OWL 2 Rules

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Our Book

Pascal Hitzler, Markus Krötzsch, Sebastian Rudolph

Foundations of Semantic Web Technologies
Chapman & Hall/CRC, 2009

Grab a flyer!

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

Overall Outline

Part 1:
• OWL 2 – An Introduction from a DL Point of View (ca. 60min)

Part 2:
• OWL 2 and Rules – Not as Incompatible as You May Think (ca. 60min)
Part 1

OWL 2

OWL 2 Document Overview: http://www.w3.org/TR/owl2-overview/

OWL – Overview

• Web Ontology Language
  – W3C Recommendation for the Semantic Web, 2004
  – OWL 2 (revised W3C Recommendation), 2009

• Semantic Web KR language based on description logics (DLs)
  – OWL DL is essentially DL SROIQ(D)
  – KR for web resources, using URIs.
  – Using web-enabled syntaxes, e.g. based on XML or RDF.
    We present
    • DL syntax (used in research – not part of the W3C recommendation)
    • (some) RDF Turtle syntax
Contents

• OWL – Basic Ideas
• OWL as the Description Logic SROIQ(D)
• Different Perspectives on OWL
• OWL Semantics
• OWL Profiles
• Proof Theory
• Tools
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Rationale behind OWL

- Open World Assumption
- Favourable trade-off between expressivity and scalability
- Integrates with RDFS
- Purely declarative semantics

Features:
- Fragment of first-order predicate logic (FOL)
- Decidable
- Known complexity classes (N2ExpTime for OWL 2 DL)
- Reasonably efficient for real KBs
OWL Building Blocks

• individuals (written as URIs)
  – also: constants (FOL), resources (RDF)
  – http://example.org/sebastianRudolph
  – we write these lowercase and abbreviated, e.g. "sebastianRudolph"

• classes (also written as URIs!)
  – also: concepts, unary predicates (FOL)
  – we write these uppercase, e.g. "Father"

• properties (also written as URIs!)
  – also: roles (DL), binary predicates (FOL)
  – we write these lowercase, e.g. "hasDaughter"
<table>
<thead>
<tr>
<th>DL syntax</th>
<th>FOL syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Person(mary)</td>
<td>• Person(mary)</td>
</tr>
<tr>
<td>• Woman ⊆ Person</td>
<td>• ∀x (Woman(x) → Person(x))</td>
</tr>
<tr>
<td>– Person ≡ HumanBeing</td>
<td></td>
</tr>
<tr>
<td>• hasWife(john,mary)</td>
<td>• hasWife(john,mary)</td>
</tr>
<tr>
<td>• hasWife ⊆ hasSpouse</td>
<td>• ∀x ∀y (hasWife(x,y) → hasSpouse(x,y))</td>
</tr>
<tr>
<td>– hasSpouse ≡ marriedWith</td>
<td></td>
</tr>
</tbody>
</table>

**ABox statements**

**TBox statements**
<table>
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<th>RDFS syntax</th>
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Special classes and properties

- **owl:Thing** (RDF syntax)
  - DL-syntax: $\top$
  - contains everything
- **owl:Nothing** (RDF syntax)
  - DL-syntax: $\bot$
  - empty class
- **owl:topProperty** (RDF syntax)
  - DL-syntax: $U$
  - every pair is in $U$
- **owl:bottomProperty** (RDF syntax)
  - empty property
Class constructors

- **conjunction**
  - Mother $\equiv$ Woman $\cap$ Parent
  - $\forall x \ (\text{Mother}(x) \leftrightarrow \text{Woman}(x) \land \text{Parent}(x))$  
  
  - $\text{:Mother owl:equivalentClass } _:x . \_:_x \text{ rdf:type owl:Class} . \_:_x \text{ owl:intersectionOf ( :Woman :Parent ) } .$

- **disjunction**
  - Parent $\equiv$ Mother $\cup$ Father
  - $\forall x \ (\text{Parent}(x) \leftrightarrow \text{Mother}(x) \land \text{Father}(x))$  
  
  - $\text{:Parent owl:equivalentClass } _:x . \_:_x \text{ rdf:type owl:Class} . \_:_x \text{ owl:unionOf ( :Mother :Father ) } .$

- **negation**
  - ChildlessPerson $\equiv$ Person $\cap$ $\neg$Parent
  - $\forall x \ (\text{ChildlessPerson}(x) \leftrightarrow \text{Person}(x) \land \neg\text{Parent}(x))$  
  
  - $\text{:ChildlessPerson owl:equivalentClass } _:x . \_:_x \text{ rdf:type owl:Class} . \_:_x \text{ owl:intersectionOf ( :Person _:y ) } . \_:_y \text{ owl:complementOf :Parent} .$
Class constructors

• existential quantification
  – only to be used with a role – also called a property restriction
  – Parent ≡ ∃hasChild.Person
    – :Parent owl:equivalentClass _:x .
      _:x rdf:type owl:Restriction .
      _:x owl:onProperty :hasChild .
      _:x owl:someValuesFrom :Person .
  – universal quantification
  – only to be used with a role – also called a property restriction
    – Person □ Happy ≡ ∀hasChild.Happy
      – _:x rdf:type owl:Class .
        _:x owl:intersectionOf ( :Person :Happy ) .
        _:x owl:equivalentClass _:y .
        _:y rdf:type owl:Restriction .
        _:y owl:onProperty :hasChild .
        _:y owl:allValuesFrom :Happy .

