Modeling with Ontologies and Rules

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Part I
Ontologies and Rules

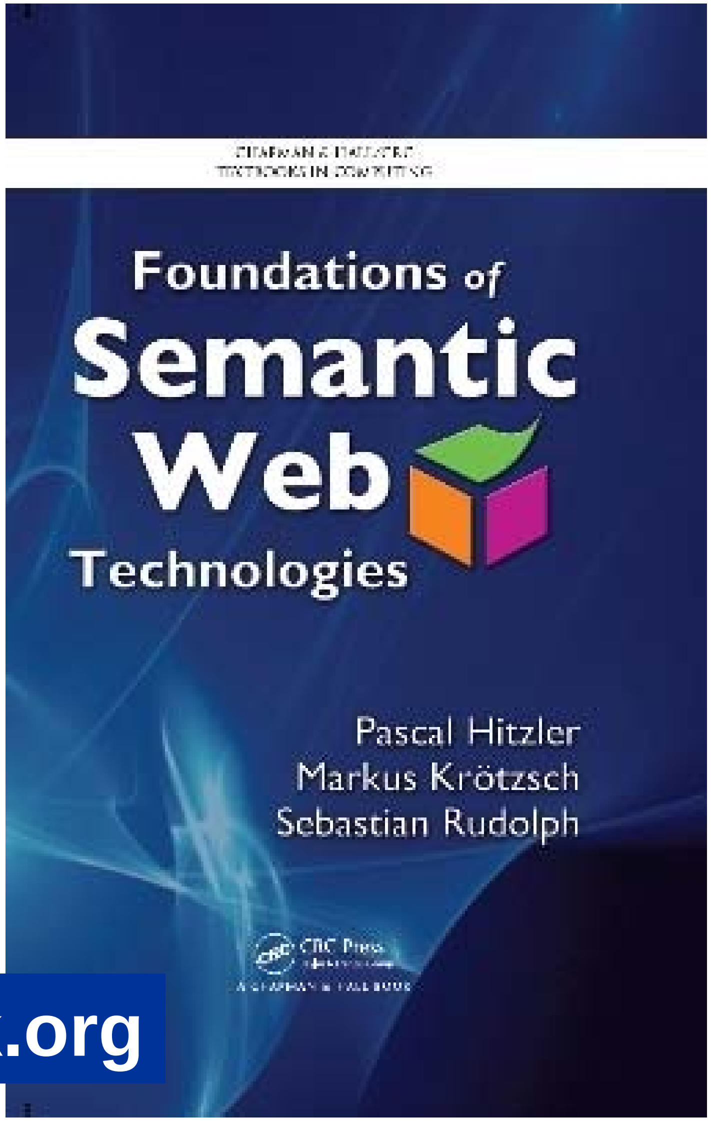
Textbook

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), 2013.

Translators:

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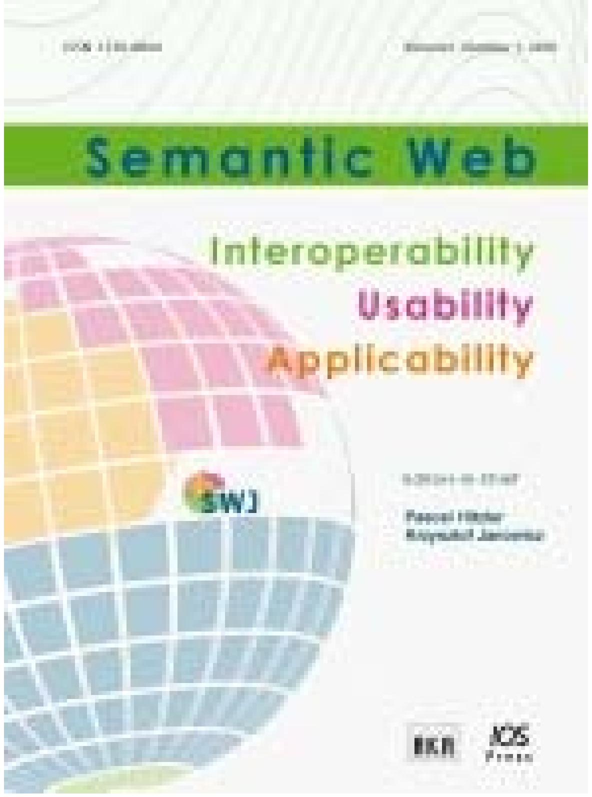
http://www.semantic-web-book.org

