Distributed RDF Query Processing and Reasoning in Peer-to-Peer Networks

Zoi Kaoudi
Postdoctoral researcher

Work done in the context of my PhD thesis at the National and Kapodistrian University of Athens

Outline

- Introduction
- The system Atlas
- RDFS Reasoning in P2P networks
- SPARQL Query Processing and Optimization
- Conclusions

Web of Documents/Web of Data

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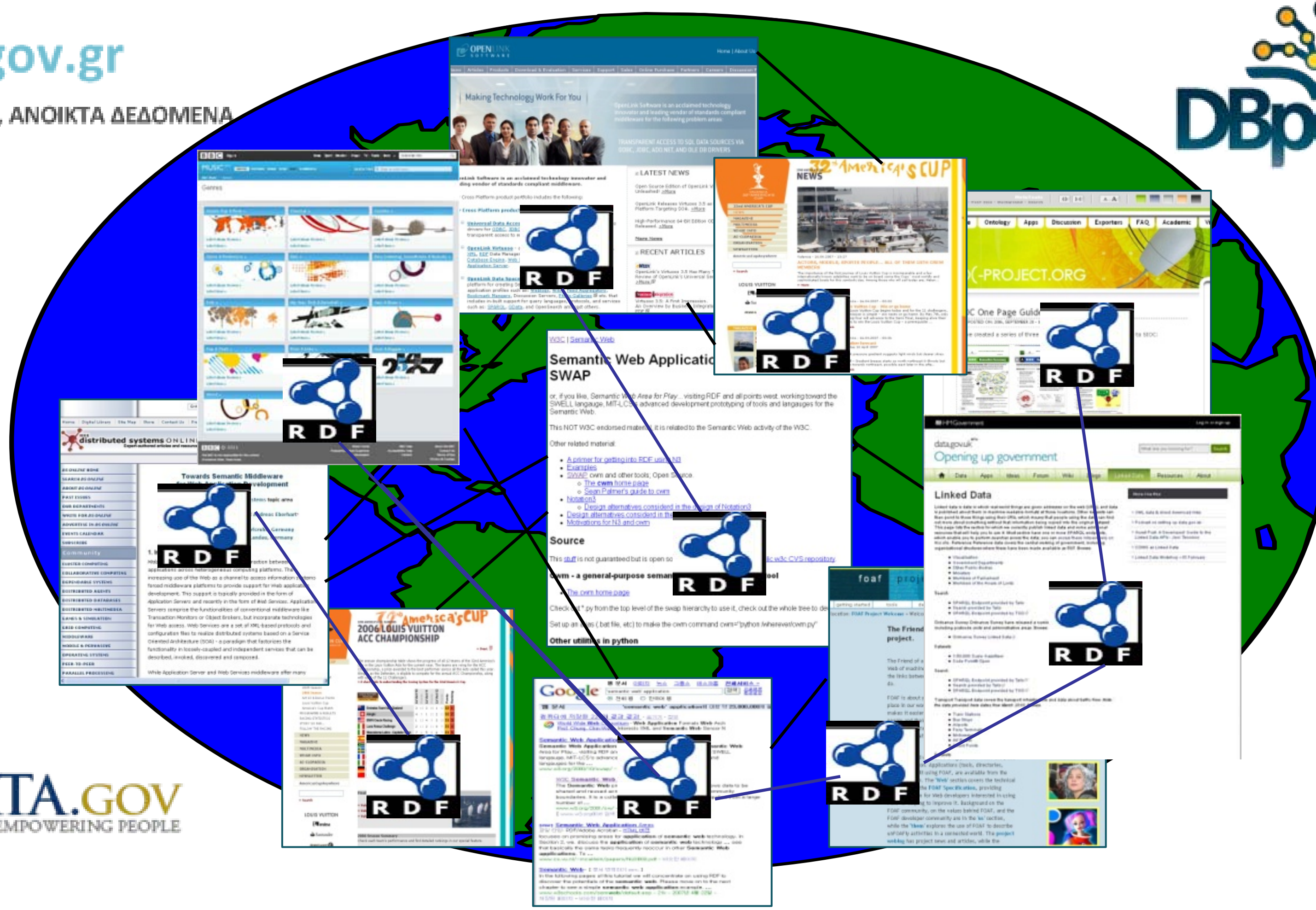
ΔΗΜΟΣΙΑ ΔΕΔΟΜΕΝΑ, ΑΝΟΙΚΤΑ ΔΕΔΟΜΕΝΑ

DBpedia



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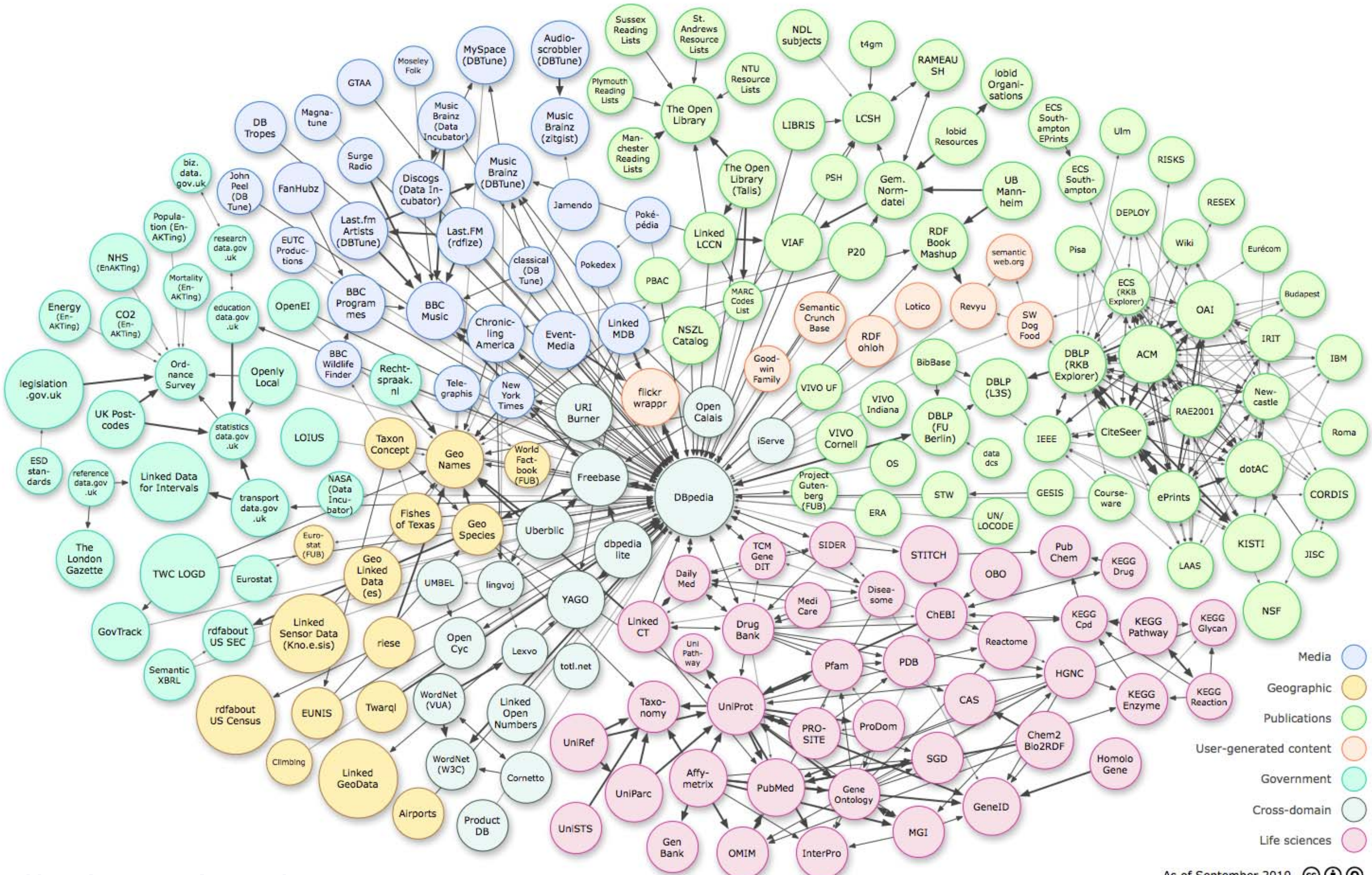
Resource Description Framework

- RDF provides a simple and abstract knowledge representation for resources on the Web which are uniquely identified by *Universal Resource Identifiers* (URIs)

- RDF Schema (RDFS) gives meaning to RDF terms and groups them to concepts

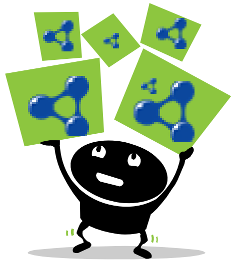
- SPARQL: official W3C recommendation language for querying RDF data

Linked Open Data Cloud



http://lod-cloud.net/

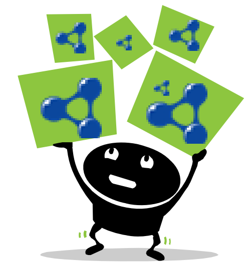
RDF Data Management



- With the vast amount of available RDF data sources on the Web increasing rapidly, there is an urgent need for RDF data management

- RDF storage, query processing and reasoning have been at the center of attention during the last years

RDF Data Management



- Centralized solutions
  - Jena, Sesame, RSSDB, Oracle, RDF-3X, etc.
- Parallel and distributed solutions
  - P2P systems
    - RDFPeers, BabelPeers, GridVine, Edutella etc.
  - Powerful clusters
    - Virtuoso, YARS2, MaRVIN
  - Cloud computing
    - Mika08, Urbani09, Stein10

Peer-to-peer (P2P) systems

- P2P systems provide nice features for Internet-scale applications (e.g., content sharing, distributed digital libraries)

- Distributed Hash Tables (DHTs)
  - answer exact match queries efficiently

Challenges

- How to index RDF data and RDFS ontologies in a DHT?
  - ***Triple indexing scheme and handle RDF and RDFS uniformly***
  - ***Distributed mapping dictionary***
- How to answer SPARQL queries efficiently? What kinds of query optimization techniques to use?
  - ***Greedy optimization algorithms to minimize the size of the intermediate results***
  - ***Selectivity estimation techniques***
  - ***RDF statistics in a DHT system***
- How to provide reasoning mechanisms for RDFS in a DHT?
  - ***Distributed forward chaining (FC)***
  - ***Distributed backward chaining (BC)***
  - ***Distributed magic sets transformation (MS)***
  - ***Comparative study (analytically and experimentally)***
  - ***Theoretical proofs of correctness***

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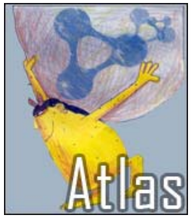
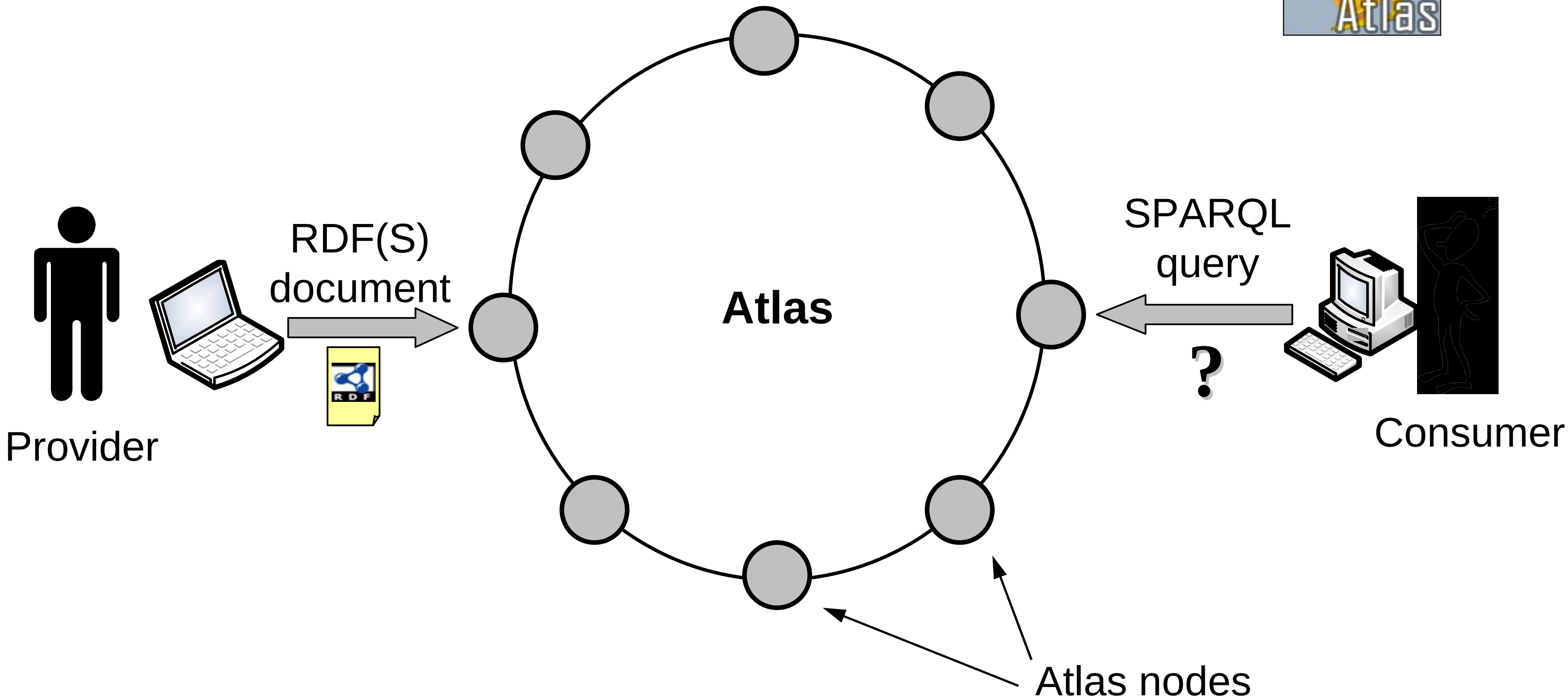
RDF Data Management in P2P networks: the system Atlas





The system Atlas

- **Atlas**: a full-blown open source P2P system for the distributed processing of RDF and RDFS data stored on top of DHTs (http://atlas.di.uoa.gr)