• Class constructors can be nested arbitrarily

∀x (Parent(x) ↔
  ∃y (hasChild(x,y) ∧ Person(y)))

∀x (Person(x) ∧ Happy(x) ↔
  ∀y (hasChild(x,y) → Happy(y)))
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Understanding SROIQ(D)

The description logic ALC

- ABox expressions:
  - Individual assignments: Father(john)
  - Property assignments: hasWife(john, mary)

- TBox expressions:
  - Subclass relationships: $\subseteq$
  - Conjunction: $\sqcap$
  - Disjunction: $\sqcup$
  - Negation: $\neg$
  - Property restrictions: $\forall$, $\exists$

Complexity: ExpTime

Also: $\top$, $\bot$
Understanding SROIQ(D)

ALC + role chains = SR

- hasParent o hasBrother ⊆ hasUncle

\[ \forall x \forall y (\exists z ((\text{hasParent}(x,z) \land \text{hasBrother}(z,y)) \rightarrow \text{hasUncle}(x,y))) \]
  - includes top property and bottom property

- includes S = ALC + transitivity
  - hasAncestor o hasAncestor ⊆ hasAncestor

- includes SH = S + role hierarchies
  - hasFather ⊆ hasParent
• O – nominals (closed classes)
  – MyBirthdayGuests ≡ \{bill, john, mary\}
  – Note the difference to
    MyBirthdayGuests(bill)
    MyBirthdayGuests(john)
    MyBirthdayGuests(mary)

• Individual equality and inequality (no unique name assumption!)
  – bill = john
    • \{bill\} ≡ \{john\}
  – bill ≠ john
    • \{bill\} \cap \{john\} ≡ \bot
Understanding SROIQ(D)

- **I** – inverse roles
  - `hasParent ≡ hasChild^-`
  - `Orphan ≡ ∀ hasChild^- . Dead`

- **Q** – qualified cardinality restrictions
  - `≤ 4 hasChild. Parent(john)`
  - `HappyFather ≡ ≥ 2 hasChild. Female`
  - `Car ⊑ =4 hasTyre. ⊤`

- **Complexity**
  - SHIQ, SHOQ, SHIO: ExpTime.
  - SHOIQ: NExpTime
  - SROIQ: N2ExpTime
Properties can be declared to be

- Transitive  hasAncestor
- Symmetric  hasSpouse
- Asymmetric hasChild
- Reflexive  hasRelative
- Irreflexive parentOf
- Functional hasHusband
- InverseFunctional hasHusband

called property characteristics
(D) – datatypes

- so far, we have only seen properties with individuals in second argument, called *object properties* or *abstract roles* (DL)

- properties with datatype literals in second argument are called *data properties* or *concrete roles* (DL)

- allowed are many XML Schema datatypes, including \texttt{xsd:integer}, \texttt{xsd:string}, \texttt{xsd:float}, \texttt{xsd:boolean}, \texttt{xsd:anyURI}, \texttt{xsd:dateTime}

and also e.g. \texttt{owl:real}
(D) – datatypes

- hasAge(john, "51"^^xsd:integer)

- additional use of constraining facets (from XML Schema)
  - e.g. Teenager \equiv Person \sqcap \exists \text{hasAge.}(xsd:integer: \geq 12 \text{ and } \leq 19)
  
  note: this is not standard DL notation!
Understanding SROIQ(D)

further expressive features

• **Self**
  – `PersonCommittingSuicide ≡ ∃kills.Self`

• **Keys** (not really in SROIQ(D), but in OWL)
  – set of (object or data) properties whose values uniquely identify an object

• **disjoint properties**
  – `Disjoint(hasParent,hasChild)`

• **explicit anonymous individuals**
  – as in RDF: can be used instead of named individuals
SROIQ(D) constructors – overview

- **ABox assignments of individuals to classes or properties**
- **ALC:** $\subseteq, \equiv$ for classes
  $\land, \lor, \neg, \exists, \forall$
  $\top, \bot$
- **SR:** + property chains, property characteristics, role hierarchies $\subseteq$
- **SRO:** + nominals $\{o\}$
- **SROI:** + inverse properties
- **SROIQ:** + qualified cardinality constraints
- **SROIQ(D):** + datatypes (including **facets**)
- + **top and bottom roles** (for objects and datatypes)
- + **disjoint properties**
- + **Self**
- + **Keys** (not in SROIQ(D), but in OWL)
Some Syntactic Sugar in OWL

This applies to the non-DL syntaxes (e.g. RDF syntax).

• disjoint classes
  – Apple ∩ Pear ⊑ ⊥

• disjoint union
  – Parent ≡ Mother ⊕ Father
    Mother ∩ Father ⊑ ⊥

• negative property assignments (also for datatypes)
  – ¬hasAge(jack,"53"^^xsd:integer)
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OWL – Extralogical Features

- **OWL ontologies** have URIs and can be referenced by others via
  - import statements
- **Namespace declarations**
- **Entity declarations** (must be done)
- **Versioning information etc.**

- **Annotations**
  - Entities and axioms (statements) can be endowed with annotations, e.g. using `rdfs:comment`.
  - **OWL syntax** provides *annotation properties* for this purpose.
The modal logic perspective

• Description logics can be understood from a modal logic perspective.

• Each pair of $\forall R$ and $\exists R$ statements give rise to a pair of modalities.

• Essentially, some description logics are multi-modal logics.

• See e.g. Baader et al., The Description Logic Handbook, Cambridge University Press, 2007.
The RDFS perspective

- :mary rdf:type :Person .
- :Mother rdfs:subClassOf :Woman .
- :john :hasWife :Mary .
- :hasWife rdfs:subPropertyOf :hasSpouse
- :hasWife rdfs:range :Woman .
- :hasWife rdfs:domain :Man .
- Person(mary)
- Mother ⊆ Woman
- hasWife(john,mary)
- hasWife ⊆ hasSpouse
- T ⊆ ∀ hasWife.Woman
- T ⊆ ∀ hasWife−.Man or ∃ hasWife. T ⊆ Man

RDFS also allows to
- make statements about statements → only possible through annotations in OWL
- mix class names, individual names, property names (they are all URIs) → punning in OWL
Punning

- Description logics impose *type separation*, i.e. names of individuals, classes, and properties must be disjoint.

- In OWL 2 Full, type separation does not apply.

- In OWL 2 DL, type separation is relaxed, but a class X and an individual X are interpreted semantically as if they were different.

