



# 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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Ph.D Defense

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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)

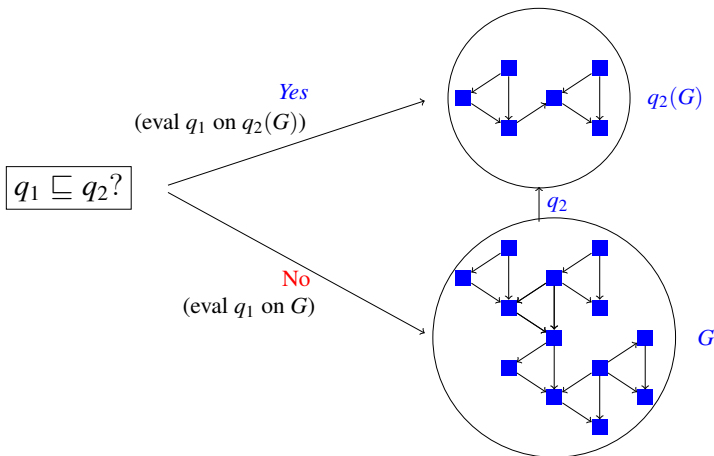
Given two queries  $q_1$  and  $q_2$ ,  $q_1$  is contained in  $q_2$ , denoted  $q_1 \sqsubseteq q_2$ , if for every dataset  $G$ ,  $q_1(G) \subseteq q_2(G)$ .

# Query containment problem

SPARQL Queries:  $q_1, q_2$

RDF Graph:  $G$

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

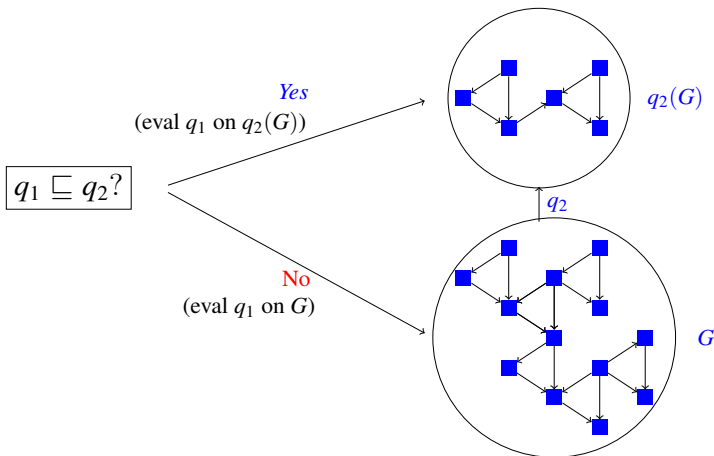


# Query containment problem

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](#)]

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but, much less for SPARQL

- union of conjunctive queries under DL schema axioms: 2EXPTIME [[Chekol-et-al:2012](#)],
- containment in presence of OPTIONAL operators:  $\Pi_2^P$ -complete [[Letelier-et-al:2012](#)]



# Outline

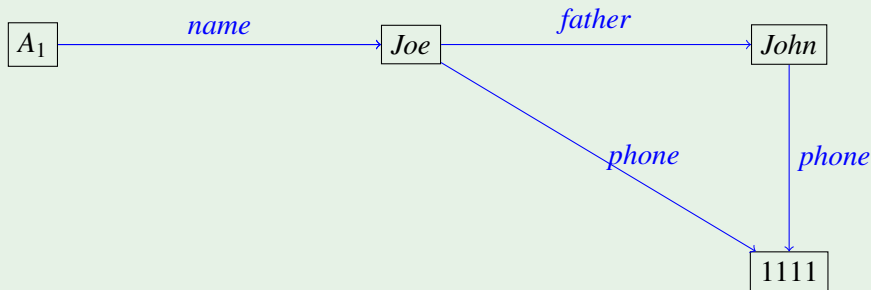
- 1 Motivation
- 2 Query Containment Problem for SPARQL
  - Preliminaries
  - Logical Approach
  - Experiments
- 3 Conclusion and Perspectives

