Expressive Ontologies – OWL

Petr Křemen

petr.kremen@fel.cvut.cz

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Outline

1. Expressive Ontologies
   - OWL 2
     - Description Logics
     - Basic Concepts
     - Properties
     - Data Ranges (Datatype expressions)
     - Class Expressions
     - Individuals
     - OWL 2 DL Constraints
     - OWL 2 – RDFS mapping
     - OWL 2 Semantics
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Expressive Ontologies

Why RDFS is not enough ?

- RDFS is rich enough for simple conceptual modeling, including resource annotations or property domains and ranges
- … but it is not enough for describing complex domain relationships

Examples

- e.g. `ex:hasAncestor` being transitive, or
- each `ex:Human` having exactly two biological parents
- two `ex:Person`s sharing exactly one parent are step-siblings

- for these cases more powerful languages are needed. Here we sketch two of them:

  Web Ontology Language (OWL) is a standard for representing complex ontologies,

  Semantic Web Rule Language (SWRL) is one of possible rule languages built upon OWL.

OWL 2

OWL 2 Basics

- state-of the art ontology modeling language extending RDFS,
- describes *individuals*, their *classes* and *properties*,

Listing 1 : Example OWL ontology in Manchester syntax [2]

```
Prefix: : <http://ex.owl/>
Ontology: <http://ex.owl/o1>
  ObjectProperty: :hasChild
  Class: :Man
  Class: :FatherOfSons
    SubClassOf: :hasChild some owl:Thing and :hasChild only :Man
  Individual: :John
    Types: :FatherOfSons
```

classes – represent sets of objects (e.g. `ex:Man`, `ex:Employee`, etc.)

individuals – represent particular objects (e.g. `ex:John`)

properties – represent binary relations between objects (e.g. `ex:hasChild`), or attributes (e.g. `ex:hasName`)

OWL namespace is `http://www.w3.org/2002/07/owl#`, prefixed as `owl:`.

OWL (2) Language Family

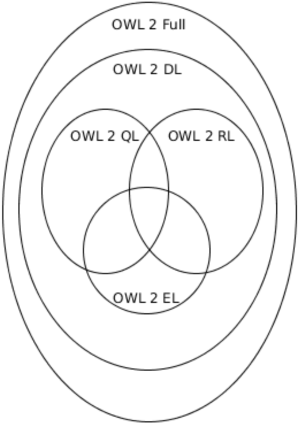
OWL 2 (Full) interprets any RDF graph under OWL-RDF entailment regime (undecidable).

OWL 2 DL interprets OWL 2 ontologies (parsed only from **compliant** RDF graphs) by means of **decidable** $\mathcal{SROIQ}$ description logic semantics,

OWL 2 EL is a subset of OWL 2 DL for rich class taxonomies,

OWL 2 QL is a subset of OWL 2 DL for large data,

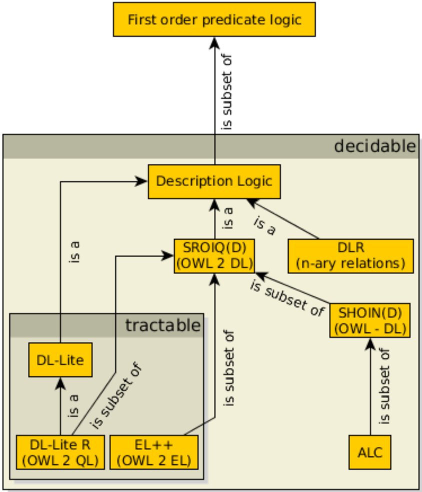
OWL 2 RL is a subset of OWL 2 DL with weaker rule-based semantic.



Description Logics

What are Description Logics (DLs) ?

- logics backing OWL languages



$\mathcal{SROIQ}$

Currently, $\mathcal{SROIQ}(\mathcal{D})$ is one of the most expressive-yet-decidable description logic.