- Father(john)  
  SocialRole(Father)

- See further below on the two different semantics for OWL.
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OWL Semantics

• There are two semantics for OWL.

1. Description Logic Semantics
   also: Direct Semantics; FOL Semantics
   Can be obtained by translation to FOL.
   Syntax restrictions apply! (see next slide)

2. RDF-based Semantics
   No syntax restrictions apply.
   Extends the direct semantics with RDFS-reasoning features.

In the following, we will deal with the direct semantics only.
OWL Direct Semantics

To obtain decidability, syntactic restrictions apply.

- Type separation / punning
- No cycles in property chains.
- No transitive properties in cardinality restrictions.
OWL Direct Semantics: Restrictions

- arbitrary property chain axioms lead to undecidability
- restriction: set of property chain axioms has to be regular
  - there must be a strict linear order \(<\) on the properties
  - every property chain axiom has to have one of the following forms:
    - \(R \circ R \subseteq R\)
    - \(S^{-} \subseteq R\)
    - \(S_{1} \circ S_{2} \circ \ldots \circ S_{n} \subseteq R\)
    - \(R \circ S_{1} \circ S_{2} \circ \ldots \circ S_{n} \subseteq R\)
    - \(S_{1} \circ S_{2} \circ \ldots \circ S_{n} \circ R \subseteq R\)
  - thereby, \(S_{i} < R\) for all \(i = 1, 2, \ldots, n\).

- Example 1: \(R \circ S \subseteq R\)  \(S \circ S \subseteq S\)  \(R \circ S \circ R \subseteq T\)  
  \(\rightarrow\) regular with order \(S < R < T\)

- Example 2: \(R \circ T \circ S \subseteq T\)  
  \(\rightarrow\) not regular because form not admissible

- Example 3: \(R \circ S \subseteq S\)  \(S \circ R \subseteq R\)  
  \(\rightarrow\) not regular because no adequate order exists
combining property chain axioms and cardinality constraints may lead to undecidability

restriction: use only *simple* properties in cardinality expressions (i.e. those which cannot be – directly or indirectly – inferred from property chains)

technically:
- for any property chain axiom $S_1 \circ S_2 \circ \ldots \circ S_n \subseteq R$ with $n > 1$, $R$ is non-simple
- for any subproperty axiom $S \subseteq R$ with $S$ non-simple, $R$ is non-simple
- all other properties are simple

Example: $Q \circ P \subseteq R \quad R \circ P \subseteq R \quad R \subseteq S \quad P \subseteq R \quad Q \subseteq S$
non-simple: $R, S$ simple: $P, Q$
OWL Direct Semantics

- model-theoretic semantics
- starts with interpretations
- an interpretation maps individual names, class names and property names...

...into a domain
• mapping is extended to complex class expressions:
  - \( \top^I = \Delta^I \)
  - \( \perp^I = \emptyset \)
  - \((C \cap D)^I = C^I \cap D^I\)
  - \((C \cup D)^I = C^I \cup D^I\)
  - \((-C)^I = \Delta^I \setminus C^I\)
  - \(\forall R.C = \{ x \mid \forall (x,y) \in R^I \rightarrow y \in C^I \}\)
  - \(\exists R.C = \{ x \mid \exists (x,y) \in R^I \land y \in C^I \}\)
  - \(\geq n R.C = \{ x \mid \#\{ y \mid (x,y) \in R^I \land y \in C^I \} \geq n \}\)
  - \(\leq n R.C = \{ x \mid \#\{ y \mid (x,y) \in R^I \land y \in C^I \} \leq n \}\)

• ...and to role expressions:
  - \(U^I = \Delta^I \times \Delta^I\)
  - \((R^-)^I = \{ (y,x) \mid (x,y) \in R^I \}\)

• ...and to axioms:
  - \(C(a)\) holds, if \(a^I \in C^I\)
  - \(R(a,b)\) holds, if \((a^I,b^I) \in R^I\)
  - \(C \subseteq D\) holds, if \(C^I \subseteq D^I\)
  - \(R \subseteq S\) holds, if \(R^I \subseteq S^I\)
  - \(\text{Dis}(R,S)\) holds if \(R^I \cap S^I = \emptyset\)
  - \(S_1 \circ S_2 \circ \ldots \circ S_n \subseteq R\) holds if \(S_1^I \circ S_2^I \circ \ldots \circ S_n^I \subseteq R^I\)
• but often OWL 2 DL is said to be a fragment of FOL (with equality)...
• yes, there is a translation of OWL 2 DL into FOL...

\[
\begin{align*}
\pi(C \sqsubseteq D) &= (\forall x)(\pi_x(C) \rightarrow \pi_x(D)) \\
\pi_x(A) &= A(x) \\
\pi_x(\neg C) &= \neg \pi_x(C) \\
\pi_x(C \cap D) &= \pi_x(C) \land \pi_x(D) \\
\pi_x(C \cup D) &= \pi_x(C) \lor \pi_x(D) \\
\pi_x(\forall R. C) &= (\forall x_1)(R(x, x_1) \rightarrow \pi_{x_1}(C)) \\
\pi_x(\exists R. C) &= (\exists x_1)(R(x, x_1) \land \pi_{x_1}(C)) \\
\pi_x(\geq n S. C) &= (\exists x_1) \ldots (\exists x_n) \left( \bigwedge_{i \neq j} (x_i \neq x_j) \land \bigwedge_i (S(x, x_i) \land \pi_{x_i}(C)) \right) \\
\pi_x(\leq n S. C) &= \neg (\exists x_1) \ldots (\exists x_{n+1}) \left( \bigwedge_{i \neq j} (x_i \neq x_j) \land \bigwedge_i (S(x, x_i) \land \pi_{x_i}(C)) \right) \\
\pi_x(\{a\}) &= (x = a) \\
\pi_x(\exists S.Self) &= S(x, x)
\end{align*}
\]