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.**



Semantic Web

Interoperability
Usability
Applicability

SWJ

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

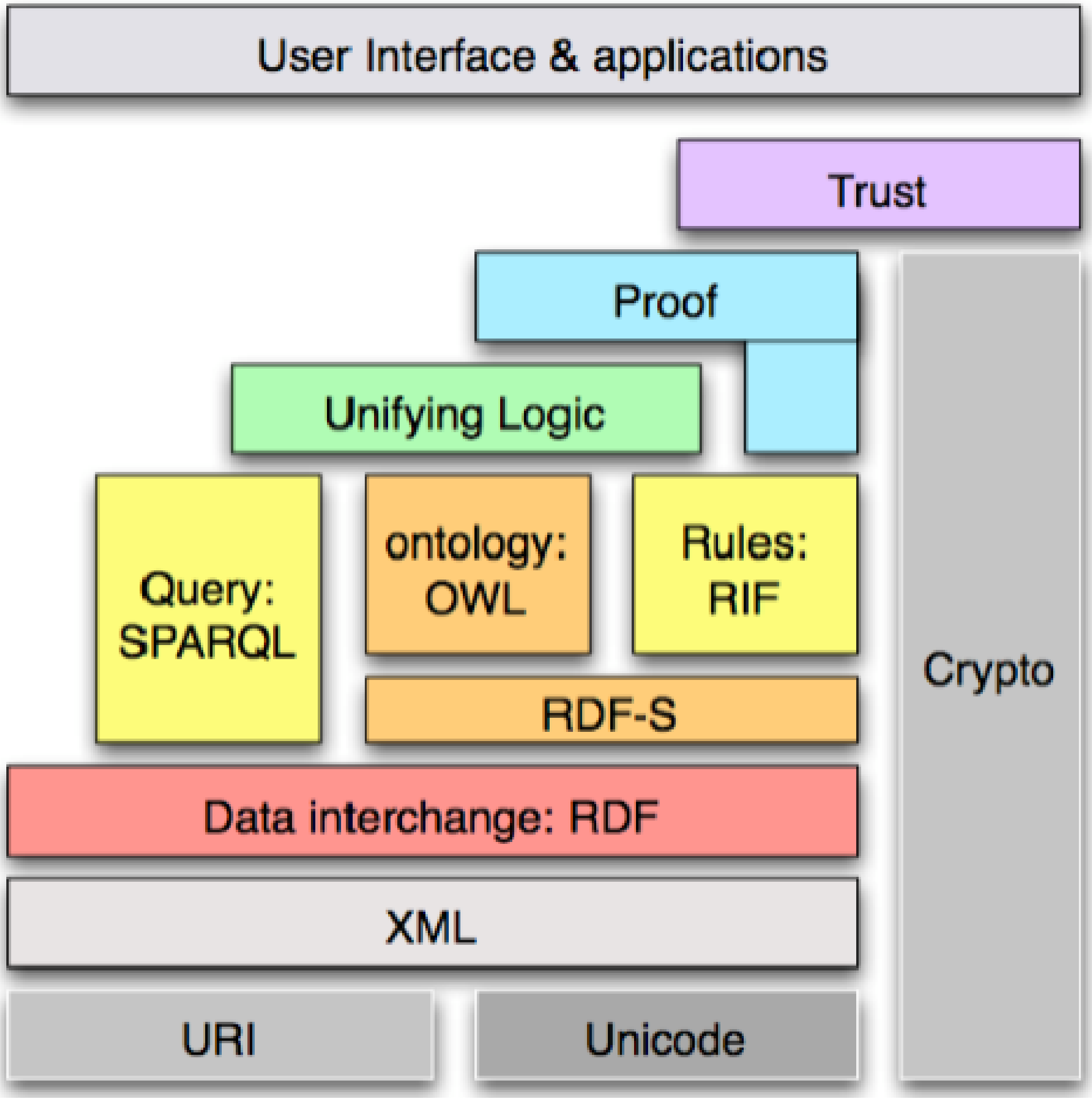
DaSe Lab for Data Semantics

Currently

8 PhD students
2 Master students

3 undergrads

The Semantic Web Stack



User Interface & applications

Trust

Proof

Unifying Logic

Query: SPARQL

ontology: OWL

Rules: RIF

RDF-S

Data interchange: RDF

XML

URI

Unicode

Crypto

Contents

OWL

Web Ontology Language (OWL)

- W3C Recommendation since 2004
- OWL 2 since 2009

- based on description logics
- essentially, a decidable fragment of first-order predicate logic

Description Logics (DLs)

classes/concepts A, B, C	**unary predicates** A(x), B(X), C(x)
roles/properties R, S	**binary predicates** R(x,y), S(x,y)
individuals a, b, c	**constants** a, b, c

Some DL constructors

class conjunction

$C \sqcap D$	$C(x) \land D(x)$

existential restriction

$\exists R.C$	$\exists y\,(R(x,y) \land C(y))$

class inclusion/subsumption

$C \sqsubseteq D$	$C(x) \rightarrow D(x)$
$C \equiv D$	$C(x) \leftrightarrow D(x)$

role chains

$R_1 \circ \ldots \circ R_n \sqsubseteq R$	$R_1\,(x,x_1) \land \ldots \land R(x_n,x_{n+1}) \rightarrow R(x,x_{n+1})$

Some DL constructors

$\text{ThaiDish} \sqsubseteq \exists\text{contains.Nut}$

$\text{Nutallergic} \sqcap \exists\text{eats.Nut} \sqsubseteq \text{Unhappy}$

$\text{eats} \circ \text{contains} \sqsubseteq \text{eats}$

inverse roles

$R \equiv S^{-}$ $\quad R(x,y) \leftrightarrow S(y,x)$

This logic is already undecidable! **(see e.g. [ISWC 2007])**

Name of the logic: ELRI

Decidability

Decidability is a central characteristics of description logics.

Retaining Decidability

1. **Disallow ∃:**
   Essentially leads to OWL RL.
   Fragment of Datalog.
   Tractable (i.e., polynomial complexity).

2. **Disallow inverse roles:**
   Essentially leads to OWL EL.
   Akin "in spirit" to existential rules/Datalog+-.
   Tractable.

3. **Restrict recursion in role chains (a.k.a. *regularity* restriction):**
   With further constructors, leads to OWL DL, a.k.a. SROIQ.
   Decidable, but not tractable.

Further essential DL constructors

The following can be used in OWL EL (logic remains tractable).

Self

$C \sqsubseteq \exists R.\mathrm{Self}$	**$C(x) \rightarrow R(x,x)$**

Can be used e.g. for typecasting.

nominals

$\{a\} \sqsubseteq C$	**$C(a)$**	**a is a constant**
$C \sqsubseteq \{a\}$	**$C(x) \rightarrow x=a$**	
$\{a\} \equiv \{b\}$	**$\rightarrow a=b$**	

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

Further essential DL constructors

The following are used in expressive (intractable) DLs

class negation		
	$\neg C$	$\neg C(x)$
class disjunction		
	$C \sqcup D$	$C(x) \vee D(x)$
universal restriction		
	$\forall R.C$	$\forall y\ (R(x,y) \rightarrow C(y))$

There are some more of course.

