The Role of Logics and Logic Programming in Semantic Web Standards (OWL2, RIF, SPARQL1.1)

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Outline

- Quick intro of RDF/OWL/Linked Open Data
- OWL2
  - Overview: from OWL 1 to OWL 2
  - Reasoning services in OWL 2
  - OWL2 Treactable Fragments (OWL2RL, OWL2EL, OWL2QL)
- OWL2 and RIF
- OWL2 and SPARQL1.1

- Time allowed: Implementing SPARQL, OWL2RL, RIF on top of DLV – The GiaBATA system

Example: Finding experts/reviewers?

***Tim Berners-Lee**, Dan Connolly, Lalana Kagal, Yosi Scharf, Jim Hendler: **N3Logic: A logical framework for the World Wide Web**. Theory and Practice of Logic Programming (TPLP), Volume 8, p249-269*

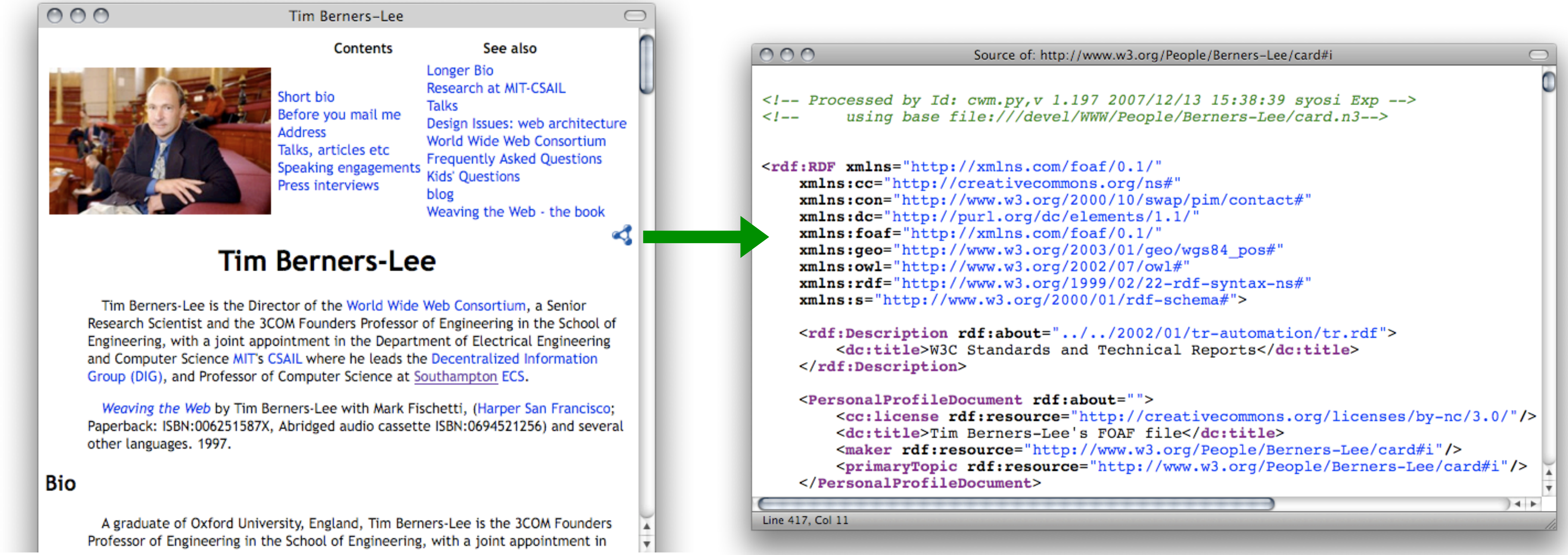
- Who are the right reviewers? Who has the right expertise?
- Which reviewers are in conflict?
- Observation: Most of the necessary data already on the Web, as **RDF**!

- More and more of it follows the **Linked Data principles**, i.e.:
  1. Use URIs as names for things
  2. Use HTTP dereferenceable URIs so that people can look up those names.
  3. When someone looks up a URI, provide useful information.
  4. Include links to other URIs so that they can discover more things.

RDF on the Web

- **(i) directly by the publishers**
- (ii) by e.g. transformations, D2R, RDFa exporters, etc.

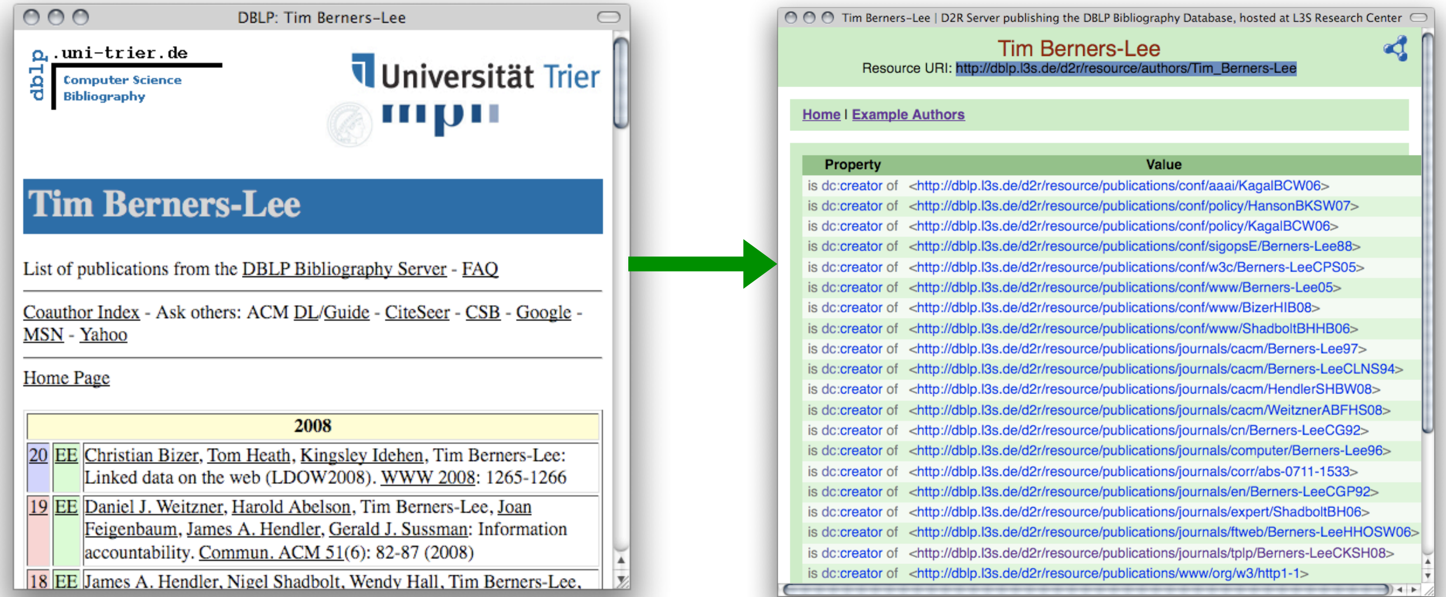
FOAF/RDF linked from a home page: personal data (foaf:name, foaf:phone, etc.), relationships foaf:knows, rdfs:seeAlso)



RDF on the Web

- (i) directly by the publishers
- **(ii) by e.g. transformations, D2R, RDFa exporters, etc.**

e.g. L3S' RDF export of the DBLP citation index, using FUB's D2R (http://dblp.l3s.de/d2r/)



