OWL 2 Rules

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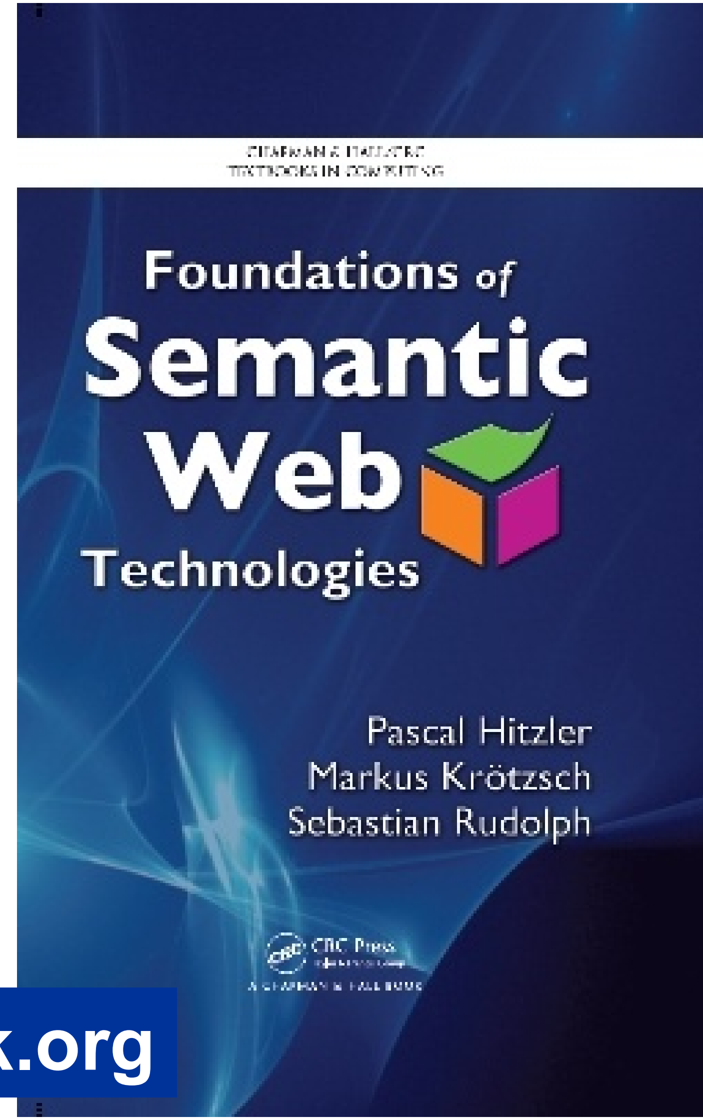
Our Book

Pascal Hitzler, Markus Krötzsch, Sebastian Rudolph

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

Grab a flyer!



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

Slides

Available from

http://www.semantic-web-book.org/page/GeoS2009_Tutorial

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

Main References Part 1

Pascal Hitzler, Markus Krötzsch, Sebastian Rudolph, Foundations of Semantic Web Technologies, Chapman & Hall/CRC, 2009

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

Pascal Hitzler, Markus Krötzsch, Bijan Parsia, Peter F. Patel-Schneider, Sebastian Rudolph, OWL 2 Web Ontology Language: Primer. W3C Recommendation, 27 October 2009. http://www.w3.org/TR/owl2-primer/

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

Contents

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

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

DL syntax / FOL syntax

DL syntax	FOL syntax
Person(mary)	Person(mary)
Woman $\sqsubseteq$ Person – Person ≡ HumanBeing	$\forall$x (Woman(x) $\rightarrow$ Person(x))
hasWife(john,mary)	hasWife(john,mary)
hasWife $\sqsubseteq$ hasSpouse – hasSpouse ≡ marriedWith	$\forall$x $\forall$y (hasWife(x,y)$\rightarrow$ hasSpouse(x,y))

ABox statements

TBox statements

DL syntax	RDFS syntax
• Person(mary)	• :mary rdf:type :Person .
• Woman ⊑ Person – Person ≡ HumanBeing	• :Woman rdfs:subClassOf :Person .
• hasWife(john,mary)	• :john :hasWife :mary .
• hasWife ⊑ hasSpouse – hasSpouse ≡ marriedWith	• :hasWife rdfs:subPropertyOf :hasSpouse .

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 $\sqcap$ Parent**
  - :Mother owl:equivalentClass _:x .
    _:x rdf:type owl:Class .
    _:x owl:intersectionOf (:Woman :Parent) .

$\forall x\ (\mathrm{Mother}(x) \leftrightarrow \mathrm{Woman}(x) \land \mathrm{Parent}(x))$

- **disjunction**
  - **Parent $\equiv$ Mother $\sqcup$ Father**
  - :Parent owl:equivalentClass _:x .
    _:x rdf:type owl:Class .
    _:x owl:unionOf (:Mother :Father) .

$\forall x\ (\mathrm{Parent}(x) \leftrightarrow \mathrm{Mother}(x) \land \mathrm{Father}(x))$

- **negation**
  - **ChildlessPerson $\equiv$ Person $\sqcap$ $\neg$Parent**
  - :ChildlessPerson owl:equivalentClass _:x .
    _:x rdf:type owl:Class .
    _:x owl:intersectionOf (:Person _:y) .
    _:y owl:complementOf :Parent .

$\forall x\ (\mathrm{ChildlessPerson}(x) \leftrightarrow \mathrm{Person}(x) \land \neg\mathrm{Parent}(x))$

Class constructors

- existential quantification
  - only to be used with a role – also called a *property restriction*
  - Parent $\equiv \exists$hasChild.Person
  - :Parent owl:equivalentClass _:x .
    _:x rdf:type owl:Restriction .
    _:x owl:onProperty :hasChild .
    _:x owl:someValuesFrom :Person .

$$\forall x\,(\mathrm{Parent}(x) \leftrightarrow \exists y\,(\mathrm{hasChild}(x,y) \wedge \mathrm{Person}(y)))$$

- universal quantification
  - only to be used with a role – also called a *property restriction*
  - Person $\sqcap$ Happy $\equiv \forall$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 .

$$\forall x\,(\mathrm{Person}(x) \wedge \mathrm{Happy}(x) \leftrightarrow \forall y\,(\mathrm{hasChild}(x,y) \rightarrow \mathrm{Happy}(y)))$$

- Class constructors can be nested arbitrarily

Contents

Understanding SROIQ(D)

The description logic ALC

Complexity: ExpTime

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

- **TBox expressions**
  subclass relationships $\sqsubseteq$

  conjunction $\sqcap$
  disjunction $\sqcup$
  negation $\neg$

  property restrictions $\forall$ $\exists$

Also: $\top$, $\bot$

Understanding SROIQ(D)

ALC + role chains = SR

- **hasParent o hasBrother $\sqsubseteq$ hasUncle**

$$\forall x\ \forall y\ (\exists z\ ((\text{hasParent}(x,z) \wedge \text{hasBrother}(z,y)) \rightarrow \text{hasUncle}(x,y)))$$

  - **includes top property and bottom property**

- **includes S = ALC + transitivity**
  - **hasAncestor o hasAncestor $\sqsubseteq$ hasAncestor**

- **includes SH = S + role hierarchies**
  - **hasFather $\sqsubseteq$ hasParent**

Understanding SROIQ(D)

- O – nominals (closed classes)
  - MyBirthdayGuests $\equiv$ {bill,john,mary}
  - Note the difference to
    MyBirthdayGuests(bill)
    MyBirthdayGuests(john)
    MyBirthdayGuests(mary)