- Atlas has been used in EU projects OntoGrid and SemsorGrid4Env as a distributed registry of metadata

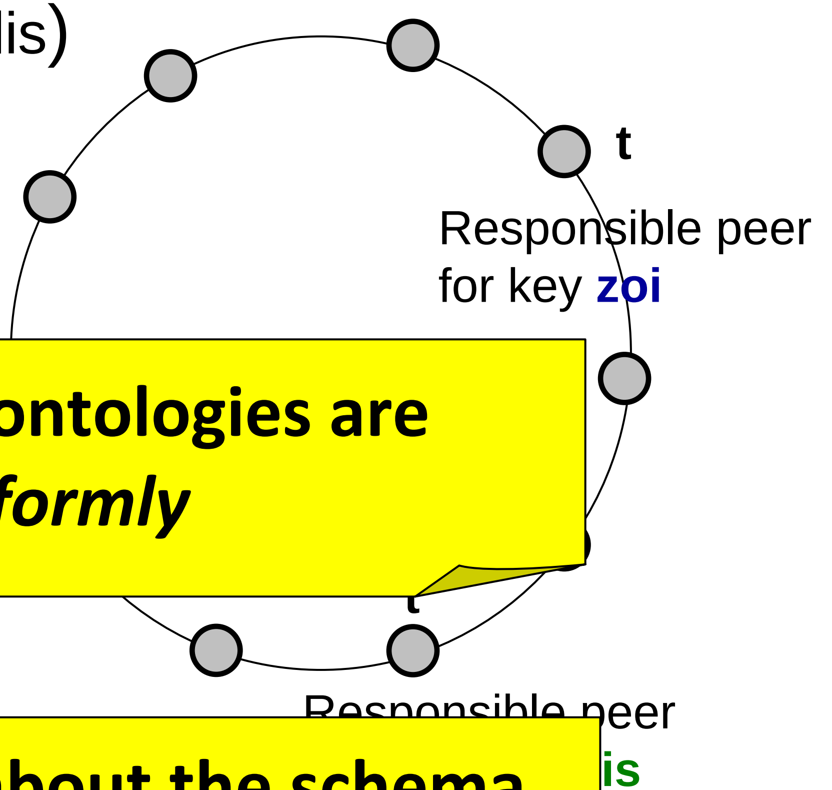
Indexing in Atlas

RDF triple t = (zoi, advisor, manolis)

Index identifier = (Hash(**zoi**))

Index identifier = (Hash(**advisor**))

Index i



RDF data and RDFS ontologies are handled *uniformly*

triple pattern tp = (?x, advisor, ?y)

Index identifier = (Hash(**advisor**))

No global knowledge about the schema

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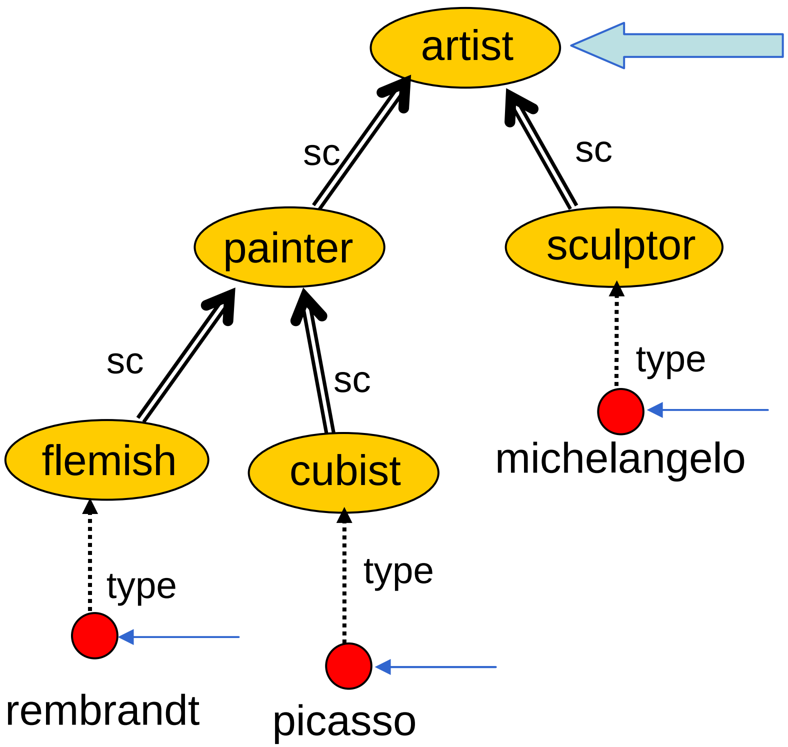
RDFS Reasoning



Query: Find all artists
q = (?x, rdf:type, artist)

RDFS entailment rules

Answer

?x
rembrandt
picasso
michelangelo

RDFS reasoning techniques

- Bottom-up approach
  - compute all inferences a priori (RDFS closure)
- Top-down approach
  - compute inferences at query run time
- Optimized bottom-up approach
  - compute inferences a priori given a specific query

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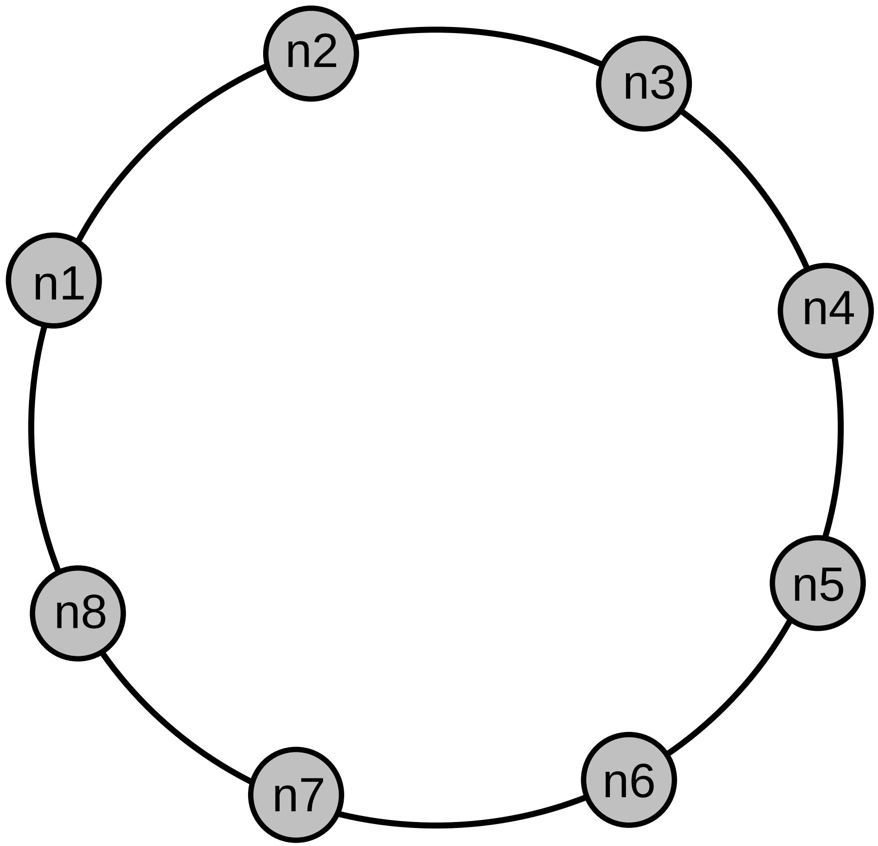
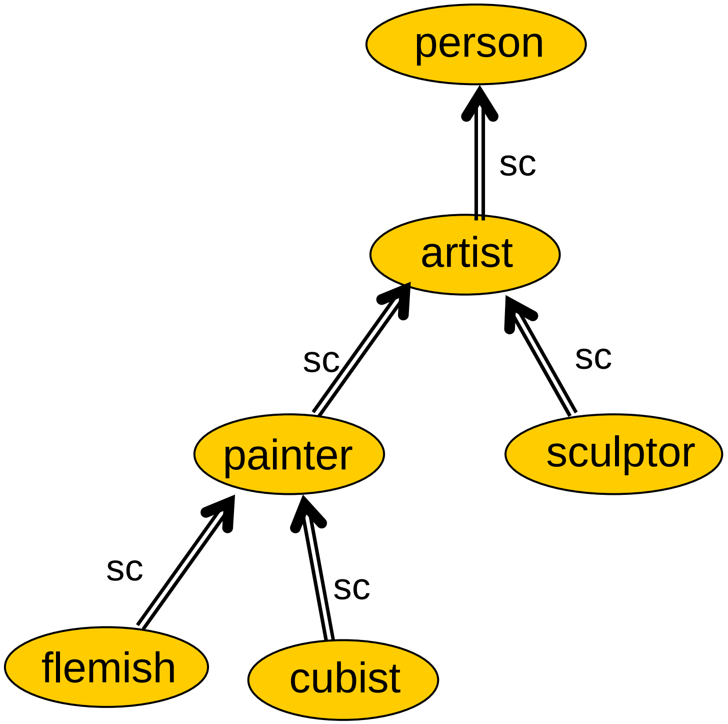
Bottom-up approach

- Distributed *forward chaining* algorithm
  - compute all inferences a priori (RDFS closure)
  - many redundant triples

Distributed Forward Chaining (FC)





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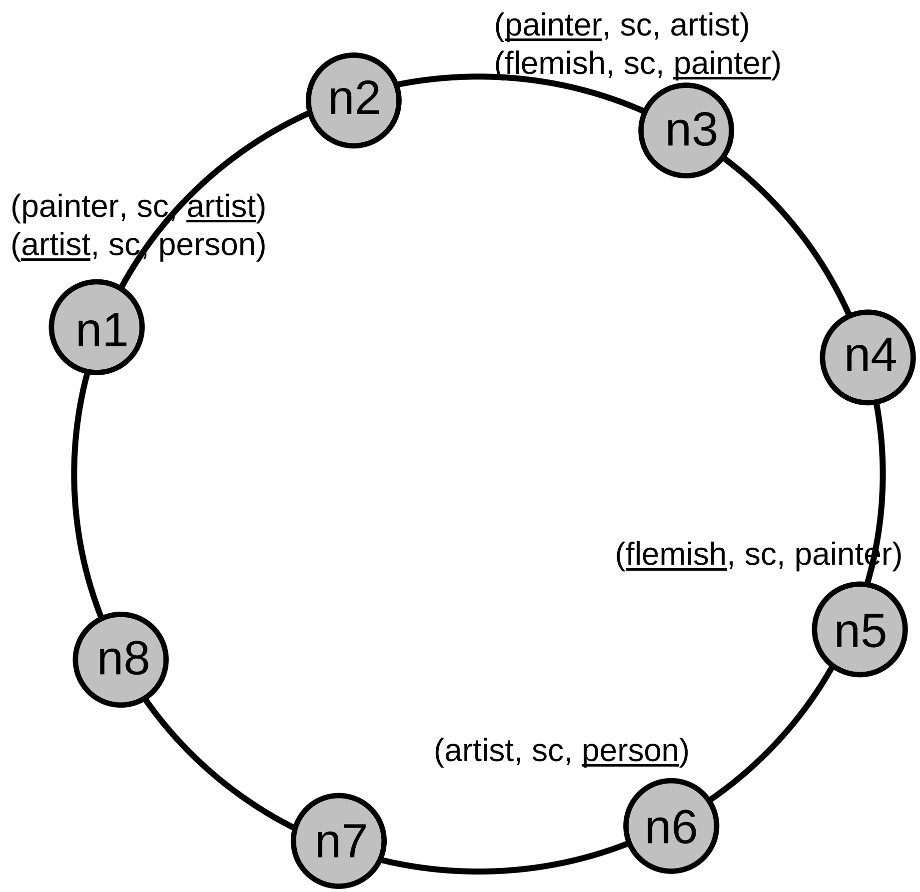

