No!
- **OWA Result:** unknown!

  - i.e., there could be a data source 2, which contains the information about a flight at 5pm!
  
  Data source 2 is maybe currently not integrated or currently not available...
Special Concepts 2/2: **No unique name assumption**

**Example:**
A child has two parents: (in DL: $\text{Person} \sqsubseteq \leq 2 \text{hasParent.Person}$), but the following facts seem to be conflicting:
Special Concepts 2/2: No unique name assumption

Example:
A child has two parents: (in DL: Person $\sqsubseteq 2 \text{hasParent}.\text{Person}$), but the following facts seem to be conflicting:

No unique names/keys

⇒ JohnDoe, JohnMine and LisaMine are not necessarily different objects (here persons)
Special Concepts 2/2: **No unique name assumption**

4 possibilities:

1. JohnDoe \equiv JohnMine
2. JohnDoe \equiv LisaMine
3. JohnMine \equiv LisaMine
4. JohnDoe \equiv JohnMine \equiv LisaMine
Special Concepts 2/2: **No unique name assumption**

4 possibilities:

1. **JohnDoe** ≡ **JohnMine**
2. **JohnDoe** ≡ **LisaMine**
3. **JohnMine** ≡ **LisaMine**
4. **JohnDoe** ≡ **JohnMine** ≡ **LisaMine**

Only **1.** is intuitive for humans!

Adding following facts and axioms:

- **Woman** with type **LisaMinelly**
- **Man** with type **JohnDoe** and disjoint with **JohnMinelly**
- **JohnDoe** is inferred as a type of **Woman**

→ automatic inference of 1. possibility!
Semantic Web DBMS **LUPOSDATE**

**Support of:**
- SPARQL Queries
- RIF Rules
- RDF Schema
- OWL (via OWL2RL in RIF)

**Indexing:**
- Stream Processing
- Main memory for small datasets
  - RDF3X
- Disk-based for large datasets
- Cloud: HBase
- P2P

**Visualizations:**
- Visual Editor
  - Queries (SPARQL)
  - Rules (RIF)
  - Data (RDF) in
    - 2D and
    - 3D
  - Logical Optimization Rules
- Summaries of RDF Data
- Operator graph
- Processing of Queries and Rules
- Optimization Steps

**Extra:**
- Parallel Processing
- Distributed Processing
- Cloud Computing
- Mobile Computing
- P2P for Internet of Things
- Compression of RDF Data
- Embedding of SW Languages in Programming Languages
- Speeding up by FPGAs
RDF3X - Indexing Scheme for large-scale RDF triple stores

Prefix-Search in Index: Index!
with (Prefix-)Key: PSO
Result of Triple Pattern: ?car

Search in PSO – B*-tree:
search(rdf:type ont:Car)
next(O ≥ HL 999)

Complexity of Merge Join $\bowtie_{Merge}$:
Worst Case (duplicates): $O(|R| \times |S|)$
without duplicates: $O(|R| + |S|)$
with sideways information passing: $O(|R \bowtie S|)$
(assuming quasi-constant access in B*-tree)
Polyglot Persistence

- data sources: integration at application level
- performance of data processing cannot be fully optimized
- fault-tolerance cannot be transparently offered across the different databases
- zoo of query languages
+ features of different types of databases can be used

Multi-Model DBMS (MM-DBMS)

+ full and uniform data integration at database level
+ performance: fully optimized across different data models
+ transparent fault-tolerance
+ SQL standards:
  relational (‘87), XML (‘03), temporal (‘11),
  JSON (‘16), Multi-dimensional Arrays (‘19), schemaless (‘19), streams (‘20?),
  property graphs (‘21?)
- features of different types of databases cannot be used
Federated DBMS

- Bottom-up-integration of existent databases
- mostly independent DBMS with private conceptual database schemes
- partially enabling external accesses (in cooperation)
- heterogeneity of data models and transaction management possible (but relational DBMS in most times)
- problems with semantic heterogeneity
- transparency in distribution only partially achievable
One Size-Approach

- M. Stonebraker, U. Cetintemel. "One Size Fits All": An Idea Whose Time Has Come and Gone. ICDE 2005
  - The last 25 years of commercial DBMS development can be summed up in a single phrase: "One size fits all".
  - ...this concept is no longer applicable to the database market...

- Our approach: Enlarge the size!
  - Over the boundaries and limitations of single platforms and their specialized approaches
  - Increase transparency, performance and ease of use
Hybrid Multi-Model Multi-Platform (HM3P) Database

- full and uniform data integration at database level
- performance: fully optimized across different data models
- transparent fault-tolerance
- SQL standards: relational ('87), XML ('03), temporal ('11), JSON ('16), Multi-dimensional Arrays ('19), schemaless ('19), streams ('20?), property graphs ('21?)
- features of different types of databases running on different platforms can be used
Variant: **Semantic HM3P (SHM3P) DB**

Single instance of **SHM3P Database** offers (fully cross-platform optimized) functionality of & replaces

- IoT DB *On the Edge*
- Main-Memory DB
  - GPU-accelerated
  - Parallel Server
- Quantum DB
  - Quantum Computer
- Cloud DB
  - Cloud

**Reasoning:**
- Lightweight reasoning on large data sizes of IoT devices
- Heavyweight reasoning on moderate data sizes
- Heavyweight reasoning on large data sizes
- Reasoning on small data sizes of mobile devices

**How to integrate the different reasoning capabilities and requirements into one transparent global reasoner?**

- **Semantic Layer as glue** between other models and platforms
- **new challenges** like integrating different types of reasoners in a transparent global reasoner

**Features of HM3P databases**

**Easier data integration**

**Performance issues** may occur due to semantic layer
Types of DBMS

The ark is too small...
The ark is too small...

