Module 15

RDF, SPARQL and Semantic Repositories

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Module 15 Outline

9.45-11.00	• RDF/S and OWL formal semantics and profiles • Querying RDF data with SPARQL
11.00-11.15	Coffee break
11.15-12.30	• Semantic Repositories • OWLIM overview
12.30-14.00	Lunch Break
14.00-16.00	• Benchmarking triplestores • Distributed approaches to RDF materialisation • From RDBMS to RDF • Other RDF tools

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About this tutorial

- RDF/S and OWL formal semantics and profiles
- Querying RDF data with SPARQL
- Semantic Repositories
- OWLIM overview
- Benchmarking triplestores
- Distributed approaches to RDF materialisation
- From RDBMS to RDF
- Other RDF tools

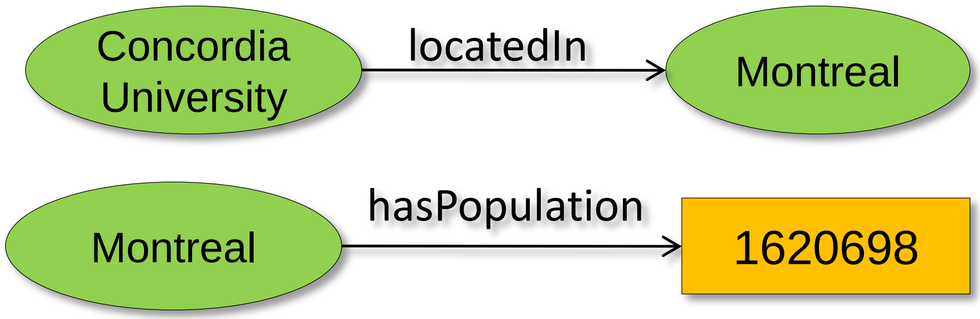
RDF/S and OWL formal semantics, dialects & profiles

Resource Description Framework (RDF)

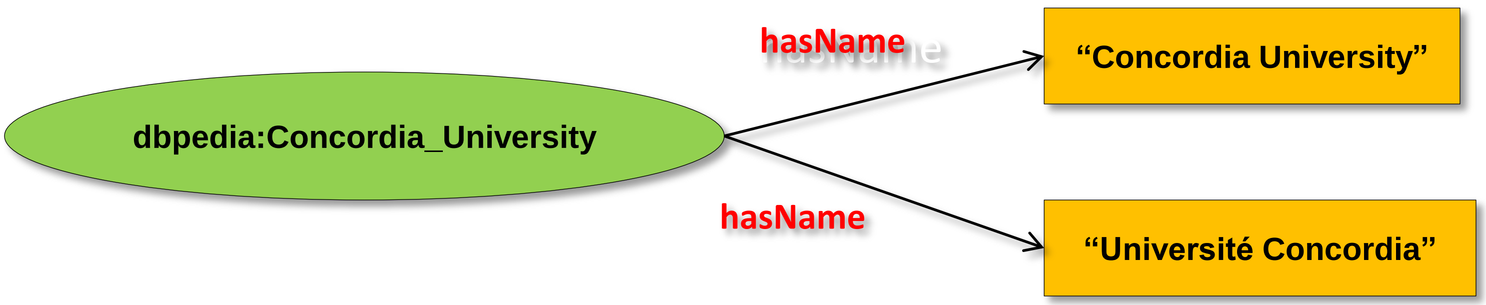
- A simple data model for
  - describing the *semantics* of information in a machine accessible way
  - representing meta-data (data about data)
- A set of representation syntaxes
  - XML (standard) but also JSON, N3, Turtle, …
- Building blocks
  - *Resources* (with unique identifiers)
  - *Literals*
  - Named *relations* between pairs of resources (or a resource and a literal)

RDF (2)

- Everything is a triple (statement)
  - **Subject** (resource), **Predicate** (relation), **Object** (resource or literal)
- The RDF graph is a collection of triples



RDF (3)



Subject	Predicate	Object
http://dbpedia.org/resource/Concordia_University	hasName	"Concordia University"
http://dbpedia.org/resource/Concordia_University	hasName	"Université Concordia"

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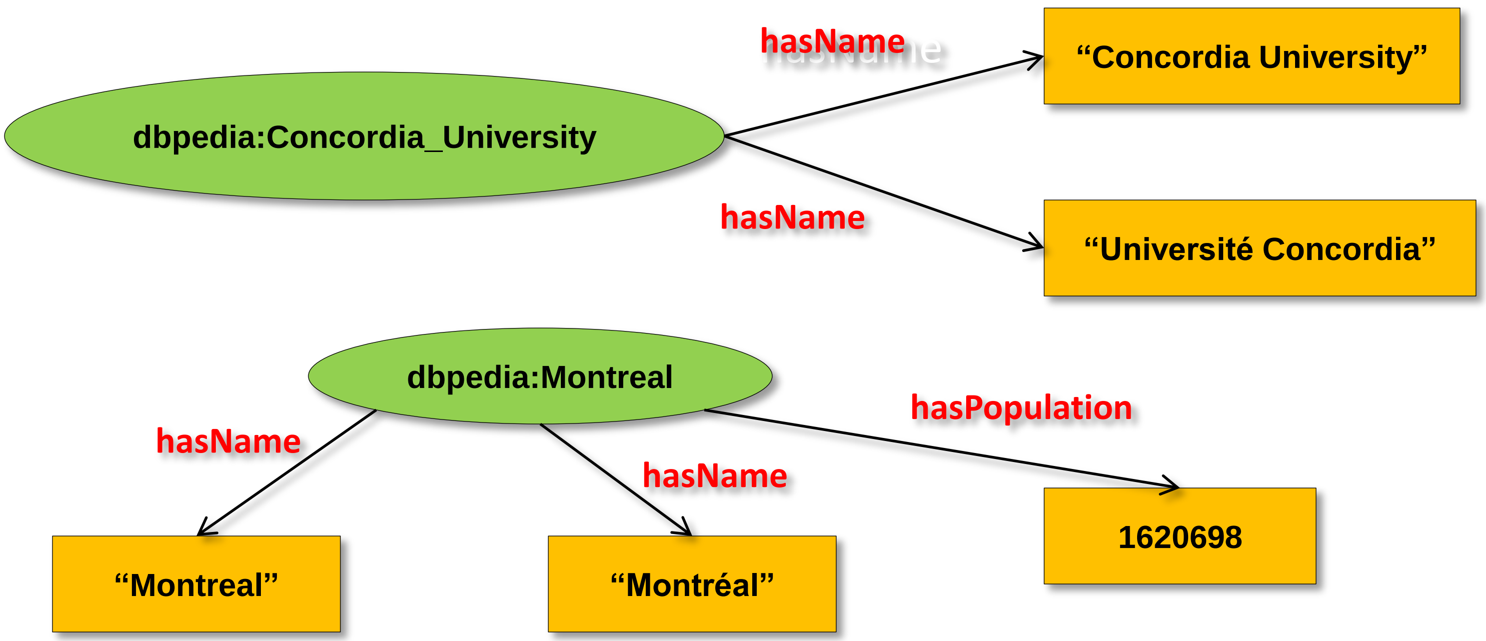
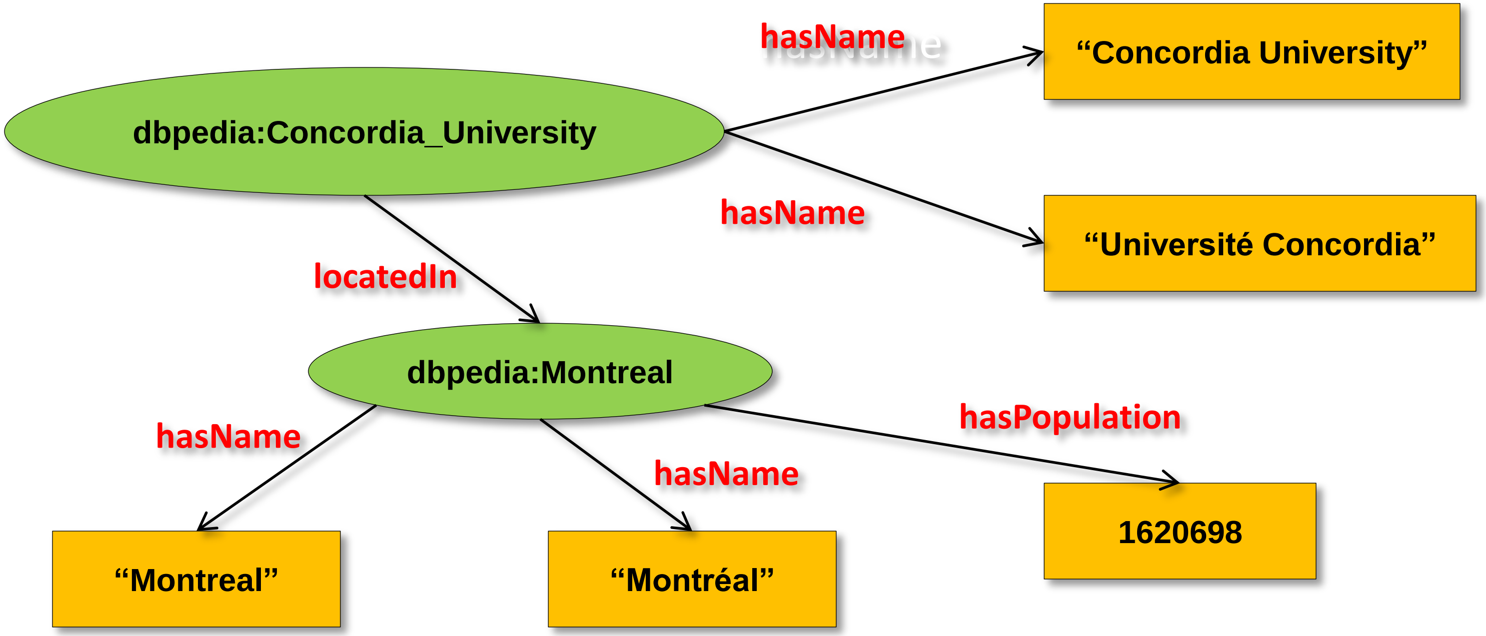
RDF (4)



Subject	Predicate	Object
http://dbpedia.org/resource/Montreal	*hasName*	*"Montreal"*
http://dbpedia.org/resource/Montreal	*hasPopulation*	*1620698*
http://dbpedia.org/resource/Montreal	*hasName*	*"Montréal"*
http://dbpedia.org/resource/Concordia_University	**hasName**	**"Concordia University"**
http://dbpedia.org/resource/Concordia_University	**hasName**	**"Université Concordia"**

RDF (5)



Subject	Predicate	Object
http://dbpedia.org/resource/Montreal	**hasName**	**"Montreal"**
http://dbpedia.org/resource/Montreal	**hasPopulation**	**1620698**
http://dbpedia.org/resource/Montreal	**hasName**	**"Montréal"**
http://dbpedia.org/resource/Concordia_University	*locatedIn*	*http://dbpedia.org/resource/Montreal*
http://dbpedia.org/resource/Concordia_University	**hasName**	**"Concordia University"**
http://dbpedia.org/resource/Concordia_University	**hasName**	**"Université Concordia"**

RDF (4)

- RDF advantages
  - Simple but expressive data model
  - Global identifiers of all resources
    - Remove ambiguity
  - Easier & incremental data integration
    - Can handle incomplete information
    - Open world assumption
  - Schema agility
  - Graph structure
    - Suitable for a large class of tasks
    - Data merging is easier

RDF Schema (RDFS)

- RDFS provides means for
  - Defining *Classes* and *Properties*
  - Defining hierarchies (of classes and properties)
- RDFS differs from XML Schema (XSD)
  - Open World Assumption
  - RDFS is about describing resources, not about validation
- Entailment rules (axioms)
  - Infer new triples

RDFS entailment rules

1:	$s\ p\ o$ (if o is a literal)		$\Rightarrow$ _:n rdf:type rdfs:Literal
2:	p rdfs:domain x	& $s\ p\ o$	$\Rightarrow$ s rdf:type x
3:	p rdfs:range x	& $s\ p\ o$	$\Rightarrow$ o rdf:type x
4a:	$s\ p\ o$		$\Rightarrow$ s rdf:type rdfs:Resource
4b:	$s\ p\ o$		$\Rightarrow$ o rdf:type rdfs:Resource
5:	p rdfs:subPropertyOf q	& q rdfs:subPropertyOf r	$\Rightarrow$ p rdfs:subPropertyOf r
6:	p rdf:type rdf:Property		$\Rightarrow$ p rdfs:subPropertyOf p
7:	$s\ p\ o$	& p rdfs:subPropertyOf q	$\Rightarrow$ $s\ q\ o$
8:	s rdf:type rdfs:Class		$\Rightarrow$ s rdfs:subClassOf rdfs:Resource
9:	s rdf:type x	& x rdfs:subClassOf y	$\Rightarrow$ s rdf:type y
10:	s rdf:type rdfs:Class		$\Rightarrow$ s rdfs:subClassOf s
11:	x rdfs:subClassOf y	& y rdfs:subClassof z	$\Rightarrow$ x rdfs:subClassOf z
12:	p rdf:type rdfs:ContainerMembershipProperty		$\Rightarrow$ p rdfs:subPropertyOf rdfs:member
13:	o rdf:type rdfs:Datatype		$\Rightarrow$ o rdfs:subClassOf rdfs:Literal

RDF entailment rules (2)

- Class/Property hierarchies
  - R5, R7, R9, R11

```
:human rdfs:subClassOf :mammal .
:man rdsf:subClassOf :human .
➔ :man rdsf:subClassOf :mammal .
```