# 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)

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

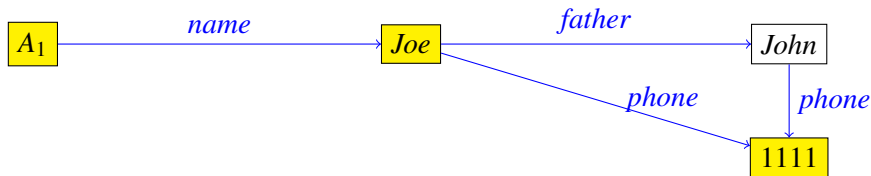


# SPARQL Protocol And RDF Query Language

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

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

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

$q_1$	$q_2$
$SELECT \quad ?a \ ?n$ $HERE \quad \{ (?a, name, ?n) \}$	$SELECT \quad ?a \ ?n \ ?p$ $WHERE \quad \{ (?a, name, ?n)$ $OPT (?a, phone, ?p) \}$

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

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

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

$\llbracket q_1 \rrbracket_G \not\subseteq \llbracket q_2 \rrbracket_G$  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	[ <a href="#">Trahtenbrot:1950</a> ]
OPT-AND	Undecidable	[ <a href="#">Letelier-et-al:2012</a> ]
UNION-AND	NP-Complete	[ <a href="#">Sagiv-et-al:1980</a> ]
AND	NP-Complete	[ <a href="#">Chandra-et-al:1977</a> ]
Well-Designed OPT-AND	$\Pi_2^P$ -Complete	[ <a href="#">Letelier-et-al:2012</a> ]

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

Restriction on variable usage

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

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

Well-designed SPARQL Queries allows a Normal Form

- (1)  $P_1 \text{ AND } (P_2 \text{ OPT } P_3) \rightarrow (P_1 \text{ AND } P_2) \text{ OPT } P_3$
- (2)  $(P_1 \text{ OPT } P_2) \text{ AND } P_3 \rightarrow (P_1 \text{ AND } P_2) \text{ OPT } P_3$

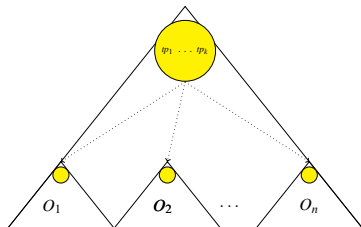
## Well-designed SPARQL queries [Perez-et-al:2009]

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

$O_1, O_2, \dots, O_n$  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,  $\Pi_2^P$ -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?



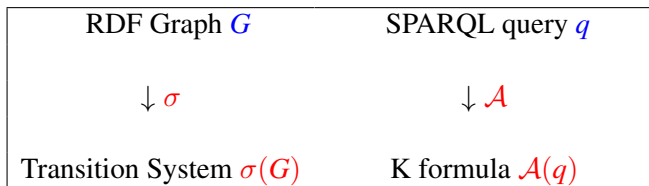
# Why a logical approach?

- 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

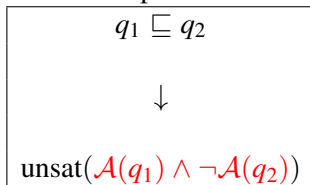
I am going to show that very efficient SPARQL containment checkers can be implemented using K Logic.

