Knowledge Representation for the Semantic Web

Winter Quarter 2012

Slides 11 – 02/23/2012

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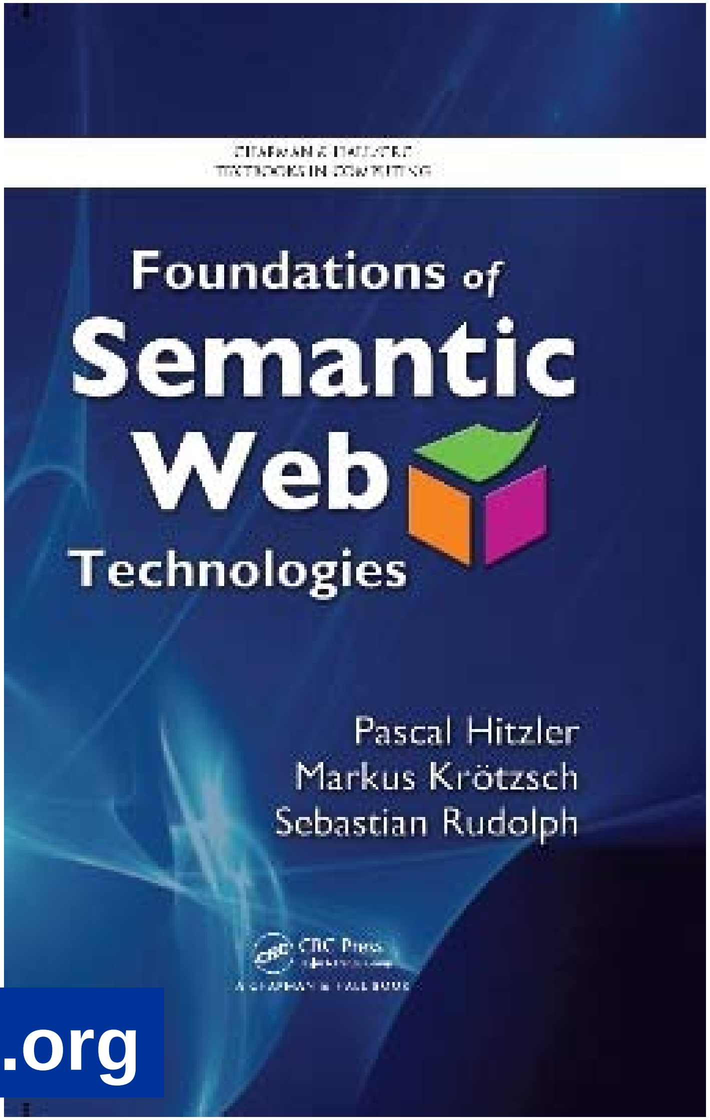
Textbook (required)