\[
\begin{align*}
\pi(R_1 \sqsubseteq R_2) &= (\forall x)(\forall y)(\pi_{x,y}(R_1) \rightarrow \pi_{x,y}(R_2)) \\
\pi_{x,y}(S) &= S(x, y) \\
\pi_{x,y}(R) &= \pi_{y,x}(R) \\
\pi_{x,y}(R_1 \circ \ldots \circ R_n) &= (\exists x_1) \ldots (\exists x_{n-1}) \left( \pi_{x,x_1}(R_1) \land \bigwedge_{t=1}^{n-2} \pi_{x_t,x_{t+1}}(R_{t+1}) \land \pi_{x_{n-1},y}(R_n) \right) \\
\pi(Ref(R)) &= (\forall x)\pi_{x,x}(R) \\
\pi(Asy(R)) &= (\forall x)(\forall y)(\pi_{x,y}(R) \rightarrow \neg \pi_{y,x}(R)) \\
\pi(Dis(R_1, R_2)) &= \neg (\exists x)(\exists y)(\pi_{x,y}(R_1) \land \pi_{x,y}(R_2))
\end{align*}
\]

…which (interpreted under FOL semantics) coincides with the definition just given.
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OWL Profiles

- OWL Full – using the RDFS-based semantics
- OWL DL – using the FOL semantics

The OWL 2 documents describe further profiles, which are of polynomial complexity:

- OWL EL (EL++)
- OWL QL (DL Lite$_R$)
- OWL RL (DLP)
• allowed:
  – subclass axioms with intersection, existential quantification, top, bottom
    • closed classes must have only one member
  – property chain axioms, range restrictions (under certain conditions)

• disallowed:
  – negation, disjunction, arbitrary universal quantification, role inverses

\[ \exists x \subseteq \bot \]

• Examples: Human \( \subseteq \exists\text{hasParent}\).Person
  \( \exists\text{married}.\top \cap \text{CatholicPriest} \subseteq \bot; \)
  hasParent \( \circ \) hasParent \( \subseteq \) hasGrandparent
Motivated by the question: what fraction of OWL 2 DL can be expressed \textit{naively} by rules (with equality)?

Examples:

- \(\exists\text{parentOf.}\exists\text{parentOf.} \top \sqsubseteq \text{Grandfather}\)
  
  \textit{rule version:} \(\text{parentOf}(x,y)\ \text{parentOf}(y,z) \rightarrow \text{Grandfather}(x)\)

- \(\forall\text{hasParent.}\exists\text{Dead}\)
  
  \textit{rule version:} \(\text{Orphan}(x)\ \text{hasParent}(x,y) \rightarrow \text{Dead}(y)\)

- \(\leq 1\text{married.}\exists\text{Alive}\)
  
  \textit{rule version:} \(\text{Monogamous}(x)\ \text{married}(x,y)\ \text{Alive}(y)\ \text{married}(x,z)\ \text{Alive}(z) \rightarrow y=z\)

- \(\text{childOf} \circ \text{childOf} \sqsubseteq \text{grandchildOf}\)
  
  \textit{rule version:} \(\text{childOf}(x,y)\ \text{childOf}(y,z) \rightarrow \text{grandchildOf}(x,z)\)

- \(\text{Disj(\text{childOf,}\text{parentOf})}\)
  
  \textit{rule version:} \(\text{childOf}(x,y)\ \text{parentOf}(x,y) \rightarrow \)
• **Syntactic characterization:**
  – essentially, all axiom types are allowed
  – disallow certain constructors on lhs and rhs of subclass statements

  \[ \forall \neg \exists \subseteq \exists \]

  – cardinality restrictions: only on rhs and only \( \leq 1 \) and \( \leq 0 \) allowed
  – closed classes: only with one member

• **Reasoner conformance requires only soundness.**
• Motivated by the question: what fraction of OWL 2 DL can be captured by standard database technology?

• Formally: query answering LOGSPACE w.r.t. data (via translation into SQL)

• Allowed:
  – subproperties, domain, range
  – subclass statements with
    • left hand side: class name or expression of type $\exists r. T$
    • right hand side: intersection of class names, expressions of type $\exists r. C$ and negations of lhs expressions
    • no closed classes!

• Example:
  $\exists \text{married.} \top \sqsubseteq \neg \text{Free} \sqcap \exists \text{has.Sorrow}$
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Proof Theory

• Traditionally using tableaux algorithms (see below)

Alternatives:
• Transformation to disjunctive datalog using basic superposition done for SHIQ
• Naive mapping to Datalog for OWL RL
• Mapping to SQL for OWL QL
• Special-purpose algorithms for OWL EL e.g. transformation to Datalog
Proof theory Via Tableaux

- Adaptation of FOL tableaux algorithms.

- Problem: OWL is decidable, but FOL tableaux algorithms do not guarantee termination.

- Solution: blocking.
**DL Tableaux Termination Problem**

TBox: $\exists R. T$

ABox: $T(a_1)$

- Is satisfiable:
  Model $M$ contains elements $a_1^M, a_2^M, ...$
  and $R^M(a_i^M, a_{i+1}^M)$ for all $i \geq 1$.
- But naive tableau does not terminate!
Nothing essentially new happens.

Idea: $y$ does not need to be expanded, because it is basically a copy of $x$.

$\Rightarrow$ Blocking
• **y is blocked (by x) if**
  – y is not an individual (but a variable),
  – y is a successor of x and $L(y) \subseteq L(x)$,
  – or an ancestor of y is blocked.

$\exists$R. T

$\exists$R. T

$\exists$R. T

y blocked by x in this example.