Contents

1. Description Logics and OWL
2. Rules expressible in description logics
3. Extending description logics with rules through nominal schemas
4. Algorithmizations for nominal schemas
5. Adding non-monotonicity
6. Conclusions

Rules in OWL

Which rules can be encoded in OWL?

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

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

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

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

$$A \sqcap B \sqsubseteq \bot \text{ becomes } A(x) \land B(x) \to f$$

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

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

Rules in OWL

Which rules can be encoded in OWL?

$A \sqsubseteq \neg B \sqcup C$ becomes $A(x) \wedge B(x) \to C(x)$

$A \sqsubseteq \forall R.B$ becomes $A(x) \wedge R(x,y) \to B(y)$

$A \sqsubseteq B \wedge C$ becomes $A(x) \to B(x)$ and $A(x) \to C(x)$

$A \sqcup B \to C$ becomes $A(x) \to C(x)$ and $B(x) \to C(x)$

Rolification

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

- **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

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

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

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

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

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

careful – regularity of RBox needs to be retained:

$$\mathrm{hasHusband} \sqsubseteq \mathrm{marriedTo}$$

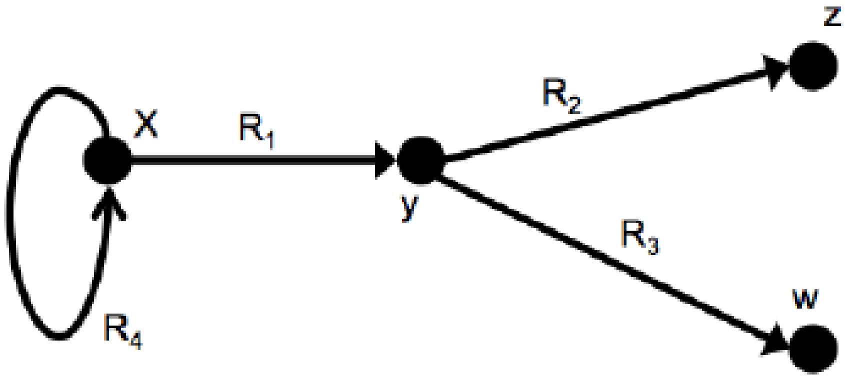
Rolification

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

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

Tree-shaped rules

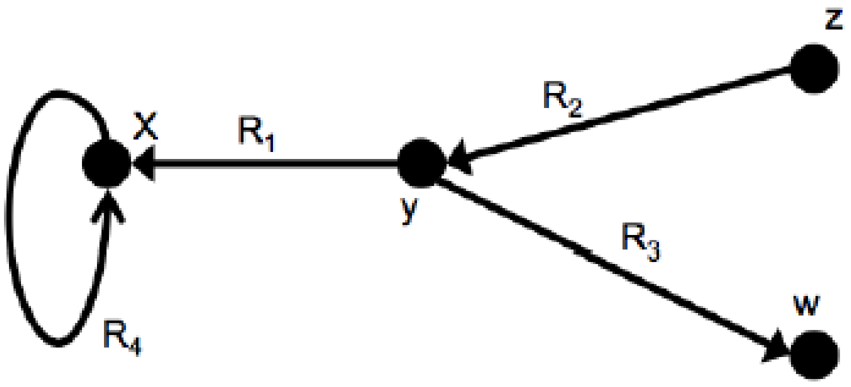
$$R_1(x,y) \wedge C_1(y) \wedge R_2(y,w) \wedge R_3(y,z) \wedge C_2(z) \wedge R_4(x,x) \rightarrow C_3(x)$$



$$\exists R_1.(C_1 \sqcap \exists R_2.\top \sqcap \exists R_3.C_2) \sqcap \exists R_4.Self \sqsubseteq C_3$$

Acyclic Rules

$$R_1(y,x) \wedge C_1(y) \wedge R_2(w,y) \wedge R_3(y,z) \wedge C_2(z) \wedge R_4(x,x) \rightarrow C_3(x)$$

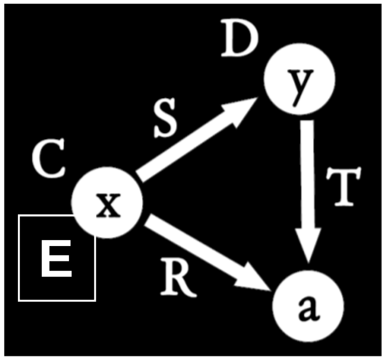


$$\exists R_1^-.(C_1 \sqcap \exists R_2^-.\top \sqcap \exists R_3.C_2) \sqcap \exists R_4.\mathit{Self} \sqsubseteq C_3$$

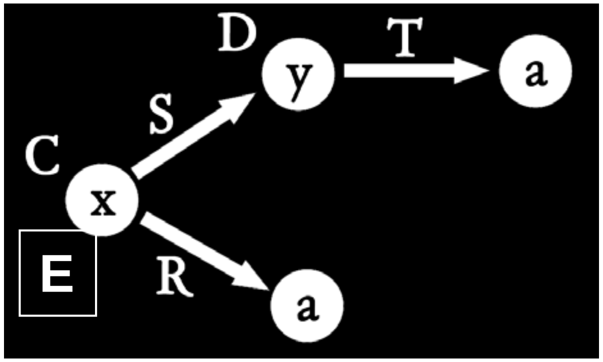
So how can we pinpoint this?