Gives unique URIs to authors, documents, etc. on DBLP! E.g.,

http://dblp.l3s.de/d2r/resource/authors/Tim_Berners-Lee,

http://dblp.l3s.de/d2r/resource/publications/journals/tplp/Berners-LeeCKSH08

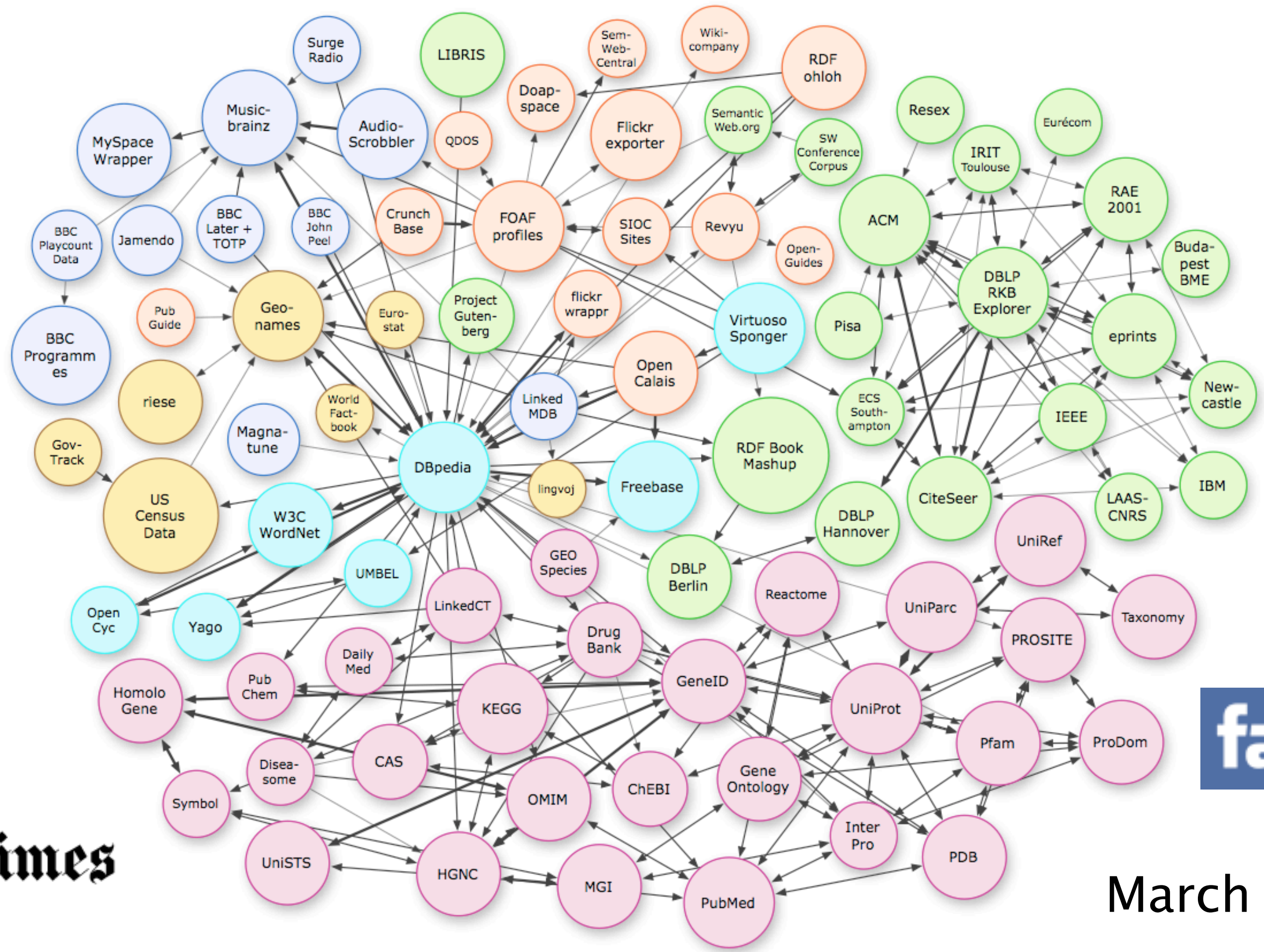
Provides RDF version of all DBLP data + query interface!

Linked Open Data

Miscellaneous YAHOO! Google

dblp.uni-trier.de Computer Science Bibliography

WIKIPEDIA



Freebase

. . .

The New York Times

facebook

March 2009

- Excellent tutorial here: http://www4.wiwiss.fu-berlin.de/bizer/pub/LinkedDataTutorial/

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RDF Data online: Example

- Data in RDF: **Triples**

subject predicate object

  - DBLP:

```
<http://dblp.l3s.de/…/journals/tplp/Berners-LeeCKSH08> rdf:type swrc:Article.
<http://dblp.l3s.de/…/journals/tplp/Berners-LeeCKSH08> dc:creator
     <http://dblp.l3s.de/d2r/…/Tim_Berners-Lee> .
  …
<http://dblp.l3s.de/d2r/…/Tim_Berners-Lee> foaf:homepage
       <http://www.w3.org/People/Berners-Lee/> .

…
<http://dblp.l3s.de/d2r/…/Dan_Brickley> foaf:name "Dan Brickley"^^xsd:string.
```

  - Tim Berners-Lee's FOAF file:

```
<http://www.w3.org/People/Berners-Lee/card#i> foaf:knows
    <http://dblp.l3s.de/d2r/…/Dan_Brickley> .
<http://www.w3.org/People/Berners-Lee/card#i> rdf:type foaf:Person .
<http://www.w3.org/People/Berners-Lee/card#i> foaf:homepage
    <http://www.w3.org/People/Berners-Lee/> .
```

How can I query such data? SPARQL

- SPARQL – W3C approved standardized query language for RDF:
  - look-and-feel of “SQL for the Web”
  - allows to ask queries like
    - “All documents by Tim Berners-Lee”

      …

Example:

```
SELECT ?D
FROM <http://dblp.l3s.de/…/authors/Tim_Berners-Lee>
WHERE {?D dc:creator <http://dblp.l3s.de/…/authors/Tim_Berners-Lee>}
```