Pascal Hitzler, Markus Krötzsch, Sebastian Rudolph

Foundations of Semantic Web Technologies

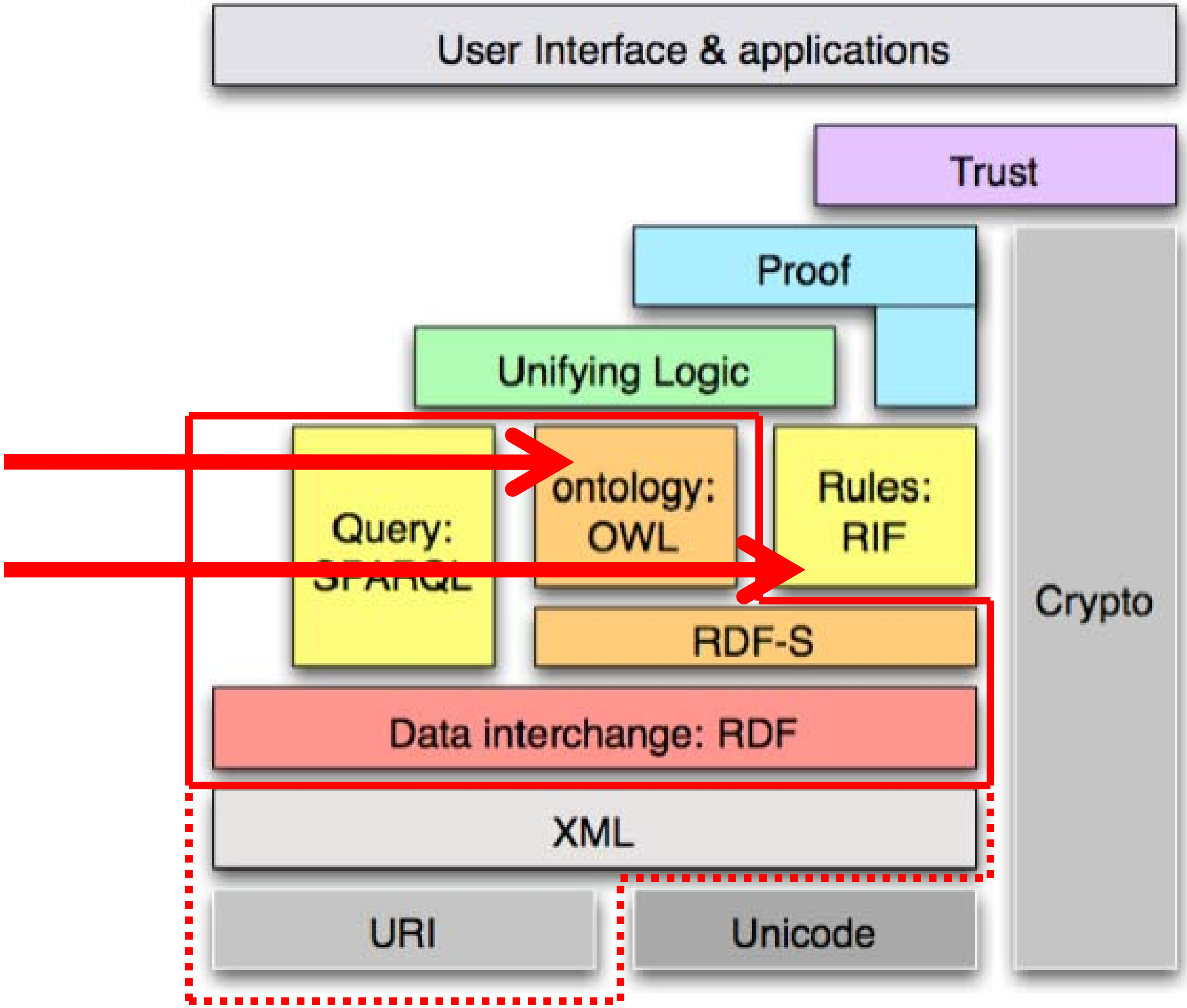
Chapman & Hall/CRC, 2010

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



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

Today: Reasoning with OWL



Contents

Rules

- **Horn Logic, often as Datalog (i.e. without function symbols) and with a modified but related semantics (Herbrand semantics).**

- **Prominent alternative to OWL modeling:**
  - **Rule-based expert systems**
  - **Prolog / Logic Programming**
  - **F-Logic [Kifer, Lausen, Wu, 1995]**
  - **W3C Rule Interchange Format RIF (standard since 2010)**

  - **Often argued to be "more intuitive" for non-logicians and domain experts.**

Modeling with Rules

Orphan(harrypotter)
hasParent(harrypotter,jamespotter)
Orphan(x) ∧ hasParent(x,y) → Dead(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

Usually, of the (syntactic) form

$$A_1 \wedge \ldots \wedge A_n \rightarrow B$$

$$\textbf{body} \rightarrow \textbf{head}$$

where A_i, B are atomic formulas.

Note:

- **no disjunctive conclusions (head)**
- **no existential quantifiers in conclusions (head)**

DLs vs. Rules

- Rules are usually considered to apply only to *known* constants.
- No possibility to "create" new things "on the fly" using ∃.

$$\mathrm{Human} \sqsubseteq \exists \mathrm{hasParent.Human}$$

- If rules are considered FOL formulas,
  then combining rules with ALC
  leads to undecidability.

  [Reduction of some type of domino problem.]