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

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

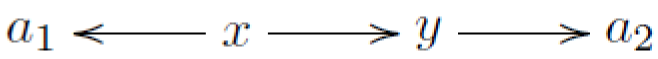


duplicating nominals is ok



Rule bodies as graphs

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



C ⊓ ∃R.{a} ⊑ ∃R1.Self

D ⊓ ∃T.{a} ⊑ ∃R2.Self

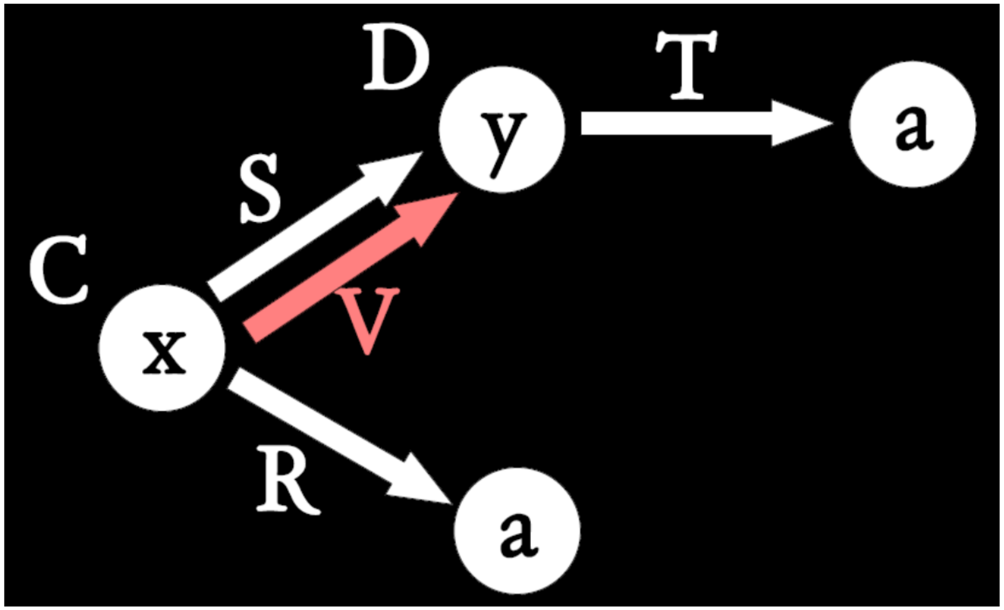
R1 ∘ S ∘ R2 ⊑ P

So how can we pinpoint this?

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

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

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



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).*

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

Theorem 1. *The following hold.*

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

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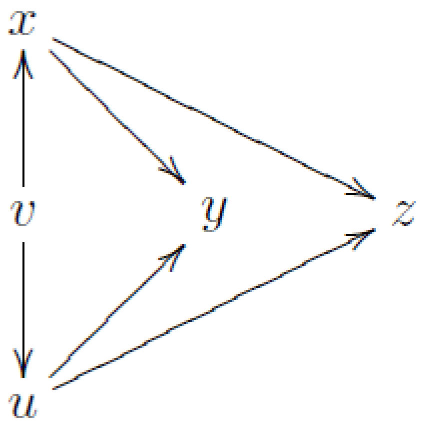
Rule bodies as graphs

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



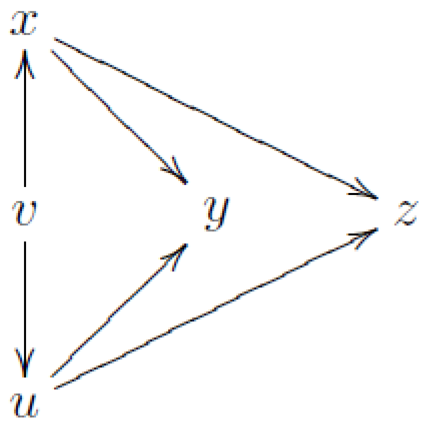
with y,z constants:

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

Non-hybrid syntax: nominal schemas

$$\begin{aligned} &\text{hasReviewAssignment}(v,x)\wedge \text{hasAuthor}(x,y)\wedge \text{atVenue}(x,z)\\ &\wedge \text{hasSubmittedPaper}(v,u)\wedge \text{hasAuthor}(u,y)\wedge \text{atVenue}(u,z)\\ &\qquad\to \text{hasConflictingAssignedPaper}(v,x)\end{aligned}$$

assume y,z bind only to named individuals
we introduce a new construct, called
nominal schemas
or *nominal variables*



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

Nominal schema example 2

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

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

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.
- A conceptual bridge to rule formalism:

  We can actually also express all DL-safe Datalog rules!

