Integrating Description Logics and Rules for the Semantic Web

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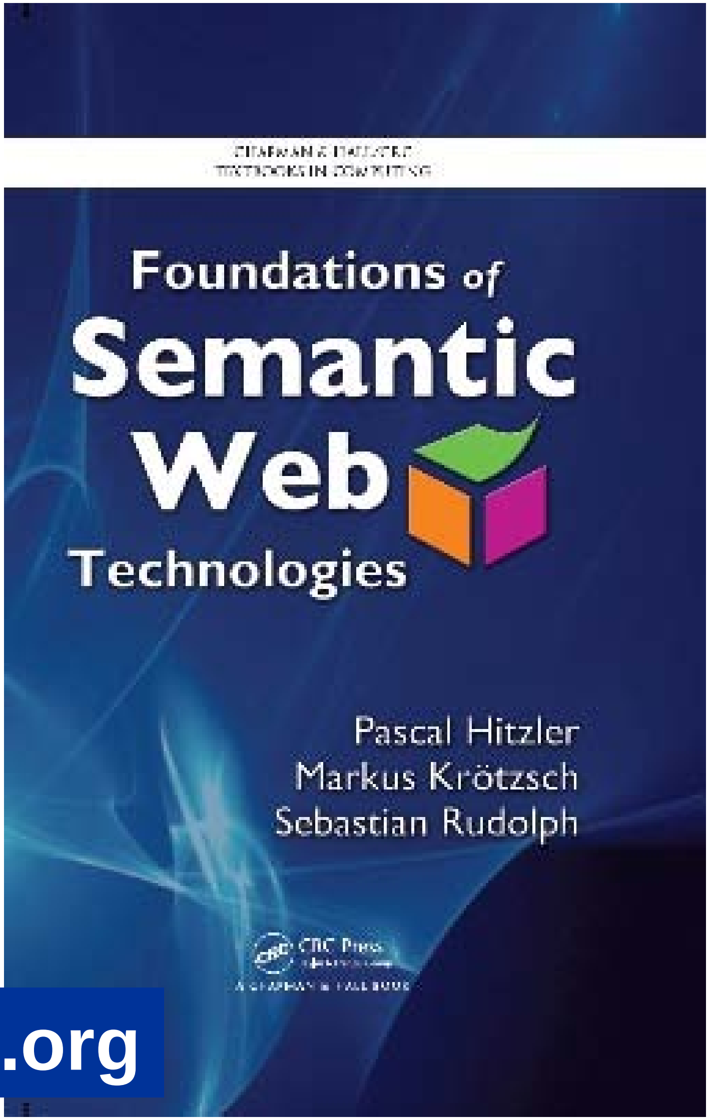
Introduction to key foundations

Pascal Hitzler, Markus Krötzsch, Sebastian Rudolph

Foundations of Semantic Web Technologies

Chapman & Hall/CRC, 2010

Choice Magazine Outstanding Academic Title 2010 (one out of seven in Information & Computer Science)



http://www.semantic-web-book.org

Textbook (Chinese translation)

Pascal Hitzler, Markus Krötzsch, Sebastian Rudolph

语义Web技术基础

Tsinghua University Press (清华大学出版社），2012, to appear

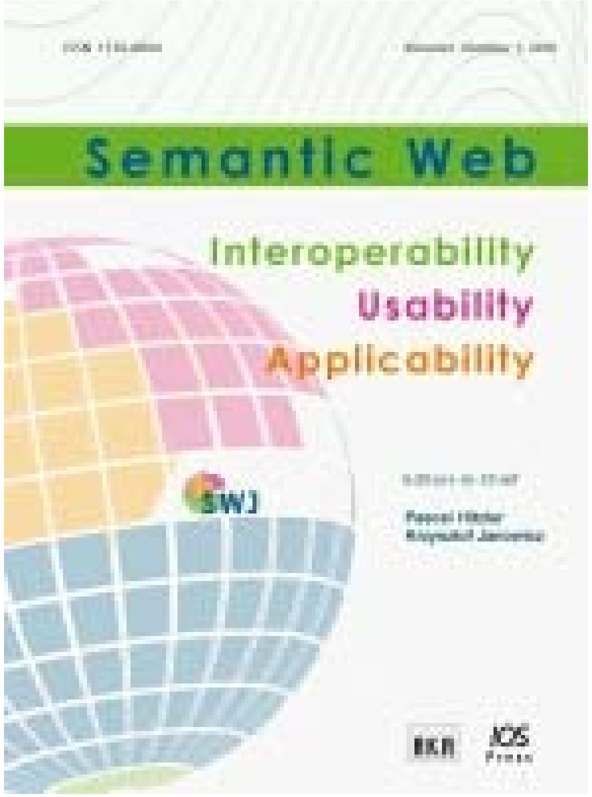
Translators:

Yong Yu, Haofeng Wang, Guilin Qi (俞勇，王昊奋，漆桂林)

http://www.semantic-web-book.org

Semantic Web journal

- **EiCs:** **Pascal Hitzler**
  Krzysztof Janowicz



- **New journal with significant initial uptake.**
- **We very much welcome contributions at the “rim” of traditional Semantic Web research – e.g., work which is strongly inspired by a different field.**
- **Non-standard (open & transparent) review process.**

- **http://www.semantic-web-journal.net/**

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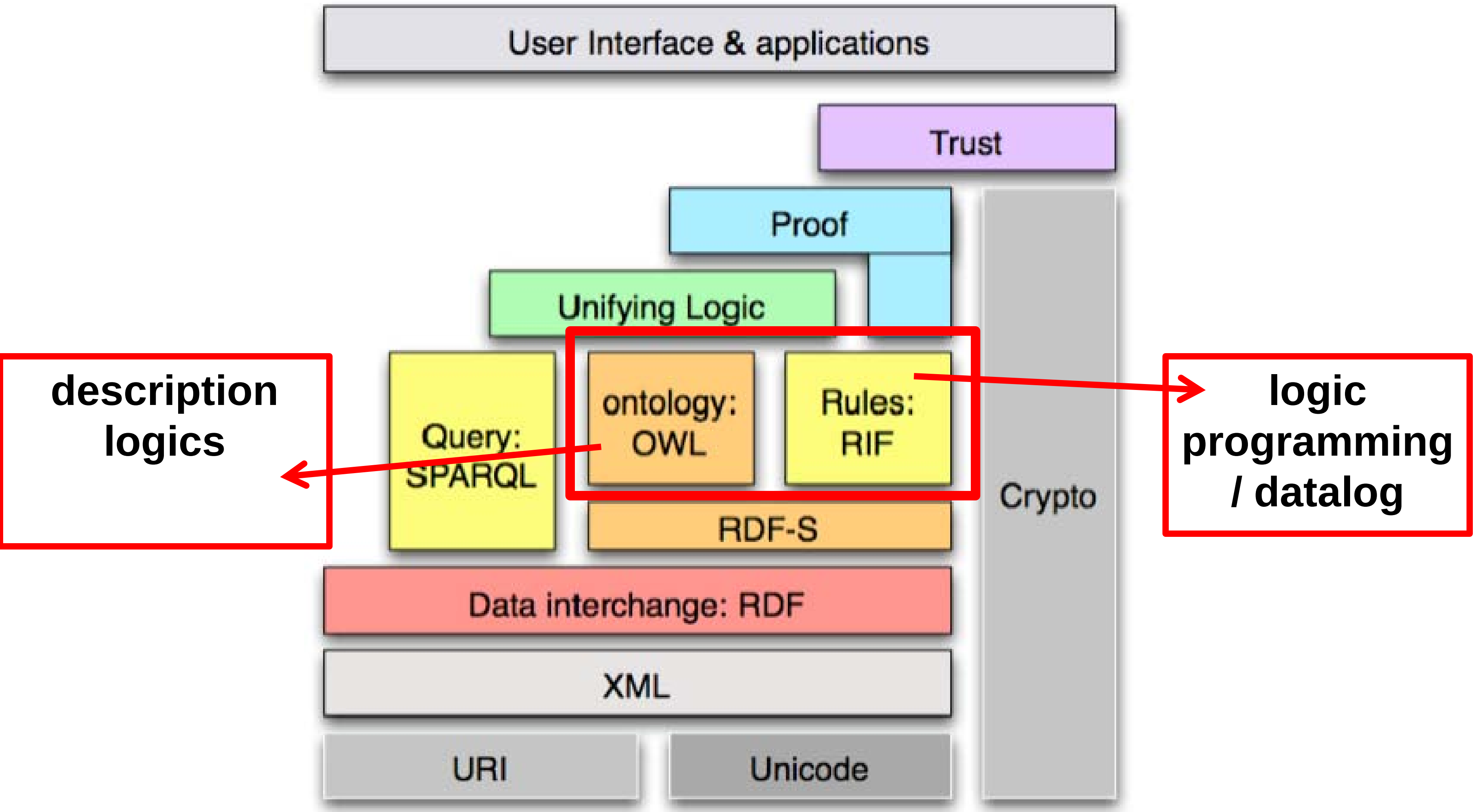
Semantic Web

Pursues the vision of making information on the web available for intelligent processing.

