RDF and SPARQL: Database Foundations

Marcelo Arenas, Claudio Gutierrez, Jorge Pérez

Department of Computer Science
Pontificia Universidad Católica de Chile
Universidad de Chile

Center for Web Research
http://www.cwr.cl/

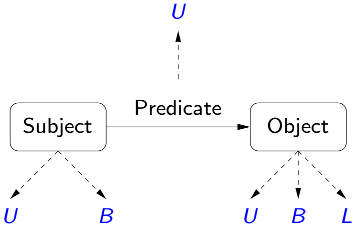
Outline

- Part I: Querying RDF Data
  - The RDF data model
  - Querying: The simple and the ideal
  - Querying: Semantics and Complexity
- Part II: Querying Data with SPARQL
  - Decisions taken
  - Decisions to be taken
- Conclusions

RDF in a nutshell

- RDF is the W3C proposal framework for representing information in the Web.
- Abstract syntax based on directed labeled graph.
- Schema definition language (RDFS): Define new vocabulary (typing, inheritance of classes and properties).
- Extensible URI-based vocabulary.
- Support use of XML schema datatypes.
- Formal semantics.

RDF formal model



U = set of Uris

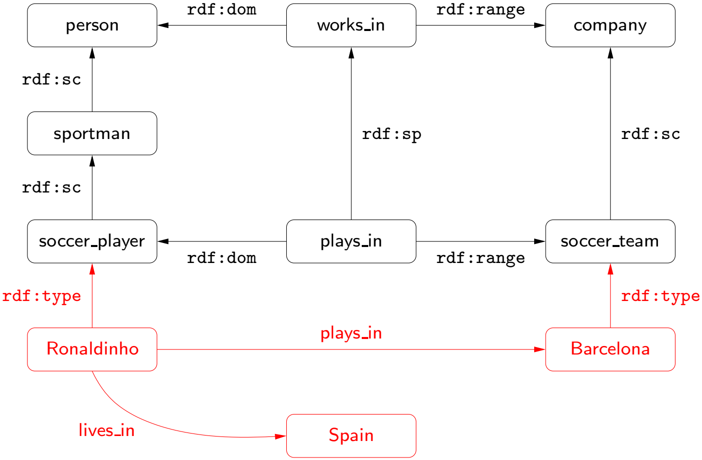
B = set of Blank nodes

L = set of Literals

$(s, p, o) \in (U \cup B) \times U \times (U \cup B \cup L)$ is called an RDF triple

A set of RDF triples is called an RDF graph

RDFS: An example



RDF model

Some difficulties:

- Existential variables as datavalues
- Built-in vocabulary with fixed semantics (RDFS)
- Graph model where nodes may also be edge labels

RDF data processing can take advantage of database techniques:

- Query processing
- Storing
- Indexing

Entailment of RDF graphs

Entailment of RDF graphs:

- Can be defined in terms of classical notions such model, interpretation, etc
  - As for the case of first order logic
- Has a graph characterization via homomorphisms.

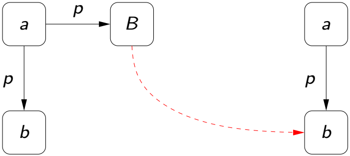
Homomorphism

A function $h : U \cup B \cup L \rightarrow U \cup B \cup L$ is a homomorphism h from G_1 to G_2 if:

- $h(c) = c$ for every $c \in U \cup L$;
- for every $(a, b, c) \in G_1$, $(h(a), h(b), h(c)) \in G_2$

Notation: $G_1 \rightarrow G_2$

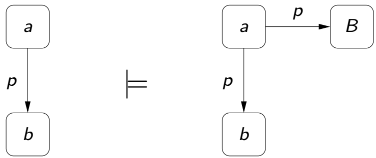
Example: $h = \{B \mapsto b\}$



Entailment

Theorem (CM77)

$G_1 \models G_2$ if and only if there is a homomorphism $G_2 \rightarrow G_1$.