Blocking conditions for more expressive DLs are more involved; the idea is the same.
Show that

\( C(a) \quad \text{C(c)} \)

\( R(a,b) \quad \text{R(a,c)} \)

\( S(a,a) \quad \text{S(c,b)} \)

\( C \sqsubseteq \forall S.A \)

\( A \sqsubseteq \exists R.\exists S.A \)

\( A \sqsubseteq \exists R.C \)

implies \( \exists R.\exists R.\exists S.A(a) \).
ALC Tableau Example

TBox:
¬C ⊓ ∀S.A
¬A ⊓ ∃R.∃S.A
¬A ⊓ ∃R.C

¬∃R.∃R.∃S.A(a) is ∀R.∀R.∀S.¬A(a)

ABox
C(a)  C(c)
R(a,b)  R(a,c)
S(a,a)  S(c,b)

A
∀R.∀S.¬A
∀S.¬A
∃S.A
∀R.∃S.A

C
∀R.∀R.∀S.¬A
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OWL tools (incomplete listing)

Reasoner:
- **OWL 2 DL:**
  - Pellet  http://clarkparsia.com/pellet/
  - Hermit  http://www.hermit-reasoner.com/
- **OWL 2 EL:**
  - CEL  http://code.google.com/p/cel/
- **OWL 2 RL:**
  - essentially any rule engine
- **OWL 2 QL:**
  - essentially any SQL engine (with a bit of query rewriting on top)

Editors:
- Protégé
- NeOn Toolkit
- TopBraid Composer
Part 2

OWL 2 and Rules
Main References:


Contents

- Motivation: OWL and Rules
- Preliminaries: Datalog

- More rules than you ever need: SWRL
- Retaining decidability I: DL-safety
- Retaining decidability II: DL Rules

- The rules hidden in OWL 2: SROIQ Rules
- Retaining tractability I: OWL 2 EL Rules
- Retaining tractability II: DLP 2

- Retaining tractability III: ELP

putting it all together

Extending OWL with Rules

Rules inside OWL
Motivation: OWL and Rules

- Rules (mainly, logic programming) as alternative ontology modelling paradigm.
- Similar tradition, and in use in practice (e.g. F-Logic)

- Ongoing: W3C RIF working group
  - Rule Interchange Format
  - based on Horn-logic
  - language standard forthcoming 2009

- Seek: Integration of rules paradigm with ontology paradigm
  - Here: Tight Integration in the tradition of OWL
  - Foundational obstacle: reasoning efficiency / decidability
    [naive combinations are undecidable]
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Extending OWL with Rules

Rules inside OWL

putting it all together
Preliminaries: Datalog

• Essentially Horn-rules without function symbols

general form of the rules:

\[ p_1(x_1,\ldots,x_n) \land \ldots \land p_m(y_1,\ldots,y_k) \rightarrow q(z_1,\ldots,z_j) \]

semantics either as in predicate logic
or as Herbrand semantics (see next slide)

• decidable
• polynomial data complexity (in number of facts)
• combined (overall) complexity: ExpTime
• combined complexity is P if the number of variables per rule is
globally bounded
Datalog semantics example

• Example:
  \( p(x) \rightarrow q(x) \)
  \( q(x) \rightarrow r(x) \)
  \( \rightarrow p(a) \)

• Predicate logic semantics:
  \( \forall x \) (\( p(x) \rightarrow r(x) \))
  and
  \( \forall x \) (\( \neg r(x) \rightarrow \neg p(x) \))
  are logical consequences

  \( q(a) \) and \( r(a) \)
  are logical consequences

• Herbrand semantics
  those on the left are not logical consequences

  \( q(a) \) and \( r(a) \)
  are logical consequences

  Material implication:
  apply only to known constants
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Extending OWL with Rules

Rules inside OWL

putting it all together
More rules than you ever need: SWRL

- Union of OWL DL with (binary) function-free Horn rules (with binary Datalog rules)
  - undecidable
  - no native tools available
  - rather an overarching formalism

- see http://www.w3.org/Submission/SWRL/
SWRL example (running example)

NutAllergic(sebastian)
NutProduct(peanutOil)
∃orderedDish.ThaiCurry(sebastian)

ThaiCurry ⊆ ∃contains.{peanutOil}
T ⊆ ∀orderedDish.Dish

NutAllergic(x) ∧ NutProduct(y) → dislikes(x,y)
dislikes(x,z) ∧ Dish(y) ∧ contains(y,z) → dislikes(x,y)
orderedDish(x,y) ∧ dislikes(x,y) → Unhappy(x)
NutAllergic(sebastian)
NutProduct(peanutOil)
\( \exists \text{orderedDish}. \text{ThaiCurry}(\text{sebastian}) \)

ThaiCurry \( \subseteq \exists \text{contains}. \{ \text{peanutOil} \} \)
\( \top \subseteq \forall \text{orderedDish}. \text{Dish} \)

NutAllergic(x) \land NutProduct(y) \rightarrow dislikes(x,y)
dislikes(x,z) \land Dish(y) \land contains(y,z) \rightarrow dislikes(x,y)
orderedDish(x,y) \land dislikes(x,y) \rightarrow Unhappy(x)

Conclusions:
dislikes(sebastian,peanutOil)
SWRL example (running example)

NutAllergic(sebastian)
NutProduct(peanutOil)
\exists \text{orderedDish}.\text{ThaiCurry}(sebastian)

\text{ThaiCurry} \subseteq \exists \text{contains}.\{\text{peanutOil}\}
\top \subseteq \forall \text{orderedDish}.\text{Dish}

\text{orderedDish} \text{rdfs:range Dish.}

\text{NutAllergic}(x) \land \text{NutProduct}(y) \rightarrow \text{dislikes}(x,y)
\text{dislikes}(x,z) \land \text{Dish}(y) \land \text{contains}(y,z) \rightarrow \text{dislikes}(x,y)
\text{orderedDish}(x,y) \land \text{dislikes}(x,y) \rightarrow \text{Unhappy}(x)

Conclusions:
\text{dislikes}(sebastian,peanutOil)
\text{orderedDish}(sebastian,y_s)
\text{ThaiCurry}(y_s)
\text{Dish}(y_s)
SWRL example (running example)