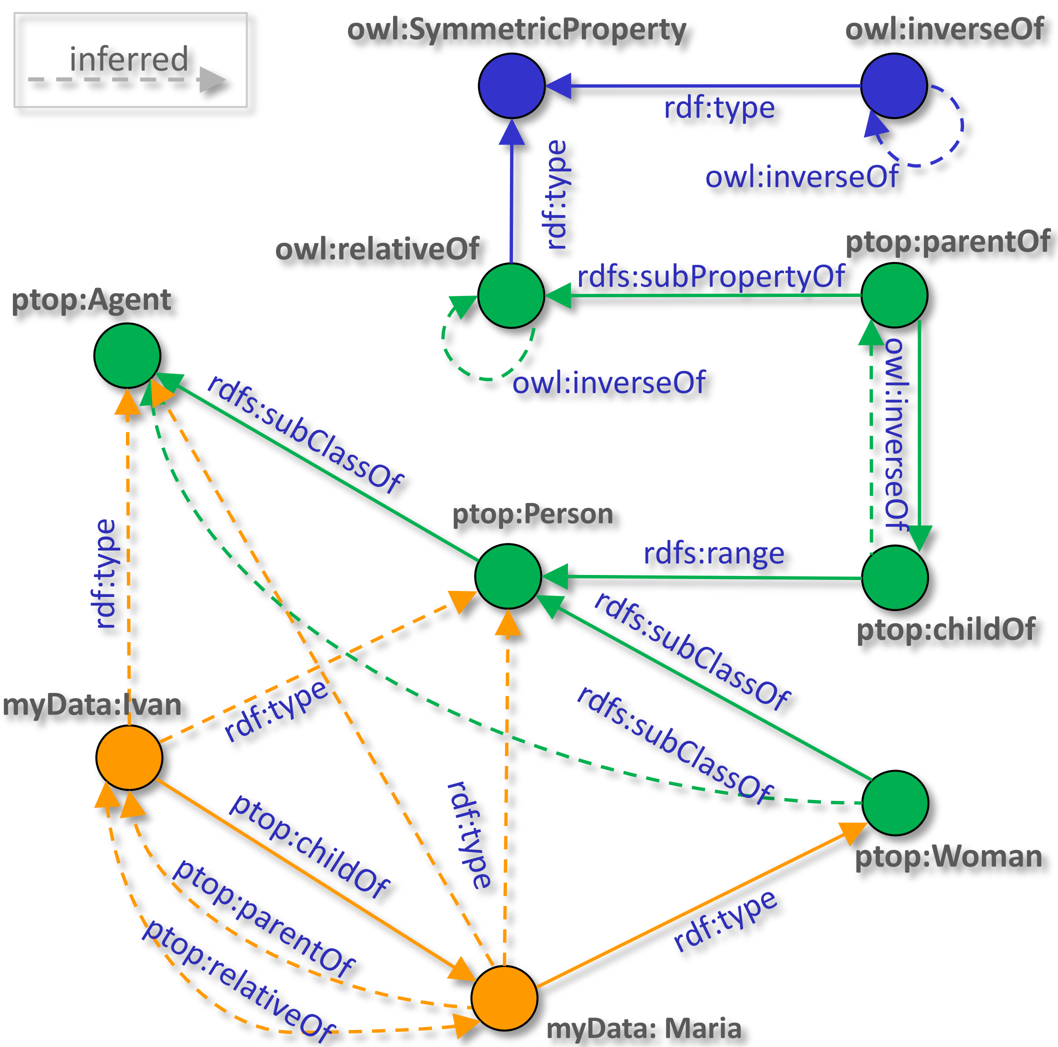
```
:John a :man .
➔ :John a :human .
➔ :John a :mammal .
```

```
:hasSpouse rdfs:subPropertyOf :relatedTo .
:John :hasSpouse :Merry .
➔ :John :relatedTo :Merry .
```

- Inferring types (domain/range restrictions)
  - R2, R3

```
:hasSpouse rdfs:domain :human ;
           rdfs:range :human .
:Adam :hasSpouse :Eve .
➔:Adam a :human .
➔:Eve a :human .
```

RDFS entailment – inferred triples



OWL (2)

- More expressive than RDFS
  - Identity equivalence/difference
    - *sameAs, differentFrom, equivalentClass/Property*
  - More expressive class definitions
    - Class intersection, union, complement, disjointness
    - Cardinality restrictions
  - More expressive property definitions
    - Object/Datatype properties
    - Transitive, functional, symmetric, inverse properties
    - Value restrictions

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OWL (3)

- Identity equivalence

```
:Montreal :hasPopulation 1620698 .
:Montreal = :Montréal .
➔ :Montréal :hasPopulation 1620698 .
```

- Transitive properties

```
:locatedIn a owl:TransitiveProperty .
:Montreal :locatedIn :Quebec .
:Quebec :locatedIn :Canada .
➔ :Montreal :locatedIn :Canada.
```

- Symmetric properties

```
:hasSpouse a owl:SymmetricProperty .
:John :hasSpouse :Merry .
➔ :Merry :hasSpouse :John .
```

- Inverse properties

```
:hasParent owl:inverseOf :hasChild .
:John :hasChild :Jane .
➔ :Jane :hasParent :John .
```

- Functional properties

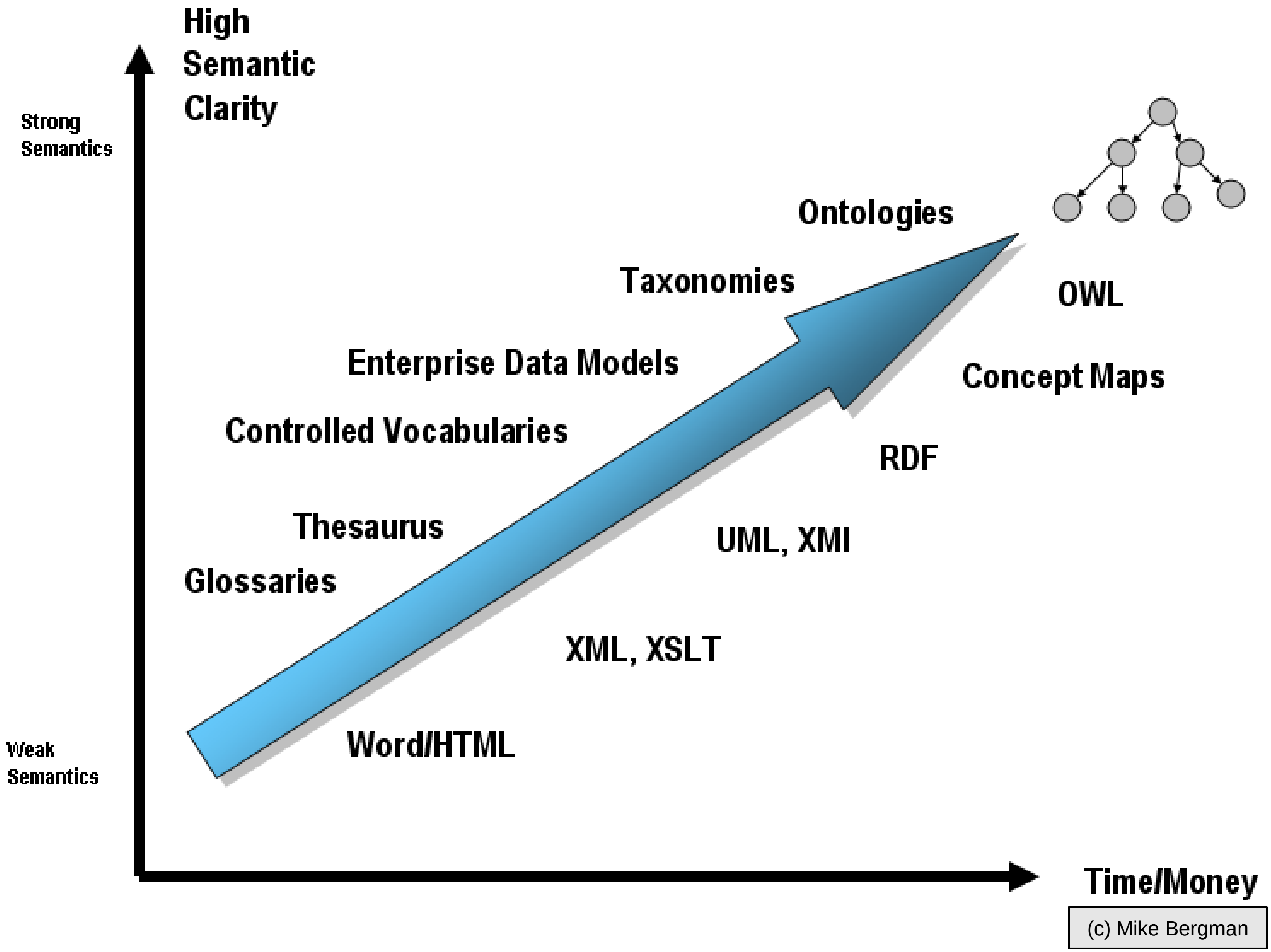
```
:hasSpouse a owl:FunctionalPropety .
:Merry :hasSpouse :John .
:Merry :hasSpouse :JohnSmith .
➔ :JohnSmith = :John .
```

OWL (4)

- Cardinality restrictions

```
:hasSpouse owl:maxCardinality 1 .
:Merry :hasSpouse :John .
:Merry :hasSpouse :JohnSmith .
➔ :JohnSmith = :John .
```

The cost of semantic clarity



OWL sublanguages – OWL Lite

- OWL Lite
  - low expressiveness / low computational complexity
  - All RDFS features
  - *sameAs*/*differentFrom*, equivalent class/property
  - inverse/symmetric/transitive/functional properties
  - property restrictions, cardinality (0 or 1)
  - class intersection

OWL DL & OWL Full

- OWL DL
  - high expressiveness / decidable & complete
  - All OWL Lite features
  - Class disjointness
  - Complex class expressions
  - Class union & complement
- OWL Full
  - max expressiveness / no guarantees
  - Same vocabulary as OWL-DL but less restrictions
    - In OWL DL, a Class <u>cannot</u> also be an Individual or a Property

OWL 2 profiles

- Goals
  - sublanguages that trade expressiveness for efficiency of reasoning
  - Cover important application areas
  - Easier to understand by non-experts
- *OWL 2 EL*
  - Best for large ontologies / small instance data (TBox reasoning)
  - A near maximal fragment of OWL2
  - Computationally optimal
    - Satisfiability checks in PTime

OWL 2 profiles (2)

- *OWL 2 QL*
  - Quite limited expressive power, but very efficient for query answering with large instance data
  - Can exploit query rewriting techniques
    - Data storage & query evaluation can be delegated to a RDBMS
- OWL 2 RL
  - Balance between scalable reasoning and expressive power (ABox reasoning)
  - OWL 2 RL rules can be expressed in RIF BLD

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OWL 2 profiles (3)

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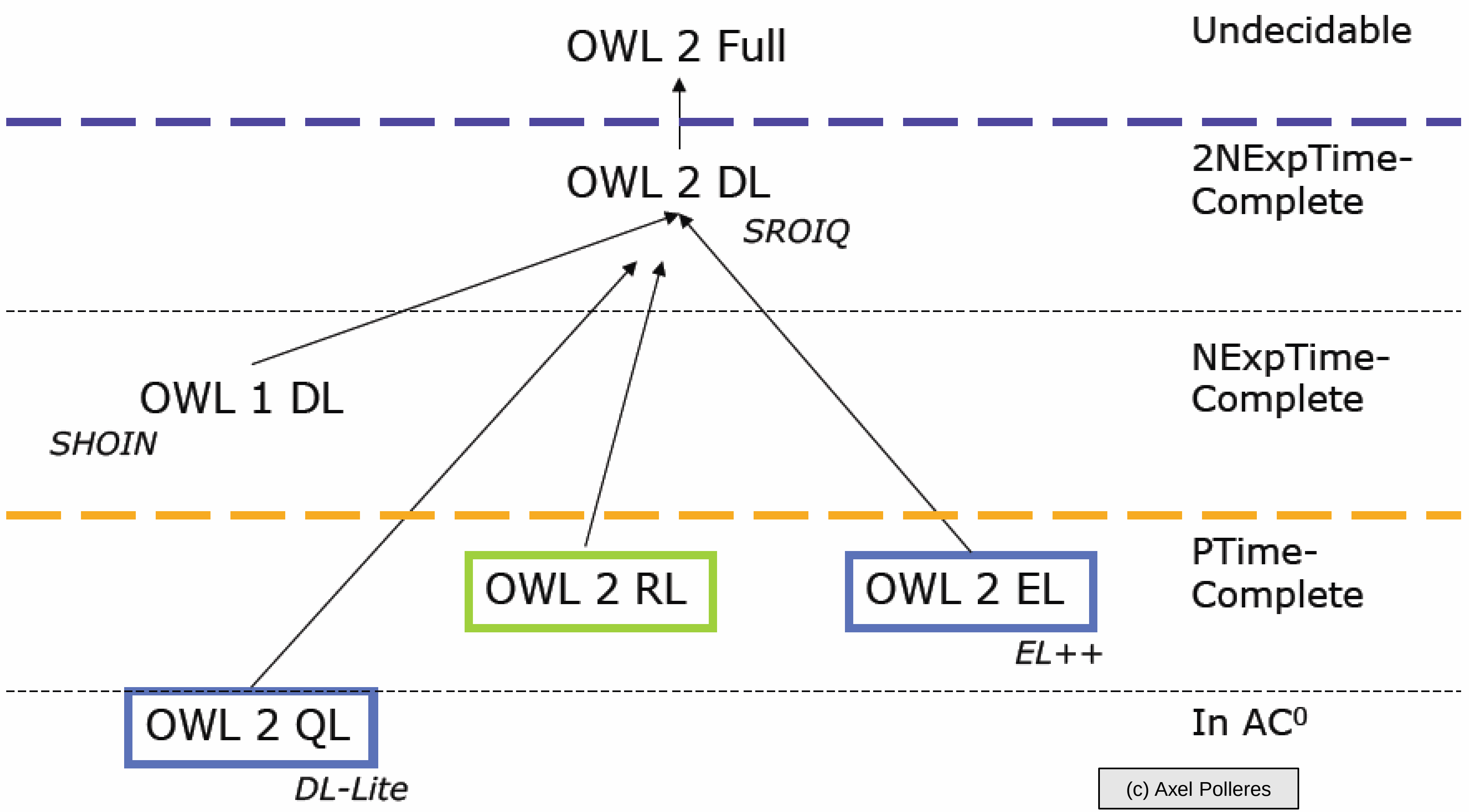