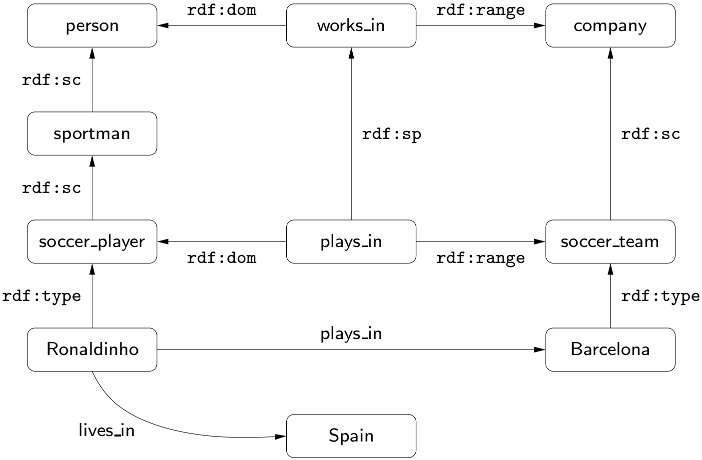


Complexity

Entailment for RDF is NP-complete

Graphs with RDFS vocabulary

Previous characterization of entailment is not enough to deal with RDFS vocabulary: $(\mathtt{Ronaldinho}, \mathtt{rdf:type}, \mathtt{person})$



Graphs with RDFS vocabulary

Built-in predicates have pre-defined semantics:

`rdf:sc`: transitive

`rdf:sp`: transitive

More complicated interactions: $\dfrac{(p, \texttt{rdf:dom}, c) \quad (a, p, b)}{(a, \texttt{rdf:type}, c)}$

RDFS-entailment can be characterized by a set of rules

- An Existential rule
- Subproperty rules
- Subclass rules
- Typing rules
- Implicit typing

Graphs with RDFS vocabulary: Inference rules

Inference system in [MPG07] has 14 rules:

Existential rule : $\frac{G_1}{G_2}$ if $G_2 \rightarrow G_1$

Subproperty rules : $\frac{(p, \texttt{rdf:sp}, q) \quad (a, p, b)}{(a, q, b)}$

Subclass rules : $\frac{(a, \texttt{rdf:sc}, b) \quad (b, \texttt{rdf:sc}, c)}{(a, \texttt{rdf:sc}, c)}$

Typing rules : $\frac{(p, \texttt{rdf:dom}, c) \quad (a, p, b)}{(a, \texttt{rdf:type}, c)}$

Implicit typing : $\frac{(q, \texttt{rdf:dom}, a) \quad (p, \texttt{rdf:sp}, q) \quad (b, p, c)}{(b, \texttt{rdf:type}, a)}$

RDFS Entailment

Theorem (H04,GHM04,MPG07)

$G_1 \models G_2$ iff there is a proof of G_2 from G_1 using the system of 14 inference rules.

Complexity

RDFS-entailment is NP-complete.

Proof idea

Membership in NP: If $G_1 \models G_2$, then there exists a polynomial-size proof of this fact.

Closure of an RDF Graph

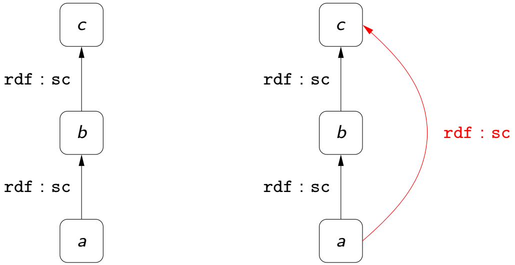
Notation:

$\text{ground}(G)$	:	Graph obtained by replacing every blank B in G by a constant c_B.
$\text{ground}^{-1}(G)$	:	Graph obtained by replacing every constant c_B in G by B.

Closure of an RDF graph G (denoted by $\text{closure}(G)$):

$$G \cup \{t \in (U \cup B) \times U \times (U \cup B \cup L) \mid \text{there exists a ground tuple } t' \text{ such that } \text{ground}(G) \models t' \text{ and } t = \text{ground}^{-1}(t')\}$$

Closure of an RDF Graph: Example



Closure of an RDF graph: complexity

Proposition (H04,GHM04,MPG07)

$G_1 \models G_2$ *iff* $G_2 \rightarrow \mathit{closure}(G_1)$

Complexity

The closure of G can be computed in time $O(|G|^4 \cdot \log |G|)$.

Can the closure be used in practice?

- Can we use an alternative materialization?
- Can we materialize a small part of the closure?