# Approach

Encoding graphs and queries into a logic

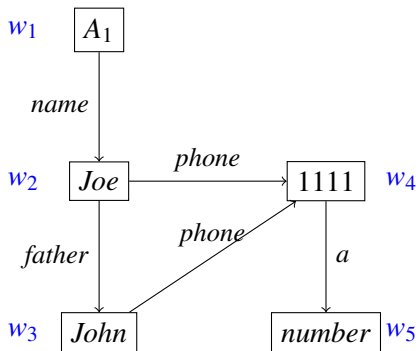


Reduce query containment to the problem of unsatisfiability in K-logic



# Transition system

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



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

## 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)

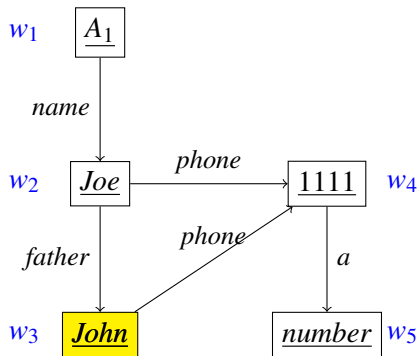
$$\forall(\underline{u}, \underline{u}') \in (\mathcal{AP}_\Sigma)^2, (\underline{u} \neq \underline{u}') \Rightarrow \neg \underline{u} \vee \neg \underline{u}'$$

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

Syntactic Sugar:

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

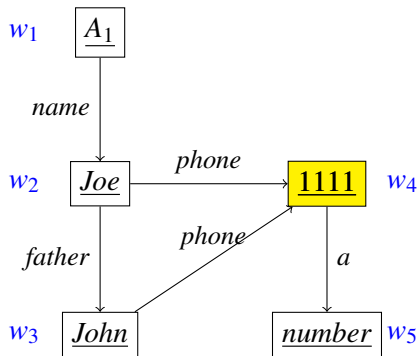
# K formulæ: Examples



Formulæ:

- $\underline{John}$

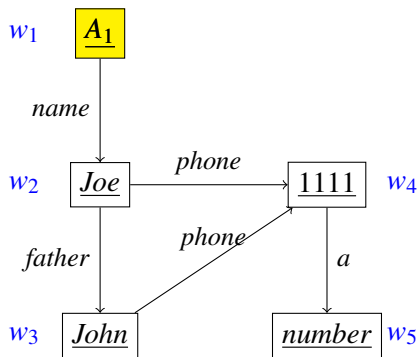
# K formulæ: Examples



Formulæ:

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

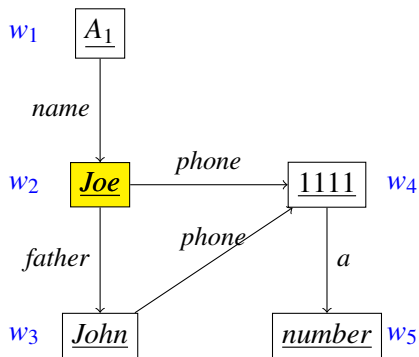
# K formulæ: Examples



Formulæ:

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

# K formulæ: Examples

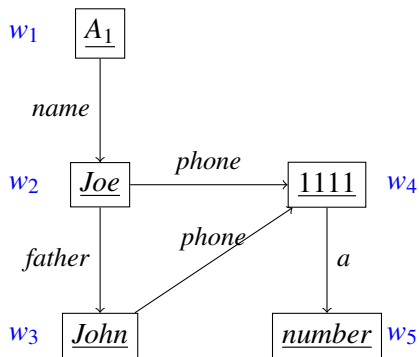


Formulæ:

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



# K formulæ: Examples

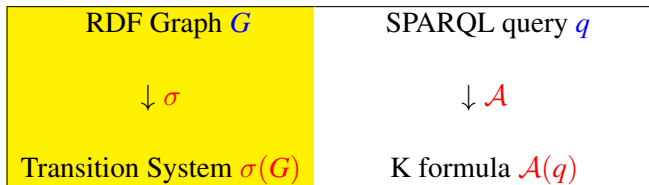


Formulæ:

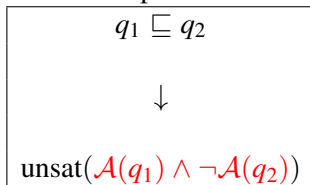
- $\underline{John}$
- $\langle a \rangle \underline{number}$
- $\langle \text{name} \rangle \langle \text{father} \rangle \underline{John}$
- $\underline{Joe} \wedge \langle \text{father} \rangle \underline{John}$
- $\underline{Joe} \wedge \underline{John}$