Querying RDF data with SPARQL

SPARQL Protocol and RDF Query Language (SPARQL)

- SQL-like query language for RDF data
- Simple protocol for querying remote databases over HTTP
- Query types
  - *select* – projections of variables and expressions
  - *construct* – create triples (or graphs) based on query results
  - *ask* – whether a query returns results (result is true/false)
  - *describe* – describe resources in the graph

Describing resources

- Go to www.FactForge.net and execute (in the "SPARQL query" tab):

```
PREFIX dbpedia: <http://dbpedia.org/resource/>

DESCRIBE dbpedia:Montreal
```

SPARQL select

```
PREFIX rdf:<http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX dbpedia: <http://dbpedia.org/resource/>
PREFIX dbp-ont: <http://dbpedia.org/ontology/>

SELECT DISTINCT ?university ?students
WHERE {
   ?university rdf:type dbpedia:University .
   ?university dbp-ont:numberOfStudents ?students .
   ?university dbp-ont:city dbpedia:Montreal .
   FILTER (?students > 5000)
}
ORDER BY DESC (?students)
```

FactForge

SPARQL Query

Results for PREFIX rdf:<http://www.w3... (6) View as Exhibit Downlo

university	students
dbpedia:Con_U	43944
dbpedia:HEC_Montreal	12000
dbpedia:Collège_Ahuntsic	10100
dbpedia:John_Molson_School_of_Business	8026
dbpedia:CEGEP_Vanier	6100
dbpedia:Cégep_du_Vieux_Montréal	6100

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Triple patterns

- Whitespace separated list of Subj, Pred, Obj
  - *?x dbp-ont:city dbpedia:Montreal*
  - *dbpedia:Concordia_University db-ont:city ?x*
- Triple patterns with common Subject

```
?uni rdf:type dbpedia:University .
?uni dbp-ont:city dbpedia:Montreal .
```

```
?uni rdf:type dbpedia:University ;
     dbp-ont:city dbpedia:Montreal .
```

  - Triple patterns with common Subject and Predicate

Triple patterns (2)

- Triple patterns with common Subject and Predicate

```
?city rdf:label 'Montreal'@en .
?city rdf:label 'Montréal'@fr .
```

```
?city rdf:label 'Montreal'@en ,'Montréal'@fr .
```

- "a" can be used as an alternative for rdf:type

```
?uni rdf:type dbpedia:University .
```

```
?uni a dbpedia:University .
```

Graph Patterns

- Basic Graph Pattern
  - A conjunction of triple patterns
- Group Graph Pattern
  - A group of 1+ graph patterns
  - Patterns are enclosed in { }
  - FILTERs can constrain the whole group

```
{
   ?uni a dbpedia:University ;
        dbp-ont:city dbpedia:Montreal ;
        dbp-ont:numberOfStudents ?students .
   FILTER (?students > 5000)
}
```

Graph Patterns (2)

- Optional Graph Pattern
  - Optional parts of a graph patterns
  - *pattern OPTIONAL {pattern}*

```
SELECT ?uni ?students
WHERE {
   ?uni a dbpedia:University ;
        dbp-ont:city dbpedia:Montreal .
   OPTIONAL {
      ?uni dbp-ont:numberOfStudents ?students
   }
}
```

Graph Patterns (3)

- Alternative Graph Pattern
  - Combine results of several alternative graph patterns
  - *{pattern} UNION {pattern}*

```
SELECT ?uni
WHERE {
   ?uni a dbpedia:University .
   {
      { ?uni dbp-ont:city dbpedia:Vancouver }
      UNION
      { ?uni dbp-ont:city dbpedia:Montreal }
   }
}
```

Anatomy of a SPARQL query

- List of namespace prefixes
  - PREFIX xyz: <URI>
- List of variables
  - ?x, $y
- Graph patterns + filters
  - Group, alternative, optional
- Modifiers
  - ORDER BY, DISTINCT, OFFSET/LIMIT

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Anatomy of a SPARQL query (2)

```
SELECT ?var1 ?var2
WHERE {
   triple-pattern1 .
   triple-pattern2 .
   OPTIONAL {triple-pattern3}
   OPTIONAL {triple-pattern4}
   FILTER (filter-expr)
}
ORDER BY DESC (?var1)
LIMIT 100
```

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example

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- Go to www.FactForge.net and execute (in the "SPARQL query" tab)
- Find all universities (and their number of students) which are located in Quebec
  - geo-ont:parentFeature, geo-ont:name, geo-ont:alternativeName
- xxx

example (2)

```
PREFIX rdf:<http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX dbpedia: <http://dbpedia.org/resource/>
PREFIX dbp-ont: <http://dbpedia.org/ontology/>
PREFIX geo-ont: <http://www.geonames.org/ontology#>

SELECT DISTINCT ?university ?city ?students
WHERE {
    ?university rdf:type dbpedia:University ;
                     dbp-ont:city ?city .
    ?city geo-ont:parentFeature ?province .
    ?province geo-ont:name 'Québec' .
    OPTIONAL {
       ?university dbp-ont:numberOfStudents ?students
    }
}
ORDER BY ASC (?city)
```

Semantic Repositories

Semantic Repositories

- Semantic repositories combine the features of:
  - Database management systems (DBMS) and
  - Inference engines
- Rapid progress in the last 5 years
  - Every couple of years the scalability increases by an order of magnitude
- “Track-laying machines” for the Semantic Web
  - Extending the reach of the “data railways” and changing the data-economy by allowing more complex data to be managed at lower cost

Semantic Repositories as Track-laying Machines

Property of MSCUA, University of Washington Libraries. Photo Coll 516

Semantic Repositories as Track-laying Machines (2)

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RDF graph materialisation

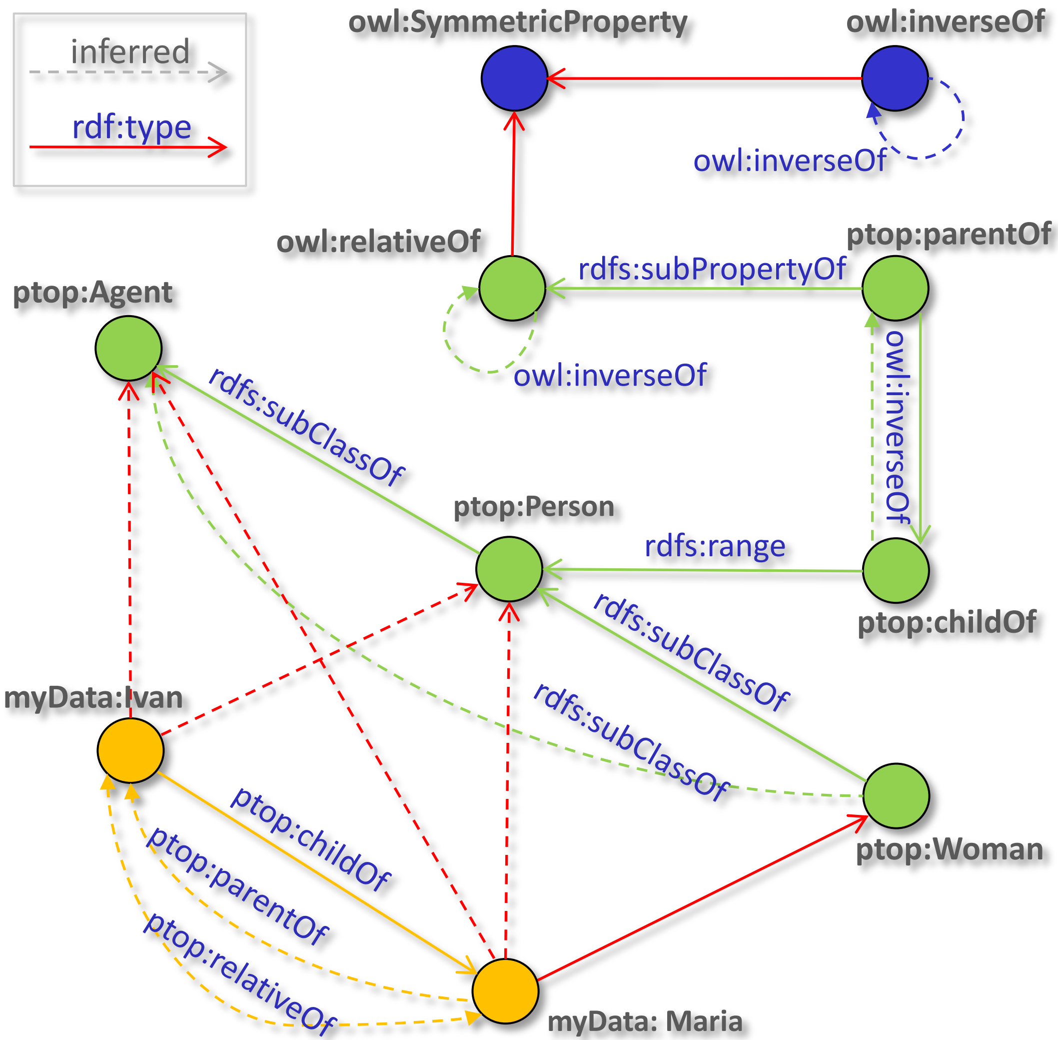
<C1,rdfs:subClassOf,C2>
<C2,rdfs:subClassOf,C3>
⇒ <C1,rdfs:subClassOf,C3>

<I,rdf:type,C1>
<C1,rdfs:subClassOf,C2>
⇒ <I,rdf:type,C2>

<I1,P1,I2>
<P1,rdfs:range,C2>
⇒ <I2,rdf:type,C2>

<P1,owl:inverseOf,P2>
<I1,P1,I2>
⇒ <I2,P2,I1>

<P1,rdf:type,owl:SymmetricProperty>
⇒ <P1,owl:inverseOf,P1>



Semantic Repositories vs. RDBMS

- The major differences with the DBMS are
  - They use **ontologies as semantic schemata**, which allows them to automatically reason about the data
  - They work with a **more generic datamodel**, which allows them more agile to updates and extensions in the schemata (i.e. in the structure of the data)

Physical Data Representation: RDF vs. RDBMS

Person		
ID	Name	Gender
1	Maria P.	F
2	Ivan Jr.	M
3	…	

Parent	
ParID	ChilD
1	2
…	

Spouse			
S1ID	S2ID	From	To
1	3		
…			

Statement		
Subject	Predicate	Object
myo:Person	rdf:type	rdfs:Class
myo:gender	rdfs:type	rdfs:Property
myo:parent	rdfs:range	myo:Person
myo:spouse	rdfs:range	myo:Person
myd:Maria	rdf:type	myo:Person
myd:Maria	rdf:label	"Maria P."
myd:Maria	myo:gender	"F"
myd:Maria	rdf:label	"Ivan Jr."
myd:Ivan	myo:gender	"M"
myd:Maria	myo:parent	Myd:Ivan
myd:Maria	myo:spouse	myd:John
…		

Major characteristics

- *Easy integration of multiple data-sources*
  - Once the schemata of the data-sources is semantically aligned, the inference capabilities of the engine assist the interlinking and combination of facts from different sources
- *Easy querying against rich or diverse data schemata*
  - Inference is applied to match the semantics of the query to the semantics of the data, regardless of the vocabulary and data modeling patterns used for encoding the data

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Major characteristics (2)

- *Great analytical power*
  - Semantics will be thoroughly applied even when this requires recursive inferences on multiple steps
  - Discover facts, by interlinking long chains of evidence
    - the vast majority of such facts would remain hidden in the DBMS
- *Efficient data interoperability*
  - Importing RDF data from one store to another is straight-forward, based on the usage of globally unique identifiers

Reasoning Strategies

- The strategies for rule-based inference are:
  - **Forward-chaining**: start from the known (explicit) facts and perform inference in an inductive manner until the complete *closure* is inferred
  - **Backward-chaining**: to start from a particular fact and to verify it against the knowledge base using deductive reasoning
    - the reasoner decomposes the query (or the fact) into simpler facts that are available in the KB or can be proven through further recursive decompositions

Reasoning Strategies (2)

- *Inferred closure*
  - the extension of a KB (a graph of RDF triples) with all the implicit facts (triples) that could be inferred from it, based on the pre-defined entailment rules
- *Materialization*
  - Maintaining an up-to-date inferred closure

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Reasoning Strategies (3)

