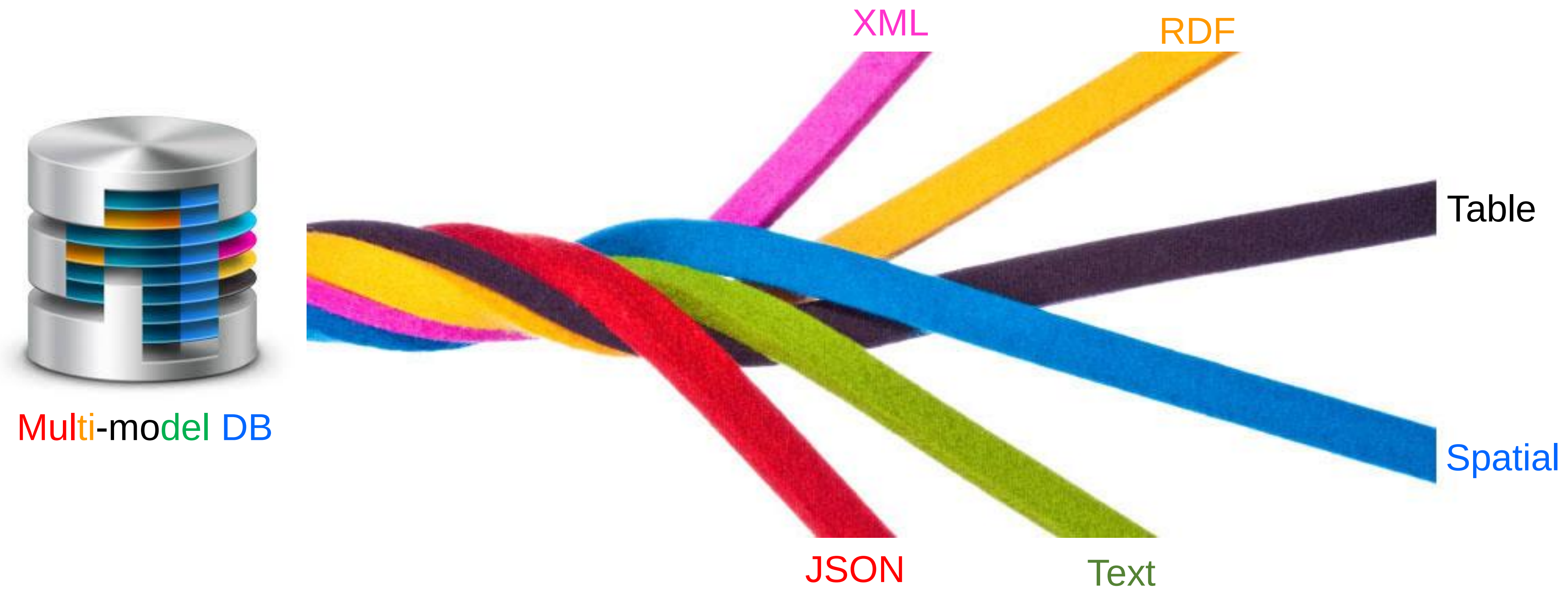



# Multi-model Data Management

Jiaheng Lu and Irena Holubová

University of Helsinki and Charles University, Prague

UNIVERSITY OF HELSINKI

# Outline

- Introduction to multi-model databases (25 minutes )
- Multi-model data storage  (25 minutes)
- Multi-model data query languages (15 minutes)
- Multi-model query optimization  (5 minutes)
- Multi-model database benchmarking  (5 minutes)
- Open problems and challenges   (10 minutes)

# Outline

- Introduction to multi-model databases
- Multi-model data storage
- Multi-model data query languages
- Multi-model query optimization
- Multi-model database benchmarking
- Open problems and challenges

# A grand challenge on Variety

- Big data: Volume, Variety, Velocity, Veracity
- Variety: tree data (XML, JSON), graph data (RDF, property graphs, networks), tabular data (CSV), temporal and spatial data, text etc.

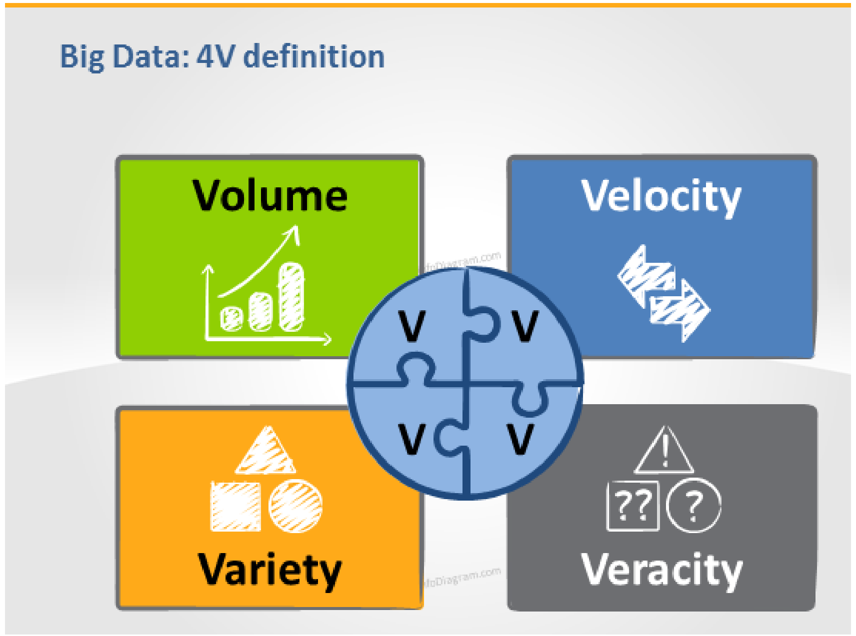
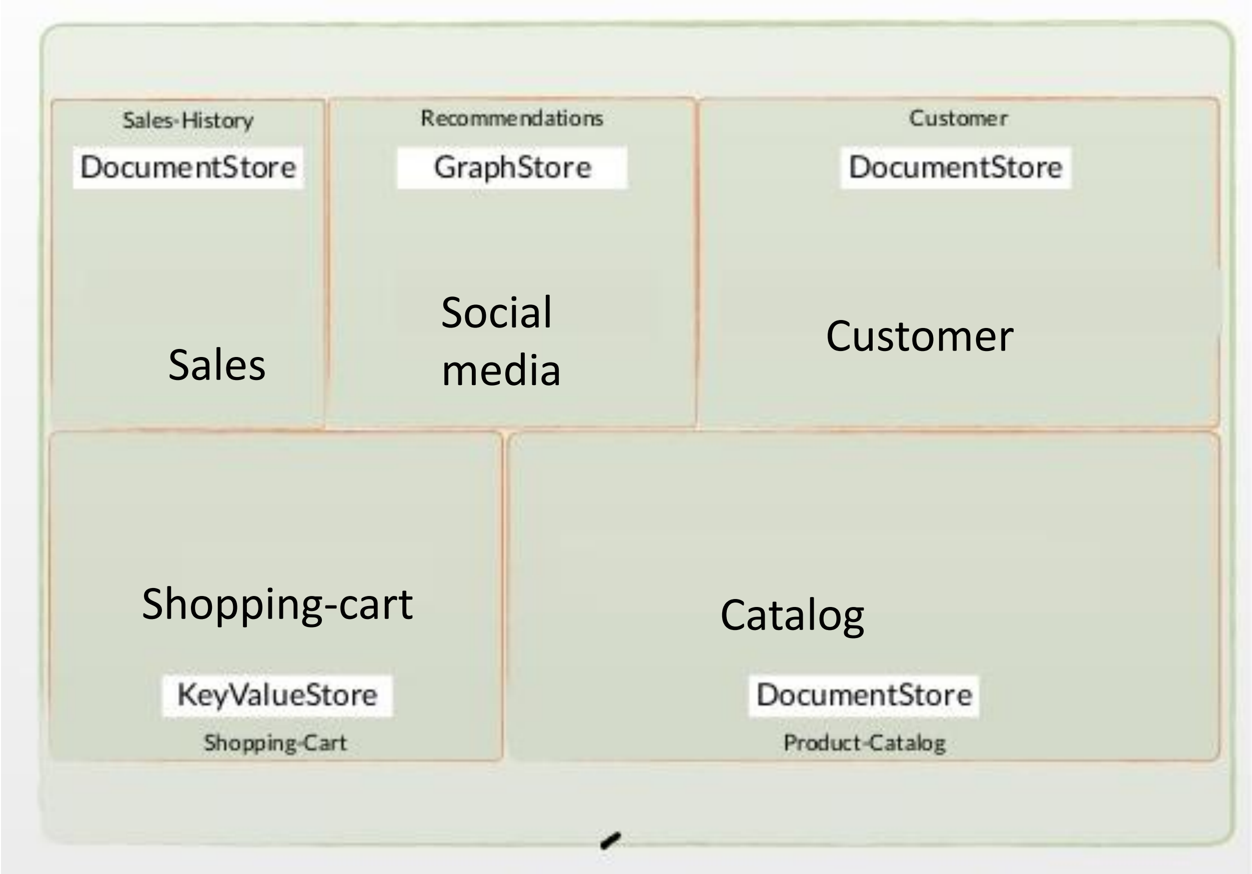



Photo downloaded from: https://blog.infodiagram.com/2014/04/visualizing-big-data-concepts-strong.html