# Approach

Encoding graphs and queries into a logic

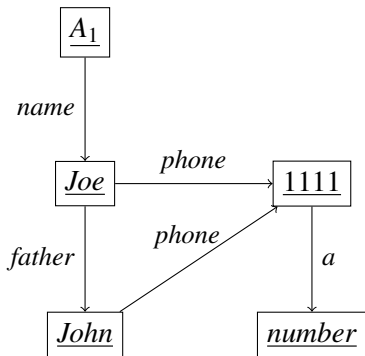


Reduce query containment to the problem of unsatisfiability in K-logic



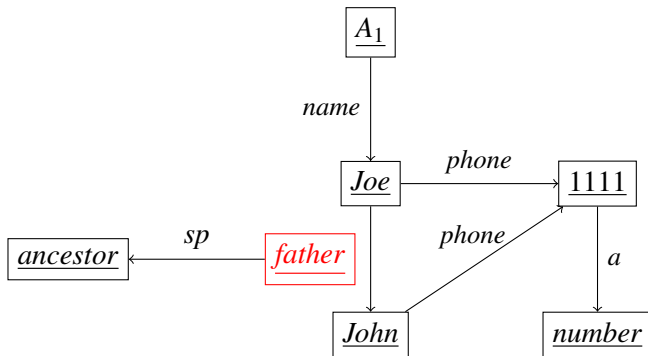
# Encoding RDF graphs as transition systems

Use RDF graph as a transition system.



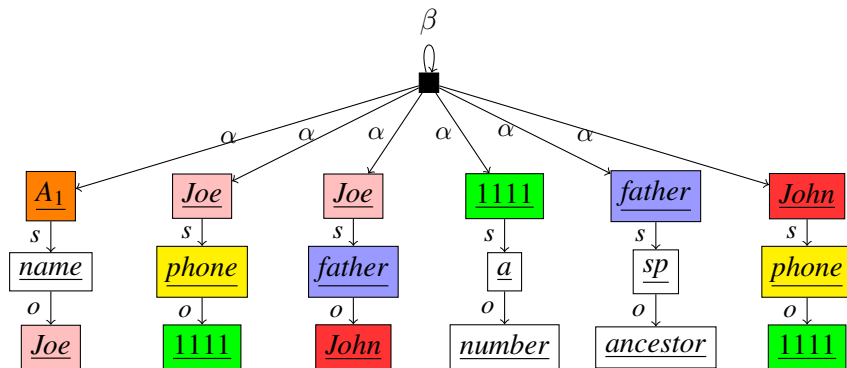
# Encoding RDF graphs as transition systems