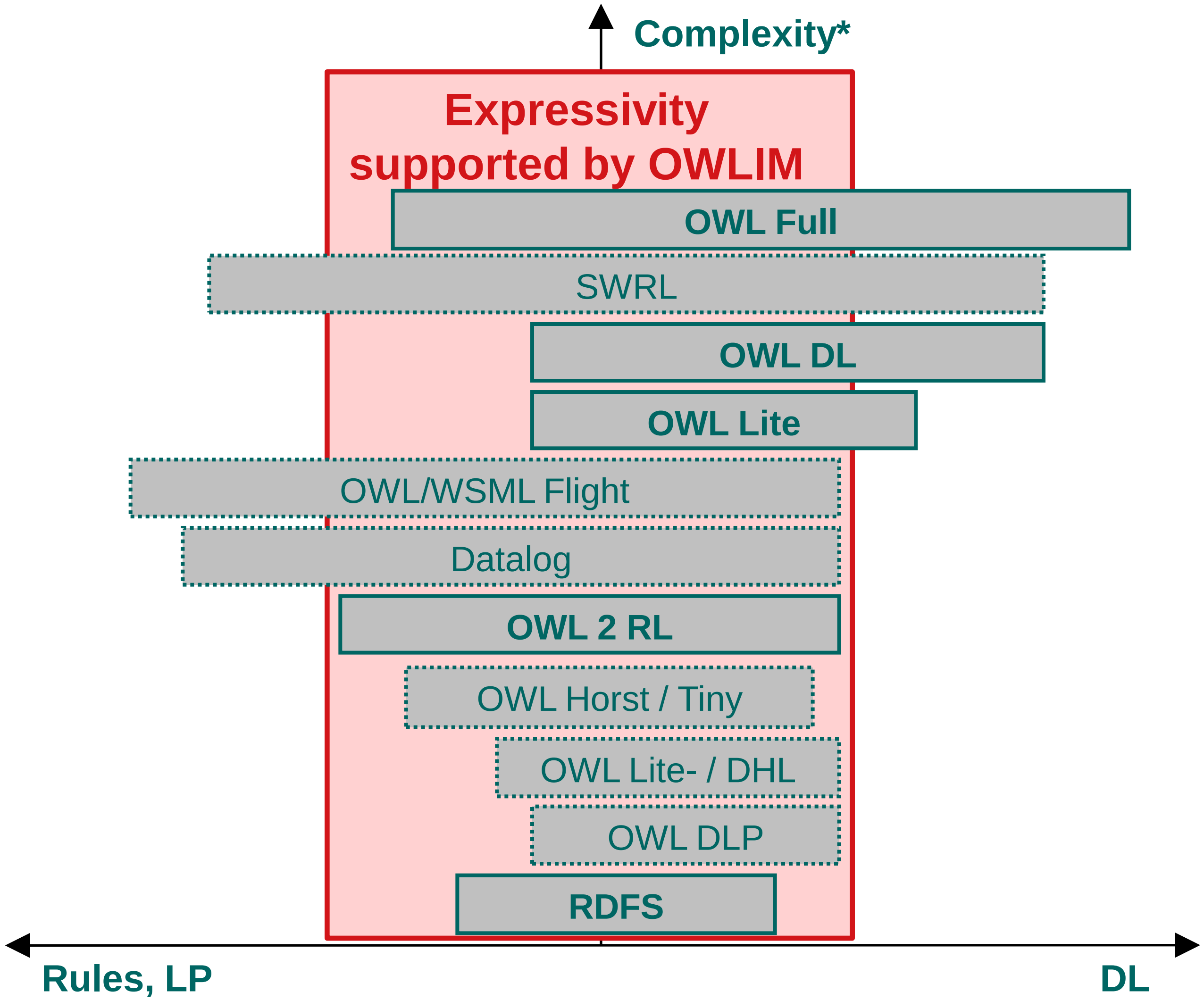
- Pros and cons of forward-chaining based materialization
  - Relatively **slow upload/store/addition** of new facts
    - the repository is extending the inferred closure after each modification (transaction)
  - **Deletion of facts is slow**
    - repository should remove all the facts that are no longer true from the inferred closure
  - The **maintenance of the inferred closure** requires considerable resources
  - **Querying and retrieval are fast**
    - no deduction, satisfiability checking, or other kind of reasoning are required at query time
    - RDBMS-like query evaluation & optimisation techniques are applicable

OWLIM overview

Semantic Repository for RDFS and OWL

- OWLIM is a family of semantic repositories
  - **SwiftOWLIM –** fast in-memory operations, scales to ~100M statements
  - **BigOWLIM –** optimized for data integration, massive query loads and critical applications, scales up to 20B statements
- OWLIM is designed and tuned to provide
  - Efficient management, integration and analysis of heterogeneous data
  - Light-weight, high-performance reasoning

Naïve OWL Fragments Map



BigOWLIM performance

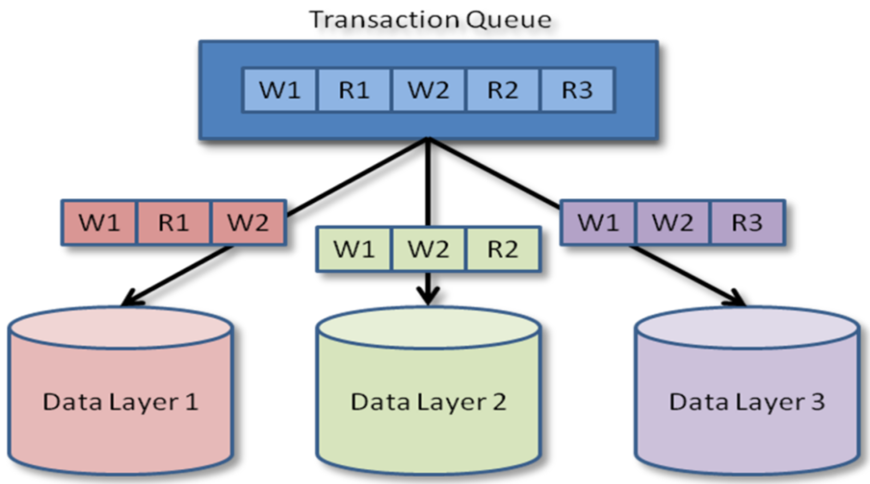
- BigOWLIM is the only engine that can reason with **more than 10B** statements, on a $10,000 server
  - It passes LUBM(90000), indexing **over 20B explicit and implicit statements** and being able to efficiently answer queries
  - It offers the most efficient query evaluation **-** the only RDF database for which full-cycle benchmarking results are published for the LUBM(8000) benchmark or higher

Key Features

- **Clustering support** brings resilience, failover and horizontally scalable parallel query processing
- **Optimized owl:sameAs** handling
- Integrated **full-text search**
- **High performance retraction** of statements and their inferences
- **Consistency checking** mechanisms
- **RDF rank** for ordering query results by relevance
- **Notification mechanism**, to allow clients to react to updates in the data stream

Replication Cluster

- Improve scalability with respect to concurrent user requests
- How does it work?
  - Each data write request is multiplexed to all repository instances
  - Each read request is dispatched to one instance only
  - To ensure load-balancing, read requests are sent to the instance with the shortest execution queue



RDF Rank

- BigOWLIM uses a modification of PageRank over RDF graphs
- The computation of the RDFRank-s for FactForge (couple of billion statements) takes just a few minutes
- Results are available through a system predicate
  - Example**:** get the 100 most “important” nodes in the RDF graph

```
SELECT ?node {?node onto:hasRDFRank ?rank}
ORDER BY DESC(?rank) LIMIT 100
```

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example

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- Go to www.FactForge.net and execute (in the "SPARQL query" tab)
- Find the 25 "most important" universities located in Quebec
  - geo-ont:parentFeature, geo-ont:name, geo-ont:alternativeName, onto:RR

example (2)

```
PREFIX rdf:<http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX dbpedia: <http://dbpedia.org/resource/>
PREFIX dbp-ont: <http://dbpedia.org/ontology/>
PREFIX geo-ont: <http://www.geonames.org/ontology#>
PREFIX om: <http://www.ontotext.com/owlim/>

SELECT DISTINCT ?university ?city ?rank
WHERE {
    ?university rdf:type dbpedia:University ;
                dbp-ont:city ?city ;
                om:hasRDFRank ?rank .
    ?city geo-ont:parentFeature ?province .
    ?province geo-ont:name 'Québec` .
}
ORDER BY DESC (?rank)
LIMIT 25
```

Full-Text Search

- Full-text search is different from SQL-type queries
  - Queries are formulated and evaluated in a different way
  - Different indices are required for efficient handling
  - URIs and literals are retrieved using a set of tokens that should appear in them
  - The matching criteria are determined via system predicates (exact, ignore case, prefix,…)

```
SELECT ?x ?label WHERE {
  ?x rdfs:label ?label .
  <term:> onto:prefixMatchIgnoreCase ?label.
}
```

RDF Search - Advanced FTS in RDF Graphs

- Objective
  - Search in an RDF graph by keywords
  - Get more usable results (standalone literals are not useful in most cases)
- What to index:
  - URIs
  - The *RDF molecule* for an URI
    - the description of the node, including all outgoing statements
- Results returned
  - List of URIs, ranked by FTS + RDF Rank metric

RDF Search – Advanced FTS in RDF Graphs (2)

- The ranking is based on the standard vector-space-model relevance, boosted by RDF Rank

```
PREFIX gossip: <http://www.....gossipdb.owl#>
PREFIX onto: <http://www.ontotext.com/>

SELECT * WHERE {
  ?person gossip:name ?name .
  ?name onto:luceneQuery "American AND life~".
}
```

owl:sameAs Optimisation

- **owl:sameAs** declares that two different URIs denote one and the same resource or object in the world
  - it is used to align different identifiers of the same real-world entity used in different data sources
  - Example, encoding that there are four different URIs for Montreal

```
dbpedia:Montreal owl:sameAs geonames:6077244
dbpedia:Montreal owl:sameAs geonames:6077243
geonames:6077243 owl:sameAs fbase:guid.9202a8c04000641f80000000000028aa7
fbase:guid.9202a8c04000641f80000000000028aa7 owl:sameAs
nytimes:N59179828586486930801
```

owl:sameAs Optimisation (2)

- According to the standard semantics of owl:sameAs:
  - It is a transitive and symmetric relationship
  - Statements, asserted using one of the equivalent URIs should be inferred to appear with all equivalent URIs placed in the same position
  - Thus the 4 statements in the previous example lead to **ten** inferred statements

owl:sameAs Optimisation (3)

```
dbpedia:Montreal owl:sameAs geonames:6077244

dbpedia:Montreal owl:sameAs geonames:6077243

dbpedia:Montreal owl:sameAs
fbase:guid.9202a8c04000641f800000000028aa7

dbpedia:Montreal owl:sameAs nytimes:N59179828586486930801

fbase:guid.9202a8c04000641f800000000028aa7 owl:sameAs
geonames:6077244

fbase:guid.9202a8c04000641f800000000028aa7 owl:sameAs
geonames:6077243

fbase:guid.9202a8c04000641f800000000028aa7 owl:sameAs
nytimes:N59179828586486930801

nytimes:N59179828586486930801 owl:sameAs geonames:6077244

nytimes:N59179828586486930801 owl:sameAs geonames:6077243

geonames:6077244 owl:sameAs geonames:6077243
```

owl:sameAs Optimisation (4)

- BigOWLIM features an optimisation that allows it to use a single master-node in its indices to represent a class of sameAs-equivalent URIs
- Avoids inflating the indices with multiple equivalent statements
- Optionally expands query results
  - The sameAs equivalence leads to multiplication of the bindings of the variables in the process of query evaluation (both forward- and backward-chaining)

Benchmarking triplestores

Tasks to be Benchmarked

- **Data loading**
  - parsing, persistence, and indexing
- **Query evaluation**
  - query preparation and optimization, fetching
- **Data modification**
  - May involve changes to the ontologies and schemata
- *Inference* is not a first-level activity
  - Depending on the implementation, it can affect the performance of the other activities

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Performance Factors for Loading

- *Materialization*
  - Whether forward-chaining is performed at load time & the complexity of forward-chaining
- *Data model complexity*
  - Support for extended RDF data models (e.g. named graphs), is computationally more expensive
- *Indexing specifics*
  - Repositories can apply different indexing strategies depending on the data loaded, usage patterns, etc.
- *Transaction Isolation*

Performance Factors for Query Evaluation

- *Deduction*
  - Whether and how complex backward-chaining is involved
- *Size of the result-set*
  - Fetching large result-sets can take considerable time
- *Query complexity*
  - Number of constraints (e.g. triple-pattern joins)
  - Semantics of the query (e.g. negation- and disjunction-related clauses)
  - Use of operators that cannot be optimized (e.g. LIKE)
- *Number of concurrent clients*

Performance Dimensions

- *Scale*
  - The size of the repository (number of triples)
- *Schema and data complexity*
  - The complexity of the ontology/logical language
  - The specific ontology (or schema) and dataset
    - E.g. a highly interconnected dataset, with long chains of transitive properties, can appear quite challenging for reasoning
  - Sparse versus dense datasets
  - Presence and size of literals
  - Number of predicates used
  - Use of **owl:sameAs**

Scalability Metrics

- *Number of inserted statements (NIS)*
- *Number of stored statements (NSS)*
  - How many statements have been stored and indexed?
  - Duplicates can make NSS smaller than NIS
  - For engines using forward-chaining and materialization, the volume of data to be indexed includes the inferred triples
- *Number of retrievable statements (NRS)*
  - How many different statements can be retrieved?
    - This number can be different from NSS when the repository supports some sort of backward-chaining

