Rules with Contextually Scoped Negation for the Web

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Overview

- The Semantic Web
- Where to add Rules in the “Layer Cake”?  
- A lightweight approach: Logic Programs with Context and Scoped Negation  
  - Contextually Bounded Semantics  
  - Contextually Closed Semantics  
  - Summary/Open Issues  
- Other approaches . . . time allowed.  
  - SWRL – Rules on top of OWL  
  - DLP – Intersection of LP and DL  
  - dl-programs – a query interface between LP and OWL
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http://imdb.com

http://badmovies.org
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I want to express taxonomies such as “Science-fiction movies are movies.”
Motivation - Semantic Web

The Semantic Web promises machine readable metadata annotations of such sites allowing to combine and query their content, draw additional inferences.

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Besides facts in RDF, I want to express more complex rules such as for instance: “All movies listed on badmovies.org are rated bad.”
The W3C’s Semantic Web “layer cake”
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Can LP style rules really be layered ON TOP of OWL?

What is the common interoperability layer?

Can we define a “safe” interface between LP and OWL?

The W3C’s Semantic Web “layer cake”

What is the “right” way to go?
RDF - A standard for metadata

Let’s start at the level where concerns are still (more or less) clear:

- RDF allows to define **factual** metadata in about resources in form of triples
  
  \[\langle \text{Subject}, \text{Predicate}, \text{Object} \rangle\]

  e.g. **StarWars** is directed by **George Lucas**.

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- The presented approach discuss rules on top of RDF(S) only.
Metadata on the Web as RDF facts.

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Figure: RDF triples for some movie information sites
RDFS semantics

RDFS semantics can (to a large extent) be captured by LP style rules:

http://www.example.org/rdfs-semantics :

triple(P,rdf:type,rdf:Property) :- triple(S,P,O).
triple(S,rdf:type,rdfs:Resource) :- triple(S,P,O).
triple(O,rdf:type,rdfs:Resource) :- triple(S,P,O).
triple(S,rdf:type,C) :- triple(S,P,O), triple(P,rdfs:domain,C).
triple(0,rdf:type,C) :- triple(S,P,O), triple(P,rdfs:range,C).
triple(C,rdfs:subClassOf,rdfs:Resource) :- triple(C,rdf:type,rdfs:Class).
triple(C1,rdfs:subClassOf,C3) :- triple(C1,rdfs:subClassOf,C2),
                                 triple(C2,rdfs:subClassOf,C3).
triple(S,rdf:type,C2) :- triple(S,rdf:type,C1),
                           triple(C1,rdfs:subClassOf,C2).
triple(C,rdf:type,rdfs:Class) :- triple(S,rdf:type,C).
triple(C,rdfs:subClassOf,C) :- triple(C,rdf:type,rdfs:Class).
triple(P1,rdfs:subPropertyOf,P3) :- triple(P1,rdfs:subPropertyOf,P2),
                                     triple(P2,rdfs:subPropertyOf,P3).
triple(S,P2,O) :- triple(S,P1,O),
                 triple(P1,rdfs:subPropertyOf,P2).

plus the respective axiomatic triples in RDF/RDFS, cf. Sections 3.1 and 4.1 of
http://www.w3.org/TR/rdf-mt/.
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The stable model semantics for logic programs (1/2)

Syntax:
A normal logic programs $P$ is a set of rules of the form:

$$h : -l_1, \ldots, l_n.$$

- $l_1, \ldots, l_n$ are literals, i.e. atoms $p(t_1, \ldots, t_m)$ or negated atoms not $p(t_1, \ldots, t_m)$, such that $t_1, \ldots, t_m$ are either constants or variables.
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- $h$ is an atom.

Semantics:
Herbrand models defined as usual:

- $U_H$ consists of the the set of all constants appearing in $P$
- $B_H$ is the set of all atoms constructible from predicate symbols in $P$ and constants in $U_H$.
- Since there are no function symbols, $B_H$ is finite.
- A Herbrand interpretation $I$ is a subset of $B_H$.
- We denote by $\text{ground}(P)$ the set of all possible ground instantiations of rules in $P$ where variables are substituted with the constants in $U_H$.
- A Herbrand interpretation $I$ is called Herbrand model of $P$ if all rules in $\text{ground}(P)$ are satisfied wrt. $I$.
- Each positive (not-free) program $P$ has a unique minimal Herbrand model $M$. 

