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Unit 6:
OWL, OWL 2, SPARQL+OWL

Some facts about OWL…

- OWL stands for Web Ontology Language
- Strongly Simplified: OWL is an Ontology language with an **RDF syntax**
  - There are different syntaxes for OWL, we will focus on RDF syntax here, but occasionally use DL syntax or First-order logics notation for explanation.
- OWL extends RDF Schema by more expressive constructs.
- **A fragment of** OWL is expressible in Description Logics (sometimes referred to as **OWL DL**)
- The original OWL standards date back to 2004 (also sometimes referred to as **OWL 1**)
- There was a significant revision in 2008 (also often referred to as **OWL 2**)

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In today's lecture:

- OWL 1 Overview
- OWL 2 new features
- OWL 2 tractable fragments: EL, QL, RL
- OWL + SPARQL

Disclaimer: We will only be able to scratch the surface
(e.g. not be able to give an in-depth Description Logics introduction)

OWL 1 Overview:

See Lecture 3 slides 31ff.

Why OWL1 is Not Enough

Too expensive to reason with

- High complexity: Satisfiability checking is NEXPTIME-complete
- Some ontologies only use some limited expressive power; e.g. The SNOMED (Systematised Nomenclature of Medicine) ontology

Not expressive enough; e.g.

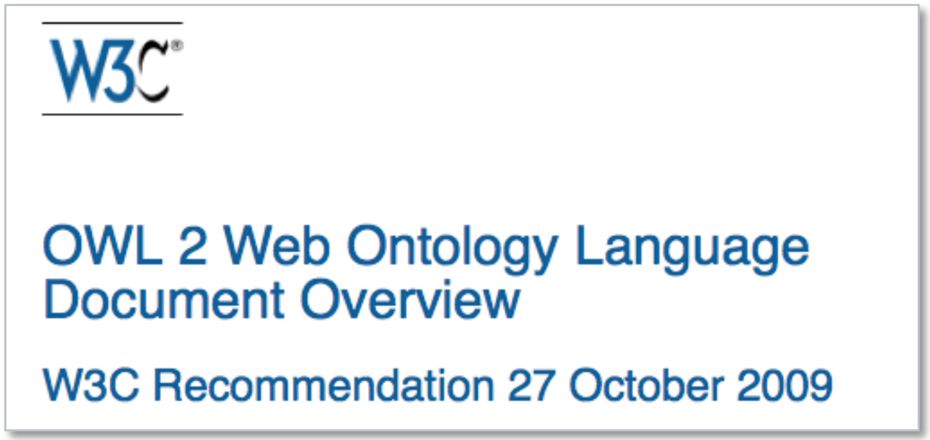
- No user defined datatypes
  [Pan 2004; Pan and Horrocks 2005; Motik and Horrocks 2008]
- No metamodeling support
  [Pan 2004; Pan, Horrocks, Schreiber, 2005; Motik 2007]
- Limited support for modeling relations between properties
  [Horrocks et al., 2006]

From OWL1 to OWL2

Since 2009: OWL 2: A new version of OWL
Two Main goals:

1. To define "profiles" of OWL that are:
   - smaller, easier to implement and deploy
   - cover important application areas and are easily understandable to non-expert users

2. To add a few extensions to current OWL that are useful, and are known to be implementable
   - many things happened in research since 2004 in research



W3C

OWL 2 Web Ontology Language
Document Overview

W3C Recommendation 27 October 2009

New expressive power

- DatatypeDefinitions: user defined datatypes using XSD restrictions, e.g.

```
:personAge owl:equivalentClass
  [ a                       rdfs:Datatype ;
    owl:onDatatype          xsd:integer ;
    owl:withRestrictions
            ( xsd:minInclusive "0"^^xsd:integer
              xsd:maxInclusive "150"^^xsd:integer ) ] .
```

dbpedia:Elizabeth_II :age "86"^^:personAge

- punning (metamodeling), e.g.:

```
:John a :Father .
:Father  a :SocialRole .
```

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New Expressiveness in OWL 2

New expressive power on **properties**

- Qualified cardinality restrictions
- Property chain axioms
- Local reflexivity restrictions
- reflexive, irreflexive, symmetric, and antisymmetric properties
- Disjoint properties
- keys

New Expressiveness in OWL 2

Qualified cardinality restrictions

- In OWL 1 you could only make general cardinality restrictions, e.g. we were cheating here:

A Senior researcher is a foaf:Person who isAuthorOf 10+ Publications

$$ex{:}Senior \equiv foaf{:}Person \sqcap \geqslant 10\ ex{:}isAuthorOf \sqcap \exists ex{:}isAuthorOf.ex{:}Publication$$

What we really wanted to say (but which wasn't expressible in OWL1)

$$ex{:}Senior \equiv foaf{:}Person \sqcap \geqslant 10\ ex{:}isAuthorOf.ex{:}Publication$$

New Expressiveness in OWL 2

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Qualified cardinality restrictions

- In OWL 1 you could only make general cardinality restrictions, e.g. we were cheating here:

A Senior researcher is a foaf:Person who isAuthorOf 10+ Publications

```
ex:Senior owl:intersectionOf (
   foaf:Person
   [ a owl:Restriction; owl:onProperty ex:isAuthorOf ; owl:minCardinality 10 ]
   [ a owl:Restriction; owl:onProperty ex:isAuthorOf ; owl:someValuesFrom ex:Publication ] ).
```

What we really wanted to say (but which wasn't expressible in OWL1)

```
ex:Senior owl:intersectionOf (
   foaf:Person
   [ a owl:Restriction; owl:onProperty ex:isAuthorOf ; owl:minQualifiedCardinality 10
       owl:onClass ex:Publication ] ) .
```