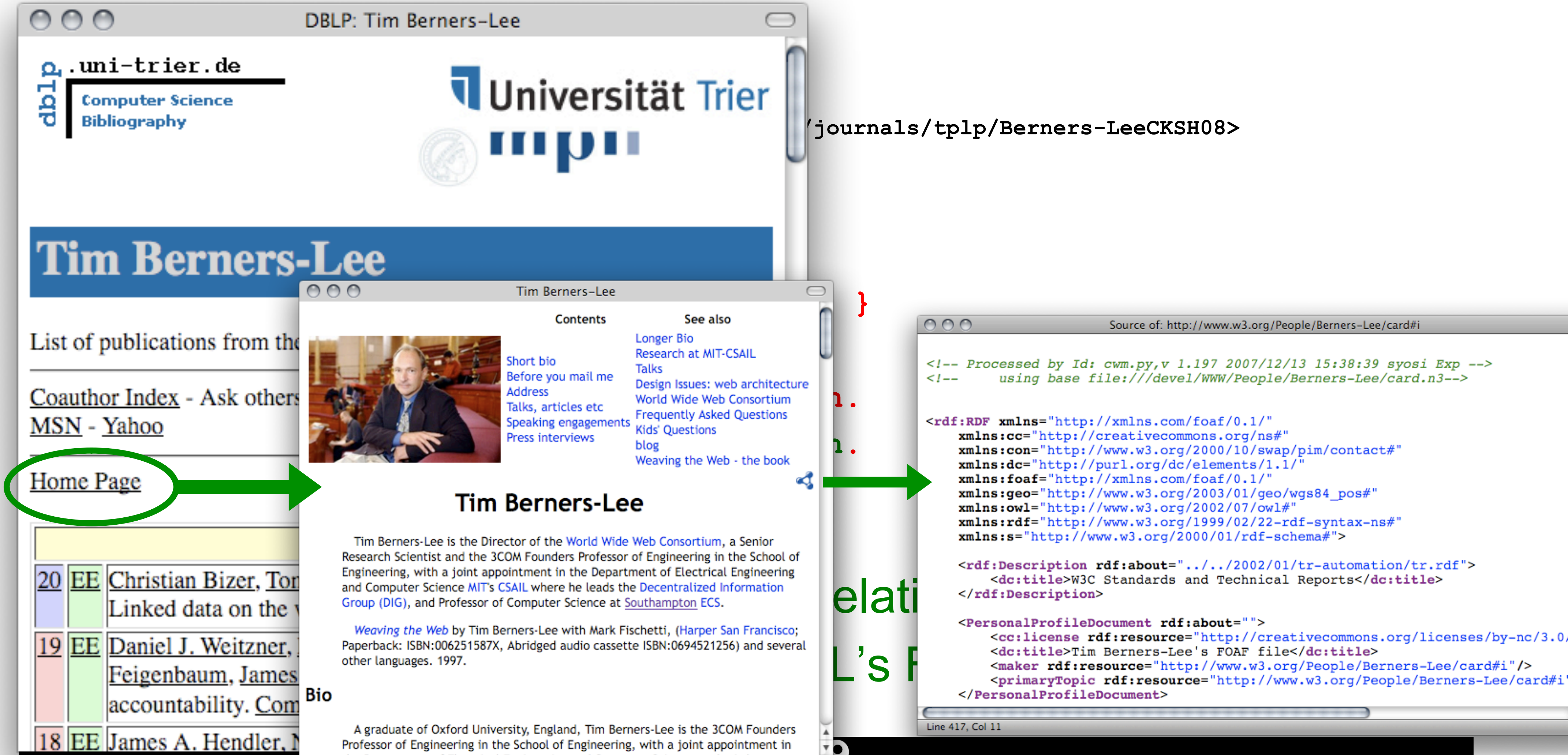
SPARQL more complex patters: e.g. CQs

- "**Names** ***of all persons who co-authored with authors of http:// dblp.l3s.de/d2r/…/Berners-LeeCKSH08***"

```
SELECT ?Name WHERE
   { <http://dblp.l3s.de/d2r/resource/publication/journals/tplp/Berners-LeeCKSH08>
        dc:creator ?Author.
        ?D dc:creator ?Author.
        ?D dc:creator ?CoAuthor.
        ?CoAuthor foaf:name ?Name
   }
```

SPARQL more complex patters: e.g. UCQs

- "Names *of all persons who* **co-authored** *with authors of http://dblp.l3s.de/d2r/…/Berners-LeeCKSH08* **or known by co-authors**"



Back to the Data:

- DBLP:

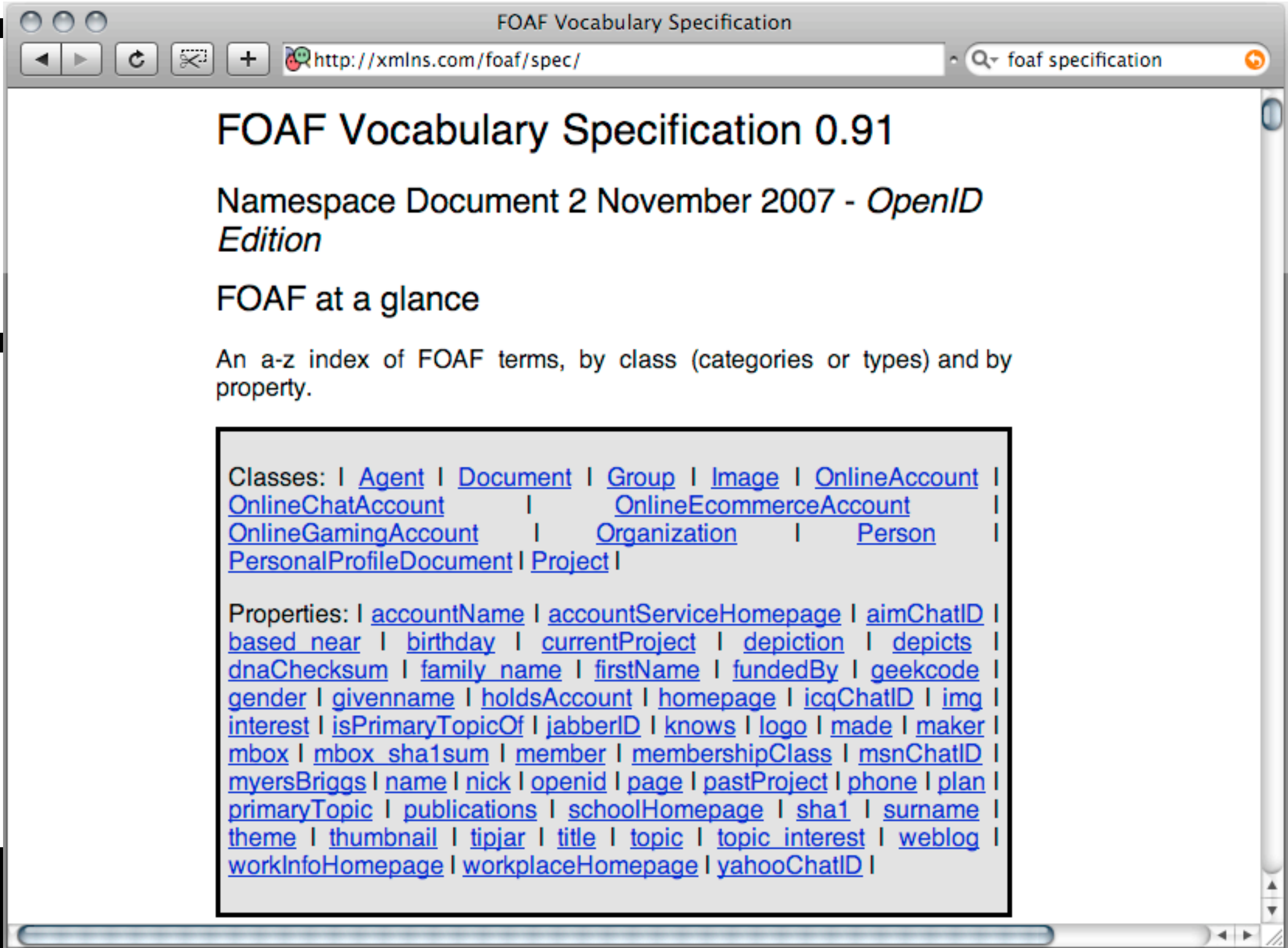
```
<http://dblp.l3s.de/…/journals/tplp/Berners-LeeCKSH08> rdf:type swrc:Article.
<http://dblp.l3s.de/…/journals/tplp/Berners-LeeCKSH08> dc:creator
     <http://dblp.l3s.de/d2r/…/Tim_Berners-Lee> .
  …
<http://dblp.l3s.de/d2r/…/Tim_Berners-Lee> foaf:homepage
       <http://www.w3.org/People/Berners-Lee/> .
```

- Tim Berners-Lee's FOAF file:

```
<http://www.w3.org/People/Berners-Lee/card#i> foaf:knows
    <http://dblp.l3s.de/d2r/…/Dan_Brickley> .
<http://www.w3.org/People/Berners-Lee/card#i> foaf:homepage
    <http://www.w3.org/People/Berners-Lee/> .
```

- Even if I have the FOAF data, I cannot answer the query:
  - Different identifiers used for Tim Berners-Lee
  - Who tells me that Dan Brickley is a foaf:Person?
- Linked Data needs **Reasoning**!

Reasoning on Semantic Web Data



FOAF Vocabulary Specification 0.91

Namespace Document 2 November 2007 - *OpenID Edition*

FOAF at a glance

An a-z index of FOAF terms, by class (categories or types) and by property.