- ... but there is always enough space for the own product/research system! → luposdate3000
Platform-specific types of DBMS
## Examples of Multi-Platform Databases 1/2

<table>
<thead>
<tr>
<th>Type</th>
<th>DBMS</th>
<th>Ext.</th>
<th>Models RCKJXGDO</th>
<th>Query Languages</th>
<th>Platforms NJWLUMSZCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relational</td>
<td>PostgreSQL</td>
<td>I</td>
<td>$R-KJX--O$</td>
<td>extended SQL</td>
<td>N-WLUMS-CH</td>
</tr>
<tr>
<td></td>
<td>MS SQL Server</td>
<td>I</td>
<td>$R--JXG--O$</td>
<td>extended SQL</td>
<td>N-WL------CH</td>
</tr>
<tr>
<td></td>
<td>IBM DB2 LUW</td>
<td>I</td>
<td>$R---XGDO$</td>
<td>extended SQL/XML</td>
<td>N-WLU-S-C-</td>
</tr>
<tr>
<td></td>
<td>IBM DB2 z/OS</td>
<td>I</td>
<td>$R---XGDO$</td>
<td>extended SQL/XML</td>
<td>N------Z--</td>
</tr>
<tr>
<td></td>
<td>Oracle DB</td>
<td>I</td>
<td>$R--JX--D0$</td>
<td>SQL/XML, SQL/JSON</td>
<td>N-WLUMS*CH</td>
</tr>
<tr>
<td></td>
<td>MySQL</td>
<td>II</td>
<td>$R-K----O$</td>
<td>SQL, memcached API</td>
<td>N-WLUMS-C-</td>
</tr>
<tr>
<td></td>
<td>Sinew¹</td>
<td>III</td>
<td>$R-K-----$</td>
<td>SQL</td>
<td>N-WLUMS-CH</td>
</tr>
<tr>
<td>Column</td>
<td>Cassandra</td>
<td>I</td>
<td>$-C----G--O$</td>
<td>SQL-like CQL</td>
<td>-JWLUMS-CH</td>
</tr>
<tr>
<td></td>
<td>CrateDB</td>
<td>I</td>
<td>$RC-J-G--$</td>
<td>SQL</td>
<td>-JWL-M--C-</td>
</tr>
<tr>
<td></td>
<td>DynamoDB</td>
<td>I</td>
<td>$-CKJ-G-O$</td>
<td>simple API (get/put/update)</td>
<td>-JWLUM--C-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ simple queries over indices</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertica</td>
<td>II</td>
<td>$-C--J-G--$</td>
<td>SQL-like</td>
<td>N--LU---CH</td>
</tr>
</tbody>
</table>

**Legend:** Ext.: I = adoption of a new storage strategy, II = extension of the original storage strategy, III = creation of a new interface, IV = no change;

**Models:** R = relational, C = column, K = key/value, J = JSON, X = XML, G = graph, D = RDF, O = object, - = no support;

**Platforms:** N = Native Machine Code, J = Java/JVM, W = Win, L = Linux, U = Unix (e.g. BSD), M = macOS, S = Solaris, Z = z/OS, C = Cloud, H = Hybrid Cloud, - = no support, * = support for old versions.

## Examples of Multi-Platform Databases 2/2

<table>
<thead>
<tr>
<th>Type</th>
<th>DBMS</th>
<th>Ext.</th>
<th>Models</th>
<th>Query Languages</th>
<th>Platforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key/value</td>
<td>Riak KV</td>
<td>I</td>
<td>--KJXG--</td>
<td>Solr</td>
<td>N--LUM--CH</td>
</tr>
<tr>
<td></td>
<td>c-treeACE</td>
<td>III</td>
<td>R--K--G--</td>
<td>SQL</td>
<td>N--WLUMS--C--</td>
</tr>
<tr>
<td></td>
<td>Oracle NoSQL DB</td>
<td>III</td>
<td>R--K--GD--</td>
<td>SQL</td>
<td>--JWLUMS--C--</td>
</tr>
<tr>
<td></td>
<td>Cosmos DB</td>
<td>I</td>
<td>--CKJ-----</td>
<td>SQL-like</td>
<td>N--------C--</td>
</tr>
<tr>
<td></td>
<td>ArangoDB</td>
<td>II</td>
<td>--KJ--G--</td>
<td>SQL-like AQL</td>
<td>N--WL--M--C--</td>
</tr>
<tr>
<td>Document</td>
<td>MongoDB</td>
<td>II</td>
<td>--KJ----0</td>
<td>JSON-based</td>
<td>N--WL--M--C--</td>
</tr>
<tr>
<td></td>
<td>Couchbase</td>
<td>III</td>
<td>--KJ-----</td>
<td>SQL-based N₁QL</td>
<td>N--WL--M--CH</td>
</tr>
<tr>
<td></td>
<td>MarkLogic</td>
<td>III</td>
<td>-----JX-D0</td>
<td>XPath, XQuery, SQL-like</td>
<td>N--WL--M--CH</td>
</tr>
<tr>
<td>Graph</td>
<td>OrientDB</td>
<td>II</td>
<td>--KJ--G--</td>
<td>Gremlin, extended SQL, SPARQL</td>
<td>N--WLUM--CH</td>
</tr>
<tr>
<td>Object</td>
<td>InterSystems Caché</td>
<td>III</td>
<td>R--JX--O</td>
<td>SQL with object extensions</td>
<td>N--WLUMS--CH</td>
</tr>
</tbody>
</table>