Predicates can be nodes in an RDF graph



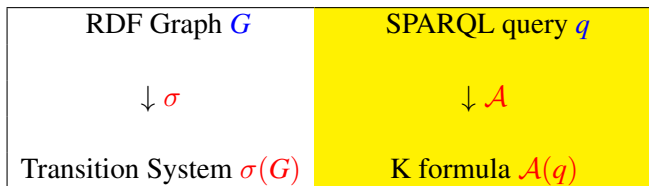
# Our encoding

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

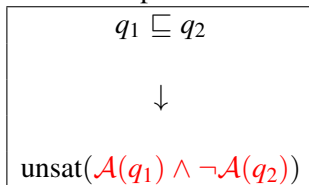


# Approach

Encoding graphs and queries into a logic

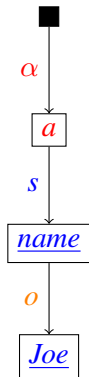


Reduce query containment to the problem of unsatisfiability in K-logic



# Encoding SPARQL queries as K formulæ

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

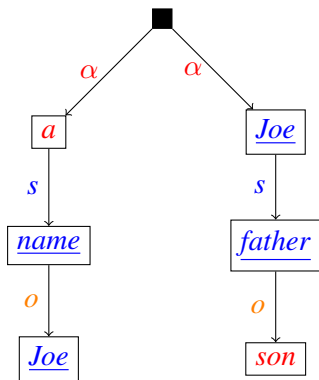


- each triple is connected to a graph node,
- the graph node is connected to a subject, a subject to a predicate and a predicate to an object
- every URI is encoded with an exclusive atomic proposition ( $\mathcal{AP}_\Sigma$ ) and  $\forall(\underline{u}, \underline{u}') \in (\mathcal{AP}_\Sigma)^2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

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



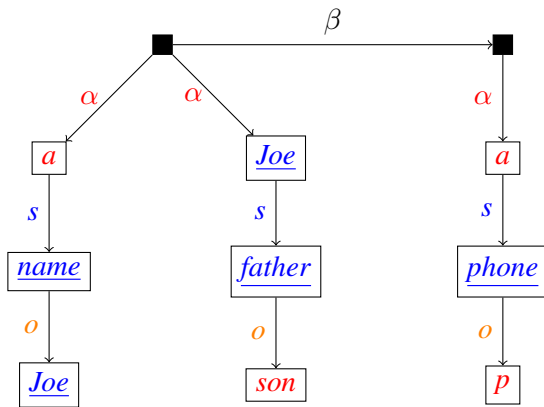
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- variables are encoded with atomic propositions ( $\mathcal{AP}$ )

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



# Encoding SPARQL queries as K formulæ

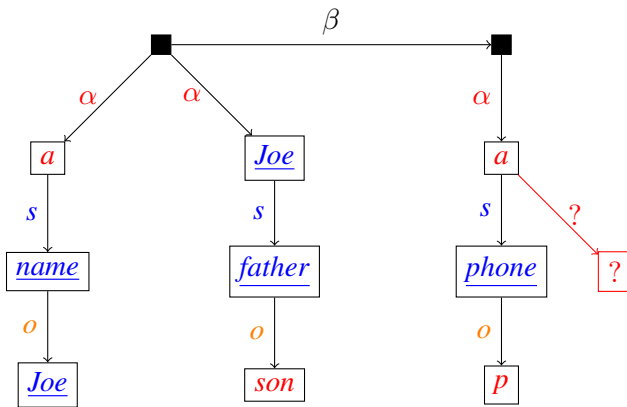
$$q = \{ \left( (?a, \text{name}, \text{Joe}) \text{ AND } (\text{Joe}, \text{father}, ?son) \right) \text{ OPT } (?a, \text{phone}, ?p) \}$$



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

# Encoding SPARQL queries as K formulæ

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



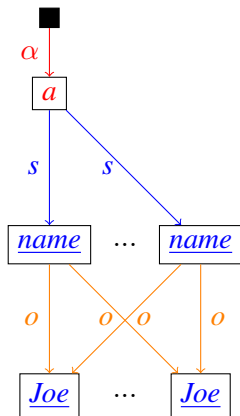
$$\langle \alpha \rangle \left( a \wedge \langle s \rangle (\underline{\text{name}} \wedge \langle o \rangle \underline{\text{Joe}}) \right) \wedge \langle \alpha \rangle \left( \underline{\text{Joe}} \wedge \langle s \rangle (\underline{\text{father}} \wedge \langle o \rangle \underline{\text{son}})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

