RDF SUMMARY

- more or less simple data model,
- possibility to use property and class names that are agreed Web-wide,
- the idea of URIs,
- the contents of RDF files can be integrated in a natural way via URIs and names.

4.10 Further Topics

- some additional RDF syntax: Reification and Collections. Later.
- Schema information: RDF Schema
- RDF/RDFS Model Theory + Reasoning
- More than schema information: Ontology specification by Description Logics and OWL
- How to provide RDF data and metadata on the Web?
  Later: RDF/XML. It's just another representation of RDF, RDF Schema and OWL data in a special XML syntax.
- What's missing?
- Rules?

Chapter 5
RDF Schema

Schema Information and Reasoning in an Open World

ONTOLOGIES

Schema languages, metadata languages, modeling languages, ontologies ...

Classical Data Models: seen as Specification and Constraints

- every schema description defines a (more or less complete) ontology:
- ER Model (1976, entity types, attributes, relationships with cardinalities),
- UML (1997, classes with subclasses, associations with cardinalities, OCL assertions to schema components etc.).

Knowledge Representation

Metadata provides additional information about resources of a type, or about a property.

- F-Logic signatures (1989),
- ... RDFS and OWL (Web Ontology Language)

SCHEMA INFORMATION IN AN OPEN WORLD

- schema describes
  - allowed properties for an object,
  - datatype constraints for literal properties [Here: XSD literal types],
  - allowed types/classes for reference properties,
  - cardinality constraints.

Closed World: Schema as Constraints

- a database must satisfy the constraints. It must be a *model* of the formulas – *the given data alone must be a model.*

Open World: potentially incomplete knowledge

- schema information as *additional information*
- since the world must be a model of the schema, some information can be *derived* from the schema.
- complain only if information is *contradictory* to the schema.

METADATA INFORMATION: TYPES, PROPERTIES, AND ONTOLOGIES

- Types and properties (i.e., everything that is used in a namespace) are not only “names”, but are resources “somewhere in the Web”, identified by a URI (used in RDF or in XML via namespaces).

⇒ a *domain ontology* describes the notions used in a namespace.

Schema and Ontology Information

- what types/classes are there,
- subclass information,
- what properties objects of a given type must/can have,
- to what types some property is applicable and what range it has,
- cardinalities of properties,
- default values,
- that some properties are transitive, symmetric, subproperties of another or excluding each other etc.

5.1 RDF Schema Notions - Overview

- RDF is the instance level
- cf. XML: DTDs and XML Schema for describing the structure/schema of the instance (DTD: no atomic datatypes, only tree structure; XSD has atomic datatypes)
- RDF Schema: stronger than DTD/XML – “semantic-level”
  - describe the structure of the RDF instance (i.e. the “schema” of the RDF graph, not of the RDF/XML file):
  - describes the schema *semantically* in terms of an (lightweight) ontology (OWL provides then much more features):
    - class/subclass
    - property/subproperty, domains and ranges
  - atomic datatypes for literal properties.

Predefined RDFS Classes

The obvious ones

rdfs:Resource is “everything”. All things described by RDF are called resources, and are instances of the class rdfs:Resource. This is the class of everything. All other classes are subclasses of this class. rdfs:Resource is an instance of rdfs:Class.

rdfs:Class : all things (resources and literals) are of rdf:type of some rdfs:Class. rdf:Properties have an rdfs:Class as domain and another rdfs:Class or rdfs:Datatype as range.

mon:Country rdf:type rdfs:Class.

An rdfs:Class is simply a resource X that is of (X rdf:type rdfs:Class). Usually, class names start with a capital letter.

Later, **owl:Class** will provide more interesting concepts of *intensionally defined* classes – like “the class father is the class of things that are male and have children”.

rdf:Property is a subset of rdfs:Resource that contains all properties.

mon:capital rdf:type rdf:Property.

Usually, property names start with a non-capital letter.

[note: it’s rdf:Property, not rdfs:Property!]

PREDEFINED RDFS CLASSES

rdfs:Datatype is the class of datatypes.

rdfs:Literal is the subclass of rdfs:Resource that contains all literals (i.e., values of rdfs:Datatypes).
Literals do (usually) not have a URI, but a literal representation (as already discussed for integers and strings).