- Individual equality and inequality (no unique name assumption!)
  - bill = john
    - $\{bill\} \equiv \{john\}$
  - bill $\neq$ john
    - $\{bill\} \sqcap \{john\} \equiv \bot$

Understanding SROIQ(D)

- I – inverse roles
  - $hasParent \equiv hasChild^{-}$
  - $Orphan \equiv \forall hasChild^{-}.Dead$
- Q – qualified cardinality restrictions
  - $\leq 4\ hasChild.Parent(john)$
  - $HappyFather \equiv \geq 2\ hasChild.Female$
  - $Car \sqsubseteq =4 hasTyre.\top$
- Complexity SHIQ, SHOQ, SHIO: ExpTime.
  Complexity SHOIQ: NExpTime
  Complexity SROIQ: N2ExpTime

Understanding SROIQ(D)

Properties can be declared to be

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

called *property characteristics*

Understanding SROIQ(D)

(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 xsd:integer, xsd:string, xsd:float, xsd:booelan, xsd:anyURI, xsd:dateTime**

  and also e.g. owl:real

Understanding SROIQ(D)

(D) – datatypes

- **hasAge(john, "51"^^xsd:integer)**
- **additional use of *constraining facets* (from XML Schema)**
  - **e.g. Teenager $\equiv$ Person $\sqcap$ $\exists$hasAge.(xsd:integer: $\geq$12 and $\leq$19)**
    note: this is not standard DL notation!

Understanding SROIQ(D)

further expressive features

- Self
  - PersonCommittingSuicide $\equiv$ $\exists$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: $\sqsubseteq$, $\equiv$ for classes
  $\sqcap$, $\sqcup$, $\neg$, $\exists$, $\forall$
  $\top$, $\bot$
- SR: + property chains, property characteristics,
  role hierarchies $\sqsubseteq$
- 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** $\sqcap$ **Pear** $\sqsubseteq \bot$
- **disjoint union**
  - **Parent** $\equiv$ **Mother** $\sqcup$ **Father**
    Mother $\sqcap$ **Father** $\sqsubseteq \bot$
- **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 ∀R and ∃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

RDFS semantics is weaker

- **:mary rdf:type :Person .**
- **:Mother rdfs:subClassOf :Woman .**
- **:john :hasWife :Mary .**
- **:hasWife rdfs:subPropertyOf :hasSpouse**

- **Person(mary)**
- **Mother $\sqsubseteq$ Woman**
- **hasWife(john,mary)**
- **hasWife $\sqsubseteq$ hasSpouse**

- **:hasWife rdfs:range :Woman .**
- **:hasWife rdfs:domain :Man .**

- **$\top \sqsubseteq \forall$hasWife.Woman**
- **$\top \sqsubseteq \forall$hasWife$^-$.Man or $\exists$hasWife.$\top \sqsubseteq$ Man**

RDFS also allows to

- make statements about statements
  $\rightarrow$ only possible through annotations in OWL
- mix class names, individual names, property names (they are all URIs)
  $\rightarrow$ *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.

Contents

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 $\prec$ on the properties
  - every property chain axiom has to have one of the following forms:

    $R \circ R \sqsubseteq R$ $\quad$ $S^- \sqsubseteq R$ $\quad$ $S_1 \circ S_2 \circ \ldots \circ S_n \sqsubseteq R$

    $R \circ S_1 \circ S_2 \circ \ldots \circ S_n \sqsubseteq R$ $\quad$ $S_1 \circ S_2 \circ \ldots \circ S_n \circ R \sqsubseteq R$
  - thereby, $S_i \prec R$ for all i= 1, 2, . . . , *n.*

- Example 1: $R \circ S \sqsubseteq R$ $\quad$ $S \circ S \sqsubseteq S$ $\quad$ $R \circ S \circ R \sqsubseteq T$

  → regular with order $S \prec R \prec T$
- Example 2: $R \circ T \circ S \sqsubseteq T$

  → not regular because form not admissible
- Example 3: $R \circ S \sqsubseteq S$ $\quad$ $S \circ R \sqsubseteq R$

  → not regular because no adequate order exists

OWL Direct Semantics: Restrictions

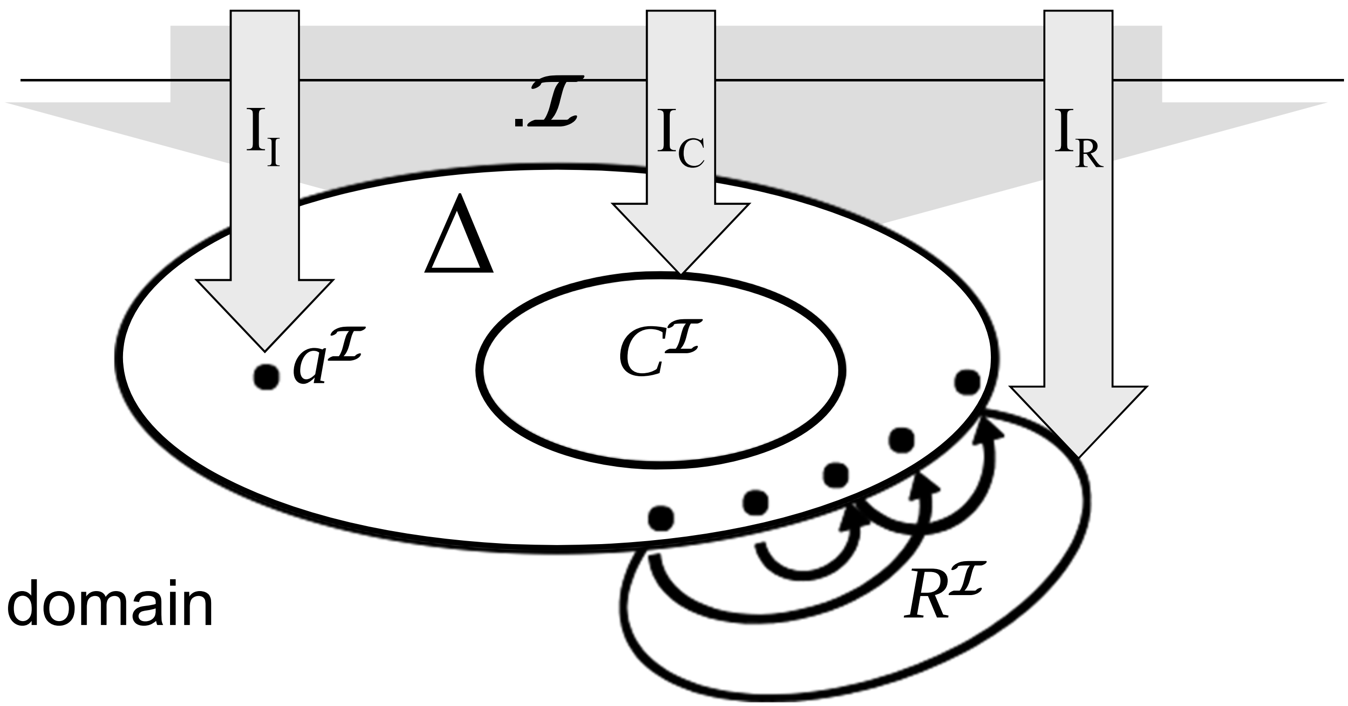
- combining property chain axioms and cardinality constraints may lead to undecidability
- restriction: use only *simple* properties in cardinality expressions (i.e. those which cannot be – directly or indirectly – inferred from property chains)
- technically:
  - for any property chain axiom $S_1 \circ S_2 \circ_{\dots} \circ S_n \sqsubseteq R$ with n>1, R is non-simple
  - for any subproperty axiom $S \sqsubseteq R$ with S non-simple, R is non-simple
  - all other properties are simple
- Example: $Q \circ P \sqsubseteq R$ $\quad R \circ P \sqsubseteq R$ $\quad R \sqsubseteq S$ $\quad P \sqsubseteq R$ $\quad Q \sqsubseteq S$