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

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

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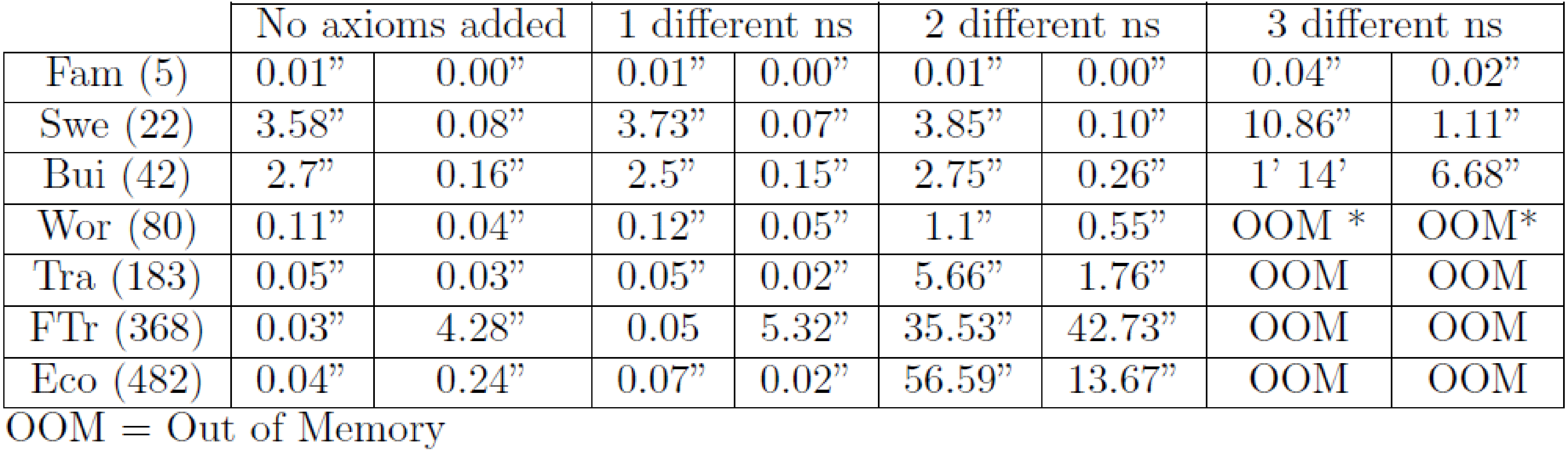
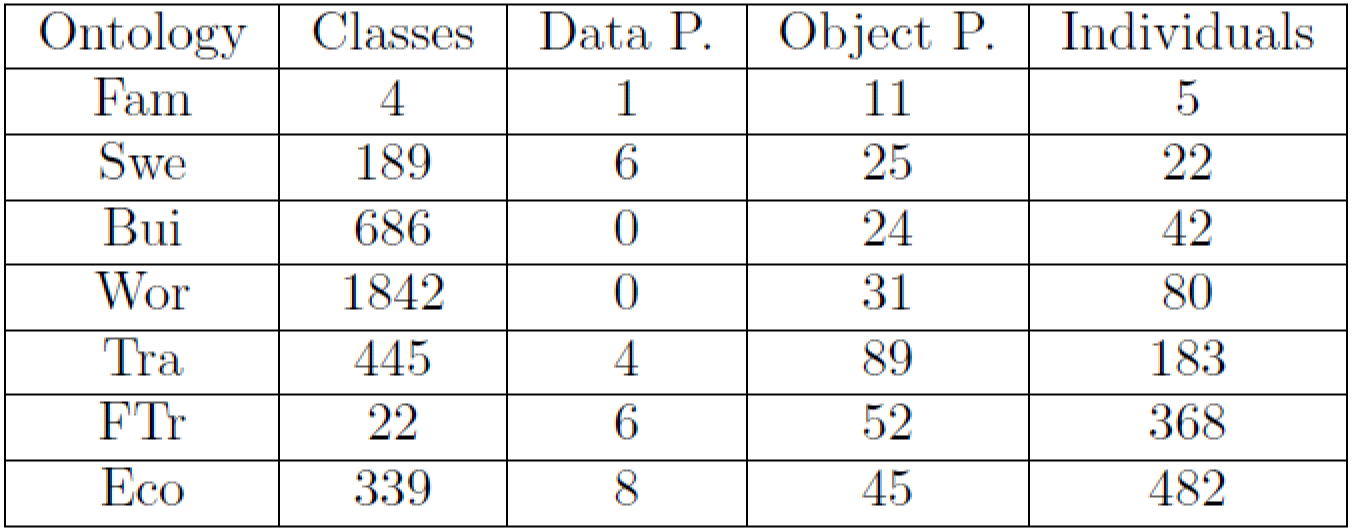
Naïve implementation – experiments



	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

Delayed grounding

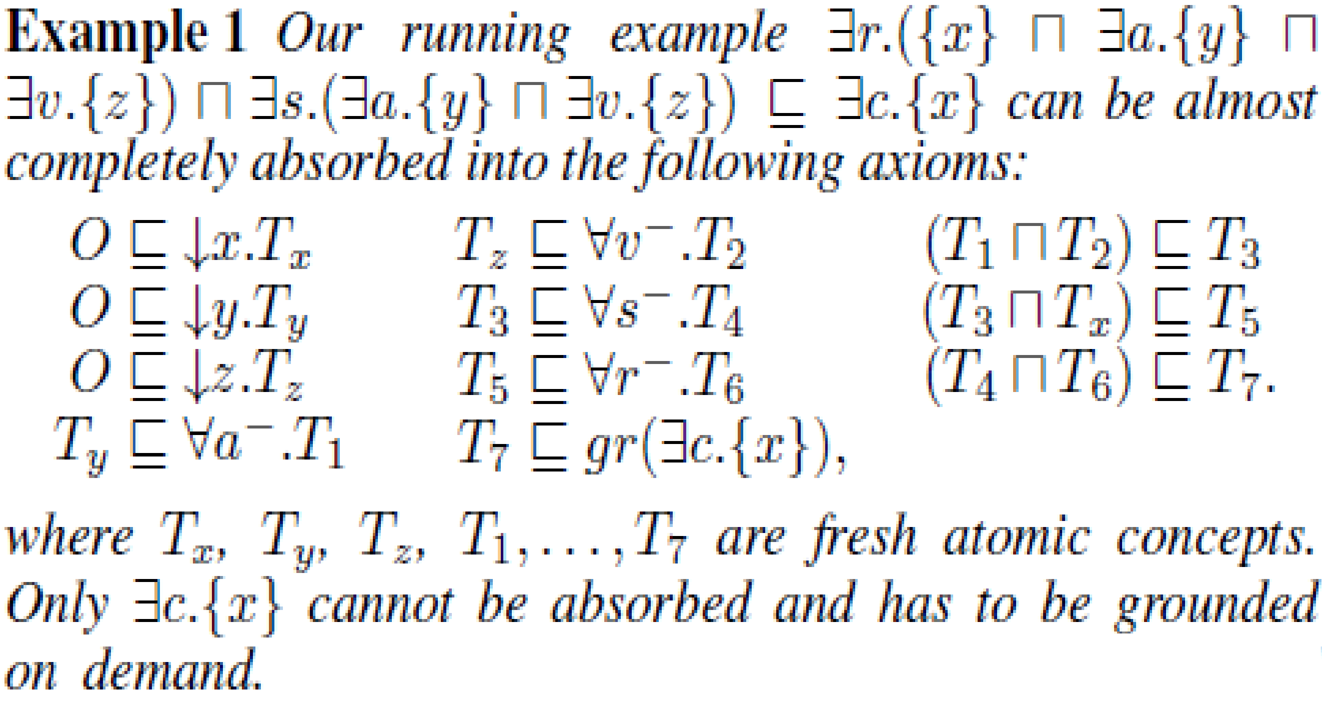
- **Adding nominal schemas to existing tableaux algorithms:**