**Legend:** Ext.: I = adoption of a new storage strategy, II = extension of the original storage strategy, III = creation of a new interface, IV = no change;

**Models:** R = relational, C = column, K = key/value, J = JSON, X = XML, G = graph, D = RDF, O = object, - = no support;

**Platforms:** N = Native Machine Code, J = Java/JVM, W = Win, L = Linux, U = Unix (e.g. BSD), M = macOS, S = Solaris, Z = z/OS, C = Cloud, H = Hybrid Cloud, - = no support, * = support for old versions.
Multi-Platform Development of DBMS

- **Native Binaries via C/C++**
  - support of a new platform: *porting code* is necessary
  - code *close to hardware, fast execution*
  - direct access to *native libraries*
  - *doesn't run in browser*
  - *most server DBMS: C/C++ code*

- **Java/Java Virtual Machine (JVM)**
  - runs on *many platforms (without porting code)*
  - interpreted bytecode, via Just-In-Time compilation *comparable speed to native execution*
  - *no direct access to native libraries*
  - *does neither run on iPhone nor in browser*
  - *many NoSQL/NewSQL/Cloud DBMS: Java (or JVM language like Scala) code*

- **Code generation for query processing** via C/C++ or Janino-Compiler (JVM)
Multi-Platform Development with Kotlin

**Targets:**

- Most target platforms are supported
- Splitting the project in platform-independent and platform-dependent code
  - Platform-dependent code can be partly coded in the programming language of the target platform (e.g., Java for JVM, JS for Web)
- Enables one code repository for various target platforms
  - Sharing of code between server & (various) clients
- Avoids efforts to port code (into other programming languages)
Multi-Platform Development with Kotlin

- **Common Module**
  - Code independent of platforms containing declarations for platform dependent code without implementation, e.g.:
    ```kotlin
    expect fun formatString(source: String, vararg args: Any): String
    ```

- **Platform Module**
  - Implementation of within the common module declared platform-dependent code (and other platform-dependent code), e.g.:
    ```kotlin
    actual fun formatString(source: String, vararg args: Any) = String.format(source, args)
    ```

- **Regular Module**
  - Depend on platform modules or platform modules depend on this module

- **However:** High compilation times, faster: Including different sets of source code directories for different targets and configurations (e.g., centralized, Cloud, P2P, browser, ...)
The Power of Multi-Platform: LUPOSDATE3000

- ultra-fast in jvm...

- ...but also enabling web demos running completely in the browser!

B. Warnke, M.W. Rehan, S. Fischer, S. Groppe: Flexible data partitioning schemes for parallel merge joins in semantic web queries in: BTW'21

**Data versus Moore**

- **Data sizes are growing faster** than computing capacity of single CPU
  - Parallel/distributed computing to overcome limitations of single CPUs

---

**Institut für Informationssysteme | Prof. Dr. habil. S. Groppe**

---

**Luposdata3000: Towards (Semantic) Hybrid Multi-model Multi-platform ((S)HM3P) Databases**

---

**Data sizes are growing faster** than computing capacity of single CPU

- Parallel/distributed computing to overcome limitations of single CPUs
Data Sizes

Size:
- **Binary:**
  - $2^1$ Byte
  - $2^{10}$ Kibi
  - $2^{20}$ Mebi
  - $2^{30}$ Gibi
  - $2^{40}$ Tebi
  - $2^{50}$ Pebi
  - $2^{60}$ Exbi
  - $2^{70}$ Zebi
  - $2^{80}$ Yobi

- **Decimal:**
  - $10^1$ Byte
  - $10^{3}$ Kilo
  - $10^{6}$ Mega
  - $10^{9}$ Giga
  - $10^{12}$ Tera
  - $10^{15}$ Peta
  - $10^{18}$ Exa
  - $10^{21}$ Zetta
  - $10^{24}$ Yotta

**Atoms on Earth**

**Data:**
- Office
- Internet
- Big Data*
- IoT

**Company:**
- SMEs
- Global Player

**Devices:**
- IoT Device
- Embedded
- Mobile
- Historical Home Computer
- Server
- Desktop

**Databases:**
- Main Memory
- Centralized
- Cloud
- Hardware
- IoT
- Mobile
- Web Cloud

**Platforms:**
- Desktop
- Cloud
- Web/Mobile
- Fog/Edge/Dew
- P2P

SMEs: Small and medium-sized enterprises  * social media, search engines
Amdahl's versus Gustafson's law

- **Amdahl's law**
  - a **sequential part** of the overall algorithm limits overall speedup (in the context of fixed problem/data size)

- **Gustafson's law:**
  - programmers tend to set the size of problems to fully exploit the computing power that becomes available as the resources improve
  - if faster equipment or more nodes are available, larger problems can be solved within the same time
PACELC Theorem as Refinement of CAP