# Motivation: one application to include multi-model data




An E-commence example with multi-model data

# NoSQL database types

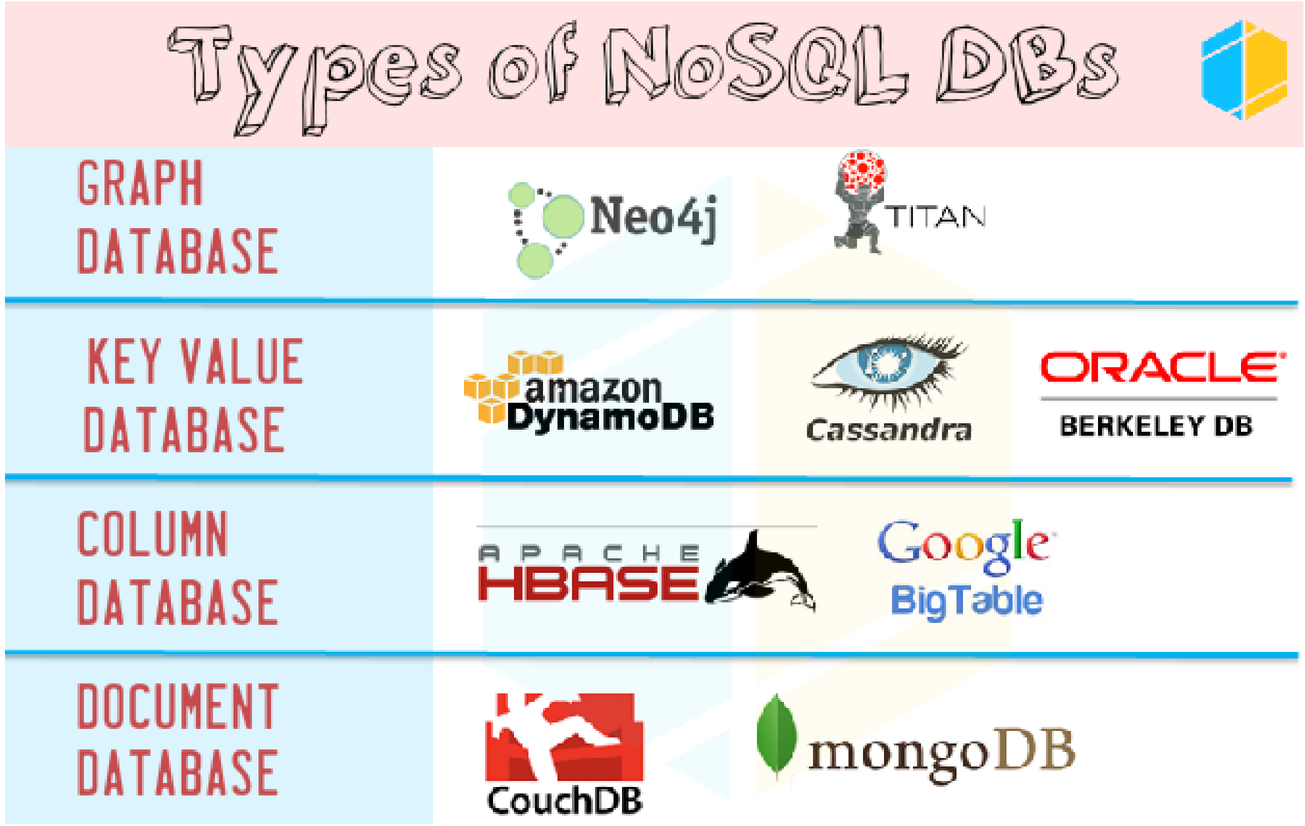
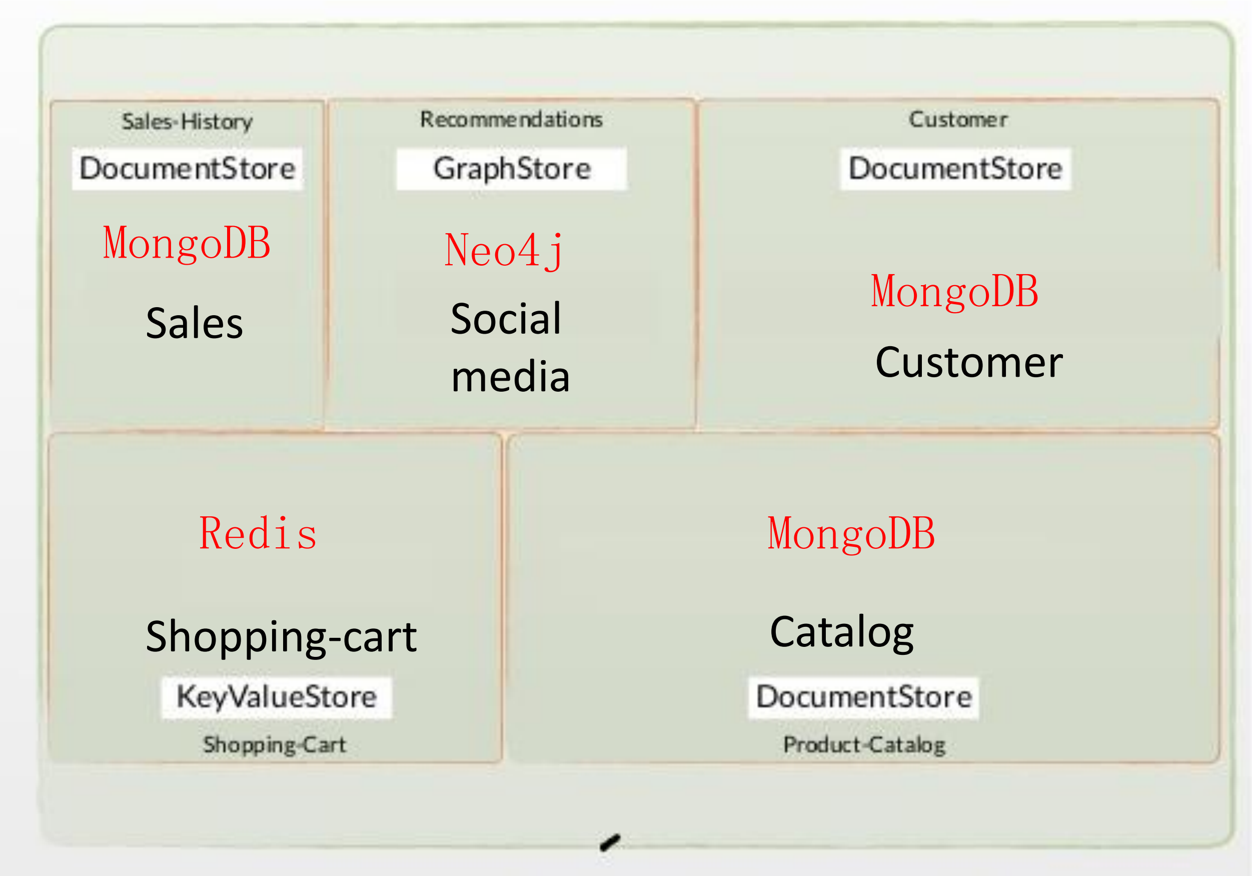



Photo downloaded from: http://www.vikramtakkar.com/2015/12/nosql-types-of-nosql-database-part-2.html

# Multiple NoSQL databases



# Polyglot Persistence

- "One size cannot fit all": use multiple databases for one application
- If you have structured data with some differences
    - Use a document store
- If you have relations between entities and want to efficiently query them
    - Use a graph database
- If you manage the data structure yourself and do not need complex queries
    - Use a key-value store

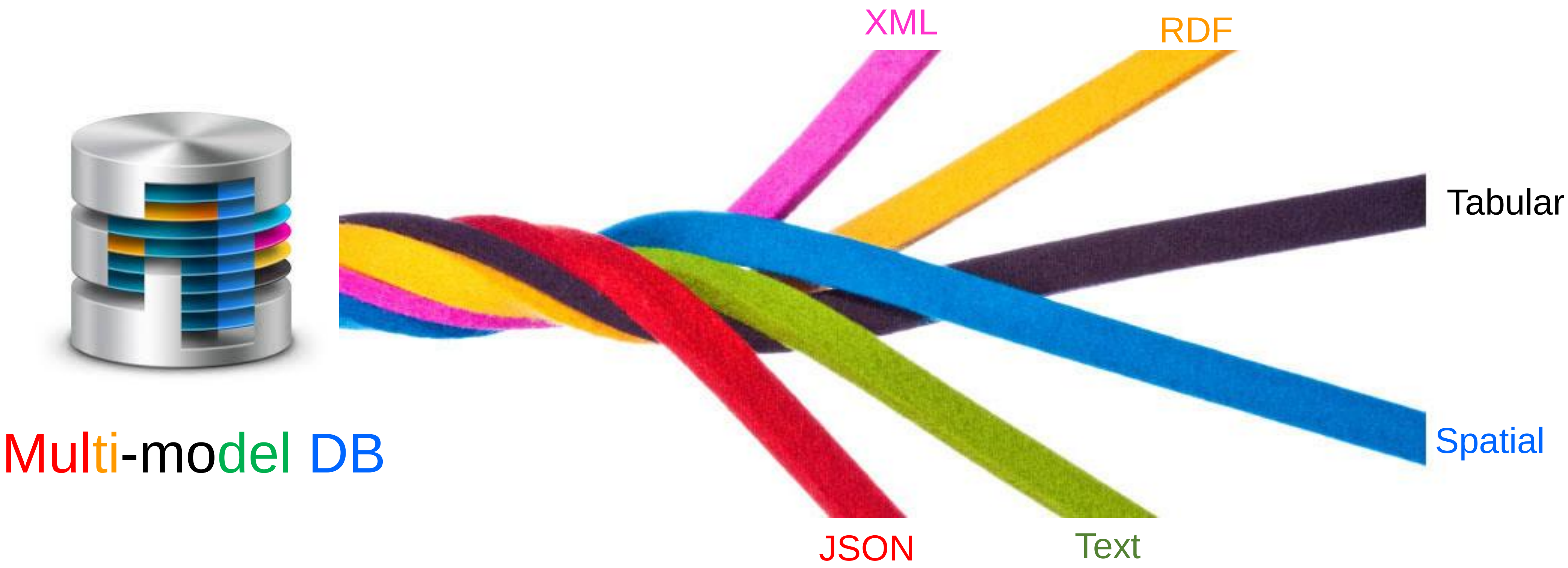
# Pros and Cons of Polyglot Persistence

- Handle multi-model data
- Help your apps to scale well
- A rich experience to manage multiple databases

- Requires the company to hire people to integrate different databases
- Implementers need to learn different databases
- Hard to handle inter-model queries and transactions

# Multi-model DB

- One unified database for multi-model data



# Multi-model databases

- A multi-model database is designed to support multiple data models against a single, integrated backend.

- Document, graph, relational, and key-value models are examples of data models that may be supported by a multi-model database.

# What is the difference between Multi-model and Multi-modal

- Multi-model: graph, tree, relation, key-value,…
- Multi-modal: video, image, audio, eye gaze data, physiological signals,…

# Three arguments on one DB engine for multiple applications

- 1. One size cannot fit all

- 2. One size can fit all

- 3. One size fits a bunch

# One size cannot fit all

“SQL analytics, real-time decision support, and data warehouses cannot be supported in one database engine.”

M. Stonebraker and U. Cetintemel. ”One Size Fits All”: An Idea Whose Time Has Come and Gone (Abstract). In ICDE, 2005.

# One size can fit all

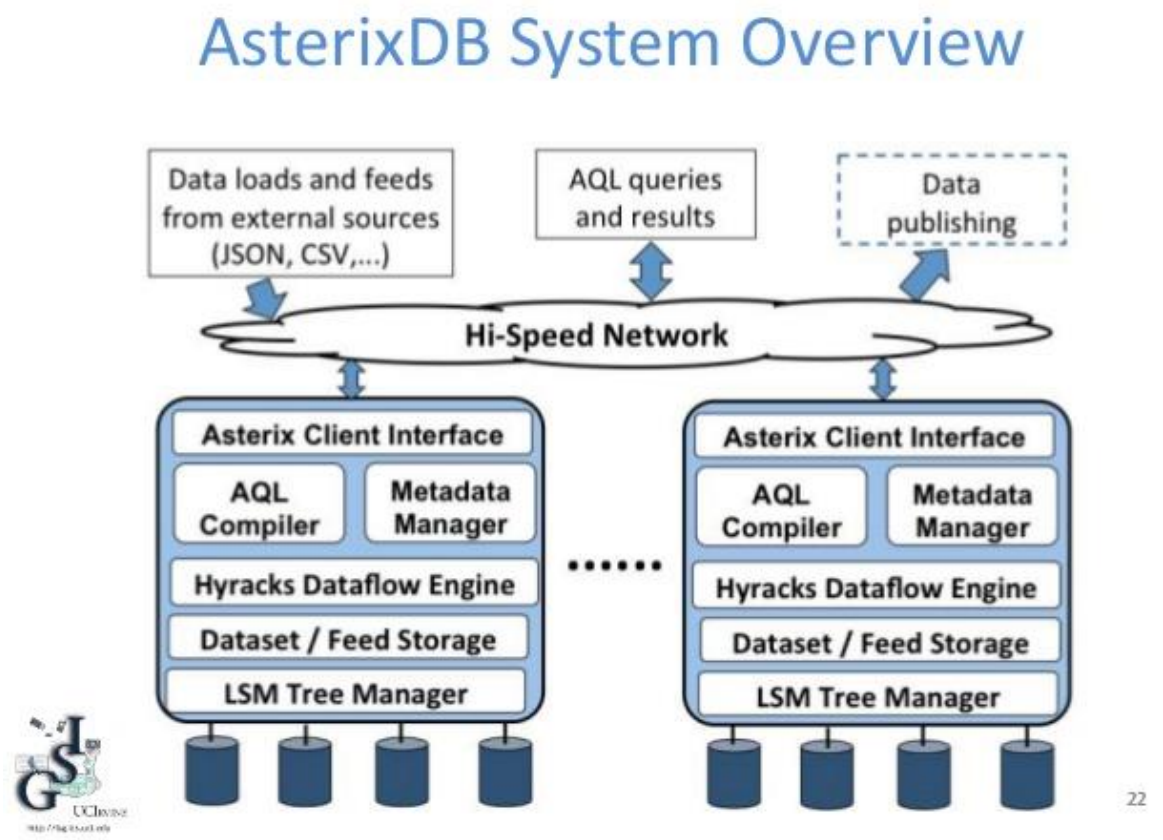
- OctopusDB suggests a unified, one size fits all data processing architecture for OLTP, OLAP, streaming systems, and scan-oriented database systems.