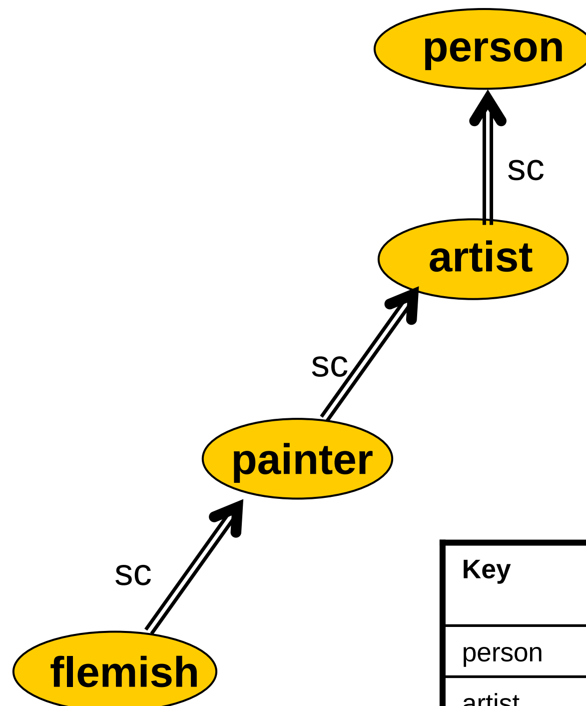

Key	Responsible peer
person	n6
artist	n1
painter	n3
flemish	n5

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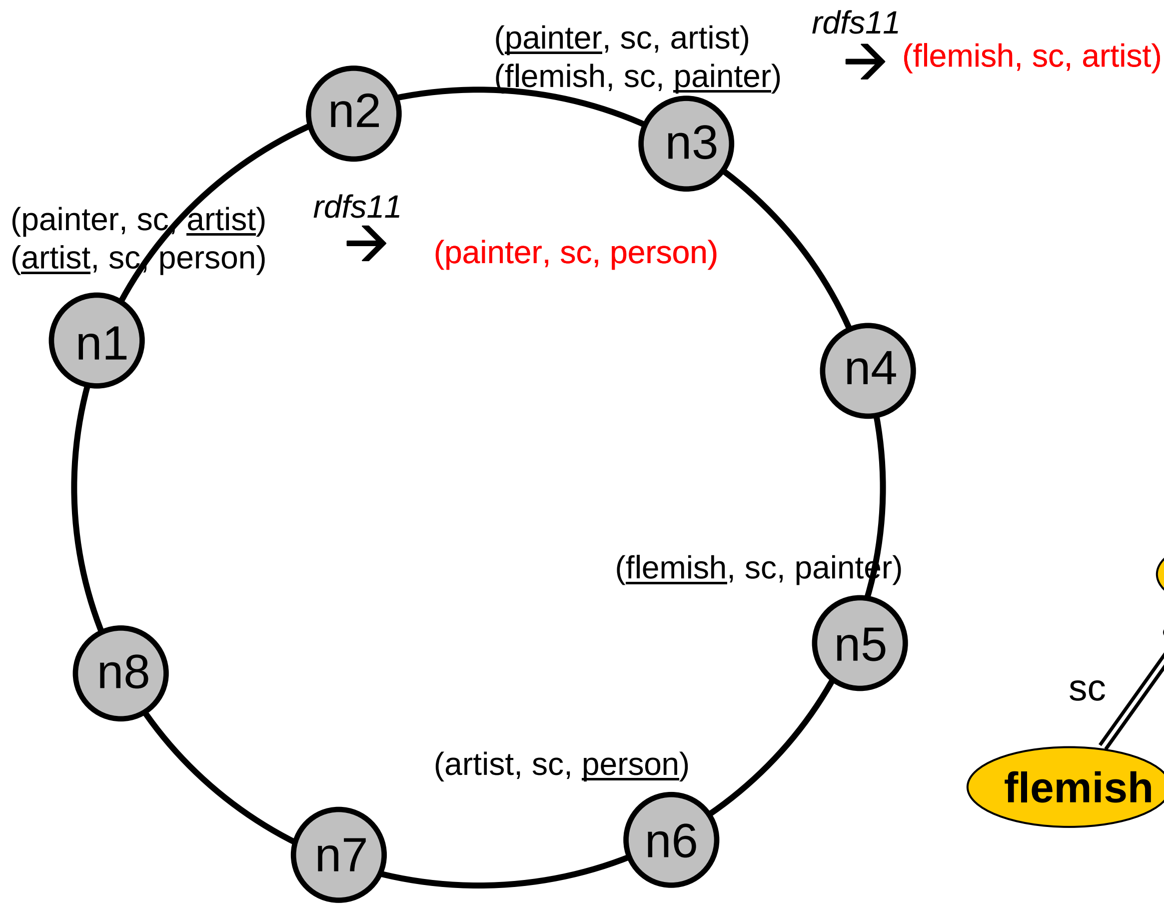

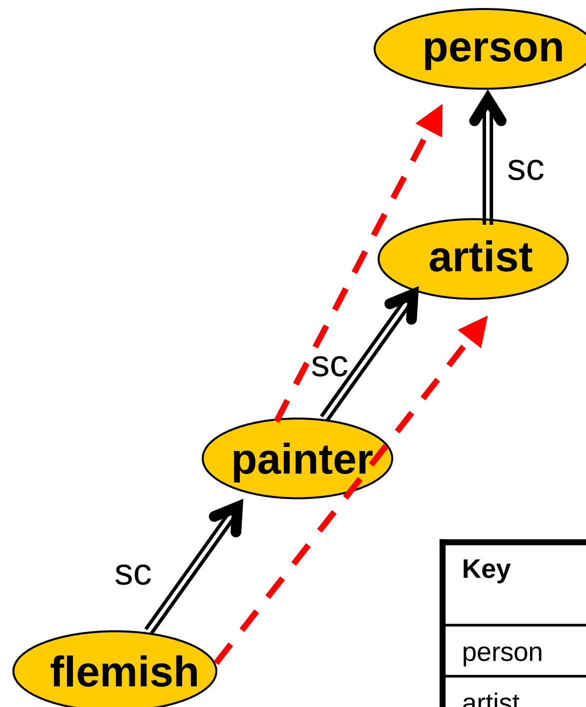

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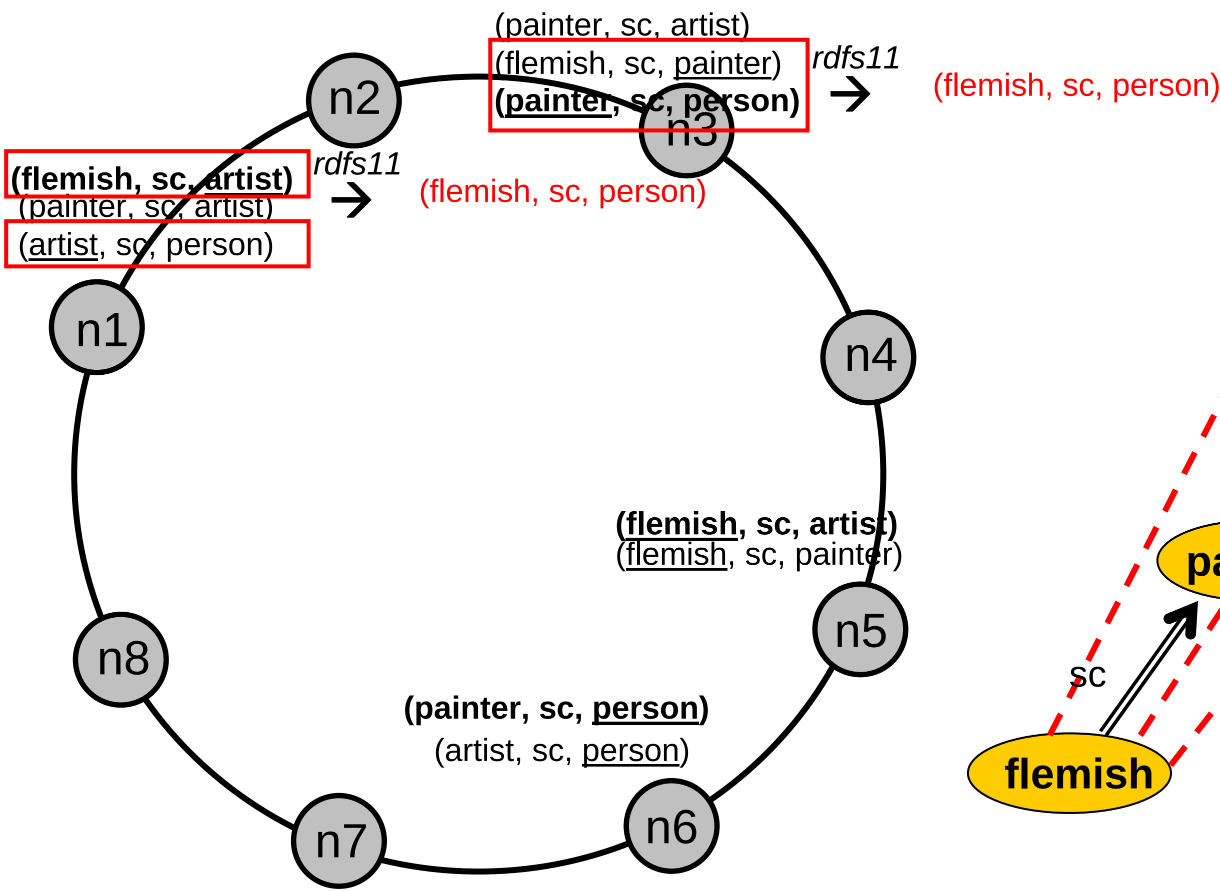
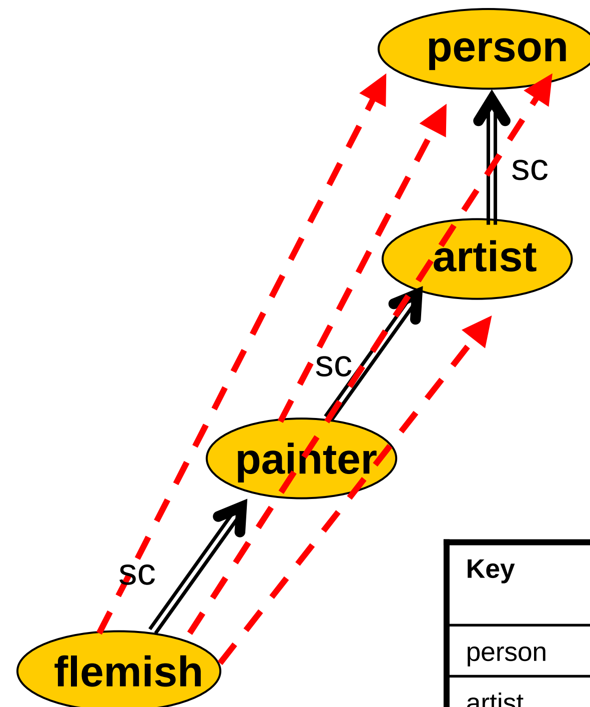
rdfs11

uuu rdfs:subClassOf vvv **vvv rdfs:subClassOf xxx** →	**uuu rdfs:subClassOf xxx**

Distributed Forward Chaining (FC)





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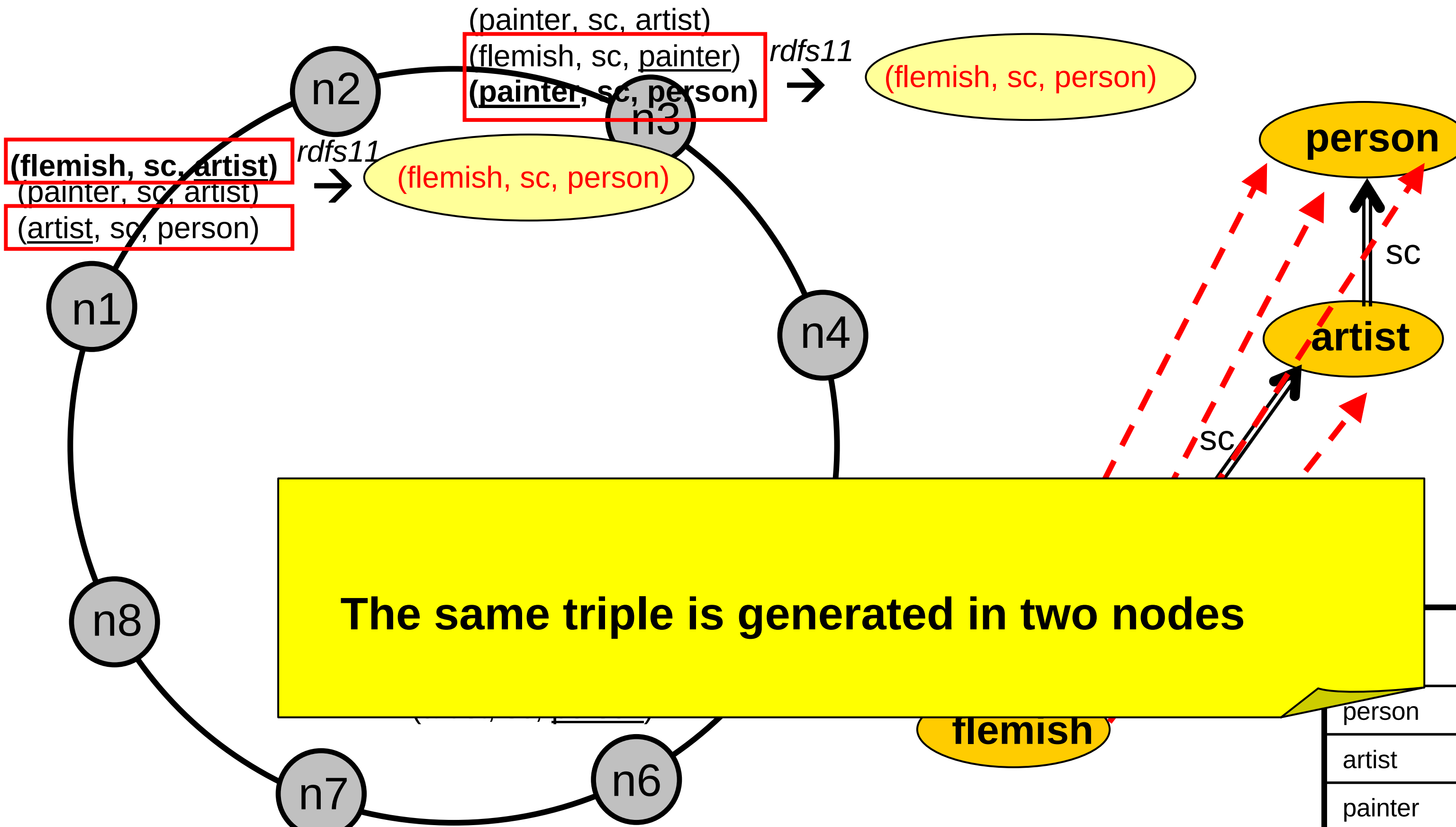