Contents

1. Rules and RIF
2. Rules expressible in OWL
3. Extending OWL with Rules: Nominal Schemas
4. References

Rules in OWL

Which rules can be encoded in OWL?

$$A \sqsubseteq B \text{ becomes } A(x) \rightarrow B(x)$$

$$R \sqsubseteq S \text{ becomes } R(x,y) \rightarrow S(x,y)$$

$$A \sqcap \exists R.\exists S.B \sqsubseteq C \text{ becomes } A(x) \wedge R(x,y) \wedge S(y,z) \wedge B(z) \rightarrow C(x)$$

$$A \sqsubseteq \forall R.B \text{ becomes } A(x) \wedge R(x,y) \rightarrow B(y)$$

Rules in OWL

Which rules can be encoded in OWL?

$$A \sqsubseteq \neg B \sqcup C \text{ becomes } A(x) \land B(x) \rightarrow C(x)$$

$$\top \sqsubseteq \leq 1 R.\top \text{ becomes } R(x,y) \land R(x,z) \rightarrow y = z$$

$$A \sqcap \exists R.\{b\} \sqsubseteq C \text{ becomes } A(x) \land R(x,b) \rightarrow C(x)$$

Rules in OWL

Which rules can be encoded in OWL?

$$\{a\} \equiv \{b\} \text{ becomes } \rightarrow a = b.$$

$$A \sqcap B \sqsubseteq \bot \text{ becomes } A(x) \wedge B(x) \rightarrow f.$$

$$A \sqsubseteq B \wedge C \text{ becomes } A(x) \rightarrow B(x) \text{ and } A(x) \rightarrow C(x)$$

$$A \sqcup B \rightarrow C \text{ becomes } A(x) \rightarrow C(x) \text{ and } B(x) \rightarrow C(x)$$

Rules in OWL

A DL axiom α can be translated into rules if, after translating α into a first-order predicate logic expression α', and after normalizing this expression into a set of clauses M, each formula in M is a Horn clause (i.e., a rule).

Issue: How complicated a translation is allowed?

Naïve translation: DLP
plus some more (since OWL 2 extends OWL 1)

e.g.,

$$R \circ S \sqsubseteq T \text{ becomes } R(x,y) \wedge S(y,z) \rightarrow T(x,z)$$

This essentially results in OWL 2 RL.

Rolification

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

- **Rolification of a concept A:** **$A \equiv \exists R_A.\text{Self}$**

$$\text{Elephant} \equiv \exists R_{\text{Elephant}}.\text{Self}$$

$$\text{Mouse} \equiv \exists R_{\text{Mouse}}.\text{Self}$$

$$R_{\text{Elephant}} \circ U \circ R_{\text{Mouse}} \sqsubseteq \text{biggerThan}$$

Rolification

$$A(x) \wedge R(x,y) \rightarrow S(x,y) \text{ becomes } R_A \circ R \sqsubseteq S$$
$$A(y) \wedge R(x,y) \rightarrow S(x,y) \text{ becomes } R \circ R_A \sqsubseteq S$$
$$A(x) \wedge B(y) \wedge R(x,y) \rightarrow S(x,y) \text{ becomes } R_A \circ R \circ R_B \sqsubseteq S$$

$$\text{Woman}(x) \wedge \text{marriedTo}(x,y) \wedge \text{Man}(y) \rightarrow \text{hasHusband}(x,y)$$

$$R_{\text{Woman}} \circ \text{marriedTo} \circ R_{\text{Man}} \sqsubseteq \text{hasHusband}$$

careful – regularity of RBox needs to be retained:

$$\text{hasHusband} \sqsubseteq \text{marriedTo}$$

Rolification

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

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

Rules in OWL 2

- **$Man(x) \wedge hasBrother(x,y) \wedge hasChild(y,z) \rightarrow Uncle(x)$**
  - **$Man \sqcap \exists hasBrother.\exists hasChild.\top \sqsubseteq Uncle$**