  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

OWL Direct Semantics

- mapping is extended to complex class expressions:
  - $\top^I = \Delta^I$ $\quad\quad$ $\bot^I = \emptyset$
  - $(C \sqcap D)^I = C^I \cap D^I$ $\quad\quad$ $(C \sqcup D)^I = C^I \cup D^I$ $\quad\quad$ $(\neg C)^I = \Delta^I \setminus C^I$
  - $\forall R.C = \{ x \mid \forall (x,y) \in R^I \rightarrow y \in C^I \}$
    $\exists R.C = \{ x \mid \exists (x,y) \in R^I \wedge y \in C^I \}$
  - $\geq nR.C = \{ x \mid \#\{ y \mid (x,y) \in R^I \wedge y \in C^I \} \geq n \}$
  - $\leq nR.C = \{ x \mid \#\{ y \mid (x,y) \in R^I \wedge y \in C^I \} \leq n \}$
- ...and to role expressions:
  - $U^I = \Delta^I \times \Delta^I$ $\quad\quad$ $(R^-)^I = \{ (y,x) \mid (x,y) \in R^I \}$
- ...and to axioms:
  - $C(a)$ holds, if $a^I \in C^I$ $\quad\quad$ $R(a,b)$ holds, if $(a^I, b^I) \in R^I$
  - $C \sqsubseteq D$ holds, if $C^I \subseteq D^I$ $\quad\quad$ $R \sqsubseteq S$ holds, if $R^I \subseteq S^I$
  - $Dis(R,S)$ holds if $R^I \cap S^I = \emptyset$
  - $S_1 \circ S_2 \circ \ldots \circ S_n \sqsubseteq R$ holds if $S_1^I \circ S_2^I \circ \ldots \circ S_n^I \subseteq R^I$

OWL Direct Semantics via FOL

- 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

$$\pi(C \sqsubseteq D) = (\forall x)(\pi_x(C) \rightarrow \pi_x(D))$$
$$\pi_x(A) = A(x)$$
$$\pi_x(\neg C) = \neg \pi_x(C)$$
$$\pi_x(C \sqcap D) = \pi_x(C) \wedge \pi_x(D)$$
$$\pi_x(C \sqcup D) = \pi_x(C) \vee \pi_x(D)$$
$$\pi_x(\forall R.C) = (\forall x_1)(R(x, x_1) \rightarrow \pi_{x_1}(C))$$
$$\pi_x(\exists R.C) = (\exists x_1)(R(x, x_1) \wedge \pi_{x_1}(C))$$
$$\pi_x(\geq nS.C) = (\exists x_1) \ldots (\exists x_n) \left(\bigwedge_{i \neq j} (x_i \neq x_j) \wedge \bigwedge_i (S(x, x_i) \wedge \pi_{x_i}(C)) \right)$$
$$\pi_x(\leq nS.C) = \neg(\exists x_1) \ldots (\exists x_{n+1}) \left(\bigwedge_{i \neq j} (x_i \neq x_j) \wedge \bigwedge_i (S(x, x_i) \wedge \pi_{x_i}(C)) \right)$$
$$\pi_x(\{a\}) = (x = a)$$
$$\pi_x(\exists S.\mathrm{Self}) = S(x, x)$$

$$\pi(R_1 \sqsubseteq R_2) = (\forall x)(\forall y)(\pi_{x,y}(R_1) \rightarrow \pi_{x,y}(R_2))$$
$$\pi_{x,y}(S) = S(x, y)$$
$$\pi_{x,y}(R^-) = \pi_{y,x}(R)$$
$$\pi_{x,y}(R_1 \circ \cdots \circ R_n) = (\exists x_1) \ldots (\exists x_{n-1}) \left(\pi_{x,x_1}(R_1) \wedge \bigwedge_{i=1}^{n-2} \pi_{x_i,x_{i+1}}(R_{i+1}) \wedge \pi_{x_{n-1},y}(R_n) \right)$$
$$\pi(\mathrm{Ref}(R)) = (\forall x)\pi_{x,x}(R)$$
$$\pi(\mathrm{Asy}(R)) = (\forall x)(\forall y)(\pi_{x,y}(R) \rightarrow \neg\pi_{y,x}(R)$$
$$\pi(\mathrm{Dis}(R_1, R_2)) = \neg(\exists x)(\exists y)(\pi_{x,y}(R_1) \wedge \pi_{x,y}(R_2))$$

- ...which (interpreted under FOL semantics) coincides with the definition just given.

Contents

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)

OWL 2 EL

- allowed:
  - subclass axioms with intersection, existential quantification, top, bottom
    - closed classs must have only one member
  - property chain axioms, range restrictions (under certain conditions)
- disallowed:
  - negation, disjunction, arbitrary universal quantification, role inverses

$$\sqcap \exists \top \bot \sqsubseteq \sqcap \exists \top \bot$$

- Examples: Human $\sqsubseteq$ $\exists$hasParent.Person
  $\exists$married.$\top$ $\sqcap$ CatholicPriest $\sqsubseteq$ $\bot$;
  hasParent $\circ$ hasParent $\sqsubseteq$ hasGrandparent

OWL 2 RL

- Motivated by the question: what fraction of OWL 2 DL can be expressed naively by rules (with equality)?
- Examples:
  - $\exists$parentOf.$\exists$parentOf.$\top \sqsubseteq$ Grandfather
    rule version: parentOf(x,y) parentOf(y,z) $\rightarrow$ Grandfather(x)
  - Orphan $\sqsubseteq \forall$hasParent.Dead
    rule version: Orphan(x) hasParent(x,y) $\rightarrow$ Dead(y)
  - Monogamous $\sqsubseteq \leq$1married.Alive
    rule version:
    Monogamous(x) married(x,y) Alive(y) married(x,z) Alive(z)$\rightarrow$ y=z
  - childOf $\circ$ childOf $\sqsubseteq$ grandchildOf
    rule version: childOf(x,y) childOf(y,z) $\rightarrow$ grandchildOf(x,z)
  - Disj(childOf,parentOf)
    rule version: childOf(x,y) parentOf(x,y) $\rightarrow$

OWL 2 RL

- Syntactic characterization:
  - essentially, all axiom types are allowed
  - disallow certain constructors on lhs and rhs of subclass statements

$$\cancel{\forall}\ \cancel{\neg}\ \sqsubseteq\ \cancel{\exists}\ \cancel{\sqcup}$$

  - cardinality restrictions: only on rhs and only ≤1 and ≤0 allowed
  - closed classes: only with one member

- Reasoner conformance requires only soundness.