- Jens Dittrich, Alekh Jindal: Towards a One Size Fits All Database Architecture. CIDR 2011: 195-198

# One size can fit all: OctopusDB

- All data is collected in a central log, i.e., all insert and update-operations create logical log-entries in that log.
- Based on that log, define several types of optional storage views
- The query optimization, view maintenance, and index selection problems suddenly become a single problem: storage view selection

# One size can fit a bunch: AsterixDB [1]




A parallel semi-structured data management system with its own storage, indexing, run-time, language, and query optimizer, supporting JSON, CSV data

Support SQL++ [2] and AQL (AsterixDB query language)


[1] AsterixDB: A Scalable, Open Source BDMS. PVLDB 7(14): 1905-1916 (2014)
[2] The SQL++ Query Language: Configurable, Unifying and Semi-structured ArXiv:1405.3631

# One size can fit a bunch: AsterixDB

- AsterixDB's data model is flexible

- Open:   you can store objects there that have those fields as well as any/all other fields that your data instances happen to have at insertion time.
- Closed: you can choose to pre-define any or all of the fields and types that objects to be stored in it will have

# A simple survey

How many of you agree that

1. One size cannot fit all ?

2. One size can fit all ?

3. One size fits a bunch ?

4. ???

# Multi-model databases:
# One size fits multi-data-model

MariaDB

mongoDB

ORACLE

ArangoDB

OrientDB

APACHE DRILL

FOUNDATIONDB

MarkLogic

AsterixDB

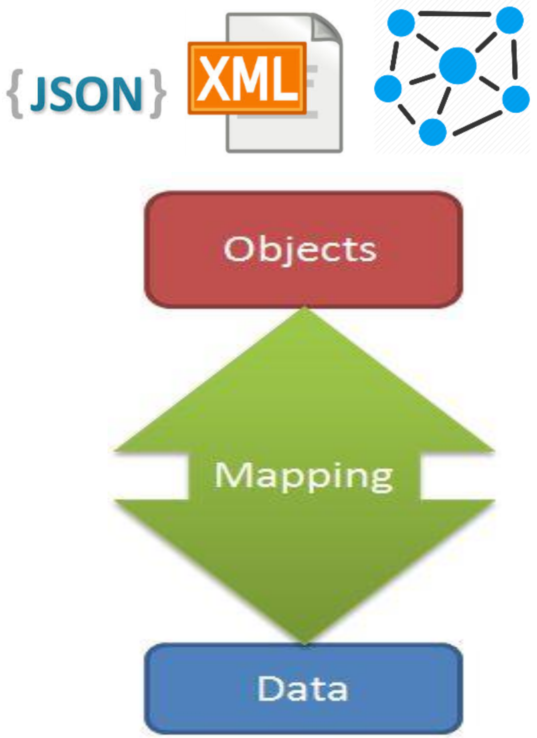
InterSystems CACHÉ

…

# Multi-model databases are not new !

- Can be traced to object-relational database (ORDBMS)

- ORDBMS framework allows users to plug in their domain and/or application specific data models as user defined functions/types/indexes



# Most of DBs will become multi-model databases in 2017


- By 2017, all leading operational DBMSs will offer multiple data models, relational and NoSQL, in a single DBMS platform.

--- Gartner report for operational databases 2016

MongoDB supports multi-model in the recent release 3.4 (**NOV 29, 2016**)

# Pros and Cons of multi-model databases

- Handle multi-model data
- One system implements fault tolerance
- One system guarantees inter-model data consistency
- Unified query language for multi-model data

- A complex system
- Immature and developing
- Many challenges and open problems

Two examples of multi-model databases:

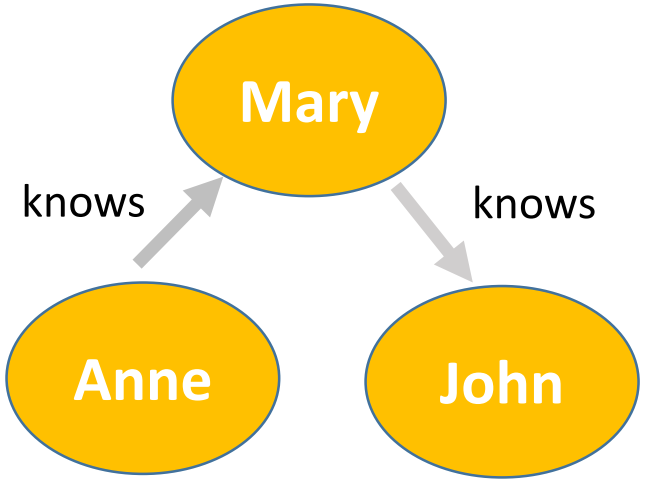
ArangoDB

OrientDB

ArangoDB

- ArangoDB is a multi-model, open-source database with flexible data models for documents, graphs, and key-values.
- They store all data as documents.
- Since vertices and edges of graphs are documents, this allows to mix all three data models (key-value, JSON and graph)

# An example of multi-model data and query




Social network graph

"1" -- > "34e5e759"

"2"-- > "0c6df508"

Shopping-cart key-value pairs

Customer_ID → Order_no

```
{"Order_no":"0c6df508",
 “Orderlines": [
   { "Product_no":"2724f”
     “Product_Name":“Toy",
     "Price":66 },
   { "Product_no":“3424g”,
     "Product_Name":“Book",
     "Price":40 } ]
}
```

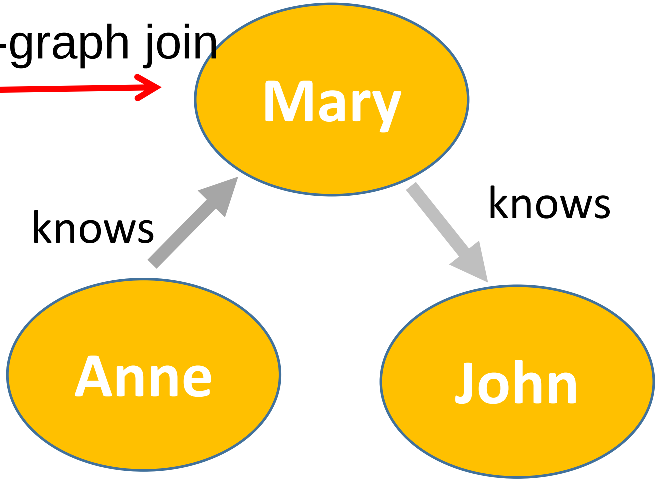
Order JSON document

Customer relation

| Customer_ID | Name | Credit_limit |
|---|---|---|
| 1 | Mary | 5,000 |
| 2 | John | 3,000 |
| 3 | William | 2,000 |

# An example of multi-model data and query

Tabular-graph join




Graph-key/value join

"1" -- > "34e5e759"
"2"-- > "0c6df508"

Key/value-JSON join

```
{"Order_no":"0c6df508",
 "Orderlines": [
   { "Product_no":"2724f",
     "Product_Name":"Toy",
     "Price":66 },
   { "Product_no":"3424g",
     "Product_Name":"Book",
     "Price":40 } ]
}
```

| Customer_ID | Name | Credit_limit |
|---|---|---|
| 1 | Mary | 5,000 |
| 2 | John | 3,000 |
| 3 | Anne | 2,000 |

Recommendation query:

Return all product_no which are ordered by a friend of a customer whose credit_limit>3000

# An example of multi-model query (ArangoDB)

Description: Return all products which are ordered by a friend of a customer whose credit_limit>3000

```
Let CustomerIDs =(FOR Customer IN Customers FILTER
Customer.CreditLimit > 3000 RETURN Customer.id)

Let FriendIDs=(FOR CustomerID in CustomerIDs FOR Friend IN
1..1 OUTBOUND CustomerID Knows return Friend.id)

For Friend in FriendIDs

For Order in 1..1 OUTBOUND Friend Customer2Order

Return Order.orderlines[*].Product_no
```

Result: `["2724f", "3424g"]`

OrientDB®

- Supporting graph, document, key/value and object models.

- The relationships are managed as in graph databases with direct connections between records.

- It supports schema-less, schema-full and schema-hybrid modes.

- Query with SQL extended for graph traversal.

Description: Return all products which are ordered by a friend of a customer whose credit_limit>3000

```
Select expand(out("Knows").Orders.orderlines.Product_no)
from Customers where Credit_limit > 3000
```

Result: ["2724f", "3424g"]

# Outline

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# Classification and Timeline

| | |
|---|---|
| **Relational** | PostgreSQL, SQL Server, IBM DB2, Oracle DB, Oracle MySQL, Sinew |
| **Column** | Cassandra, CrateDB, DynamoDB, HPE Vertica |
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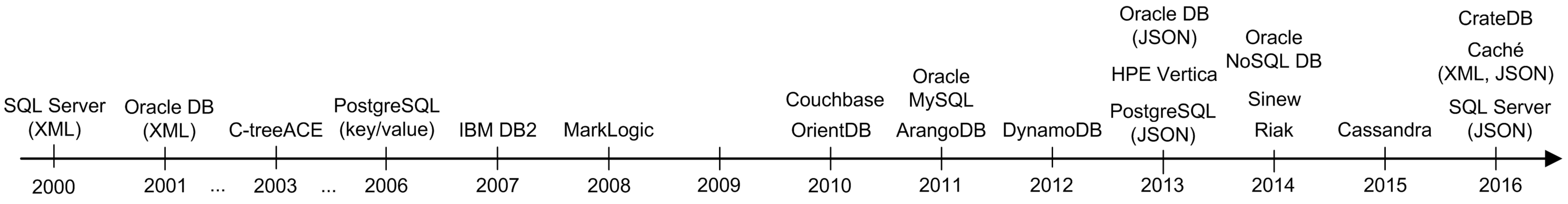

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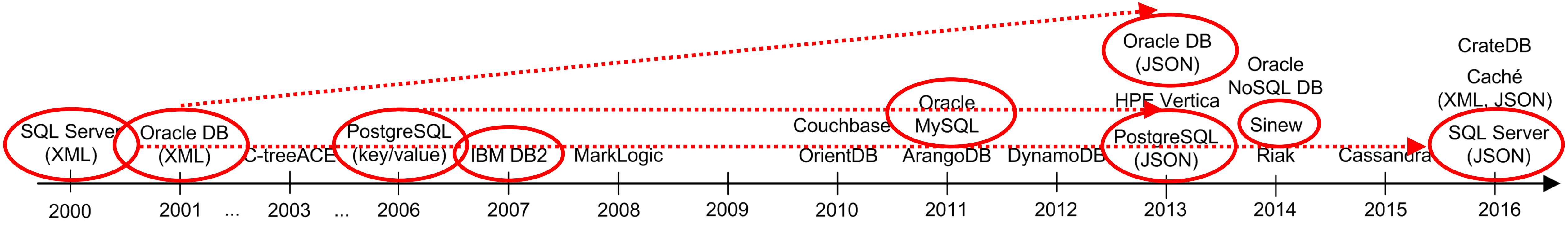

# Relational Multi-Model DBMSs

## Storage

- Biggest set:
  1. Most popular type of DBMSs
  2. Extended to other models long before Big Data arrival
  3. Relational model enables simple extension
- **PostgreSQL**
  - Many NoSQL features: materialized views (data duplicities), master/slave replication
  - Data types: `XML`, `HSTORE` (key/value pairs), `JSON` / `JSONB` (JSON)
- **SQL Server**
  - Data types: `XML`, `NVARCHAR` (JSON)
  - SQLXML (not SQL/XML)
  - Function `OPENJSON`: JSON text → relational table
    - Pre-defined schema and mapping rules / without a schema (a set of key/value pairs)

# Relational Multi-Model DBMSs

Storage

- **IBM DB2**
  - PureXML – native XML storage (or shredding into tables)
  - DB2-RDF – RDF graphs
    - Direct primary – triples + associated graph, indexed by subject
    - Reverse primary – triples + associated graph, indexed by object
    - Direct secondary – triples that share the subject and predicate within an RDF graph
    - Reverse secondary – triples that share the object and predicate within an RDF graph
    - Datatypes – mapping of internal integer values for SPARQL data types
- **Oracle DB**
  - Data types: `XMLType` (or shredded into tables), `VARCHAR` / `BLOB` / `CLOB` (JSON)
    - `is_json` check constraint

# Relational Multi-Model DBMSs

Storage

- **Oracle MySQL**
  - Memcached API (2011): key/value data access
    - Default: key/value pairs are stored in rows of the same table
    - Key prefix can be defined to specify the table to be stored
  - Stength: combination with relational data access
  - MySQL cluster (2014): sharding and replication
- **Sinew**
  - Idea: a new layer above a relational DBMS that enables SQL queries over multi-structured data without having to define a schema
    - Relational, key-value, nested document etc.
  - Logical view = a universal relation
    - One column for each unique key in the data set
    - Nested data is flattened into separate columns

Daniel Tahara, Thaddeus Diamond, and Daniel J. Abadi. 2014. Sinew: a SQL system for multi-structured data.*2014 ACM SIGMOD*. ACM, New York, NY, USA, 815-826.