# 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

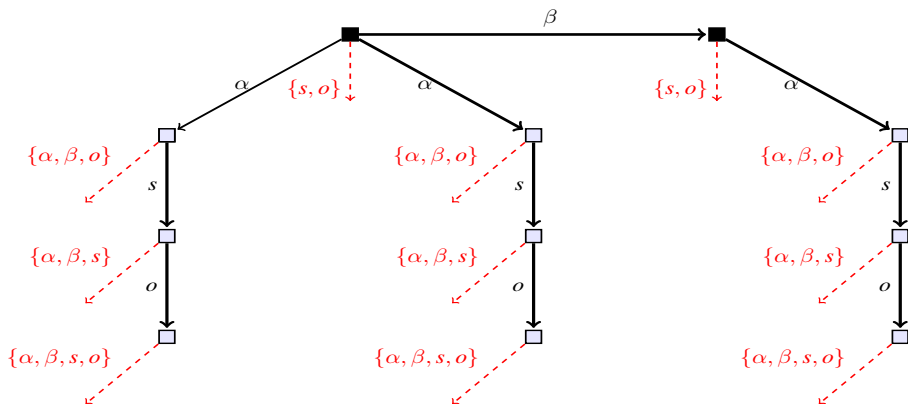
$$\xi = \text{isG} \wedge [\alpha](\text{isS} \wedge [s](\text{isP} \wedge [o]\text{isO}))$$

$$\text{isG} = \neg\langle s \rangle \top \wedge \neg\langle o \rangle \top$$

$$\text{isO} = \neg\langle \beta \rangle \top \wedge \neg\langle \alpha \rangle \top \wedge \neg\langle s \rangle \top \wedge \neg\langle o \rangle \top$$

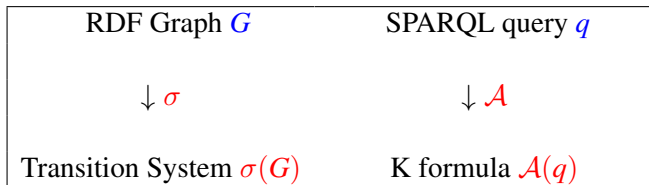
$$\text{isS} = \neg\langle \beta \rangle \top \wedge \neg\langle \alpha \rangle \top \wedge \neg\langle o \rangle \top$$

$$\text{isP} = \neg\langle \beta \rangle \top \wedge \neg\langle \alpha \rangle \top \wedge \neg\langle s \rangle \top$$

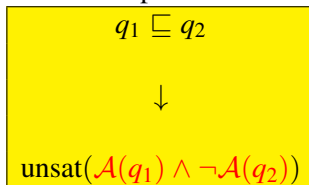


# Approach

Encoding graphs and queries into a logic



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



## Reduce query containment to unsatisfiability in $K$

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

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

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

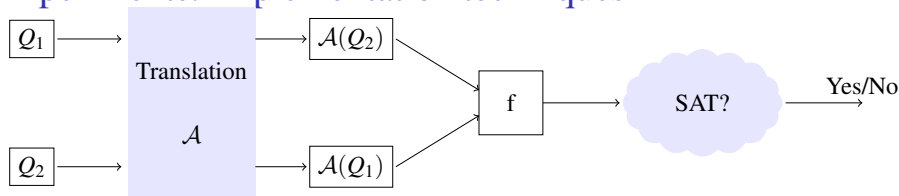
$$\mathcal{A}(q_1) = \underbrace{\xi \wedge \langle\alpha\rangle\mathcal{A}(?a, \text{email}, ?e)}_{\varphi} \wedge \neg\langle\beta\rangle\top$$

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

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

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]

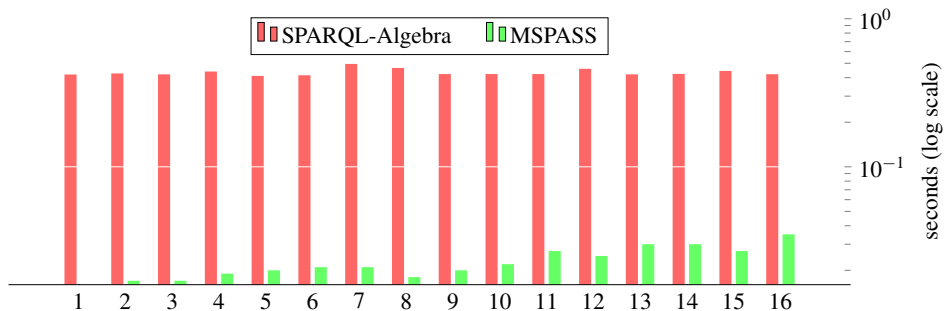
- better understanding of the logical approach
- java implementation with BDDs based on [pan-et-al.:2005]
- **Solves the problem**

### 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:

- ➊ 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.
- ➋ implementation of the approach and experiments with benchmarks;
- ➌ 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  $\eta$  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](#)]?