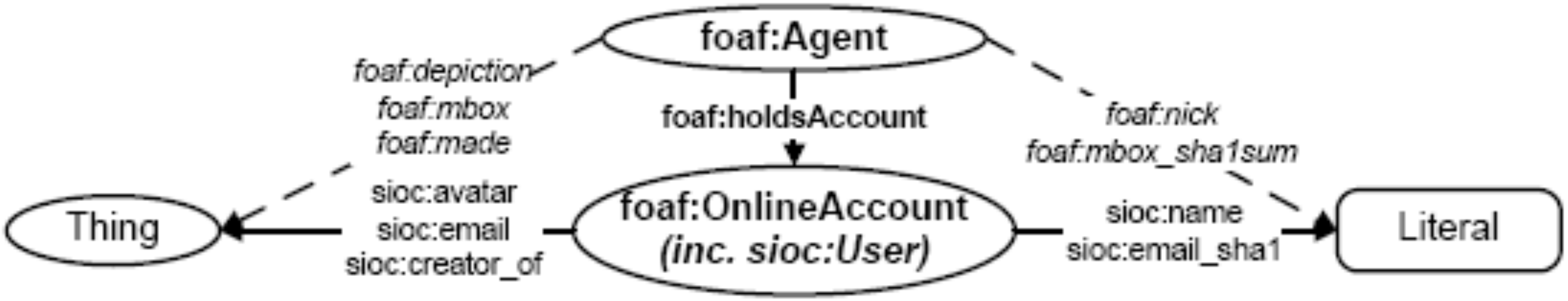
New Expressiveness in OWL 2

Property Chain axioms:

– E.g. could be useful to tie sioc:name and foaf:nick via foaf:holdsAccount:

$$(foaf{:}holdsAccount \circ sioc{:}name) \sqsubseteq foaf{:}nick$$

```
foaf:nick owl:propertyChainAxiom (foaf:holdsAccount sioc:name) .
```



New Expressiveness in OWL 2

local reflexivity restrictions

$$Narcissist \equiv \exists loves.self()$$

```
:Narcissist owl:equivalentClass
      [ a owl:Restriction ;
        owl:onProperty :loves ;
        owl:hasSelf "true"^^xsd:boolean  ] .
```

New Expressiveness in OWL 2

In OWL 1, you can define tgat a property is functional, transitive, symmetric, inverseFunctional…

```
owl:SymmetricProperty
owl:FunctionalProperty
owl:InverseFunctionalProperty
owl:TransitiveProperty
```

… additional property features in OWL2:

reflexive, irreflexive, and asymmetric, properties.

```
owl:ReflexiveProperty
owl:IrreflexiveProperty
owl:AsymmetricProperty
```

New Expressiveness in OWL 2

Disjoint properties:

In OWL 1 disjointness can only be asserted for classes

```
:Animal owl:disjointWith :Person .
```

In OWL2 also allowed to assert disjointness of Properties

```
:childOf  owl:propertyDisjointWith :spouseOf .
```

New Expressiveness in OWL 2

Keys

Multi-attribute Keys now possible in OWL 2, e.g. `foaf:OnlineAccount/` members are uniquely identified by a combination of `foaf:accountName` and `foaf:accountServiceHomepage:`

```
foaf:OnlineAccount owl:hasKey
      (foaf:accountName foaf:accountServiceHomepage) .
```

New Expressiveness in OWL 2

Syntactic sugar (make things easier to say)

- Disjoint unions, e.g.:

  Element owl:DisjointUnionOf (Metal Wood Water Fire Earth)

- Disjoint classes, and propertiese.g.:

```
[ a owl:AllDisjointClasses ;
  owl:members ( University Department Professor Student ) ] .
[ a owl:AllDisjointProperties ;
  owl:members ( spouseOf childOf grandChildOf ) ] .
```

- More Syntactic sugar for Negative assertions, e.g.:

  owl:NegativePropertyAssertion

  *allows to state negated facts, such as (but the RDF syntax for it looks quite ugly ;-)):**

$$\neg childOf(adam, eve)$$

** Note: this is already expressible in OWL1:* $\{adam\} \sqsubseteq \neg\exists childOf.\{eve\}$

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OWL 2 DL

$\mathcal{S}$ used for ALC with role transitivity (also reflexivity, symmetry)

$\mathcal{H}$ used for role hierarchy

$\mathcal{R}$ (subsumes $\mathcal{H}$) often used for with role (property chain) inclusion axioms.

Additional letters indicate other extensions, e.g.:

- $\mathcal{S}$ for property characteristics (e.g., reflexive and symmetric)
- $\mathcal{O}$ for **nominals**/singleton classes
- $\mathcal{I}$ for inverse roles
- $\mathcal{N}$ for unqualified number restrictions
- $\mathcal{Q}$ for qualified number restrictions

property characteristics ($\mathcal{S}$) + $\mathcal{R}$ + nominals ($\mathcal{O}$) + inverse ($\mathcal{I}$) + qualified number restrictions($\mathcal{Q}$) = $\mathcal{SROIQ}$

$\mathcal{SROIQ}$ [Horrocks et al., 2006] is the basis for OWL 2 DL

OWL 2 Profiles

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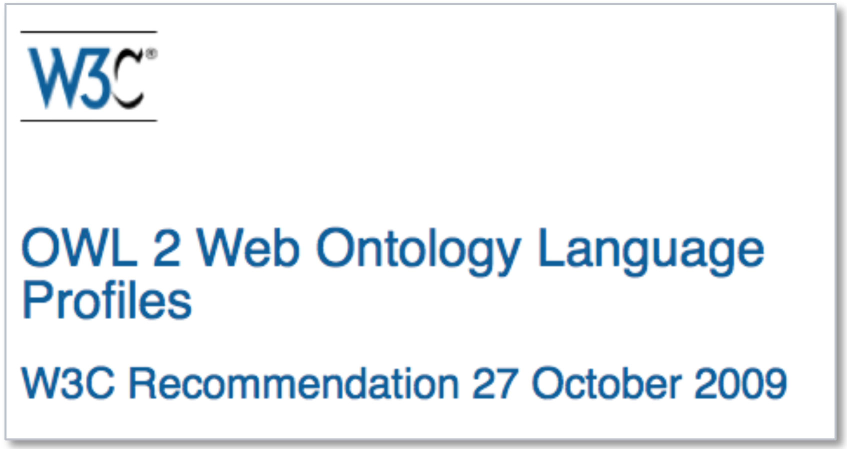
Rationale:

- Tractable
- Tailored to specific reasoning services

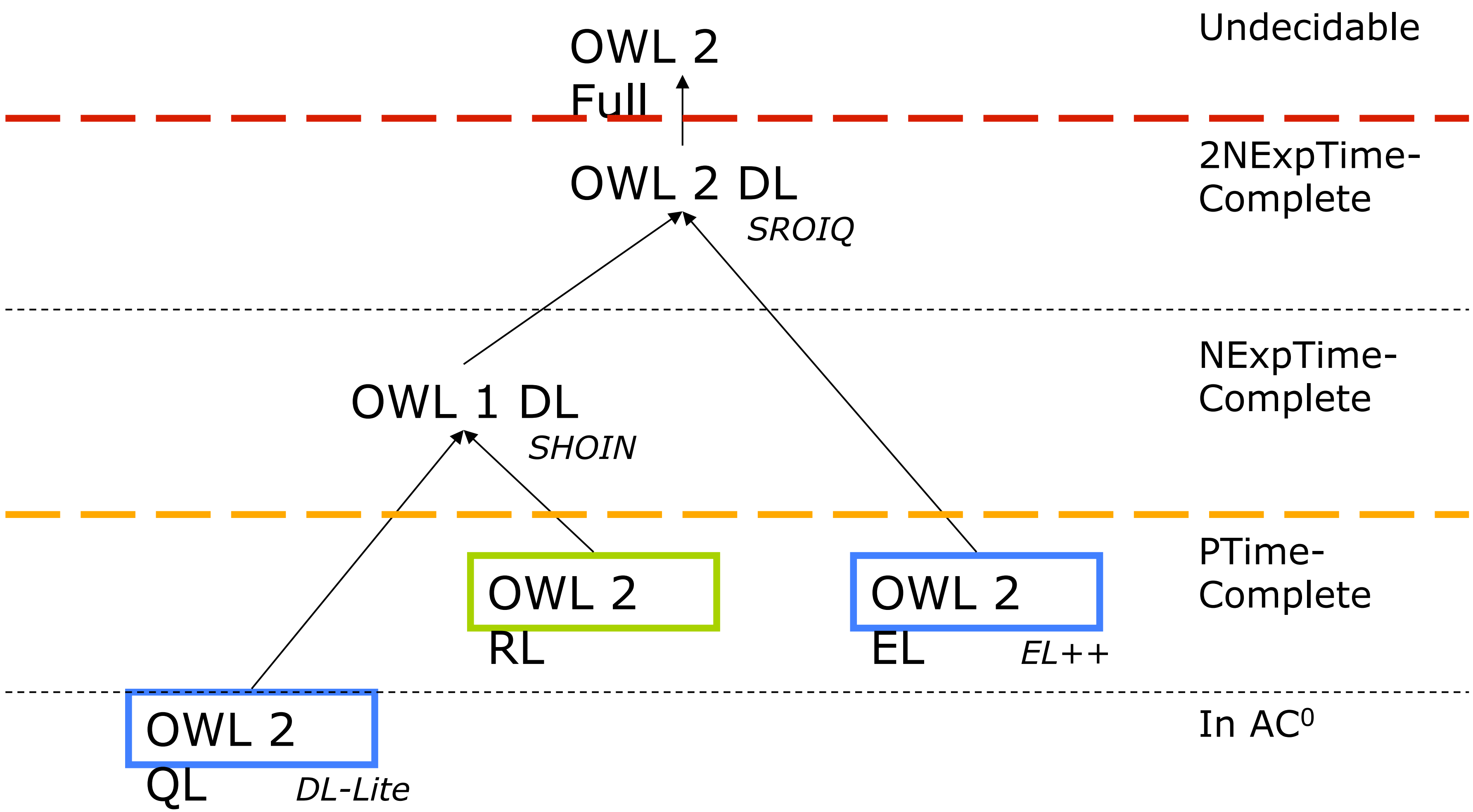
Popular reasoning services

- Instance reasoning: OWL 2 RL
- Query answering: OWL 2 QL
- Terminological reasoning (reasoning about classes and Properties): OWL 2 EL

Specification: http://www.w3.org/TR/owl2-profiles/



The family tree



OWL 2 RL: OWL reasoning via rules

Ontologies: Example FOAF

`foaf:knows rdfs:domain foaf:Person`

$$\exists knows.\top \sqsubseteq Person$$

`foaf:knows rdfs:range foaf:Person`

$$\exists knows^{-}.\top \sqsubseteq Person$$

`foaf:Person rdfs:subclassOf foaf:Agent`

$$Person \sqsubseteq Agent$$

`foaf:homepage rdf:type owl:inverseFunctionalProperty .`

$$\top \sqsubseteq \leq 1 homepage^{-}$$

…

RDFS+OWL inference by rules 1/2

Recall that the semantics of RDFS can be expressed as (Datalog like) rules:

```
rdfs1: { ?S rdf:type ?C } :- { ?S ?P ?O . ?P rdfs:domain ?C . }
rdfs2: { ?O rdf:type ?C } :- { ?S ?P ?O . ?P rdfs:range ?C . }

rdfs3: { ?S rdf:type ?C2 } :- {?S rdf:type ?C1 . ?C1 rdfs:subclassOf ?C2 . }

rdfs4: { ?S ?P2 ?O } :- {?S ?P1 ?O . ?P1 rdfs:subPropertyOf ?P2 . }
```

cf. informative Entailment rules in [RDF-Semantics, W3C, 2004] from Lecture 3.