Classes: | Agent | Document | Group | Image | OnlineAccount | OnlineChatAccount | OnlineEcommerceAccount | OnlineGamingAccount | Organization | Person | PersonalProfileDocument | Project |

Properties: | accountName | accountServiceHomepage | aimChatID | based_near | birthday | currentProject | depiction | depicts | dnaChecksum | family_name | firstName | fundedBy | geekcode | gender | givenname | holdsAccount | homepage | icqChatID | img | interest | isPrimaryTopicOf | jabberID | knows | logo | made | maker | mbox | mbox_sha1sum | member | membershipClass | msnChatID | myersBriggs | name | nick | openid | page | pastProject | phone | plan | primaryTopic | publications | schoolHomepage | sha1 | surname | theme | thumbnail | tipjar | title | topic | topic_interest | weblog | workInfoHomepage | workplaceHomepage | yahooChatID |

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 inference by rules 1/2

- Semantics of RDFS can be partially expressed as (Datalog like) rules:

```
rdfs1: triple(S,rdf:type,C) :- triple(S, P, O), triple(P, rdfs:domain, C)
rdfs2: triple(O,rdf:type,C) :- triple(S, P, O), triple(P, rdfs:range, C)
```

```
rdfs3: triple(S,rdf:type,C2):-triple(S,rdf:type,C1),triple(C1,rdfs:subclassOf,C2)
```

cf. informative Entailment rules in [RDF-Semantics, W3C, 2004], [Muñoz et al. 2007]

RDFS inference by rules 1/2

- Semantics of RDFS can be partially 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 . }
```

cf. informative Entailment rules in [RDF-Semantics, W3C, 2004], [Muñoz et al. 2007]

RDFS+OWL inference by rules 2/2

- OWL Reasoning e.g. inverseFunctionalProperty can also (partially) 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 }
```

cf. pD* fragment of OWL, [ter Horst, 2005], SAOR [Hogan et al. 2009] or, more recent: **OWL2 RL**

RDFS+OWL inference by rules: Example:

- By rules of the previous slides we can infer additional information needed, e.g.

TimBL's FOAF: `<…/Berners-Lee/card#i> foaf:knows <…/Dan_Brickley> .`
FOAF Ontology: `foaf:knows rdfs:range foaf:Person`

by rdfs2 → `<…/Dan_Brickley> rdf:type foaf:Person.`

TimBL's FOAF: `<…/Berners-Lee/card#i> foaf:homepage <http://www.w3.org/People/Berners-Lee/> .`
DBLP: `<…/dblp.l3s.de/d2r/…/Tim_Berners-Lee> foaf:homepage <http://www.w3.org/People/Berners-Lee/> .`
FOAF Ontology: `foaf:homepage rdfs:type owl:InverseFunctionalProperty.`

by owl1 → `<…/Berners-Lee/card#i> owl:sameAs <…/Tim_Berners-Lee>.`

- Who tells me that Dan Brickley is a foaf:Person? → solved!
- Different identifiers used for Tim Berners-Lee → solved!

RDFS+OWL inference, what's missing?

- Note: Not all of OWL Reasoning can be expressed in Datalog straightforwardly, 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: $Person \sqcap Organisation \sqsubseteq \bot$

Problem: Inconsistencies! **Complete** FOL/DL reasoning is often not suitable per se for Web data… [Hogan et al.2009,]

But can be "approximated" by Rules (without explosion):

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

The more "common" view on OWL…

Expressing property characteristics:

OWL property axioms as RDF triples	DL syntax	FOL short representation
P rdfs:domain C .	$\top \sqsubseteq \forall P^{-}.C$	$\forall x, y. P(x, y) \supset C(x)$
P rdfs:range C .	$\top \sqsubseteq \forall P.C$	$\forall x, y. P(x, y) \supset C(y)$
P owl:inverseOf P_0 .	$P \equiv P_0^{-}$	$\forall x, y. P(x, y) \equiv P_0(y, x)$
P rdf:type owl:SymmetricProperty.	$P \equiv P^{-}$	$\forall x, y. P(x, y) \equiv P(y, x)$
P rdf:type owl:FunctionalProperty.	$\top \sqsubseteq \leqslant 1P$	$\forall x, y, z. P(x, y) \wedge P(x, z) \supset y = z$
P rdf:type owl:InverseFunctionalProperty.	$\top \sqsubseteq \leqslant 1P^{-}$	$\forall x, y, z. P(x, y) \wedge P(z, y) \supset x = z$
P rdf:type owl:TransitiveProperty.	$P^{+} \sqsubseteq P$	$\forall x, y, z. P(x, y) \wedge P(y, z) \supset P(x, z)$

Expressing complex class descriptions:

OWL complex class descriptions*	DL syntax	FOL short representation
owl:Thing	$\top$	$x = x$
owl:Nothing	$\bot$	$\neg x = x$
owl:intersectionOf $(C_1 \ldots C_n)$	$C_1 \sqcap \cdots \sqcap C_n$	$C_1(x) \wedge \cdots \wedge C_n(x)$
owl:unionOf $(C_1 \ldots C_n)$	$C_1 \sqcup \cdots \sqcup C_n$	$C_1(x) \vee \cdots \vee C_n(x)$
owl:complementOf (C)	$\neg C$	$\neg C(x)$
owl:oneOf $(o_1 \ldots o_n)$	$\{o_1, \ldots, o_n\}$	$x = o_1 \vee \cdots \vee x = o_n$
owl:restriction (P owl:someValuesFrom (C))	$\exists P.C$	$\exists y. P(x, y) \wedge C(y)$
owl:restriction (P owl:allValuesFrom (C))	$\forall P.C$	$\forall y. P(x, y) \supset C(y)$
owl:restriction (P owl:value (o))	$\exists P.\{o\}$	$P(x, o)$
owl:restriction (P owl:minCardinality (n))	$\geqslant nP$	$\exists y_1 \ldots y_n . \bigwedge_{k=1}^{n} P(x, y_k) \wedge \bigwedge_{i<j} y_j \neq y_j$
owl:restriction (P owl:maxCardinality (n))	$\leqslant nP$	$\forall y_1 \ldots y_{n+1} . \bigwedge_{k=1}^{n+1} P(x, y_k) \supset \bigvee_{i<j} y_i = y_j$

* For reasons of legibility, we use a variant of the OWL abstract syntax [Patel-Schneider *et al.*, 2004] in this table.

Why OWL1 is Not Enough

- Too expensive to reason with
  - High complexity: NEXPTIME-complete
  - The most lightweight sublanguage OWL-Lite is **NOT** lightweight
  - 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 property support [Horrocks et al., 2006]

From OWL1 to OWL2

- OWL2: A new version of OWL
- 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 is known to be implementable
   - many things happened in research since 2004

OWL2

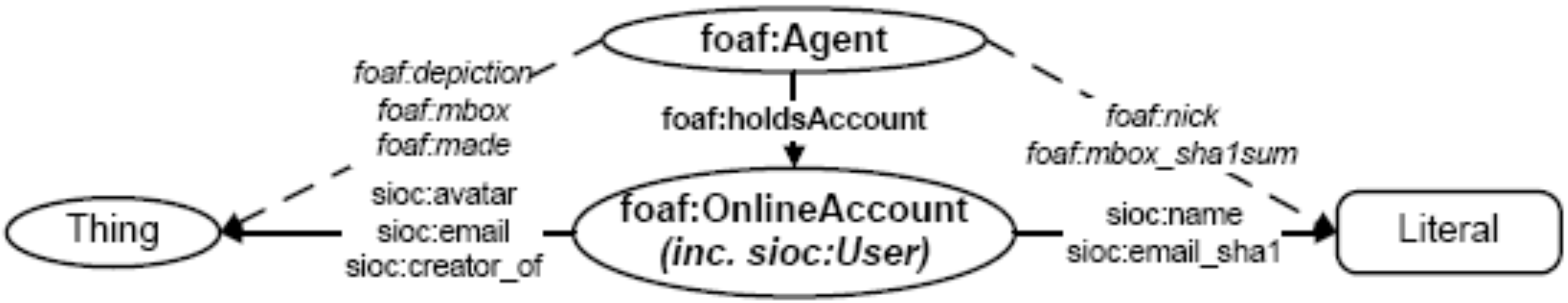
HOT! NEW!

Common ontologies on the Web don't use it a lot as of yet…

… but adds interesting functionality, potentially useful for Web ontologies, e.g.

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

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



OWL2

HOT!
NEW!

Common ontologies on the Web don't use it a lot as of yet…

… but adds interesting functionality, potentially useful for Web ontologies, e.g.

