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Sur l'analyse statique des requêtes SPARQL avec la logique modale

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On the Static Analysis for SPARQL Queries using Modal Logic

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Motivation

Context

- Semantic Web - web of data that can be processed by machines
- Technologies: URI, Unicode, XML and Namespace
- W3C Standards: RDF, RDFS, OWL, ...
- Huge graphs that can be queried with SPARQL

Problem

- Querying huge graphs is time consuming
- Query optimization benefits from **Static Analysis**

Static analysis

Many optimization tasks rely on three simple questions:

- Does query q ever produce a non-empty result?
- Does query q_1 always produce the same result as query q_2 ?
- Does query q_1 always produce a subset of the results of query q_2 ?

Definition (Query containment)

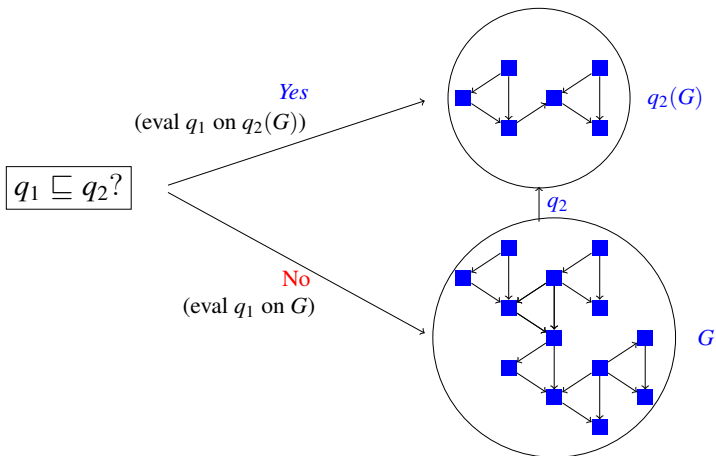
Given two queries q_1 and q_2 , q_1 is contained in q_2 , denoted $q_1 \sqsubseteq q_2$, if for every dataset G , $q_1(G) \subseteq q_2(G)$.

Query containment problem

SPARQL Queries: q_1, q_2

RDF Graph: G

$|q_2(G)| \ll |G|$

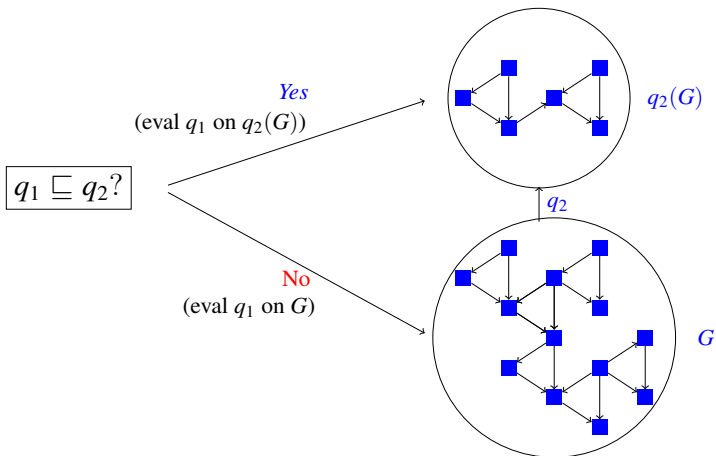


Query containment problem

SPARQL Queries: q_1, q_2

RDF Graph: G

$|q_2(G)| \ll |G|$



Main difficulty: containment must hold for **ALL** graphs

Query containment is well-studied

- ① conjunctive queries [[Chandra-and-Merlin:1977](#)], NP-Complete
- ② union of conjunctive queries: NP-Complete [[Sagiv-et-al:1980](#)]
- ③ conjunctive query containment under DL schema axioms: 2EXPTIME [[Calvanese-et-al:2008](#)]
- ④ static analysis of XPath queries: $2^{O(|n|)}$ [[Geneves-et-al:2007](#)]

Query containment is well-studied

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- 4 static analysis of XPath queries: $2^{O(|n|)}$ [[Geneves-et-al:2007](#)]

but, much less for SPARQL

- union of conjunctive queries under DL schema axioms: 2EXPTIME [[Chekol-et-al:2012](#)],
- containment in presence of OPTIONAL operators: Π_2^P -complete [[Letelier-et-al:2012](#)]

Outline

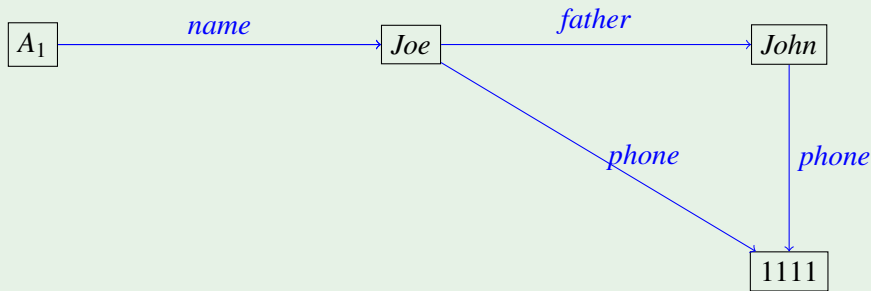
- 1 Motivation
- 2 Query Containment Problem for SPARQL
 - Preliminaries
 - Logical Approach
 - Experiments
- 3 Conclusion and Perspectives

Resource Description Framework

- is a graph data format for the representation of information in the Web
- subject-predicate-object structures
- an RDF graph is a set of triples

Example (An RDF graph describing employers information)