Uses many methods from different fields in AI / CS.

Knowledge representation and reasoning (using so-called ontology languages) is a key component of the approach.

Semantic Web Technology Stack



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Rules

$$A(x) \wedge R(x,y) \wedge S(y,z) \wedge B(z) \rightarrow C(x)$$

$$\mathrm{Elephant}(x) \wedge \mathrm{Mouse}(y) \rightarrow \mathrm{biggerThan}(x,y)$$

$$\mathrm{worksAt}(x,y) \wedge \mathrm{University}(y) \wedge \mathrm{supervises}(x,z) \wedge \mathrm{PhDStudent}(z) \rightarrow \mathrm{professorOf}(x,z)$$

$$\mathrm{hasReviewAssignment}(v,x) \wedge \mathrm{hasAuthor}(x,y) \wedge \mathrm{atVenue}(x,z) \wedge \mathrm{hasSubmittedPaper}(v,u) \wedge \mathrm{hasAuthor}(u,y) \wedge \mathrm{atVenue}(u,z) \rightarrow \mathrm{hasConflictingAssignedPaper}(v,x)$$

Rules to DL conversion

$$A(x) \wedge R(x,y) \wedge S(y,z) \wedge B(z) \rightarrow C(x)$$

$$A \sqcap \exists R.\exists S.B \sqsubseteq C$$

$$\text{Elephant}(x) \wedge \text{Mouse}(y) \rightarrow \text{biggerThan}(x,y)$$

$$\text{Elephant} \equiv \exists R_{\text{Elephant}}.\text{Self}$$
$$\text{Mouse} \equiv \exists R_{\text{Mouse}}.\text{Self}$$
$$R_{\text{Elephant}} \circ U \circ R_{\text{Mouse}} \sqsubseteq \text{biggerThan}$$

Rules to DL conversion

$$\text{worksAt}(x,y) \wedge \text{University}(y) \wedge \text{supervises}(x,z) \wedge \text{PhDStudent}(z) \rightarrow \text{professorOf}(x,z)$$

$$R_{\exists\text{worksAt.University}} \circ \text{supervises} \circ R_{\text{PhDStudent}} \sqsubseteq \text{professorOf}.$$

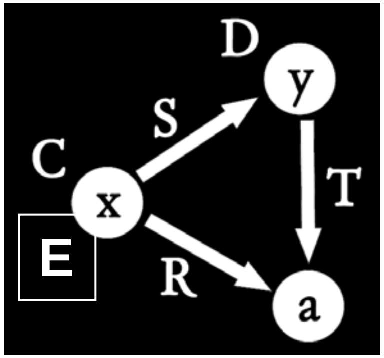
But we can’t express the following in SROIQ:

$$\text{hasReviewAssignment}(v,x) \wedge \text{hasAuthor}(x,y) \wedge \text{atVenue}(x,z) \wedge \text{hasSubmittedPaper}(v,u) \wedge \text{hasAuthor}(u,y) \wedge \text{atVenue}(u,z) \rightarrow \text{hasConflictingAssignedPaper}(v,x)$$

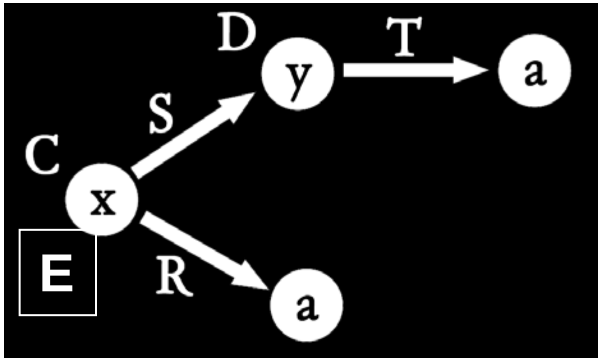
So how can we pinpoint this?