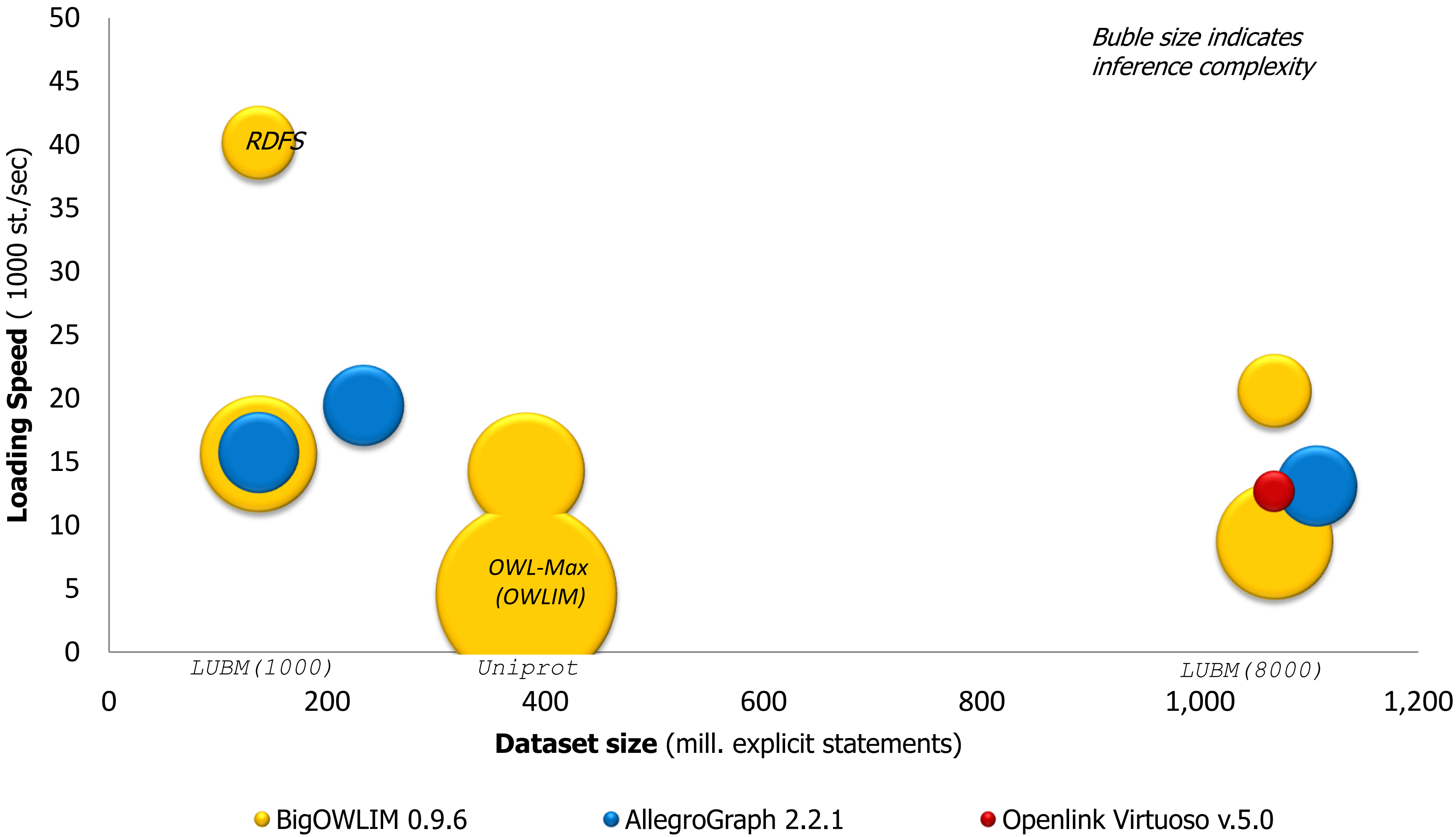
Full-Cycle Benchmarking

- We call *full-cycle benchmarking* any methodology that provides a complete picture of the performance with respect to the full "life cycle" of the data within the engine
  - publication of data for both loading and query evaluation performance in the framework of a single experiment or benchmark run
  - Full-cycle benchmarking requires load performance data to be matched with query evaluation performance
    - "5 billion triples of LUBM were loaded in 30 hours"
    - "… and the evaluation of the 14 queries took 1 hour on a warm database."

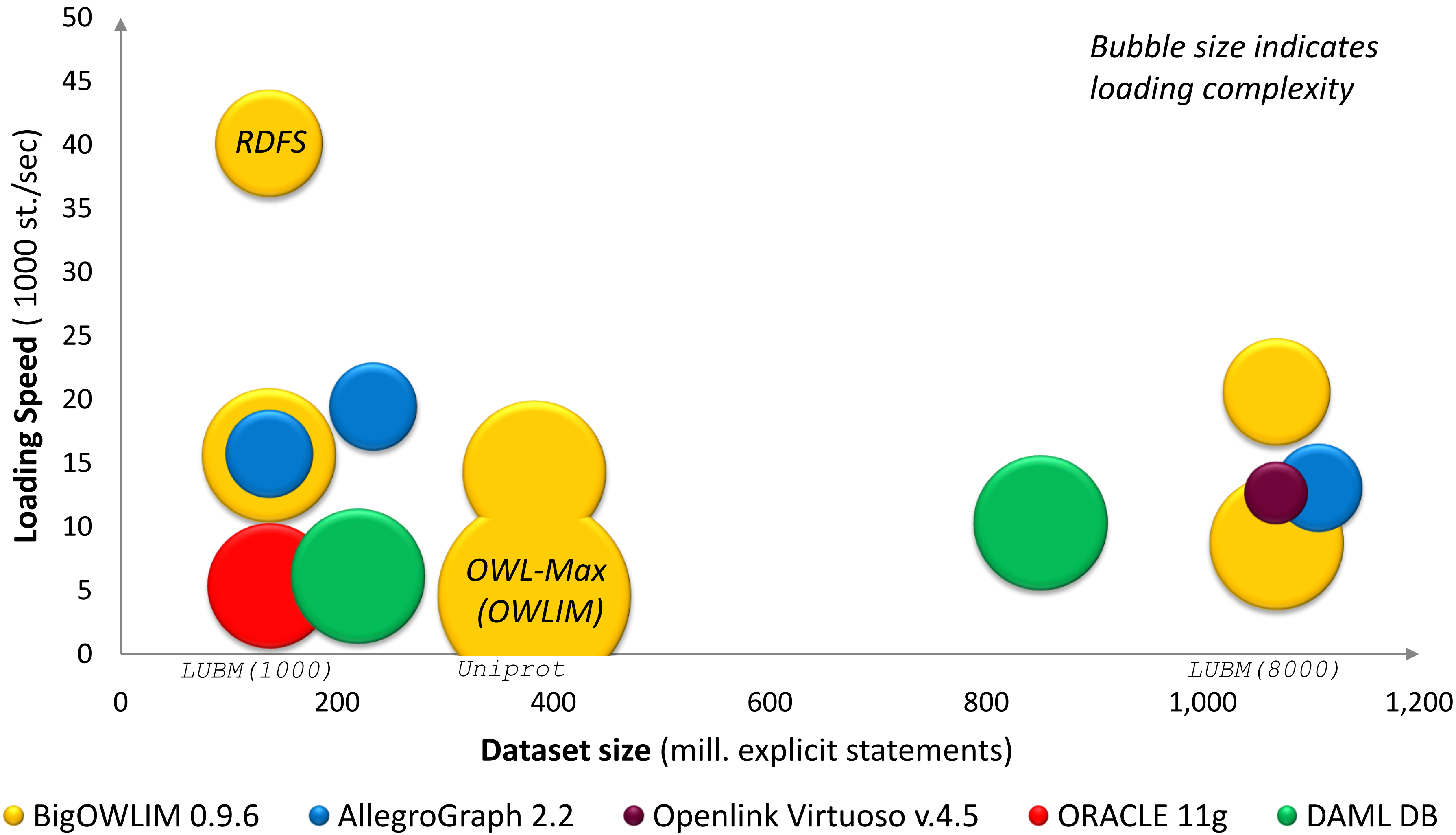
Full-Cycle Benchmarking (2)

- Typical set of activities to be covered:
  1. Loading input RDF files from the storage system
  2. Parsing the RDF files
  3. Indexing and storing the triples
  4. Forward-chaining and materialization (optional)
  5. Query parsing
  6. Query optimization
     - Query re-writing (optional)
  7. Query evaluation, involving
     - Backward-chaining (optional)
     - Fetching the results

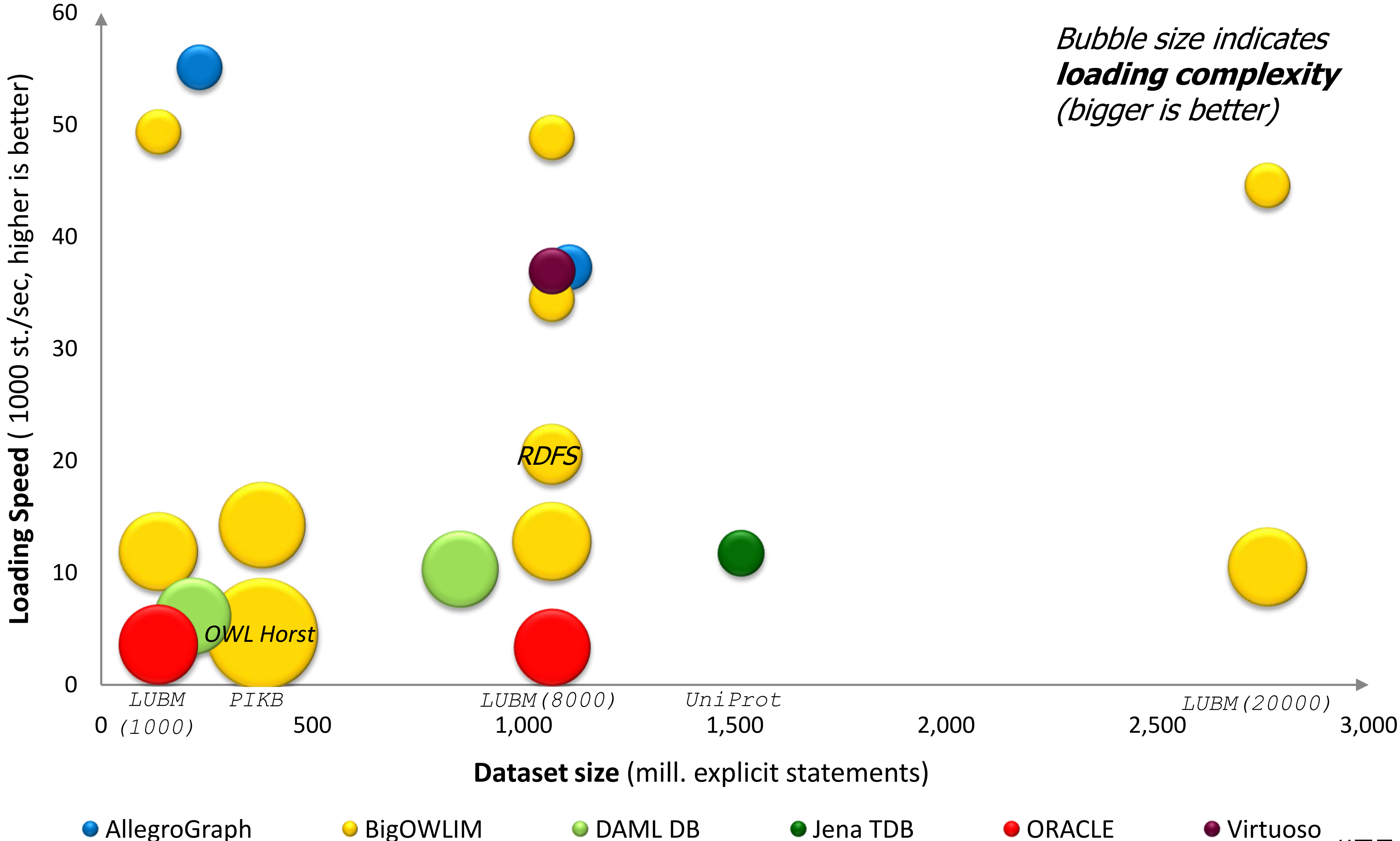
Scalable Inference Map (Sep'07)



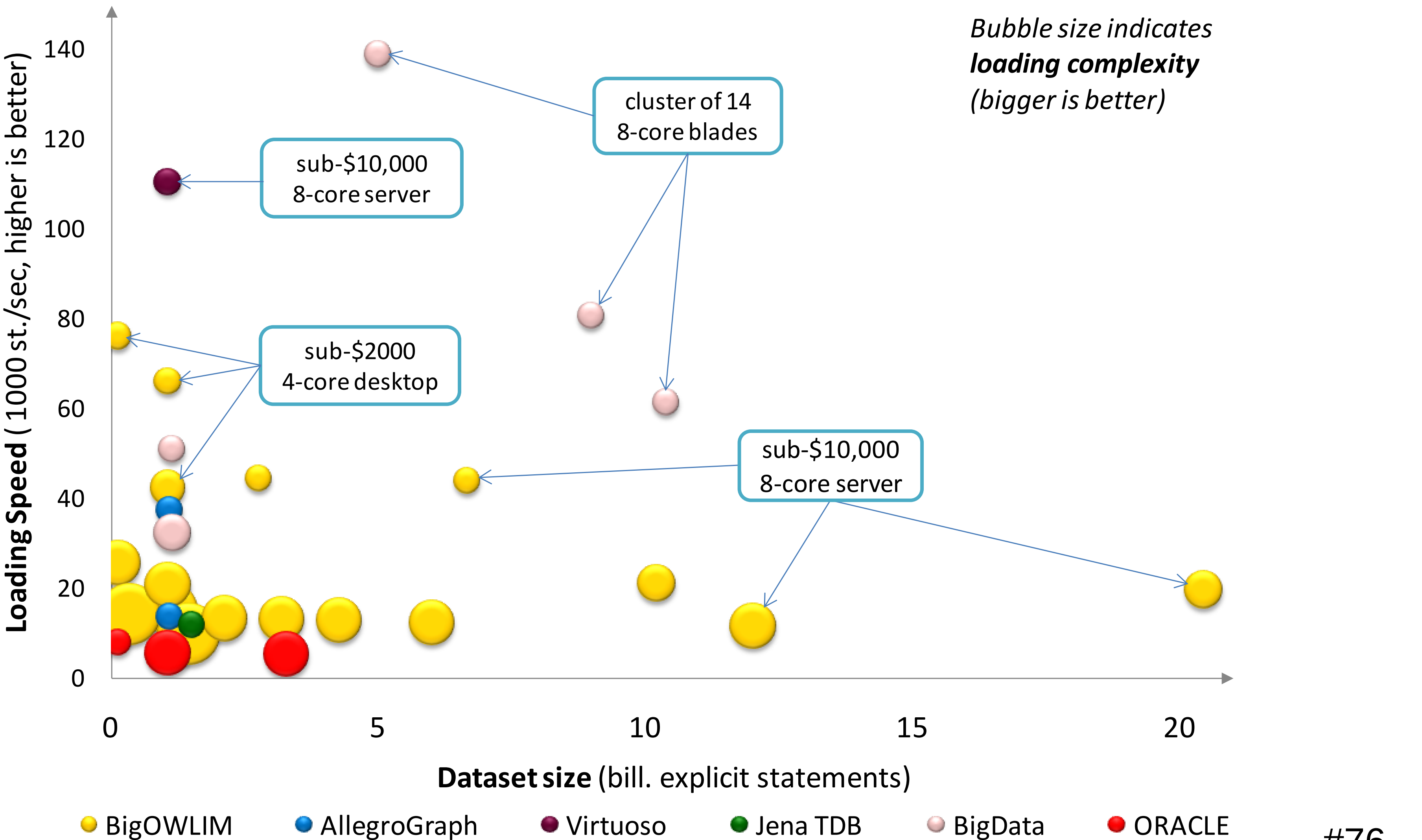
Scalable Inference Map (Nov'07)



Scalable Inference Map (Oct'08)