NutAllergic(sebastian)
NutProduct(peanutOil)
∃orderedDish.ThaiCurry(sebastian)

\[
\begin{align*}
\text{ThaiCurry} & \subseteq \exists \text{contains.}{\text{peanutOil}} \\
\top & \subseteq \forall \text{orderedDish.Dish}
\end{align*}
\]

NutAllergic(x) ∧ NutProduct(y) → dislikes(x,y)
dislikes(x,z) ∧ Dish(y) ∧ contains(y,z) → dislikes(x,y)
orderedDish(x,y) ∧ dislikes(x,y) → Unhappy(x)

Conclusions:
dislikes(sebastian,peanutOil)
contains(y_s,peanutOil)
orderedDish(sebastian,y_s)
ThaiCurry(y_s)
Dish(y_s)
SWRL example (running example)

NutAllergic(sebastian)
NutProduct(peanutOil)
∃orderedDish.ThaiCurry(sebastian)

\[ \text{ThaiCurry} \subseteq \exists \text{contains.\{peanutOil\} \quad \top \subseteq \forall \text{orderedDish.Dish} \]

\[ \text{NutAllergic}(x) \land \text{NutProduct}(y) \rightarrow \text{dislikes}(x,y) \]
\[ \text{dislikes}(x,z) \land \text{Dish}(y) \land \text{contains}(y,z) \rightarrow \text{dislikes}(x,y) \]
\[ \text{orderedDish}(x,y) \land \text{dislikes}(x,y) \rightarrow \text{Unhappy}(x) \]

Conclusions:
\[ \text{dislikes}(\text{sebastian},\text{peanutOil}) \]
\[ \text{contains}(y_{s},\text{peanutOil}) \]
\[ \text{dislikes}(\text{sebastian},y_{s}) \]
\[ \text{orderedDish}(\text{sebastian},y_{s}) \]
\[ \text{ThaiCurry}(y_{s}) \]
\[ \text{Dish}(y_{s}) \]
SWRL example (running example)

NutAllergic(sebastian)
NutProduct(peanutOil)
\(\exists\)orderedDish.ThaiCurry(sebastian)

\[\text{ThaiCurry} \subseteq \exists\text{contains.}\{\text{peanutOil}\}\]
\[\top \subseteq \forall\text{orderedDish.Dish}\]

NutAllergic(x) \land NutProduct(y) \rightarrow dislikes(x,y)
dislikes(x,z) \land Dish(y) \land contains(y,z) \rightarrow dislikes(x,y)

orderedDish(x,y) \land dislikes(x,y) \rightarrow Unhappy(x)

Conclusions:
dislikes(sebastian,peanutOil)
contains(y_s,peanutOil)
orderedDish(sebastian,y_s)
dislikes(sebastian,y_s)
ThaiCurry(y_s)
Dish(y_s)
Unhappy(sebastian)
NutAllergic(sebastian)
NutProduct(peanutOil)
\exists orderedDish.ThaiCurry(sebastian)

\textbf{ThaiCurry} \subseteq \exists \text{contains}.\{\text{peanutOil}\}
T \subseteq \forall \text{orderedDish}.\text{Dish}

\text{NutAllergic}(x) \land \text{NutProduct}(y) \rightarrow \text{dislikes}(x,y)
\text{dislikes}(x,z) \land \text{Dish}(y) \land \text{contains}(y,z) \rightarrow \text{dislikes}(x,y)
\text{orderedDish}(x,y) \land \text{dislikes}(x,y) \rightarrow \text{Unhappy}(x)

\textbf{Conclusion: Unhappy}(sebastian)
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- Extending OWL with Rules
- Rules inside OWL
- putting it all together
Retaining decidability I: DL-safety

• Reinterpret SWRL rules:
  Rules apply only to individuals which are explicitly given in the knowledge base.
  – Herbrand-style way of interpreting them

• OWL DL + DL-safe SWRL is decidable

• Native support e.g. by KAON2 and Pellet

DL-safe SWRL example

\[
\begin{align*}
\text{NutAllergic} & (\text{sebastian}) \\
\text{NutProduct} & (\text{peanutOil}) \\
\exists \text{orderedDish} & . \text{ThaiCurry} (\text{sebastian}) \\
\end{align*}
\]

\[
\begin{align*}
\text{ThaiCurry} & \sqsubseteq \exists \text{contains} . \{ \text{peanutOil} \} \\
\top & \sqsubseteq \forall \text{orderedDish} . \text{Dish} \\
\end{align*}
\]

\[
\begin{align*}
\text{NutAllergic}(x) \land \text{NutProduct}(y) & \rightarrow \text{dislikes}(x,y) \\
\text{dislikes}(x,z) \land \text{Dish}(y) \land \text{contains}(y,z) & \rightarrow \text{dislikes}(x,y) \\
\text{orderedDish}(x,y) \land \text{dislikes}(x,y) & \rightarrow \text{Unhappy}(x) \\
\end{align*}
\]

Unhappy(sebastian) cannot be concluded
DL-safe SWRL example

NutAllergic(sebastian)
NutProduct(peanutOil)
\exists orderedDish.ThaiCurry(sebastian)

\text{ThaiCurry} \sqsubseteq \exists \text{contains.} \{\text{peanutOil}\}
\text{T} \sqsubseteq \forall \text{orderedDish.Dish}

\text{Dislikes(x, y)} \rightarrow \text{Unhappy(x)}

Conclusions:
\text{dislikes(sebastian, peanutOil)}
\text{orderedDish(sebastian, } y_s \text{)}
\text{ThaiCurry}(y_s)
\text{Dish}(y_s)
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Putting it all together

Extending OWL with Rules

Rules inside OWL
Retaining decidability II: DL Rules

- General idea:
  Find out which rules can be encoded in OWL (2 DL) anyway

- $\text{Man}(x) \land \text{hasBrother}(x,y) \land \text{hasChild}(y,z) \rightarrow \text{Uncle}(x)$
  - $\text{Man} \sqcap \exists \text{hasBrother}.\exists \text{hasChild}.\top \sqsubseteq \text{Uncle}$