RDFS+OWL inference by rules 2/2

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Some OWL Reasoning e.g. inverseFunctionalProperty can also be expressed by Rules:

```
owl1: { ?S1 owl:SameAs ?S2 } :-
          { ?S1 ?P ?O . ?S2 ?P ?O . ?P rdf:type owl:InverseFunctionalProperty }


owl2: { ?Y ?P ?O } :- { ?X owl:SameAs ?Y . ?X ?P ?O }
owl3: { ?S ?Y ?O } :- { ?X owl:SameAs ?Y . ?S ?X ?O }
owl4: { ?S ?P ?Y } :- { ?X owl:SameAs ?Y . ?S ?P ?X }
```

→ **OWL 2 RL is the maximal fragment of OWL DL such that reasoning can be expressed in Rules!**

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Example OWL 2 RL inference:

Rules of the previous slides are sufficient e.g. for the example I showed you last time:

```
<http://dbpedia.org/resource/Tim_Berners-Lee>
  foaf:homepage
         <http://www.w3.org/People/Berners-Lee/> .
```

dbpedia.org

```
foaf:name rdfs:subPropertyOf rdfs:label .
foaf:homepage a owl:InverseFunctionalProperty .
```

xmlns.com/foaf/

```
<http://dblp.l3s.de/d2r/page/authors/Tim_Berners-Lee>
   foaf:homepage
          <http://www.w3.org/People/Berners-Lee/> ;
   foaf:name "Tim Berners-Lee".
```

dblp.l3s.de

```
by owl1  →   <…/dblp…/Tim_Berners-Lee> owl:sameAs <…/dbpedia…/Tim_Berners-Lee>.
by owl2  →   <…/dbpedia…/Tim_Berners-Lee> foaf:name "Tim Berners-Lee".
by rdfs4 →   <…/dbpedia…/Tim_Berners-Lee> rdfs:label "Tim Berners-Lee".
```

```
SELECT ?P ?O
WHERE { <http://dbpedia.org/resource/Tim_Berners-Lee>  rdfs:label ?O }
```

?O
"Tim Berners-Lee"

RDFS+OWL inference in OWL 2 RL, what's missing?

Note: Not all of OWL Reasoning can be expressed in Datalog, e.g.:

```
foaf:Person owl:disjointWith foaf:Organisation
```

Can be written/and reasoned about with FOL/DL reasoners:

FOL Syntax: $\forall X.Person(X) \supset \neg Organisation(X)$

DL Syntax: $Person \sqcap Organisation \sqsubseteq \bot$

But can be "**approximated**" by Rules (this is what is done in OWL 2 RL):

```
owl5: ERROR :- { ?X a ?C1; a ?C2. ?C1 owl:disjointWith ?C2.}
```

RDFS+OWL inference in OWL 2 RL, NOW what's not expressible?

Some expressions are only allowed on one side of a subclassOf axiom, e.g.

$$\exists isAuthorOf.Publication \sqsubseteq Scientist$$

is ok, can be covered by a simple Datalog-style rule:

```
{ ?S a ?D } :- { [owl:onProperty ?P ; owl:someValuesFrom ?C]
                 rdfs:subClassOf ?D.
                 ?S ?P ?O . ?O a ?C .  }
```

But not the other way around (would need a rule with "existential" in the head):

$$Scientist \sqsubseteq \exists isAuthorOf.Publication$$

This is why OWL 2 RL forbids e.g. certain constructs on the right/left-hand-side of rdfs:subClassOf.

OWL 2 QL

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A (near maximal) fragment of OWL 2 such that

- Data complexity of conjunctive query answering in **AC^0**

Based on **DL-Lite** family of description logics [Calvanese et al. 2005; 2006; 2008]

Can exploit **query rewriting** based reasoning technique

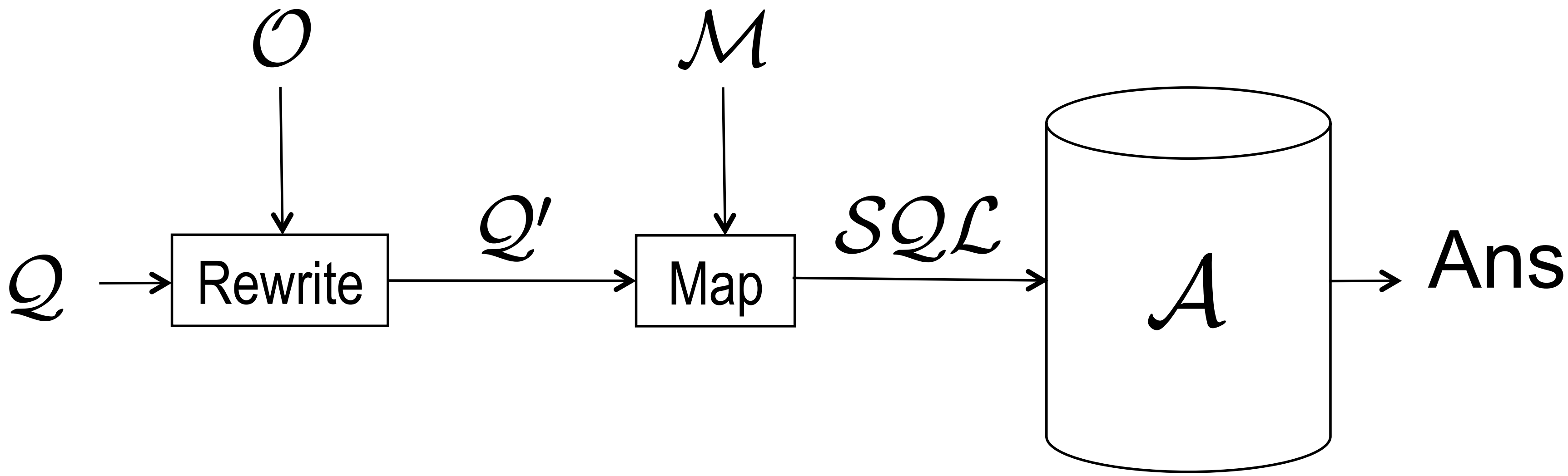
- Computationally optimal
- Data storage and query evaluation can be delegated to standard RDBMS or RDF Store/SPARQL engine.
- Novel technique to prevent exponential blowup produced by rewritings [Kontchakov et al. 2010, Rosati and Almatelli 2010]
- Can be extended to more expressive languages (beyond AC^0) by delegating query answering to a Datalog engine [Perez-Urbina et al. 2009]