The stable model semantics for logic programs (2/2)

The stable models for programs with negation is defined via the Gelfond-Lifschitz-reduct:
Let \( I \) be a Herbrand interpretation of \( P \). Then the reduct \( P^I \) denotes the set of rules obtained from \( \text{ground}(P) \) by

- removing all rules \( r \) such that \( \text{not } a \) occurs in the body of \( r \) for some \( a \in I \)
- removing all literals \( \text{not } a \) from the remaining rules.

A Herbrand interpretation \( M \) is called a stable model of a normal logic program \( P \) iff \( M \) is the minimal Herbrand model of \( P \).

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Incomplete knowledge on the Web

Problems:

- **Incompleteness**: The knowledge of a search engine about the Web is notoriously incomplete, i.e. it does not know about all available Websites.

  “Search for all movies by Ed Wood”

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  “Search for **science fiction movies which are NOT rated as bad**?”

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Solution: Enforce to make the scope for negation as failure always explicit!
Metadata on the Web as distributed rule sets

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rated(m1,bad).
rated(X,bad) :-
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sciFiMovie(m3). hasTitle(m3,"Bride of the Monster").
directedBy(m3,"Ed Wood").
movie(X) :- sciFiMovie(X).
...

Figure: We use a more LP notation than before ...and add rules
Syntax: Logic Programs with scoped literals

Assumption: A *program* is a set of rules associated with a URI $u$, where it is accessible:

$$h : \neg l_1, \ldots, l_n.$$  

- Body Literals:

```plaintext
http://moviereviews.com: rated(X,bad) :- directedBy(X,"Ed Wood").
http://badmovies.org: movie(m1). ...
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  - open (unscoped) literals $a$.

Examples of open and scoped rules:

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Requirements for a reasonable semantics for such rules

Let $Cn_S(P)$ denote the set of consequences from a set of programs $P$ wrt. semantics $S$.
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Let $Cn_S(\mathcal{P})$ denote the set of consequences from a set of programs $\mathcal{P}$ wrt. semantics $S$

**R1** **Context-Monotonicity:** When asking query $q$ over (open and scoped) literals to an agent which is aware of a set of programs $\mathcal{P}$ (query context), I expect that I don’t need to retract any inferences when asking another agent aware of $\mathcal{R} \supset \mathcal{P}$, i.e.

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**R2  ** The chosen semantics should be closed under context closure, i.e.

$$Cn_S(\mathcal{P}) = Cn_S(Cl(\mathcal{P}))$$

where $Cl(\mathcal{P})$ is the set of all programs in $\mathcal{P}$ plus the ones “linked” recursively via scoped literals.
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We define two semantics based on the stable model semantics, both fulfilling R1, one of them fulfilling R2.
Contextually Bounded semantics: $Cn_{CB}$ (1/2)

Intuitively, scoping negative literals alone is not enough, since scoped literals can again depend on open rules, e.g.

```prolog
interestingmovie(X) :- movie(X),
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depends on whether the agent evaluating this rule knows http://imdb.com or not.
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1\textsuperscript{st} proposal to deal with this: Allow only contextually bounded negation.

\textit{We call a (set of) rules contextually bounded if no negative literal recursively depends on unscoped (open) literals.}
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Attention: This rule is NOT contextually bounded:

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Let $\mathcal{P}_{CB} = \bigcup_{p \in \mathcal{Cl}(\mathcal{P})} p_{CB}$, then

$$Cn_{CB}(\mathcal{P}) = \bigcap \mathcal{M}(\mathcal{P}_{CB})$$

where $\mathcal{M}(p)$ is defined as the set of all stable models of program $p$
Contextually Bounded semantics: Implications

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Problem:

► Contextual boundedness is a prerequisite:

\[
p:
\begin{align*}
a & :- \text{not } b@p. \\
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\text{a} & : - \text{not \ b@p} \quad \text{c}.
\end{align*}
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\text{b} : - \quad \text{c}.
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Contextually Bounded semantics: Implications

**R1** holds, by contextual boundedness (easy proof in [Polleres, et al. 2006]).

**R2** holds trivially ($\mathcal{P}_{CB}$ is defined via the closure of $\mathcal{P}$).

Problem:

- Contextual boundedness is a prerequisite:
  
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  c &.
  \end{align*}
  \]

- Contextual boundedness is hardly maintainable in an open context, especially when contexts change (adding open rule):
  
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Contextually Closed semantics $C_{nCC}$ (1/2)

Alternative approach: Intuitively “close off”, all open rules if referenced via a scoped literal.