The same triple is generated in two nodes

	Responsible peer
person	n6
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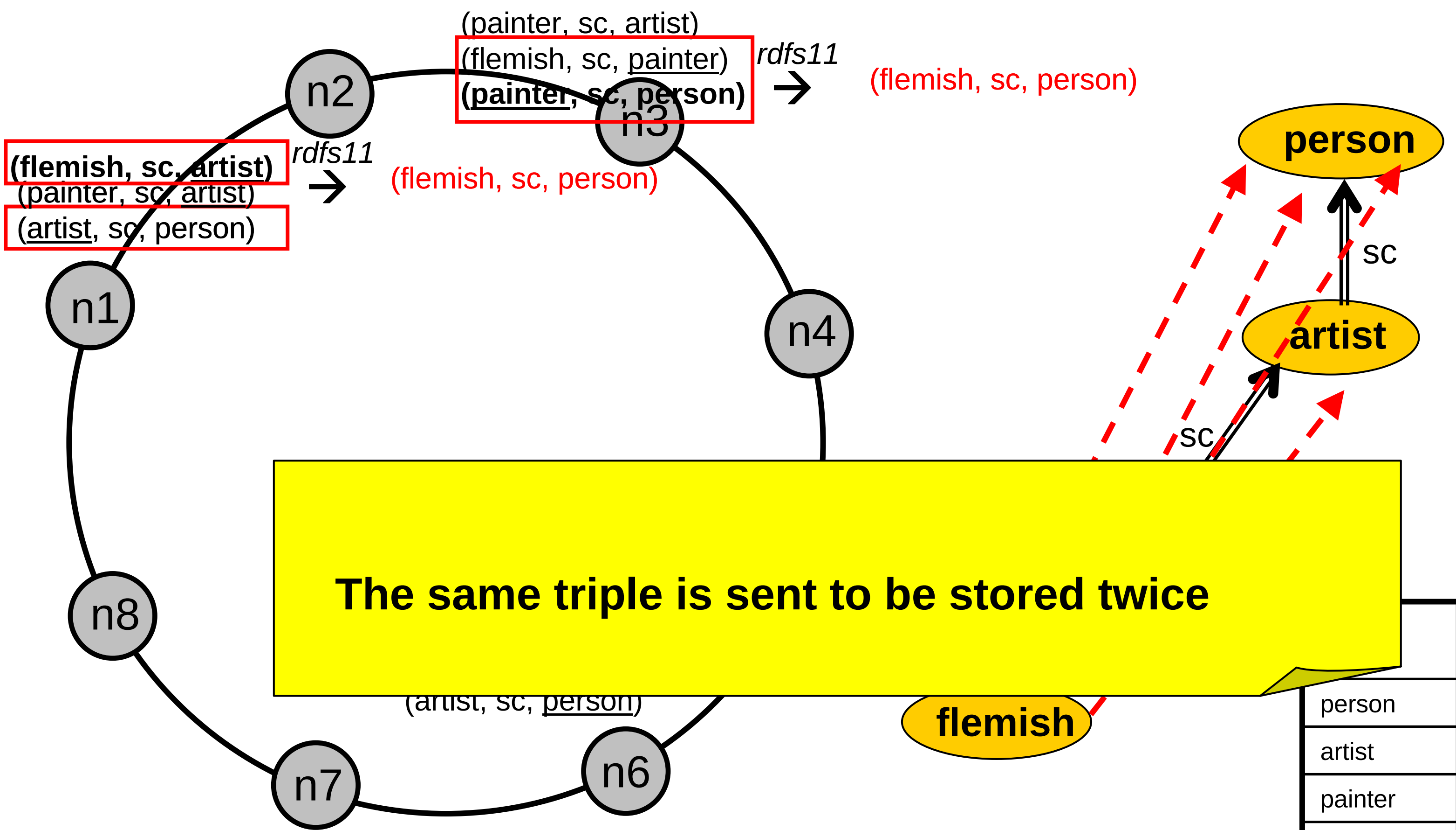
rdfs11

uuu rdfs:subClassOf vvv **vvv rdfs:subClassOf xxx**	→	**uuu rdfs:subClassOf xxx**

Distributed Forward Chaining (FC)



The same triple is sent to be stored twice

	Responsible peer
person	n6
artist	n1
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rdfs11

uuu rdfs:subClassOf vvv **vvv rdfs:subClassOf xxx**	→	**uuu rdfs:subClassOf xxx**

RDFS Entailment Rules

(Only the RDFS rules proposed in the minimal deductive system **mrdf** of [Munoz et al.2009])

- subClass(X,Y) :- triple(X, rdfs:subClassOf, Y).
- subClass(X,Y) :- triple(X, rdfs:subClassOf, Z), subClass(Z, Y).

edb relation: triple

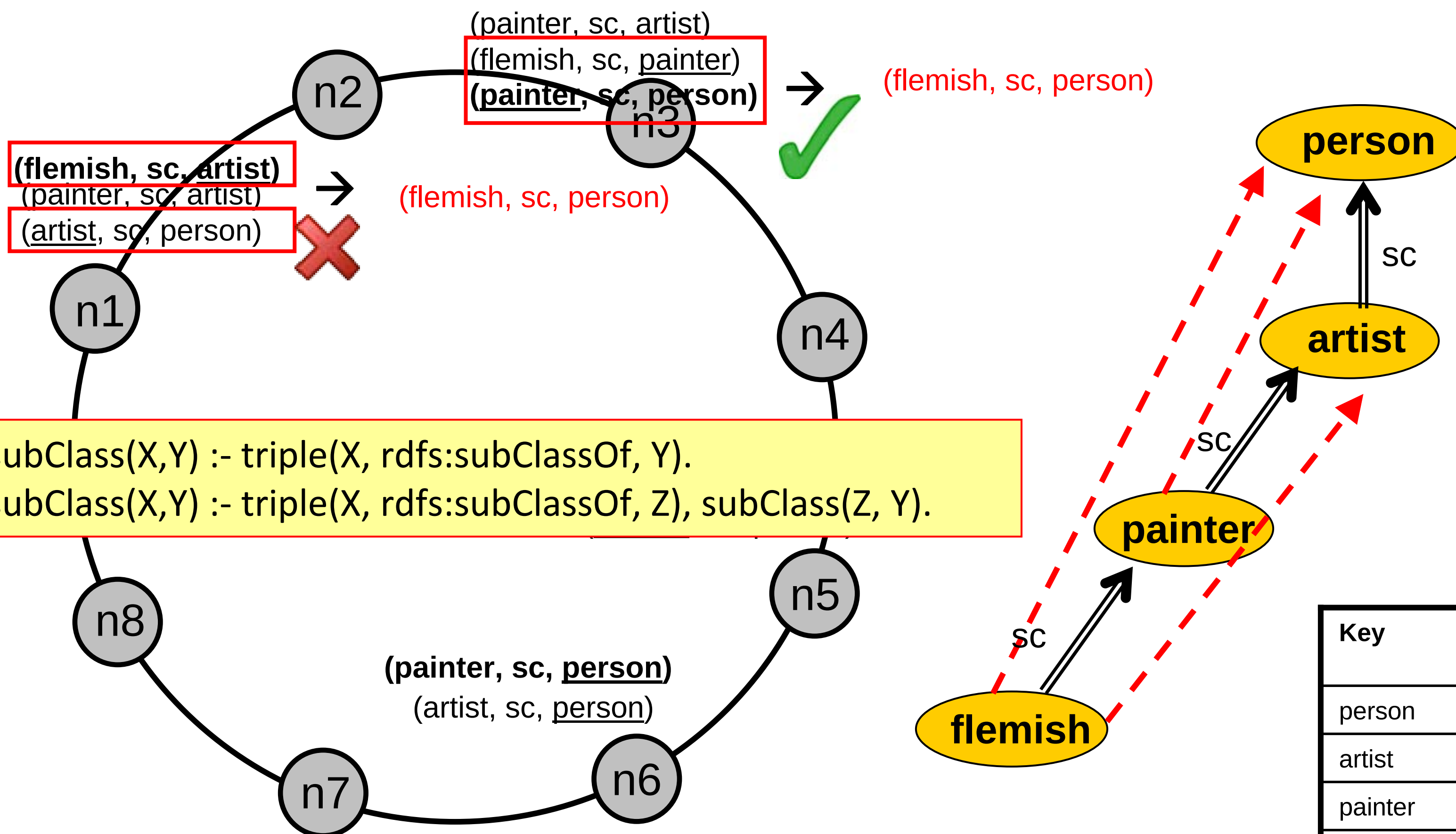
- subProperty(X, Y) :- triple(X, rdfs:subPropertyOf, Y).
- subProperty(X, Y) :- triple(X, rdfs:subPropertyOf, Z), subProperty(Z, Y).

idb relations: subClass, subProperty, newTriple, type

- newTriple(X, P, Y) :- triple(X, P, Y).
- newTriple(X, P, Y) :- triple(X, P1, Z), subProperty(P1, P).

- type(**Safe** , Y).
- type((Z, rdfs:subC **Linear**
- type(X, Y) :- triple(X, P, Z), triple(P, rdfs:domain, Y).
- type(X, Y) :- triple(Z, P, X), triple(P, rdfs:range, Y).

Distributed Forward Chaining (FC*)



subClass(X,Y) :- triple(X, rdfs:subClassOf, Y).
subClass(X,Y) :- triple(X, rdfs:subClassOf, Z), subClass(Z, Y).

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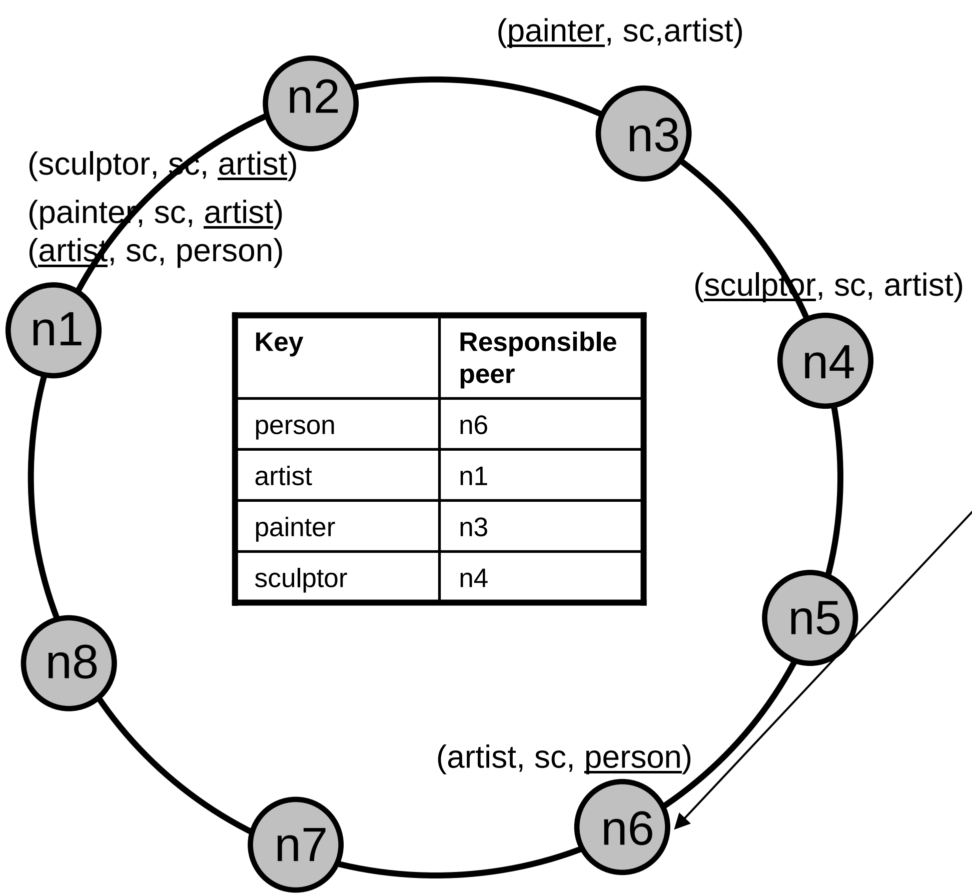
Top-down approach

- Distributed *backward chaining* algorithm
  - store only the given triples
  - compute necessary inferences at query run time

Distributed Backward Chaining (BC)

Query: Find all subclasses of person
q = (X, sc, person)



Key	Responsible peer
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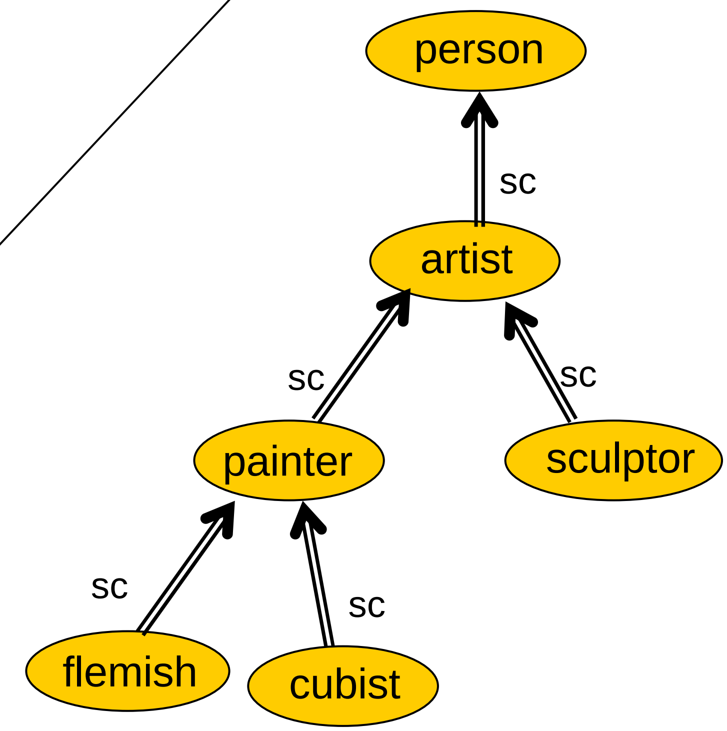
painter	n3
sculptor	n4



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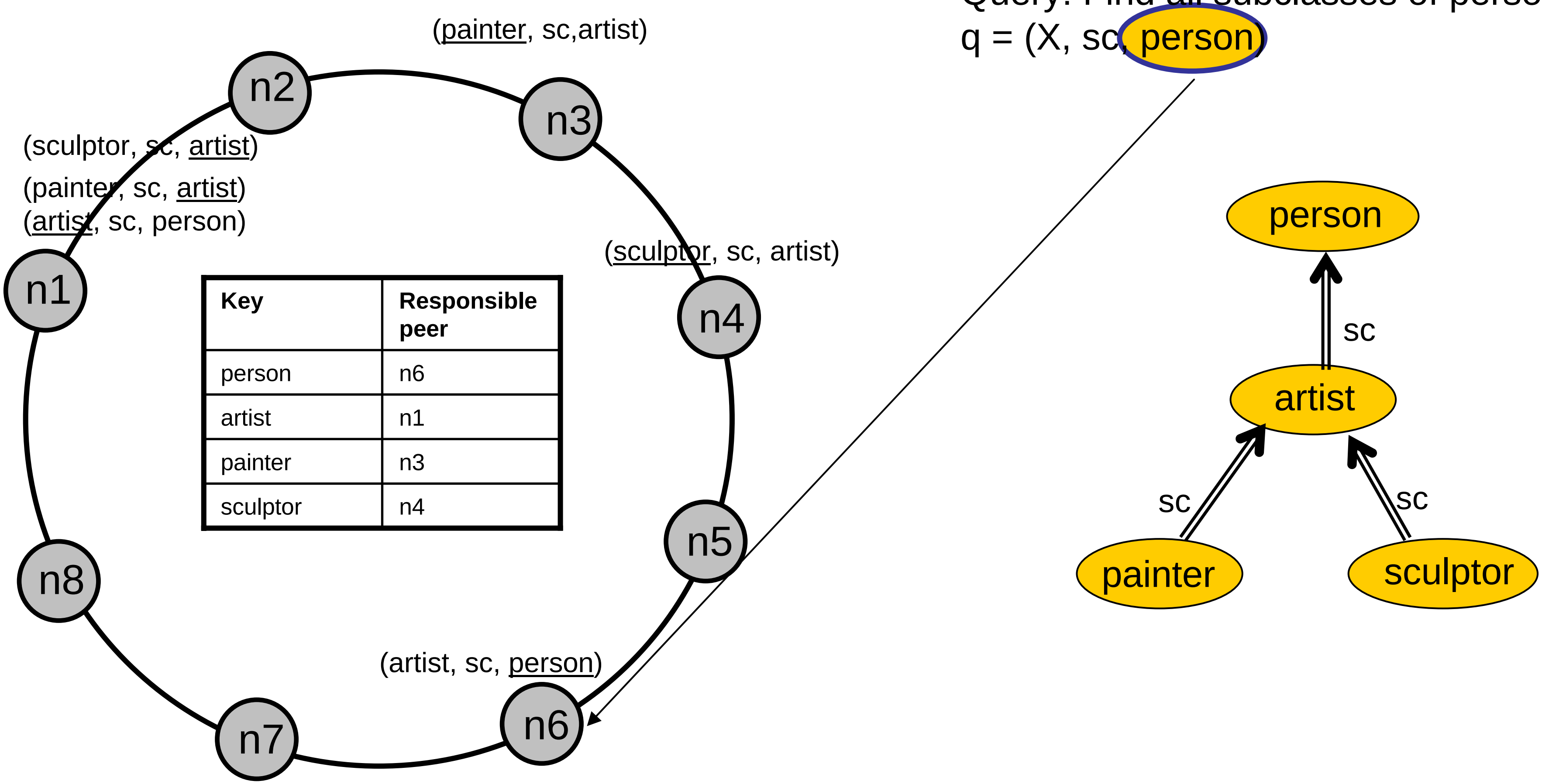