Scalable Inference Map (Jun'09)

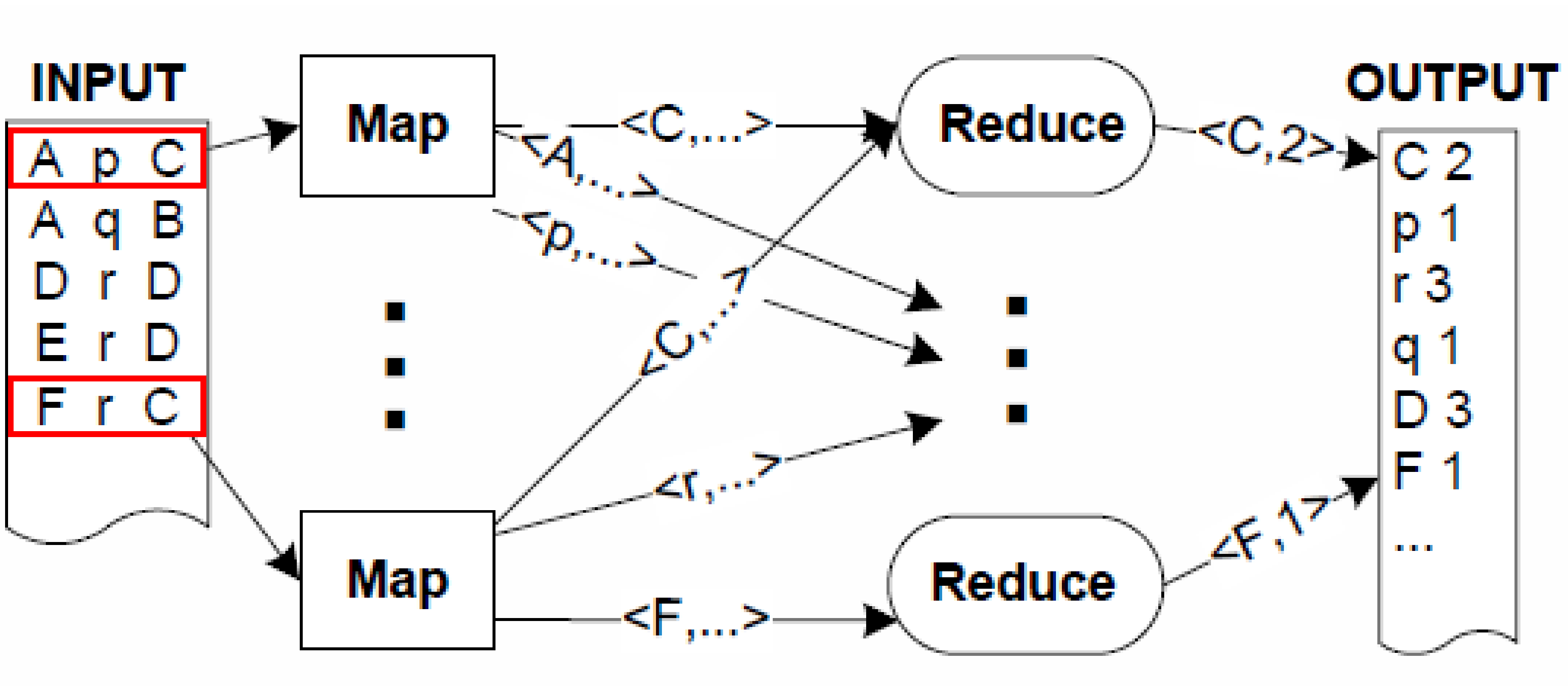


Distributed approaches to RDF materialisation

Distributed RDF materialisation with MapReduce

- Distributed approach by Urbani et al., ISWC'2009
  - "*Scalable Distributed Reasoning using MapReduce*"
- 64 node Hadoop cluster
- MapReduce
  - *Map* phase – partitions the input space by *some* key
  - *Reduce* phase – perform some aggregated processing on a partition (from the *Map* phase)
    - The partition contains all elements for a particular key
    - Skewed key distribution leads to uneven load on *Reduce* nodes
    - Balanced *Reduce* load almost impossible to achieve (major M/R drawback)

Distributed RDF materialisation with MapReduce (2)



(c) Urbani et al.

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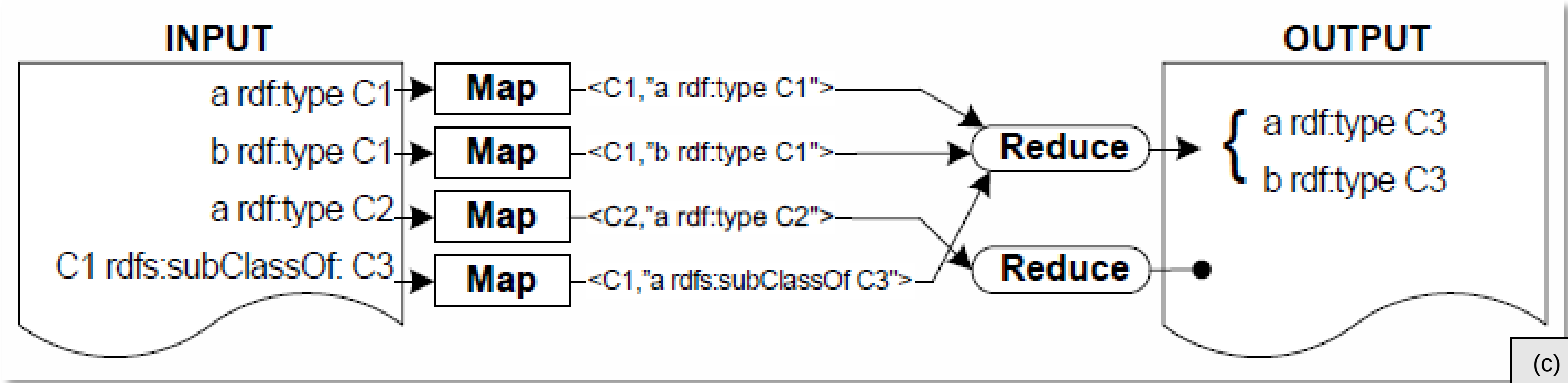
Distributed RDF materialisation with MapReduce (3)

- RDFS entailment rules

1:	$s\ p\ o$ (if o is a literal)		$\Rightarrow$ _:n rdf:type rdfs:Literal
2:	p rdfs:domain x	& $s\ p\ o$	$\Rightarrow$ s rdf:type x
3:	p rdfs:range x	& $s\ p\ o$	$\Rightarrow$ o rdf:type x
4a:	$s\ p\ o$		$\Rightarrow$ s rdf:type rdfs:Resource
4b:	$s\ p\ o$		$\Rightarrow$ o rdf:type rdfs:Resource
5:	p rdfs:subPropertyOf q	& q rdfs:subPropertyOf r	$\Rightarrow$ p rdfs:subPropertyOf r
6:	p rdf:type rdf:Property		$\Rightarrow$ p rdfs:subPropertyOf p
7:	$s\ p\ o$	& p rdfs:subPropertyOf q	$\Rightarrow$ $s\ q\ o$
8:	s rdf:type rdfs:Class		$\Rightarrow$ s rdfs:subClassOf rdfs:Resource
9:	s rdf:type x	& x rdfs:subClassOf y	$\Rightarrow$ s rdf:type y
10:	s rdf:type rdfs:Class		$\Rightarrow$ s rdfs:subClassOf s
11:	x rdfs:subClassOf y	& y rdfs:subClassof z	$\Rightarrow$ x rdfs:subClassOf z
12:	p rdf:type rdfs:ContainerMembershipProperty		$\Rightarrow$ p rdfs:subPropertyOf rdfs:member
13:	o rdf:type rdfs:Datatype		$\Rightarrow$ o rdfs:subClassOf rdfs:Literal

Distributed RDF materialisation with MapReduce (4)

- “naïve” approach
  - applying all RDFS rules iteratively on the input until no new data is derived (fixpoint)
    - rules with one antecedent are easy
    - rules with 2 antecedents require a join
  - Map function
    - Key is *S*, *P* or *O*, value is original triple
  - Reduce function – performs the join



(c) Urbani et al.

Distributed RDF materialisation with MapReduce (4)

- Problems
  - One iteration is not enough!
  - Too many duplicates generated
    - Ration unique/duplicate triples is more than 1/50
- Optimised approach
  - Load schema triples in memory (0.001-0.01% of triples)
    - On each node joins are made between a very small set of schema triples and a large set of instance triples
    - Only the instance triples are streamed by the MapReduce pipeline

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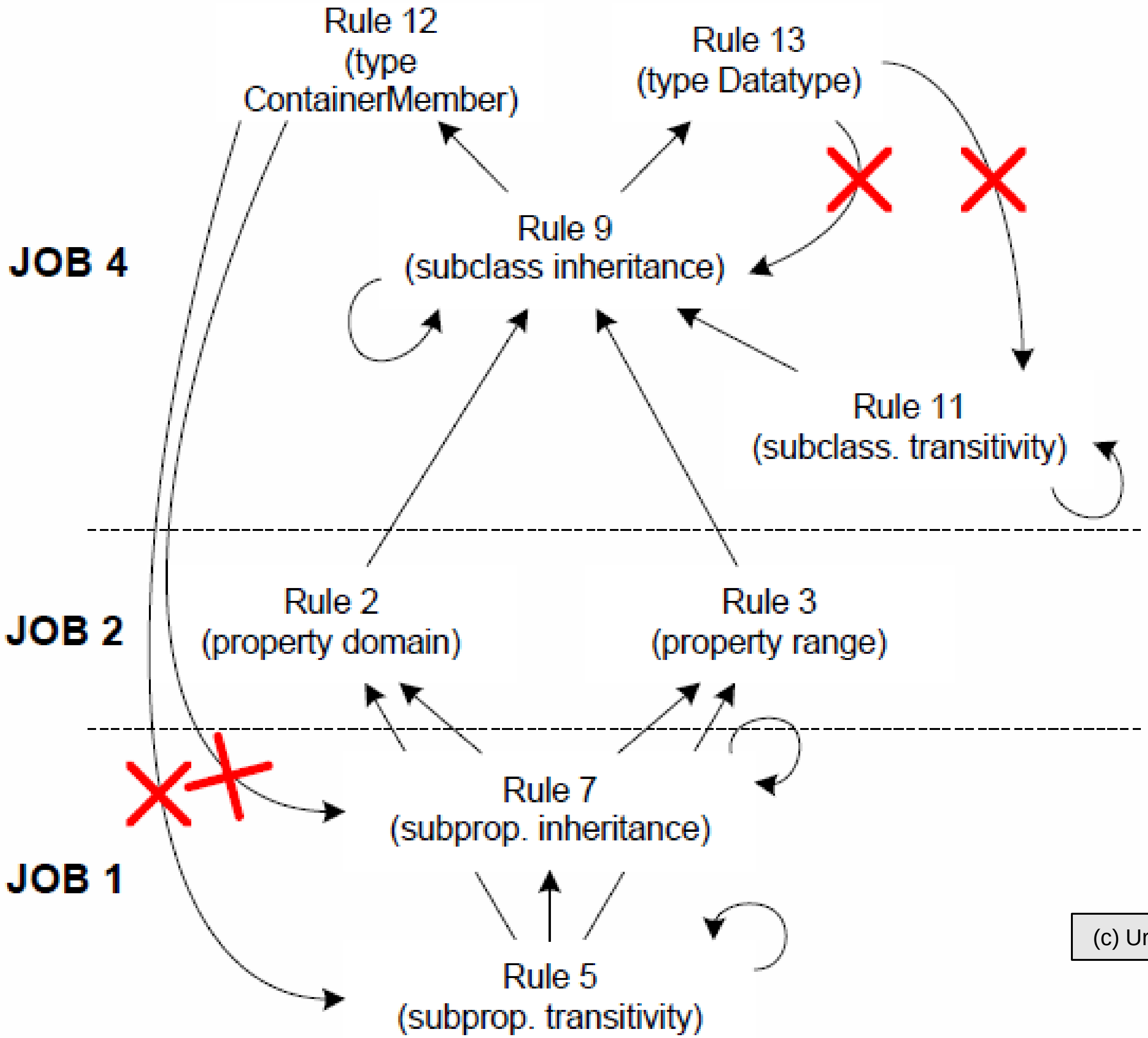
Distributed RDF materialisation with MapReduce (5)

- Optimised approach (2)
  - Data Grouping to Avoid Duplicates
    - Map phase: set as key those parts of the input (S/P/O) that are also used in the derived triple. All triples that produce the same triple will be sent to the same Reducer
    - Join schema triples during the *Reduce* phase to reduce duplicates
  - Ordering the Sequence of the Rules
    - Analyse the ruleset and determine which rules may triggered other rules
    - Dependency graph, optimal application of rules from bottom-up

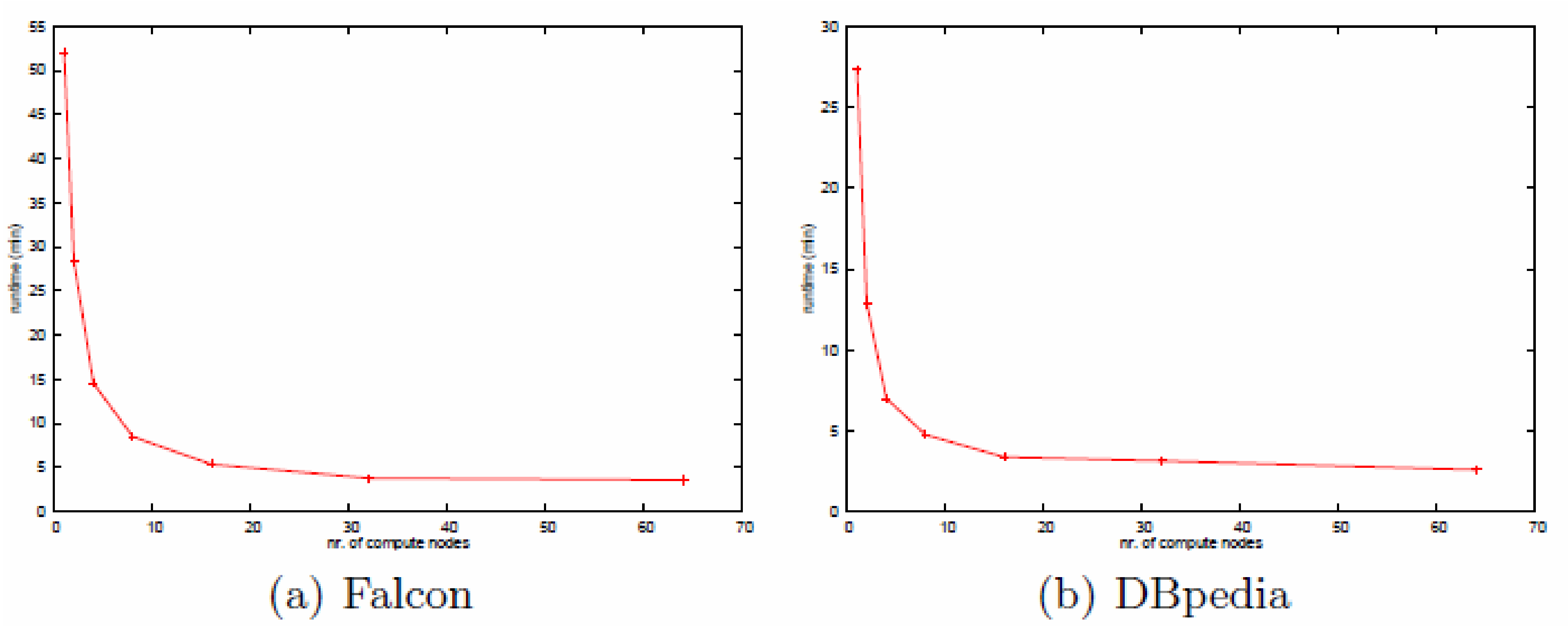
Distributed RDF materialisation with MapReduce (6)



(c) Urbani et al.