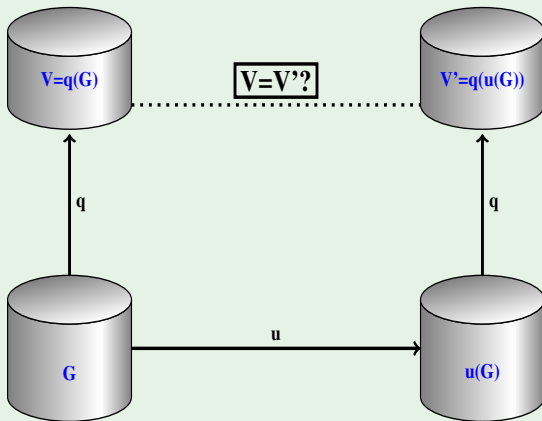
# Any Questions?



# 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

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

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

$$\llbracket q \rrbracket_G = \{\varrho_1 = \{?a \rightarrow A_1, ?n \rightarrow \text{Joe}, ?p \rightarrow 1111\}, \varrho_2 = \{?a \rightarrow A_4, ?n \rightarrow \text{John}, ?p \rightarrow 4444\}\}$$

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$$q = \begin{array}{ll} \text{SELECT} & ?a \ ?n \ ?p \\ \text{WHERE} & \{ (?a, \text{name}, ?n) \text{ AND } (?a, \text{phone}, ?p) \} \end{array}$$

$$\llbracket q \rrbracket_G = \{ \varrho_1 = \{ ?a \rightarrow A_1, ?n \rightarrow \text{Joe}, ?p \rightarrow 1111 \}, \varrho_2 = \{ ?a \rightarrow A_4, ?n \rightarrow \text{John}, ?p \rightarrow 4444 \} \}$$

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

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

# Example

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

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$$\llbracket q \rrbracket_{u(G)} = \{ \varrho_1 = \{ ?a \rightarrow A_1, ?n \rightarrow \text{Joe}, ?p \rightarrow 1111 \} \}$$

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



# Example

## Example

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

$$q = \begin{array}{ll} \text{SELECT} & ?a ?n ?p \\ \text{WHERE} & \{ (?a, \text{name}, ?n) \text{ AND } (?a, \text{phone}, ?p) \} \end{array}$$

$$\llbracket q \rrbracket_G = \{ \varrho_1 = \{ ?a \rightarrow A_1, ?n \rightarrow \text{Joe}, ?p \rightarrow 1111 \}, \varrho_2 = \{ ?a \rightarrow A_4, ?n \rightarrow \text{John}, ?p \rightarrow 4444 \} \}$$

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

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

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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

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

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

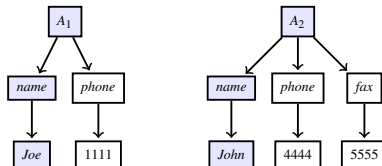
What happens in the presence of the following triple pattern in the DeleteClause or in the InsertClause?

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

# Approaches

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

$t_1 \equiv A_1 \text{ name Joe}$        $t_1 \equiv A_2 \text{ name John}$   
 $t_2 \equiv A_1 \text{ phone 1111}$      $t_2 \equiv A_2 \text{ phone 4444}$   
 $t_3 \equiv A_2 \text{ fax 5555}$

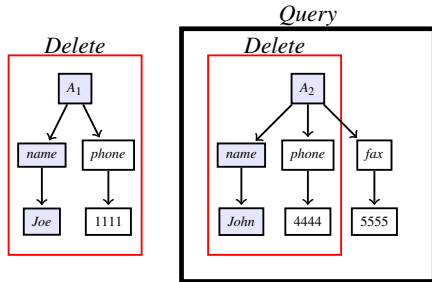


When the containment study concludes that the query is more constrained than the delete operation or the insert operation is more constrained than the query, it is possible to avoid a full re-computation of a query over an updated graph.