- hasKey:
  - *Multi-attribute Keys now possible in OWL, e.g.*
    - `foaf:OnlineAccount/sioc:User` 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

- New expressive power
  - user defined datatypes, e.g.:

    "Ages are integers between 0 and 150"

```
personAge owl:equivalentClass _:x
_:x rdf:type rdfs:Datatype
_:x owl:onDatatype xsd:integer
_:x owl:withRestrictions (_:y1 _:y2)
_:y1 xsd:minInclusive "0"^^xsd:integer
_:y2 xsd:maxInclusive "150"^^xsd:integer
```

  - punning (metamodeling), e.g.:

```
John rdf:type Father
Father rdf:type SocialRole
```

New Expressiveness in OWL 2

- New expressive power on properties
  - qualified cardinality restrictions, e.g.:

```
_:x rdf:type owl:Restriction
_:x owl:onProperty foaf:knows
_:x owl:minQualifiedCardinality "10"^^xsd:nonNegativeInteger
_:x owl:onClass Irish
```

  - property chain inclusion axioms, e.g.:

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

  - local reflexivity restrictions, e.g.:

```
_:x rdf:type owl:Restriction
_:x owl:onProperty like
_:x owl:hasSelf "true"^^xsd:boolean
```

[for narcissists]

  - reflexive, irreflexive, symmetric, and antisymmetric properties, e.g.:

```
foaf:know rdf:type owl:ReflexiveProperty
rel:childOf rdf:type owl:IrreflexiveProperty
```

  - disjoint properties, e.g.:

```
rel:childOf owl:propertyDisjointWith rel:parentOf
```

  - keys, e.g.:

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

New Expressiveness in OWL 2

- Syntactic sugar (make things easier to say)
  - Disjoint unions, e.g.:

    ```
    child owl:disjointUnionOf (boy girl)
    ```

  - Disjoint classes, e.g.:

    ```
    _:x rdf:type owl:AllDisjointClasses
    _:x owl:members (boy girl)
    ```

  - Negative assertions, e.g.:

    ```
    _:x rdf:type owl:NegativePropertyAssertion
    _:x owl:sourceIndividual John
    _:x owl:assertionProperty foaf:know
    _:x owl:targetIndividual Mary
    ```

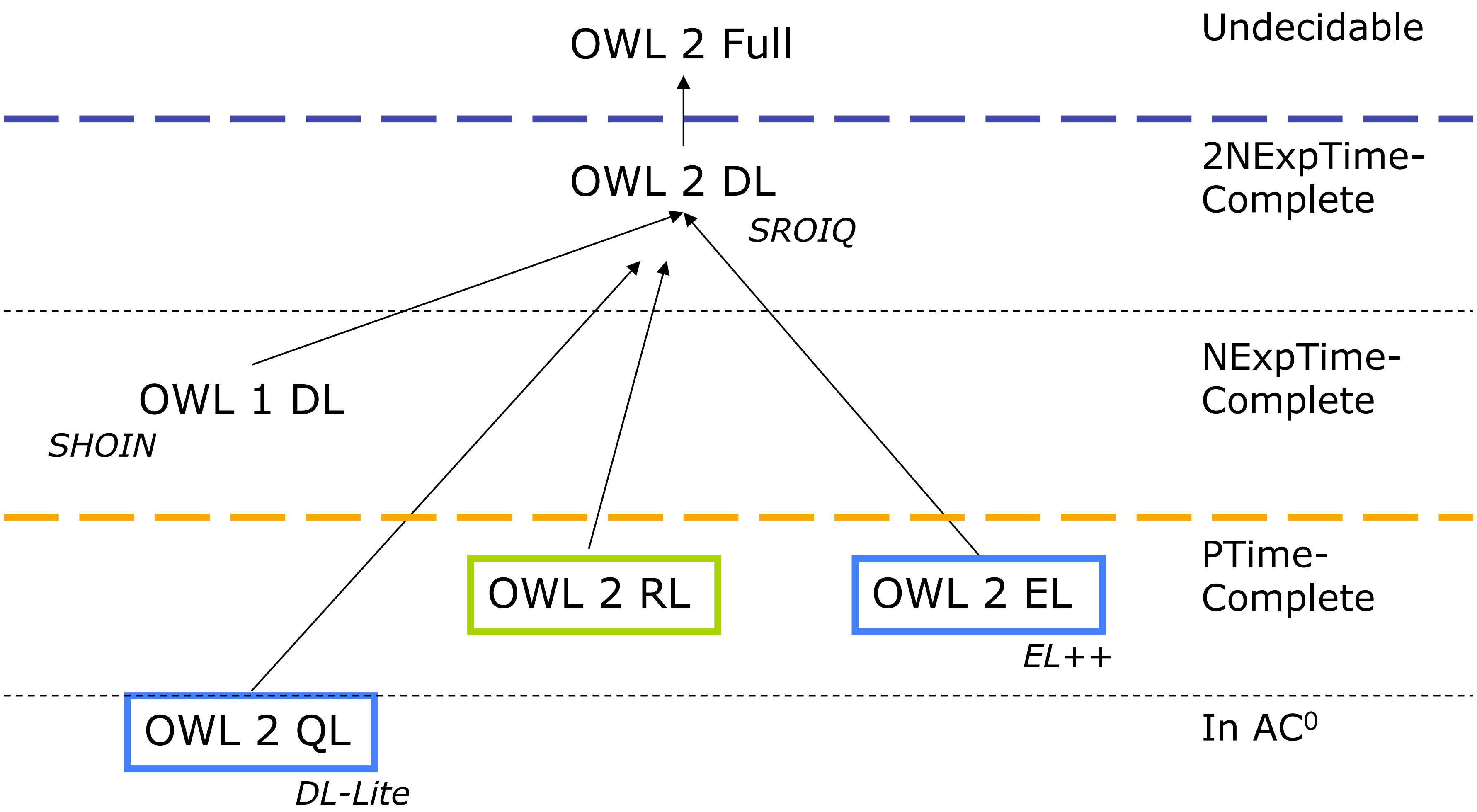
OWL 2 DL

- $\mathcal{R}$ often used for $\mathcal{ALC}$ extended with property chain inclusion axioms
  - following the notion introduced in $\mathcal{RIQ}$ [Horrocks and Sattler, 2003]
  - including transitive property 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
  - $\mathcal{Q}$ 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
- Available Reasoners: Hermit (Oxford), Pellet (Clark&Parsia)

OWL 2 Profiles and Reasoning Services

- Rationale:
  - Tractable
  - Tailored to specific reasoning services
- Popular reasoning services
  - ABox reasoning: OWL 2 RL
  - TBox reasoning: OWL 2 EL
  - Query answering: OWL 2 QL
- Specification: http://www.w3.org/TR/2009/owl2-profiles/

The family tree



OWL2RL

- Maximal fragment of OWL expressible in Horn Rules
  - Rules for subclassing, subproperties, propChains, (inverse) functionalProperties, hasValue…
  - No support for arbitrary card restrictions, existentials in rule heads, etc.
  - See before… more later…
- See also discussion of the rule set in [Hogan&Decker, 2009]

OWL 2 EL

- 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]

Saturation-based Technique (basics)

- 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:

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

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

- Extension to Horn fragment requires (many) more rules

Saturation-based Technique (basics)

Example:

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

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

```
foaf:Person rdfs:subClassOf foaf:Agent .
foaf:Agent rdfs:subClassOf owl:Thing.

foaf:Person rdfs:subclassOf
                 [ a owl:Restriction ;
          owl:onProperty :hasFather ;
          owl:someValuesFrom foaf:Person. ].

:hasFather domain :Child.
```