Query Rewriting Technique (basics)

Given ontology $\mathcal{O}$ and query $\mathcal{Q}$, use $\mathcal{O}$ to rewrite $\mathcal{Q}$ as $\mathcal{Q}'$ s.t., for any set of ground facts $\mathcal{A}$:

- ans($\mathcal{Q}$, $\mathcal{O}$, $\mathcal{A}$) = ans($\mathcal{Q}'$, $\emptyset$, $\mathcal{A}$)

Use (GAV) mapping $\mathcal{M}$ to map $\mathcal{Q}'$ to SQL query



Query Rewriting Technique (basics)

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- ans($\mathcal{Q}$, $\mathcal{O}$, $\mathcal{A}$) = ans($\mathcal{Q}'$, $\emptyset$, $\mathcal{A}$)

Resolution based query rewriting

- **Clausify** ontology axioms (using Skolemization)
- **Saturate** (clausified) ontology and query using resolution
- **Prune** redundant query clauses

Query Rewriting Technique (basics)

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Example:

$$\mathsf{Doctor} \sqsubseteq \exists \mathsf{treats}.\mathsf{Patient}$$

$$\mathsf{Consultant} \sqsubseteq \mathsf{Doctor}$$

$$Q(x) \leftarrow \mathsf{treats}(x, y) \land \mathsf{Patient}(y)$$

Query Rewriting Technique (basics) - Clausify

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Example:

$$\mathsf{Doctor} \sqsubseteq \exists \mathsf{treats}.\mathsf{Patient}$$

$$\mathsf{Consultant} \sqsubseteq \mathsf{Doctor}$$

$$\mathsf{treats}(x, f(x)) \leftarrow \mathsf{Doctor}(x)$$

$$\mathsf{Patient}(f(x)) \leftarrow \mathsf{Doctor}(x)$$

$$\mathsf{Doctor}(x) \leftarrow \mathsf{Consultant}(x)$$

Clausified ontology

$$Q(x) \leftarrow \mathsf{treats}(x, y) \wedge \mathsf{Patient}(y)$$

Query Rewriting Technique (basics) - Saturate

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Example:

$$\mathsf{Doctor} \sqsubseteq \exists \mathsf{treats}.\mathsf{Patient}$$

$$\mathsf{Consultant} \sqsubseteq \mathsf{Doctor}$$

$$\mathsf{treats}(x, f(x)) \leftarrow \mathsf{Doctor}(x)$$

$$\mathsf{Patient}(f(x)) \leftarrow \mathsf{Doctor}(x)$$

$$\mathsf{Doctor}(x) \leftarrow \mathsf{Consultant}(x)$$

$$Q(x) \leftarrow \mathsf{treats}(x, y) \wedge \mathsf{Patient}(y)$$

$$Q(x) \leftarrow \mathsf{Doctor}(x) \wedge \mathsf{Patient}(f(x))$$

Query Rewriting Technique (basics) - Saturate

Example:

$$\mathsf{Doctor} \sqsubseteq \exists \mathsf{treats}.\mathsf{Patient}$$
$$\mathsf{Consultant} \sqsubseteq \mathsf{Doctor}$$

$$\mathsf{treats}(x, f(x)) \leftarrow \mathsf{Doctor}(x)$$
$$\mathsf{Patient}(f(x)) \leftarrow \mathsf{Doctor}(x)$$
$$\mathsf{Doctor}(x) \leftarrow \mathsf{Consultant}(x)$$

$$Q(x) \leftarrow \mathsf{treats}(x, y) \wedge \mathsf{Patient}(y)$$
$$Q(x) \leftarrow \mathsf{Doctor}(x) \wedge \mathsf{Patient}(f(x))$$
$$Q(x) \leftarrow \mathsf{treats}(x, f(x)) \wedge \mathsf{Doctor}(x)$$

Query Rewriting Technique (basics) - Saturate

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Example:

$$\text{Doctor} \sqsubseteq \exists \text{treats}.\text{Patient}$$

$$\text{Consultant} \sqsubseteq \text{Doctor}$$

$$\text{treats}(x, f(x)) \leftarrow \text{Doctor}(x)$$

$$\text{Patient}(f(x)) \leftarrow \text{Doctor}(x)$$

$$\text{Doctor}(x) \leftarrow \text{Consultant}(x)$$

$$Q(x) \leftarrow \text{treats}(x, y) \wedge \text{Patient}(y)$$

$$Q(x) \leftarrow \text{Doctor}(x) \wedge \text{Patient}(f(x))$$

$$Q(x) \leftarrow \text{treats}(x, f(x)) \wedge \text{Doctor}(x)$$

$$Q(x) \leftarrow \text{Doctor}(x)$$

Query Rewriting Technique (basics) - Saturate

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Example:

$$\mathsf{Doctor} \sqsubseteq \exists \mathsf{treats}.\mathsf{Patient}$$

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$$\mathsf{treats}(x, f(x)) \leftarrow \mathsf{Doctor}(x)$$

$$\mathsf{Patient}(f(x)) \leftarrow \mathsf{Doctor}(x)$$

$$\mathsf{Doctor}(x) \leftarrow \mathsf{Consultant}(x)$$

$$Q(x) \leftarrow \mathsf{treats}(x, y) \wedge \mathsf{Patient}(y)$$

$$Q(x) \leftarrow \mathsf{Doctor}(x) \wedge \mathsf{Patient}(f(x))$$

$$Q(x) \leftarrow \mathsf{treats}(x, f(x)) \wedge \mathsf{Doctor}(x)$$

$$Q(x) \leftarrow \mathsf{Doctor}(x)$$

$$Q(x) \leftarrow \mathsf{Consultant}(x)$$

Query Rewriting Technique (basics) - Prune

Example:

$$\text{Doctor} \sqsubseteq \exists \text{treats}.\text{Patient}$$

$$\text{Consultant} \sqsubseteq \text{Doctor}$$

$$\text{treats}(x, f(x)) \leftarrow \text{Doctor}(x)$$

$$\text{Patient}(f(x)) \leftarrow \text{Doctor}(x)$$

$$\text{Doctor}(x) \leftarrow \text{Consultant}(x)$$

$$Q(x) \leftarrow \text{treats}(x, y) \wedge \text{Patient}(y)$$

~~$Q(x) \leftarrow \text{Doctor}(x) \wedge \text{Patient}(f(x))$~~

~~$Q(x) \leftarrow \text{treats}(x, f(x)) \wedge \text{Doctor}(x)$~~

$$Q(x) \leftarrow \text{Doctor}(x)$$

$$Q(x) \leftarrow \text{Consultant}(x)$$

The result is a union of conjunctive queries

$$Q(x) \leftarrow (\text{treats}(x, y) \wedge \text{Patient}(y)) \vee \text{Doctor}(x) \vee \text{Consultant}(x)$$

Could be used to answer some SPARQL queries over ontologies:

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Example

$$\text{Doctor} \sqsubseteq \exists \text{treats}.\text{Patient}$$

$$\text{Consultant} \sqsubseteq \text{Doctor}$$

y is also called a **non-distinguished** query variable. **Distinguished** variables in a conj. Query are output variables

Original Query:

$$Q(x) \leftarrow \text{treats}(x, y) \wedge \text{Patient}(y)$$

```
SELECT ?X  WHERE { ?X :treats ?Y .?Y a :Patient }
```

The resulting union of conjunctive queries:

$$Q(x) \leftarrow (\text{treats}(x, y) \wedge \text{Patient}(y)) \vee \text{Doctor}(x) \vee \text{Consultant}(x)$$

```
SELECT ?X  WHERE {  { ?X :treats ?Y .?Y a :Patient }
                    UNION { ?X a :Doctor .}
                    UNION { ?X a :Consultant.}   }
```

OWL 2 QL - Summary

→ **OWL 2 QL is the maximal fragment of OWL DL such that Query Answering can be expressed by (polynomial) Query rewriting techniques!**

Again: several restrictions on what can and can't be used, e.g. owl:sameAs is not allowed in OWL 2 QL … unfortunately, in the general case, ***non-distinguished*** variables can make trouble…

OWL 2 EL

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A (near maximal) fragment of OWL 2 such that

- Satisfiability checking is in PTime (**PTime-Complete**)
- Data complexity of query answering also PTime-Complete

Based on $\mathcal{EL}$ family of description logics [Baader et al. 2005]

Can exploit **saturation** based reasoning techniques

- Computes complete classification in "one pass"
- Computationally optimal (PTime for EL)
- Can be extended to Horn fragment of OWL DL [Kazakov 2009]

Will skip over this since it's mainly useful for terminological reasoning, less for query answering…

Saturation-based Technique (basics)

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Normalise ontology axioms to standard form:

$$A \sqsubseteq B \quad A \sqcap B \sqsubseteq C \quad A \sqsubseteq \exists R.B \quad \exists R.B \sqsubseteq C$$

Saturate using inference rules:

$$\frac{A \sqsubseteq B \quad B \sqsubseteq C}{A \sqsubseteq C} \qquad \frac{A \sqsubseteq B \quad A \sqsubseteq C \quad B \sqcap C \sqsubseteq D}{A \sqsubseteq D}$$

$$\frac{A \sqsubseteq \exists R.B \quad B \sqsubseteq C \quad \exists R.C \sqsubseteq D}{A \sqsubseteq D}$$

(This is a simplification, the whole EL requires (many) more rules)

Saturation-based Technique (basics)

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Example:

$$\mathsf{OrganTransplant} \equiv \mathsf{Transplant} \sqcap \exists \mathsf{site}.\mathsf{Organ}$$
$$\mathsf{HeartTransplant} \equiv \mathsf{Transplant} \sqcap \exists \mathsf{site}.\mathsf{Heart}$$
$$\mathsf{Heart} \sqsubseteq \mathsf{Organ}$$

$$\mathsf{OrganTransplant} \sqsubseteq \mathsf{Transplant}$$
$$\mathsf{OrganTransplant} \sqsubseteq \exists \mathsf{site}.\mathsf{Organ}$$
$$\exists \mathsf{site}.\mathsf{Organ} \sqsubseteq \mathsf{SO}$$
$$\mathsf{Transplant} \sqcap \mathsf{SO} \sqsubseteq \mathsf{OrganTransplant}$$
$$\mathsf{HeartTransplant} \sqsubseteq \mathsf{Transplant}$$
$$\mathsf{HeartTransplant} \sqsubseteq \exists \mathsf{site}.\mathsf{Heart}$$
$$\exists \mathsf{site}.\mathsf{Heart} \sqsubseteq \mathsf{SH}$$
$$\mathsf{Transplant} \sqcap \mathsf{SH} \sqsubseteq \mathsf{HeartTransplant}$$
$$\mathsf{Heart} \sqsubseteq \mathsf{Organ}$$

Saturation-based Technique (basics)

Example:

$$\text{OrganTransplant} \equiv \text{Transplant} \sqcap \exists \text{site}.\text{Organ}$$
$$\text{HeartTransplant} \equiv \text{Transplant} \sqcap \exists \text{site}.\text{Heart}$$
$$\text{Heart} \sqsubseteq \text{Organ}$$

$$\frac{A \sqsubseteq \exists R.B \quad B \sqsubseteq C \quad \exists R.C \sqsubseteq D}{A \sqsubseteq D}$$

$$\text{OrganTransplant} \sqsubseteq \text{Transplant}$$
$$\text{OrganTransplant} \sqsubseteq \exists \text{site}.\text{Organ}$$
$$\exists \text{site}.\text{Organ} \sqsubseteq \text{SO}$$
$$\text{Transplant} \sqcap \text{SO} \sqsubseteq \text{OrganTransplant}$$
$$\text{HeartTransplant} \sqsubseteq \text{Transplant}$$
$$\text{HeartTransplant} \sqsubseteq \exists \text{site}.\text{Heart}$$
$$\exists \text{site}.\text{Heart} \sqsubseteq \text{SH}$$
$$\text{Transplant} \sqcap \text{SH} \sqsubseteq \text{HeartTransplant}$$
$$\text{Heart} \sqsubseteq \text{Organ}$$