E.g. the following holds

```
@prefix xsd: <http://www.w3.org/2001/XMLSchema#>.
xsd:int rdf:type rdfs:Datatype .
```

- Note that *reification* takes place here: rdfs:Datatype is both an instance of and a subclass of rdfs:Class! Each instance of rdfs:Datatype is a subclass of rdfs:Literal.

PROPERTIES (OF CLASSES AND PROPERTIES) IN THE RDFS VOCABULARY

rdfs:subClassOf specifies that one rdfs:Class is an rdfs:subClassOf another:

```
:Cat rdfs:subClassOf :Animal .
```

rdfs:subPropertyOf specifies that one rdf:Property is an rdfs:subPropertyOf another:

```
:hasCat rdfs:subPropertyOf :hasAnimal .
```

rdfs:domain specifies that the domain of an rdf:Property is a certain rdfs:Class:

```
:hasCat rdfs:domain :Person .
```

rdfs:range specifies that the range of an rdf:Property is a certain rdfs:Class (note that rdfs:Datatype is a subclass (and an instance) of rdfs:Class):

```
:hasCat rdfs:range :Cat .
:age rdfs:range xsd:int .
```

Inference Rules

- until now, the SPARQL query language was applied to pure RDF facts (*extensional knowledge*)
- RDFS adds *inference rules* (= *intensional knowledge*)
- Queries are then not evaluated against the *fact base*, but against the *model* of the factbase and the rules.
- for this, a *reasoner* is required.

⇒ underlying *entailment relationship* based on *model theory*.

5.2 RDF/RDFS Model Theory

- FOL: Recall the definition of an *interpretation*: constants are mapped to the domain, while predicate symbols are mapped to relations over the domain.
- In RDF, predicates (predicate symbols) are also objects of discourse. [note that classes are just unary predicates while properties are binary predicates]
  One of the important goals of RDF and the Semantic Web is to make statements *about* classes and predicates!

Further reading

1. "Three Theses of Representation in the Semantic Web",
   Ian Horrocks and Peter Patel-Schneider.
   In *World-Wide-Web Conference (WWW 2003)*
   Note: can be found by google or via `http://www.dblp.de`
   (discusses three ways to define a model theory for RDFS)

RDFS Axiomatic Triples

Some axioms that are expected to hold in any RDFS model can be expressed inside RDF itself independent from the chosen logic (cf. `http://www.w3.org/TR/rdf-mt`):

```
rdf:type rdfs:domain rdfs:Resource .
rdfs:domain rdfs:domain rdf:Property .
rdfs:range rdfs:domain rdf:Property .
rdfs:subPropertyOf rdfs:domain rdf:Property .
rdfs:subClassOf rdfs:domain rdfs:Class .

rdf:type rdfs:range rdfs:Class .
rdfs:domain rdfs:range rdfs:Class .
rdfs:range rdfs:range rdfs:Class .
rdfs:subPropertyOf rdfs:range rdf:Property .
rdfs:subClassOf rdfs:range rdfs:Class .

rdfs:Datatype rdfs:subClassOf rdfs:Class .
```

... and some more.
The interesting things with RDFS are not these (rather trivial) axioms, but the built-in semantics of rdfs:domain/range/subClassOf/subPropertyOf.
For them, some model theory is required.

General Considerations

Needed: a *domain* (the things talked about), and a signature (the predicate names (that are used in the *logic formalization*)).

Straightforward (and intuitive) idea

- the domain are the resources and the blank nodes,
  classes are mapped to unary properties,
  (e.g. *person(john)*), properties are mapped to binary predicates,
  (e.g. *age(john,32)* and child(john,alice)) .
- problem: rdfs:subClassOf, rdfs:range etc. talk *about* classes and properties

Alternatives (see subsequent slides)

1. FOL with reification, i.e., handling classes and properties also as domain items, and having only one meta-predicate “holds”,
2. resorting to Second-Order-Logic,
3. a special model theory not based on any other logic (as in `http://www.w3.org/TR/rdf-mt`) .