$G = \{(A_1, \textit{name}, \textit{Joe}), (\textit{Joe}, \textit{father}, \textit{John}), (\textit{Joe}, \textit{phone}, 1111), (\textit{John}, \textit{phone}, 1111)\}$

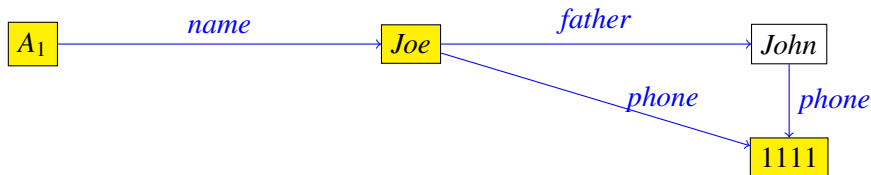


SPARQL Protocol And RDF Query Language

- W3C standard query language for RDF graphs
- based-on subgraph matching

$$q = \text{SELECT } ?a ?n ?p \\ \text{WHERE } \left\{ \left((?a, \text{name}, ?n) \text{ AND } (?n, \text{phone}, ?p) \right) \right\}$$

Evaluation:


$$\llbracket q \rrbracket_G = \{ \varrho = \{ ?a \rightarrow A_1, ?n \rightarrow \text{Joe}, ?p \rightarrow 1111 \} \}, \quad \text{where } \varrho : V \rightarrow U$$

SPARQL queries containment: example

q_1	q_2
<pre>SELECT ?a ?n HERE {(?a, name, ?n)}</pre>	<pre>SELECT ?a ?n ?p WHERE {(?a, name, ?n) OPT (?a, phone, ?p)}</pre>

$$G = \{(A_1, name, Joe), (A_1, phone, 1111)\}$$

$$\llbracket q_1 \rrbracket_G = \{\varrho_1 = \{?a \rightarrow A_1, ?n \rightarrow Joe\}\}$$

$$\llbracket q_2 \rrbracket_G = \{\varrho_2 = \{?a \rightarrow A_1, ?n \rightarrow Joe, ?p \rightarrow 1111\}\}$$

$\llbracket q_1 \rrbracket_G \not\subseteq \llbracket q_2 \rrbracket_G$ we have that $\varrho_1 \notin \llbracket q_2 \rrbracket_G$

We consider **subsumption**:

$\llbracket q_1 \rrbracket_G \subseteq \llbracket q_2 \rrbracket_G$ because q_2 contains more information than that of q_1

Expressivity, decidability and complexity

Abstract syntax of graph patterns:

$$P ::= tp \mid P \text{ AND } P \mid P \text{ OPT } P \mid P \text{ UNION } P$$

Complexity of query containment

SPARQL FRAGMENT	COMPLEXITY
UNION-OPT-AND	Undecidable [Trahtenbrot:1950]
OPT-AND	Undecidable [Letelier-et-al:2012]
UNION-AND	NP-Complete [Sagiv-et-al:1980]
AND	NP-Complete [Chandra-et-al:1977]
Well-Designed OPT-AND	Π_2^P -Complete [Letelier-et-al:2012]

Well-designed SPARQL queries [Perez-et-al:2009]

Restriction on variable usage

$$P = (?a, name, Joe) OPT \underbrace{\left((?y, email, ?e) OPT (?a, phone, ?p) \right)}_{P_1} \quad \times$$

$$P = (?a, name, Joe) OPT \underbrace{\left((?a, email, ?e) OPT (?a, phone, ?p) \right)}_{P_1} \quad \checkmark$$

Well-designed SPARQL Queries allows a Normal Form

$$(1) P_1 AND (P_2 OPT P_3) \rightarrow (P_1 AND P_2) OPT P_3$$

$$(2) (P_1 OPT P_2) AND P_3 \rightarrow (P_1 AND P_2) OPT P_3$$

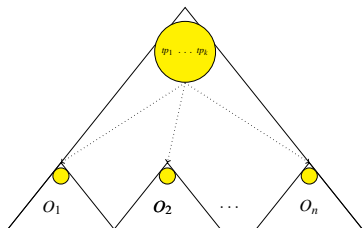
Well-designed SPARQL queries [Perez-et-al:2009]

$$\underbrace{\left(\dots (tp_1 \text{ AND } tp_2 \text{ AND } \dots \text{ AND } tp_k) \text{ OPT } O_1 \right) \text{ OPT } O_2 \dots \text{ OPT } O_n \right)}_{O_0} \quad (\star)$$

O_1, O_2, \dots, O_n have the same form of (\star)

OPT **only** outside the scope of *AND* components.

OPT operators define a tree structure of *AND* components.



- Well-designed SPARQL queries support the Berlin Benchmark [Bizer-et-al:2009].
- 48% of DBpedia queries using OPT are well-designed [Picalausa-et-al:2011]

This fragment preserves decidability of containment in presence of OPT-AND

State-of-the-art Implementations for SPARQL Containment

- 1 SPARQL-Algebra for well-designed OPT-AND queries, Π_2^P -complete [Letelier-et-al, 2012] (No OWL constraints)
- 2 Logical approach for UNION-AND queries (+ OWL constraints), $2Exptime$ upper bound [Chekol-et-al, 2012] (No OPT)

Initial questions:

- Is it possible to extend the SPARQL Algebra with OWL constraints?
- Is it possible to find an intermediate approach with a better complexity?
- Is it possible to extend the logical approach to support OPT constructors?