OWL 2 QL

- 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 $\exists r.\top$
    - right hand side: intersection of class names, expressions of type $\exists r.C$ and negations of lhs expressions
    - no closed classes!
- Example:

$$\exists \text{married}.\top \sqsubseteq \neg \text{Free} \sqcap \exists \text{has}.\text{Sorrow}$$

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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

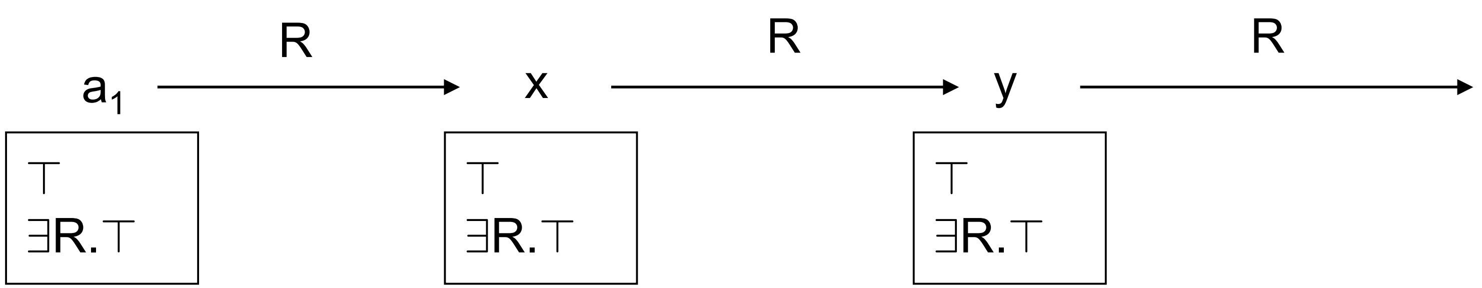
- **Adaptation of FOL tableaux algorithms.**
- **Problem: OWL is decidable, but FOL tableaux algorithms do not guarantee termination.**
- **Solution: *blocking*.**

DL Tableaux Termination Problem

TBox: $\exists R.\top$

ABox: $\top(a_1)$

- **Is satisfiable:**
  Model M contains elements $a_1^M, a_2^M, \ldots$
  and $R^M(a_i^M, a_{i+1}^M)$ for all $i \geq 1$.
- **But naive tableau does not terminate!**

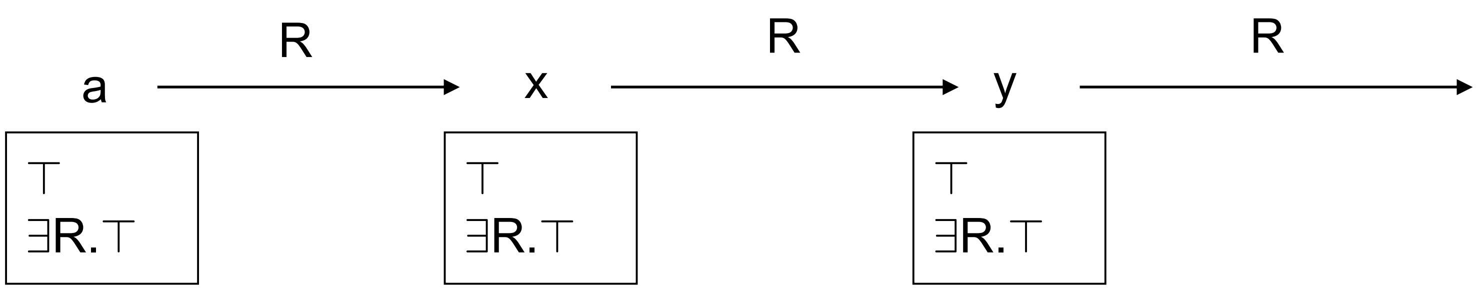


DL Tableaux Termination Problem

Nothing essentially new happens.

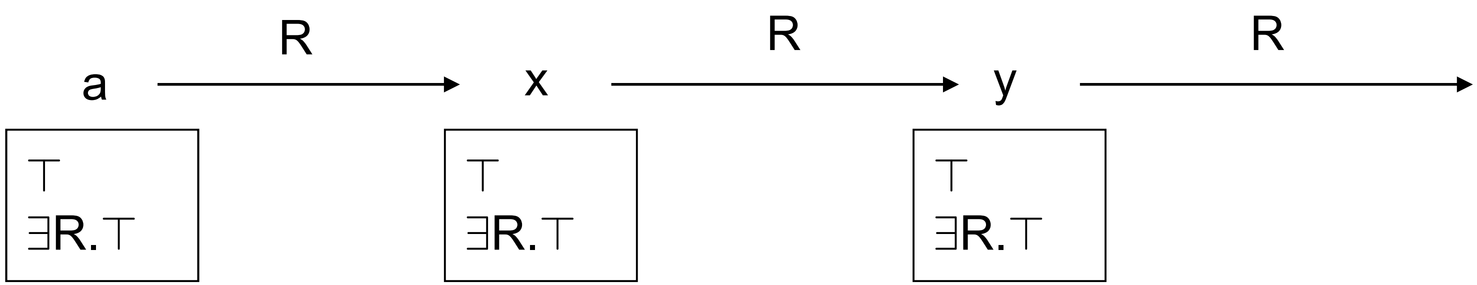
Idea: y does not need to be expanded, because it is basically a copy of x.

⇒ Blocking



Blocking (in ALC)

- 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.



y blocked by x in this example.

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

ALC Tableau example

Show that

C(a)	**C(c)**
R(a,b)	**R(a,c)**
S(a,a)	**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:

$\neg C \sqcup \forall S.A$

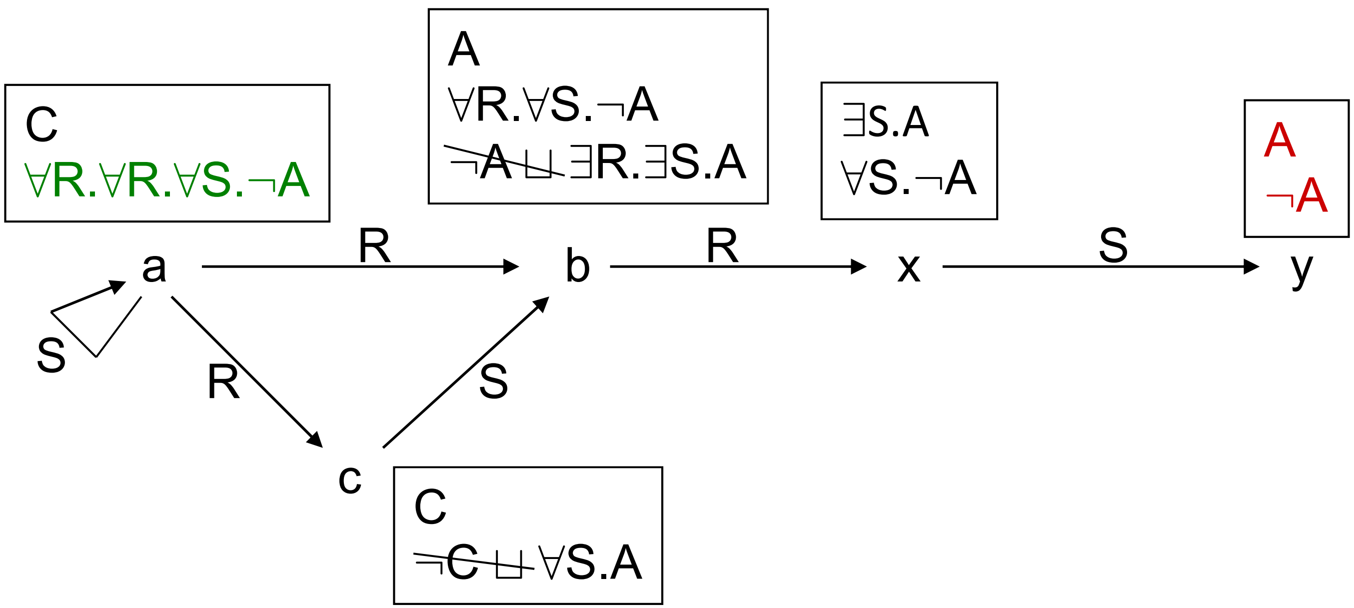
$\neg A \sqcup \exists R.\exists S.A$

$\neg A \sqcup \exists R.C$

ABox

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

$\neg\exists R.\exists R.\exists S.A(a)$ is $\forall R.\forall R.\forall S.\neg A(a)$



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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 Part 2

Main References:

- 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 (**ECAI-08**), pp. 80–84. IOS Press 2008.
- Markus Krötzsch, Sebastian Rudolph, Pascal Hitzler, ELP: Tractable Rules for OWL 2. In Amit Sheth, Steffen Staab, Mike Dean, Massimo Paolucci, Diana Maynard, Timothy Finin, Krishnaprasad Thirunarayan, eds.: Proceedings of the 7th International Semantic Web Conference (**ISWC-08**), pp. 649–664. Springer 2008.