A Mapping of RDF/RDFS to FOL

- The set of constant symbols consists of all IRIs, Blank node identifiers RDF-B, and Literals RDF-L as constant symbols,
- there is a a single "holds" predicate that represents the triples.
- Herbrand-style interpretation: all terms are "interpreted by themselves", i.e., since there are no function symbols in RDF, the domain $\mathcal{D}$ *is* just the set of constant symbols (which include everything: individuals, literals, classes, properties).
- a single "holds" property that represents the triples:

$$\mathcal{I}(\text{holds}) = \{(s,p,o) | (s,p,o) \text{ holds in the given RDF ontology}\}$$

Advantages

- mapping to a well-known and well-investigated formalism,
- RDFS semantics can easily be specified by logical axioms, e.g., rdfs:range specifies that the range of an rdf:Property is a certain rdfs:Class:

$$\mathcal{M} \models \forall c,p : (\ \text{holds}(p, \text{rdfs:range}, c) \rightarrow (\forall x,y : \text{holds}(x,p,y) \rightarrow \text{holds}(y, \text{rdf:type}, c)))$$

Mapping of RDF/RDFS to FOL (cont'd)

$$\mathcal{I}(\text{holds}) = \{(s,p,o) | (s,p,o) \text{ holds in the given RDF ontology}\}$$

Problems

This is just a *mapping* to an artificial predicate.

1. FOL in general is undecidable (i.e. there are no complete reasoners for it), while RDFS reasoning itself decidable, even only polynomial.
2. later: OWL builds on RDF and is based on the DL $\mathcal{SHOIN}(D)$, which is a decidable subset of FOL.
   The original translation of $\mathcal{SHOIN}(D)$ to FOL has also to be mapped to the "holds" predicate.
   Again, this would be a mapping from a decidable formalism to an undecidable one.
3. Unrestricted reification can lead to paradoxes (cf. Slide 224).
   $\Rightarrow$ Sorted FOL can be used to partition the domain into "sorts" (individuals, classes, properties) and to constrain the usage of the quantifiers.
4. Equality: for properties p_1, p_2, $p_1 = p_2$ holds by definition only if $I(p_1) = I(p_2)$ which means identity
   $\Rightarrow$ needs actually FOL+Equality

A Mapping to Higher-Order Logic

A second-order-logic domain $\mathcal{D}$ consists of two *disjoint* subsets:

- first-order objects $\mathcal{D}_1$: Let IRI$_{obj}$ and RDF-B$_{obj}$ denote all IRIs and blank nodes that denote objects. Literals also belong to that partition.
- second-order objects $\mathcal{D}_1$: predicates (and functions).
  For RDF, the predicates are classes IRI$_{cls}$ and properties IRI$_{prop}$.
  (only when defining derived classes (in OWL), there will be blank nodes RDF-B$_{cls}$ that represent classes.)
- 1st-order predicates are interpreted by relationships over the object domain.
- general: predicates of order n are interpreted over the domain of order n and are objects of the domain of order $n+1$.
- Quantifiers range either over 1st-order objects or over 2nd-order objects, e.g. rdfs:range is now a 2nd-order predicate:

$$\mathcal{M} \models \forall C, P : \text{rdfs:range}(P, C) \rightarrow (\forall x, y : P(x, y) \rightarrow C(y))$$

Mapping to Higher-Order Logic (cont'd)

Assuming a given alphabet of rdfs:Classes and rdf:Properties, each of them induces a unary or binary predicate, respectively.

- Objects: IRI$_{obj}$ $\cup$ RDF-B$_{obj}$
- Predicates: IRI$_p$ (note that rdf:type and rdf:Property are excluded)
- for class symbols c in IRI$_c$: $\mathcal{I}(c) \subseteq$ IRI$_{obj}$ $\cup$ RDF-B$_{obj}$
  E.g. <foo://bla/meta#Person>(<foo://bla/persons/john>)
- for property symbols p in IRI$_p$ ($p \neq$ rdf:Type):
  $\mathcal{I}(p) \subseteq$ (IRI$_{obj}$ $\cup$ RDF-B$_{obj}$) $\times$ (IRI$_{obj}$ $\cup$ RDF-B$_{obj}$ $\cup$ RDF-L)
  E.g. <foo://bla/meta#child>(<foo://bla/persons/john>, <foo://bla/persons/alice>)
- the class rdf:Property is mapped to a 3rd-order unary predicate s.t.
  I(rdf:Property) $=$ IRI$_{prop}$.
- rdf:type is only implicitly represented by the *interpretation* of IRI$_{cls}$.