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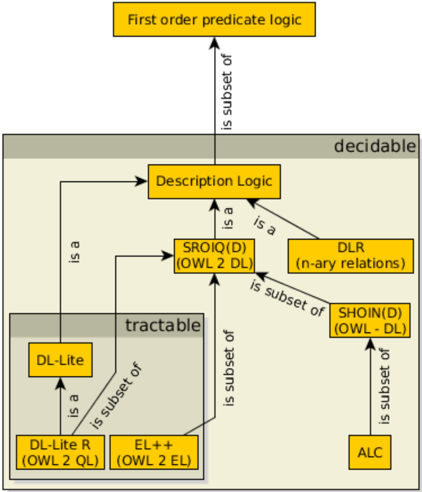
- *decidable subsets of first-order predicate logic (FOPL)*



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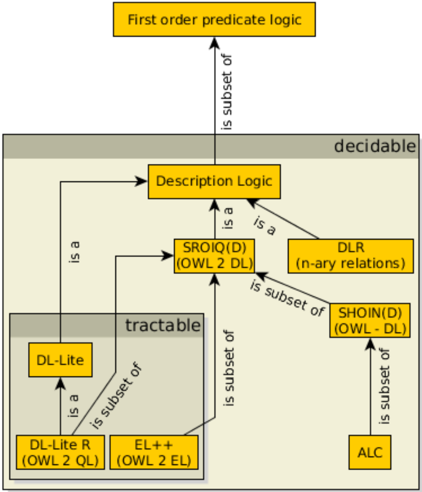

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- *decidable subsets of first-order predicate logic (FOPL)*
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- in 2009 description logic $\mathcal{SROIQ}(\mathcal{D})$ – OWL 2

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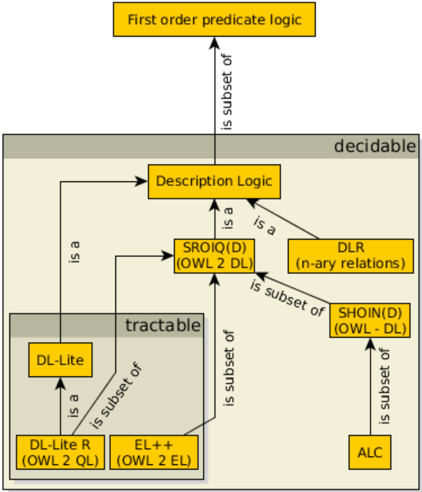

Characteristics of Description Logics

- suitable for descriptive tasks (conceptualization tasks),
- reasoning requires *satisfiability checking* (typically by means of a tableau algorithm),
- high complexity – even simple DLs are exponential, and thus poorly scalable on large datasets
- complexity of $\mathcal{SROIQ}(\mathcal{D})$ = N2ExpTime.
- complexity of $\mathcal{EL}++$, $DLLite_R$ = PTime.

Reasoning in Description Logics

Description logic reasoners take an ontology $\mathcal{O} = \{\alpha_i\}$, where α_i are axioms and are able to reason about

- consistency, i.e. whether $\mathcal{O}$ is consistent (whether there exists at least one "realization" of the ontology that fullfills all α_i)
- entailment, i.e. whether $\mathcal{O} \models \alpha$ for some axiom α

Basic Concepts

OWL Ontology Header

```
Prefix: : <http://ex.owl/>
Prefix: rdfs: <http://www.w3.org/2000/01/rdf-schema#>
Ontology: <http://ex.owl/o3> <http://ex.owl/o3-v1>
 Import: <http://ex.owl/o4>
 Import: <http://ex.owl/o5>
 Annotations: rdfs:comment "An example ontology"@en,
          :creator :John
 AnnotationProperty: :creator
 Individual: :John
```

- An ontology is identified by

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  - version IRI (`http://ex.owl/o3-v1`) which is optional
- `Import:` allows importing other ontologies (for backward compatibility with OWL 1, the imported ontology is syntactically included in case it has no `Ontology:` header)
- `Annotations:` allows arbitrary ontology annotations (creators, comments, backward compatibility, etc.)

Ontology structure

Logically, an OWL 2 DL ontology is a set of axioms (see above). Each axiom represents a statement that must be valid in the domain, e.g

```
Class: :FatherOfSons
  SubClassOf: :hasChild some owl:Thing and :hasChild only :Man
```

says that a father of sons is someone who has at least one child and each his child is a man. These axioms are serialized as sets of RDF triples in RDF syntaxes, or as human-readable frames in Manchester syntax.