- **Tree-shaped bodies**
- **First argument of the conclusion is the root**

- **$C(x) \wedge R(x,a) \wedge S(x,y) \wedge D(y) \wedge T(y,a) \rightarrow E(x)$**
  - **$C \sqcap \exists R.\{a\} \sqcap \exists S.(D \sqcap \exists T.\{a\}) \sqsubseteq E$**



duplicating nominals is ok

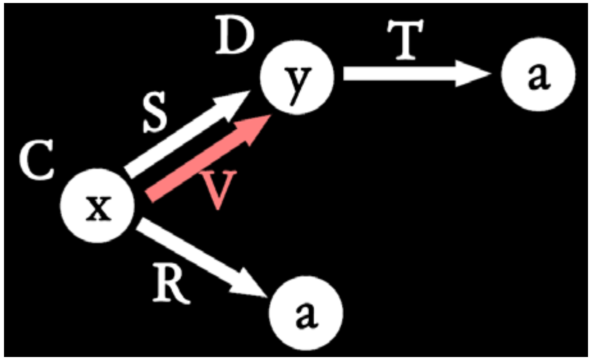


So how can we pinpoint this?

- **Tree-shaped bodies**
- **First argument of the conclusion is the root**

- $C(x) \wedge R(x,a) \wedge S(x,y) \wedge D(y) \wedge T(y,a) \rightarrow V(x,y)$

  $C \sqcap \exists R.\{a\} \sqsubseteq \exists R1.Self$
  $D \sqcap \exists T.\{a\} \sqsubseteq \exists R2.Self$
  $R1 \circ S \circ R2 \sqsubseteq V$



Rule bodies as graphs

$$C(x) \wedge R(x,a) \wedge S(x,y) \wedge D(y) \wedge T(y,a) \rightarrow P(x,y)$$

$$a_1 \longleftarrow x \longrightarrow y \longrightarrow a_2$$

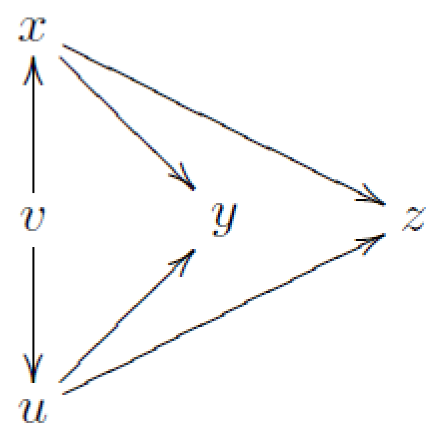
C ⊓ ∃R.{a} ⊑ ∃R1.Self

D⊓ ∃T.{a}) ⊑ ∃R2.Self

R1 ∘ S ∘ R2 ⊑ P

Rule bodies as graphs

$$\mathrm{hasReviewAssignment}(v,x) \wedge \mathrm{hasAuthor}(x,y) \wedge \mathrm{atVenue}(x,z)$$
$$\wedge\ \mathrm{hasSubmittedPaper}(v,u) \wedge \mathrm{hasAuthor}(u,y) \wedge \mathrm{atVenue}(u,z)$$
$$\rightarrow \mathrm{hasConflictingAssignedPaper}(v,x)$$



with y,z constants:

$$R_{\exists \mathrm{hasSubmittedPaper}.(\exists \mathrm{hasAuthor}.\{y\} \sqcap \exists \mathrm{atVenue}.\{z\})} \circ \mathrm{hasReviewAssignment}$$
$$\circ\ R_{\exists \mathrm{hasAuthor}.\{y\} \sqcap \exists \mathrm{atVenue}.\{z\}}$$
$$\sqsubseteq \mathrm{hasConflictingAssignedPaper}$$

Formally

Given a rule with body B, we construct a directed graph as follows:

1. **Rename individuals (i.e., constants) such that each individual occurs only once – a body such as R(a,x) ∧ S(x,a) becomes R(a1,x) ∧ S(x,a2). Denote the resulting new body by B'.**
2. **The vertices of the graph are then the variables and individuals occurring in B', and there is a directed edge between t and u if and only if there is an atom R(t,u) in B'.**

$$C(x) \land R(x,a) \land S(x,y) \land D(y) \land T(y,a) \rightarrow P(x,y)$$

$$a_1 \longleftarrow x \longrightarrow y \longrightarrow a_2$$

Formally

Definition 1. *We call a rule with head H* tree-shaped *(respectively,* acyclic*), if the following conditions hold.*