Mapping to Higher-Order Logic (cont'd)

Advantages

- intuitive mapping of properties and classes
- equality: for properties p_1, p_2, $p_1 = p_2$ holds $I(p_1) = I(p_2)$ which is the case if both have the same extension,
- can also express OWL notions like transitivity of properties.

Problems

- some RDF/RDFS notions don't even fit:
  - the class rdf:Property is mapped to a 3rd-order unary predicate,
  - rdf:type would have one first-order argument and one second-order argument.
- Usage of Higher-Order Logics:
  - can be used to axiomatize complex domains, like mathematics
  - highly intractable (= non-decidable, often even no heuristics-based incomplete proof methods)
  - HOL provers exist: they are used for *interactively* proving correctness, safety etc. (e.g., HOL (1993) and Isabelle (1994))

REIFICATION

Reification means to treat a higher-order object like a lower-order object:

- treat a class as an object, or
- treat a property as an object

i.e., to break the partitioning of the sorts/orders (which puts the mapping to Sorted FOL into FOL).

REIFICATION CAN LEAD TO PARADOXES

Reasoning with things that are both classes and instances reveals a famous paradox:

- define p as the set of all sets that do not contain themselves as an element:
  $\forall s: \ (p(s) \ \leftrightarrow \ \neg s(s))$
- is p in p?
  $p(p) \leftrightarrow \neg p(p)$
- any set of formulas that contains this definition has no model!

W3C RDF/RDFS Model Theory

RDF Semantics, W3C Recommendation 10 February 2004

(`http://www.w3.org/TR/rdf-mt`)

- a semantics and model theory for RDFS (which borrows some features from higher-order ideas) (see next slide)
- without resorting to an encoding in any other logic
  ⇒ no possibility to use theoretical results or reasoning algorithms.

Advantages

- handles intensional equality of classes or properties,
- expresses the specific RDF/RDFS ideas

Problems

- RDF constructs are not axiomatized logically as formulas,
- but incorporated into the semantics/model theory.
- no support by any reasoner,
- not extensible/adaptable to OWL.

Aside: formal details of `http://www.w3.org/TR/rdf-mt`

An RDF/RDFS interpretation I consists of the following:

- Universe = set IR of Resources: includes resources and literals (!?)
- IS interprets URIs (= constant symbols) into the universe IR
  (`http://www.w3.org/TR/rdf-mt` defines and uses $I(X) := IS(x)$ here).
- mappings $ICEXT$ (for classes) and $IEXT$ (for properties) from IR to 2^{IR} and $2^{(IR \times IR)}$:
- the set of classes is $IC = ICEXT(IS(\text{rdfs:Class})) \subset IR$,
- for each class URI y and each URI x,
  $IS(x) \in ICEXT(IS(y)) \Leftrightarrow (IS(x), IS(y)) \in IEXT(IS(\text{rdf:type}))$
- the set of properties, $IP \subset IR$.
  for each URI x, $IS(x) \in IP \Leftrightarrow (IS(x), IS(\text{rdf:Property})) \in IEXT(IS(\text{rdf:type}))$
- for each property URI p, $IEXT(IS(p)) \subset IR \times IR$ models the triples.
- RDFS notions are not expressed by formulas, but as “semantic conditions” in the model theory, e.g.,
  - (for rdfs:range): if $(IS(x), IS(y)) \in IEXT(IS(\text{rdfs:range}))$ and $(IS(u), IS(v)) \in IEXT(IS(x))$ then $IS(v) \in ICEXT(IS(y))$.