Listing 2 : Turtle version of the axiom above

```
:FatherOfSons rdf:type owl:Class ;
   rdfs:subClassOf [ rdf:type owl:Class ;
   owl:intersectionOf ( [ rdf:type owl:Restriction ;
                          owl:onProperty :hasChild ;
                          owl:someValuesFrom owl:Thing
                        ]
                        [ rdf:type owl:Restriction ;
                          owl:onProperty :hasChild ;
                          owl:allValuesFrom :Man
                        ]
                      )
```

Annotations

Each resource can be assigned a set of annotations (i.e. classes, properties, reified axioms, or even annotations themselves):

```
Class: :FatherOfSons
 Annotations:
      :creator :John,
      Annotations: :creator :Jack
            rdfs:label "Father of sons"@en
 SubClassOf:
      Annotations: :creator :Mary
            :hasChild some owl:Thing and :hasChild only :Man
```

Question

What do different creators refer to ?

Punning

Should `ex:Dog` be considered a class (representing a set of dogs), or an individual (representing a particular species) ?

Punning is the mechanism of reusing the same IRI for entities of different type for the sake of metamodeling but certain typing constraints must be fulfilled to stay in OWL 2 DL.

OWL 2 DL Typing constraints

- All IRIs have to be declared to be either *class*, *datatype*, *object property*, *data property*, *annotation property*, *individual* in the *axiom closure of an ontology*
- Each IRI can be (declared/used as) only one of (object property, data property, annotation property)
- Each IRI can be (declared/used as) only one of (class, datatype)

Punning example

Listing 3 : A valid punning example – `ex:Dog` is used as both individual and class

```
Individual: ex:Dog
 Types: ex:Dog
```

Listing 4 : An invalid punning example – `ex:hasName` is used as both object and data property

```
Individual: ex:John
 Facts: ex:hasName ex:firstName
 Facts: ex:hasName "John"@en
```

Properties

Property Expressions

OWL 2 supports no data property expressions and the only object property expresion:

`inverse` means an inverse property (i.e. property going in the opposite direction),

```
inverse :hasChild
```

Inverse properties can be used in class frames, property frames as well as individuals frames.

Object Property Frames

```
ObjectProperty: :hasMother
   Characteristics: Functional, Irreflexive, Asymmetric
   Domain: :Person
   Range: :Woman
   SubPropertyOf: :hasParent
   EquivalentTo: inverse :isMotherOf
   DisjointWith: :hasFather
   InverseOf: :isMotherOf
   SubPropertyChain: :hasFather o :isWifeOf
```

`Characteristics` – selection of `Functional`, `InverseFunctional`, `Transitive`, `Reflexive`, `Irreflexive`, `Symmetric`, `Asymmetric` – interpreted in their mathematical sense

`Domain,Range` have the same meaning as in RDFS

`SubPropertyOf` specifies props representing supersets of the frame property

`EquivalentTo` specifies props semantically equivalent to the frame class

`DisjointWith` specifies props disjoint with the frame property

Data Property Frames

```
DataProperty: :hasBirthNumber
   Characteristics: Functional
   Domain: :Person
   Range: xsd:string
   SubPropertyOf: :hasIdentifyingNumber
```

The only **Characteristics** available is `Functional`. Other sections have the same meaning

Data Ranges (Datatype expressions)

Basic Data Ranges

OWL 2 supports basic modeling constructs for custom data ranges:

and,or,not have the meaning of standard set intersection, union and complement,

```
(xsd:nonNegativeInteger and xsd:nonPositiveInteger) or xsd
    :string
```

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`and,or,not` have the meaning of standard set intersection, union and complement,

```
(xsd:nonNegativeInteger and xsd:nonPositiveInteger) or xsd
    :string
```

individual enumeration lists individuals belonging to a class expression.

```
{"true"^^xsd:boolean 1}
```

Facets

Facets restrict a particular datatype to a subset of its values.

```
xsd:integer[ >= 5, < 10 ]
```

Available facets

length, minLength, maxLength – string lengths

pattern – string regular expression

langRange – range of language tags

$<=, <, >=, >$ – number comparison

New datatypes can be used by means of datatype frame axioms:

```
Datatype: :MyNumber
   EquivalentTo: xsd:integer[ >= 5, < 10 ]
```

Class Expressions

Boolean operators

OWL 2 supports many class modeling constructs including boolean connectives, individual enumeration, and object/data value restrictions.