– *Each of the maximally connected components of the corresponding graph is in fact a tree (respectively, an acyclic graph)—or in other words, if it is a* forest, *i.e., a set of trees (respectively, a set of acyclic graphs).*
– *If H consists of an atom $A(t)$ or $R(t,u)$, then t is a root in the tree (respectively, in the acyclic graph).*

$$R(x,z) \wedge S(y,z) \rightarrow T(x,y) \text{ is acyclic but not tree-shaped}$$

Theorem 1. *The following hold.*

– *Every tree-shaped rule can be expressed in $\mathcal{SROEL}$.*
– *Every acyclic rule can be expressed in $\mathcal{SROIEL}$.*

The regularity issue

$hasChild(x,y) \wedge female(y) \rightarrow hasDaughter(x,y)$

$hasDaughter(x,y) \rightarrow hasChild(x,y)$

Each of these is representable in SROIQ, but together they are not.

We need to weaken regularity requirements!

Rule representation wish list

- class conjunctions
- role chains (without regularity constraint)
- existential quantifier
- inverse roles
- universal role
- nominals
- Self construct

Seems this is SROIEL.

How much can we push decidability?

Some form of negation would be really nice for modeling class disjointness.

Extending ERI

- **ERI: existential, role chains, inverse roles**

The following two can be shown by reduction of the domino problem.

- **ERI(¬) is undecidable**
- **ERI(⊔,⊥) is undecidable**

However, the following works:

- **SROIEL(⊥) is decidable, even after dropping the regularity condition.**

[David Carral Martinez, Cong Wang, H, in preparation]

SROIEL(⊓,⊥)

I.e., adding unrestricted role conjunction.

SROIEL(⊓,⊥) is decidable, and

- **covers ELP [Krötzsch, Rudolph, H 2008]**
- **covers the tractable OWL profiles**
  OWL EL (SROEL)
  OWL QL (DL Lite$_R$)
  OWL RL (naïve rules fragment)

- **We also have the “logical” fragment of RDF Schema covered (critical are range declarations, which we have via role inverses)**

Why role conjunction?

$$\text{hasFather}(x, y) \wedge \text{hasBrother}(y, z) \wedge \text{hasTeacher}(x, z) \rightarrow \text{TaughtByUncle}(x)$$

is not expressible in SROIEL without role conjunction, but can be expressed with role conjunction as

$$\begin{aligned}
&\text{hasFather} \circ \text{hasBrother} \sqsubseteq \text{hasUncle} \\
&\text{hasUncle} \sqcap \text{hasTeacher} \sqsubseteq \text{hasTeacherAndUncle} \\
&\exists \text{hasTeacherAndUncle}.\top \sqsubseteq \text{TaughtByUncle}
\end{aligned}$$

Coverage of SROIEL(⊓,⊥)

Essentially, all binary rules with

- body such that graph does not contain four (variable) nodes which are connected by paths such that the pattern forms a 4-clique.

[David Carral Martinez, H, ESWC2012]

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Nominal Schemas

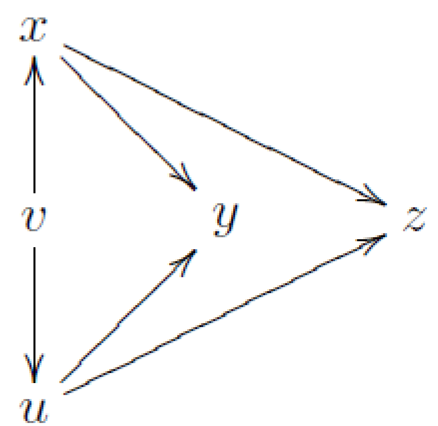
$$\text{hasReviewAssignment}(v,x) \wedge \text{hasAuthor}(x,y) \wedge \text{atVenue}(x,z) \wedge \text{hasSubmittedPaper}(v,u) \wedge \text{hasAuthor}(u,y) \wedge \text{atVenue}(u,z) \rightarrow \text{hasConflictingAssignedPaper}(v,x)$$