# Relational Multi-Model DBMSs

## Storage – PostgreSQL Example

PostgreSQL

```
CREATE TABLE customer (
id        INTEGER PRIMARY KEY,
          name    VARCHAR(50),
          address VARCHAR(50),
              orders  JSONB
              );
```

```
INSERT INTO customer
VALUES (1, 'Mary', 'Prague',
 '{"Order_no":"0c6df508",
   "Orderlines":[
    {"Product_no":"2724f", "Product_Name":"Toy",  "Price":66 },
    {"Product_no":"3424g", "Product_Name":"Book", "Price":40}]
 }');

INSERT INTO customer
VALUES (2, 'John', 'Helsinki',
 '{"Order_no":"0c6df511",
   "Orderlines":[
    { "Product_no":"2454f", "Product_Name":"Computer", "Price":34 }]
 }');
```

| id<br>integer | name<br>character varying (50) | address<br>character varying (50) | orders<br>jsonb |
|---|---|---|---|
| 1 | Mary | Prague | {"Orderlines":[{"Price":66,"Product_Name":"Toy","Product_no":"2724f"},{"Price":40,"Product_Name":... |
| 2 | John | Helsinki | {"Orderlines":[{"Price":34,"Product_Name":"Computer","Product_no":"2454f"}],"Order_no":"0c6df511"} |

# Relational Multi-Model DBMSs

## Storage – PostgreSQL Example

```
SELECT json_build_object('id',id,'name',name,'orders',orders) FROM customer;
```

| json_build_object<br>json |
|---|
| {"orders":{"Orderlines":[{"Price":66,"Product_Name":"Toy","Product_no":"2724f"},{"Price":40,"Product_Name":"Book","Product_no":"3... |
| {"orders":{"Orderlines":[{"Price":34,"Product_Name":"Computer","Product_no":"2454f"}],"Order_no":"0c6df511"},"id":2,"name":"John"} |

```
SELECT jsonb_each(orders) FRO
```

| jsonb_each<br>record |
|---|
| (Order_no,"""0c6df508""") |
| (Orderlines,"[{""Price"": 66, ""Product_no"": ""2724f"", ""Product_Name"": ""To... |
| (Order_no,"""0c6df511""") |
| (Orderlines,"[{""Price"": 34, ""Product_no"": ""2454f"", ""Product_Name"": ""Co... |

```
SELECT jsonb_object_keys(orders) FROM cust
```

| jsonb_object_keys<br>text |
|---|
| Order_no |
| Orderlines |
| Order_no |
| Orderlines |

# Relational Multi-Model DBMSs

| | Formats | Storage strategy | Query languages | Indices | Scale out | Flexible schema | Comb. data | Cloud |
|---|---|---|---|---|---|---|---|---|
| PostgreSQL | relational, key/value, JSON, XML | relational tables - text or binary format + indices | SQL ext. | inverted | N | Y | Y | N |
| SQL Server | relational, XML, JSON, ... | text, relational tables | SQL ext. | B-tree, full-text | Y | Y | Y | N |
| IBM DB2 | relational, XML, RDF | native XML type / relations for RDF | Extended SQL / XML / SPARQL 1.0/1.1 | XML paths / B+ tree, fulltext | Y | Y | Y | N |
| Oracle DB | relational, XML, JSON | relational, native XML | SQL/XML, JSON SQL ext. | bitmap, B+ tree, function-based, XMLIndex | Y | N | Y | Y |
| Oracle MySQL | relational, key/value | relational | SQL, memcached API | B-tree | Y | N | Y | Y |
| Sinew | relational, key/value, nested document, ... | logically a universal relation, physically partially materialized | SQL | - | - | Y | Y | N |

# Classification and Timeline

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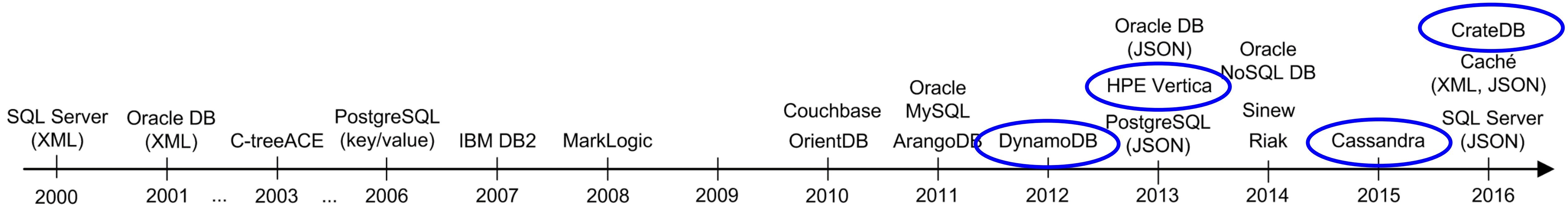

# Column Multi-Model DBMSs

## Storage

- Two meanings:
  1. Column-oriented (columnar, column) DBMS stores data tables as columns rather than rows
     - Not necessarily NoSQL, usually in analytics tools
  2. Column (wide-column) DBMS = a NoSQL database which supports tables having distinct numbers and types of columns
     - Underlying storage strategy can be columnar, or any other
- **Cassandra**
  - Column store with sparse tables
    - SSTables (Sorted String Tables) – proposed in Google system Bigtable
  - SQL-like query and manipulation language CQL
    - Scalar data types (text, int), collections (list, set, map), tuples, and UDTs
    - 2015: JSON format (schema of tables must be defined)
      - Keys ↔ column names
      - JSON values ↔ column values

# Column Multi-Model DBMSs

## Storage

CRATE.IO

- **CrateDB**
  - Distributed columnar SQL database, dynamic schema
    - Built upon Elasticsearch, Lucene, …
  - Nested JSON documents, arrays, BLOBs
  - Row of a table = (nested) structured document
    - Operations on documents are atomic
- **DynamoDB**
  - Document (JSON) and key/value flexible data models
  - (Schemaless) table = collection of items
    - Item (uniquely identified by a primary key) = collection of attributes
      - Attribute = name + data type + value
      - Data type: value (string, number, Boolean …), document (list or map), set of scalar values
  - Data items in a table need not have the same attributes

Amazon DynamoDB

# Column Multi-Model DBMSs

## Storage

- **HPE Vertica**
  - High-performance analytics engine
  - Storage organization: column oriented + SQL interface + analytics capabilities
  - 2013 – flex tables
    - Do not require schema definitions
    - Enable to store semi-structured data (JSON, CSV,…)
    - Support SQL queries
    - Loaded data stored in internal map (set of key/value pairs) = virtual columns
      - Selected keys can be materialized = real table columns

# Column Multi-Model DBMSs

## Storage – Cassandra Example

```
create keyspace myspace
WITH REPLICATION = { 'class' : 'SimpleStrategy', 'replication_factor' : 3 };

CREATE TYPE myspace.orderline (
product_no text,
product_name text,
price float
);

CREATE TYPE myspace.myorder (
order_no text,
orderlines list<frozen <orderline>>
);

CREATE TABLE myspace.customer (
id INT PRIMARY KEY,
name text,
address text,
orders list<frozen <myorder>>
);
```

# Column Multi-Model DBMSs

## Storage – Cassandra Example

```
INSERT INTO myspace.customer JSON
                       ' {"id":1,
                  "name":"Mary",
             "address":"Prague",
                     "orders" : [
        { "order_no":"0c6df508",
                  "orderlines":[
       { "product_no" : "2724f",
         "product_name" : "Toy",
                  "price" : 66 },
        { "product_no" : "3424g",
         "product_name" :"Book",
            "price" : 40 } ] } ]
                              }';
```

```
INSERT INTO myspace.customer JSON
                       ' {"id":2,
                  "name":"John",
           "address":"Helsinki",
                     "orders" : [
        { "order_no":"0c6df511",
                  "orderlines":[
       { "product_no" : "2454f",
    "product_name" : "Computer",
           "price" : 34 } ] } ]
                              }';
```

# Column Multi-Model DBMSs

## Storage – Cassandra Example

```
CREATE TABLE myspace.users (
   id text PRIMARY KEY,
   age int,
   country text
   );

INSERT INTO myspace.users (id, age, state) VALUES ('Irena', 37, 'CZ');

SELECT JSON * FROM myspace.users;


[json]
------------------------------------------
{"id": "Irena", "age": 37, "country": "CZ"}
```

# Column Multi-Model DBMSs

| | Formats | Storage strategy | Query languages | Indices | Scale out | Flexible schema | Comb. data | Cloud |
|---|---|---|---|---|---|---|---|---|
| **Cassandra** | text, user-defined type | sparse tables | SQL-like CQL | inverted, B+ tree | Y | N | Y | Y |
| **CrateDB** | relational, JSON, BLOB, arrays | columnar store based on Lucene and Elasticsearch | SQL | Lucene | Y | Y | Y | N |
| **DynamoDB** | key/value, document (JSON) | column store | simple API (get / put / update) + simple queries over indices | hashing | Y | Y | Y | Y |
| **HPE Vertica** | JSON, CSV | flex tables + map | SQL-like | for materialized data | Y | Y | Y | N |

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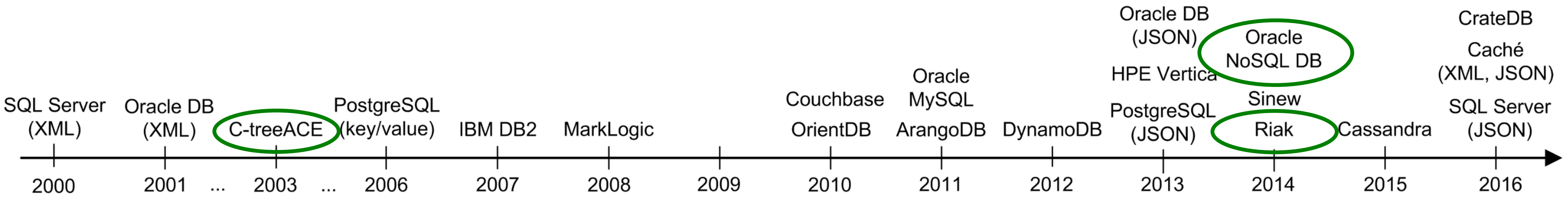


# Key/Value Multi-Model DBMSs

Storage

- Riak
  - 2009: classical key/value DBMS
  - 2014: document store with querying capabilities
    - Riak Data Types – conflict-free replicated data type
      - Sets, maps (enable embedding), counters,…
    - Riak Search – integration of Solr for indexing and querying
      - Indices over particular fields of XML/JSON document, plain text, …
- c-treeACE
  - No+SQL = both NoSQL and SQL in a single database
  - Key/value store + support for relational and non-relational APIs
  - Record-oriented Indexed Sequential Access Method (ISAM) structure
    - Operations with records, their sets, or files in which they are stored

# Key/Value Multi-Model DBMSs

## Storage

- **Oracle NoSQL DB**
  - Built upon the Oracle Berkeley DB
    - Released in 2011
  - Key/value store which supports table API = SQL (since 2014)
    - Data can be modelled as:
      - Relational tables
      - JSON documents
      - Key/value pairs
  - Definition of tables must be provided
    - Table and attribute names, data types, keys, indices, …
    - Data types: scalar types, arrays, maps, records, child tables (nested subtables)

# Key/Value Multi-Model DBMSs

## Storage – Oracle NoSQL DB Example

ORACLE NOSQL DATABASE

```
create table Customers (
  id integer,
  name string,
  address string,
  orders array (
    record (
      order_no string,
      orderlines array (
        record (
          product_no string,
          product_name string,
          price integer ) ) )
    ),
  primary key (id)
);

import -table Customers -file customer.json
```

customer.json:

```
{   "id":1,
    "name":"Mary",
    "address":"Prague",
    "orders" : [
      { "order_no":"0c6df508",
        "orderlines":[
          { "product_no" : "2724f",
            "product_name" : "Toy",
            "price" : 66 },
          { "product_no" : "3424g",
            "product_name"  :"Book",
            "price" : 40 } ] } ]
}
{   "id":2,
    "name":"John",
    "address":"Helsinki",
    "orders" : [
      {"order_no":"0c6df511",
       "orderlines":[
        { "product_no" : "2454f",
          "product_name" : "Computer",
          "price" : 34  } ] } ]
}
```