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```
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```
(:FlyingObject and not :Bat) or :Pinguin
```

individual enumeration lists individuals belonging to a class expression.

```
{:John :Mary}
```

Object value Restrictions (1)

existential quantification says that a property filler exists (not necessarily in data !)

Listing 5 : A set of objects having at least one son

```
:hasChild some :Man
```

Object value Restrictions (1)

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Listing 8 : A set of objects having at least one son

```
:hasChild some :Man
```

universal quantification says that each property filler belongs to a class

Listing 9 : A set of objects having no child or only sons

```
:hasChild only :Man
```

Object value Restrictions (1)

existential quantification says that a property filler exists (not necessarily in data !)

Listing 11 : A set of objects having at least one son

```
:hasChild some :Man
```

universal quantification says that each property filler belongs to a class

Listing 12 : A set of objects having no child or only sons

```
:hasChild only :Man
```

cardinality restriction restricts the number of property fillers

Listing 13 : Sets of objects exactly two (min four/max one) wheels

```
:hasPart exactly 2 :Wheel
:hasPart min 4 :Wheel
:hasPart max 1 :Wheel
```

Object Value Restrictions (2)

individual value restriction restricts a property filler to a specified individual

Listing 14 : A set of objects having John as their child

```
:hasChild value :John
```

Object Value Restrictions (2)

individual value restriction restricts a property filler to a specified individual

Listing 16 : A set of objects having John as their child

```
:hasChild value :John
```

self restriction restricts a property filler to the same individual

Listing 17 : A set of objects trusting themselves

```
:trusts Self
```

Complex Value Restrictions

- analogous counterparts to the object value restrictions are available (except the Self restriction) as *data value restrictions*:

```
:hasName some xsd:string[length 2]
```

What does this class expression describe ?

```
(:hasPart only (not :Tail))
and (:hasPart max 2 (:hasPart some :Knee))
and (:doesAssignmentWith Self)
and (:hasGrade only xsd:string[pattern "[AB]"])
```

Class frames

```
Class: :Father
  SubClassOf: :Parent
  EquivalentTo: :Man and :hasChild some :Person
  DisjointWith: :Mother
  DisjointUnionOf: :HappyFather :SadFather
  HasKey: :hasBirthNumber
```

SubClassOf section defines axioms specifying supersets of the frame class

EquivalentTo section defines axioms specifying classes semantically equivalent to the frame class

DisjointWith section defines classes sharing no individuals with the frame class

DisjointUnionOf section defines classes that are mutually disjoint and union of which is semantically equivalent to the frame class

HasKey section defines a set of properties that build up a *key* for the class – all instances of `Father` sharing the same value for the key (`:hasBirthNumber`) are semantically identical (`owl:sameAs`)

Individuals

Individual Frames

```
Individual: :John
 Types: :Person , :hasName value "Johnny"
 Facts: :hasChild :Jack, not :hasName "Bob"
 SameAs: :Johannes
 DifferentFrom: :Jack
```

Individual frames contain assertions, subject of which is the individual.

`Types` specifies class descriptions that are types (`rdf:type`) for the frame individual,

`Facts` specifies the object and data property assertions,

`SameAs` specifies individuals being semantically identical to the frame individual,

`DifferentFrom` specifies individuals being semantically different to the frame individual

Unique Name Assumption

OWL **does not accept** unique name assumption, i.e. it is not known whether two individuals `:John` and `:Jack` represent the same object, or not. By `SameAs` and `DifferentFrom`, either possibility can be enforced.

Listing 18 : This fragment does not cause ontology inconsistency as `:Jack` *and* `:Jim` *might be interpreted as the same individual*

```
Individual: :John
 Types: :hasChild exactly 1 owl:Thing
 Facts: :hasChild :Jack, :hasChild :Jim
```

OWL 2 DL Constraints

Global Constraints

We have discussed the typing constraints. Additionally, there are syntactic constraints that ensure decidability of reasoning. These constraints must be fulfilled for each OWL 2 DL ontology:

simple object property
: are properties that have no direct or indirect (through property hierarchy) subproperties that are transitive or defined by means of a property chain.