RDFS Entailment

An RDF Graph G *RDFS-entails* another RDF Graph H (which extends G with some edges)

- if every RDFS-interpretation which satisfies G also satisfies H.

For the *translation to FOL*, the following holds,

- if $\phi_G \cup \phi_{RDFS} \models_{FOL} \phi_H$ where ϕ_G and ϕ_H denote the FOL-translations of G and H, and ϕ_{RDFS} encodes the RDFS axioms (e.g. by rules), then $G \models_{RDFS} H$.
  [this is what rule-based reasoners do]

SPARQL on RDFS

- input: Turtle triples, seen as an RDF Graph G (including RDFS statements)
- query: a SPARQL graph pattern P
- answers: the answer bindings of all ground instances $\beta(P)$ of P s.t. $G \models_{RDFS} \beta(P)$.

⇒ query wrt. RDFS answering requires (a bit) more than only algebraic evaluation of conjunctive queries.

RDFS Reasoning

- expressible in a decidable fragment of FOL: positive recursive Datalog
  - naive implementation: bottom-up graph completion by rules
  - querying: top-down Datalog evaluation (of any Datalog/Prolog system)
  - only issue: existentials from blank nodes (blank nodes mapped by skolemization, but it must be considered that two blank nodes describe the same individual)

⇒ use the FOL mapping

⇒ the following slides give the semantics of RDFS notions wrt. the FOL mapping.

REASONING WITH RDF, RDF SCHEMA AND OWL

- theoretical details will be discussed later. The underlying thing is either
  - graph completion by rules (RDFS, OWL-RL profile),
    (can be translated to positive Datalog)
  - *Description Logic (DL) Reasoning* (OWL DL)
    (requires a DL reasoner, based on Tableaux techniques)
- there are reasoners available for the Jena Framework:
  - an internal one:
    `jena -q -inf -qf` *sparql-file*
    for invoking SPARQL with its internal reasoner
  - an external one:
    (integrated into the semweb.jar used in the lecture as plug-in)
    `jena -q -pellet -qf` *sparql-file*
    for invoking SPARQL with the Pellet DL reasoner class
  - external ones as Web Services ...

USE OF THE JENA TOOL

- option “-t”: transform (between Turtle and RDF/XML)
  jena -t -pellet -if *rdf-file* .
  (-t is not complete for checking inconsistencies)
- option “-q”: query
  jena -q -pellet [-if rdf-input-file] -qf *query-file* .
- option “-e”: export the class tree (available only when the pellet reasoner is activated).
  Input is an RDF or OWL file:
  jena -e -pellet -if *rdf-file*.
  (for checking consistency, use -e)

PELLET COMMANDLINE FOR SPARQL-DL QUERIES

- download pellet, set alias for pellet/pellet.sh
- see `pellet help` for further information
- `pellet query -q` *`query-file input-file`*
  - does not use FROM line(s) in SPARQL, input file must be given explicitly,
  - only one input file possible.

ASIDE: DIG INTERFACE - DESCRIPTION LOGIC IMPLEMENTATION GROUP

- Web page: http://dl.kr.org/dig/
- agreed “tell-and-ask-interface” of DL Reasoners as Web Service:
- tell them the facts and ask them queries, or for the whole inferred model
- e.g. supported by “Pellet”
- URL for download see Lecture Web page

```
may@dbis01:~/SemWeb-Tools/pellet-1.3$ ./pellet-dig.sh &
PelletDIGServer Version 1.3 (April 17 2006)
Port: 8081
```

- invoke the SPARQL Jena interface by
  `jena -q -qf` *`sparql-file`* `-inf -r` *`reasoner-url`*
  (e.g.: `http://localhost:8081`)
- note: the tell-functionality seems to transfer only part of the knowledge → incomplete reasoning → currently not recommended.