Key	Responsible peer
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Distributed Backward Chaining (BC)

subClass (X, person)

n6

Which predicate should we evaluate first?

subClass (X,Y) :- triple (X, rdfs:subClassOf, Y).
subClass (X,Y) :- triple(X, rdfs:subClassOf, Z), subClass(Z, Y).

Evaluate first the predicate that can be evaluated locally!

RDFS Entailment Rules - revisited

- Recursive rules
- Rule adornment from recursive query processing
  - Good orderings for evaluating predicates
  - eg. subClass(X, artist) → subClass^{fb} (X,Y)
- Extended adornment
  - Ordered string of *f, b,* ***k***
    - ***k*** **: an argument that is bound and the <u>key</u>**
    - *b* : bound argument (not the key)
    - *f* : free argument
  - eg. At node responsible for key artist:
    triple(X, rdf:type, artist) → triple^{fbk} (X, rdf:type, Y).

  - Good ordering for evaluating predicates in a distributed environment

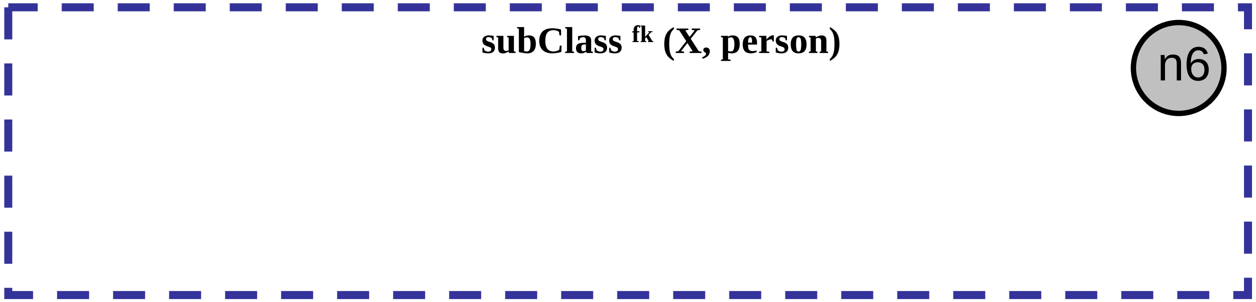
RDFS Entailment Rules - revisited

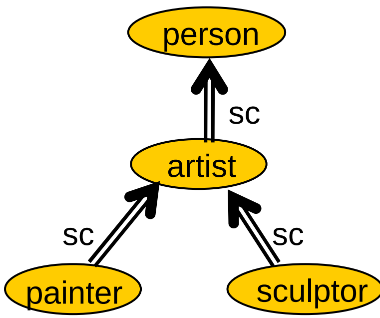
- $subClass^{kf}$ (X,Y) :- $triple^{\mathbf{k}bf}$ (X, rdfs:subClassOf, Y).
- $subClass^{kf}$ (X,Y) :- $triple^{\mathbf{k}bf}$ (X, rdfs:subClassOf, Z), $subClass^{ff}$ (Z, Y).
- $subClass^{fk}$ (X,Y) :- $triple^{fb\mathbf{k}}$ (X, rdfs:subClassOf, Y).
- $subClass^{fk}$ (X,Y) :- $subClass^{ff}$(X, Z), $triple^{fb\mathbf{k}}$ (Z, rdfs:subClassOf, Y).

- $subProperty^{kf}$ (X,Y) :- $triple^{\mathbf{k}bf}$ (X, rdfs:subPropertyOf, Y).
- $subProperty^{kf}$ (X,Y) :- $triple^{\mathbf{k}bf}$ (X, rdfs:subPropertyOf, Z), $subProperty^{ff}$ (Z, Y).
- $subProperty^{fk}$ (X,Y) :- $triple^{fb\mathbf{k}}$ (X, rdfs:subPropertyOf, Y).
- $subProperty^{fk}$ (X,Y) :- $subProperty^{ff}$(X, Z), $triple^{fb\mathbf{k}}$ (Z, rdfs:subPropertyOf, Y).

- $type^{kf}$ (X, Y) :- $triple^{\mathbf{k}bf}$ (X, rdf:type, Y).
- $type^{kf}$ (X, Y) :- $triple^{\mathbf{k}ff}$ (X, P, Z), $triple^{fbf}$ (P, rdfs:domain, Y).
- $type^{kf}$ (X, Y) :- $triple^{ff\mathbf{k}}$ (Z, P, X), $triple^{fbf}$ (P, rdfs:range, Y).
- $type^{kf}$ (X, Y) :- $triple^{\mathbf{k}bf}$ (X, rdf:type, Z), $subClass^{ff}$ (Z, Y).
- $type^{fk}$ (X, Y) :- $triple^{fb\mathbf{k}}$ (X, rdf:type, Y).
- $type^{fk}$ (X, Y) :- $triple^{fff}$ (X, P, Z), $triple^{fb\mathbf{k}}$ (P, rdfs:domain, Y).
- $type^{fk}$ (X, Y) :- $triple^{fff}$ (Z, P, X), $triple^{fb\mathbf{k}}$ (P, rdfs:range, Y).
- $type^{fk}$ (X, Y) :- $type^{ff}$ (X, Z), $triple^{fb\mathbf{k}}$ (Z, rdfs:subClassOf, Y).

Distributed Backward Chaining (BC)





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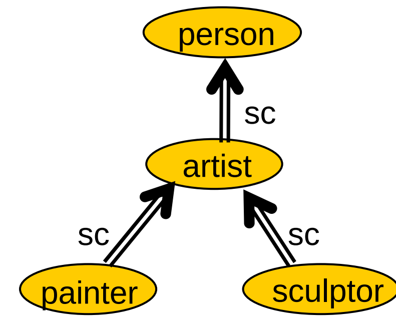
Distributed Backward Chaining (BC)

subClass ^{fk} (X, person)

r1: triple ^{fbk} (X, rdfs:subClassOf, person)

r2: triple ^{fbk} (Z, rdfs:subClassOf, person)
subClass ^{ff} (X, Z)

n6



subClass^{fk} (X,Y) :- triple^{fbk} (X, rdfs:subClassOf, Y). **(r1)**
subClass^{fk} (X,Y) :- subClass^{ff}(X, Z), triple^{fbk} (Z, rdfs:subClassOf, Y). **(r2)**

Key	**Responsible peer**
person	n6
artist	n1
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Distributed Backward Chaining (BC)

subClass ^{fk} (X, person)

n6

r1

r2

triple ^{fbk} (X, rdfs:subClassOf, person)

triple ^{fbk} (Z, rdfs:subClassOf, person)
subClass ^{ff} (X, Z)

Z / artist

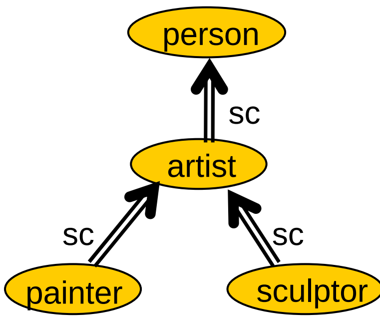
subClass^{fk} (X,Y) :- triple^{fbk} (X, rdfs:subClassOf, Y). **(r1)**
subClass^{fk} (X,Y) :- subClass^{ff}(X, Z), triple^{fbk} (Z, rdfs:subClassOf, Y). **(r2)**

triple ^{fbk} (X, rdfs:subClassOf, artist)

triple ^{fbk} (Z, rdfs:subClassOf, artist)
subClass ^{ff} (X, Z)

Z / painter

Z / sculptor



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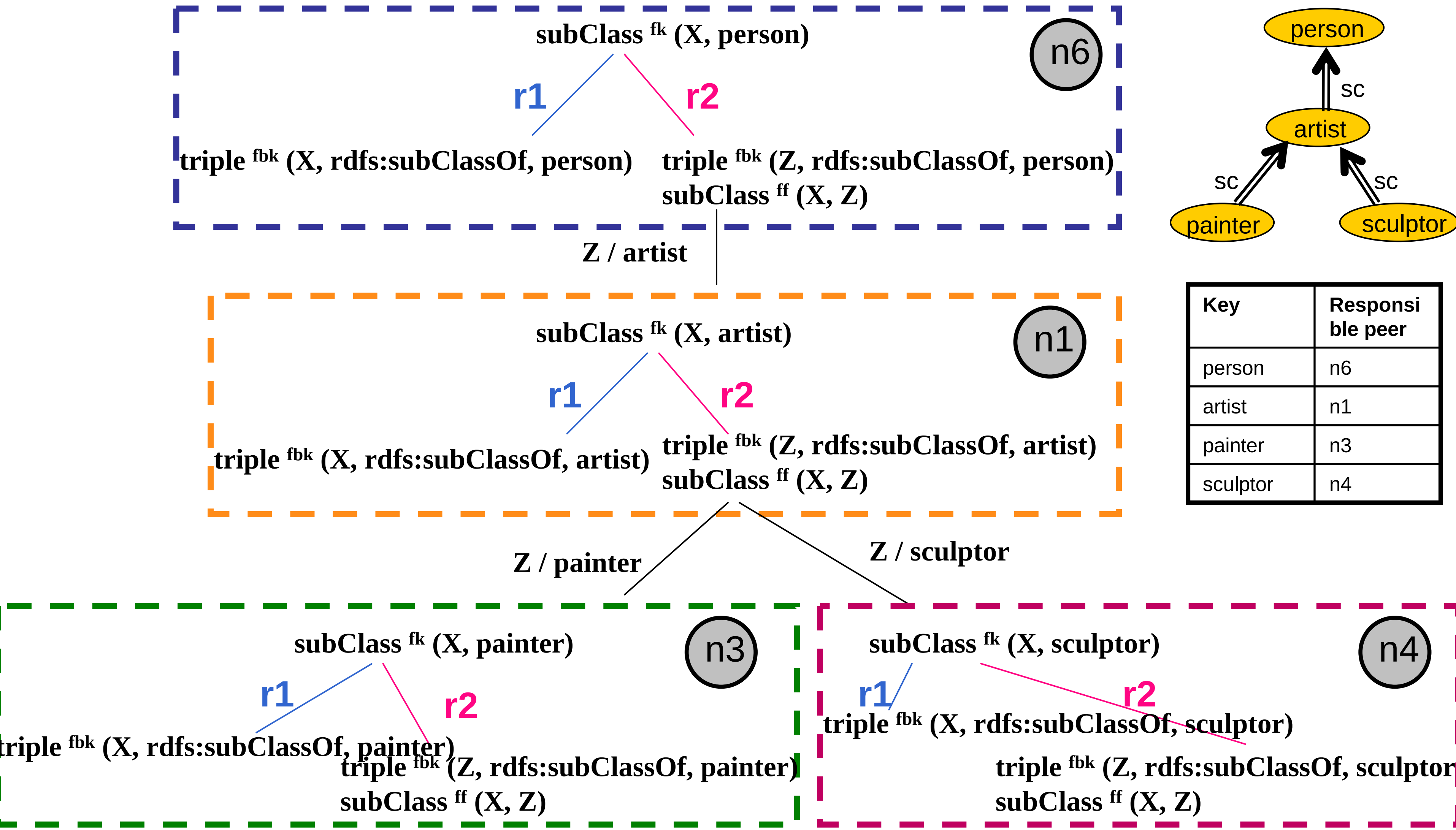

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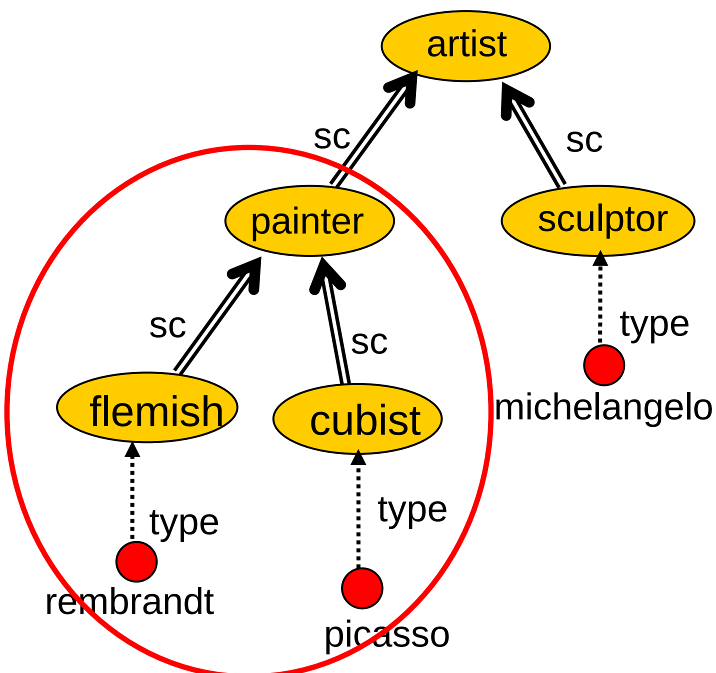
Forward chaining for magic rules (MS)