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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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Preliminaries: Datalog

- **Essentially Horn-rules without function symbols**

  general form of the rules:

  $p_1(x_1,\ldots,x_n) \wedge \ldots \wedge p_m(y_1,\ldots,y_k) \rightarrow q(z_1,\ldots,z_j)$

  $\boxed{\text{body} \rightarrow \text{head}}$

  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

Contents

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)

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

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

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

SWRL example (running example)

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

ThaiCurry $\sqsubseteq$ $\exists$contains.{peanutOil}
$\top \sqsubseteq \forall$orderedDish.Dish

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

Conclusions:
dislikes(sebastian,peanutOil)

SWRL example (running example)

NutAllergic(sebastian)

NutProduct(peanutOil)

$\exists$orderedDish.ThaiCurry(sebastian)

ThaiCurry $\sqsubseteq$ $\exists$contains.{peanutOil}

$\top$ $\sqsubseteq$ $\forall$orderedDish.Dish

orderedDish rdfs:range Dish.

NutAllergic(x) $\wedge$ NutProduct(y) $\rightarrow$ dislikes(x,y)

dislikes(x,z) $\wedge$ Dish(y) $\wedge$ contains(y,z) $\rightarrow$ dislikes(x,y)

orderedDish(x,y) $\wedge$ dislikes(x,y) $\rightarrow$ Unhappy(x)

Conclusions:

dislikes(sebastian,peanutOil)

orderedDish(sebastian,y_s)

ThaiCurry(y_s)

Dish(y_s)

SWRL example (running example)

$\text{NutAllergic}(\text{sebastian})$

$\text{NutProduct}(\text{peanutOil})$

$\exists\text{orderedDish.ThaiCurry}(\text{sebastian})$

$\text{ThaiCurry} \sqsubseteq \exists\text{contains}.\{\text{peanutOil}\}$

$\top \sqsubseteq \forall\text{orderedDish.Dish}$

$\text{NutAllergic}(x) \land \text{NutProduct}(y) \to \text{dislikes}(x,y)$

$\text{dislikes}(x,z) \land \text{Dish}(y) \land \text{contains}(y,z) \to \text{dislikes}(x,y)$

$\text{orderedDish}(x,y) \land \text{dislikes}(x,y) \to \text{Unhappy}(x)$

Conclusions:

$\text{dislikes}(\text{sebastian},\text{peanutOil})$

$\text{orderedDish}(\text{sebastian},y_s)$

$\text{ThaiCurry}(y_s)$

$\text{Dish}(y_s)$

$\text{contains}(y_s,\text{peanutOil})$

SWRL example (running example)

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

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

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

Conclusions:

dislikes(sebastian,peanutOil)

orderedDish(sebastian,y_s)

ThaiCurry(y_s)

Dish(y_s)

contains(y_s,peanutOil)

dislikes(sebastian,y_s)

SWRL example (running example)

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

ThaiCurry $\sqsubseteq$ $\exists$contains.{peanutOil}
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dislikes(x,z) $\wedge$ Dish(y) $\wedge$ contains(y,z) $\rightarrow$ dislikes(x,y)
orderedDish(x,y) $\wedge$ dislikes(x,y) $\rightarrow$ Unhappy(x)

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

SWRL example (running example)

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

Conclusion: Unhappy(sebastian)

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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**

- See e.g. Boris Motik, Ulrike Sattler, and Rudi Studer. Query Answering for OWL-DL with Rules. Journal of Web Semantics 3(1):41–60, 2005.

DL-safe SWRL example

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

$$\mathbf{ThaiCurry} \sqsubseteq \exists\mathbf{contains.\{peanutOil\}}$$
$$\top \sqsubseteq \forall\mathbf{orderedDish.Dish}$$

$$\text{DL-safe} \left\{ \begin{array}{c} \mathbf{NutAllergic(x)} \wedge \mathbf{NutProduct(y)} \rightarrow \mathbf{dislikes(x,y)} \\ \mathbf{dislikes(x,z)} \wedge \mathbf{Dish(y)} \wedge \mathbf{contains(y,z)} \rightarrow \mathbf{dislikes(x,y)} \\ \mathbf{orderedDish(x,y)} \wedge \mathbf{dislikes(x,y)} \rightarrow \mathbf{Unhappy(x)} \end{array} \right.$$

Unhappy(sebastian) can*not* be concluded

DL-safe SWRL example

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

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

DL-safe
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)
orderedDish(sebastian,y_s)
ThaiCurry(y_s)
Dish(y_s)

contains(y_s,peanutOil)
~~dislikes(sebastian,y_s)~~

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

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

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

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

Note: with these two axioms,
suicide is basically the same as *kills*

DL Rules: more examples

- NutAllergic(x) ∧ NutProduct(y) → dislikes(x,y)
  - NutAllergic ≡ ∃nutAllergic.Self
    NutProduct ≡ ∃nutProduct.Self
    nutAllergic o U o nutProduct ⊑ dislikes

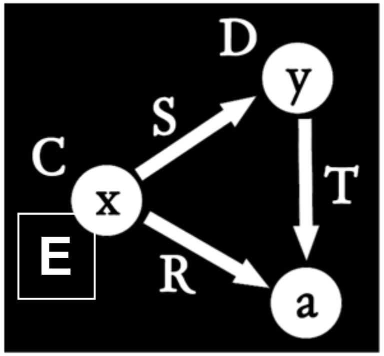
- dislikes(x,z) ∧ Dish(y) ∧ contains(y,z) → dislikes(x,y)
  - Dish ≡ ∃dish.Self
    dislikes o contains⁻ o dish ⊑ dislikes

- worksAt(x,y) ∧ University(y) ∧ supervises(x,z) ∧ PhDStudent(z) → professorOf(x,z)
  - ∃worksAt.University ≡ ∃worksAtUniversity.Self
    PhDStudent ≡ ∃phDStudent.Self
    worksAtUniversity o supervises o phDStudent ⊑ professorOf