$$Person \sqsubseteq \top$$

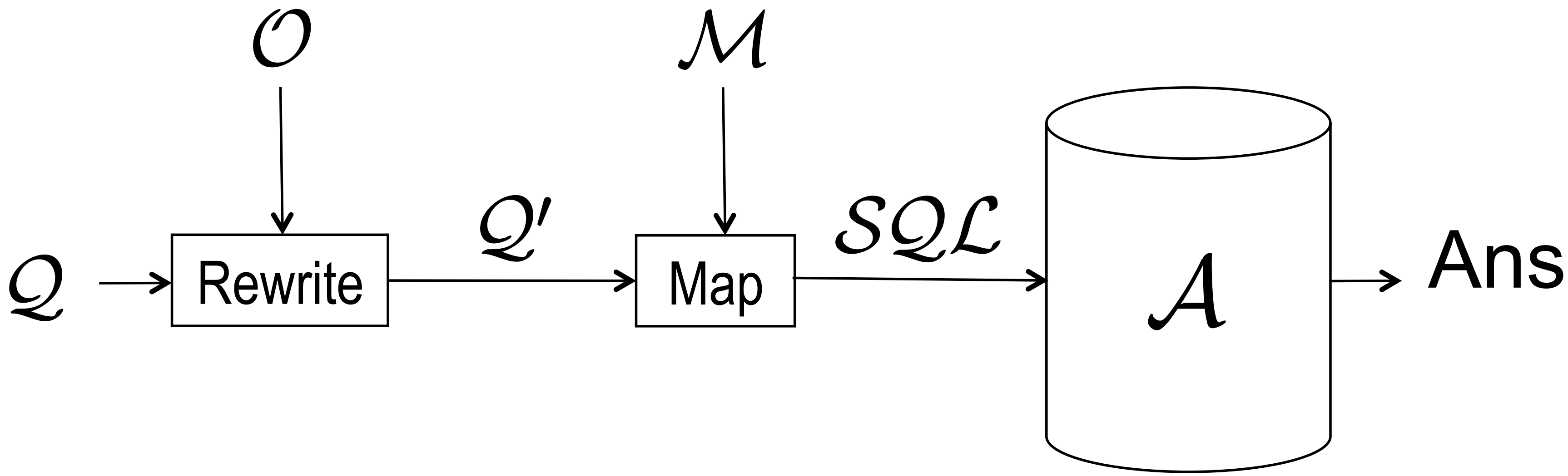
$$Person \sqsubseteq Child$$

OWL 2 QL

- 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
  - 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 $\mathcal{A}$:
  - $\text{ans}(\mathcal{Q}, \mathcal{O}, \mathcal{A}) = \text{ans}(\mathcal{Q}', \emptyset, \mathcal{A})$
- Use (GAV) mapping $\mathcal{M}$ to map $\mathcal{Q}'$ to SQL query



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

Query Rewriting Technique (basics)

- Example:

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

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

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

Query Rewriting Technique (basics)

- 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)

- 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)

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

Query Rewriting Technique (basics)

- Example:

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

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

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

Query Rewriting Technique (basics)

- Example:

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

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

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

- For DL-Lite, result is a union of conjunctive queries

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

Query Rewriting Technique (basics)

- UCQ translated into **SQL query** → OWL2QL can be "delegated" to RDBMS:

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

$$\rightsquigarrow$$

SELECT Name FROM Doctor UNION
SELECT DName FROM Treats, Patient WHERE PName=Name

Interplay OWL2 ←→ RIF ←→ SPARQL1.1

- OWL2 and RIF
  - RIF fly-over
  - OWL2RL in RIF
  - RIF/OWL joint interpretations and what you need to know about them
- OWL2 and SPARQL1.1
  - SPARQL Entailment Regimes
  - Challenges+Pitfalls
  - What's in the current SPARQL 1.1 Draft?
- GiaBATA
  - A prototype implementation of SPARQL with dynamic Entailment regimes (e.g. RDFS, OWL2RL).

RIF fly-over

OWL and RIF

- RIF: Rule Interchange Format (rather than Rule language)
  - Framework for Rule Languages
  - Support RDF import: interesting for rule languages on top of RDF
  - Built-Ins support (close to XPath/XQuery functions and operators)
  - RIF Dialects:
    - RIF BLD: basic logic dialect = Horn rules with Built-ins, Equality
    - RIF Core: Datalog fragment (no logical function symbols, no head-equality)
    - RIF PRD: Production rules dialect
  - Normative XML syntax

- Commonalities with OWL:
  - RIF can model OWL2 RL
  - Share same Datatypes (XSD Datatypes, most OWL2 Datatypes)

- Differences
  - Different target audience: E.g. production rules (RIF PRD dialect)
  - Not necessarily focused on decidability, BLD = generic HORN rules with built-ins and function symbols (Turing-complete language)

RIF Dialects

Core

- horn rules, monotonic
- datatypes & built-ins
- external functions
- Frames, class memberships
- equality (in conditions)
- ground lists
- existential quantification (in conditions)

BLD

- equality, class membership in conclusions
- frame subclasses
- open lists

PRD

- non-monotonic
- actions in conclusions
- negation
- subclasses
- membership in conclusion

Example – RIF Core

- Full name in FOAF from givenName, familyName

```
if ({ ?X a foaf:Person ; foaf:givenName ?F ; foaf:familyName ?S } AND
     ?N = fn:concat(?F, " ", ?S) )
then { ?F foaf:name ?N }
```

  - Not expressible in OWL2, neither in SPARQL1.0 CONSTRUCT

```
CONSTRUCT { ?X foaf:name ?N }
WHERE {?X a foaf:Person; foaf:givenName ?F ; foaf:familyName ?S
          FILTER (?N = fn:concat(?F, " ", ?S)) }
```

Example – RIF Core

- Full name in FOAF from givenName, familyName

```
{ ?F foaf:name ?N } :-
{ ?X foaf:givenName ?F ; foaf:familyName ?S } AND
     ?N = fn:concat(?F, " ", ?S)
```

  - Can be read like Logic Programming rule
  - Presentation syntax not normative, we use a Mix of N3 and non-normative Presentation syntax in the spec here.

Example – RIF Core

- Full name in FOAF from givenName, familyName

```
?F[->foaf:name ?N]  :-
        ?X[foaf:givenName ?F], ?X[foaf:familyName->?S],
        ?N = fn:concat(?F, " ", ?S) .
```

- Can be read like Logic Programming rule
- Presentation syntax not normative, we use a Mix of N3 and non-normative Presentation syntax in the spec here.
  - RIF has F-Logic style Frames (e.g. FLORA-2)… same semantics as RDF-Triples
  - Further in rif # corresponds to class membership, ## to subclassing
  - in combination with RDF, # is the same as rdf:type)

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Example – RIF BLD

- ATTENTION: Class membership # in conclusions is not in RIF Core.

```
{ ?x rdf:type ?y } :- ?x # ?y
 ?x # ?y :- { ?x rdf:type ?y }
```

Translating OWL2RL into RIF

OWL 2RL can be rewritten to RIF

- http://www.w3.org/TR/rif-owl-rl/

- Translates OWL2RL profile into RIF, relatively straightforward translation of abstract rules from
http://www.w3.org/TR/owl2-profiles/#Reasoning_in_OWL_2_RL_and_RDF_Graphs_using_Rules
  - Appendix 7: Static ruleset

  - Appendix 8: Dynamically instantiating a RIF Core rule set for a given OWL 2 RL, similar in spirit to the embedding in http://www.w3.org/TR/rif-rdf-owl/ Section 9.2

Static ruleset

- Some rules straightforward,e.g.

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

eq-rep-s: { ?Y ?P ?O } :- { ?X owl:SameAs ?Y . ?X ?P ?O }
eq-rep-p: { ?S ?Y ?O } :- { ?X owl:SameAs ?Y . ?S ?X ?O }
eq-rep-o: { ?S ?P ?Y } :- { ?X owl:SameAs ?Y . ?S ?P ?X }
```

- Others need auxiliary predicates for the static version:

prp-spo2: **{?S ?P ?O$_{n+1}$} :- { ?P owl:propertyChainAxiom ?pc }**
AND _checkChain(?S ?pc ?O$_{n+1}$)

We’d need that rule for all n, i.e. different property chain lenghts appearing in the ontology at hand.

Static ruleset:

prp-spo2: **Can be handled with auxiliary predicates:**

```
{ ?S ?P ?On+1 } :-  { ?P owl:propertyChainAxiom ?pc }
                  AND _checkChain(?S ?pc ?On+1)

 _checkChain(?start ?pc  ?last) :-
      { ?pc rdf:first ?p ; rdf:rest rdf:nil . ?start ?p ?last }

_checkChain(?start ?pc  ?last) :- And (
      { ?pc rdf:first ?p ; rdf:rest ?tl . ?start ?p ?next }
      _checkChain(?next ?tl ?last) ))
```

Other rules, e.g. subclassOf, inverseOf

cax-sco:

```
{ ?S rdf:type ?D } :-  { ?S rdf:type ?C . ?C rdfs:subclassOf ?D }
```

prp-inv1:

```
{ ?O ?P2 ?S } :-  { ?P1 inverseOf ?P2 . ?S ?P1 ?O }
```

prp-inv2:

```
{ ?O ?P1 ?S } :-  { ?P1 inverseOf ?P2 . ?S ?P2 ?O }
```

Similarly for other rules:

- all of OWL2RL can be translated to RIF Core rules, fed into your favorite rules engine, used for
  - Query answering,
  - Consistency checking

Dynamic ruleset (Template-Rules)

- Idea:
  - Translate each ontology **axiom by axiom** dynamically
  - E.g. ontology in RDF

```
foaf:Person rdfs:subClassOf foaf:Agent

foaf:topic owl:inverseOf foaf:page
```

Dynamic ruleset (Template-Rules)

- Idea:
  - Translate each ontology **axiom by axiom** dynamically
  - E.g. ontology in RDF
- Matching Template Rules in Appendix 8.2:

```
{?x rdf:type foaf:Agent} :- {?x rdf:type foaf:Person }

{ ?Y foaf:topic ?X } :- { ?Y foaf:page ?X }
{ ?Y foaf:page ?X }  :- { ?Y foaf:topic ?X }
```

Plus some fixed ruleset (Appendix 8.1 FixedRules in http://www.w3.org/TR/rif-owl-rl/

Embedding OWL2RL Ontologies into RIF

for combinations with arbitrary RIF rulesets

RIF + RDF and OWL in combination

- RIF/OWL joint interpretations
  - http://www.w3.org/TR/rif-rdf-owl/ defines semantic correspondence between RIF and RDF/RDFS/OWL interpretations,
- i.e., semantics for combinations of RDF graphs, OWL ontologies and RIF rulesets
- Defines:
  - ***RIF-OWL-Direct Entailment:*** *Based on OWL direct semantics*

    RIF-OWL-DL combination disallows certain RIF documents

    (only constants for classes in #, ##, only constants for predicates in frames) …
  - ***RIF-OWL RDF-Based Entailment:***

    Based on OWL RDF-Based Semantics.

Embedding

- (Informative) Embedding in http://www.w3.org/TR/rif-rdf-owl/ give rise for implementation of combination of OWL2RL and RIF :

1. Embedding RIF DL-document formulas into RIF BLD, , Section 9.2.1
2. **Embedding OWL 2 RL axioms into RIF BLD, Section 9.2.2**

We focus on the latter part…

Embedding OWL2RL axioms into rules:

- Section 9.2.2 defines recursive translation from OWL axioms to RIF rules… tr()
- Very similar to Dynamic Rules we saw before
- E.g. OWL2RL ontology in RDF

```
foaf:Person rdfs:subClassOf foaf:Agent
```

```
foaf:topic owl:inverseOf foaf:page
foaf:topic type owl:ObjectProperty
foaf:page type owl:ObjectProperty
```

Embedding OWL2RL axioms into rules:

- Section 9.2.2 defines recursive translation from OWL axioms to RIF rules… tr()
- Very similar to Dynamic Rules we saw before
- Translated to OWL abstract syntax axioms:

```
SubClassOf(foaf:Person foaf:Agent)

InverseObjectProperties(foaf:topic foaf:page)
```

Embedding OWL2RL axioms into rules:

- Section 9.2.2 defines recursive translation from OWL axioms to RIF rules… tr()
- Very similar to Dynamic Rules we saw before
- Translated to RIF by translation tr() in Section 9.2.2 of http://www.w3.org/TR/rif-rdf-owl/ :

```
{?x rdf:type foaf:Agent} :- {?x rdf:type foaf:Person }

{ ?Y foaf:topic ?X } :- { ?Y foaf:page ?X }
{ ?Y foaf:page ?X }  :- { ?Y foaf:topic ?X }
```

Plus some static ruleset ($R^{OWL\text{-}Direct}(V,R)$ ***)***

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Subtle differences to direct OWL2RL translation from before:

- Most fundamentally **equality**: owl:sameAs is directly translated to RIF's =, rather than axiomatised as in slide 54:

- OWL RDF:

```
<http://a> owl:sameAs <http://b> .
```

  is embedded as:

```
<http://a> = <http://b>
```

- E.g. in Combination with RIF ruleset:

```
_q(<http://a>).
_p(?x) :- iri-to-string(?y, ?x) and _q(?y)
```

  entails:

```
_p("http://a").
_p("<http://b>").
```

- Not so if I take the axiomatisation of sameAs from above
- ***Bottomline: To straightforwardly implement the embedding for combinations, You need a rule system that supports equality.***

SPARQL 1.1 querying over OWL2 ontologies?

OWL2 and SPARQL1.1

- SPARQL1.1 working group will define SPARQL query answering over OWL2 ontologies and RIF rule sets:
  - http://www.w3.org/TR/sparql11-entailment/
- Latest Working Draft just released…
  - Contains Draft Semantics for
    - SPARQL1.1 on top of RDFS
    - **SPARQL1.1 on top of OWL2**
    - SPARQL1.1 on top of RIF

OWL2 and SPARQL1.1

- General Idea: Answer Queries with implicit answers
- E.g. Graph

```
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 }`

Pure SPARQL 1.0 returns only `:Jeff`,
should also return `:aidan`

SPARQL+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: Aggregates

SPARQL+RDFS/OWL: Challenges+Pitfalls

- Current Solution:
  - 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 entailment.*
  - SPARQL 1.1 other features: Aggregates
    - *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 ;-)

Possibly Infinite answers RDF(S): Container Membership

- Graph:

```
:me :hasFavouritePresenter [ a rdf:Seq;
                                    rdf:_1 :jeff.
                                    rdf:_2 :aidan.
                                    rdf:_3 :axel.  ]
```

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:

```
:me :hasFavouritePresenter [ a rdf:Seq;
                               rdf:_1 :jeff.
                               rdf:_2 :aidan.
                               rdf:_3 :axel.  ]
```

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 are:

```
{ ?CM/rdfs:_1, ?CM/rdfs:_2, ?CM/rdfs:_3 }
```

Possibly Infinite answers OWL: datatype reasoning

Stupid way to say Peter is 50:

```
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**

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. ]
:jeff a Person
:jeff foaf:knows :aidan
foaf:knows rdfs:range foaf:Person.
```

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

No answer, because no known value for ?Y in the data graph.

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. ]
:jeff a Person
:jeff foaf:knows :aidan
foaf:knows rdfs:range foaf:Person.
```

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 ➔ 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: takes place before projection
    - That is: **non-distinguished variables can't occur "by design"**
  - In fact, conjunctive queries with non-distinguished variable still an open research problem for OWL:
    - Decidable for SHIQ, [B. Glimm et al. 2008]
    - Decidable for OWL1 DL without transitive properties OWL1 Lite without nominals [B. Glimm, KR-10]
    - Decidability for SHOIN, SROIQ though still unknown…

SPARQL 1.1 other features: 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}

SPARQL 1.1 other features: 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 ?Y AS Count(?X)  { ?X a foaf:Person }
```

Under RDFS/OWL entailment returns : {?Y/2}

GiaBATA

Implementing SPARQL, OWL2RL, RIF on top of DLV

GiaBATA

- Time allowed, we will show a system which implements dynamic SPARQL querying, under different entailment regimes and how it can be implemented.