- **In case of network partitions (P):**
  - Guarantee of either Availability (A) or Consistency (C) (like CAP theorem)
- **In normal operation without network partitions errors: "Else (E)"**
  - Guarantee of either small Latency (L) or strong Consistency (C)
- **NoSQL-DBMS**
  - some with several configuration possibilities
  - challenge for hybrid: transparent global approaches supporting different PACELC properties for different partitions at the same time

<table>
<thead>
<tr>
<th>Distributed DBMS</th>
<th>P+A</th>
<th>P+C</th>
<th>E+L</th>
<th>E+C</th>
</tr>
</thead>
<tbody>
<tr>
<td>DynamoDB, Cassandra, Cosmos DB, Riak</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Couchbase, FaunaDB</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VoltDB/H-Store, Megastore, BigTable/HBase, MySQL Cluster</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>MongoDB</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>PNUTS</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Hazelcast IMDG</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Platform-specific types of DBMS

- Parallel
  - Server
  - Main Memory
  - Cluster
  - Hardware-Accelerated
- Distributed
  - Federated
  - Cloud
    - Web Cloud
    - DBMS on Small Devices
- Processing in Cloud
  - Mobile
  - IoT
  - Embedded
  - Smart SSD
  - Many-Core
  - GPU
  - FPGA
  - Quantum Computer
  - Quantum Annealer
  - Fog
  - Edge
  - Dew
Cloud Computing Architecture

- **Large cluster** with up to several thousand nodes
- **Replication** of data blocks (default 3 times)
- **Simple error detection and recovery by job repetition**
Capacity-Cost Performance

(CPU, RAM, HDD, SDD, ...)

Capacity

Time

High capital expenditures for buying new hardware

Additional costs

Area of loosing clients!

Predicted capacity

Traditional hardware

Currently needed capacity

Automatic Cloud capacity
**Cloud DBMS**

- **Scalability**
  - Petabytes of data
  - Thousands of Computers

- **Flexibility**
  - Processing of any data format
  - Schemaless/without schema

**Traditional DBMS**

- **High performance**
  - only for read-heavy workloads

- **Updates are relatively slow**

- **Uniform Data format**
  - Separation of schema and content
Cloud DBMS

- (Relatively) cheap (commodity-) hardware
- Efficient and simple fault-tolerant mechanisms
  - Dealing with frequent errors (hardware/communication)

Traditional DBMS

- Few high-end server
  - few hardware crashes
- Transactions: Guarantee of
  Atomicity, Consistency, Isolation, Durability
- Properties
  - Assumption: Error case is seldom
P-LUPOSDATE - Stack

LUPOSDATE

HBase
HDFS
Pig
MapReduce
P-LUPOSDATE - Bloomfilter and Query Processing

**Phase 1a: SPARQL Query Transformation into PigLatin Program**

- `SELECT ?car WHERE { ?car rdf:type ont:Car. data:Sven ont:Owns ?car. }

**Phase 1b: Generate Bloomfilter**

- **Bloomfilter1 of key rdf:type ont:Car in PO_S**
  - `0 1 1,3,5,6 0 (for sparse vectors)
  - `0 1 1 1 1 0

- **Bloomfilter1 of key data:Sven ont:Owns ?car in SP_O**
  - `1 1 1

**Phase 2: Query Processing**

- **Data of key rdf:type ont:Car in PO_S**
  - `0101001

- **Data of key data:Sven ont:Owns ?car in SP_O**
  - `0101001

**Node 1 Node 2**

- Triple Pattern

- Reduce Map
P-LUPOSDATE - Indexing Scheme

Tabelle: P_SO
... 

Tabelle: O_SP
... 

Tabelle: SP_O
... 

Tabelle: SO_P
... 

Tabelle: PO_S
... 

Tabelle: S_PO

KEY

Rowkey 1:
<http://domain.org/Reifen>

VALUE

Column Family 1: Hexa
Columnname 1:
Columnname 2:

CF 2: Bloomfilter1
KEY
Columnname 1: 4
Columnname 2: 8

CF 3: Bloomfilter2
KEY
Columnname 1: 15
Columnname 2: 16

KEY

Rowkey 2:
<http://domain.org/Motor>

VALUE

Column Family 1: Hexa
Columnname 1:

CF 2: Bloomfilter1
KEY
Columnname 1: 4

CF 3: Bloomfilter2
KEY
Columnname 1: 15
P-LUPOSDATE - Experimental Evaluation

1 Billion Triples

Speedup between 1 and 2.24 (Avg.: 1.34)

- with Bloomfilter
- without Bloomfilter

Queries
Typical **Big Data Analytics Stack** (e.g. Spark, Flink, Storm)

- **Streaming Processing**
  - Spark: Streaming
  - Flink: DataStream

- **Scripting Language/Applications**
  - Spark: Spark SQL
  - Flink: Table API & SQL

- **Machine Learning**
  - Spark: MLlib
  - Flink: FlinkML

- **Graph Processing**
  - Spark: GraphX
  - Flink: Gelly

**Execution Engine**

**Resource Management**

**Database**

**Storage**

**Streams**
Evolution of Big Data Analytics Engines

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing Model</td>
<td>MapReduce</td>
<td>DAG Dataflows</td>
<td>Resilient Distributed Datasets (RDD)</td>
<td>Cyclic Dataflows</td>
<td>?</td>
</tr>
<tr>
<td>Engine</td>
<td>Hadoop</td>
<td>TEZ</td>
<td>Spark</td>
<td>Flink</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 via "Mini-Batches"
What is **missing**: Maximizing **local Joins**