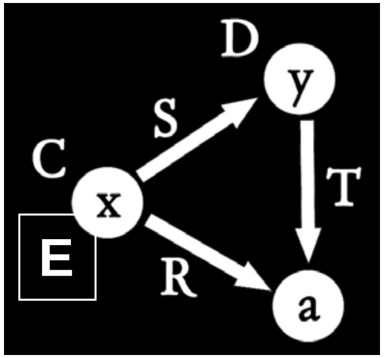
- **$NutAllergic(x) \wedge NutProduct(y) \rightarrow dislikes(x,y)$**
  - **$NutAllergic \equiv \exists nutAllergic.Self$**
    $NutProduct \equiv \exists nutProduct.Self$
    $nutAllergic \circ U \circ nutProduct \sqsubseteq dislikes$

- **$dislikes(x,z) \wedge Dish(y) \wedge contains(y,z) \rightarrow dislikes(x,y)$**
  - **$Dish \equiv \exists dish.Self$**
    $dislikes \circ contains^{-} \circ dish \sqsubseteq dislikes$

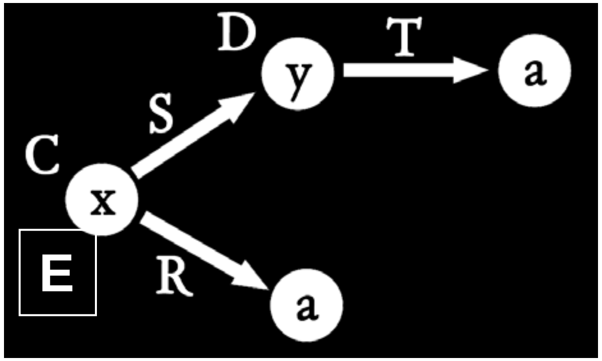
So how can we pinpoint this?

- **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

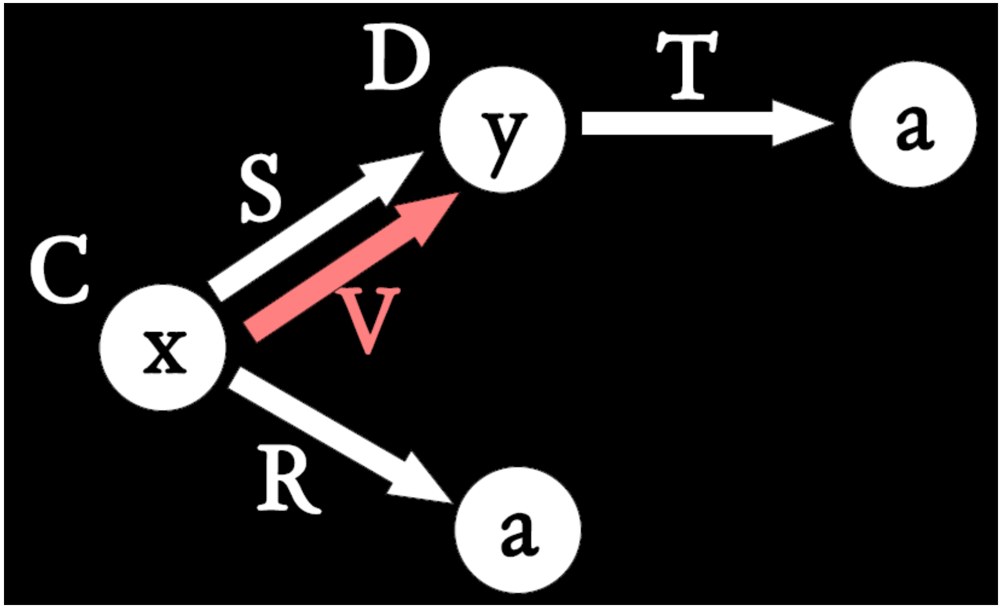


So how can we pinpoint this?

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

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

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



Rule bodies as graphs

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

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

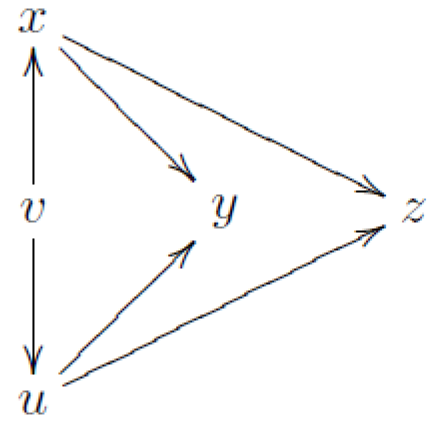
$C \sqcap \exists R.\{a\} \sqsubseteq \exists R1.\mathrm{Self}$