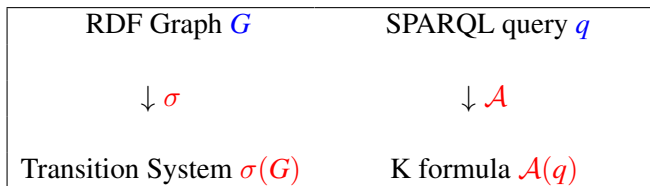
Why a logical approach?

- 1 close connection between query containment and validity of a formula in logic
- 2 approach successfully applied for UNION-AND fragments
- 3 it is efficiently implementable and extensible
- 4 existing solvers optimized for years
- 5 transferring complexity results.
- 6 possibility of query evaluation through model checking

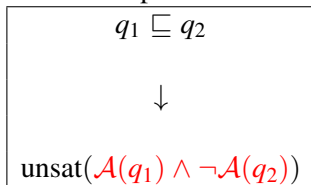
I am going to show that very efficient SPARQL containment checkers can be implemented using K Logic.

Approach

Encoding graphs and queries into a logic

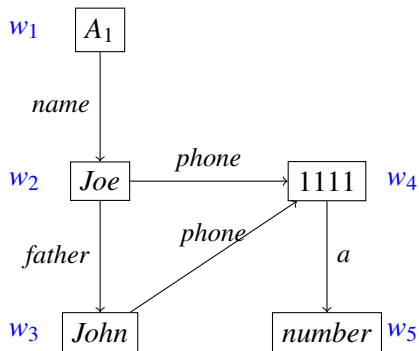


Reduce query containment to the problem of unsatisfiability in K-logic



Transition system

- consists of a set of states and transitions between states, formally,
 $\mathcal{M} = (W, R, V)$



- $W = \{w_1, w_2, w_3, w_4, w_5\}$
- $R(\textit{name}) = \{(w_1, w_2)\}$
 $R(\textit{phone}) = \{(w_2, w_4), (w_3, w_4)\}$
...
- $V(w_1) = \{A_1\}; \dots$

Syntax

$$\varphi ::= \top \mid q \mid \underline{q} \mid \neg\varphi \mid \varphi \wedge \varphi \mid \langle m \rangle \varphi$$

where:

$q \in \mathcal{AP}$ (Atomic Propositions)

$\underline{q} \in \mathcal{AP}_\Sigma$ (Exclusive Atomic Propositions)

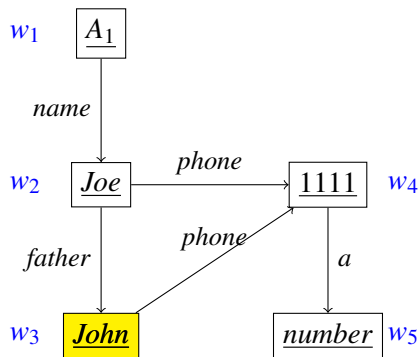
$$\forall(\underline{u}, \underline{u}') \in (\mathcal{AP}_\Sigma)^2, (\underline{u} \neq \underline{u}') \Rightarrow \neg\underline{u} \vee \neg\underline{u}'$$

$m \in MOD = \{\alpha, \beta, s, o, ..\}$ (Modalities)

Syntactic Sugar:

<i>Abbreviation</i>	<i>Formula</i>
\perp	$\neg\top$
$\varphi \vee \psi$	$\neg(\neg\varphi \wedge \neg\psi)$
$[m]\varphi$	$\neg\langle m \rangle\neg\varphi$

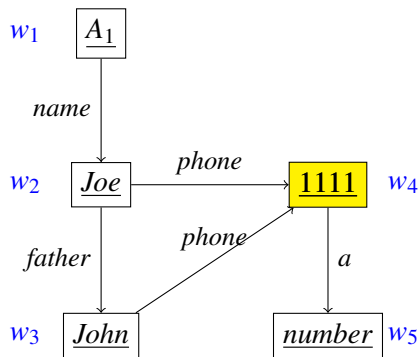
K formulæ: Examples



Formulæ:

- \underline{John}

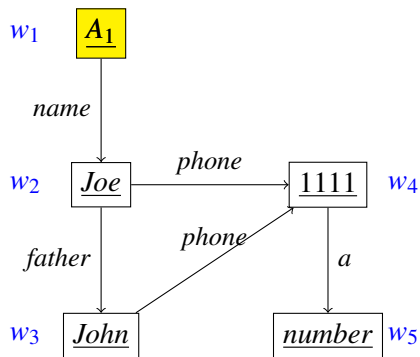
K formulæ: Examples



Formulæ:

- \underline{John}
- $\langle a \rangle \underline{number}$

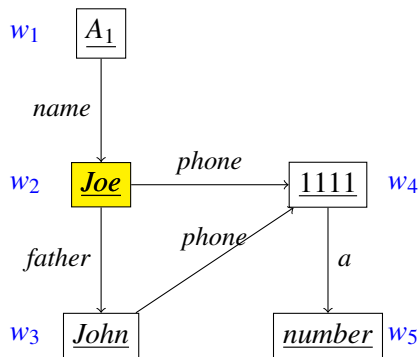
K formulæ: Examples



Formulæ:

- \underline{John}
- $\langle a \rangle \underline{number}$
- $\langle \text{name} \rangle \langle \text{father} \rangle \underline{John}$

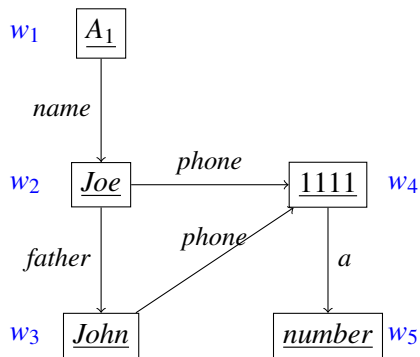
K formulæ: Examples



Formulæ:

- \underline{John}
- $\langle a \rangle \underline{number}$
- $\langle \text{name} \rangle \langle \text{father} \rangle \underline{John}$
- $\underline{Joe} \wedge \langle \text{father} \rangle \underline{John}$

K formulæ: Examples

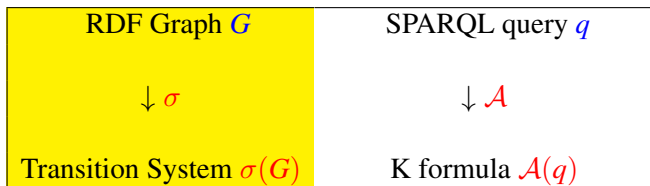


Formulæ:

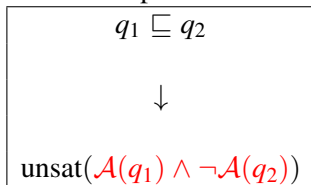
- \underline{John}
- $\langle a \rangle \underline{number}$
- $\langle \text{name} \rangle \langle \text{father} \rangle \underline{John}$
- $\underline{Joe} \wedge \langle \text{father} \rangle \underline{John}$
- $\underline{Joe} \wedge \underline{John}$

Approach

Encoding graphs and queries into a logic

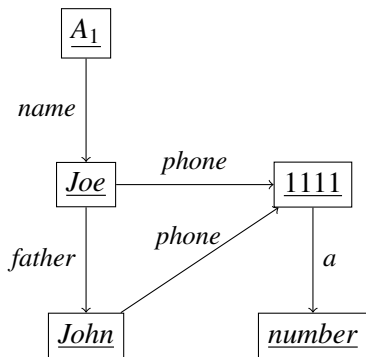


Reduce query containment to the problem of unsatisfiability in K-logic



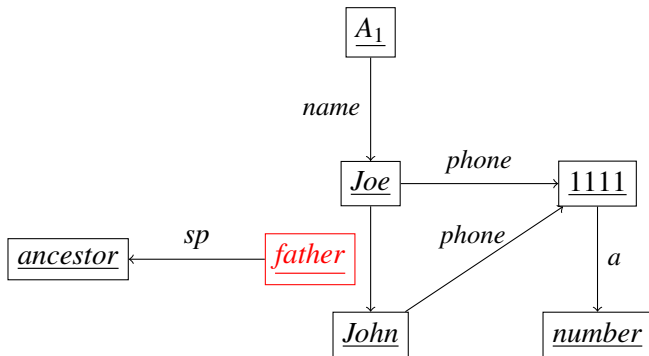
Encoding RDF graphs as transition systems

Use RDF graph as a transition system.



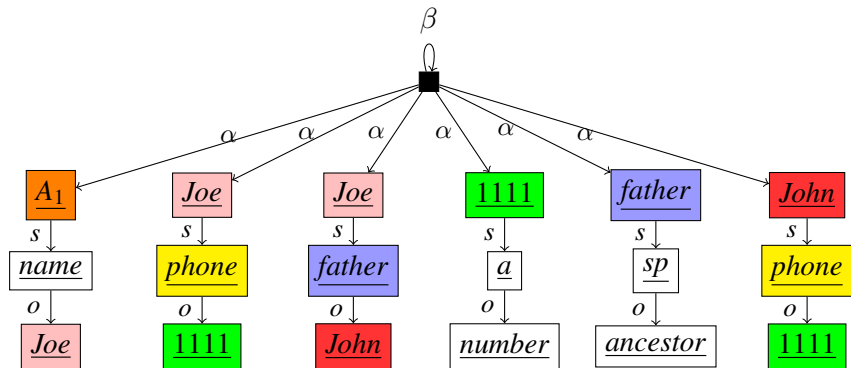
Encoding RDF graphs as transition systems

Predicates can be nodes in an RDF graph



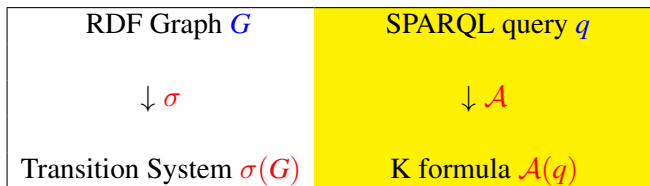
Our encoding

- we add a node called *graph node* ■
- connect it to all subject nodes
- finite set of modalities $\{\alpha, \beta, s, o\}$.
- α for *AND* operators and β for *OPT* operators

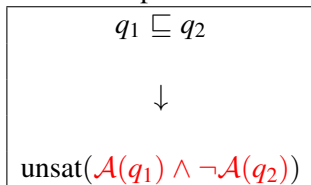


Approach

Encoding graphs and queries into a logic

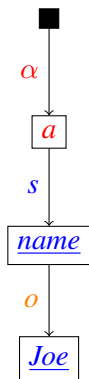


Reduce query containment to the problem of unsatisfiability in K-logic



Encoding SPARQL queries as K formulæ

$$q = \{(?a, name, Joe)\}$$

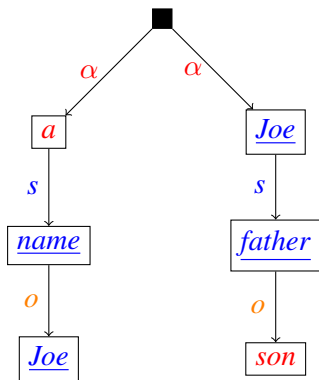


- each triple is connected to a graph node,
- the graph node is connected to a subject, a subject to a predicate and a predicate to an object
- every URI is encoded with an exclusive atomic proposition (\mathcal{AP}_Σ) and $\forall(\underline{u}, \underline{u}') \in (\mathcal{AP}_\Sigma)^2 (\underline{u} \neq \underline{u}') \Rightarrow \neg \underline{u} \vee \neg \underline{u}'$
- variables are encoded with atomic propositions (\mathcal{AP})

$$\langle \alpha \rangle \left(a \wedge \langle s \rangle (\underline{name} \wedge \langle o \rangle \underline{Joe}) \right)$$