**Node 1**

**Node 2**

**Node 3**

**Node 4**

*Iterative Optimization*

Migrate node:

\[-3 + 1 = -2\] edges

⇒ more local joins
Platform-specific types of DBMS

- Server
- Main Memory
- Cluster
- Hardware-Accelerated
- Smart SSD
- Many-Core
- GPU
- FPGAs
- Quantum Computer
- Quantum Annealer
- Federated
- Cloud
- Web Cloud
- Mobile
- IoT
- Embedded
- DBMS on Small Devices
- Processing in Cloud
- Fog
- Edge
- Dew
### Architectures of Emergent Hardware

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MIMD + SIMD</td>
<td>Thread and Data Parallel</td>
<td>Shared</td>
<td>150 W</td>
<td>Query Optimization (Enumeration of Plans), Concurrency Control</td>
</tr>
<tr>
<td></td>
<td>SIMD</td>
<td>Data Parallel</td>
<td>Distributed</td>
<td>200 W</td>
<td>Efficient Processing Of Query Processing</td>
</tr>
<tr>
<td></td>
<td>Data-Flow</td>
<td></td>
<td></td>
<td>250 W</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50 W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quantum (0)</td>
<td></td>
<td></td>
<td>25 KW</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Cores**: ~10, ~100, ~1000, ~100 000, ~50 / ~5000 qubits
- **Core Complexity**: Complex (optimized for single thread performance), Simple
- **Computational Model**: MIMD + SIMD, SIMD, Data-Flow, Universal/Adiabatic Quantum computing
- **Parallelism**: Thread and Data Parallel, Data Parallel, Arbitrary, Quantum Logic Gates / Fluctuation (glob. Min.)
- **Memory Model**: Shared, Distributed, Quantum Superposition
- **Power**: 150 W, 200 W, 250 W, 50 W, 25 KW
- **Query Optimization (Enumeration of Plans), Concurrency Control**
- **Efficient Processing Of Query Processing**

---

**Legend:**
- Computational Unit
- Execution Controller
- Interconnection Network
- On-Chip Memory
General Purpose Graphics Processing Unit (GPGPU)

- turns the massive computational power of a modern graphics accelerator's shader pipeline into general-purpose computing power
- Single instruction, multiple data (SIMD)
- Up to several thousand computing cores
- Programming languages for SIMD computations
  - Open Computing Language (OpenCL): Vendor-independent programming standard
  - CUDA (formerly Compute Unified Device Architecture): NVIDIA-dependent parallel computing platform and API model
  - Open Graphics Library (OpenGL): mainly cross-language, cross-platform API for rendering 2D and 3D vector graphics
Hybrid Search in Adaptive Radix Tree (ART) on GPGPUs

CPU Experiments:

GPU Experiments:
Approximate Search in Adaptive Radix Tree (ART) on GPGPUs

- **Levenshtein-distance:** number of operations to transform one string into another:

<table>
<thead>
<tr>
<th>institute</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>n</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>c</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>o</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>m</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>i</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>n</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>g</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

  e.g. 5 operations are needed to transform "institu" into "incom' or vice versa

- **Speedup over 4 dependent on ART properties (1.43 for real-world BTC data)**
High-End Parallel GPU System: **DGX-2**

- **16X NVIDIA Tesla V100 32GB**
  - Total: GPU Memory: 512GB total
  - Performance: 2 petaFLOPS
  - CUDA® Cores: 81,920
  - Tensor Cores: 10,240

- **12X NVSwitches**
  - 2.4 TB/sec bi-section bandwidth

- **2X GPU Boards**
  - Per Board: 8 V100 32GB GPUs
  - 6 NVSwitches interconnected by Plane Card

- **30 TB NVME SSDs**
  - Internal Storage

- **Eight EDR Infiniband/100 GigE**
  - 1,600 Gb/sec Total
  - Bi-directional Bandwidth

- **PCIe Switch Complex**

- **2X Intel Xeon Platinum CPUs**
  - 8168, 2.7 GHz (Turbo 3.7GHz), 24-cores (48 threads)

- **1.5 TB System Memory**
  - Image by NVIDIA
High-End Parallel GPU System: **DGX A100**

- **8X NVIDIA A100**
  - Total:
  - GPU Memory: 320GB total
  - Performance:
    - 5 petaFLOPS (AI)
  - CUDA® Cores: 55,296
  - Tensor Cores: 3,456
  - 12 NVLinks/GPU
  - 600 GB/s bandwidth between GPUs

- **9 Mellanox ConnectX-6 VPI HDR InfiniBand/200 GB Ethernet**
  - Total bi-dir. bandwidth

- **2X AMD Rome CPUs**
  - Epyc 7742
  - 2.25 GHz
  - Turbo 3.4GHz
  - 64-cores
  - 128 threads

- **1 TB System Memory**

- **6X NVSwitches**
  - 4.8 TB/s bi-section bandwidth

- **15 TB GEN4 NVME SSDs**
  - Internal Storage
  - 25.6 GB/s max. bandwidth

Images by NVIDIA
Field-Programmable Gate Array (FPGA)

- contains an array of **programmable logic blocks and a hierarchy of reconfigurable interconnects**
- Specification of configuration typically by hardware description language (HDL)
- Recently **High Level Synthesis** (e.g., OpenCL) more mature (but still performance-critical parts should not be implemented in OpenCL)
- Long **synthesis time**
• Generation of Reconfigurable Modules (RMs) at system deployment time
• Selection of RMs and configuration into Reconfigurable Partitions at system runtime \(\leadsto \text{avoids long synthesis time}\)
Configuring the **Semi-Static Operator Graph**