- $\text{ThaiCurry}(x) \rightarrow \exists \text{contains.FishProduct}(x)$
  - $\text{ThaiCurry} \sqsubseteq \exists \text{contains.FishProduct}$

- $\text{kills}(x,x) \rightarrow \text{suicide}(x)$
  - $\exists \text{kills.Self} \sqsubseteq \text{suicide}$

Note: with these two axioms, $\text{suicide}$ is basically the same as $\text{kills}$
DL Rules: more examples

• NutAllergic(x) \land NutProduct(y) \rightarrow dislikes(x,y)
  – NutAllergic \equiv \exists nutAllergic.Self
  NutProduct \equiv \exists nutProduct.Self
  nutAllergic o U o nutProduct \sqsubseteq dislikes

• dislikes(x,z) \land Dish(y) \land contains(y,z) \rightarrow dislikes(x,y)
  – Dish \equiv \exists dish.Self
    dislikes o contains^\rightarrow o dish \sqsubseteq dislikes

• worksAt(x,y) \land University(y) \land supervises(x,z) \land PhDStudent(z)
  \rightarrow professorOf(x,z)
  – \exists worksAt.University \equiv \exists worksAtUniversity.Self
    PhDStudent \equiv \exists phDStudent.Self
    worksAtUniversity o supervises o phDStudent \sqsubseteq professorOf
DL Rules: definition

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

\[ C(x) \land R(x,a) \land S(x,y) \land D(y) \land T(y,a) \rightarrow E(x) \]

- \[ C \cap \exists R.\{a\} \cap \exists S. \left( D \cap \exists T.\{a\} \right) \subseteq E \]
DL Rules: definition

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

\[ C(x) \land R(x,a) \land S(x,y) \land D(y) \land T(y,a) \rightarrow V(x,y) \]

\[ C \sqcap \exists R.\{a\} \sqsubseteq \exists R1.\text{Self} \]
\[ D \sqcap \exists T.\{a\} \sqsubseteq \exists R2.\text{Self} \]
\[ R1 \circ S \circ R2 \sqsubseteq V \]
DL Rules: definition

- Tree-shaped bodies
- First argument of the conclusion is the root
- Complex classes are allowed in the rules
  - \( \text{Mouse}(x) \land \exists \text{hasNose.TrunkLike}(y) \rightarrow \text{smallerThan}(x,y) \)
  - \( \text{ThaiCurry}(x) \rightarrow \exists \text{contains.FishProduct}(x) \)

Note: This allows to reason with unknowns (unlike Datalog)

- Allowed class constructors depend on the chosen underlying description logic!
Given a description logic $\mathcal{D}$, the language $\mathcal{D}$ Rules consists of:

- all axioms expressible in $\mathcal{D}$,
- plus all rules with
  - tree-shaped bodies, where
  - the first argument of the conclusion is the root, and
  - complex classes from $\mathcal{D}$ are allowed in the rules.
- <plus possibly some restrictions concerning e.g. the use of simple roles – depending on $\mathcal{D}$>
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Putting it all together
The rules hidden in OWL 2: SROIQ Rules

- N2ExpTime complete
- In fact, SROIQ Rules can be translated into SROIQ i.e. they don't add expressivity.
  
  Translation is polynomial.
- SROIQ Rules are essentially helpful syntactic sugar for OWL 2.
SROIQ Rules example

NutAllergic(sebastian)
NutProduct(peanutOil)
\exists orderedDish. ThaiCurry(sebastian)

\textbf{ThaiCurry} \subseteq \exists \text{contains.\{peanutOil\}}
\top \subseteq \forall \text{orderedDish. Dish}

\textbf{NutAllergic}(x) \land \textbf{NutProduct}(y) \rightarrow \text{dislikes}(x,y)
\text{dislikes}(x,z) \land \text{Dish}(y) \land \text{contains}(y,z) \rightarrow \text{dislikes}(x,y)
\textbf{orderedDish}(x,y) \land \text{dislikes}(x,y) \rightarrow \textbf{Unhappy}(x)

\textbf{not a SROIQ Rule!}
SROIQ Rules normal form

- Each SROIQ Rule can be written ("linearised") such that
  - the body-tree is linear,
  - if the head is of the form $R(x,y)$, then $y$ is the leaf of the tree, and
  - if the head is of the form $C(x)$, then the tree is only the root.

- $\text{worksAt}(x,y) \land \text{University}(y) \land \text{supervises}(x,z) \land \text{PhDStudent}(z) \rightarrow \text{professorOf}(x,z)$
  - $\exists \text{worksAt.University}(x) \land \text{supervises}(x,z) \land \text{PhDStudent}(z) \rightarrow \text{professorOf}(x,z)$

- $C(x) \land R(x,a) \land S(x,y) \land D(y) \land T(y,a) \rightarrow V(x,y)$
  - $\{C \sqcap \exists R.\{a\}\}(x) \land S(x,y) \land \{D \sqcap \exists T.\{a\}\}(y) \rightarrow V(x,y)$
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- Retaining tractability III: ELP

putting it all together

Extending OWL with Rules

Rules inside OWL
Retaining tractability I: OWL 2 EL Rules

- EL++ Rules are PTime complete
- EL++ Rules offer expressivity which is not readily available in EL++.
OWL 2 EL Rules: normal form

• Every EL++ Rule can be converted into a normal form, where
  – occurring classes in the rule body are either atomic or nominals,
  – all variables in a rule's head occur also in its body, and
  – rule heads can only be of one of the forms $A(x)$, $\exists R.A(x)$, $R(x,y)$, where $A$ is an atomic class or a nominal or $\top$ or $\bot$.

• Translation is polynomial.

• $\exists \text{worksAt.University}(x) \land \text{supervises}(x,z) \land \text{PhDStudent}(z) \rightarrow \text{professorOf}(x,z)$

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

• $\text{ThaiCurry}(x) \rightarrow \exists \text{contains}.\text{FishProduct}(x)$
Essentially, OWL 2 EL Rules is

- Binary Datalog with tree-shaped rule bodies,
- extended by
  - occurrence of nominals as atoms and
  - existential class expressions in the head.