Core of an RDF Graph

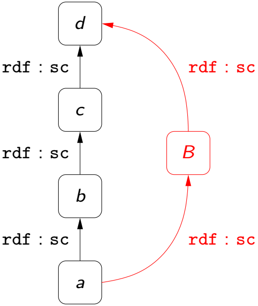
An RDF Graph G is a *core* if there is no homomorphism from G to a proper subgraph of it.

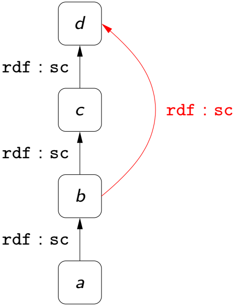
Theorem (HN92,FKP03,GHM04)

- *Each RDF graph G has a unique core (denoted by $\text{core}(G)$).*
- *Deciding if G is a core is coNP-complete.*
- *Deciding if $G = \text{core}(G')$ is DP-complete.*

Core and RDFS

For RDF graphs with RDFS vocabulary, the core of G may contain redundant information:





A normal form for RDF graphs

To reduce the size of the materialization, we can combine both core and closure.

- $\text{nf}(G) = \text{core}(\text{closure}(G))$

Theorem (GHM04)

- G_1 *is equivalent to* G_2 *iff* $nf(G_1) \cong nf(G_2)$.
- $G_1 \models G_2$ *iff* $G_2 \rightarrow nf(G_1)$

Complexity

The problem of deciding if $G_1 = nf(G_2)$ *is DP-complete.*

Querying RDF data: Desiderata

Let D be a database, Q a query, and $Q(D)$ the answer.

- Outputs should belong to the same family of objects as inputs
- If $D \equiv D'$, then $Q(D) = Q(D')$
  (Weaker) If $D \equiv D'$, then $Q(D) \cong Q(D')$
- $Q(D)$ should have no (or minimal) redundancies
- The framework should be extensible to RDFS
  (Should the framework be extensible to OWL?)
- Incorporate to the framework the notion of entailment

Querying RDF data: Desiderata

Outputs should belong to the same family of objects as inputs

- Allows compositionality of queries
- Allows defining views
- Allows rewriting

In RDF, the natural objects of input/output are RDF graphs.

Querying RDF data: Desiderata

If $D \equiv D'$, then $Q(D) = Q(D')$
(Weaker) If $D \equiv D'$, then $Q(D) \cong Q(D')$

- Outputs are syntactic or semantic objects?
- Need a notion of "equivalent" databases ($\equiv$)
  (In RDF, there is a standard notion of logical equivalence)
- One could just ask logical equivalence in the output
- In RDF there is an intermediate notion: graph isomorphism

Querying RDF data: Desiderata

$Q(D)$ should have no (or minimal) redundancies

- Desirable to avoid inconsistencies
- Desirable to improve processing time and space
- Standard requirement for exchange information

Querying RDF data: Desiderata

The framework should be extensible to RDFS
(Should the framework be extensible to OWL?)

- A basic requirement of the Semantic Web Architecture
- Extension to OWL are not trivial because of the known mismatch
- Not necessarily related to the type of semantics given (logical framework, graph matching, etc.)

Querying RDF data: Desiderata

Incorporate to the framework the notion of entailment

- RDF graphs are not purely syntactic objects
- Would like to incorporate KB framework
- Beware of the complexity issues! RDF navigates on the Web
- Find the good compromise

A conjunctive query Q is a pair of RDF graphs H, B where some resources have been replaced by variables $\bar{X}, \bar{Y}$ in V.

$$Q: \quad H(\bar{X}) \leftarrow B(\bar{X}, \bar{Y})$$

Issues:

- Free variables in B (projection)
- Treatment of blank nodes in B
- Treatment of blank nodes in H

Querying RDF data: Definitions (cont.)

A valuation is a function $v : V \to U \cup B \cup L$

A matching of a graph B in the database D is a valuation v such that $v(B) \subseteq D$.

A pre-answer to Q over D is the set

$$preans(Q, D) = \{v(H) : \ v \text{ is a matching of } B \text{ in } D \ \}$$

A single answer is an element of $preans(Q, D)$

Querying RDF data: Two semantics

Union: answer $Q(D)$ is the union of all single answers

$$ans_U(Q, D) = \bigcup preans(Q, D)$$

Merge: answer $Q(D)$ is the merge of all single answers

$$ans_M(Q, D) = \biguplus preans(Q, D)$$

Proposition

1. *For both semantics, if $D \models D'$ then $ans(Q, D') \models ans(Q, D)$*
2. *For all D, $ans_U(Q, D) \models ans_M(Q, D)$*
3. *With merge semantics, we cannot represent the identity query*

Querying RDF data: refined semantics

Problem

Two non-isomorphic datasets D, D' give different answers to the same query.