assume y,z bind only to named individuals

we introduce a new construct, called

nominal schemas

or *nominal variables*



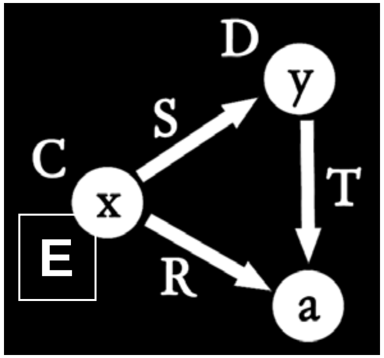
$$R_{\exists\text{hasSubmittedPaper}.(\exists\text{hasAuthor}.\{y\}\sqcap\exists\text{atVenue}.\{z\})} \circ \text{hasReviewAssignment} \circ R_{\exists\text{hasAuthor}.\{y\}\sqcap\exists\text{atVenue}.\{z\}} \sqsubseteq \text{hasConflictingAssignedPaper}$$

DL-safe variables

- **A generalisation of DL-safety of rules.**
- **DL-safe variables are special variables which bind only to named individuals (like in DL-safe rules).**

- **$C(x) \wedge R(x,x_s) \wedge S(x,y) \wedge D(y) \wedge T(y,x_s) \rightarrow E(x)$**
  with x_s a safe variable

  $C(x) \wedge R(x,a) \wedge S(x,y) \wedge D(y) \wedge T(y,a) \rightarrow E(x)$
  can be translated into OWL 2 (SROIQ).



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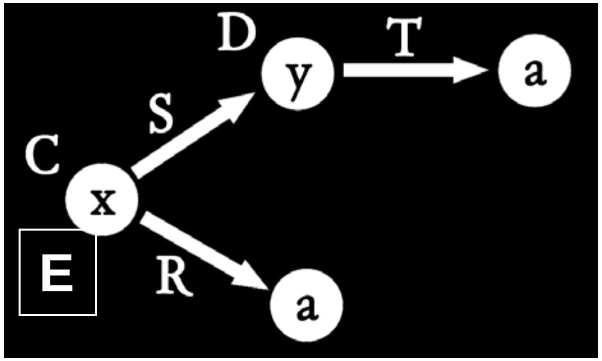

DL-safe variables

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  with x_s a safe variable

  $C(x) \land R(x,a) \land S(x,y) \land D(y) \land T(y,a) \rightarrow E(x)$
  can be translated into OWL 2.

- **with, say, 100 individuals, we would obtain 100 new OWL axioms from the single rule above**

DL-safety

- **DL-safe variables:**
  variables in rules which bind only to named individuals

- **Idea:**
  - **start with rule not expressible in DL**
  - **select some variables and declare them DL-safe such that resulting rule can be translated into several DL axioms**

- ***DL-safe rule:* A rule with only DL-safe variables.**

It is known that "OWL 2 DL + DL-safe rules" is decidable.
It is a *hybrid* formalism.
E.g. OWL plus DL-safe SWRL.

Nominal schema example 2

$$\text{hasChild}(x, y) \wedge \text{hasChild}(x, z) \wedge \text{classmate}(y, z) \rightarrow C(x)$$

$$\exists \text{hasChild}.\{z\} \sqcap \exists \text{hasChild}.\exists \text{classmate}.\{z\} \sqsubseteq C$$

Adding nominal schemas to SROIQ

- **Decidability is retained.**
- **Complexity is *the same*.**

[Krötzsch, Maier, Krisnadhi, H, WWW2011]

- **A naïve implementation is straightforward:**

Replace every axiom with nominal schemas by a set of SROIQ (OWL 2 DL) axioms, obtained from *grounding* the nominal schemas.

**However, this may result in a lot of new axioms.
This naïve approach will probably only work for ontologies with *few* nominal schemas.**

What do we gain?