5.3 RDFS Vocabulary

Semantics of Subclasses and Subproperties

rdfs:subClassOf specifies that one rdfs:Class is an rdfs:subClassOf another:
for any model $\mathcal{M}$ of the RDFS model theory,

$$\mathcal{M} \models \forall C_1, C_2 : (\text{ holds}(C_1, \text{rdfs:subClassOf}, C_2) \rightarrow (\forall x : (\text{holds}(x, \text{rdf:type}, C_1) \rightarrow \text{holds}(x, \text{rdf:type}, C_2))))$$

rdfs:subPropertyOf specifies that one rdf:Property is an rdfs:subPropertyOf another:

$$\mathcal{M} \models \forall P_1, P_2 : (\text{ holds}(P_1, \text{rdfs:subPropertyOf}, P_2) \rightarrow (\forall x, y : (\text{holds}(x, P_1, y) \rightarrow \text{holds}(x, P_2, y))))$$

Semantics of Domain and Range

rdfs:domain specifies that the domain of an rdf:Property is a certain rdfs:Class:

$$\mathcal{M} \models \forall C, P : (\text{ holds}(P, \text{rdfs:domain}, C) \rightarrow (\forall x : (\exists y : \text{holds}(x, P, y)) \rightarrow \text{holds}(x, \text{rdf:type}, C)))$$

rdfs:range specifies that the range of an rdf:Property is a certain rdfs:Class
(note that rdfs:Datatype is a subclass (and an instance) of rdfs:Class):

$$\mathcal{M} \models \forall C, P : (\text{ holds}(P, \text{rdfs:range}, C) \rightarrow (\forall y : (\exists x : \text{holds}(x, P, y)) \rightarrow \text{holds}(y, \text{rdf:type}, C)))$$

Exercise

- Give an implementation by Datalog Rules for RDFS constructs.

SUBCLASS, DOMAIN, RANGE: EXAMPLE

```
@prefix : <foo://bla/meta#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>.
  :has_cat rdfs:domain :Person .
  :has_cat rdfs:range :Cat .
  :Person rdfs:subClassOf :LivingBeing .
  :Cat rdfs:subClassOf :LivingBeing .
  <foo://bla/persons/john> :has_cat <foo://bla/cats/garfield>.
  <foo://bla/persons/mary> rdf:type :Person.
```

[Filename: RDF/subclass.n3]

```
prefix : <foo://bla/meta#>
prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
select ?X ?T
from <file:subclass.n3>
where {?X rdf:type ?T}
```

[Filename: RDF/subclass.sparql]

- activate the reasoner (internal or pellet) when invoking Jena.

SUBCLASS, DOMAIN, RANGE: EXAMPLE (CONT'D)

Recall the previous example. Given the following facts:

```
:has_cat rdfs:domain :Person .
:has_cat rdfs:range :Cat .
:Person rdfs:subClassOf :LivingBeing .
:Cat rdfs:subClassOf :LivingBeing .
<foo://bla/persons/john> :has_cat <foo://bla/cats/garfield>.
<foo://bla/persons/mary> rdf:type :Person.
```

The domain/range information does not act as a constraint, but as information. From that knowledge, the following facts can be *inferred*:

- :has_cat implies that the subject (John) is a Person, and the object (Garfield) is a cat,
- both are thus LivingBeings.

SUBPROPERTIES

- outlook: combine it with owl:TransitiveProperty.

```
@prefix : <foo://bla/meta#> .
@prefix family: <foo://bla/persons/> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>.
@prefix owl: <http://www.w3.org/2002/07/owl#>.
  family:john :hasChild family:alice, family:bob.
  family:kate :hasChild family:john.
  :hasChild rdfs:subPropertyOf :descendant.
  :descendant rdf:type owl:TransitiveProperty.
```

[Filename: RDF/descendants.n3]

```
prefix : <foo://bla/meta#>
select ?X ?Y
from <file:descendants.n3>
where {?X :descendant ?Y}
```

[Filename: RDF/descendants.sparql]

COMPARISON

SQL

- queries only against the database (no intensional knowledge),
- equivalent to tree expressions in relational algebra, based on set theory,
- formal semantics can be given purely syntactically with the algebra,

⇒ in the DB lecture, we did not need logic.

- equivalent to the relational calculus, semantics of queries can be given by the calculus. Equivalent to *nonrecursive Datalog* (cf. Database Theory Lecture) with “negation as failure” (top-down) stratification (bottom-up).