```
ObjectProperty: :hasChild
  SubPropertyOf: :hasDescendant
ObjectProperty: :hasDescendant
  Characteristics: Transitive
  SubPropertyOf: :hasRelative
ObjectProperty: :hasSon
  SubPropertyOf: :hasChild
ObjectProperty: :hasDaughter
  SubPropertyOf: :hasChild
ObjectProperty: :hasUncle
  SubPropertyOf: :hasRelative
  SubPropertyChain: :hasParent o :hasSibling
```

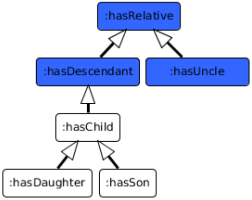

Figure : White properties are simple, blue ones are not

Global Constraints (2)

Formal specification is in [3], informally:

- `owl:topDataProperty` cannot be stated equal to any other data property (e.g. through `EquivalentTo` or `SubPropertyOf`).
- datatype definitions must be acyclic
- the following constructs are only allowed with *simple properties*:
  - cardinality restrictions (`min`, `max`, `exactly`),
  - self restriction ((Self)),
  - property characteristics `Functional`, `InverseFunctional`, `Irreflexive`,`Asymmetric`,
  - property axiom `DisjointWith`
- property chains must not be cyclic
- (restriction on anonymous individuals (that we haven't discussed))

OWL 2 – RDFS mapping

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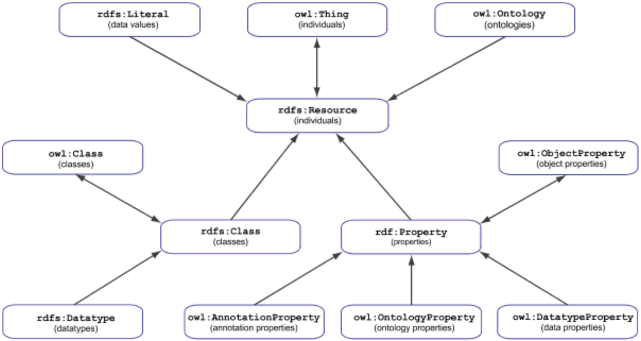


Figure : Informal relationships between OWL parts (taken from [3]). Arrows represent subparts (either `rdf:type` or `rdfs:subClassOf`)

The vocabulary for serializing OWL ontologies into RDF contains plenty of resource (e.g. `owl:Class`,`owl:someValuesFrom`,`owl:Axiom`), see [3] for details.

OWL 2 Semantics

OWL 2 RDF-Based Semantics

defines an entailment $\models_{OWL2-RDF}$) allowing to **interpret all RDF graphs** (called *OWL 2 Full*)

- is an extension of *D*-entailment (inteprets the whole RDF graph)
- undecidable, but *incomplete* entailment rules are provided [4]

Listing 19 : RDF graph G_1

```
@prefix rdfs: <http://www.w3.org/2000/01/rdf-
     schema#>.
@prefix owl: <http://www.w3.org/2002/07/owl#>.
@prefix : <http://example.org/2014-osw-14/>.
_:y a owl:Ontology .
_:x rdfs:subClassOf :Parent ;
   a owl:Restriction ;
:hasChild a owl:ObjectProperty .
:John :hasChild :Mary .
```

Listing 20 : RDF graph G_2

```
@prefix : <http://www.example.org/2014-osw-14/>
     .
:hasChild a rdf:Property .
:Mary a owl:NamedIndividual .
```

The following entailment holds:

$$G_1 \models_{OWL2-RDF} G_2$$

OWL 2 Direct Semantics

defines an entailment $\models_{OWL2-DL}$ in terms of the $\mathcal{SROIQ}(\mathcal{D})$ DL.

- interprets only "logically-backed" knowledge, while **ignoring the rest** (e.g. annotations, declarations, etc.)
- $F(G)$ is an OWL 2 DL ontology, for G sat. OWL 2 DL restrictions.

Listing 21 : RDF graph G_3