# Key/Value Multi-Model DBMSs

## Storage – Oracle NoSQL DB Example

ORACLE NOSQL DATABASE

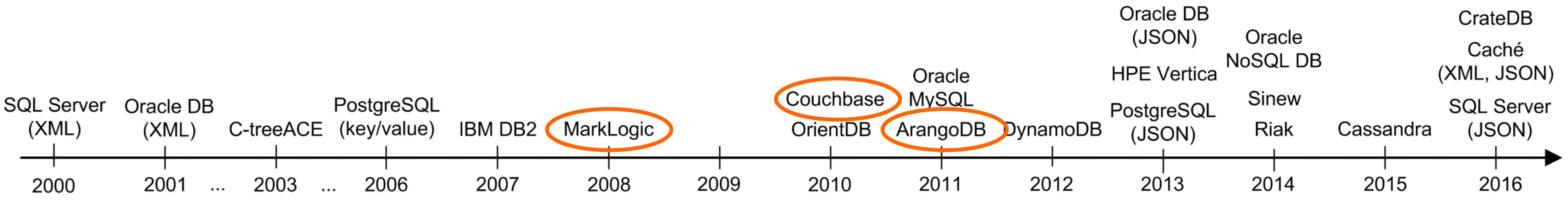
```
sql-> select * from Customers
  -> ;
 +----+------+----------+------------------------------+
 | id | name | address  |            orders            |
 +----+------+----------+------------------------------+
 |  2 | John | Helsinki | order_no           | 0c6df511 |
 |    |      |          | orderlines                   |
 |    |      |          |     product_no     | 2454f    |
 |    |      |          |     product_name   | Computer |
 |    |      |          |     price          | 34       |
 +----+------+----------+------------------------------+
 |  1 | Mary | Prague   | order_no           | 0c6df508 |
 |    |      |          | orderlines                   |
 |    |      |          |     product_no     | 2724f    |
 |    |      |          |     product_name   | Toy      |
 |    |      |          |     price          | 66       |
 |    |      |          |                              |
 |    |      |          |     product_no     | 3424g    |
 |    |      |          |     product_name   | Book     |
 |    |      |          |     price          | 40       |
 +----+------+----------+------------------------------+
```

# Key/Value Multi-Model DBMSs

| | Formats | Storage strategy | Query languages | Indices | Scale out | Flexible schema | Comb. data | Cloud |
|---|---|---|---|---|---|---|---|---|
| **Riak** | key/value, XML, JSON | key/value pairs in buckets | Solr | Solr | Y | N | Y | N |
| **c-treeACE** | key/value + SQL API | record-oriented ISAM | SQL | ISAM | Y | Y | - | N |
| **Oracle NoSQL DB** | key/value, (hierarchical) table API | key/value | SQL | B-tree | Y | N | Y | N |

# Classification and Timeline

| | |
|---|---|
| **Relational** | PostgreSQL, SQL Server, IBM DB2, Oracle DB, Oracle MySQL, Sinew |
| **Column** | Cassandra, CrateDB, DynamoDB, HPE Vertica |
| **Key/value** | Riak, c-treeACE, Oracle NoSQL DB |
| **Document** | ArangoDB, Couchbase, MarkLogic |
| **Graph** | OrientDB |
| **Object** | InterSystems Caché |
| **Special** | • Not yet multi-model – NuoDB, Redis, Aerospike<br>• Multi-use-case – SAP HANA DB, Octopus DB |



# Document Multi-Model DBMSs

## Storage

- Document DB = key/value, where value is complex
  - Multi-model extension is natural
- **ArangoDB**
  - Denoted as native multi-model database
  - Key/value, (JSON) documents and graph data
    - Document collection – always a primary key attribute
      - No secondary indices → simple key/value store
    - Edge collection – two special attributes `from` and `to`
      - Relations between documents
- **Couchbase**
  - Key/value + (JSON) document
    - No pre-defined schema
  - SQL-based query language
  - Memcached buckets – support caching of frequently-used data
    - Reduce the number of queries

# Document Multi-Model DBMSs

## Storage

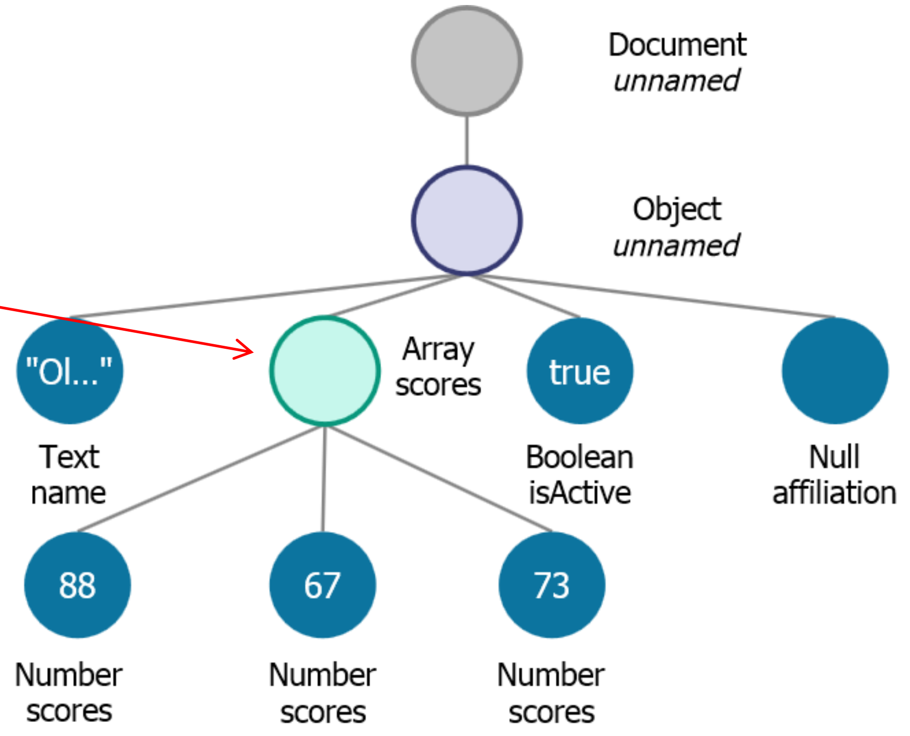
- **MarkLogic**
  - Originally XML
    - Since 2008: JSON
    - Currently: RDF, textual, binary data
  - Models a JSON document similarly to an XML document = a tree
    - Rooted at an auxiliary document node
    - Nodes below: JSON objects, arrays, and text, number, Boolean, null values

  → unified way to manage and index documents of both types

# Document Multi-Model DBMSs

## Storage – MarkLogic Example

```
{
  "name": "Oliver",
  "scores": [88, 67, 73],
  "isActive": true,
  "affiliation": null
}
```



# Document Multi-Model DBMSs

MarkLogic

## Storage – MarkLogic Example

JavaSript:

```
declareUpdate();
xdmp.documentInsert("/myJSON1.json",
{
  "Order_no":"0c6df508",
   "Orderlines":[
    { "Product_no":"2724f",
      "Product_Name":"Toy",
      "Price":66 },
    {"Product_no":"3424g",
     "Product_Name":"Book",
     "Price":40}]
}
);
```

XQuery:

```
xdmp:document-insert("/myXML1.xml",
<product no="3424g">
  <name>The King's Speech</name>
  <author>Mark Logue</author>
  <author>Peter Conradi</author>
</product>
);;
```

# Document Multi-Model DBMSs

| | Formats | Storage strategy | Query languages | Indices | Scale out | Flexible schema | Comb. data | Cloud |
|---|---|---|---|---|---|---|---|---|
| **ArangoDB** | key/value, document, graph | document store allowing references | SQL-like AQL | mainly hash (eventually unique or sparse) | Y | Y | Y | N |
| **Couchbase** | key/value, document, distributed cache | document store + append-only write | SQL-based N1QL | B+tree, B+trie | Y | Y | Y | N |
| **MarkLogic** | XML, JSON, RDF, binary, text, ... | storing like hierarchical XML data | XPath, XQuery, SQL-like | inverted + native XML | Y | Y | Y | N |

# Classification and Timeline

| | |
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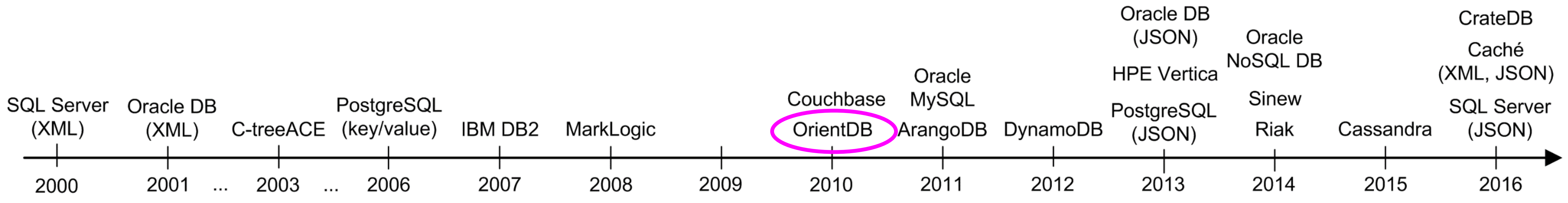


# Graph Multi-Model DBMSs

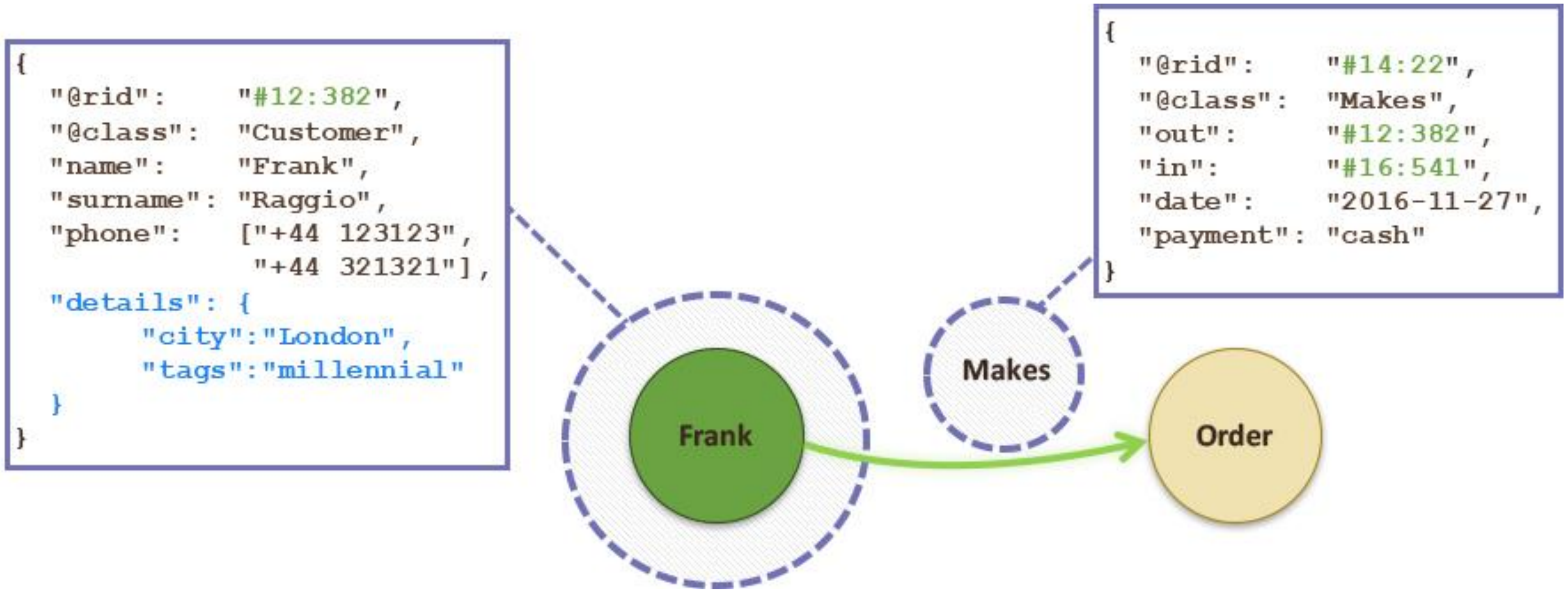
## Storage

- **OrientDB**
  - Data models: graph, document, key/value, object
  - Element of storage = a record corresponding to document / BLOB / vertex / edge
    - Having a unique ID
  - Classes – contain and define records
    - Schema-less / schema-full / schema-mixed
    - Can inherit (all properties) from other classes
      - Class properties are defined, further constrained or indexed
  - Classes can have relationships:
    - Referenced relationships – stored similarly to storing pointers between two objects in memory
      - `LINK`, `LINKSET`, `LINKLIST`, `LINKMAP`
    - Embedded relationships – stored within the record that embed
      - `EMBEDDED`, `EMBEDDEDSET`, `EMBEDDEDLIST`. `EMBEDDEDMAP`

| | Formats | Storage strategy | Query languages | Indices | Scale out | Flexible schema | Comb. data | Cloud |
|---|---|---|---|---|---|---|---|---|
| OrientDB | graph, document, key/value, object | key/value pairs + object-oriented links | Gremlin, SQL ext. | SB-tree, ext. hashing, Lucene | Y | Y | Y | N |