- The existentials really make the difference.

- Arguably the better alternative to OWL 2 EL (aka EL++)?
  - (which is covered anyway)
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Extending OWL with Rules

Putting it all together
Retaining tractability II: DLP 2

- DLP 2 is
  - DLP (aka OWL 2 RL) extended with
  - DL rules, which use
    - left-hand-side class expressions in the bodies and
    - right-hand-side class expressions in the head.

- Polynomial transformation into 5-variable Horn rules.

- PTime.

- Quite a bit more expressive than DLP / OWL 2 RL ...
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Putting it all together
Retaining tractability III: ELP (aka putting it all together)

- ELP is
  - OWL 2 EL Rules +
  - a generalisation of DL-safety +
  - variable-restricted DL-safe Datalog +
  - role conjunctions (for simple roles).

- PTime complete.
- Contains OWL 2 EL and OWL 2 RL.
- Covers variable-restricted Datalog.
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).
- DL-safe variables can replace individuals in EL++ rules.

- \( C(x) \land R(x, x_s) \land S(x, y) \land D(y) \land T(y, x_s) \rightarrow E(x) \)
  with \( x_s \) a safe variable is allowed, because
  \( C(x) \land R(x, a) \land S(x, y) \land D(y) \land T(y, a) \rightarrow E(x) \)
  is an EL++ rule.

![Diagram](image-url)
Variable-restricted DL-safe Datalog

- n-Datalog is Datalog, where the number of variables occurring in rules is globally bounded by $n$.

- complexity of n-Datalog is PTime (for fixed $n$)
  - (but exponential in $n$)

- in a sense, this is cheating.

- in another sense, this means that using a few DL-safe Datalog rules together with an EL++ rules knowledge base shouldn't really be a problem in terms of reasoning performance.
Role conjunctions

- \(\text{orderedDish}(x,y) \land \text{dislikes}(x,y) \rightarrow \text{Unhappy}(x)\)

- In fact, role conjunctions can also be added to OWL 2 DL without increase in complexity.

Retaining tractability III: ELP (aka putting it all together)

- $\text{ELP}_n$ is
  - OWL 2 EL Rules generalised by DL-safe variables +
  - DL-safe Datalog rules with at most $n$ variables +
  - role conjunctions (for simple roles).

- PTime complete (for fixed $n$).
  - exponential in $n$
- Contains OWL 2 EL and OWL 2 RL.
- Covers all Datalog rules with at most $n$ variables. (!)
ELP example

NutAllergic(sebastian)
NutProduct(peanutOil)
∃orderedDish.ThaiCurry(sebastian)

ThaiCurry ⊆ ∃contains.{peanutOil}
T ⊆ ∀orderedDish.Dish

[okay]
NutAllergic(x) ∧ NutProduct(y) → dislikes(x,y)
dislikes(x,z) ∧ Dish(y) ∧ contains(y,z) → dislikes(x,y)
orderedDish(x,y) ∧ dislikes(x,y) → Unhappy(x)

[okay – role conjunction]

not an EL++ rule
ELP example

- dislikes(x,z) ∧ Dish(y) ∧ contains(y,z) → dislikes(x,y)

as SROIQ rule translates to

\[
\text{Dish} \equiv \exists\text{dish} \cdot \text{Self}
\]

\[
\text{dislikes} \circ \text{contains}^- \circ \text{dish} \sqsubseteq \text{dislikes}
\]

but we don't have inverse roles in ELP!

- solution: make z a DL-safe variable:

\[
\text{dislikes}(x,!z) \land \text{Dish}(y) \land \text{contains}(y,!z) \rightarrow \text{dislikes}(x,y)
\]

this is fine 😊
DL-safe SWRL example

NutAllergic(sebastian)
NutProduct(peanutOil)
∃orderedDish.ThaiCurry(sebastian)

ThaiCurry ⊑ ∃contains.{peanutOil}
T ⊑ ∀orderedDish.Dish

NutAllergic(x) ∧ NutProduct(y) → dislikes(x,y)
dislikes(x,!z) ∧ Dish(y) ∧ contains(y,!z) → dislikes(x,y)

Conclusions:
dislikes(sebastian,peanutOil)
contains(y_s,peanutOil)
dislikes(sebastian,y_s)
orderedDish(sebastian,y_s)
ThaiCurry(y_s)
Dish(y_s)
ELP example

NutAllergic(sebastian)
NutProduct(peanutOil)
\exists orderedDish. ThaiCurry(sebastian)

ThaiCurry \subseteq \exists contains\{peanutOil\}
T \subseteq \forall orderedDish. Dish

NutAllergic(x) \land NutProduct(y) \rightarrow dislikes(x,y)
dislikes(x,!z) \land Dish(y) \land contains(y,!z) \rightarrow dislikes(x,y)
orderedDish(x,y) \land dislikes(x,y) \rightarrow Unhappy(x)

Conclusion: Unhappy(sebastian)
ELP Reasoner ELLY

- Implementation currently being finalised.
- Based on IRIS Datalog reasoner.
- In cooperation with STI Innsbruck (Barry Bishop, Daniel Winkler, Gulay Unel).
The Big Picture

ELP

OWL 2
= SROIQ Rules

OWL 2 EL Rules

OWL 2 EL

>ExpTime
tractable
Thanks!

Closed World and ELP

- There's an extension of ELP using (non-monotonic) closed-world reasoning – based on a well-founded semantics for hybrid MKNF knowledge bases.

The Big Picture II

- ELP
- OWL 2 EL
- OWL 2 EL Rules
- OWL 2
  - = SROIQ Rules
- hybrid ELP
  - (local closed world)

- >ExpTime
- tractable
- data-tractable
References Part 2

- http://www.w3.org/Submission/SWRL/
References Part 2


See also our books


(Grab a flyer.)