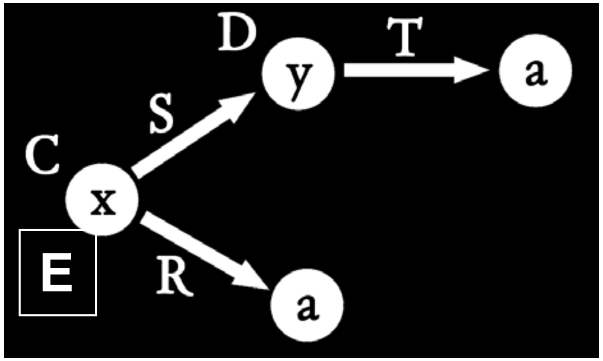
DL Rules: definition

- **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

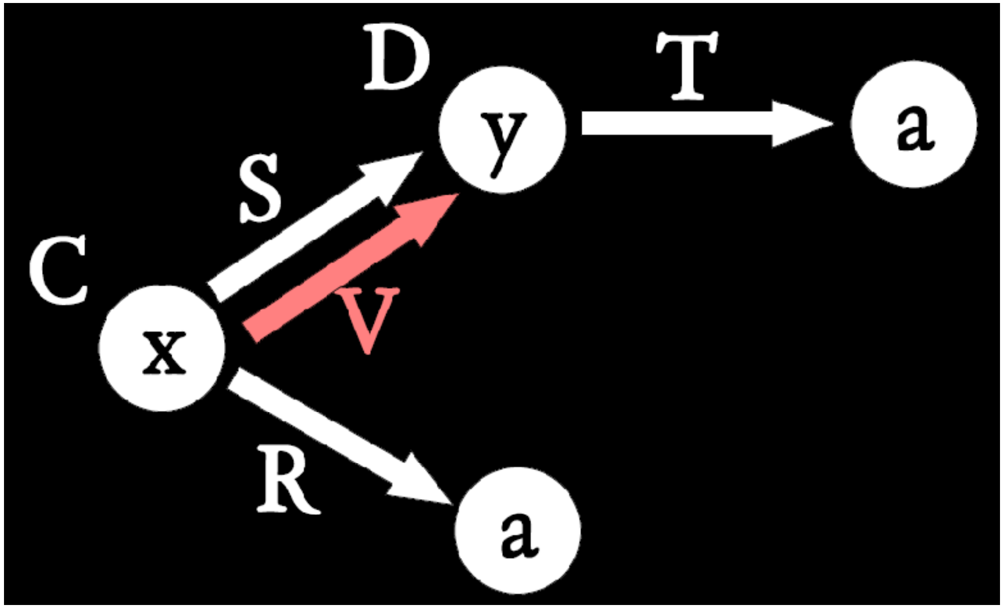


DL Rules: definition

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

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

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



DL Rules: definition

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

- complex classes are allowed in the rules
  - Mouse(x) $\wedge$ $\exists$hasNose.TrunkLike(y) $\rightarrow$ smallerThan(x,y)
  - ThaiCurry(x) $\rightarrow$ $\exists$contains.FishProduct(x)

    Note: This allows to reason with unknowns (unlike Datalog)
  - allowed class constructors depend on the chosen underlying description logic!

DL Rules: definition

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 $\mathcal{D}$>

Contents

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)

ThaiCurry $\sqsubseteq$ $\exists$contains.{peanutOil}
$\top \sqsubseteq \forall$orderedDish.Dish

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

!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.

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

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

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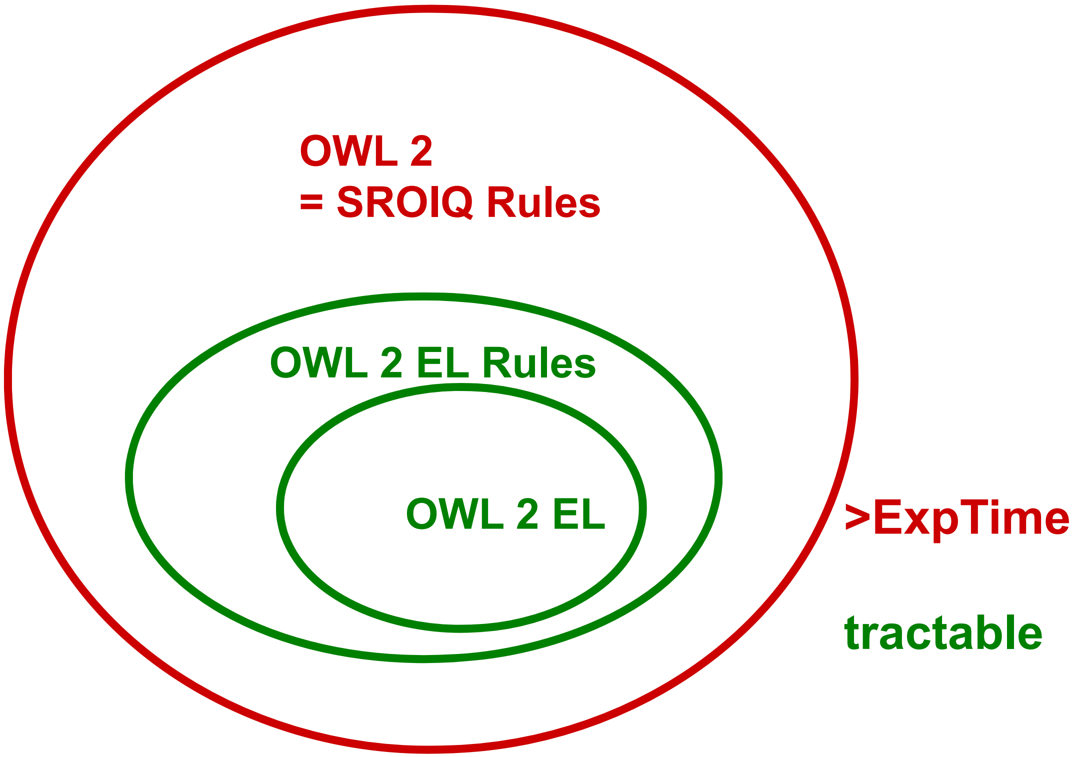
putting it all together

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), ∃R.A(x), R(x,y), where A is an atomic class or a nominal or $\top$ or $\bot$.

- Translation is polynomial.

- ∃worksAt.University(x) ∧ supervises(x,z) ∧ PhDStudent(z) → professorOf(x,z)
  - worksAt(x,y) ∧ University(y) ∧ supervises(x,z) ∧ PhDStudent(z) → professorOf(x,z)

- ThaiCurry(x) → ∃contains.FishProduct(x)

OWL 2 EL Rules in a nutshell

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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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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Rules inside OWL

- **Retaining tractability III: ELP**

putting it all together

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

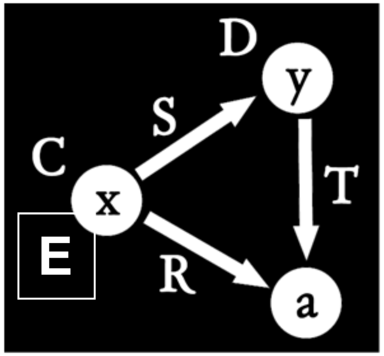
- ELP is
  - OWL 2 EL Rules +
  - a generalisation of DL-safety +
  - variable-restricted DL-safe Datalog +
  - role conjunctions (for simple roles).

- PTime complete.
- Contains OWL 2 EL and OWL 2 RL.
- Covers variable-restricted Datalog.

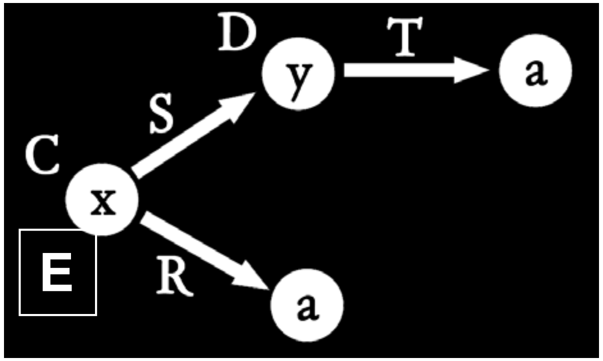
DL-safe variables

- 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.