# Graph Multi-Model DBMSs

Storage –OrientDB Example



# Graph Multi-Model DBMSs

## Storage – OrientDB Example

```
CREATE CLASS orderline EXTENDS V
CREATE PROPERTY orderline.product_no STRING
CREATE PROPERTY orderline.product_name STRING
CREATE PROPERTY orderline.price FLOAT

CREATE CLASS order EXTENDS V
CREATE PROPERTY order.order_no STRING
CREATE PROPERTY order.orderlines EMBEDDEDLIST orderline

CREATE CLASS customer EXTENDS V
CREATE PROPERTY customer.id INTEGER
CREATE PROPERTY customer.name STRING
CREATE PROPERTY customer.address STRING

CREATE CLASS orders EXTENDS E

CREATE CLASS knows EXTENDS E
```

# Graph Multi-Model DBMSs

## Storage – OrientDB Example

```
CREATE VERTEX order CONTENT {
   "order_no":"0c6df508",
   "orderlines":[
    { "@type":"d",
      "@class":"orderline",
      "product_no":"2724f",
      "product_name":"Toy",
      "price":66 },
    { "@type":"d",
      "@class":"orderline",
      "product_no":"3424g",
      "product_name":"Book",
      "price":40}]
}
```

```
CREATE VERTEX order CONTENT {
   "order_no":"0c6df511",
   "orderlines":[
    { "@type":"d",
      "@class":"orderline",
      "product_no":"2454f",
      "product_name":"Computer",
      "price":34 }]
}
```

```
CREATE VERTEX customer CONTENT {
  "id" : 1,
  "name" : "Mary",
  "address" : "Prague"
  }
```

```
CREATE VERTEX customer CONTENT {
  "id" : 2,
  "name" : "John",
  "address" : "Helsinki"
  }
```

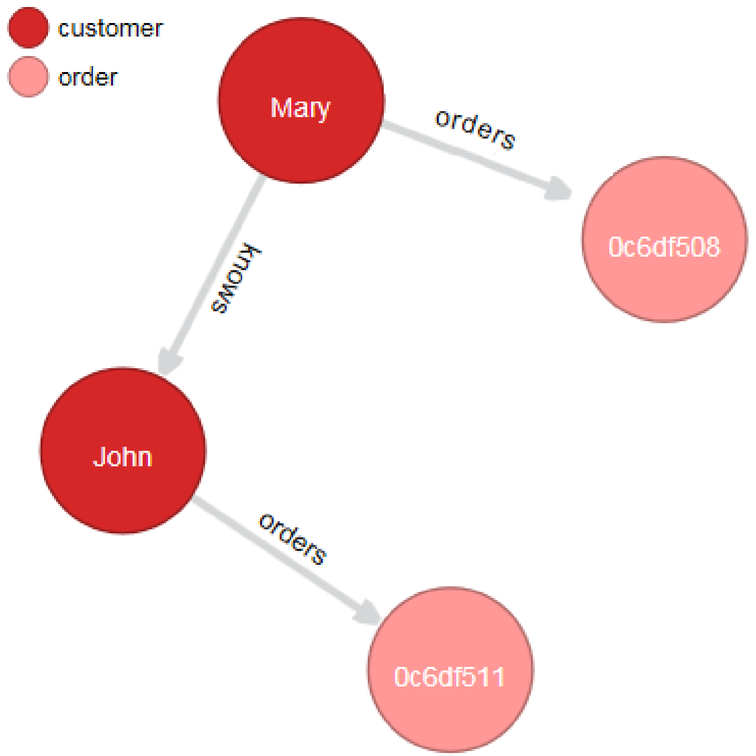
# Graph Multi-Model DBMSs

## Storage – OrientDB Example

```
CREATE EDGE orders FROM
    (SELECT FROM customer WHERE name = "Mary")
   TO
    (SELECT FROM order WHERE order_no = "0c6df508")

CREATE EDGE orders FROM
    (SELECT FROM customer WHERE name = "John")
   TO
    (SELECT FROM order WHERE order_no = "0c6df511")

CREATE EDGE knows FROM
    (SELECT FROM customer WHERE name = "Mary")
   TO
    (SELECT FROM customer WHERE name = "John")
```



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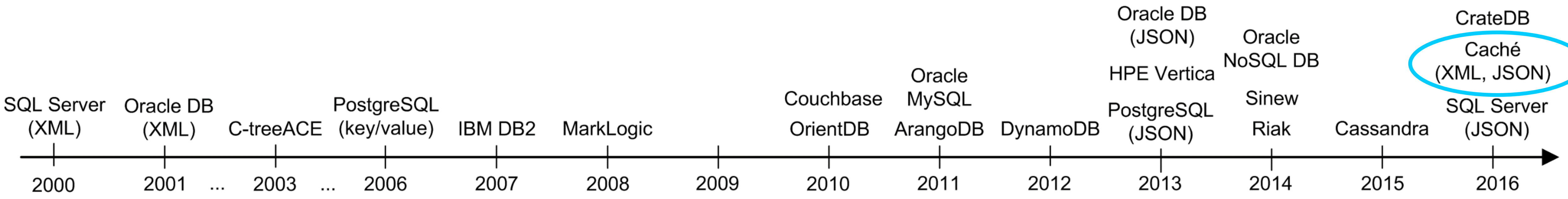

# Object Multi-Model DBMSs

## Storage

- Object model = storing any kind of data → multi-model extension is natural
- **InterSystems Caché**
  - Stores data in sparse, multidimensional arrays
    - Capable of carrying hierarchically structured data
  - Access APIs: object (ODMG), SQL, direct manipulation of multidimensional data structures
    - Schemaless and schema-based storage strategy is available
  - 2016: JSON, XML

| | Formats | Storage strategy | Query languages | Indices | Scale out | Flexible schema | Comb. data | Cloud |
|---|---|---|---|---|---|---|---|---|
| **Caché** | object, SQL or multi-dimensional, document (JSON, XML) API | multi-dimensional arrays | SQL with object extensions | bitmap, bitslice, standard | Y | Y | - | N |

# Not (yet) multi-model

- **NuoDB** – NewSQL cloud DBMS
  - Data is stored in and managed through objects called Atoms
    - Self-coordinating objects (data, indices or schemas)
  - Atomicity, Consistency and Isolation are applied to Atom interaction
    - Replacing the SQL front-end would have no impact
- **Redis** – NoSQL key/value DBMS
  - Support for strings + a list of strings, an (un)ordered set of strings, a hash table, … + respective operations
  - Redis Modules – add-ons which extend Redis to cover most of the popular use cases
- **Aerospike** – NoSQL key/value DBMS
  - Support for maps and lists in the value part that can nest
  - 2012 - Aerospike acquired AlchemyDB
    - Aim: to integrate its index, document store, graph database, and SQL functionality

# Outline

- Introduction to multi-model databases
- Multi-model data storage
- Multi-model data query languages
- Multi-model query optimization
- Multi-model database benchmarking
- Open problems and challenges

# Classification of Approaches

- Simple API
  - Store, retrieve, delete data
    - Typically key/value, but also other use cases
  - **DynamoDB** – simple data access + querying over indices using comparison operators
- SQL Extensions and SQL-Like Languages
  - Most common
  - **PostgreSQL** – SQL extension for JSON
  - **Cassandra** – CQL = subset of SQL, lots of limitations
  - **OrientDB** – Gremlin or SQL extended for graph traversal
  - **SQL Server** – SQLXML + similar extension for JSON
    - Not SQL/XML standard!

# Classification of Approaches

- **IBM DB2** – SQL/XML + further extensions for XML
- **Oracle DB** – SQL/XML + further extensions for JSON
- **ArangoDB** – AQL = SQL-like + concept of loops
- **InterSystems Caché** – SQL + object concepts
  - Instances of classes accessible as rows of tables
  - Inheritance is “flattened”
- **Couchbase** – $N_1QL$ = SQL-like for JSON
- **CrateDB** – standard ANSI SQL 92 + usage of nested JSON attributes

| | | |
|---|---|---|
| **PostgreSQL** | relational | Getting an array element by index, an object field by key, an object at a specified path, containment of values/paths, top-level key-existence, deleting a key/value pair / a string element / an array element with specified index /a field / an element with specified path,… |
| **SQL Server** | relational | JSON: export relational data in the JSON format, test JSON format of a text value, JavaScript-like path queries,<br>SQLXML: SQL view of XML data + XML view of SQL relations |
| **IBM DB2** | relational | SQL/XML + e.g. embedding SQL queries to XQuery expressions |
| **Oracle DB** | relational | SQL/XML + JSON extensions (`JSON_VALUE`, `JSON_QUERY`, `JSON_EXISTS`,…) |
| **Couchbase** | document | Classical clauses such as `SELECT`, `FROM` (multiple buckets), … for JSON |
| **ArangoDB** | document | key/value: insert, look-up, update<br>document: simple QBE, complex joins, functions, …<br>graph: traversals, shortest path searches |
| **Oracle NoSQL DB** | key/value | SQL-like, extended for nested data structures |
| **c-treeACE** | key/value | SQL-like language |
| **Cassandra** | column | `SELECT`, `FROM`, `WHERE`, `ORDER BY`, `LIMIT` with limitations |
| **CrateDB** | column | Standard ANSI SQL 92 + usage nested JSON attributes |
| **OrientDB** | graph | Classical joins not supported, the links are simply navigated using dot notation; main SQL clauses + nested queries |
| **Caché** | object | SQL + object extensions (e.g. object references instead of joins) |

# SQL Extensions and SQL-Like Languages

## PostgreSQL Example (relational)

PostgreSQL

| id integer | name character varying (50) | address character varying (50) | orders jsonb |
|---|---|---|---|
| 1 | Mary | Prague | {"Orderlines":[{"Price":66,"Product_Name":"Toy","Product_no":"2724f"},{"Price":40,"Product_Name":... |
| 2 | John | Helsinki | {"Orderlines":[{"Price":34,"Product_Name":"Computer","Product_no":"2454f"}],"Order_no":"0c6df511"} |

```
{"Order_no":"0c6df508",
   "Orderlines":[
    { "Product_no":"2724f",
      "Product_Name":"Toy",
      "Price":66 },
    {"Product_no":"3424g",
     "Product_Name":"Book",
     "Price":40}]
}
```

```
SELECT name,
orders->>'Order_no' as Order_no,
orders#>'{Orderlines,1}'->>'Product_Name' as Product_Name
FROM customer
where orders->>'Order_no' <> '0c6df511';
```

| name character varying (50) | order_no text | product_name text |
|---|---|---|
| Mary | 0c6df508 | Book |