- **A powerful macro.**
- **We can actually also express *all* DL-safe Datalog rules!**

$$R(x,y) \wedge A(y) \wedge S(z,y) \wedge T(x,z) \rightarrow P(z,x)$$

$$\begin{aligned}
&\exists U.(\{x\} \sqcap \exists R.\{y\}) \\
&\quad \sqcap \exists U.(\{y\} \sqcap A) \\
&\quad \sqcap \exists U.(\{z\} \sqcap \exists S.\{y\}) \\
&\quad \sqcap \exists U.(\{x\} \sqcap \exists T.\{z\}) \\
&\quad \sqsubseteq \exists U.(\{z\} \sqcap \exists P.\{x\})
\end{aligned}$$

(this works similarly for arbitrary arity)

A tractable fragment

Definition 2. *An occurrence of nominal schema* $\{x\}$ *in a concept* C *is* safe *if* C *contains a sub-concept of the form* $\{v\} \sqcap \exists R.D$ *for some nominal schema or nominal* $\{v\}$ *such that* $\{x\}$ *is the only nominal schema that occurs (possibly more than once) in* D*. In this case,* $\{v\} \sqcap \exists R.D$ *is a* safe environment *for this occurrence of* $\{x\}$*, sometimes written as* $S(v, x)$*.*

Definition 3. *Let* $n \geq 0$ *be an integer. A* $\mathcal{SROELV}(\sqcap, \times)$ *knowledge base* KB *is a* $\mathcal{SROELV}_n(\sqcap, \times)$ *knowledge base if in each of its axioms* $C \sqsubseteq D$*, there are at most* n *nominal schemas appearing more than once in non-safe form, and all remaining nominal schemas appear only in* C*.*

$\mathcal{SROELV}_n(\sqcap, \times)$

is tractable (Polytime)
covers OWL 2 EL
covers OWL 2 RL (DL-safe)
covers most of OWL 2 QL

Tractable rules approximation

We saw earlier that SROIEL(⊓) is *the* DL for capturing rules.

However, it is not polytime.

But we can do a polytime *approximation* by removing role inverses:

$R \sqsubseteq S$

becomes

{x}v⊓⊑∃R.{y} ⊑ {y} ⊓ ∃S.{x}.

I.e. we're approximating in $\mathrm{SROELV}_n(\sqcap)$**.**

Polytime smart transformation

$$\exists \text{hasReviewAssignment}.((\{x\} \sqcap \exists \text{hasAuthor}.\{y\}) \sqcap (\{x\} \sqcap \exists \text{atVenue}.\{z\}))$$
$$\sqcap\, \exists \text{hasSubmittedPaper}.(\exists \text{hasAuthor}.\{y\} \sqcap \exists \text{atVenue}.\{z\})$$
$$\sqsubseteq \exists \text{hasConflictingAssignedPaper}.\{x\}$$

becomes (a_i, a_j range over all named individuals)

$$(\exists U.O_y) \sqcap (\exists U.O_z) \sqcap \exists \text{hasReviewAssignment}.(\{a_i\} \sqcap \{a_i\})$$
$$\sqcap\, \exists \text{hasSubmittedPaper}.(\exists \text{hasAuthor}.O_y \sqcap \exists \text{atVenue}.O_z)$$
$$\sqsubseteq \exists \text{hasConflictingAssignedPaper}.\{a_i\}$$

$$\exists U.(\{a_i\} \sqcap \exists \text{hasAuthor}.\{a_j\}) \sqsubseteq \exists U.(\{a_j\} \sqcap O_y)$$
$$\exists U.(\{a_i\} \sqcap \exists \text{atVenue}.\{a_j\}) \sqsubseteq \exists U.(\{a_j\} \sqcap O_z)$$

Nominal Schema Algorithms

For avoiding full grounding, we require *delayed* grounding, i.e., grounding by need at runtime of algorithm.

We have successfully developed:

- SROIQV tableau algorithm
- SROELV ordered resolution algorithm (polytime)

But results need to be published and implemented.

[work in cooperation with Adila Alfa Krisnadhi and Cong Wang]

SROIELV(⊓,⊥)

In SROIELV(⊓,⊥) (i.e., with nominal schemas), we have:

- Every rule with m>3 different variables can be expressed using at most m-2 nominal schemas.
- Every rule with m different free variables can be expressed by fully grounding m-3 variables.

[David Carral Martinez, H, ESWC2012]

Local Closed World

[Knorr, Maier, H 2012]

- Introducing the MKNF DL $\mathcal{SROIQV}(\mathcal{B}^s, \times)\mathcal{K}_{\mathcal{NF}}$
  - decidable (some restrictions on modal operators apply)
  - covers key proposals for local closed world rule+DL:
    - SROIQ (OWL 2 DL) and all tractable profiles
    - RIF-Core (n-ary Datalog) as DL-safe rules
    - DL-safe SWRL
    - $ALCK_{NF}$
    - Closed Reiter and DL defaults [Baader Hollunder 1995]
    - Hybrid MKNF
    - Answer Set Programing
    - AL-log, CARIN, DL+log(?), disjunctive dl-programs

Thanks!