$$\begin{aligned}\textsf{grounding}: \quad & \text{if } C \in \mathsf{L}(s), \{z\} \text{ is a nominal schema in } C,\\ & \quad C[z/a_i] \notin \mathsf{L}(s) \text{ for some } i, 1 \le i \le \ell\\ & \text{then } \mathsf{L}(s) := \mathsf{L}(s) \cup \{C[z/a_i]\}\end{aligned}$$

plus some restrictions on existing tableaux rules, essentially to ensure that (1) no variable binding is broken and (2) nominal schemas are not propagated through the tableau.

Further Tableaux Optimizations

- **variant of absorption [Steigmiller, Glimm, Liebig, IJCAI-13]**
- **essentially, a sort of smart rewriting as pre-processing**



Example 1 *Our running example* $\exists r.(\{x\} \sqcap \exists a.\{y\} \sqcap \exists v.\{z\}) \sqcap \exists s.(\exists a.\{y\} \sqcap \exists v.\{z\}) \sqsubseteq \exists c.\{x\}$ *can be almost completely absorbed into the following axioms:*

$$\begin{array}{lll} O \sqsubseteq {\downarrow}x.T_x & T_z \sqsubseteq \forall v^-.T_2 & (T_1 \sqcap T_2) \sqsubseteq T_3 \\ O \sqsubseteq {\downarrow}y.T_y & T_3 \sqsubseteq \forall s^-.T_4 & (T_3 \sqcap T_x) \sqsubseteq T_5 \\ O \sqsubseteq {\downarrow}z.T_z & T_5 \sqsubseteq \forall r^-.T_6 & (T_4 \sqcap T_6) \sqsubseteq T_7. \\ T_y \sqsubseteq \forall a^-.T_1 & T_7 \sqsubseteq gr(\exists c.\{x\}), & \end{array}$$

where T_x, T_y, T_z, $T_1, \ldots, T_7$ *are fresh atomic concepts. Only* $\exists c.\{x\}$ *cannot be absorbed and has to be grounded on demand.*

Further Tableaux Optimizations

[Steigmiller, Glimm, Liebig, IJCAI-13]