# SQL Extensions and SQL-Like Languages

## Oracle NoSQL DB Example (key/value)

ORACLE NOSQL DATABASE

```
sql-> SELECT c.name, c.orders.order_no, c.orders.orderlines[0].product_name
   -> FROM customers c
   -> where c.orders.orderlines[0].price > 50;
 +------+----------+--------------+
 | name | order_no | product_name |
 +------+----------+--------------+
 | Mary | 0c6df508 | Toy          |
 +------+----------+--------------+
```

```
sql-> SELECT c.name, c.orders.order_no,
   -> [c.orders.orderlines[$element.price >35]]
   -> FROM customers c;
 +------+----------+------------------------+
 | name | order_no |        Column_3        |
 +------+----------+------------------------+
 | Mary | 0c6df508 | product_no   | 2724f   |
 |      |          | product_name | Toy     |
 |      |          | price        | 66      |
 |      |          |                         |
 |      |          | product_no   | 3424g   |
 |      |          | product_name | Book    |
 |      |          | price        | 40      |
 +------+----------+------------------------+
 | John | 0c6df511 |                         |
 +------+----------+------------------------+
```

```
sql-> select * from Customers
  -> ;
 +----+------+----------+---------------------------+
 | id | name | address  |          orders           |
 +----+------+----------+---------------------------+
 |  2 | John | Helsinki | order_no        | 0c6df511 |
 |    |      |          | orderlines               |
 |    |      |          |     product_no   | 2454f    |
 |    |      |          |     product_name | Computer |
 |    |      |          |     price        | 34       |
 +----+------+----------+---------------------------+
 |  1 | Mary | Prague   | order_no        | 0c6df508 |
 |    |      |          | orderlines               |
 |    |      |          |     product_no   | 2724f    |
 |    |      |          |     product_name | Toy      |
 |    |      |          |     price        | 66       |
 |    |      |          |                           |
 |    |      |          |     product_no   | 3424g    |
 |    |      |          |     product_name | Book     |
 |    |      |          |     price        | 40       |
 +----+------+----------+---------------------------+
```

# Classification of Approaches

- SPARQL Query Extensions
  - **IBM DB2** - SPARQL 1.0 + subset of features from SPARQL 1.1
    - `SELECT`, `GROUP BY`, `HAVING`, `SUM`, `MAX`, …
    - Probably no extension for relational data
      - But: RDF triples are stored in table → SQL queries can be used over them too
- XML Query Extensions
  - **MarkLogic** – JSON can be accessed using XPath
    - Tree representation like for XML
    - Can be called from XQuery and JavaScript
- Full-text Search
  - In general quite common
  - **Riak** – Solr index + operations
    - Wildcards, proximity search, range search, Boolean operators, grouping, …

# XML Query Extensions

## MarkLogic Example

MarkLogic

JavaSript:

```
declareUpdate();
xdmp.documentInsert("/myJSON1.json",
{
  "Order_no":"0c6df508",
   "Orderlines":[
    { "Product_no":"2724f",
      "Product_Name":"Toy",
      "Price":66 },
    {"Product_no":"3424g",
     "Product_Name":"Book",
     "Price":40}]
}
);
```

XQuery:

```
xdmp:document-insert("/myXML1.xml",
<product no="3424g">
  <name>The King's Speech</name>
  <author>Mark Logue</author>
  <author>Peter Conradi</author>
</product>
);
```

XQuery:

```
let $product := fn:doc("/myXML1.xml")/product
let $order := fn:doc("/myJSON1.json")[Orderlines/Product_no = $product/@no]
return $order/Order_no

Result: 0c6df508
```

# Outline

- Introduction to multi-model databases
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# Classification of Approaches

- Inverted Index
  - PostgreSQL – data in `jsonb`: GIN index = `(key, posting list)` pairs
    - But also B-tree and hash index
- B-tree, B+ tree
  - Cassandra
    - Primary key = always indexed using inverted index (auxiliary table)
    - Secondary index = memory mapped B+trees (range queries)
  - SQL Server – no special index for JSON (B-tree or full-text indices)
  - Couchbase – B+tree / B+trie (a hierarchical B+tree-based Trie) = a shallower tree hierarchy
  - Oracle DB
    - Shredded XML data = B+tree index
    - To index fields of a JSON object = virtual columns need to be created for them first + B+tree index
  - Oracle MySQL – mostly classical B-trees (spatial data R-trees)
  - Oracle NoSQL DB – secondary indices = distributed, shard-local B-trees
    - Indexing over simple, scalar as well as over non-scalar and nested data values

# Classification of Approaches

- Materialization
  - **HPE Vertica** – flex table can be processed using SQL commands + custom views can be created
    - SELECT invokes `maplookup()` function
    - Promoting virtual columns to real columns improves query performance
- Hashing
  - **OrientDB**
    - SB trees – B-tree optimized for data insertions and range queries
    - Extendible hashing – significantly faster
  - **ArangoDB**
    - Primary index – hash index for document `_key` attributes of all documents in a collection
    - Edge index – hash index for `_from` and `_to` attributes
    - User-defined indices – hash, unsorted (can be unique or sparse) → no range queries
  - **DynamoDB**
    - Primary key index: partition key (determine partition) + sort key (within partition)
    - Secondary index: global (involving partition key) and local (within a partition)

# Classification of Approaches

- Bitmap
  - **InterSystems Caché** – a series of highly compressed bitstrings to represent the set of object IDs = indexed value
    - Extended with bitslice index for numeric data fields used for a `SUM`, `COUNT`, or `AVG`
  - **Oracle DB** – can be created for a value returned by `json_exists`
- Function based
  - **Oracle DB** –indexes the function on a column = the product of the function
    - Can be created for SQL function `json_value`
    - For XML data deprecated

# Classification of Approaches

- Native XML
  - **MarkLogic**
    - Universal index – inverted index for each word (or phrase), XML element and JSON property and their values
      - Further optimized using hashing
    - Index of parent-child relationships
    - (User-specified) range indices – for efficient evaluation of range queries
      - An array of document ids and values sorted by document ids + an array of values and document ids sorted by values
      - Path range index – to index JSON properties defined by an XPath expression
  - **DB2** – XML region index, XML column path index, XML index
  - **Oracle DB** – XMLIndex = path index + order index + value index
    - Position of each node is preserved using a variant of the ORDPATHS numbering schema

# Query Optimization – Inverted Index

PostgreSQL Example (GIN – Generalized Inverted Index)

- Two types:
  - Default (`jsonb_ops`) - key-exists operators `?`, `?&` and `?|` and path/value-exists operator `@>`
    - Independent index items for each key and value in the data
  - Non-default (`jsonb_path_ops`) - indexing the `@>` operator only
    - Index items only for each value in the data
      - A hash of the value and the key(s) leading to it
- Example: `{"foo": {"bar": "baz"}}`
  - Default: three index items representing `foo`, `bar`, and `baz` separately
    - Containment query looks for rows containing all three of these items
  - Non-default: single index item (hash) incorporating `foo`, `bar`, and `baz`
    - Containment query searches for specific structure

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# Some Big data benchmarking initiatives

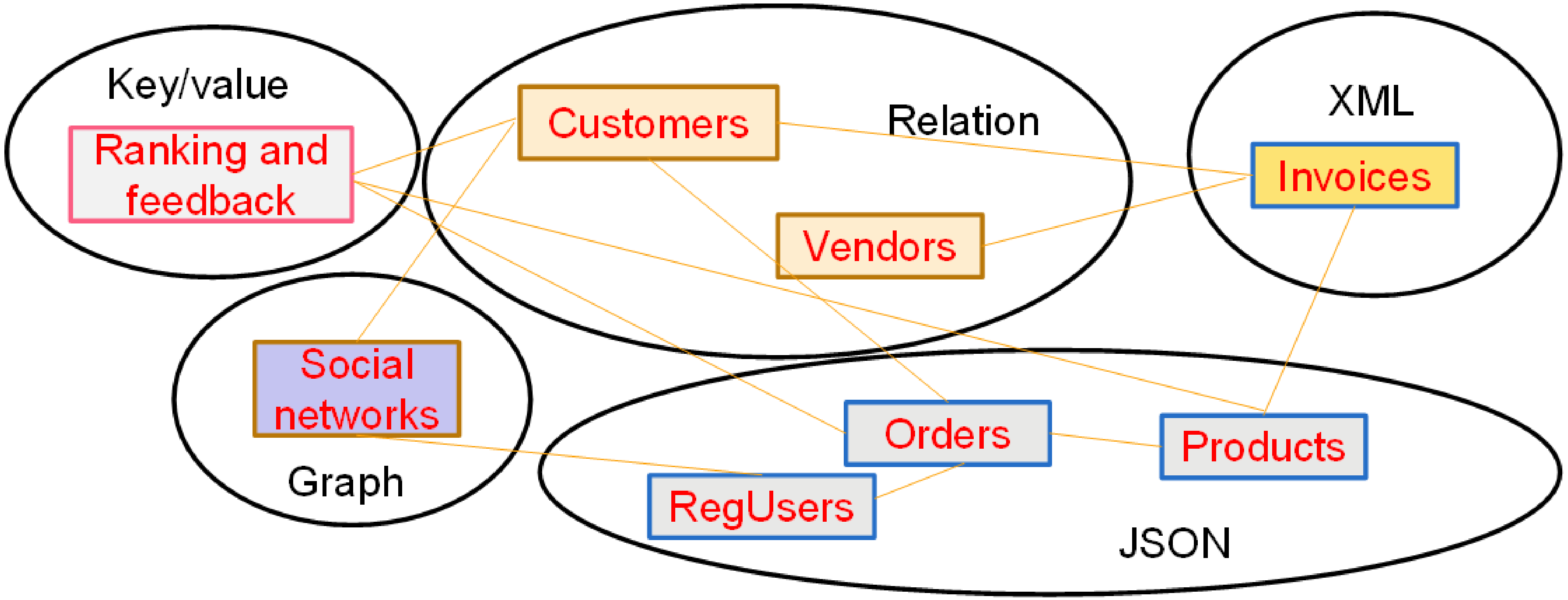
- HiBench, Yan Li et al., Intel
- Yahoo Cloud Serving Benchmark (YCSB), Brian Cooper et al., Yahoo!
- Berkeley Big Data Benchmark, Pavlo et al., AMPLab
- BigDataBench, Jianfeng Zhan, Chinese Academy of Sciences
- Bigframe
- LDCS graph and RDF benchmarking
- ……

# New challenges for multi-model databases

- Cross-model query processing
  - Complex joins of cross-model data
- Cross-model transaction
  - Transactions support cross-model
- Open schema data and model evolution
  - Query data with varied schemas and models

# UniBench: A unified benchmark for multi-model data

An E-commerce application involving multi-model data




J. Lu: Towards Benchmarking Multi-Model Databases. CIDR 2017

# Workloads

- Workload A: Data Insertion and reading
- Workload B: Cross-model query
- Workload C: Cross-model Transaction

# On-going work on multi-model benchmarking

- Flexible schema management
- Model evolution
- HTAP (Hybrid Transaction/Analytical Processing)

- The data and code (on-going update) can be downloaded at:
- http://udbms.cs.helsinki.fi/?projects/ubench

# Outline

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# Six challenges

Open data model

Unified query language

Schema evolution and model evolution

Multi-model databases

Multi-model index structure

Multi-model transactions

Multi-model main memory structure

# Open data model

A flexible data model to accommodate multi-model data
Providing a convenient unique interface to handle data from different sources