Collaborators on the covered topics

Jose Alferes	UNL Lisboa
David Carral Martinez	Kno.e.sis
Matthias Knorr	UNL Lisboa
Adila Alfa Krisnadhi	Kno.e.sis
Markus Krötzsch	University of Oxford
Frederick Maier	Aston Business School
Sebastian Rudolph	KIT
Cong Wang	Kno.e.sis

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References

Tutorial and overview:

- **Adila A. Krisnadhi, Frederick Maier, Pascal Hitzler, OWL and Rules. In: A. Polleres, C. d'Amato, M. Arenas, S. Handschuh, P. Kroner, S. Ossowski, P.F. Patel-Schneider (eds.), Reasoning Web. Semantic Technologies for the Web of Data. 7th International Summer School 2011, Galway, Ireland, August 23-27, 2011, Tutorial Lectures. Lecture Notes in Computer Science Vol. 6848, Springer, Heidelberg, 2011, pp. 382-415. http://pascal-hitzler.de/resources/publications/OWL-Rules-2011.pdf**

- **Matthias Knorr, David Carral Martinez, Pascal Hitzler, Adila A. Krisnadhi, Frederick Maier, Cong Wang, Recent Advances in Integrating OWL and Rules (Technical Communication). Technical Report, 2012.**

References

Rules in OWL:

- Markus Krötzsch, Sebastian Rudolph, Pascal Hitzler, Description Logic Rules. In: Malik Ghallab, Constantine D. Spyropoulos, Nikos Fakotakis, Nikos Avouris (eds.), Proceedings of the 18th European Conference on Artificial Intelligence, ECAI2008, Patras, Greece, July 2008. IOS Press, 2008, pp. 80-84. http://pascal-hitzler.de/resources/publications/dlrules-ecai08.pdf
- Markus Krötzsch. Description Logic Rules. Studies on the Semantic Web, Vol. 008, IOS Press, 2010. http://www.semantic-web-studies.net/
- David Carral Martinez, Pascal Hitzler, Extending Description Logic Rules. In: Proceedings of the 9th Extended Semantic Web Conference, ESWC2012, Heraklion, Crete, Greece, May 2012.

References

Nominal Schemas:

- Markus Krötzsch, Frederick Maier, Adila Alfa Krisnadhi, Pascal Hitzler, A Better Uncle For OWL – Nominal Schemas for Integrating Rules and Ontologies. In: S. Sadagopan, Krithi Ramamritham, Arun Kumar, M.P. Ravindra, Elisa Bertino, Ravi Kumar (eds.), WWW '11 20th International World Wide Web Conference, Hyderabad, India, March/April 2011. ACM, New York, 2011, pp. 645-654. http://pascal-hitzler.de/resources/publications/WWW2011.pdf
- Matthias Knorr, Pascal Hitzler, Frederick Maier, Reconciling OWL and Non-monotonic Rules for the Semantic Web. Technical Report, 2011.
- Adila Krisnadhi, Pascal Hitzler, A Tableau Algorithm for Description Logics with Nominal Schemas. Technical Report, 2011.
- Cong Wang, Pascal Hitzler, A Tractable Resolution Procedure for $\mathcal{SROELV}_n(\sqcap,\times)$. Technical Report, 2012.

References

Other relevant:

- Markus Krötzsch, Sebastian Rudolph, Pascal Hitzler, ELP: Tractable Rules for OWL 2. In: A.P. Sheth et al. (eds.), Proceedings of the 7th International Semantic Web Conference, ISWC 2008, Karlsruhe, Germany, October 2008. Lecture Notes in Computer Science 5318, pp. 649-664. Springer, 2008.
- Matthias Knorr, Pascal Hitzler, Frederick Maier, Reconciling OWL and non-monotonic rules for the Semantic Web. Technical Report, 2012.
- David Carral Martinez, Adila Alfa Krisnadhi, Pascal Hitzler, Integrating OWL and Rules: A Syntax Proposal for Nominal Schemas. In: Proceedings OWLED2012, to appear.