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



duplicating
nominals
is
ok



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

- **orderedDish(x,y) $\wedge$ dislikes(x,y) $\rightarrow$ Unhappy(x)**

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

- Sebastian Rudolph, Markus Krötzsch, Pascal Hitzler, Cheap Boolean Role Constructors for Description Logics. In: Steffen Hölldobler and Carsten Lutz and Heinrich Wansing (eds.), Proceedings of 11th European Conference on Logics in Artificial Intelligence (JELIA), volume 5293 of LNAI, pp. 362-374. Springer, September 2008.

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

- 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

KNO.E.SIS

$$\text{NutAllergic}(\text{sebastian})$$

$$\text{NutProduct}(\text{peanutOil})$$

$$\exists\text{orderedDish.ThaiCurry}(\text{sebastian})$$

$$\text{ThaiCurry} \sqsubseteq \exists\text{contains.}\{\text{peanutOil}\}$$

$$\top \sqsubseteq \forall\text{orderedDish.Dish}$$

[okay] $\text{NutAllergic}(x) \wedge \text{NutProduct}(y) \rightarrow \text{dislikes}(x,y)$

$\text{dislikes}(x,z) \wedge \text{Dish}(y) \wedge \text{contains}(y,z) \rightarrow \text{dislikes}(x,y)$

$\text{orderedDish}(x,y) \wedge \text{dislikes}(x,y) \rightarrow \text{Unhappy}(x)$

[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

  Dish ≡ ∃dish.Self
  dislikes o contains⁻ o dish ⊑ dislikes

  but we don't have inverse roles in ELP!

- solution: make z a DL-safe variable:

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

  this is fine ☺

DL-safe SWRL example

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

$$ThaiCurry \sqsubseteq \exists contains.\{peanutOil\}$$
$$\top \sqsubseteq \forall orderedDish.Dish$$

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

Conclusions:

dislikes(sebastian,peanutOil)
orderedDish(sebastian,y_s)
ThaiCurry(y_s)
Dish(y_s)

contains(y_s,peanutOil)
dislikes(sebastian,y_s)

ELP example

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

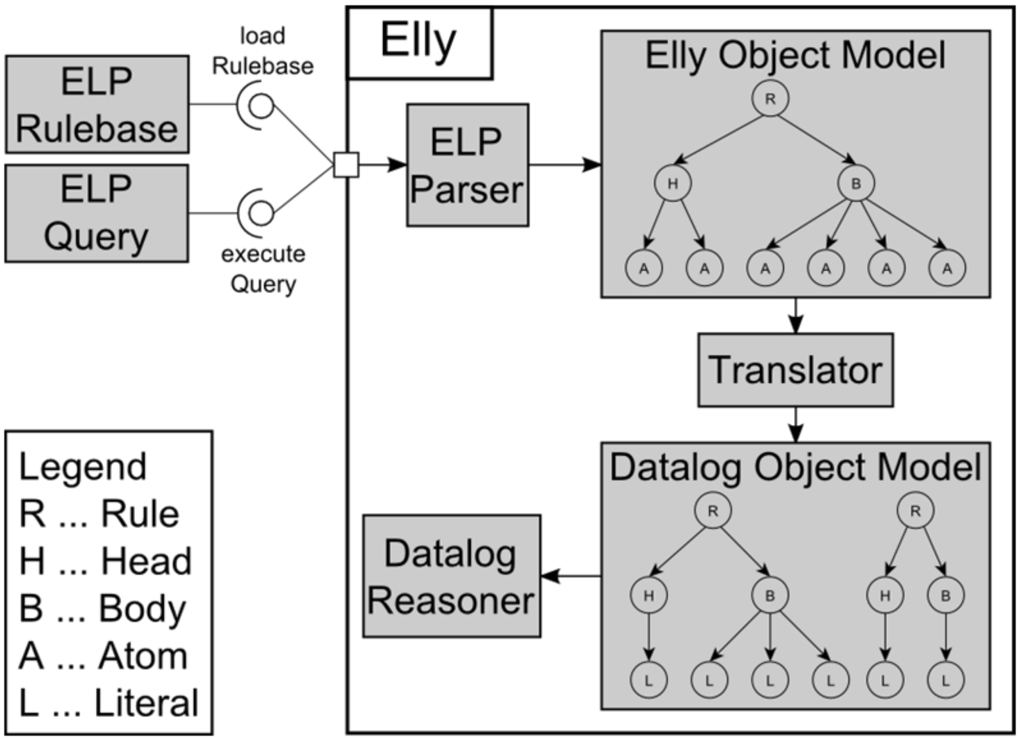
ThaiCurry $\sqsubseteq$ $\exists$contains.{peanutOil}
$\top$ $\sqsubseteq$ $\forall$orderedDish.Dish

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

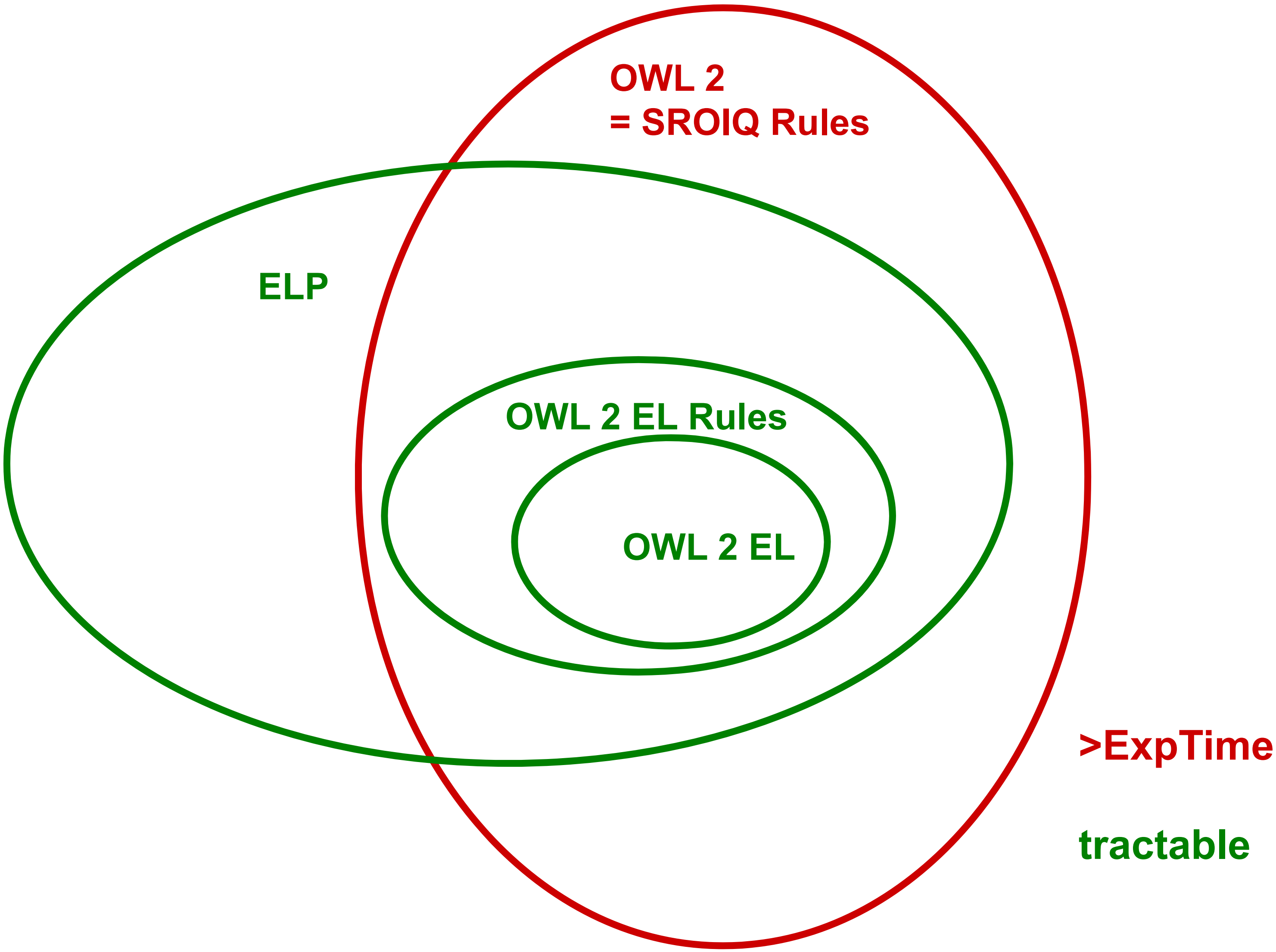
Conclusion: Unhappy(sebastian)