A slightly refined semantics:

1. Normalize D before querying
2. Then query as usual over $nf(D)$

Good News: if $D \equiv D'$ then $Q(D) \cong Q(D')$
Bad News: computing $nf(D)$ is hard

Querying RDF data: refined semantics (cont.)

The news as formal results:

Theorem (MPG07)

Do not need to compute the normal form.

Theorem (FG06)

If a query language has the following two properties:

1. *for all Q, if $D \equiv D'$ then $Q(D) = Q(D')$,*
2. *can represent the identity query,*

then the complexity of evaluation is NP-hard (in data complexity).

Querying RDF data: Containment

A query Q contains a query Q, denoted $Q \sqsubseteq Q'$ iff $ans(Q, D)$ comprises all the information of $ans(Q', D)$.

In classical DB: $ans(Q, D) \subseteq ans(Q', D)$

In our setting we have two versions:

- $ans(Q', D) \subseteq ans(Q, D) \quad (Q \sqsubseteq_p Q')$
- $preans(Q, D) \subseteq preans(Q', D)$ (modulo iso) $(Q \sqsubseteq_m Q')$

For ground RDF both notions coincide.

Querying RDF data: Complexity

Query complexity version: The evaluation problem is NP-complete

Data complexity version: The evaluation problem is polynomial

Querying with SPARQL

- SPARQL is the W3C candidate recommendation query language for RDF.
- SPARQL is a graph-matching query language.
- A SPARQL query consists of three parts:
  - Pattern matching: optional, union, nesting, filtering.
  - Solution modifiers: projection, distinct, order, limit, offset.
  - Output part: construction of new triples, ...

Recall the formalization from Unit-2

Syntax:

- Triple patterns: RDF triple + variables (no bnodes)
- Operators between triple patterns: AND, UNION, OPT.
- Filtering of solutions: FILTER.
- A full parenthesized algebra.

Recall the formalization from Unit-2

Semantics:

- Based on mappings, partial functions from variables to terms.
- A mapping μ is a solution of triple pattern t in G iff
  - $\mu(t) \in G$
  - $\mathrm{dom}(\mu) = \mathrm{var}(t)$.
- $[\![t]\!]_G$ is the evaluation of t in G, the set of solutions.

Example

G:

$(R_1, \text{name}, \text{john})$
$(R_1, \text{email}, \text{J@ed.ex})$
$(R_2, \text{name}, \text{paul})$

t:

$(?X, \text{name}, ?Y)$

$[\![t]\!]_G$:

	$?X$	$?Y$
μ_1:	R_1	john
μ_2:	R_2	paul

Compatible mappings

Definition

Two mappings are compatible if they agree in their shared variables.

Example

	?X	?Y	?Z	?V
μ_1 :	R_1	john		
μ_2 :	R_1		J@edu.ex	
μ_3 :			P@edu.ex	R_2
$\mu_1 \cup \mu_2$:	R_1	john	J@edu.ex	
$\mu_1 \cup \mu_3$:	R_1	john	P@edu.ex	R_2

- μ_2 and μ_3 are not compatible

Sets of mappings and operations

Let M_1 and M_2 be sets of mappings:

Definition

Join: $M_1 \bowtie M_2$

- extending mappings in M_1 with compatible mappings in M_2

Difference: $M_1 \smallsetminus M_2$

- mappings in M_1 that cannot be extended with mappings in M_2

Union: $M_1 \cup M_2$

- mappings in M_1 plus mappings in M_2 (set theoretical union)

Definition

Left Outer Join: $M_1 ⟕ M_2 = (M_1 \bowtie M_2) \cup (M_1 \smallsetminus M_2)$

Semantics of general graph patterns

Definition

Given a graph G the evaluation of a pattern is recursively defined

- $[\![(P_1 \text{ AND } P_2)]\!]_G = [\![P_1]\!]_G \bowtie [\![P_2]\!]_G$
- $[\![(P_1 \text{ UNION } P_2)]\!]_G = [\![P_1]\!]_G \cup [\![P_2]\!]_G$
- $[\![(P_1 \text{ OPT } P_2)]\!]_G = [\![P_1]\!]_G ⟕ [\![P_2]\!]_G$
- $[\![(P \text{ FILTER } R)]\!]_G = \{\mu \in [\![P]\!]_G \mid \mu \text{ satisfies } R\}$