$D \sqcap \exists T.\{a\}) \sqsubseteq \exists R2.\mathrm{Self}$

$R1 \circ S \circ R2 \sqsubseteq P$

Rule bodies as graphs

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



with y,z constants:

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

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'.**

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

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

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).*

$R(x,z) \wedge S(y,z) \rightarrow T(x,y)$ 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 $\mathcal{SROIEL}$.*

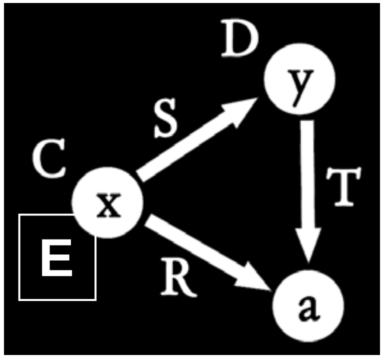
Contents

DL-safe variables

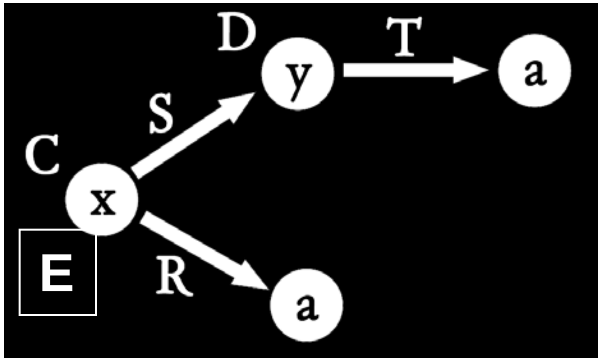
- A generalisation of DL-safety.
- DL-safe variables are special variables which bind only to named individuals (like in DL-safe rules).

- $C(x) \wedge R(x,x_s) \wedge S(x,y) \wedge D(y) \wedge T(y,x_s) \rightarrow E(x)$
  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.



duplicating nominals is ok



DL-safe variables

- A generalisation of DL-safety.
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  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.

- **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 OWL 2**
  - **select some variables and declare them DL-safe such that resulting rule can be translated into several OWL 2 rules**

- ***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.

Non-hybrid syntax: nominal schemas

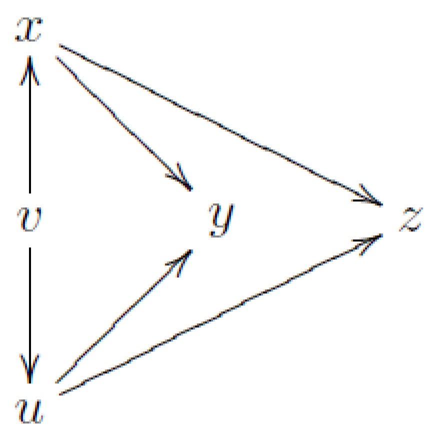
$$\text{hasReviewAssignment}(v,x) \land \text{hasAuthor}(x,y) \land \text{atVenue}(x,z)$$
$$\land\, \text{hasSubmittedPaper}(v,u) \land \text{hasAuthor}(u,y) \land \text{atVenue}(u,z)$$
$$\rightarrow \text{hasConflictingAssignedPaper}(v,x)$$

assume y,z bind only to named individuals

we introduce a new construct, called

nominal schemas

or *nominal variables*



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

Nominal schema example 2

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

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

Adding nominal schemas to OWL 2 DL

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

- **A naïve implementation is straightforward:**

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

  However, this may result in a lot of new OWL 2 axioms.
  The 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 (binary) Datalog rules!**

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

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

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

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)**

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

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

OWL syntax for nominal schemas

Functional Syntax:

Add the last line, (ObjectVariable), to the ClassExpression production rule:

ClassExpression :=
Class |
ObjectIntersectionOf | ObjectUnionOf ObjectComplementOf | ObjectOneOf |
ObjectSomeValuessFrom | ObjectAllValuesFrom | ObjectHasValue | ObjectHasSelf |
ObjectMinCardinality | ObjectMaxCardinality | ObjectExactCardinality |
DataSomeValuesFrom | DataAllValuesFrom | DataHasValue |
DataMinCardinality | DataMaxCardinality | DataExactCardinality |
ObjectVariable