- Magic sets transformation technique
  - Rewrite rules given a specific query
  - Bottom-up evaluation (forward chaining)
  - No unnecessary information is inferred

Rule	Head	Body
1	m_newTriple(P)	sup_{61}(P, Y)
2	m_newTriple(P)	sup_{71}(P, Y)
3	m_subProperty(Z)	sup_{21}(Z,Y)
4	m_subProperty(P)	m_newTriple(P)
5	m_subClass(Z)	sup_{41}(Z,Y)
6	m_type(Z)	sup_{51}(Z,Y)
7	sup_{21}(Z, Y)	m_subProperty(Y), triple(Z, sp, Y)
8	sup_{31}(P1, P)	m_newTriple(P), subProperty(P1, P)
9	sup_{41}(Z, Y)	m_subClass (Y), triple(Z, sc, Y)
10	sup_{51}(Z, Y)	m_type(Y), triple(Z, sc, Y)
11	sup_{61}(P, Y)	m_type(Y), triple(P, dom, Y)
12	sup_{71}(P, Y)	m_type(Y), triple(P, range, Y)
13	newTriple(X, P ,Y)	m_newTriple(P), triple(X, P, Y)
14	subProperty(X, Y)	m_subProperty(Y), triple(X, sp, Y)
15	subProperty(X, Y)	sup_{21}(Z,Y), subProperty(X, Z)
16	newTriple(X, P, Y)	sup_{31}(P1,P), triple(X,P1,Y)
17	subClass(X, Y)	m_subClass(Y), triple(X, sc, Y)
18	subClass(X, Y)	sup_{41}(Z,Y), subClass(X, Z)
19	type(X, Y)	m_type(Y), triple(X, type, Y)
20	type(X, Y)	sup_{51}(Z, Y), type(X, Z)
21	type(X, Y)	sup_{61}(P, Y), newTriple(X, P, Z)
22	type(X, Y)	sup_{71}(P, Y), newTriple(Z, P, X)
23	m_type(a)	



Query: Find all painters
q = (?x, rdf:type, painter)

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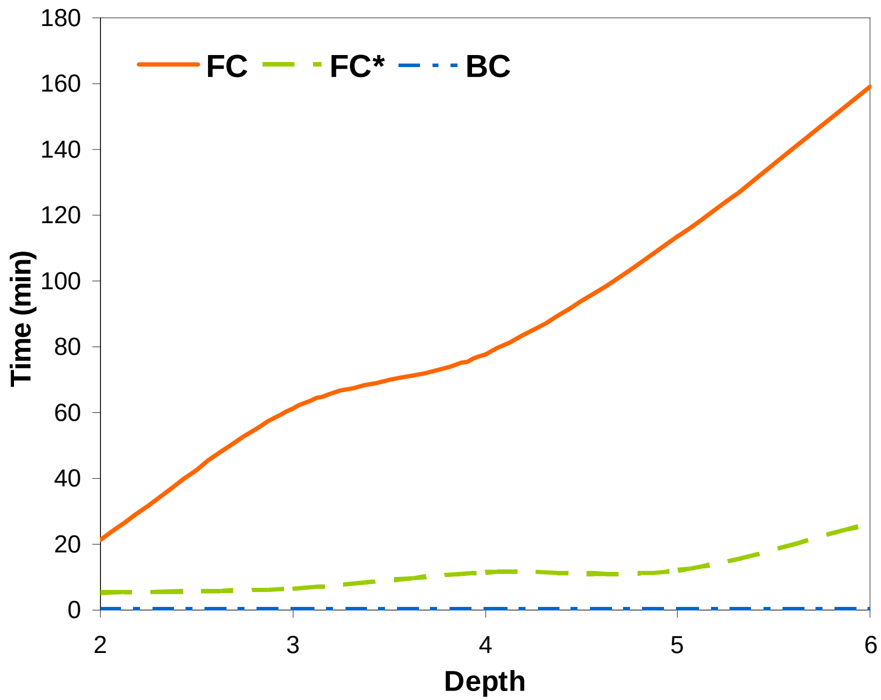
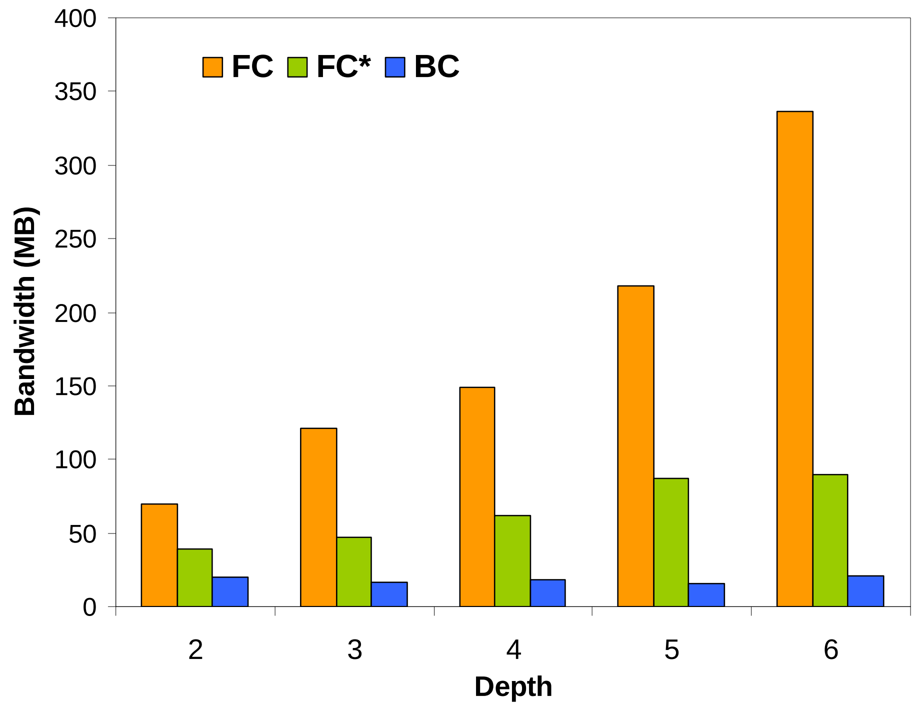
Experimental setup

- Algorithms have been implemented in Atlas system using Bamboo DHT [Rhea04]
- Testbeds
  - **PlanetLab** (~210 nodes available at the time of the experiments)
  - **local cluster** (30 machines – 4 Atlas nodes per machine)
- Datasets
  - Synthetic data from RBench generator [Theoharis05]
    - Number of instances: 10,000 to 1M
    - RDFS class hierarchy tree depth: 2-6 (7 to 128 classes)
    - Query: Give me the instances of the root class
  - LUBM benchmark
    - Number of triples: ~110,000 to ~2,700,00
    - Query: Give me the instances of a class

Store time and network traffic

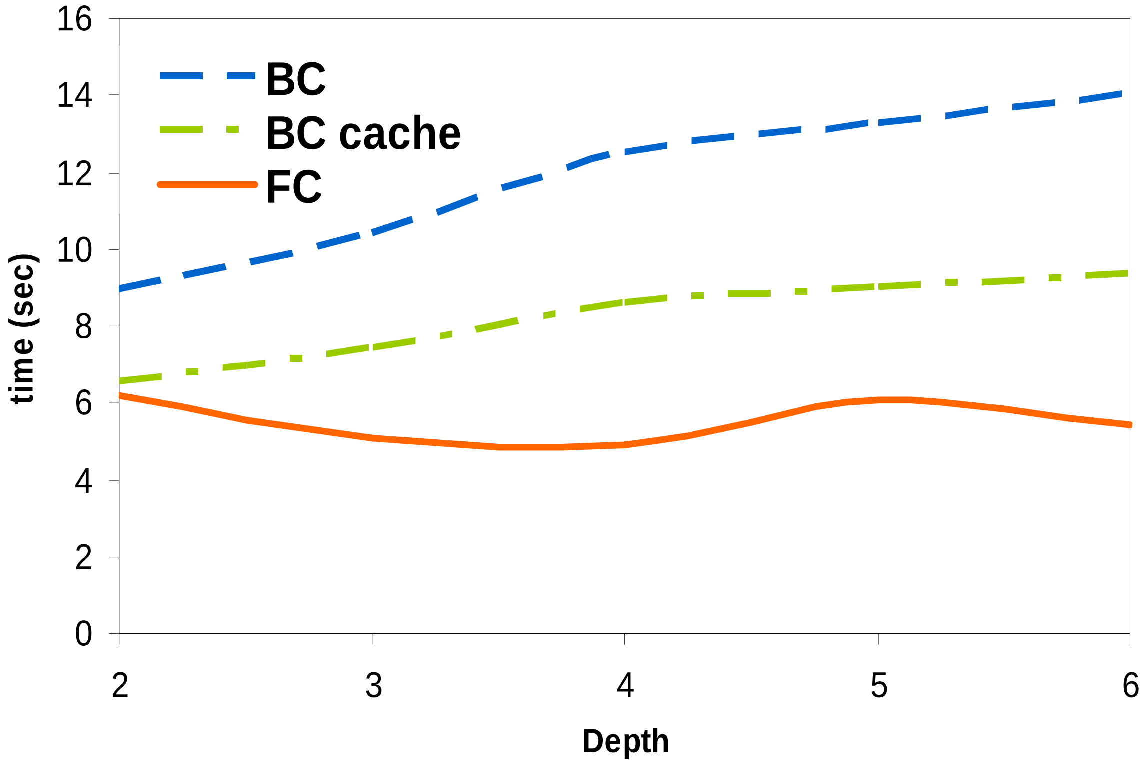
PlanetLab, RBench with 10,000 instances





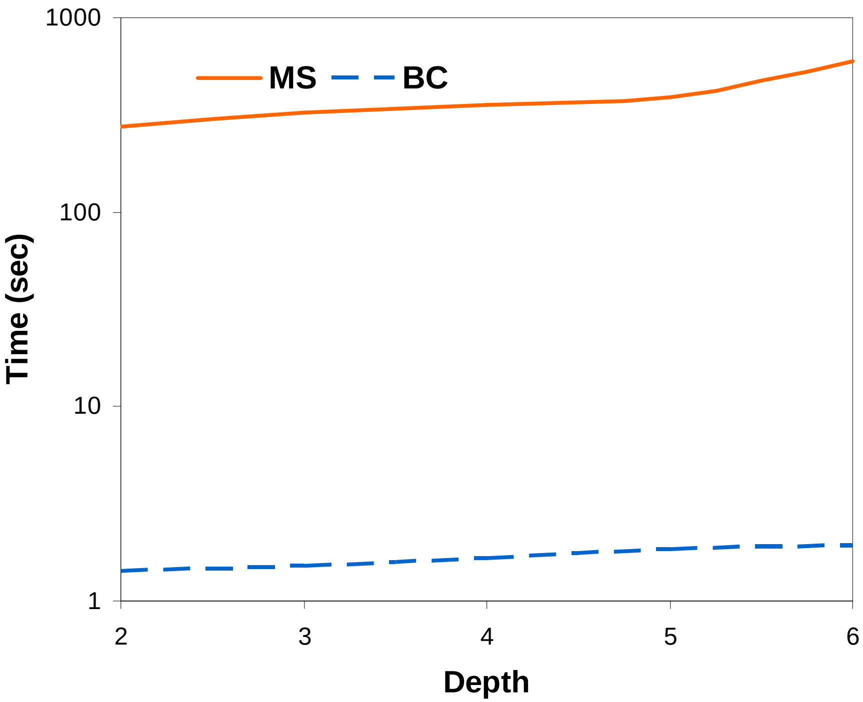
Query response time

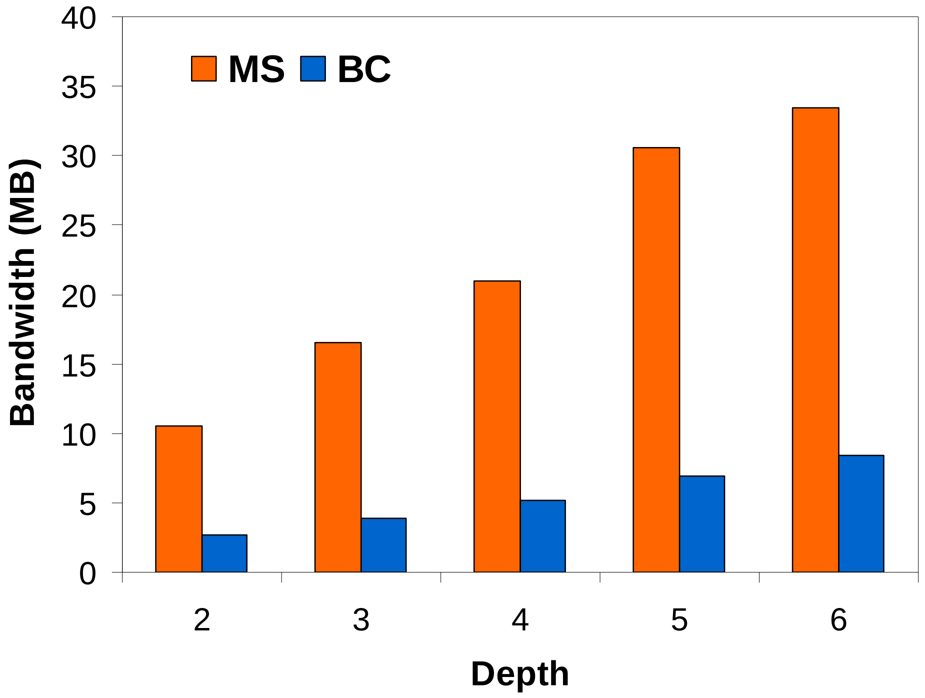
PlanetLab, RBench with 10,000 instances



Backward chaining vs. magic sets

Cluster: RBench with 1M instances





Outline

- Introduction
- The system Atlas
- RDFS Reasoning in P2P networks
- **SPARQL Query Processing and Optimization**
- Conclusions