Differences with Relational Algebra / SQL

- Not a fixed output schema
  - mappings instead of tables
  - schema is implicit in the domain of mappings
- Too many NULLs
  - mappings with disjoint domains can be joined
  - mappings with distinct domains in output solutions
- SPARQL-to-SQL translations experience this issues
  - need of `IS NULL`/`IS NOT NULL` in join/outerjoin conditions
  - need of `COALESCE` in constructing output schema

SPARQL complexity: the evaluation problem

Input:

A mapping μ, a graph pattern P, and an RDF graph G.

Question:

Is the mapping in the evaluation of the pattern against the graph?

$$\mu \in [\![P]\!]_G?$$

Evaluation of AND-FILTER patterns is polynomial.

Theorem (PAG06)

For patterns using only AND *and* FILTER *operators, the evaluation problem is polynomial:*

$$O(|P| \times |G|).$$

Proof idea

- *Check that the mapping makes every triple to match.*
- *Then check that the mapping satisfies the* FILTERs*.*

Evaluation including UNION is NP-complete.

Theorem (PAG06)

For patterns using AND, FILTER *and* UNION *operators, the evaluation problem is NP-complete.*

Proof idea

- *Reduction from 3SAT.*
- *A pattern encodes the propositional formula.*
- $\neg$ bound *is used to encode negation.*

Evaluation including OPT is PSPACE-complete.

Theorem (PAG06)

For patterns using AND, FILTER *and* OPT *operators, the evaluation problem is PSPACE-complete.*

Proof idea

- *Reduction from QBF*
- *A pattern encodes a quantified propositional formula:*

$$\forall x_1 \exists y_1 \forall x_2 \exists y_2 \cdots \psi.$$

- *nested* OPT*s are used to encode quantifier alternation.*

  (This time, we do not need $\neg$ bound.*)*

PSPACE-hardness: A closer look

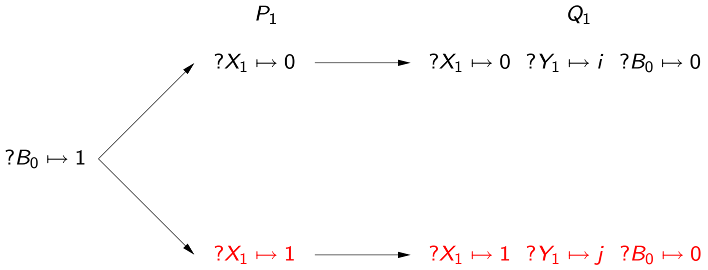
Assume $\varphi = \forall x_1 \exists y_1\, \psi$, where $\psi = (x_1 \vee \neg y_1) \wedge (\neg x_1 \vee y_1)$.

We generate G, P_φ and μ_0 such that μ_0 belongs to the answer of P_φ over G iff φ is valid:

$$
\begin{array}{lcl}
G & : & \{(a, \mathtt{tv}, 0),\ (a, \mathtt{tv}, 1),\ (a, \mathtt{false}, 0),\ (a, \mathtt{true}, 1)\} \\
 & & \\
P_\psi & : & ((a, \mathtt{tv}, ?X_1)\ \text{AND}\ (a, \mathtt{tv}, ?Y_1))\ \text{FILTER} \\
 & & ((?X_1 = 1 \vee ?Y_1 = 0) \wedge (?X_1 = 0 \vee ?Y_1 = 1)) \\
P_\varphi & : & (a, \mathtt{true}, ?B_0)\ \text{OPT}\ (P_1\ \text{OPT}\ (Q_1\ \text{AND}\ P_\psi)) \\
 & & \\
\mu_0 & : & \{?B_0 \mapsto 1\}
\end{array}
$$

PSPACE-hardness: A closer look

$$
\begin{array}{lcl}
P_\varphi & : & (a, \texttt{true}, ?B_0) \ \text{OPT} \ (P_1 \ \ \text{OPT} \ (Q_1 \ \ \text{AND} \ \ P_\psi)) \\
P_1 & : & (a, \texttt{tv}, ?X_1) \\
Q_1 & : & (a, \texttt{tv}, ?X_1) \ \text{AND} \ (a, \texttt{tv}, ?Y_1) \ \text{AND} \ (a, \texttt{false}, ?B_0)
\end{array}
$$



Data–complexity is polynomial

Theorem (PAG06)

When patterns are consider to be fixed (data complexity), the evaluation problem is in LOGSPACE.