Encoding SPARQL queries as K formulæ

$q = \{(?a, name, Joe) \text{ AND } (Joe, father, ?son)\}$

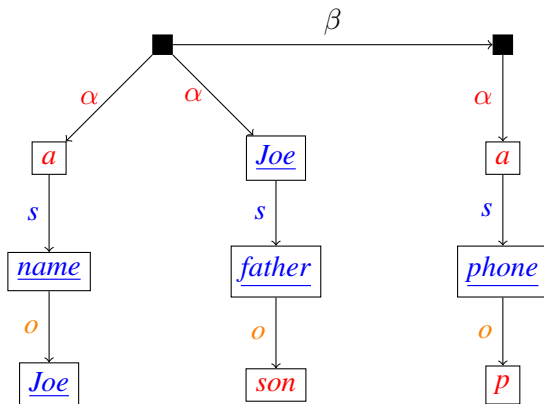


- each triple is connected to a graph node,
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- variables are encoded with atomic propositions (\mathcal{AP})

$$\langle \alpha \rangle \left(a \wedge \langle s \rangle (\underline{\text{name}} \wedge \langle o \rangle \underline{\text{Joe}}) \right) \wedge \langle \alpha \rangle \left(\underline{\text{Joe}} \wedge \langle s \rangle (\underline{\text{father}} \wedge \langle o \rangle \text{son}) \right)$$

Encoding SPARQL queries as K formulæ

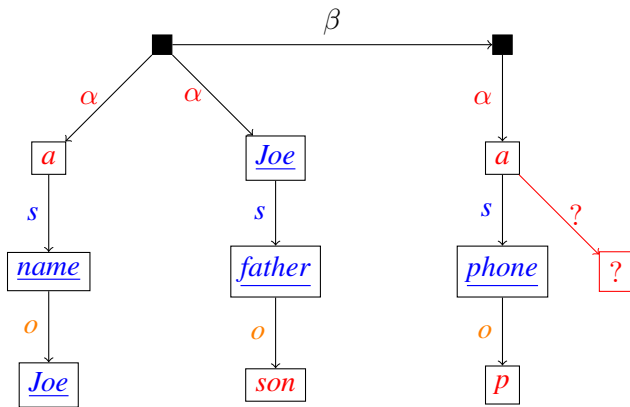
$q = \{((?a, name, Joe) \text{ AND } (Joe, father, ?son)) \text{ OPT } (?a, phone, ?p)\}$



$\langle \alpha \rangle \left(a \wedge \langle s \rangle (\underline{name} \wedge \langle o \rangle \underline{Joe}) \right) \wedge \langle \alpha \rangle \left(\underline{Joe} \wedge \langle s \rangle (\underline{father} \wedge \langle o \rangle \underline{son}) \right) \wedge [\beta] \langle \alpha \rangle \left(a \wedge \langle s \rangle (\underline{phone} \wedge \langle o \rangle \underline{p}) \right)$

Encoding SPARQL queries as K formulæ

$q = \{((?a, name, Joe) \text{ AND } (Joe, father, ?son)) \text{ OPT } (?a, phone, ?p)\}$



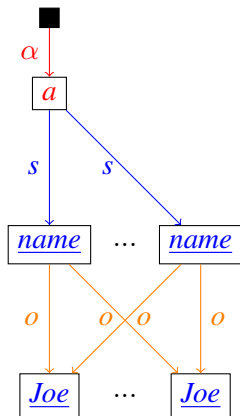
$\langle \alpha \rangle \left(a \wedge \langle s \rangle (\underline{name} \wedge \langle o \rangle \underline{Joe}) \right) \wedge \langle \alpha \rangle \left(\underline{Joe} \wedge \langle s \rangle (\underline{father} \wedge \langle o \rangle \underline{son}) \right) \wedge [\beta] \langle \alpha \rangle \left(a \wedge \langle s \rangle (\underline{phone} \wedge \langle o \rangle \underline{p}) \right)$

Query encoding: requirements on outgoing edges

$$q = \{(?a, \textit{name}, \textit{Joe})\}$$

$\downarrow \mathcal{A}$

$$\mathcal{A}(?a, \textit{name}, \textit{Joe}) = \langle \alpha \rangle (a \wedge \langle s \rangle T \wedge [s](\underline{\textit{name}} \wedge \langle o \rangle T \wedge [o]\underline{\textit{Joe}}))$$



- All s -transitions from a subject node go to predicate nodes labelled name.
- All o -transitions from a predicate node go to object nodes labelled Joe

$$\langle a \rangle \varphi = \langle a \rangle \top \wedge [a] \varphi \quad a = \{s, o\}$$