```
@prefix rdfs: <http://www.w3.org/2000/01/rdf-
    schema#>.
@prefix owl: <http://www.w3.org/2002/07/owl#>.
@prefix : <http://example.org/2014-osw-14/>.
_:y a owl:Ontology .
_:x rdfs:subClassOf :Parent ;
   a owl:Restriction ;
   owl:onProperty :hasChild ;
   owl:someValuesFrom owl:Thing .
:John :hasChild :Mary .
:John a owl:NamedIndividual .
:Mary a owl:NamedIndividual .
:hasChild a owl:ObjectProperty .
```

Listing 22 : RDF graph G_4

```
@prefix : <http://www.example.org/2014-osw-14/>
    .
:John a :Parent .
:John rdfs:label "john"@en .
```

The following entailment holds:

$$F(G_3) \models_{OWL2-DL} F(G_4)$$

(For the sake of brevity, $F(\bullet)$ is often omitted whenever G is a serialization of an OWL-DL ontology $F(G)$)

OWL 2 Correspondence Theorem (CT)

- direct and RDF-based semantics for OWL are different (i.e. there exist entailments valid for one semantic and not for the other one)
- CT says that **OWL RDF semantic can express anything that OWL DL semantics can**

OWL 2 Correspondence Theorem – simplified version

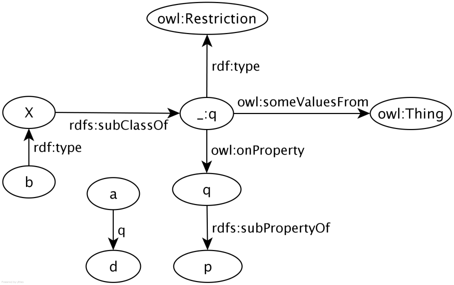
For any two RDF graphs G_1 and G_2, there exist two RDF graphs G_1' and G_2', s.t. $F(G_1) \models\mid_{OWL-DL} F(G_1')$ and $F(G_2) \models\mid_{OWL2-DL} F(G_2')$, and

$$F(G_1') \models_{OWL2-DL} F(G_2') \quad \text{implies} \quad G_1' \models_{OWL2-RDF} G_2',$$

where $F(G)$ is an OWL-DL ontology corresponding to the RDF graph G.

- For example $G_1 \not\models_{OWL2-DL} G_2$, while $G_3 \not\models_{OWL2-RDF} G_4$
- Removing last triple (label) from G_4, we get G_4', s.t. $F(G_4) \models\mid_{OWL-DL} F(G_4')$ and $G_4 \models_{OWL-RDF} G_4'$

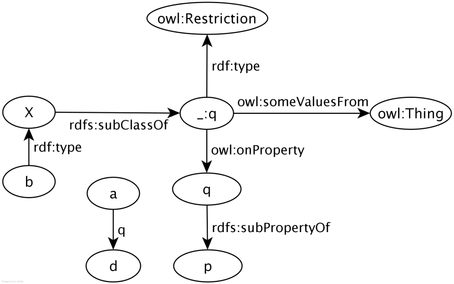
OWL 2 Entailment in SPARQL




```
PREFIX : <http://ex.org/e1>
SELECT ?x
WHERE { ?x :p _:y }
```

Simple-entailment No result.

OWL 2 Entailment in SPARQL

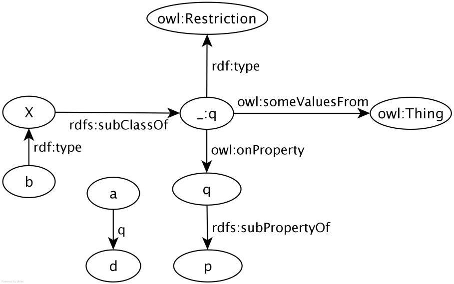