Distributed RDF materialisation with MapReduce (7)

- Performance benchmarks
  - 4.3 million triples / sec (30 billion in ~2h)

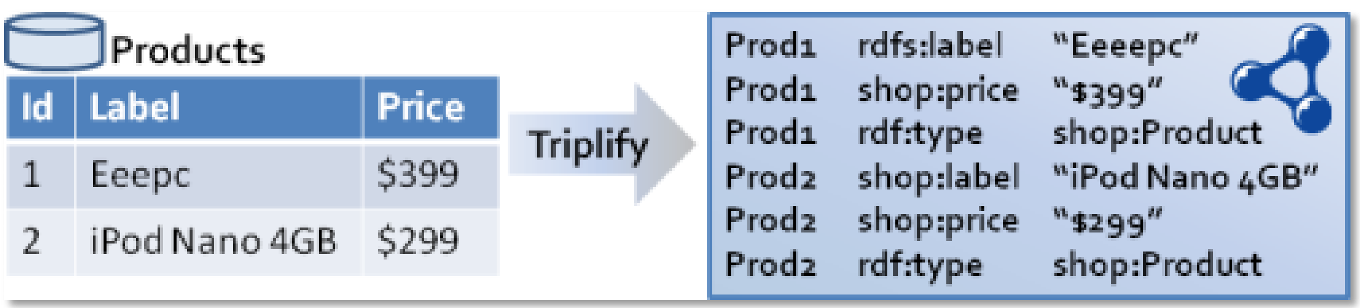


(c) Urbani et al.

From RDBMS to RDF

RDB2RDF

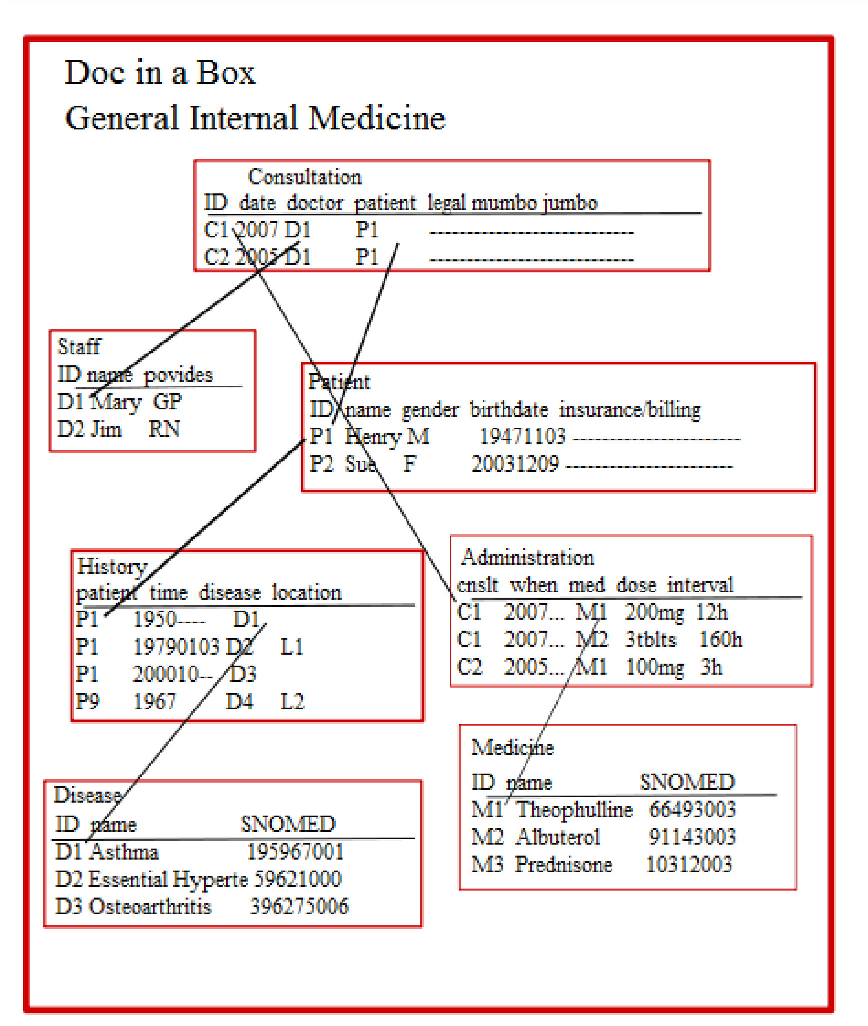
- RDB2RDF working group @ W3C
  - http://www.w3.org/2001/sw/rdb2rdf/
  - standardize a language (R2RML) for mapping relational data / database schemas into RDF / OWL
- Existing RDF-izers
  - Triplify, D2RQ, RDF Views

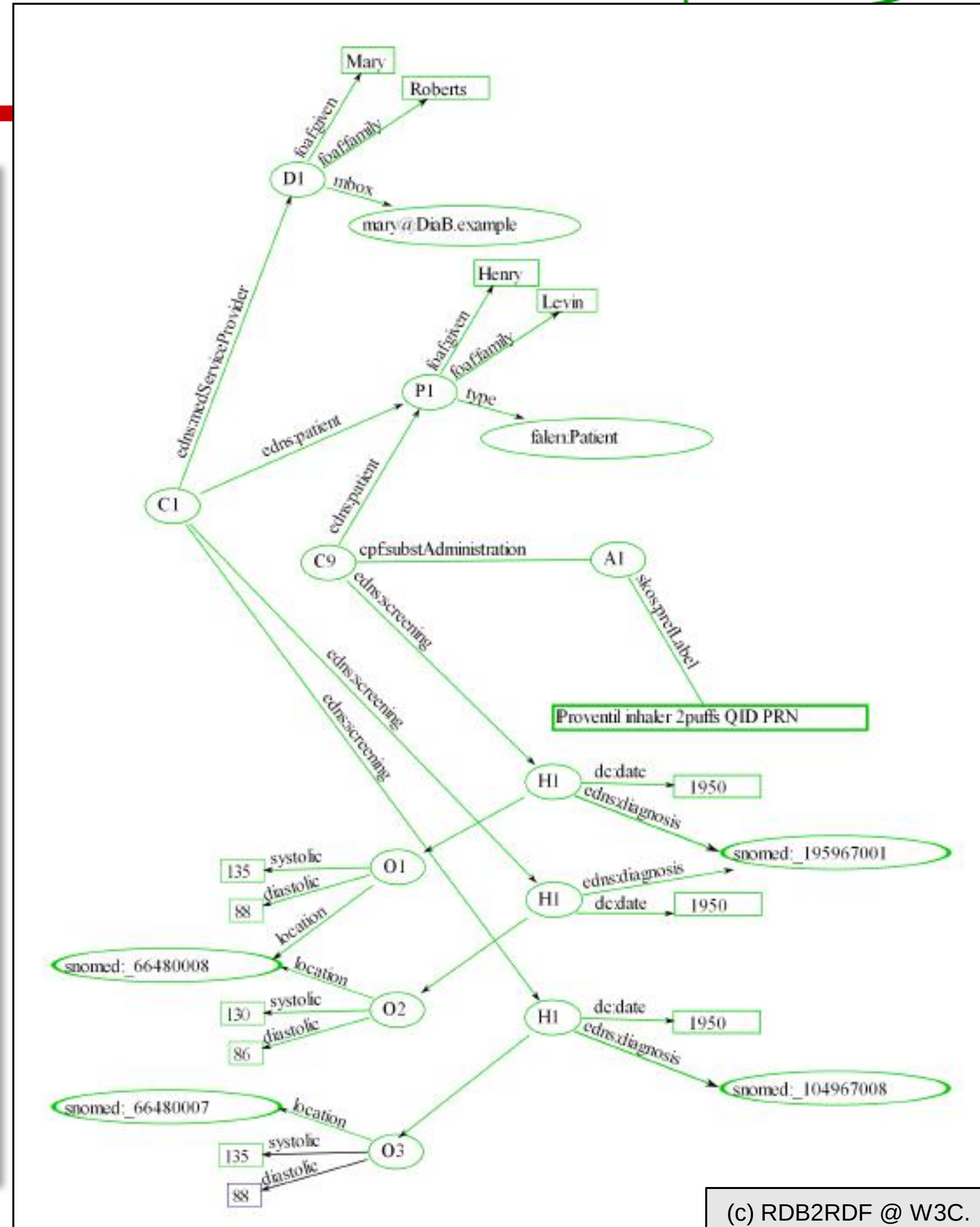


RDB2RDF (2)

- Table-to-class mapping approach
  - Each RDB table is a RDF class
  - Each RDB record is a RDF node
    - Each PK column value is a Subject URI
    - Each non-PK column name in a RDB table is a RDF predicate
    - Each RDB table cell value (non-PK) is a value (Object)

Mapping example





Other RDF tools

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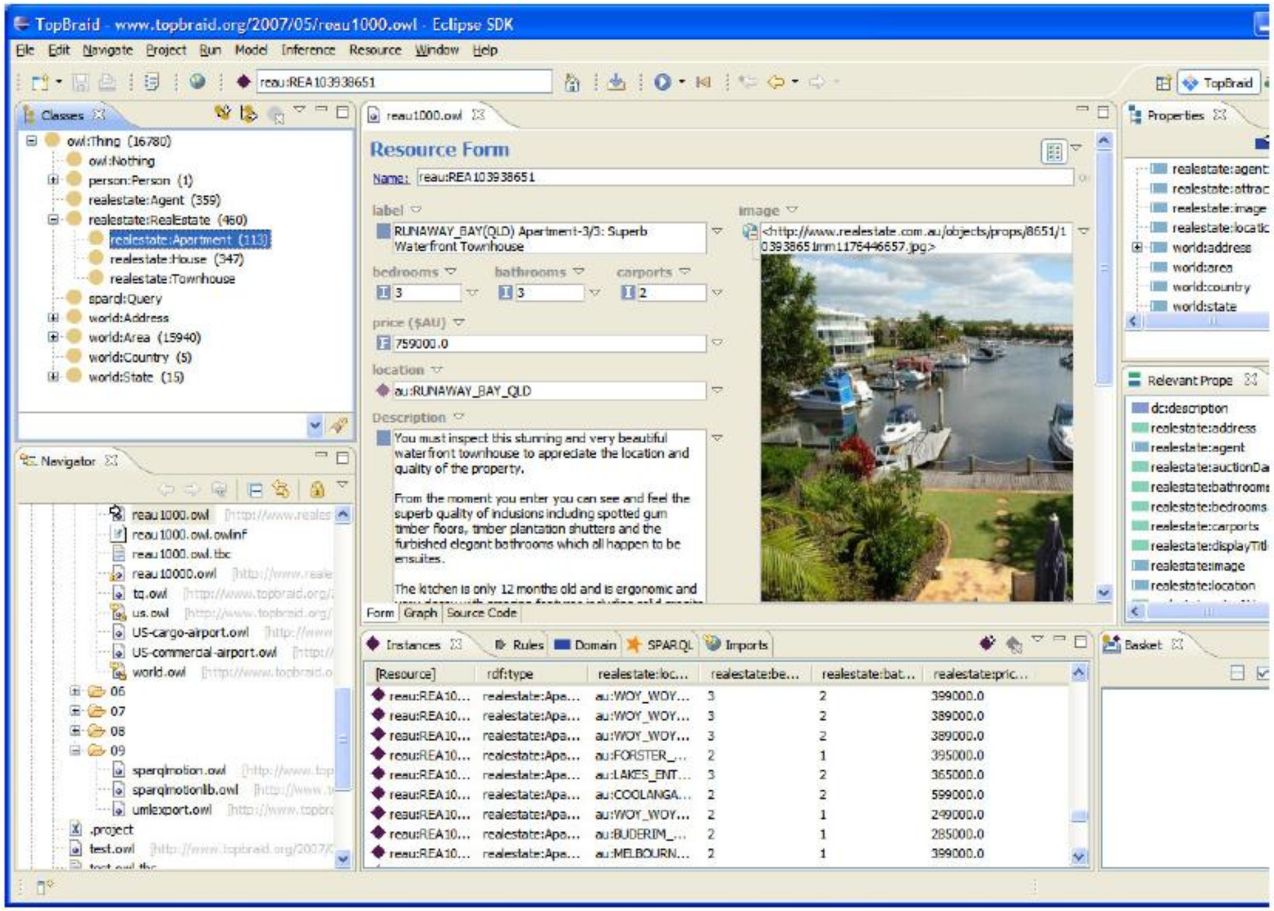
GATE