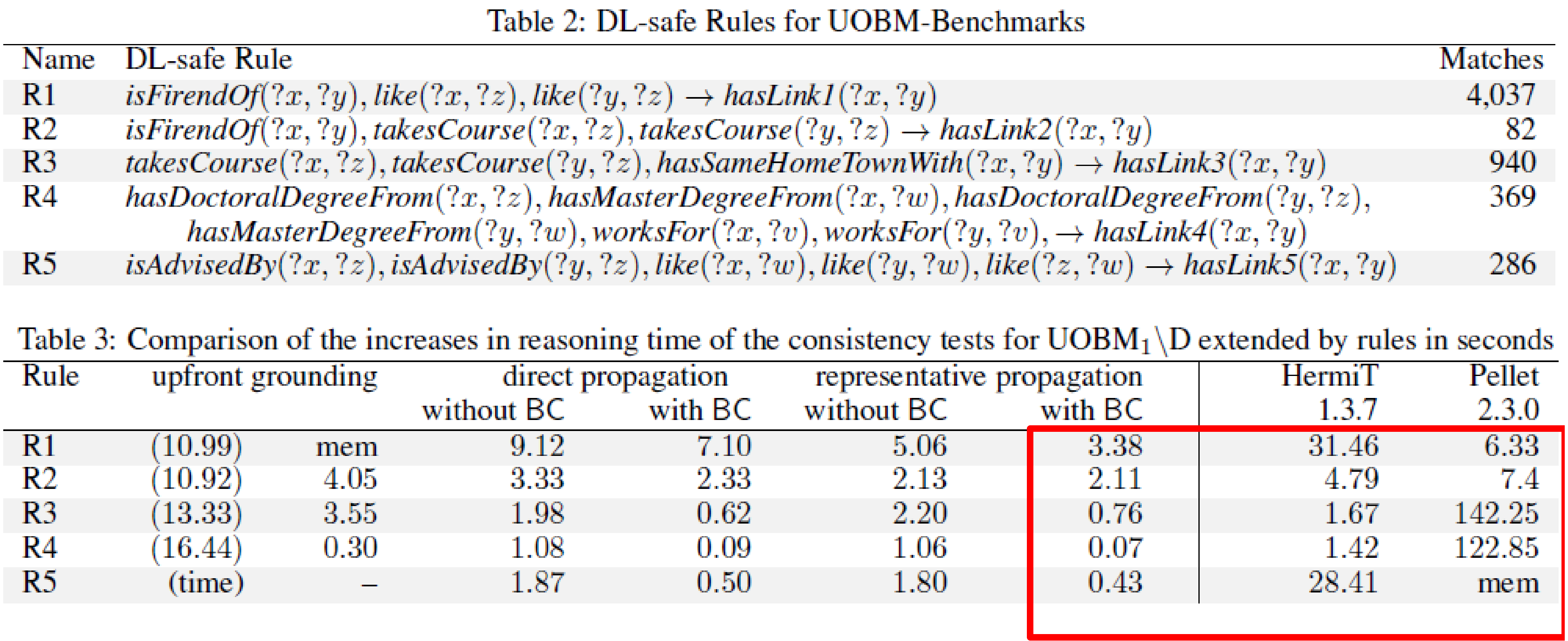


Table 2: DL-safe Rules for UOBM-Benchmarks

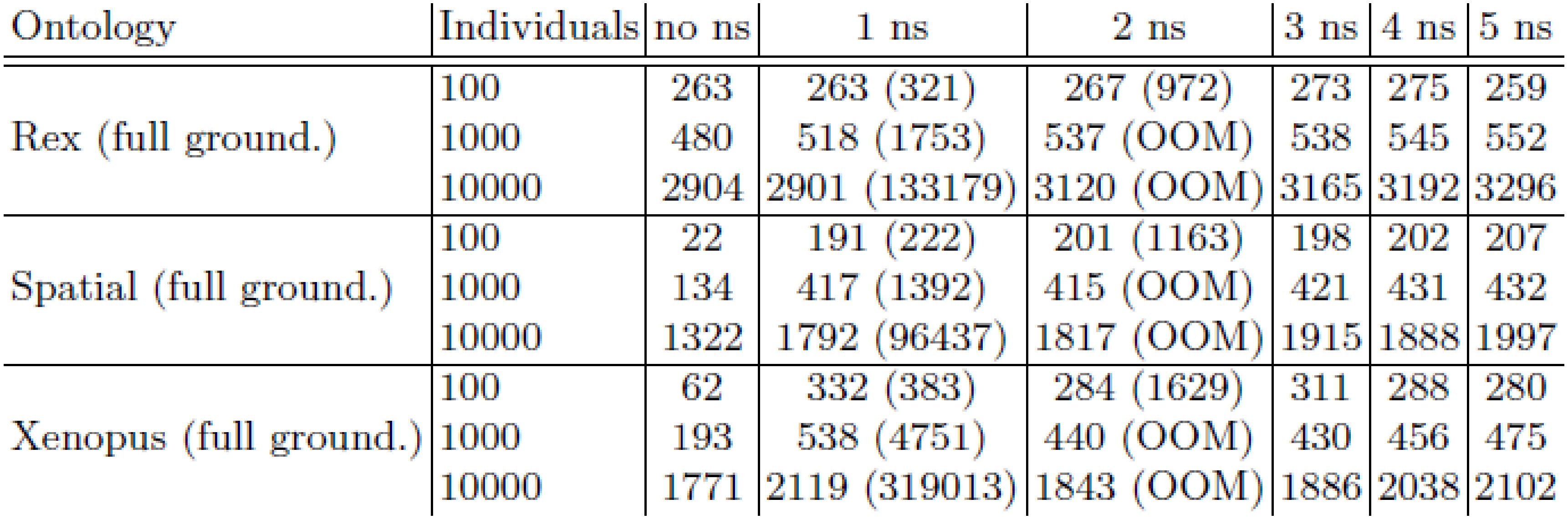
Name	DL-safe Rule	Matches
R1	$\mathit{isFirendOf}(?x,?y), \mathit{like}(?x,?z), \mathit{like}(?y,?z) \rightarrow \mathit{hasLink1}(?x,?y)$	4,037
R2	$\mathit{isFirendOf}(?x,?y), \mathit{takesCourse}(?x,?z), \mathit{takesCourse}(?y,?z) \rightarrow \mathit{hasLink2}(?x,?y)$	82
R3	$\mathit{takesCourse}(?x,?z), \mathit{takesCourse}(?y,?z), \mathit{hasSameHomeTownWith}(?x,?y) \rightarrow \mathit{hasLink3}(?x,?y)$	940
R4	$\mathit{hasDoctoralDegreeFrom}(?x,?z), \mathit{hasMasterDegreeFrom}(?x,?w), \mathit{hasDoctoralDegreeFrom}(?y,?z),$ $\mathit{hasMasterDegreeFrom}(?y,?w), \mathit{worksFor}(?x,?v), \mathit{worksFor}(?y,?v), \rightarrow \mathit{hasLink4}(?x,?y)$	369
R5	$\mathit{isAdvisedBy}(?x,?z), \mathit{isAdvisedBy}(?y,?z), \mathit{like}(?x,?w), \mathit{like}(?y,?w), \mathit{like}(?z,?w) \rightarrow \mathit{hasLink5}(?x,?y)$	286

Table 3: Comparison of the increases in reasoning time of the consistency tests for $\mathrm{UOBM}_1 \setminus \mathrm{D}$ extended by rules in seconds

Rule	upfront grounding		direct propagation		representative propagation		HermiT	Pellet
			without BC	with BC	without BC	with BC	1.3.7	2.3.0
R1	(10.99)	mem	9.12	7.10	5.06	3.38	31.46	6.33
R2	(10.92)	4.05	3.33	2.33	2.13	2.11	4.79	7.4
R3	(13.33)	3.55	1.98	0.62	2.20	0.76	1.67	142.25
R4	(16.44)	0.30	1.08	0.09	1.06	0.07	1.42	122.85
R5	(time)	–	1.87	0.50	1.80	0.43	28.41	mem