```
PREFIX : <http://ex.org/e1>
SELECT ?x
WHERE { ?x :p _:y }
```

Simple-entailment No result.

RDF-entailment No result.

OWL 2 Entailment in SPARQL



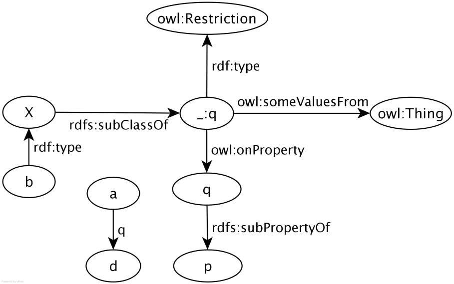

```
PREFIX : <http://ex.org/e1>
SELECT ?x
WHERE { ?x :p _:y }
```

Simple-entailment No result.

RDF-entailment No result.

RDFS-entailment One result: ?x=a.

OWL 2 Entailment in SPARQL

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PREFIX : <http://ex.org/e1>
SELECT ?x
WHERE { ?x :p _:y }
```

Simple-entailment No result.

RDF-entailment No result.

RDFS-entailment One result: ?x=a.

OWL 2 DL entailment Two results: ?x=a and ?x=b.

```
Individual: :b
  Types: :X
Class: :X
  SubClassOf: :q some owl:Thing
```

SWRL

SWRL Basics

- SWRL [1] is a rule language for OWL
- allows rules of the form (Protégé syntax)

$$a_1(?x_1^1, \ldots, ?x_{n_1}^1), \ldots, a_m(?x_1^m, \ldots, ?x_{n_m}^m) \rightarrow \\ c_1(?x_1^{m+1}, \ldots, ?x_{l_1}^{m+1}), \ldots, c_k(?x_1^{m+k}, \ldots, ?x_{l_k}^{m+k}) \quad (1)$$

where all $a_t^{(s)}$ are antecedents and $c_t^{(s)}$ consequents of the rule. Each $a_t^{(s)}$, $c_t^{(s)}$ is of the following form:

$\mathtt{C}(z)$, where $\mathtt{C}$ is a class expression, or

$\mathtt{P}(z_1, z_2)$, where $\mathtt{P}$ is a property expression,

$\mathtt{SameAs}(z_1, z_2)$, or

$\mathtt{DifferentFrom}(z_1, z_2)$, or

$built-in(z_1, \ldots, z_p)$, where $built-in$ is one of the built-in atoms, e.g. $\mathtt{add}(?x, 3, 4)$

where each $z_{(i)}$ is either a variable $?x$ or an individual, or a literal.

Example Rules

Listing 23 : Transitivity of hasAncestor

```
hasAncestor(?x,?y), hasAncestor(?y,?z) -> hasAncestor(?x,?z)
```

Listing 24 : One parent is a man

```
Man(?y), hasParent(?x,?y), hasParent(?x,?z), DifferentFrom(?y,?z) ->
    Woman(?z)
```

Listing 25 : Women share surnames of their husbands.

```
hasHusband(?x,?y), hasSurname(?y,?z) -> hasSurname(?x,?z), Man(?x)
```

SWRL Reasoning

- SWRL rules can be embedded into OWL ontologies

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- SWRL rules can be embedded into OWL ontologies
- unrestricted, they are *undecidable*
- their decidable subset is called **DL-safe rules** which shares their syntax but variables match only **known** data (not entailed)
- SWRL support (DL-safe rules) is implemented in Protégé, as well as major reasoners, like Pellet, HermiT, etc.

References

[1] Ian Horrocks et al. *SWRL: A Semantic Web Rule Language Combining OWL and RuleML*. W3C Member Submission. World Wide Web Consortium, 2004. URL: http://www.w3.org/Submission/SWRL.

[2] Peter Patel-Schneider, Bijan Parsia, and Boris Motik. *OWL 2 Web Ontology Language Structural Specification and Functional-Style Syntax (Second Edition)*. W3C Recommendation. http://www.w3.org/TR/2012/REC-owl2-syntax-20121211/. W3C, Dec. 2012.

[3] Peter Patel-Schneider, Bijan Parsia, and Boris Motik. *OWL 2 Web Ontology Language Structural Specification and Functional-Style Syntax (Second Edition)*. W3C Recommendation. http://www.w3.org/TR/2012/REC-owl2-syntax-20121211/. W3C, Dec. 2012.

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