Query encoding: requirements on outgoing edges

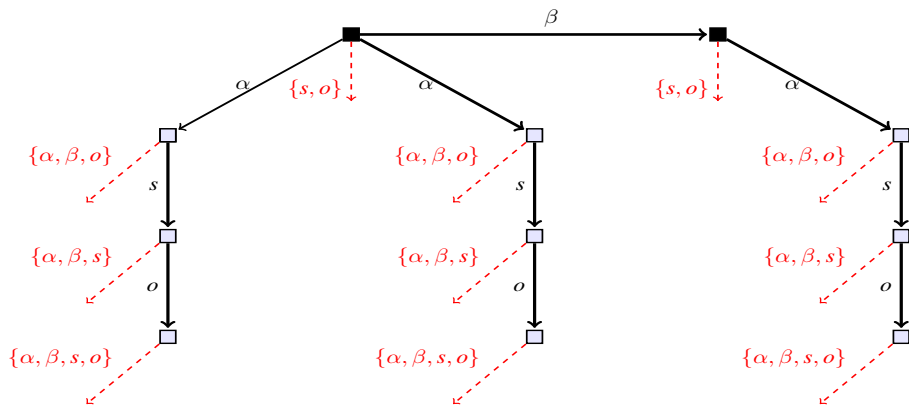
$$\xi = isG \wedge [\alpha](isS \wedge [s](isP \wedge [o]isO))$$

$$isG = \neg\langle s \rangle T \wedge \neg\langle o \rangle T$$

$$isO = \neg\langle \beta \rangle T \wedge \neg\langle \alpha \rangle T \wedge \neg\langle s \rangle T \wedge \neg\langle o \rangle T$$

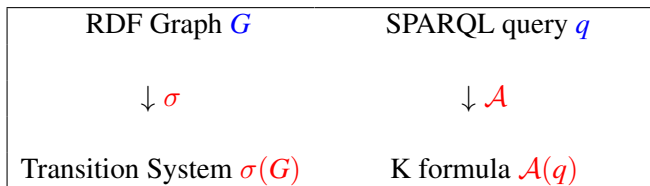
$$isS = \neg\langle \beta \rangle T \wedge \neg\langle \alpha \rangle T \wedge \neg\langle o \rangle T$$

$$isP = \neg\langle \beta \rangle T \wedge \neg\langle \alpha \rangle T \wedge \neg\langle s \rangle T$$

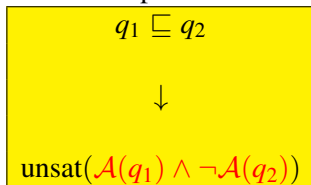


Approach

Encoding graphs and queries into a logic



Reduce query containment to the problem of unsatisfiability in K-logic



Reduce query containment to unsatisfiability in K

$$q_1 \sqsubseteq q_2 \Leftrightarrow \text{val}\left(\mathcal{A}(q_1) \rightarrow \mathcal{A}(q_2)\right) \Leftrightarrow \text{val}\left(\neg\mathcal{A}(q_1) \vee \mathcal{A}(q_2)\right)$$

$$q_1 : \{(?a, \text{name}, ?n)\}$$

$$q_2 : \{(?a, \text{name}, ?n) \text{ OPT } (?a, \text{phone}, ?p)\}$$

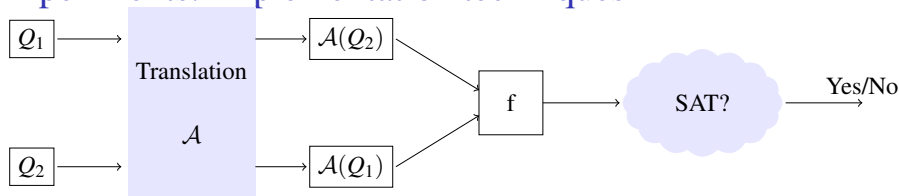
$$\mathcal{A}(q_1) = \underbrace{\xi \wedge \langle\alpha\rangle\mathcal{A}(?a, \text{email}, ?e)}_{\varphi} \wedge \neg\langle\beta\rangle\top$$

$$\mathcal{A}(q_2) = \underbrace{\xi \wedge \langle\alpha\rangle\mathcal{A}(?a, \text{email}, ?e)}_{\varphi} \wedge [\beta] \left(\underbrace{\xi \wedge \langle\alpha\rangle\mathcal{A}(?a, \text{phone}, ?p)}_{\psi} \wedge [\beta]\perp \right)$$

$$\text{val}\left(\neg\mathcal{A}(q_1) \vee \mathcal{A}(q_2)\right) \Leftrightarrow \text{unsat}\left(\mathcal{A}(q_1) \wedge \neg\mathcal{A}(q_2)\right)$$

Is there a model for $(\varphi \wedge \neg\langle\beta\rangle\top) \wedge \neg(\varphi \wedge [\beta]\psi)$? **NO**

Experiments: implementation techniques



Custom implementation of K-SOLVER [Chapter 5]

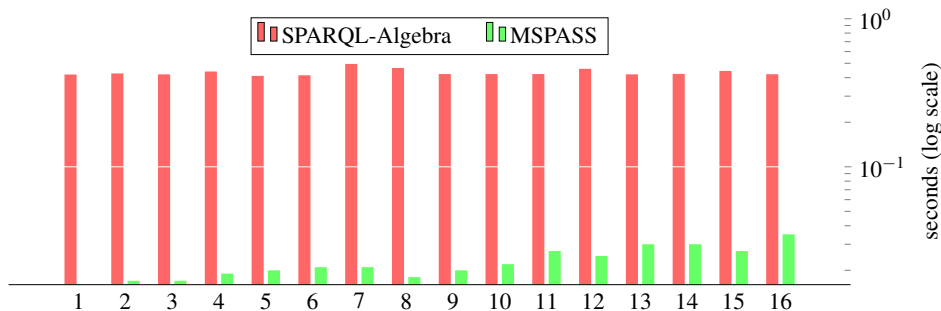
- better understanding of the logical approach
- java implementation with BDDs based on [pan-et-al.:2005]
- **Solves the problem**

MSPASS [Hustadt-et-al:2000]

- Optimized solver supporting K logic
- **Solves the problem much faster** [finding of Chapter 6]

Experiments

Queries taken either from third-party benchmarks (BERLIN Bench) or that we have automatically generated.