RP: Reconfigurable Partition  
SRE: Semi-static Routing Element

**Query 4**

SP$^2$B
LUPOSDATE on FPGA – Benchmark Results

- **Reconfiguration** reduced from about half hour to few milliseconds (< 20 ms for all queries) when using semi-static operator graphs

- **SP²B Benchmark**
  - Dataset sizes from 66 to 262 million triples
  - **Speedups between 4 and 32 times**
    (dependent on query and dataset size)
Hybrid Index - FPGA Accelerated Index

- **B⁺-Tree** (compact static index: CSB⁺-Tree): Speedup of 2.3
  Larger speedups possible via pipelining and usage of memory hierarchies (currently only BRAM)
Quantum Computer

- use of quantum-mechanical phenomena such as superposition and entanglement to perform computation
- Different types of quantum computer, e.g.
  - Universal Quantum Computer
    - uses quantum logic gates arranged in a circuit to do computation
    - measurement (sometimes called observation) assigns the observed variable to a single value
  - Quantum Annealing
    - metaheuristic for finding the global minimum of a given objective function over a given set of candidate solutions
    - i.e., some way to solve a special type of mathematical optimization problem
Timeline of Quantum Computers

- IBM
- IBM Roadmap’20
- Google
- Google Roadmap’21
- Intel
- Rigetti
- QuTech
- USTC
- Xanadu Quantum Technologies
- Quantum Brilliance
- Roadmap’21 (Room Temperature)
- D-Wave
- D-Wave Roadmap’21

Main Data Source: IBM, Google, Quantum Brilliance, D-Wave
Using **Hardware Accelerator** for optimizing Transaction Schedules
2 Phase Locking (2PL) versus Strict Conservative 2PL

- required locks to be determined by
  - static analysis of transaction, or if static analysis is not possible:
  - an additional phase at runtime before transaction processing
Optimizing Transaction Schedules

- Job shop schedule problem (JSSP):
  - Multi-Core CPU
    - Process whole job (here transaction) on core X
  - Schedule: \( \forall \) cores: Sequence of jobs to be processed
  - What is the optimal schedule for minimal overall processing time?

- Additionally to JSSP:
  Blocking transactions not to be processed in parallel

- Example:

- JSSP is among the hardest combinatorial optimizing problems
- \( \Rightarrow \) Hardware accelerating the optimization of transaction schedules

---

Optimizing Transaction Schedules via Quantum Annealing

- **Scenario:** Strict conservative 2-Phase Locking
  - Preclaiming of all locks at *Begin of Transaction* (avoids deadlocks)
  - Holding all locks until *End of Transaction* (avoids cascading aborts)
- **Solution** formulated as set of binary variables
  - $X_{i,j,s}$ is 1 iff transaction $t_i$ is started at time $s$ on machine $m_j$, otherwise 0
- **Example:**

  ![Transaction schedule diagram]

  - Solution:
    - $X_{1,1,0}$, $X_{3,1,2}$, $X_{4,2,0}$,
    - $X_{7,2,1}$, $X_{6,2,3}$, $X_{5,2,6}$,
    - $X_{2,3,0}$, $X_{8,3,5}$

  Black: Blocking transactions

  Transaction schedule
Optimizing Transaction Schedules via Quantum Annealing

- **Transaction Model**
  - $T$: set of transactions with $|T| = n$
  - $M$: set of machines with $|M| = k$
  - $O \subseteq T \times T$: set of blocking transactions
  - $l_i$: length of transaction $i$
  - $R$: maximum execution time
  - upper bound $r_i = R - l_i$ for start time of transaction $i$

- **Example**
  - $T = \{t_1, t_2, t_3\}$, $n=3$
  - $M = \{m_1, m_2\}$, $k=2$
  - $O = \{(t_2, t_3)\}$
  - $l_1 = 2, l_2 = 1, l_3 = 1$
  - $R = 2$
  - $r_1 = 0, r_2 = 1, r_3 = 1$

- **Quadratic unconstrained binary optimization (QUBO) problems (solving is NP-hard)**
  - A QUBO-problem is defined by $N$ weighted binary variables
  \[
  X_1, \ldots, X_N \in 0, 1, \text{either as linear or quadratic term to be minimized:}
  \sum_{0<i\leq N} w_i X_i + \sum_{i\leq j\leq N} w_{ij} X_i X_j, \text{where } w_i, w_{ij} \in \mathbb{R}
  \]
Optimizing Transaction Schedules via Quantum Annealing

- **Valid Solution**
  
  - A: each transaction starts exactly once
    \[
    A = \sum_{i=1}^{n} \left( \sum_{j=1}^{k} \sum_{s=0}^{r_i} X_{i,j,s} - 1 \right)^2
    \]
    transactions machines start times

  - B: transactions cannot be executed at the same time on the same machine
    \[
    B = \sum_{j=1}^{k} \sum_{i_1=1}^{n-1} \sum_{s_1=0}^{r_{i_1}} \sum_{i_2=i_1+1}^{n} \sum_{s_2=q}^{p} X_{i_1,j,s_1} X_{i_2,j,s_2}
    \text{ for } q = \max\{0, s_1 - l_{i_2} + 1\}, p = \min\{s_1 + l_{i_1}, r_{i_2}\}
    \]
    transactions without \( t_n \) remaining transactions machines start times invalid start times