SPARQL

- SPARQL queries of basic graph patterns

```
SELECT ?x ?y ?z
WHERE {
   ?x rdf:type ub:Student .  (tp1)
   ?x ub:takesCourse ?z .    (tp2)
   ?x ub:advisor ?y .        (tp3)
   ?y ub:teacherOf ?z .      (tp4)
 }
```

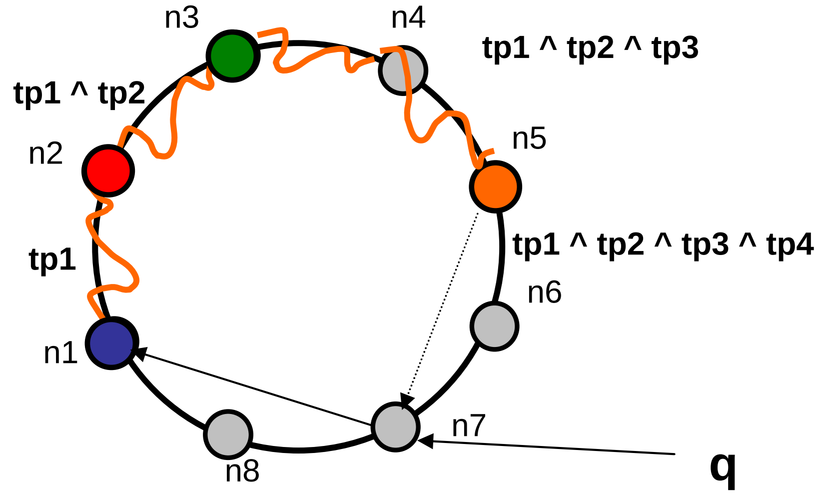
  - conjunctive triple patterns

```
tp1 ^ tp2 ^ tp3 ^ tp4
```

SPARQL query processing

- SPARQL queries of basic graph patterns

```
SELECT ?x ?y ?z
WHERE {
   ?x rdf:type ub:Student .(tp1)
   ?x ub:takesCourse ?z .  (tp2)
   ?x ub:advisor ?y .      (tp3)
   ?y ub:teacherOf ?z      (tp4)
 }
```



Query Optimization

- Find a query plan that optimizes the performance of a system with respect to a metric of interest

Query response time

Bandwidth consumption

- Find a good ordering of the triple patterns

Minimize the size of intermediate results

Lower bandwidth consumption

Joins with smaller intermediate relations

Query Optimization

- Greedy optimization algorithms
  - **selectivity-based** heuristics
  - **minimize** the size of **intermediate results**

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Selectivity estimation

- Single triple pattern
  - Bound-is-easier heuristic
  - Analytical estimation: $sel(tp) = sel(s) \times sel(p) \times sel(o)$

$$sel(v) = \frac{freq_c(v)}{T}$$

frequency of value v as a component c

total triples stored in the network

- Joins of triple patterns: $sel(tp_1 \wedge tp_2) = \frac{join\_card(tp_1, tp_2)}{T^2}$

$$join\_card(tp_1, tp_2) = \frac{T_{tp_1} \times T_{tp_2}}{\max(I_{tp_1(?x)}, I_{tp_2(?x)})}$$

number of triples matching tp_1, tp_2

size of the domain of ?x in tp_i

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Required statistics

- Frequency of a triple component *c* with value *v* ($\boldsymbol{freq_c(v)}$)

- Size of the domain of a variable in a triple pattern ($\boldsymbol{I_{tpi(?x)}}$)

Frequency and variable domain size - example

(?x, advisor, ?y)

frequency of advisor → # occurrences of advisor as a **predicate** (**freq$_p$(*advisor*)**)

domain size of ?x → # **distinct subject** values of **predicate** *advisor* (**ds$_p$(*advisor*)**)

domain size of ?y → # **distinct object** values of **predicate** *advisor* (**do$_p$(*advisor*)**)

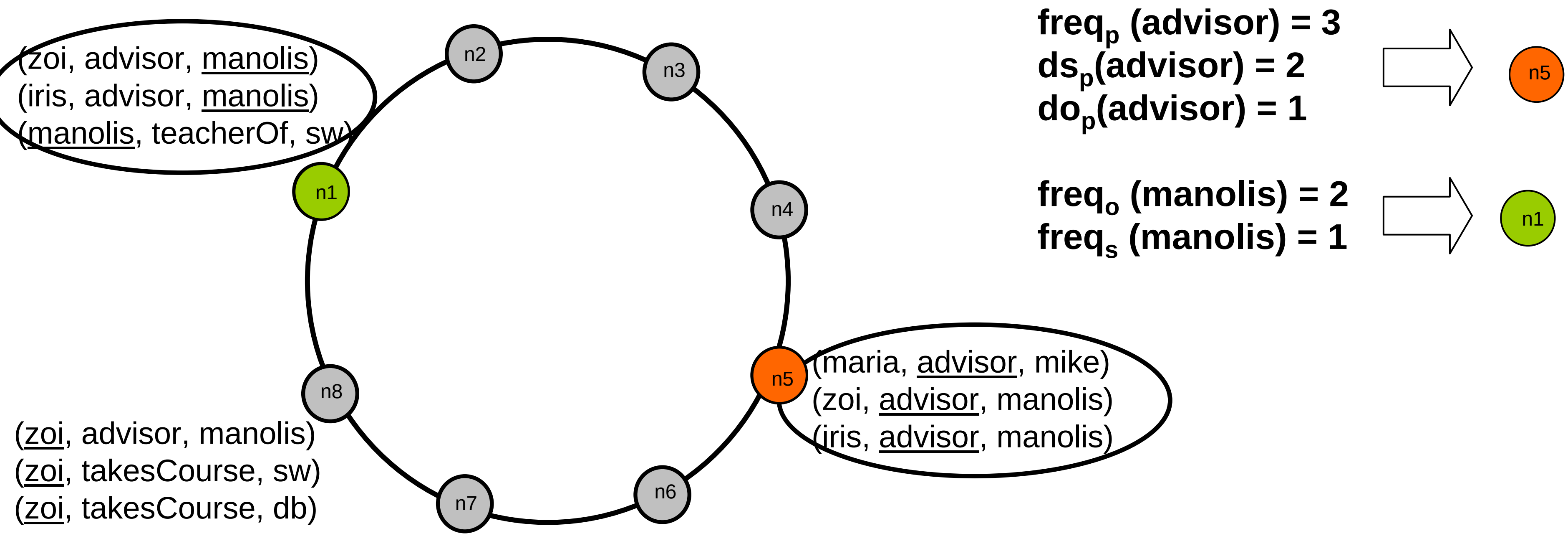
RDF triples

subject	predicate	object
zoi	*advisor*	*manolis*
iris	*advisor*	*manolis*
maria	*advisor*	*mike*
zoi	*takesCourse*	*db*
zoi	*takesCourse*	*sw*
manolis	*teacherOf*	*sw*

statistics for predicates

Value	freq$_p$	ds$_p$	do$_p$
advisor	**3**	**3**	**2**
takesCourse	2	1	2
teacherOf	1	1	1

Statistics in DHTs



Each peer is responsible for creating and maintaining statistics of its **locally** stored data and only for triple component values which are <u>**key**</u> at the specified peer

Statistics at each DHT peer

- Each peer creates statistics for each triple component separately
  - distinguish resource objects from class objects

subject	predicate	object	object-class
$freq_s$	$freq_p$	$freq_o$	$freq_c$
dp_s	ds_p	ds_o	–
do_s	dp_p	dp_o	–

- Given a space budget, each peer can keep the ***exact frequency distribution*** or an estimation by using **v-optimal *histograms***

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Optimization algorithms

- **Static optimization**
  - Before the query evaluation begins, at the peer that receives the query request
    - **Naïve optimization algorithm (NA):** Orders triple patterns based on their selectivity, from the most selective to the least selective
    - **Semi-naïve optimization algorithm (SNA):** Orders triple patterns based on the join selectivity between pairs of triple patterns

Optimization algorithms

- **Dynamic optimization**
  - During the query evaluation, at each peer participating in the query processing
    - **Dynamic optimization algorithm (DA)**: join selectivity is computed at each peer participating in the query processing and estimated between the **real** intermediate results so far and a triple pattern

- All algorithms (static and dynamic) use a query graph (QG) representation to avoid Cartesian products

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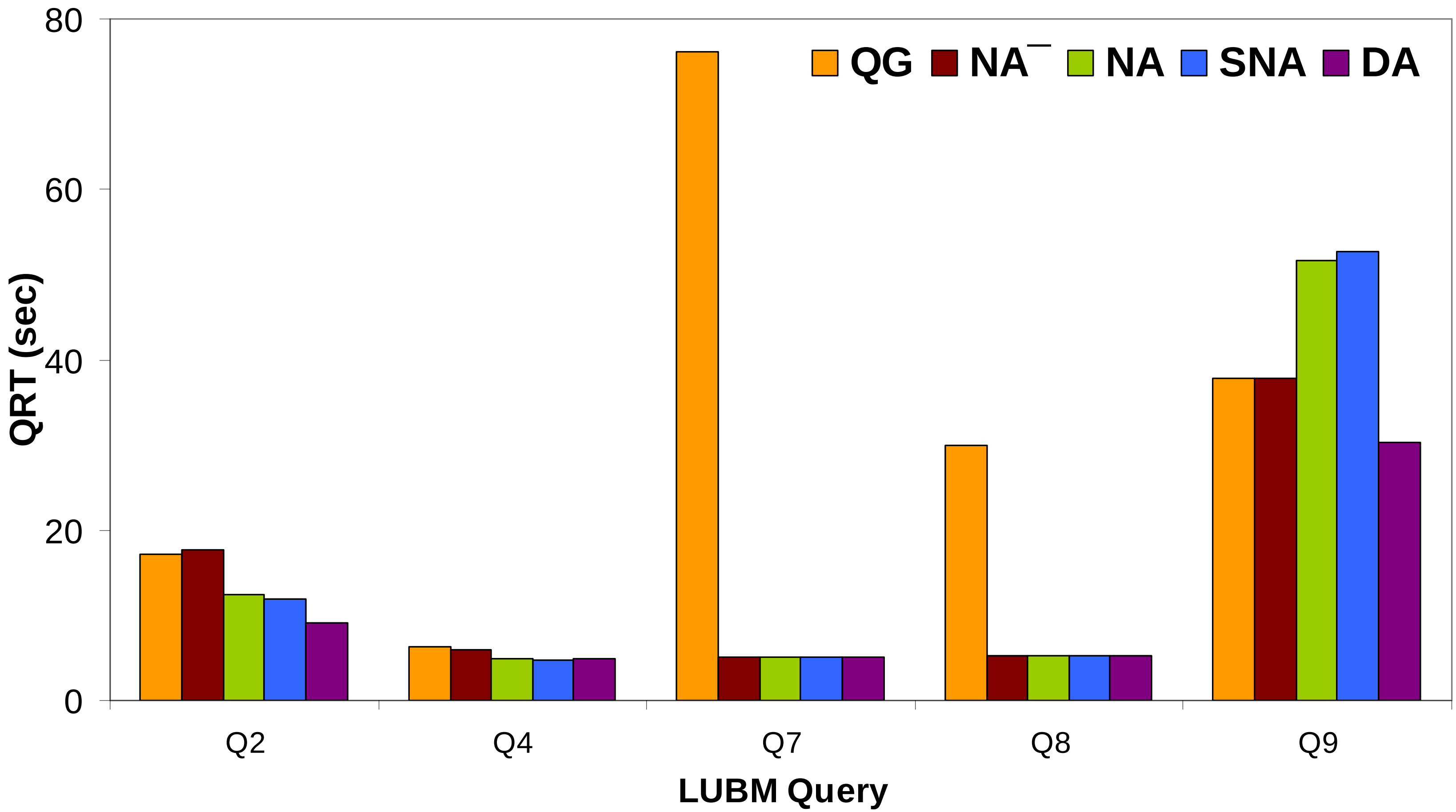
Experimental setup

- All algorithms and techniques have been implemented in Atlas
  - Mapping dictionary
- We used as a testbed PlanetLab and a **local cluster** server blade machines with two processors at 2.6GHz and 4GB memory 30 available machines – up to 4 nodes per machine → up to 120 DHT peers
- LUBM Benchmark (queries with more than 4 triple patterns)