We define an alternative rewriting $p_{CC}$ for each rule in program $p$:

\[ h : - \ l_1, \ldots, l_n. \]
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\[
\text{\texttt{h}} :- \ l_1, \ldots, \ l_n.
\]

\[
\Rightarrow
\]

\[
\text{\texttt{h}@}_p := \ l'_1, \ldots, \ l'_n.
\]

where \( l'_i = l_i \) for scoped literals and \( l'_i = l_i@_p \) otherwise.
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Let $P_{CC} = \bigcup_{p \in \mathcal{P}} \bigcup_{p \in Cl(\mathcal{P})} p_{CC}$, then

$$ Cn_{CC}(\mathcal{P}) = \bigcap M(P_{CC}) $$

where $M(p)$ is defined as the set of all stable models of program $p$
Intuitively, contextually closed semantics is more cautious or “local”:

\[ C_{nCC} \subseteq C_{nCB} \text{ (proof in [Polleres, et al. 2006]).} \]

It does not “traverse” closure concerning open literals, i.e. \( R_2 \) does not hold:

\[ p : r : a :- b \text{ at } r. \]

\[ b :- c. \]

\[ c. \]

Here, \( \in C_{nCB}(p) \), but \( \notin C_{nCC}(p) \), which one might consider more intuitive, i.e. cross-effects of open literals only within the query context.
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- $\text{Contextually Closed semantics } Cn_{CC} (2/2)$

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\[
p: \quad \text{a :- b@r.}
\]
\[
r: \quad \text{c.}
\]

Here, $c \in Cn_{CB}(p)$, but $c \not\in Cn_{CC}(p)$
Contextually Closed semantics $Cn_{CC}$ (2/2)

Intuitively, contextually closed semantics is more cautious or "local":

- $Cn_{CC}(\mathcal{P}) \subseteq Cn_{CB}(\mathcal{P})$ (proof in [Polleres, et al. 2006]).
- It does not "traverse" closure concerning open literals, i.e. R2 does not hold:

  $$p:\begin{array}{l}
a :- b@r. \\
  b :- c.
\end{array} \quad r:\begin{array}{l}
c.
\end{array}$$

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Summary of this approach

- Can be used on top of RDF (modulo blank nodes)

The two solutions proposed are simple/cautious on purpose, trying to start discussion about the “right” semantics of scoped negation for the Semantic Web.
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- The two solutions proposed are simple/cautious on purpose, trying to start discussion about the “right” semantics of scoped negation for the Semantic Web.
Related works

- FLORA-2 (Kifer): an engine for F-Logic programs, allows modules, i.e. contexts, open literals/rules supported by allowing variables in place of modules, e.g.
  \[ a : -b@X. \]
  No requirement for context-monotonicity though, well-founded semantics

- TRIPLE (Decker, et al.) allows parametrized contexts, union, intersection, set difference of contexts, also parameters allowed. Negation unsupported in current implementation, AFAIK.

- C-OWL extension of OWL by contexts and bridge rules, *local model semantics*, i.e. local inconsistencies do not spread over to the whole.

Sideremark: The approach is orthogonal to LCWA (Local closed world assumption) approaches allowing local completeness statements.
Issues/Future work

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- Exact relation with SPARQL, RIF
- Complexity, Prototype implementation (DLV, YARS)
- Investigate different semantics (well-founded vs. stable)
- Classical Negation, integration with the Ontology Layer (OWL)
**Time allowed... How to integrate OWL with Rules?**

OWL (Web Ontology Language) adds more expressivity on top of RDF, allows to define taxonomies based on intersection, complement, cardinality restrictions, etc.