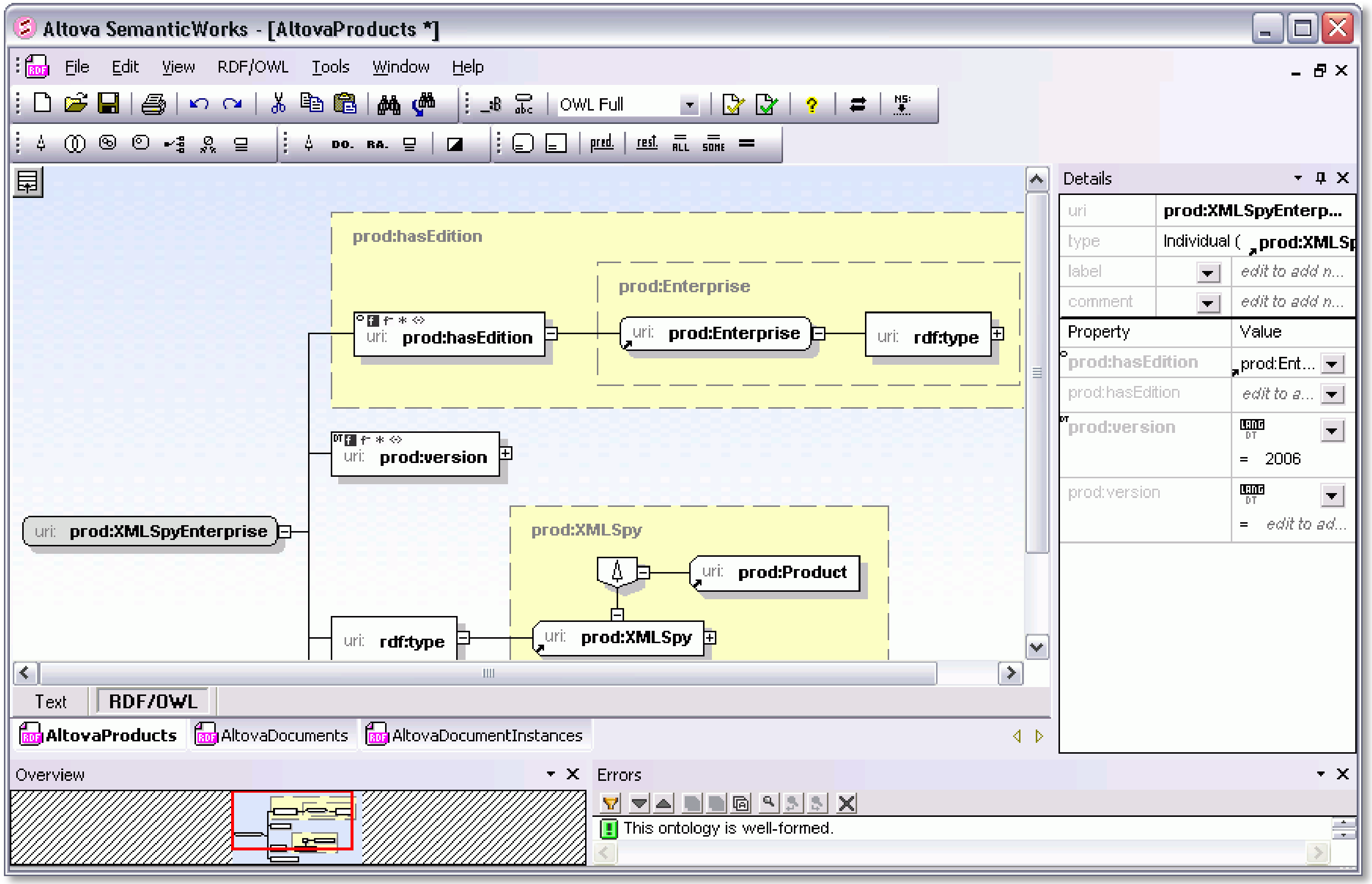
Ontology editors

- TopBraid Composer
  - http://www.topquadrant.com



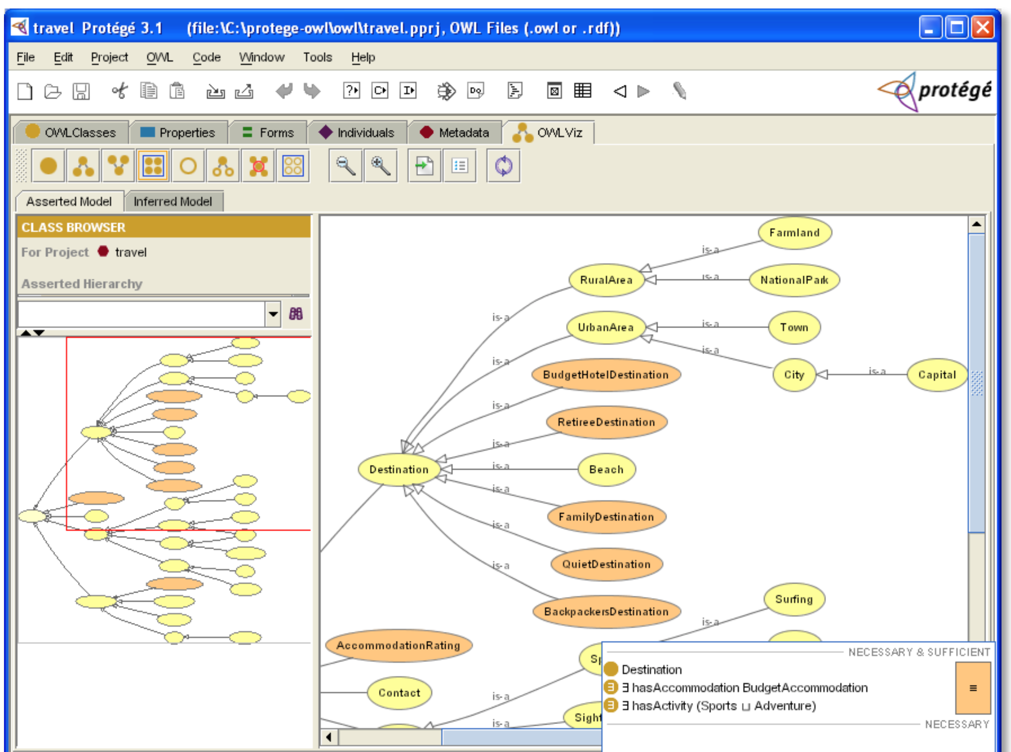
Ontology editors (2)

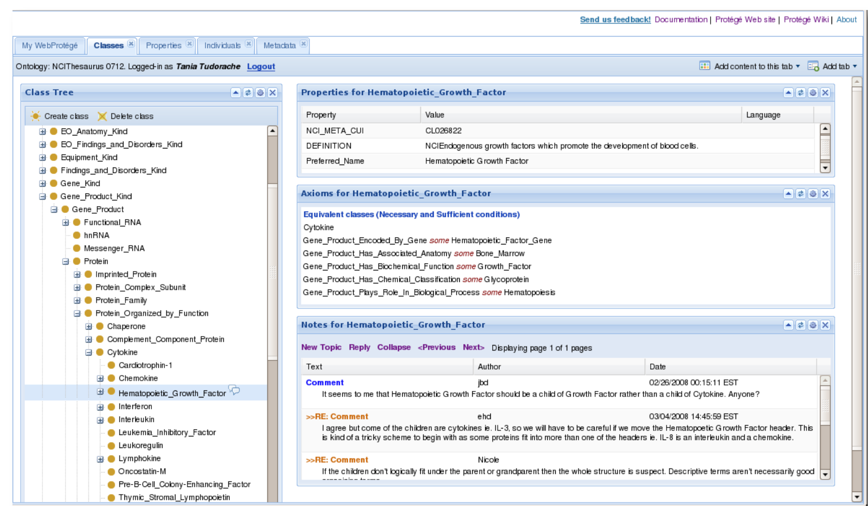
- Altova SemanticWorks
  - http://www.altova.com/semanticworks.html



Ontology editors (3)

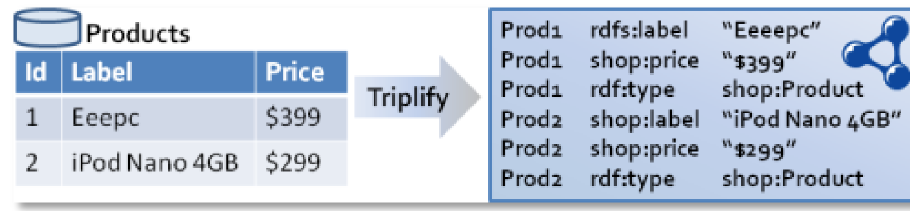
- Protégé
  - http://protege.stanford.edu
  - http://webprotege.stanford.edu



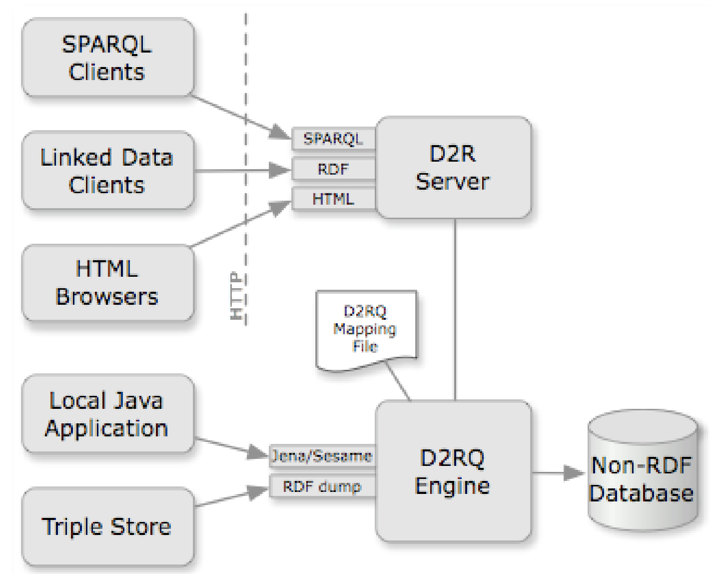


RDF-izers

- Triplify
  - http://triplify.org
  - Transform relational data into RDF / Linked Data



- D2RQ platform
  - http://www4.wiwiss.fu-berlin.de/bizer/d2rq/index.htm
  - D2RQ mapping language
  - D2RQ plugin for Sesame/Jena
  - D2R server
    - Linked Data & SPARQL endpoint



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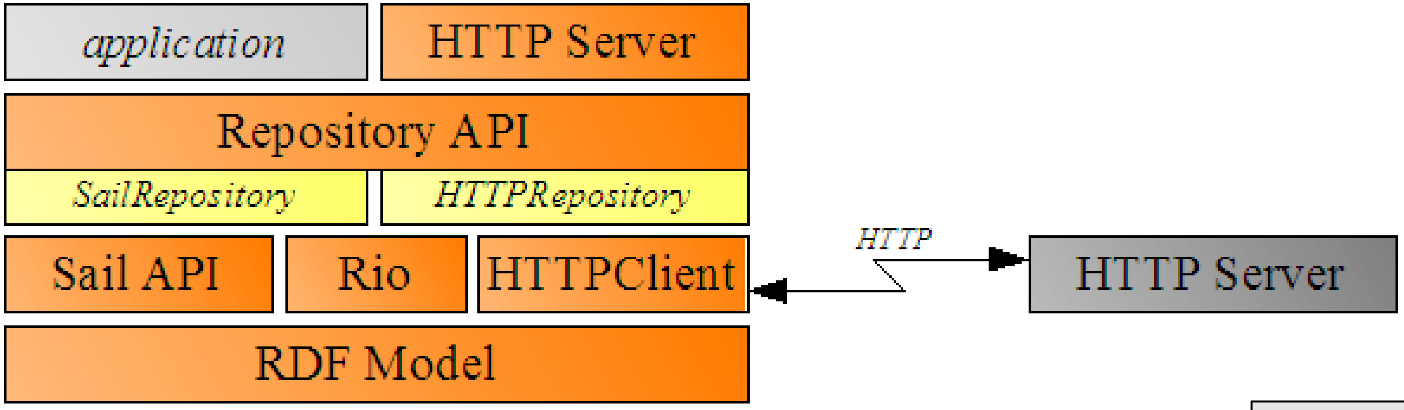
RDF APIs

- Jena
  - http://jena.sourceforge.net
  - RDF/OWL API (Java)
  - In-memory or persistent storage
  - SPARQL query engine
- OpenRDF (Sesame)
  - http://www.openrdf.org
  - RDF API (Java), high performance parser
  - Persistent storage
  - SPARQL query engine

Sesame API

- Architecture
  - RDF Model
  - RDF I/O (parsers & serializars)
  - Storage & Inference Layer (for reasoners & databases)
  - High-level Repository API
  - HTTP & REST service frontend



(c) OpenRDF.org

Sesame API (2)

- RDF model
  - Create statements, get S/P/O
- SAIL API
  - Initialise, shut-down repositories
  - Add/remove/iterate statements
  - queries
- Repository API
  - Create a repository (in-memory, filesystem), connect
  - Add, retrieve, remove triples
  - Queries

Sesame API – REST interface

resource	GET	POST	PUT	DELETE
/repositories	List available repositories	-	-	-
/repositories/ID	query evaluation • query text • Bindings • Inference	Query evaluation	-	-
/repositories/ID/statements	Get statements in repository • S, P, O • inference	Adds/updates statements	Modifies existing statements	Deletes statements • S, P, O
/repositories/ID/namesapces	List Namespace definitions	-	-	Deletes all namespace definitions
/repositories/ID/namesapces/PREF	Gets the namespace for a prefix	-	Defines/updates the namespace for a prefix	Removes a namespace declaration

Sesame – OpenRDF Workbench