Proof idea

From data–complexity of first–order logic.

SPARQL reordering/optimization: a simple normal from

- AND and UNION are commutative and associative.
- AND, OPT, and FILTER distribute over UNION.

Theorem (UNION Normal Form)

Every graph pattern is equivalent to one of the form

$$P_1 \text{ UNION } P_2 \text{ UNION } \cdots \text{ UNION } P_n$$

where each P_i is UNION–free.

We concentrate in UNION-free patterns.

Well–designed patterns

Definition

A graph pattern is well–designed iff for every OPT in the pattern

$$(\cdots\cdots\cdots \quad (\quad A \quad \text{OPT} \quad B \quad) \quad \cdots\cdots\cdots)$$
$$\quad\uparrow \qquad\qquad \uparrow \qquad\qquad \uparrow \qquad\qquad \uparrow$$

if a variable occurs inside B and anywhere outside the OPT, then the variable must also occur inside A.

Example

$(\; (\; (?Y, \text{name}, \text{paul}) \text{ OPT } (?X, \text{email}, ?Z) \;) \quad \text{AND} \quad (?X, \text{name}, \text{john}) \;)$

$\quad\quad\times \qquad\qquad\qquad \uparrow \qquad\qquad\qquad\qquad \uparrow$

Well–designed patterns and PSPACE-hardness

In the PSPACE-hardness reduction we use this formula:

$$
\begin{array}{lcl}
P_\varphi & : & (a, \texttt{true}, ?B_0) \text{ OPT } (P_1 \text{ OPT } (Q_1 \text{ AND } P_\psi)) \\
P_1 & : & (a, \texttt{tv}, ?X_1) \\
Q_1 & : & (a, \texttt{tv}, ?X_1) \text{ AND } (a, \texttt{tv}, ?Y_1) \text{ AND } (a, \texttt{false}, ?B_0)
\end{array}
$$

It is not well-designed: B_0

Well–designed patterns: reordering/optimization

For well-designed patterns

- P_1 AND $(P_2$ OPT $P_3) \equiv (P_1$ AND $P_2)$ OPT P_3
- $(P_1$ OPT $P_2)$ OPT $P_3 \equiv (P_1$ OPT $P_3)$ OPT P_2

Theorem (OPT Normal Form)

Every well–designed pattern is equivalent to one of the form

$$(\cdots(\, t_1 \text{ AND } \cdots \text{ AND } t_k\,) \text{ OPT } O_1\,)\cdots) \text{ OPT } O_n\,)$$

where each t_i is a triple pattern, and each O_j is a pattern of the same form.

Final remarks

- RDFS can be considered a new data model.
  - It is the W3C's recommendation for describing Web metadata.
- RDFS can definitely benefit from database technology.
  - RDFS: Formal semantics, entailment of RDFS graphs, normal forms for RDFS graphs (closure and core).
  - SPARQL: Formal semantics, complexity of query evaluation, query optimization.
  - Updating
  - ...

References

- A. Chandra, P. Merlin, *Optimal Implementation of Conjunctive Queries in Relational Databases*. In *STOC* 1977.
- R. Fagin, P. Kolaitis, L. Popa, *Data Exchange: Getting to the Core*. In *PODS* 2003.
- C. Gutierrez, C. Hurtado, A. O. Mendelzon, *Foundations of Semantic Web Databases*. In *PODS* 2004.
- P. Hayes, *RDF Semantics*. W3C Recommendation 2004.
- P. Hell, J. Nesetril, *The Core of a Graph*. *Discrete Mathematics* 1992.
- S. Muñoz, J. Pérez, C. Gutierrez, *Minimal Deductive Systems for RDF*. In *ESWC* 2007.
- J. Pérez, M. Arenas, C. Gutierrez, *Semantics and Complexity of SPARQL*. In *ISWC* 2006.