  - C: transactions that block each other cannot be executed at the same time
    \[
    C' = \sum_{\{t_1,t_2\} \in O} \sum_{j_1=1}^{k} \sum_{s_1=0}^{r_{i_1}} \sum_{j_2 \in J}^{r_{i_2}} \sum_{s_2=q}^{p} X_{i_1,j_1,s_1} X_{i_2,j_2,s_2}
    \text{ for } J = \{1, \ldots, k\} \setminus \{j_1\}, q = \max\{0, s_1 - l_{i_2} + 1\}, p = \min\{s_1 + l_{i_1}, r_{i_2}\}
    \]
    blocking transactions remaining machines start times invalid start times
Optimizing Transaction Schedules via Quantum Annealing

- **Optimal Solution**
  - D: minimizing the maximum execution time
  \[
  D = \sum_{i=1}^{n} \sum_{j=1}^{k} \sum_{s=0}^{r_i} w_{s+l_i} X_{i,j,s}, \quad \text{where } w_{s+l_i} = \frac{(k + 1)^{s+l_i-1}}{(k + 1)^R} < 1
  \]
  - Increasing weights: Weight of step n is larger than of all preceding steps 1 to n-1 ⇒ preferring transactions ending earlier
  - Weights in A, B and C ≥ 1
    ⇒ first priority is validity, second priority is optimality

- **Overall Solution**
  - Minimize \( P = A + B + C + D \)
Optimizing Transaction Schedules via Quantum Annealing

- Experiments on real Quantum Annealer (D-Wave 2000Q cloud service)
  - first minute free
  - (afterwards too much for our budget)
- Versus Simulated Annealing on CPU
- Preprocessing time/Number of QuBits: $O((n \cdot k \cdot R)^2)$

<table>
<thead>
<tr>
<th>Fig.</th>
<th>$k$</th>
<th>$n$</th>
<th>$R$</th>
<th>$O$</th>
<th>$l_1, \ldots, l_n$</th>
<th>$r_1, \ldots, r_n$</th>
<th>req. var.</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>$(t_1, t_3)$</td>
<td>4, 5, 1</td>
<td>1, 0, 4</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>$(t_2, t_4)$</td>
<td>3, 2, 1, 2</td>
<td>1, 2, 3, 2</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2</td>
<td>8</td>
<td>$(t_1, t_2), (t_4, t_5)$</td>
<td>1, 1, 1, 1, 1</td>
<td>1, 1, 1, 1, 1</td>
<td>10</td>
</tr>
</tbody>
</table>
Optimizing Transaction Schedules via Quantum Computing

Diagram showing a process involving a Hardware Accelerator, a Quantum Computer, and a Database Server, with transactions and results flowing through a Client system.
Overview of Optimizing Transaction Schedules via Quantum Computing

Transactions Lengths

Code Generation

Check:
\[ \{0, \ldots, 2^b - 1\} \rightarrow \{\text{True, False}\} \]

Grover’s Search

Encoding Scheme of Solution:
\[ \{0, \ldots, 2^b - 1\} \rightarrow \alpha \]

Transaction Schedule \( \alpha \)

Core 0

\[ T_{\alpha(0,0)} \rightarrow T_{\alpha(0,m_1-1)} \]

Core \( m-1 \)

\[ T_{\alpha(m-1,0)} \rightarrow T_{\alpha(m-1,m_m-1)} \]
Grover's Search Algorithm

- **Black box** function $f : \{0, \ldots, 2^b - 1\} \mapsto \{true, false\}$
- Grover's search algorithm finds one $x \in \{0, \ldots, 2^b - 1\}$, such that $f(x) = true$
  - if there is only one solution: $\frac{\pi}{4} \cdot \sqrt{2^b}$ basic steps each of which calls $f$
    - Let $f'(b)$ be runtime complexity of $f$ for testing $x$ to be true:
      $$\Rightarrow O(\sqrt{2^b} \cdot f'(b))$$
  - if there are $k$ possible solutions: $O(\sqrt{\frac{2^b}{k}} \cdot f'(b))$
### Complexity Analysis: QC versus QA for Optimizing Transaction Schedules

<table>
<thead>
<tr>
<th>Approach Preprocessing</th>
<th>CPU</th>
<th>Quantum Computer</th>
<th>Quantum Annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$O(1)$</td>
<td>$O(n^2 \cdot c)$</td>
<td>$O(m \cdot R^2 \cdot (c \cdot m + n^2))$</td>
</tr>
<tr>
<td>Execution</td>
<td>$O(\frac{(m+n-1)!}{(m-1)!} \cdot (n + c))$</td>
<td>$O(\sqrt{n! \cdot \frac{n^m}{k}} \cdot (n \cdot \log_2(n) + c))$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>Space</td>
<td>$O(n + m + c)$</td>
<td>$O((n + m) \cdot \log_2(n))$</td>
<td>$O(m \cdot R^2 \cdot (c \cdot m + n^2))$</td>
</tr>
<tr>
<td>Code</td>
<td>$O(1)$</td>
<td>$O(n^2 \cdot c)$</td>
<td>$O(m \cdot R^2 \cdot (c \cdot m + n^2))$</td>
</tr>
</tbody>
</table>