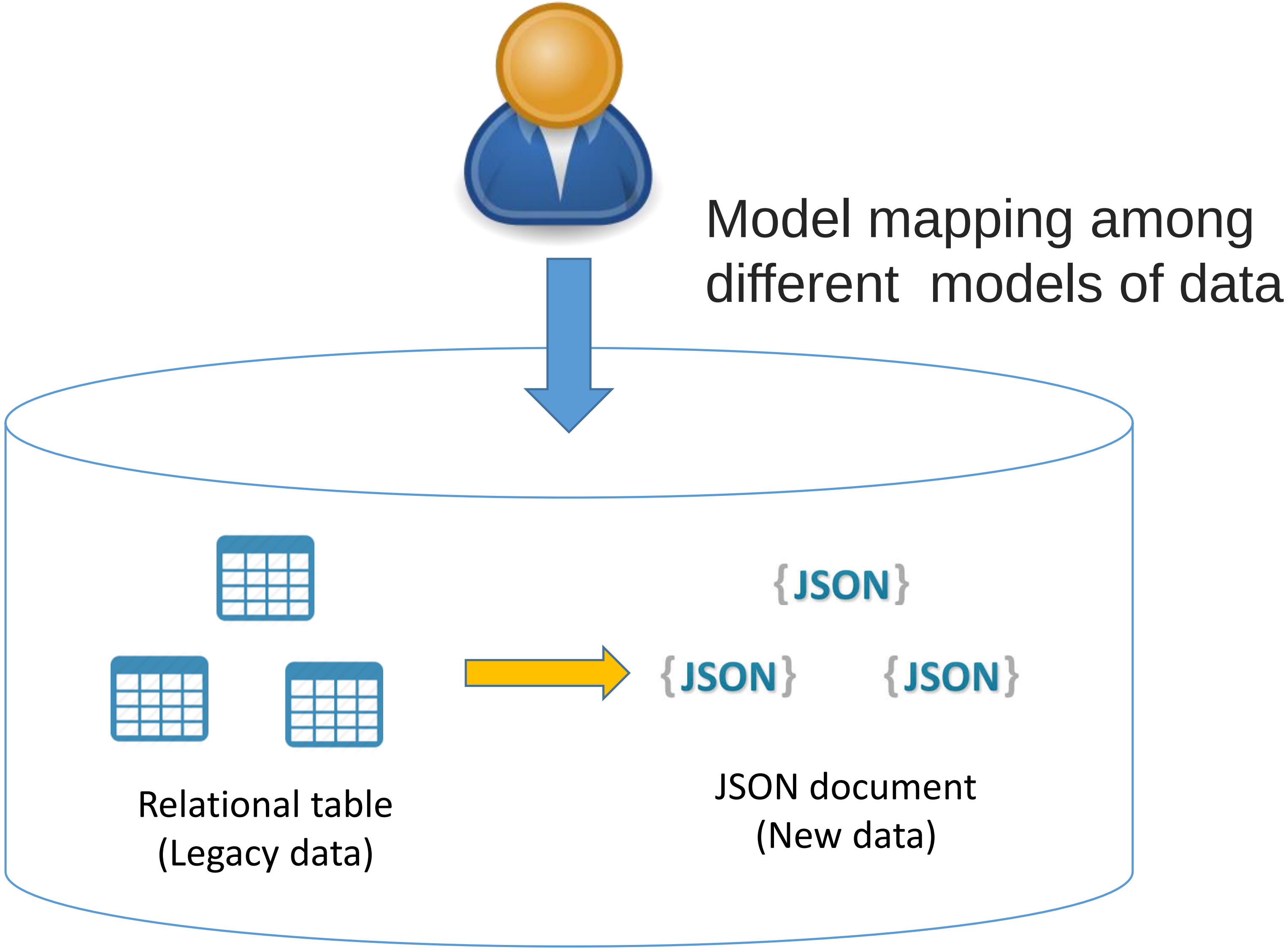
# Unified query language


A new  unified query language can query multi-model data together

# Multi-model query language

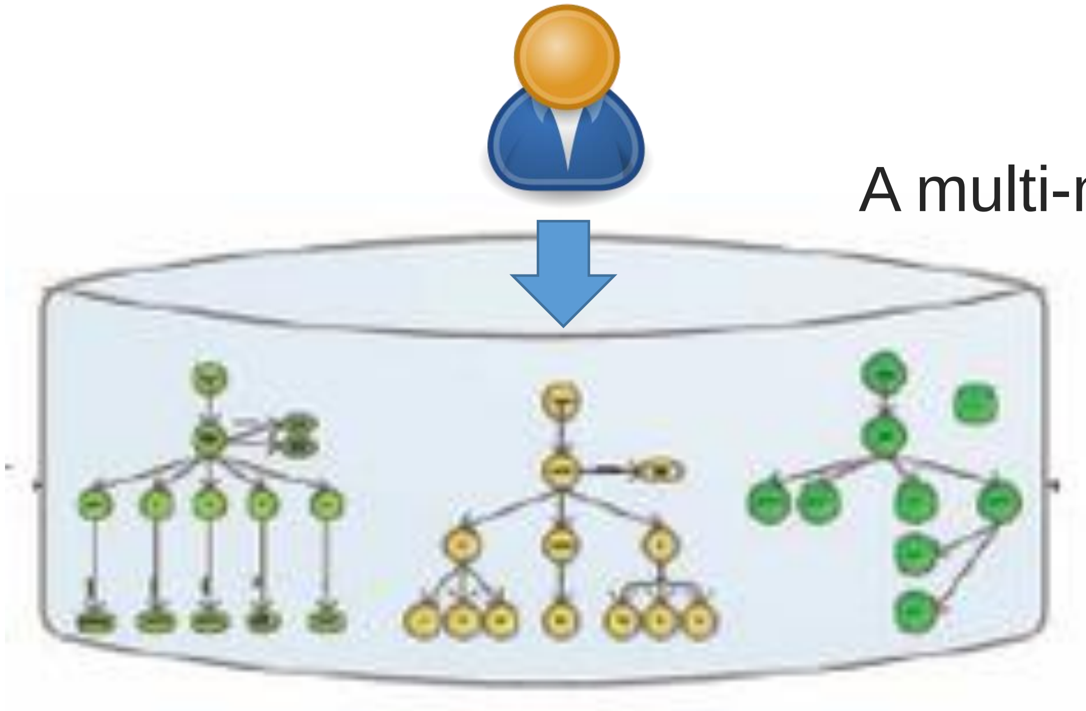
- SQL extension embedding data model specific languages
  - ORACLE: SQL/XML, SQL/JSON, SQL/SPARQL
- Graph extension
  - AQL ArangoDB language
- XQuery extension
  - MarkLogic
- JSON extension
  - MongoDB $graphLookup

# Model evolution



# Multi-model index structures

- Inter-model indexes to speedup the inter-model query processing




- A new index structure for graph, document and relational joins

# Multi-model main memory structure

- As the in-memory technology going forward, disk based index and data storage model are constantly being challenged.

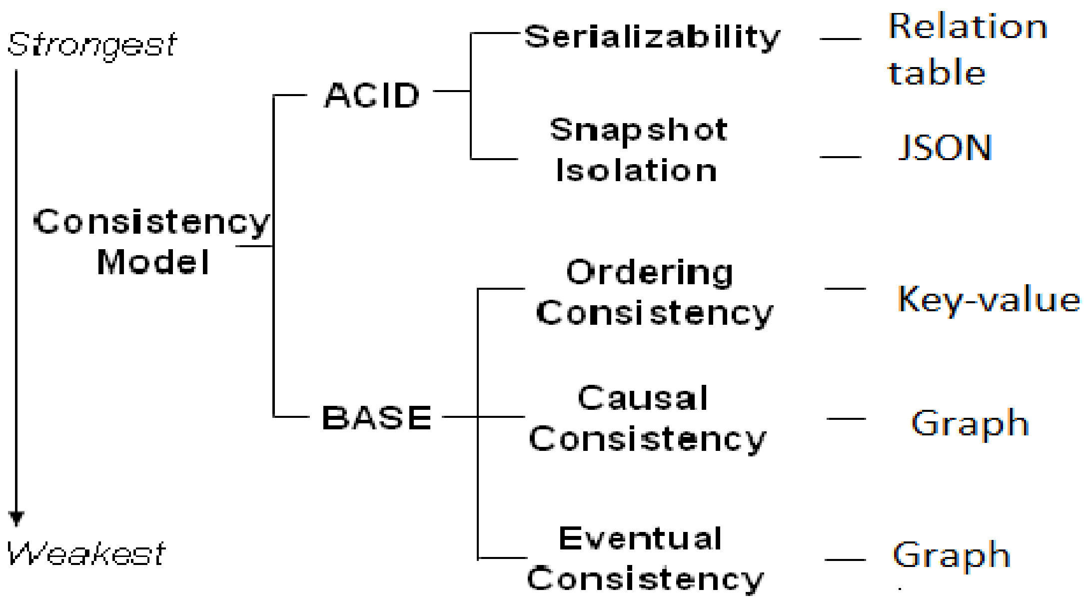
- Building up just-in-time multi-model data structure is a new challenge on main memory multi-model database.

- For example, In-memory virtual column[1] --> In-memory virtual model

[1] Aurosish Mishra et al. Accelerating analytics with dynamic in-memory expressions. PVLDB, 9(13):1437–1448, 2016

# Multi-model transaction

- How to process inter-model transactions ?
- Graph data and relational data may have different requirements on the consistency models



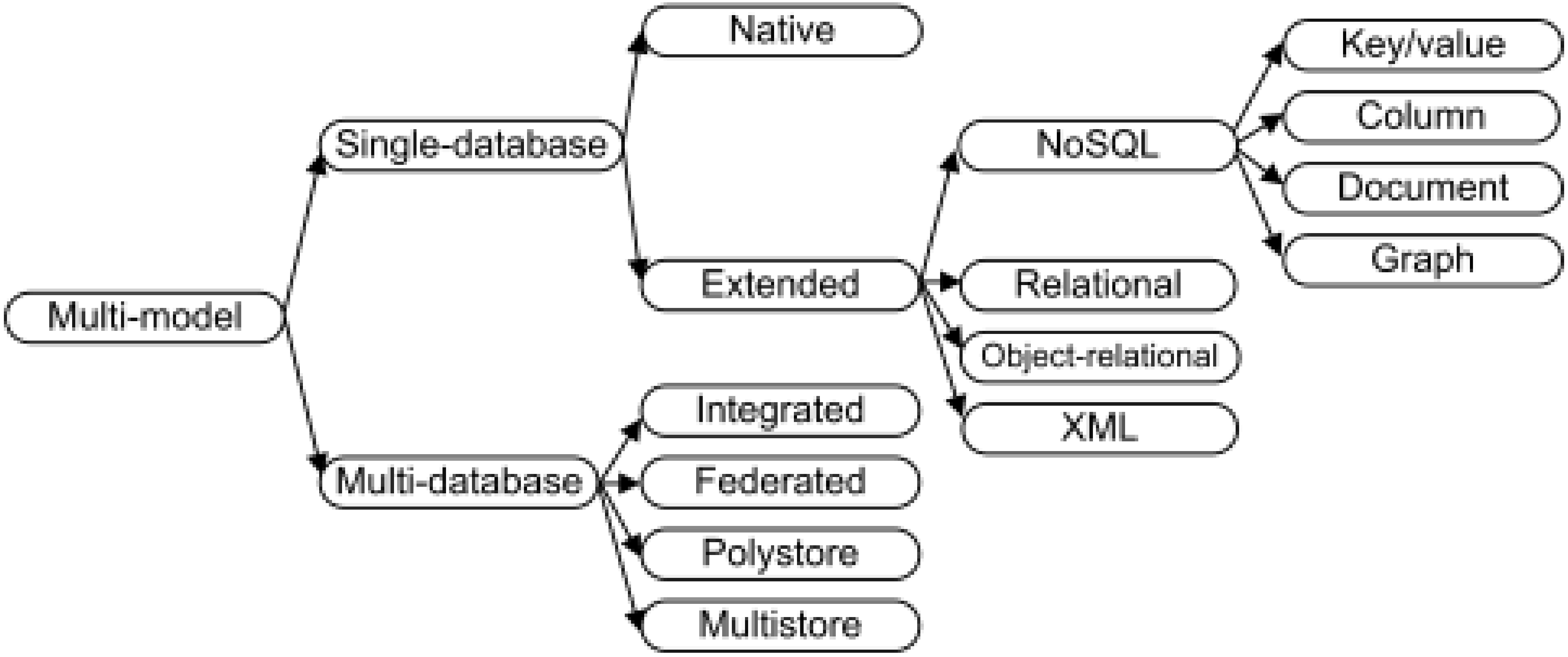

An example of multi-model data hybrid consistency models

# Some theoretical challenges on multi-model databases

- Schema language for multi-model data and schema extraction
- Multi-model query language:  expressive power or higher complexity of query language (involving logic, complexity and automata theories )
- Query evaluation and optimization on inter-model

Serge Abiteboul et al: Research Directions for Principles of Data Management, Dagstuhl Perspectives Workshop 16151 (2017)

# Conclusion




Classification of multi-model data management

# Conclusion

- Multi-model database is not new
  - Can be traced to ORDBMS
  - A number of DBs can manage multiple models of data
  - By 2017, most of leading operational DBs will support multi-models.
- Multi-model database is new and open
  - New query language for multi-model data
  - New query optimization and indexes
  - Open data model and model evolution
  - …

- Slides and papers are available at:
- http://udbms.cs.helsinki.fi/?tutorials

- Open multi-model datasets
- http://udbms.cs.helsinki.fi/?datasets

- Multi-model database benchmark
- http://udbms.cs.helsinki.fi/?projects/ubench