Algorithm for ELROVn

Based on [Krötzsch, JELIA10]



Ontology	Individuals	no ns	1 ns	2 ns	3 ns	4 ns	5 ns
Rex (full ground.)	100	263	263 (321)	267 (972)	273	275	259
	1000	480	518 (1753)	537 (OOM)	538	545	552
	10000	2904	2901 (133179)	3120 (OOM)	3165	3192	3296
Spatial (full ground.)	100	22	191 (222)	201 (1163)	198	202	207
	1000	134	417 (1392)	415 (OOM)	421	431	432
	10000	1322	1792 (96437)	1817 (OOM)	1915	1888	1997
Xenopus (full ground.)	100	62	332 (383)	284 (1629)	311	288	280
	1000	193	538 (4751)	440 (OOM)	430	456	475
	10000	1771	2119 (319013)	1843 (OOM)	1886	2038	2102

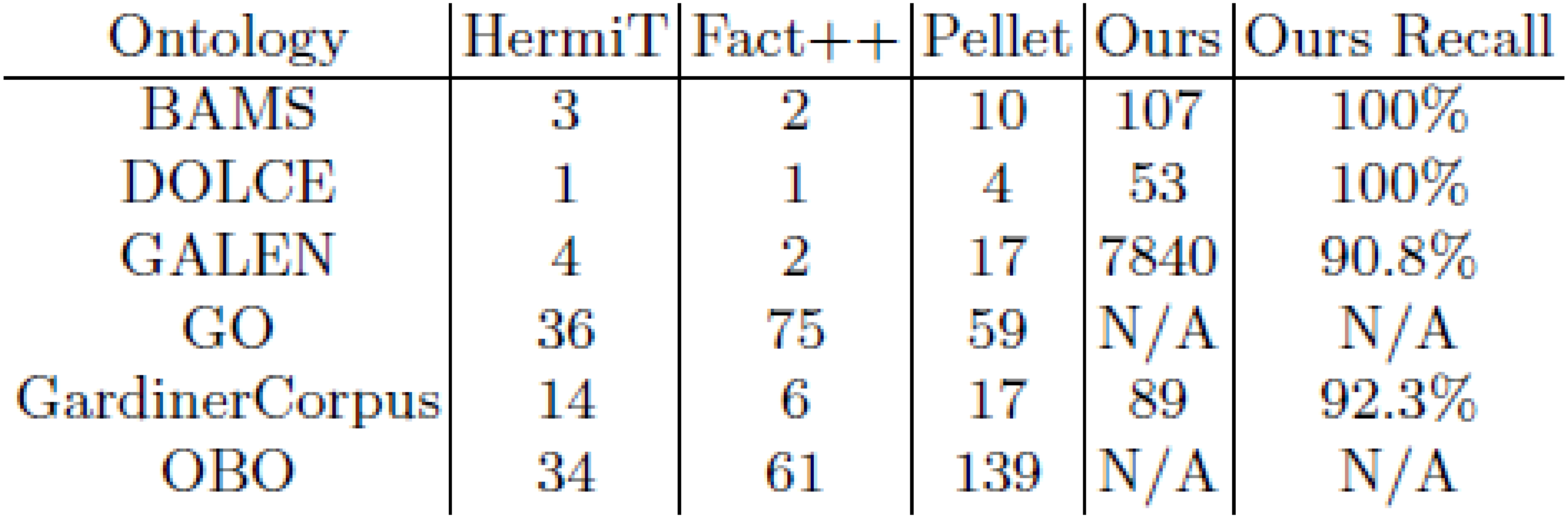
Approximating OWL through ELROVn

- We rewrite mincardinality restrictions into maxcardinality restrictions or approximate using an existential.
- We rewrite universal quantification into existential quantification.
- We approximate maxcardinality restrictions using functionality.
- We approximate inverse roles and functionality using nominal schemas.
- We approximate negation using class disjointness.
- We approximate disjunction using conjunction.

- **inverses:** $\{x\} \sqcap \exists R.\{y\} \sqsubseteq \{y\} \sqcap \exists S.\{x\}$
- **functionality** $C \sqsubseteq \leq 1 R.D$ **:**

$$C \sqcap \exists R.(\{z1\} \sqcap D) \sqcap \exists R.(\{z2\} \sqcap D) \sqsubseteq \exists U.(\{z1\} \sqcap \{z2\})$$

Approximation results (using IRIS)



Ontology	HermiT	Fact++	Pellet	Ours	Ours Recall
BAMS	3	2	10	107	100%
DOLCE	1	1	4	53	100%
GALEN	4	2	17	7840	90.8%
GO	36	75	59	N/A	N/A
GardinerCorpus	14	6	17	89	92.3%
OBO	34	61	139	N/A	N/A

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4. Algorithmizations for nominal schemas
5. Adding non-monotonicity
6. Conclusions

Adding non-monotonicity

- **[Knorr, Hitzler, Maier ECAI2012]**

- **Extension of an autoepistemic description logic approach by nominal schemas.**
- **Results in a language which incorporates most of the major approaches to non-monotonic extensions of DLs.**
- **E.g. covers**
  - **hybrid MKNF [Motik & Rosati], which in turn covers**
  - **non-disjunctive ASP**
  - **DL Programs / dlvhex (Eiter et al.)**
- **Also covers OWL / SROIQ(D) of course.**

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Conclusions

- Paradigms are converging.
- More work needed e.g. re.
  - algorithmizations
  - relating OWL EL and existential rules research
  - making non-monotonic reasoning fit for semantic web applications

Collaborators

Collaborators on the covered topics

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