- Based on LP engine DLV
  - Datalog with built-ins (covers roughly RIF Core),
  - persistent Database backend (DLV-DB)
  - Optimisations (rewriting to push join processing into SQL as far as possible, magic sets,…)
  - plus a lot more features (nonmonotonicity, aggregates, …)

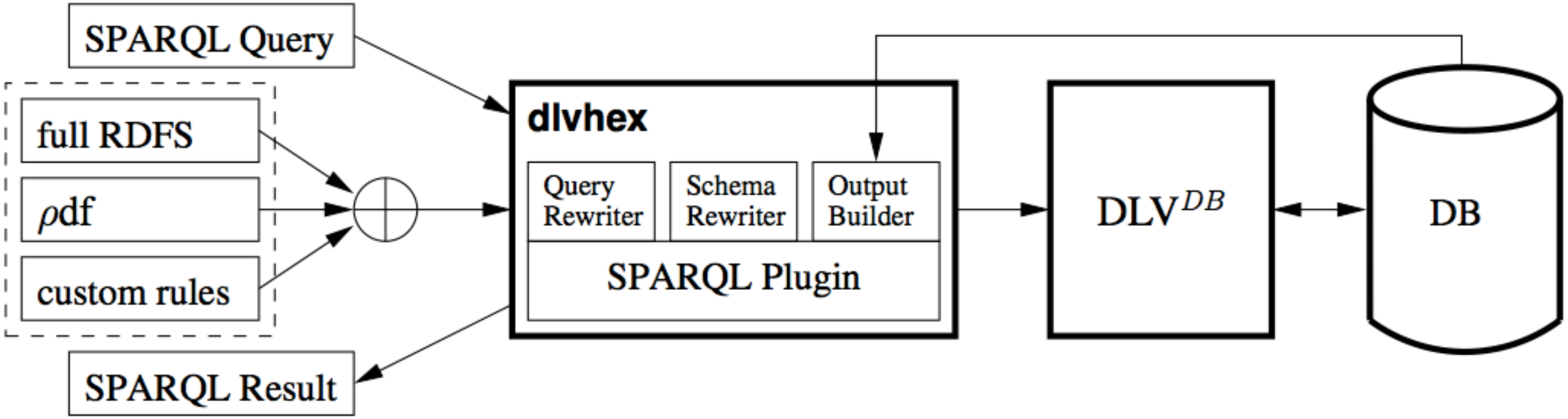
- Overall idea for SPARQL+RDFS/OWL2RL over RDF graphs:
  - Translate OWL2RL to Datalog rules a la RIF, see above.
  - Translate SPARQL query to Datalog [Polleres, WWW2007]
  - Feed resulting program into a rules engine (DLV-DB) that runs over a Rel DB storing RDF graphs.

- Check Details at:
- http://axel.deri.ie/~axepol/presentations/20091029iann-etal-ISWC2009_GiaBATA.pptx

How to implement this?

- GiaBATA system [Ianni et al., 2009]:
  - SPARQL → dlvhex (logic program)
  - Ruleset → dlvhex (logic program)

→ SQL



- Deductive Database techniques:
  - Datalog engine (dlvhex)
  - Postgres SQL Database underneath (dlv-db)
  - RDF storable in different schemas in RDB
  - Magic sets, storage

SPARQL → dlvhex (logic program)

- Based on [Polleres ,WWW2007]

```
select * from <http://alice.org/>
 where { ?X a foaf:Person. ?X foaf:name ?N.
         filter ( ?N != "Alice") optional { ?X foaf:mbox ?M } }
```

```
(r1) "triple"(S,P,O,default)     :- &rdf[ "alice.org" ](S,P,O).
(r2) answer1(X_N,X_X,default)    :- "triple"(X_X,"rdf:type","foaf:Person",default),
                                    "triple"(X_X,"foaf:name",X_N,default),
                                    &eval[" ?N != 'Alice' ","N", X_N ](true).
(r3) answer2(X_M,X_X,default)    :- "triple"(X_X,"foaf:mbox",X_M,default).
(r4) answer_b_join_1(X_M,X_N,X_X,default)   :- answer1(X_N,X_X,default),
                                               answer2(X_M,X_X,default).
(r5) answer_b_join_1(null,X_N,X_X,default) :- answer1(X_N,X_X,default),
                                               not answer2_prime(X_X,default).
(r6) answer2_prime(X_X,default) :- answer1(X_N,X_X,default),
                                    answer2(X_M,X_X,default).
(r7) answer(X_M,X_N,X_X)         :- answer_b_join1(X_M,X_N,X_X,default).
```

OWL2RL Static Ruleset → dlvhex (logic program)

- Straighforward, just translates rules in a way “compatible” with the SPARQL translation:

```
{?s ?q ?o } <= {?s ?p ?o . ?p rdfs:subPropertyOf ?q}
```

```
%FROM CLAUSES
triple(P,SubPropertyOf,P,G)  :- triple(P,Type,Property,G),graph(G,D),data(D),defaultGraph(D),
                                resource_literal(Type,"<http://www.w3.org/1999/02/22-rdf-syntax-ns#type>",_),
                                resource_literal(Property,"<http://www.w3.org/1999/02/22-rdf-syntax-ns#Property>",_),
                                resource_literal(SubPropertyOf,"<http://www.w3.org/2000/01/rdf-schema#subPropertyOf>",_).

%FROM NAMED CLAUSES
triple(P,SubPropertyOf,P,G)  :- triple(P,Type,Property,G),graph(G,D),data(D),namedGraph(D),
                                resource_literal(Type,"<http://www.w3.org/1999/02/22-rdf-syntax-ns#type>",G),
                                resource_literal(Property,"<http://www.w3.org/1999/02/22-rdf-syntax-ns#Property>",G),
                                resource_literal(SubPropertyOf,"<http://www.w3.org/2000/01/rdf-schema#subPropertyOf>",G).

%USING ONTOLOGIES
triple(P,SubPropertyOf,P,G) :- triple(P,Type,Property,G),graph(G,D),data(D),ontology(D),
                               resource_literal(Type,"<http://www.w3.org/1999/02/22-rdf-syntax-ns#type>",G),
                               resource_literal(Property,"<http://www.w3.org/1999/02/22-rdf-syntax-ns#Property>",G),
                               resource_literal(SubPropertyOf,"<http://www.w3.org/2000/01/rdf-schema#subPropertyOf>",G).
```

SPARQL+Rules → SQL

- Done by dlv-DB, cf. [Terracina, et al.,2008]
  - All non-recursive parts are pushed to the Database
  - All recursive parts handled by semi-naïve evaluation

    (more efficient than WITH RECURSIVE views in SQL, where necessary, intermediate results temporarily materialized into the DB)

- Some necessary optimisations to make this *reasonably* performant:
  - FILTER expression evaluation is pushed to SQL (3-valued semantics of SPARQL Filters is handled natively in SQL)
  - No miracles… but magic: Magic set optimisations for focused fwd-chaining evaluation.
  - Join-reordering, not yet implemented, but we did some manual reordering to optimize the query plan in the experiments.

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Relevant W3C Standard Specs

- RDF Semantics http://www.w3.org/TR/rdf-mt/

- OWL2 Web Ontology Language Primer http://www.w3.org/TR/owl2-primer/
- OWL2 Web Ontology Language Profiles http://www.w3.org/TR/owl2-profiles/

- SPARQL Query Language for RDF http://www.w3.org/TR/rdf-sparql-query/
- SPARQL1.1 Query Language for RDF (working draft) http://www.w3.org/TR/sparql11-query/
- SPARQL1.1 Entailment Regimes (working draft) http://www.w3.org/TR/sparql11-entailment/

- RIF Core Dialect http://www.w3.org/TR/rif-core/
- RIF Basic Logic Dialect http://www.w3.org/TR/rif-bld/
- RIF RDF and OWL compatibility http://www.w3.org/TR/rif-rdf-owl/

Other Tutorials

- Some more basic lectures&Tutorials on my Website: http://www.polleres.net/ e.g.
  - Semantic Web and ASP Tutorial ESWC2006
  - SPARQL Tutorial ESWC2007
  - Scalable OWL Reasoning Tutorial ESWC2010

- Also recommended:
  - Reasoning Web Summer Schools (since 2005), many good tutorials/slides:
    - http://reasoningweb.org/2005/
    - http://reasoningweb.org/2006/
    - http://reasoningweb.org/2007/
    - http://reasoningweb.org/2008/
    - http://reasoningweb.org/2009/
    - http://reasoningweb.org/2010/
- Linked Data Tutorial:
  - http://www4.wiwiss.fu-berlin.de/bizer/pub/LinkedDataTutorial/

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