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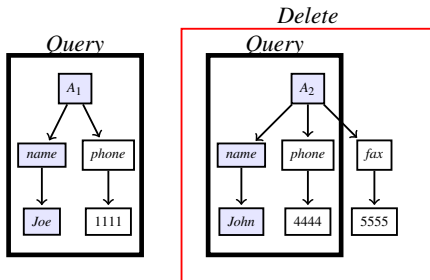
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$$\begin{aligned}
 \rightarrow \text{Delete} = \{t_1, t_2\} &\subseteq \text{Query} = \{t_1, t_2, t_3\} \\
 \text{Query} = \{t_1, t_2\} &\subseteq \text{Delete} = \{t_1, t_2, t_3\} \\
 \text{Insert} = \{t_1, t_2\} &\subseteq \text{Query} = \{t_1, t_2, t_3\} \\
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 \end{aligned}$$

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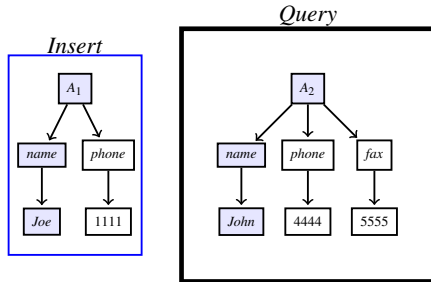
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$$\begin{aligned}
 Delete &= \{t_1, t_2\} \subseteq Query = \{t_1, t_2, t_3\} \\
 \rightarrow Query &= \{t_1, t_2\} \subseteq Delete = \{t_1, t_2, t_3\} \\
 Insert &= \{t_1, t_2\} \subseteq Query = \{t_1, t_2, t_3\} \\
 Query &= \{t_1, t_2\} \subseteq Insert = \{t_1, t_2, t_3\}
 \end{aligned}$$

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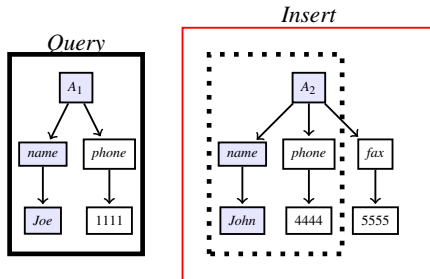
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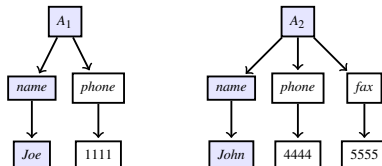
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# Perspective - Query-Update Independence under Schema

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

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

<i>SELECT</i>	$?s$	<i>DELETE</i>	$(?s, ?p, ?o)$
<i>WHERE</i>	$\{(?s, \text{phone}, 1111)\}$	<i>WHERE</i>	$\{(A_4, \text{phone}, ?s)\}$

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

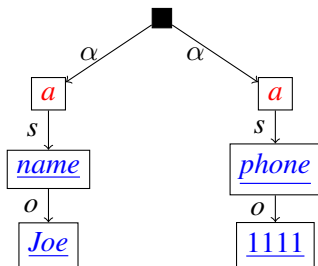
- MSPASS

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

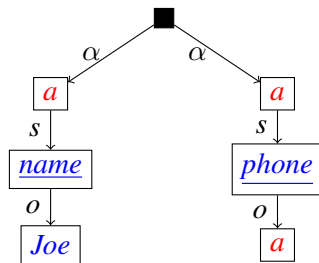
- SPARQL-Algebra

# 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