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



Thanks!

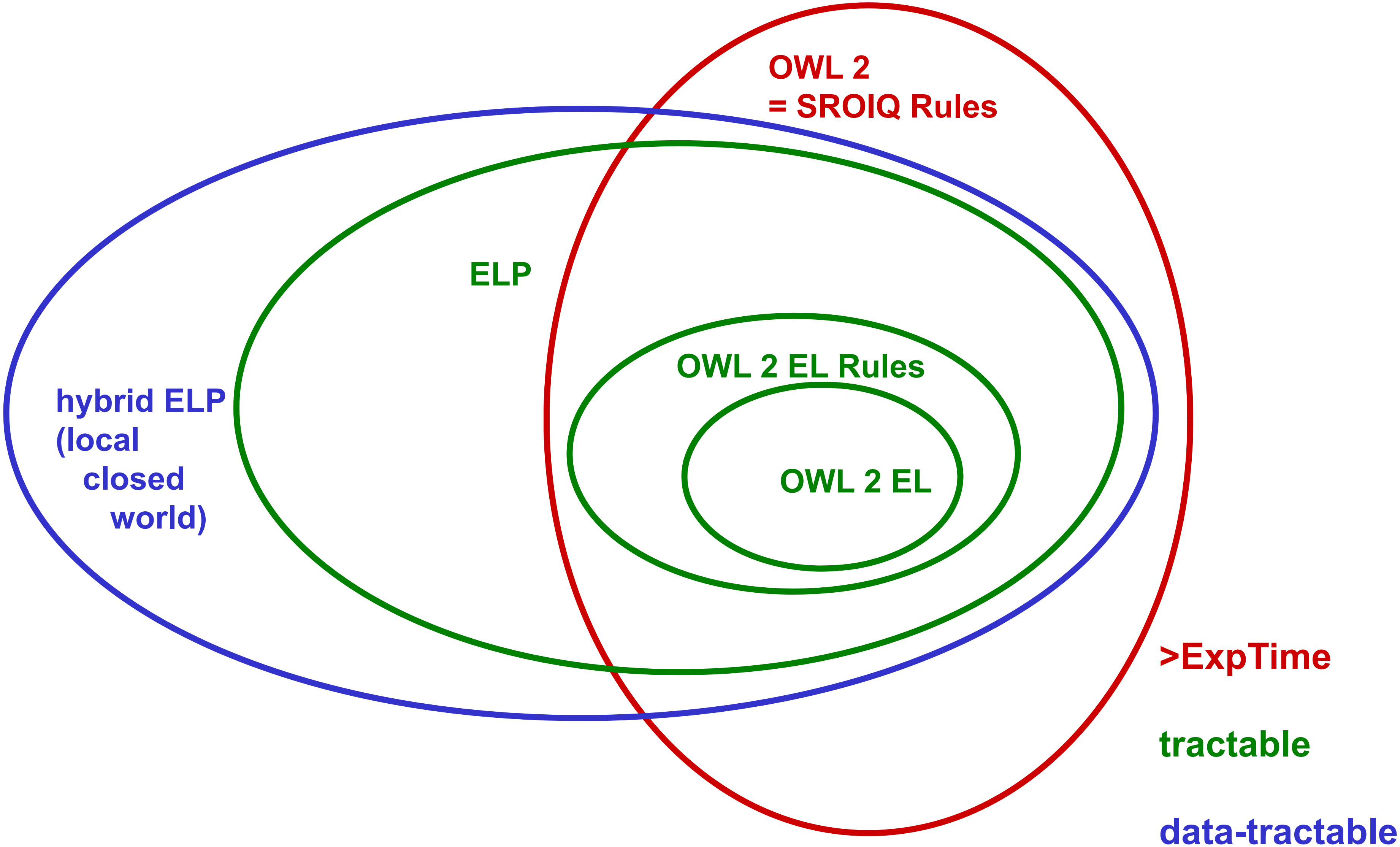
http://www.semantic-web-book.org/page/GeoS2009_Tutorial

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.**

- Matthias Knorr, Jose Julio Alferes, Pascal Hitzler, A Coherent Well-founded model for Hybrid MKNF knowledge bases. 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. 99-103.

The Big Picture II



References Part 2

- 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 (ECAI-08), pp. 80–84. IOS Press 2008.
- Markus Krötzsch, Sebastian Rudolph, Pascal Hitzler, ELP: Tractable Rules for OWL 2. In Amit Sheth, Steffen Staab, Mike Dean, Massimo Paolucci, Diana Maynard, Timothy Finin, Krishnaprasad Thirunarayan, eds.: Proceedings of the 7th International Semantic Web Conference (ISWC-08), pp. 649–664. Springer 2008.
- http://www.w3.org/Submission/SWRL/
- Boris Motik, Ulrike Sattler, and Rudi Studer. Query Answering for OWL-DL with Rules. Journal of Web Semantics 3(1):41–60, 2005.

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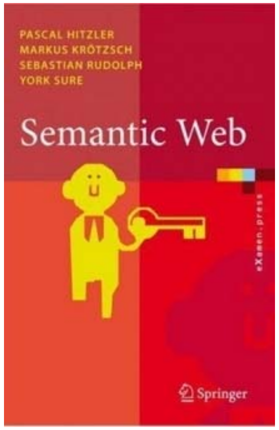
- Sebastian Rudolph, Markus Krötzsch, Pascal Hitzler, Cheap Boolean Role Constructors for Description Logics. In: Steffen Hölldobler and Carsten Lutz and Heinrich Wansing (eds.), Proceedings of 11th European Conference on Logics in Artificial Intelligence (JELIA), volume 5293 of LNAI, pp. 362-374. Springer, September 2008.
- Matthias Knorr, Jose Julio Alferes, Pascal Hitzler, A Coherent Well-founded model for Hybrid MKNF knowledge bases. 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. 99-103.

See also our books

- **Pascal Hitzler, Markus Krötzsch, Sebastian Rudolph, York Sure,**
  Semantic Web – Grundlagen. Springer, 2008.
  http://www.semantic-web-grundlagen.de/



- **Pascal Hitzler, Markus Krötzsch, Sebastian Rudolph, Foundations of Semantic Web Technologies. Chapman & Hall/CRC, 2009.**
  http://www.semantic-web-book.org/wiki/FOST

  (Grab a flyer.)