Saturation-based Technique (basics)

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Example:

$$\mathsf{OrganTransplant} \equiv \mathsf{Transplant} \sqcap \exists \mathsf{site}.\mathsf{Organ}$$

$$\mathsf{HeartTransplant} \equiv \mathsf{Transplant} \sqcap \exists \mathsf{site}.\mathsf{Heart}$$

$$\mathsf{Heart} \sqsubseteq \mathsf{Organ}$$

$$\frac{A \sqsubseteq \exists R.B \quad B \sqsubseteq C \quad \exists R.C \sqsubseteq D}{A \sqsubseteq D}$$

$$\mathsf{OrganTransplant} \sqsubseteq \mathsf{Transplant}$$

$$\mathsf{OrganTransplant} \sqsubseteq \exists \mathsf{site}.\mathsf{Organ}$$

$$\exists \mathsf{site}.\mathsf{Organ} \sqsubseteq \mathsf{SO}$$

$$\mathsf{Transplant} \sqcap \mathsf{SO} \sqsubseteq \mathsf{OrganTransplant}$$

$$\mathsf{HeartTransplant} \sqsubseteq \mathsf{Transplant}$$

$$\mathsf{HeartTransplant} \sqsubseteq \exists \mathsf{site}.\mathsf{Heart}$$

$$\exists \mathsf{site}.\mathsf{Heart} \sqsubseteq \mathsf{SH}$$

$$\mathsf{Transplant} \sqcap \mathsf{SH} \sqsubseteq \mathsf{HeartTransplant}$$

$$\mathsf{Heart} \sqsubseteq \mathsf{Organ}$$

$$\mathsf{HeartTransplant} \sqsubseteq \mathsf{SO}$$

SPARQL and OWL

… Now what about SPARQL1.1 and OWL?

SPARQL1.1 Entailment Regimes

SPARQL1.1 defines SPARQL query answering over RDFS and OWL2 ontologies (as well as RIF rule sets):

- http://www.w3.org/TR/sparql11-entailment/

Particularly:

- RDF Entailment Regime
- RDFS Entailment Regime
- D-Entailment Regime
- OWL 2 RDF-Based Semantics Entailment Regime
- OWL 2 Direct Semantics Entailment Regime
  - Won’t go into details of those, but sketch the main ideas!

RDFS/OWL2 and SPARQL1.1

General Idea: Answer Queries with implicit answers

```
<http://dbpedia.org/resource/Tim_Berners-Lee>
  foaf:homepage
         <http://www.w3.org/People/Berners-Lee/> .

 foaf:name rdfs:subPropertyOf rdfs:label .
 foaf:homepage a owl:InverseFunctionalProperty .

<http://dblp.l3s.de/d2r/page/authors/Tim_Berners-Lee>
   foaf:homepage
          <http://www.w3.org/People/Berners-Lee/> ;
   foaf:name "Tim Berners-Lee".
```

```
SELECT ?P ?O
WHERE { <http://dbpedia.org/resource/Tim_Berners-Lee>  rdfs:label ?O }
```

?O
"Tim Berners-Lee"

OWL2 and SPARQL1.1

General Idea: Answer Queries with implicit answers

E.g. Graph/Ontology:

```
foaf:Person rdfs:subClassOf foaf:Agent .
foaf:Person rdfs:subclassOf
                [ a owl:Restriction ;
       owl:onProperty :hasFather ;
       owl:someValuesFrom foaf:Person. ]
 foaf:knows rdfs:range foaf:Person.

 :jeff a Person .
 :jeff foaf:knows :aidan .
```

`SELECT ?X { ?X a foaf:Person }`

Pure SPARQL 1.0 returns only `:Jeff`,

should also return `:aidan`

SPARQL1.1+RDFS/OWL: Challenges+Pitfalls

Challenges+Pitfalls:

- Possibly Infinite answers (by RDFS ContainerMembership properties, OWL datatype reasoning, etc.)
- Conjunctive Queries: **non-distinguished variables**
- SPARQL 1.1 features: e.g. Aggregates

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SPARQL1.1+RDFS/OWL: Challenges+Pitfalls

Pragmatic Solution within SPARQL1.1:

- Possibly Infinite answers (by RDFS ContainerMembership properties, OWL datatype reasoning, etc.)
  - Restrict answers to rdf:/rdfs:/owl:vocabulary minus rdf:_1 … rdf:_n plus terms occurring in the data graph

- Non-distinguished variables
  - *No non-distinguished variables, answers must result from BGP matching, projection a post-processing step not part of SPARQL entailment regimes.*

- SPARQL 1.1 other features: e.g. Aggregates, etc.
  - *Again not affected, answers must result from BGP matching, projection a post-processing step not part of entailment.*

- Simple, BUT: maybe not always entirelty intuitive, so
  - Good to know what to expect … ;-)

Possibly Infinite answers RDF(S): Container Membership

Graph:

```
:rr2010Proceedings :hasEditors [ a rdf:Seq;
                                   rdf:_1 :pascal_hitzler.
                                   rdf:_2 :thomas_lukasiewicz.
                                 ]
```

Query with RDFS Entailment in mind:

`SELECT ?CM { ?CM a rdfs:ContainerMembershipProperty}`

Entailed by RDFS (axiomatic Triples):

```
rdfs:_1 a rdfs:ContainerMembershipProperty .
rdfs:_2 a rdfs:ContainerMembershipProperty .
rdfs:_3 a rdfs:ContainerMembershipProperty .
rdfs:_4 a rdfs:ContainerMembershipProperty .
…
```