$m$: number of machines  
$n$: number of transactions  
$c$: number of conflicts  
$R$: max. runtime  
$k$: number of solutions
Number of Solutions - QC approach

\[
|S_{R \leq 1}| = 8,589,934,592,2,199,023,255,552,48,384,000,559,872
\]

\[
m = 2, \quad m = 4
\]

<table>
<thead>
<tr>
<th>(N)</th>
<th>(k)</th>
<th>(k) for (\leq 1.25 \cdot R_{opt})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m = 2)</td>
<td>(8,589,934,592)</td>
<td>(2,199,023,255,552)</td>
</tr>
<tr>
<td>(m = 4)</td>
<td>(48,384,000)</td>
<td>(559,872)</td>
</tr>
<tr>
<td>(m = 2)</td>
<td>(1,472,567,040)</td>
<td>(2,047,306,752)</td>
</tr>
</tbody>
</table>

\[
R \text{ as factor of } R_{opt}
\]
Platform-specific types of DBMS

- Parallel
  - Server
  - Main Memory
  - Cluster
    - Hardware-Accelerated
  - Federated
  - Cloud
    - Web Cloud
      - DBMS on Small Devices
- Distributed
  - Processing in Cloud
  - Fog
  - Edge
  - Dew
- Smart SSD
- Many-Core
  - GPU
  - FPGA
  - Quantum Computer
  - Quantum Annealer
- Mobile
- IoT
- Embedded
IoT Architectures

Cloud Computing

Bottleneck

Edge Computing

Fog Computing

Dew Computing

Institut für Informationssysteme | Prof. Dr. habil. S. Groppe
Platform-specific types of DBMS

DBMS

- Parallel
  - Server
  - Main Memory
  - Cluster
  - Hardware-Accelerated
- Distributed
  - Federated
  - Cloud
  - Web Cloud
  - DBMS on Small Devices
- Mobile
  - IoT
  - Embedded
- Processing in Cloud
  - Fog
  - Edge
  - Dew
Mobile DBMS integrated into Architecture for Mobile Phones
Platform-specific types of DBMS
## Features of different types of databases

<table>
<thead>
<tr>
<th>Feature</th>
<th>DBMS</th>
<th>Main Memory</th>
<th>Parallel</th>
<th>Distributed</th>
<th>Federated</th>
<th>Cloud</th>
<th>Web Cloud</th>
<th>Mobile</th>
<th>IoT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transaction rates</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intra-Transaction Parallelism</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atomicity</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Durability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consistency</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extensibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schemaless</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Availability</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transparency of Distribution</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geographical Distribution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Node Autonomy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heterogeneity of DBMS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Administration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardware Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reasoning</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Hybrid Multi-Model Multi-Platform (HM3P) Database

- How to integrate the features of different types of databases into one single database running also on different platforms?
Challenges for HM3P Databases 1/2

- developing only one code base for the different platforms, but not introducing performance overhead in comparison to single platform databases
- identifying common properties of several platforms and reusing those approaches (like fault tolerance mechanisms) in different combinations, which are best suitable for these considered platforms
- data distribution among different platforms (applying different data distribution approaches as well)
- data distribution strategies considering overall the different properties of used platforms and models (like fast reads on parallel servers (using relational databases) and fast updates in cloud databases)
Challenges for HM3P Databases 2/2

- query optimization and other database tasks across different platforms, which apply different database approaches
- dealing with and integrating different privacy and security mechanisms supporting different privacy and security levels in the different platforms (with research e.g. on querying heterogeneous encrypted data)
- concurrency control approaches of different type have to be combined and work in cooperation (like 2 phase locking for server platforms and optimistic concurrency control for P2P networks)
- combining different types of databases (on different platforms) to offer the best of these databases and platforms under one hood to applications and users transparently or via intelligent integration into query language and API, e.g.,
  - guaranteeing atomicity and isolation in transactions for the data stored on a parallel server, but not for those data in the cloud supporting fast updates
Semantic Hybrid Multi-Model Multi-Platform (SHM3P) Database

How to integrate the different reasoning capabilities and requirements into one transparent global reasoner?

- How to integrate the semantic layer between different types of databases and support semantic processing specialities like reasoning over the boundaries of different platforms?
Challenges for SHM3P Databases

- integrating different data models in a semantic layer on top of the underlying data models
- efficient transformations from and to the semantic model in an operational system
- developing efficient semantic querying and reasoning over the integrated data of different models
- global reasoning over reasoners running on different platforms supporting some kind of distributed heterogeneous reasoning
- developing a combination of stream reasoning over streaming data (e.g. of IoT devices) with static reasoning over large-scale data sets (stored e.g. in clouds)
- supporting transactions over semantic data by integrating the reasoner in transaction synchronization
Proposals for **Cooperation & Collaborations**

- **Contributions to luposdate3000** are welcome:
  - [https://github.com/luposdate3000/luposdate3000](https://github.com/luposdate3000/luposdate3000)
  - current status: SMP DBMS, soon SHMP DBMS
- **Any other computer science topic** in my expertise area
- **Please contact me:** groppe@ifis.uni-luebeck.de
Summary and Conclusions

- Different **data models** and their special features
  - ➔ Multi-Model Databases

- Different **platforms and a need for different types of databases**
  - Different features
  - ➔ Multi-Platform Databases

- **Databases spanning over different platforms in operation** (supporting multiple data models)
  - ➔ Hybrid Multi-Model Multi-Platform (HM3P) Databases