Result: the use of our translation and the MSPASS solver offers 10x performance gain compared to SPARQL Algebra (the closest competitor).

Conclusion

Main contributions:

- 1 A translation of well-designed (OPT-AND) queries in terms of formulas expressed in the modal logic and a formulation of the containment problem as unsatisfiability in logic.
- 2 implementation of the approach and experiments with benchmarks;
- 3 a finding: the use of the MSPASS solver in this context provides a 10x performance gain compared to SPARQL Algebra.

Perspectives:

- Study extensions to support constraints

Perspectives: containment under schema

Motivation: Reduction of the input graphs

Let $\mathcal{C} = \{c_1, \dots, c_n\}$ be a finite set of constraints.

- We define a function η that encode our set of constraints as modal formulæ

$$\eta(\mathcal{C}) = \eta(c_1) \wedge \dots \wedge \eta(c_n)$$

- Let q_1 and q_2 be two well-designed queries and \mathcal{C} be a set of axioms, we should have

$$q_1 \sqsubseteq_{\mathcal{C}} q_2 \Leftrightarrow \eta(\mathcal{C}) \wedge \mathcal{A}(q_1) \wedge \neg \mathcal{A}(q_2)$$

Open Questions:

- 1 Complexity?
- 2 What kind of schemas can be captured by K?
- 3 To which extent my performance gains transfer to this setting?
- 4 How to generalize this approach to the query-update independence problem [[Guido-et-al:2015](#)]?

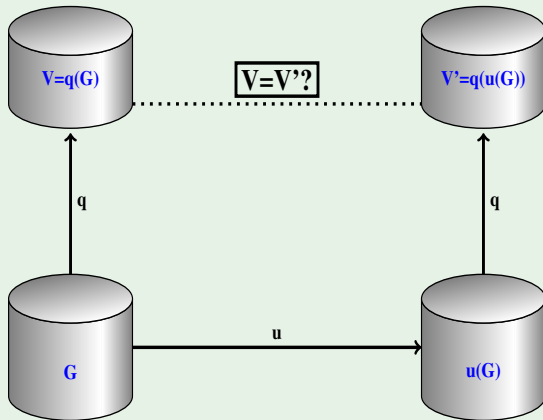
Any Questions?



Query-Update Independence

The release of an update language for SPARQL introduces a setting where one might now study the problem of determining independence between SPARQL queries and SPARQL Updates

Example



Condition of Independence

Definition (Condition for independence)

Let \mathcal{Q} be the set of all triple patterns that appear in the query pattern of the query q and \mathcal{U} be the set of all quad patterns that appear in the DeleteClause and InsertClause of an update u :

$$\forall G. \llbracket q \rrbracket_G = \llbracket q \rrbracket_{u(G)} \Leftrightarrow \mathcal{Q} \cap \mathcal{U} = \emptyset$$

where $\mathcal{Q} \cap \mathcal{U} = \emptyset$ is defined as follows:

$$\forall t_q \in \mathcal{Q}, \forall t_u \in \mathcal{U}, t_q \neq t_u$$

and $t_q \neq t_u \Leftrightarrow \forall \varrho_q \in \llbracket t_q \rrbracket_G, \forall \varrho_u \in \llbracket t_u \rrbracket_G, \varrho_q(t_q) \neq \varrho_u(t_u)$.

Example

Example

$$G = \{(A_1, \text{name}, \text{Joe}), (A_1, \text{phone}, 1111), (A_4, \text{name}, \text{John}), (A_4, \text{phone}, 4444), (A_4, \text{fax}, 5555)\}$$
$$q = \begin{array}{l} \text{SELECT} \quad ?a \ ?n \ ?p \\ \text{WHERE} \quad \{ (?a, \text{name}, ?n) \text{ AND } (?a, \text{phone}, ?p) \} \end{array}$$
$$\llbracket q \rrbracket_G = \{ \varrho_1 = \{ ?a \rightarrow A_1, ?n \rightarrow \text{Joe}, ?p \rightarrow 1111 \}, \varrho_2 = \{ ?a \rightarrow A_4, ?n \rightarrow \text{John}, ?p \rightarrow 4444 \} \}$$

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$$u = \begin{array}{l} \text{DELETE} \quad (?a, \text{name}, ?n) \\ \text{WHERE} \quad \{(?a, \text{name}, ?n) \text{ AND } (?a, \text{fax}, ?f)\} \end{array}$$

$$u(G) = \{(A_1, \text{name}, \text{Joe}), (A_1, \text{phone}, 1111), (A_4, \text{phone}, 4444), (A_4, \text{fax}, 5555)\}$$

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$$\llbracket q \rrbracket_{u(G)} \neq \llbracket q \rrbracket_G \Leftrightarrow q \text{ and } u \text{ are dependent}$$

Example

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$$\llbracket q \rrbracket_{\hat{u}(G)} = \llbracket q \rrbracket_G \Leftrightarrow q \text{ and } u \text{ are independent}$$

Approaches

Syntactic checking - We define the function $\underline{Equiv} : T \times T \rightarrow \{true, false\}$ that returns *true* if the pair of terms in input matches, *false* otherwise

$$\underline{Equiv}(t_1, t_2) = \begin{cases} true & \text{if } t_1 \in BV \text{ or } t_2 \in BV \text{ or } t_1 = t_2 \\ false & \text{otherwise} \end{cases}$$

$$\underline{Equiv}(t_1, t_2) = \underline{Equiv}(s_1, s_2) \ \&\& \ \underline{Equiv}(p_1, p_2) \ \&\& \ \underline{Equiv}(o_1, o_2)$$

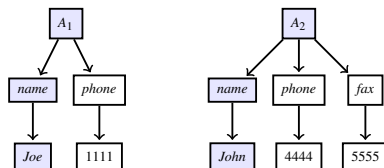
What happens in the presence of the following triple pattern in the DeleteClause or in the InsertClause?