Possibly Infinite answers RDF(S): Container Membership

Graph:

```
:rr2010Proceedings :hasEditors [ a rdf:Seq;
                                  rdf:_1 :pascal_hitzler.
                                  rdf:_2 :thomas_lukasiewicz.
                                ]
```

Query with RDFS Entailment in mind:

`SELECT ?CM { ?CM a rdfs:ContainerMembershipProperty}`

SPARQL 1.1 restricts answers to rdf:/rdfs:/owl:vocabulary minus rdf:_1 … rdf:_n **plus terms occurring in the data graph**

So, the only answers in SPARQL1.1 are:

`{ ?CM/rdfs:_1, ?CM/rdfs:_2, }`

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Possibly Infinite answers OWL: datatype reasoning

Stupid way to say Peter is 50 in OWL:

```
ex:Peter a [ a owl:Restriction ;
             owl:onProperty ex:age ;
             owl:allValuesFrom [ rdf:type rdfs:Datatype .
             owl:oneOf ("50"^^xsd:integer) ] ]
```

Stupid query asking What is NOT Peters age:

```
SELECT ?x WHERE {
      ex:Peter a [ a owl:Restriction ; owl:onProperty ex:age ;
              owl:allValuesFrom [ a rdfs:Datatype ;
                                owl:datatypeComplementOf [ a
                 rdfs:Datatype ; owl:oneOf (?x) ] ] ] }
```

Theoretical answer: all literal different from 50

No danger in SPARQL 1.1 restricts answers to rdf:/rdfs:/owl:vocabulary minus rdf:_1 … rdf:_n **plus terms occurring in the data graph**

Now What about Non-distinguished variables?

E.g. Graph

```
foaf:Person rdfs:subClassOf foaf:Agent .
foaf:Person rdfs:subclassOf
           [ a owl:Restriction ;
      owl:onProperty :hasFather ;
      owl:someValuesFrom foaf:Person. ]
foaf:knows rdfs:range foaf:Person.
:jeff a Person
:jeff foaf:knows :aidan
```

SELECT ?X ?Y { ?X :hasFather ?Y }

No answer, because no known value for ?Y in the data graph (here, ?Y is a distinguished variable, according to the previous definition)

Now What about Non-distinguished variables?

E.g. Graph

```
foaf:Person rdfs:subClassOf foaf:Agent .
foaf:Person rdfs:subclassOf
             [ a owl:Restriction ;
       owl:onProperty :hasFather ;
       owl:someValuesFrom foaf:Person. ]
foaf:knows rdfs:range foaf:Person.
:jeff a Person
:jeff foaf:knows :aidan
```

SELECT ?X { ?X :hasFather ?Y }

But what about this one? ?Y looks like a “non-distinguished” variable

Solution: In SPARQL 1.1 answers must result from BGP matching, projection a post-processing step not part of entailment, i.e. SPARQL1.1 treats ALL variables as distinguished ➔ so, still no answer.

Non-distinguished variables:

Simple Solution may seem not always intuitive, but:

- OWL Entailment in SPARQL based on BGP matching, i.e.
  - always only returns results with named individuals
  - Doesn't affect SELECT: BGP matching takes place before projection
  - That is: **non-distinguished variables can't occur "by design"**

- Conjunctive queries with non-distinguished variable still an open research problem for OWL:
  - Decidable for SHIQ, [B. Glimm et al. 2008]
  - Decidable for OWL 1 DL without transitive properties [B. Glimm, KR-10]
  - Particularly though: Decidability for the *SROIQ* Description Logics still unknown…

SPARQL1.1 Entailment & complex graph patterns

Once again: SPARQL entailment defined only at the level of **BGP** matching
➔SPARQL1.1 Algebra is layered "on top", no interaction

```
:person1 rdf:type [ owl:unionOf (:male :female) ]
```

```
SELECT ?X { {?X rdf:type :male }
            UNION
            {?X rdf:type :female }
          }
```

➔No result!

SPARQL1.1 Entailment & Aggregates

Similar as before… aggregates are evaluated as post-processing **after** BGP matching, so, no effect:

```
foaf:Person rdfs:subClassOf foaf:Agent .
  foaf:Person rdfs:subclassOf
                [ a owl:Restriction ;
        owl:onProperty :hasFather ;
        owl:someValuesFrom foaf:Person. ]
  :jeff a Person .
  :jeff foaf:knows :aidan
  foaf:knows rdfs:range foaf:Person.
```

```
SELECT ?X { ?X a foaf:Person }
```

Under RDFS/OWL entailment returns : {?X/jeff, ?X/aidan}

Similar as before… aggregates are evaluated as post-processing **after** BGP matching, so, no effect:

```
foaf:Person rdfs:subClassOf foaf:Agent .
  foaf:Person rdfs:subclassOf
               [ a owl:Restriction ;
        owl:onProperty :hasFather ;
        owl:someValuesFrom foaf:Person. ]
  :jeff a Person
  :jeff foaf:knows :aidan
  foaf:knows rdfs:range foaf:Person.
  :jeff :hasFather [a Person].
  :jeff owl:sameAs :aidan.
```

Attention! owl:sameAs inference does **NOT** affect counting!!! … But bnodes do!

```
SELECT (Count(?X) AS ?Y) { ?X a foaf:Person }
```

Under RDFS/OWL entailment returns : {?Y/3}

Lessons learnt

OWL adds more expressivity on top of what can be said in RDF Schema about properties and Classes

OWL 2

1) adds more expressivity on top
2) defines tractable fragments that are implementable efficiently

OWL+SPARQL gives implicit answers, but poses some challenges…

Will – by the end of the week – publish some last small assignment on:

Mini-assignment:

1. *Write down statement (vii) from Unit3, slide 37 in Turtle Syntax.*
2. *Freestyle: Write your own ontology in OWL... Be creative! Your ontology should allow some useful inferences from your FOAF file.*