RDFS + SPARQL

- only restricted negation
- RDFS: built-in rules (positive, recursive Datalog)
- SPARQL: positive, nonrecursive Datalog
- intuitive bottom-up semantics

USING RDF IN THE WORLD WIDE WEB

- The (Semantic) Web is not seen as a collection of documents, but as a collection of correlated information (described via documents)
- using RDF, everybody can make statements about any resource (cf. link-bases in XLink)
  - incremental, world wide data and meta-data
  - distributed RDFS,
  - distributed RDF,
  - real URLs (Linked Open Data; cf. Slides 280 ff) vs. only virtual resources (URIs).
- not assumed that complete information about any resource is available.
- Open world, no notion of (implicit) negation.
- potentially inconsistent information;
- statements can be equipped with probabilities or labeled as opinions; fuzzy reasoning, belief revision ...
- ... lots of artificial intelligence applications ...

REASONING BASED ON RDFS

- RDF/RDFS *model theory* as above,
- rather simple Datalog rules, graph completion,
- queries: against the (completed) graph by matching (SPARQL).
- incomplete knowledge when reasoning: "open world assumption"
- only very restricted negation (none in RDFS; "!bound" in SPARQL 1.0 and "FILTER NOT EXISTS" in SPARQL 1.1 allow for negation of failure)

Preview: OWL

- based on DLs
- OWL-DL includes constructs that are not expressible by Datalog (union/disjunction) – requires "Disjunctive Datalog"
  $\Rightarrow$ totally different complexity and reasoning algorithms
- OWL-Lite is a simpler fragment (e.g., only 0-1-*-cardinalities) ... turned out that tools are not much simpler to design
- The OWL-RL profile: can be translated to positive recursive Datalog.

EXAMPLE/EXERCISE

Consider again the employee-manages-departments example (Slide 22).

- Give the RDF Graph.
- give the Turtle triples and feed them into the Jena tool.

ADDITIONAL RDF/RDFS VOCABULARY

The rdf/rdfs namespaces provide some more vocabulary:

Like most data models, RDF provides a representation for *Collections*:

- Collections: `rdf:Alt`, `rdf:Bag`, `rdf:Seq`, `rdf:List` are collections.
  Lists have properties `rdf:first` (a resource) and `rdf:rest` (a list). Others have properties `_1`, `_2`, ... that refer to their members.
- (rdfs:Container, rdfs:member, rdfs:ContainerMembershipProperty)

... these are partially used implicitly (e.g., collections in owl:intersectionOf, owl:OneOf), but often not supported by OWL reasoners if used explicitly (see Slides 417 ff.).

EXAMPLE: THE MONDIAL ONTOLOGY

See mondial.n3, mondial-europe.n3 and mondial-meta.n3 on the Web page.

Note that it is highly redundant: defining just rdfs:domain and rdfs:range of properties implies most of the classes (and also most of the rdfs:type relationships in mondial.n3).

```
prefix mon: <http://www.semwebtech.org/mondial/10/meta#>
prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
select ?X
from <file:mondial.n3>
from <file:mondial-meta.n3>
where {?X rdf:type mon:Country}
```

[Filename: RDF/mondial-meta-query.sparql]

- activate Jena with reasoner (if mondial.n3 is too big, use mondial-europe.n3 instead)

Mondial is not an interesting example for RDFS (and OWL):

- it's mainly data, no intensional knowledge, no complex ontology
- for that reason it is a good example for SQL and XML.
- RDFS and OWL is interesting when information is *combined* and additional knowledge can be derived.

Developing Ontologies

- have an idea of the required concepts and relationships (ER, UML, ...),
- generate a (draft) n3 or RDF/XML instance,
- write a separate file for the metadata,
- load it into Jena with activating a reasoner.
- If the reasoner complains about an inconsistent ontology, check the metadata file alone. If this is consistent, and it complains only when also data is loaded:
  - it may be due to populating a class whose definition is inconsistent and that thus must be empty.
  - often it is due to wrong datatypes. Recall that datatype specification is not interpreted as a constraint (that is violated for a given value), but as additional knowledge.