$\{?s \ ?p \ ?o\}$

Approaches

We study the structure of a query and an update in terms of their graph patterns.

$t_1 \equiv A_1 \text{ name Joe}$ $t_1 \equiv A_2 \text{ name John}$
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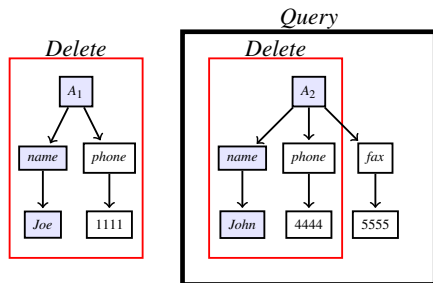


When the containment study concludes that the query is more constrained than the delete operation or the insert operation is more constrained than the query, it is possible to avoid a full re-computation of a query over an updated graph.

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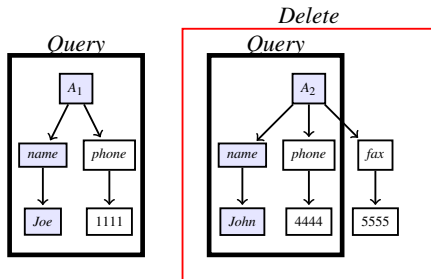
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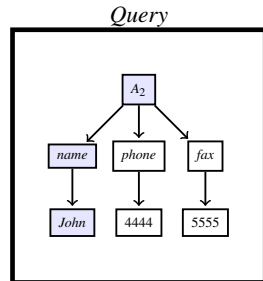
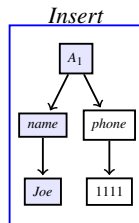
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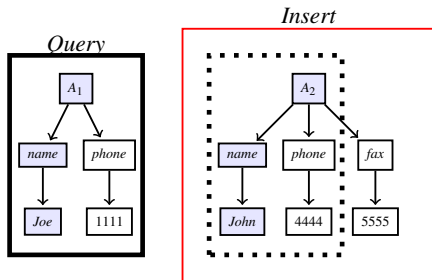
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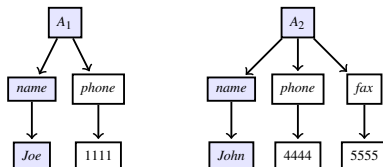
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 $Query = \{t_1, t_2\} \subseteq Insert = \{t_1, t_2, t_3\}$

Perspective - Query-Update Independence under Schema

Constraints expressed in a description logic supporting negation are game-changers for the independence problem.

$$G = \{(A_1, \textit{name}, \textit{Joe}), (A_1, \textit{phone}, 1111), (A_4, \textit{name}, \textit{John}), (A_4, \textit{phone}, 4444), (A_4, \textit{fax}, 5555)\}$$

SELECT $?s$

WHERE $\{(?s, \textit{phone}, 1111)\}$

DELETE $(?s, ?p, ?o)$

WHERE $\{(A_4, \textit{phone}, ?s)\}$

In absence of a schema the query and the update are dependent. The situation changes in presence of the following schema

Domain(phone, Person)

Range(phone, Number)

DisjointClasses(Person, Number)

The variable $?x$ has type *Person* in the query and type *Number* in the update, hence a contradiction has been detected that should imply independence.

Experiments: The Benchmark

Benchmark

- Queries based on the specific requirements of a real world use case.
- Increasing expected difficulty by using more constructors.
 - ▶ OPT-AND constructors;
 - ▶ the number of triple patterns;
 - ▶ the number of nested OPT constructors;

The Logical Approach

- MSPASS

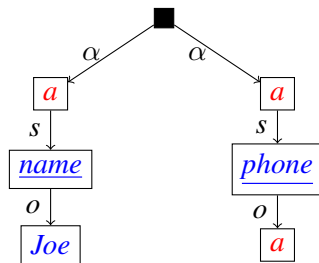
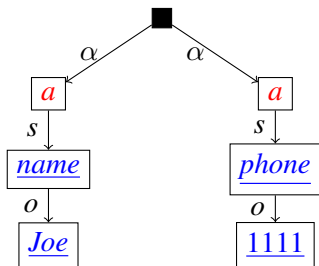
Ad Hoc Approach [Letelier-et-al.:2012]

- SPARQL-Algebra

Encoding of variables

SELECT ?*a*
WHERE {(?*a*, *name*, *Joe*) AND
(?*a*, *phone*, 1111)}

SELECT ?*a*
WHERE {(?*a*, *name*, *Joe*) AND
(?*a*, *phone*, ?*a*)}



- Subjects = {}
- Predicates = {name, phone}
- Objects = {Joe, 1111}

?*a* → *a* is in subject and object position

- ?*a* → *a* ∨ *Joe*
- ?*a* → *a* ∨ 1111