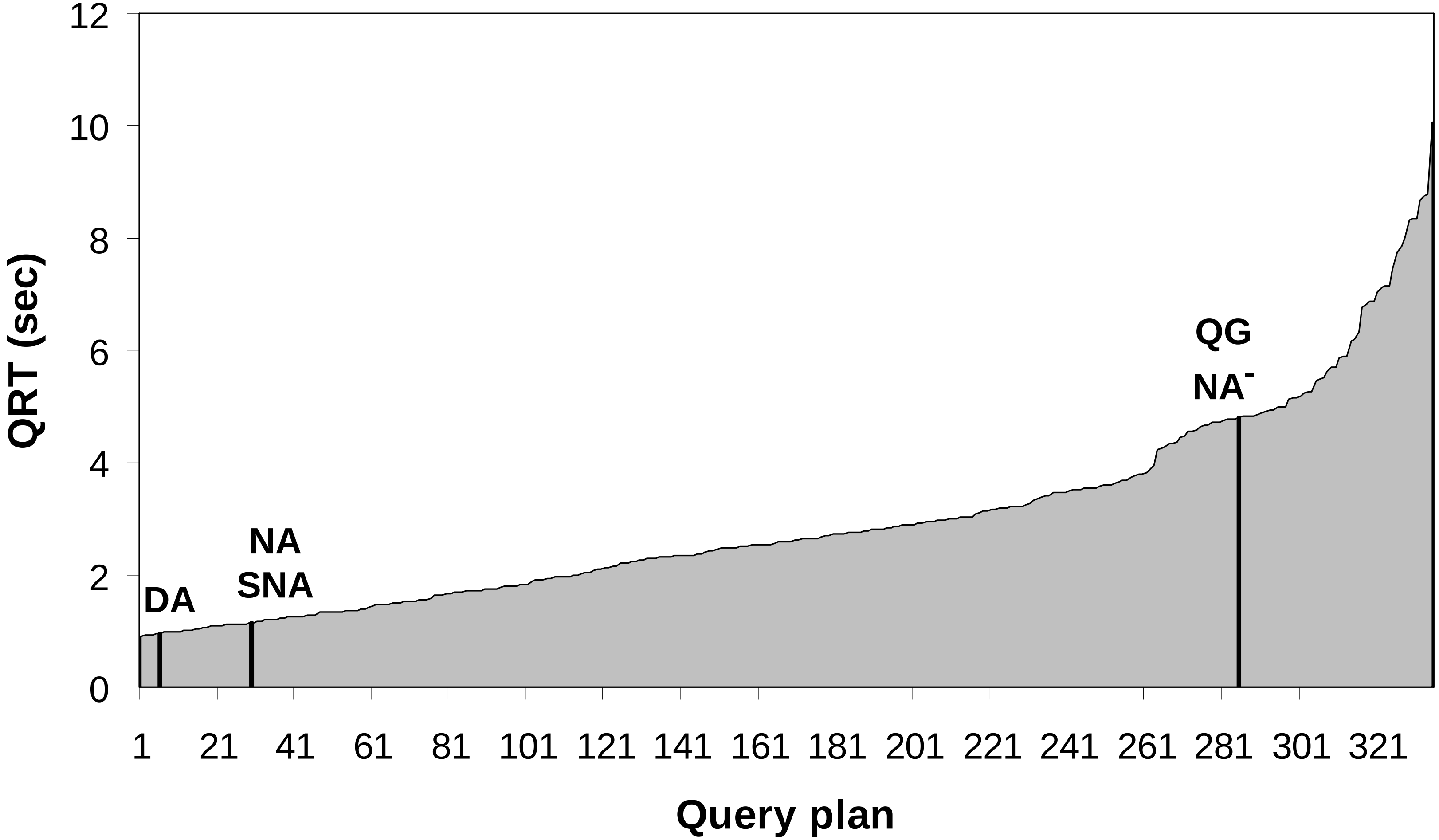
Query response time (LUBM-50)



Q7: select ?X ?Y where { ?X rdf:type ub:Student . ?Y rdf:type ub:Course . ub:AssociateProfessor147 ub:teacherOf ?Y. ?X ub:takesCourse ?Y}

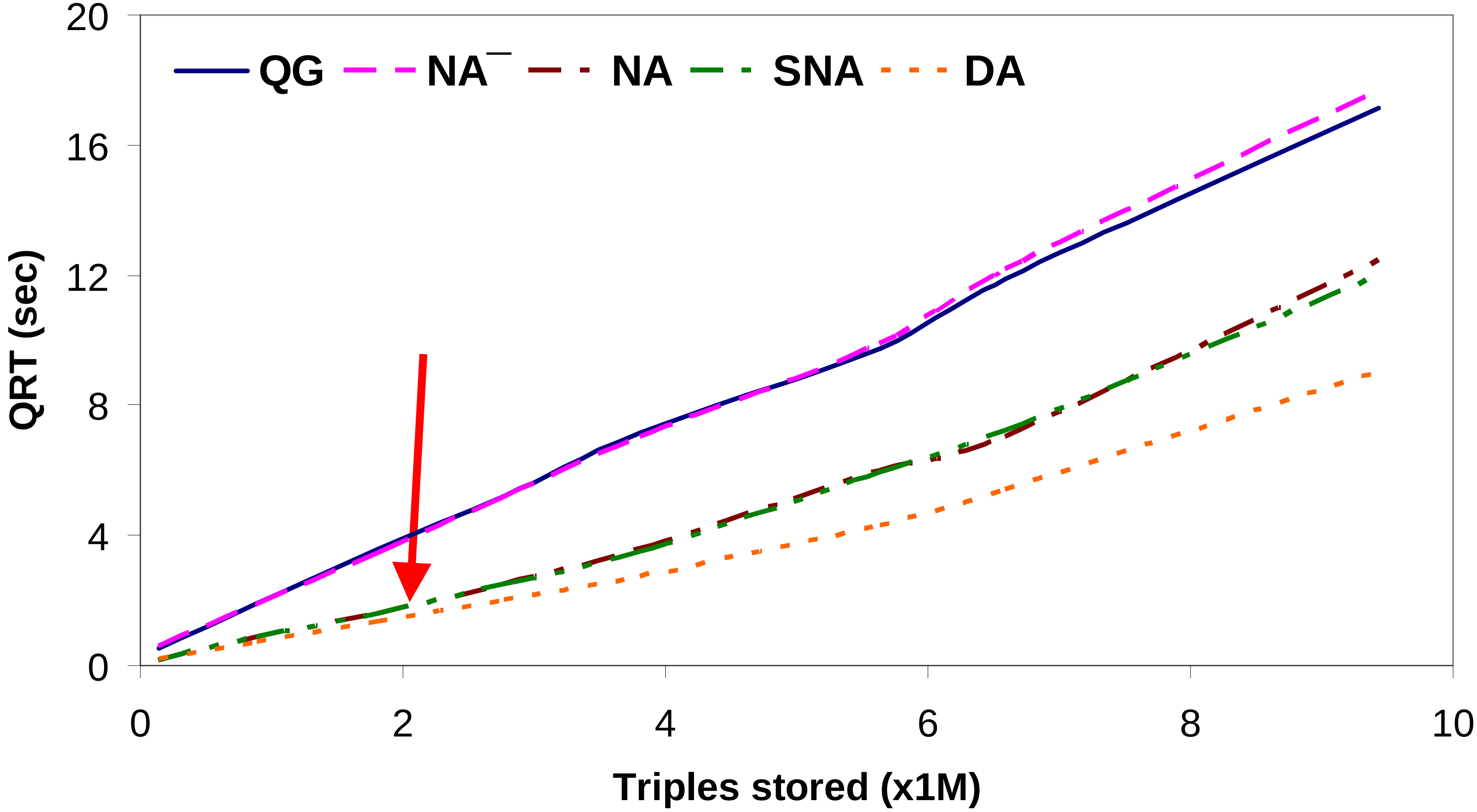
Q9: select ?X ?Y ?Z where {?X rdf:type ub:Student . ?Y rdf:type ub:Faculty . ?Z rdf:type ub:Course. ?X ub:advisor ?Y . ?X ub:takesCourse ?Z . ?Y ub:teacherOf ?Z . }

Q2 query plan space (LUBM-10)

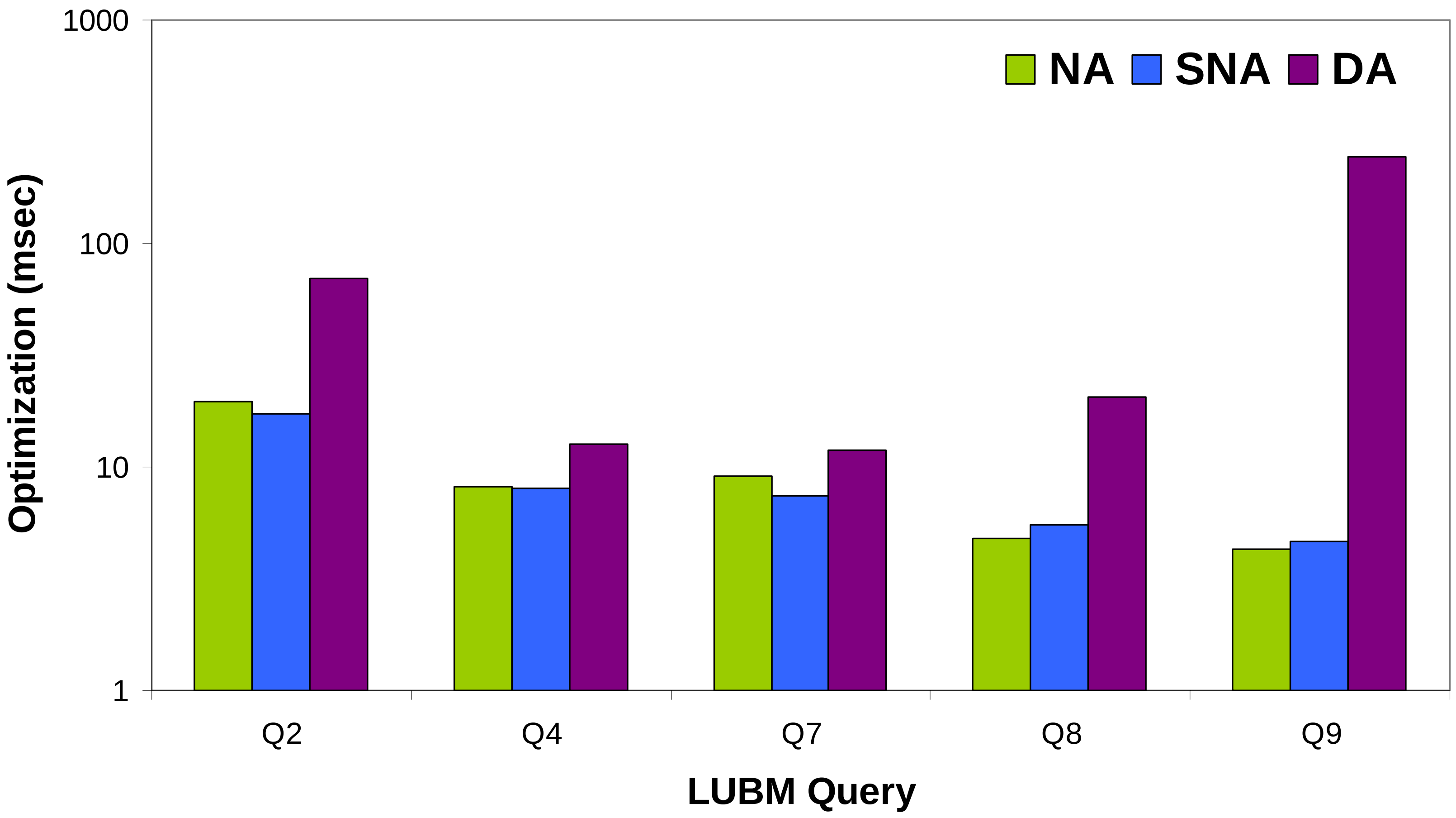


Q2: select ?X ?Y ?Z where { ?X rdf:type ub:GraduateStudent . ?X ub:undergraduateDegreeFrom ?Y . ?Y rdf:type ub:University . ?Z ub:subOrganizationOf ?Y . ?Z rdf:type ub:Department . ?X ub:memberOf ?Z . }

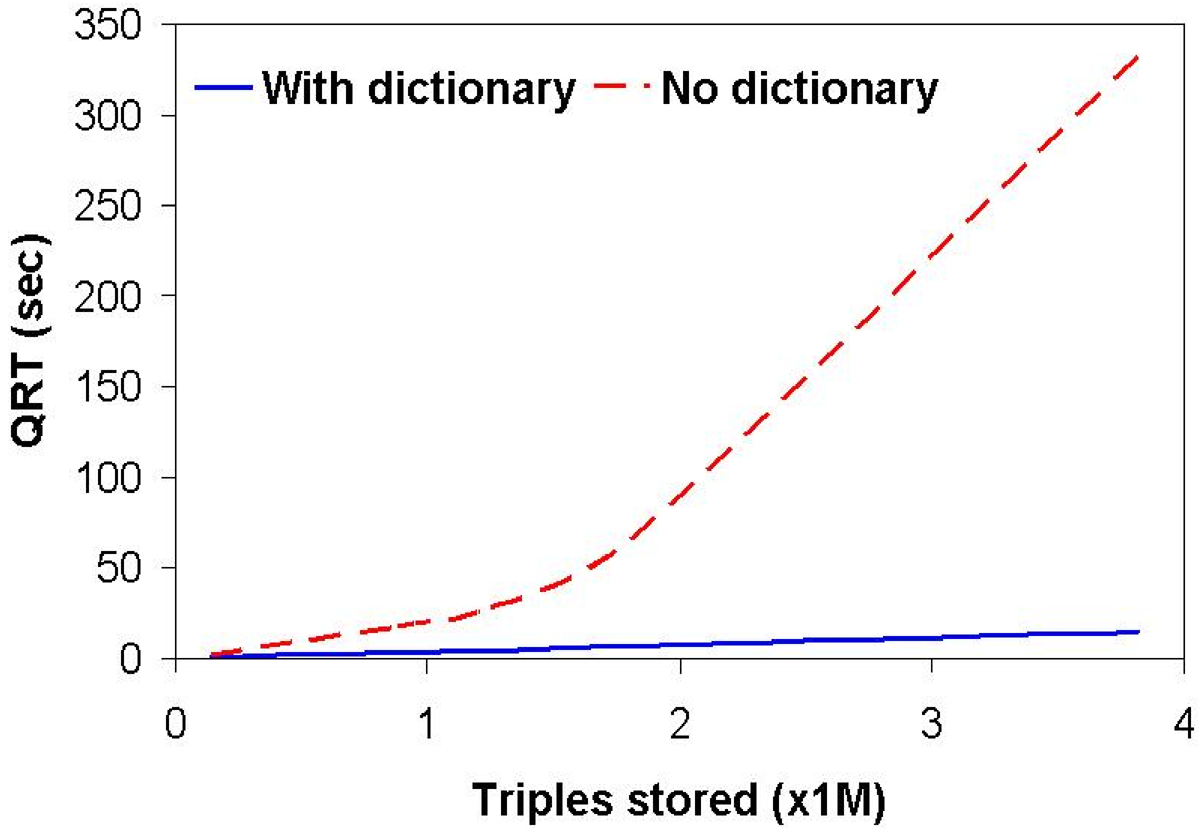
Query response time of Q2 for increasing dataset size



Optimization time (LUBM-50)



Mapping dictionary



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Conclusions

- **Atlas:** a P2P system for the distributed query processing and reasoning of RDF and RDFS data which is built on top of DHTs

- RDFS Reasoning on top of DHTs
  - Distributed forward chaining
  - Distributed backward chaining
  - Distributed magic sets transformation
  - Comparative study (analytically and experimentally)
  - Theoretical proofs of correctness

- SPARQL Query Processing and Optimization on top of DHTs
  - Selectivity estimation techniques
  - Statistics for RDF
  - Optimization algorithms
  - Distributed mapping dictionary

Future directions

- Distributed recursive queries using Datalog
- **RDF in the cloud!**

Thank you

Questions?

References 

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