Add the next production rule to the grammar:

ObjectVariable := 'ObjectVariable (' quotedString ' ^^ xsd:string)'

OWL syntax for nominal schemas

Translation to Turtle:

Functional-Style Syntax	S Triples Generated in an Invocation of T(S)	Main Node of T(S)
ObjectVariable("v1" ^^ xsd:string)	_:x rdf:type owl:ObjectVariable _:x owl:variableId "v1"^^xsd:string	_:x

Naïve implemenation – experiments

	No axioms added		1 different ns		2 different ns		3 different ns	
Fam (5)	0.01"	0.00"	0.01"	0.00"	0.01"	0.00"	0.04"	0.02"
Swe (22)	3.58"	0.08"	3.73"	0.07"	3.85"	0.10"	10.86"	1.11"
Bui (42)	2.7"	0.16"	2.5"	0.15"	2.75"	0.26"	1' 14'	6.68"
Wor (80)	0.11"	0.04"	0.12"	0.05"	1.1"	0.55"	OOM *	OOM*
Tra (183)	0.05"	0.03"	0.05"	0.02"	5.66"	1.76"	OOM	OOM
FTr (368)	0.03"	4.28"	0.05	5.32"	35.53"	42.73"	OOM	OOM
Eco (482)	0.04"	0.24"	0.07"	0.02"	56.59"	13.67"	OOM	OOM

OOM = Out of Memory

from the TONES repository:

Ontology	Classes	Data P.	Object P.	Individuals
Fam	4	1	11	5
Swe	189	6	25	22
Bui	686	0	24	42
Wor	1842	0	31	80
Tra	445	4	89	183
FTr	22	6	52	368
Eco	339	8	45	482

Naïve implemenation – experiments

Optimization through smart grounding (all ns occuring safely)

	No ns		1 ns		2 ns		3 ns	
Rex (100)	0.025	0.009	0.031	0.013	1.689	0.112	OOM	OOM
Rex Optimized (100)			0.058	0.023	0.046	0.011	0.053	0.009
Spatial (100)	0.035	0.029	0.021	0.014	1.536	0.101	OOM	OOM
Spatial Optimized (100)			0.018	0.013	0.033	0.007	0.044	0.011
Xenopus (100)	0.063	0.018	0.07	0.19	1.598	0.112	OOM	OOM
Xenopus Optimized (100)			0.099	0.037	0.083	0.018	0.097	0.063

Ontology	Classes	Data P.	Object P.	Individuals
Rex	552	0	6	100
Spatial	106	0	13	100
Xenopus	710	0	5	100

Naïve implemenation – experiments

Note: with 2 different ns we cover all of OWL 2 RL (but functionality)

	No axioms added		1 different ns		2 different ns		3 different ns	
Fam (5)	0.01”	0.00”	0.01”	0.00”	0.01”	0.00”	0.04”	0.02”
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Xenopus (100)	0.063	0.018	0.07	0.19	1.598	0.112	OOM	OOM
Xenopus Optimized (100)			0.099	0.037	0.083	0.018	0.097	0.063

Remember the partonomies problem?

In the partonomies lecture, we had several issues with modeling the part-of ontology following Winston.

E.g., relations cannot be transitive, asymmetric, and irreflexive at the same time.

We can now approximate this as follows:

Characterize the relation (e.g., R) as transitive and asymmetric.

Furthermore, specify $\{x\} \sqcap \exists R.\{x\} \sqsubseteq \bot$.

More generally, if you run into a rule which you cannot model in OWL, simply approximate using nominal schemas.

Contents

1. Reasoning Needs
2. Rules expressible in OWL
3. Extending OWL with Rules: Nominal Schemas
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References

This part of the lecture is very close to:

- **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

- **For RIF, see**
  Michael Kifer, Harold Boley, RIF Overview. W3C Working Group Note 22 June 2010. http://www.w3.org/TR/rif-overview/

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. Technical Report, 2011.

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