<table>
<thead>
<tr>
<th>Axiom</th>
<th>DL Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>subClassOf</td>
<td>$C_1 \sqsubseteq C_2$</td>
</tr>
<tr>
<td>equivalentClass</td>
<td>$C_1 \equiv C_2$</td>
</tr>
<tr>
<td>disjointWith</td>
<td>$C_1 \sqsubseteq \neg C_2$</td>
</tr>
<tr>
<td>sameIndividualAs</td>
<td>${x_1} \equiv {x_2}$</td>
</tr>
<tr>
<td>differentFrom</td>
<td>${x_1} \sqsubseteq \neg {x_2}$</td>
</tr>
<tr>
<td>subPropertyOf</td>
<td>$P_1 \sqsubseteq P_2$</td>
</tr>
<tr>
<td>equivalentProperty</td>
<td>$P_1 \equiv P_2$</td>
</tr>
<tr>
<td>inverseOf</td>
<td>$P_1 \equiv P_2^-$</td>
</tr>
<tr>
<td>transitiveProperty</td>
<td>$P \sqsubseteq P$</td>
</tr>
<tr>
<td>functionalProperty</td>
<td>$T \sqsubseteq \leq 1P$</td>
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<table>
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<tr>
<th>Constructor</th>
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<tbody>
<tr>
<td>intersectionOf</td>
<td>$C_1 \cap \ldots \cap C_n$</td>
</tr>
<tr>
<td>unionOf</td>
<td>$C_1 \cup \ldots \cup C_n$</td>
</tr>
<tr>
<td>complementOf</td>
<td>$\neg C$</td>
</tr>
<tr>
<td>oneOf</td>
<td>${x_1} \sqcup \ldots \sqcup {x_n}$</td>
</tr>
<tr>
<td>allValuesFrom</td>
<td>$\forall P.C$</td>
</tr>
<tr>
<td>someValuesFrom</td>
<td>$\exists P.C$</td>
</tr>
<tr>
<td>maxCardinality</td>
<td>$\leq nP$</td>
</tr>
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Expressivity in principle based on the description logic $\mathcal{SHOIN}(D)$. (OWL DL, this is not completely true for OWL Full)
Interoperability on the common (Horn) intersection only

The Horn fragment of SHOIN(D) can be understood as a rule set. So, you can understand a small part of OWL as rules.

\[ \text{father}(X) \leftarrow \text{parent}(X,Y), \text{person}(Y), \text{male}(X). \]

\[ \iff \]

\[ F \sqsubseteq \exists P \neg 1 \cdot \text{Human} \sqcap \text{Male} \]

BUT: cannot cover much either on the rules part, nor on the DL part. Only a basis for extensions in either direction.
Interoperability on the common (Horn) intersection only

**DLP:**
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e.g. father(X) ← parent(X,Y), person(Y), male(X).
\[\Leftrightarrow \quad Father \sqsubseteq \exists \text{Parent}^{-1}.\text{Human} \cap \text{Male}\]
BUT: cannot cover much either on the rules part, nor on the DL part.
Only a basis for extensions in either direction.
SWRL:
Add Horn rules to OWL syntax, allows you to express e.g.

\[ \text{uncle}(X,Y) \leftarrow \text{male}(X), \text{_sibling}(X,Z), \text{parent}(Z,Y). \]

But, also:

\[ \exists X \text{parent}(X,Y) \leftarrow \text{male}(Z). \]

(from \[ \exists P \text{arent} \sqsubseteq \text{male} \])

On the one hand naive combination of Horn + DL destroys decidability of either.

On the other hand SWRL does not even allow arbitrary HORN but only binary/unary predicates.

Issues like open vs. closed rules, negation as failure untouched.
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- On the one hand naive combination of Horn + DL destroys decidability of either.
- On the other hand SWRL does not even allow arbitrary HORN but only binary/unary predicates.
- Issues like open vs. closed rules, negation as failure untouched.
Define an extension of LP under the stable model semantics by so-called dl-atoms in the body, which allow to query a DL Knowledge base, but also interchange facts in the other direction. Authors define minimal Herbrand models and stable models for dl-programs.

- **pro** Decidability remains.
- **con** DL KB and LP program talk about different things, exchange only via “import/export”.

Generalization of this technique available, HEX-programs. Extension to scoped literals? Not straightforward.
Thank you for your attention!