1 Introduction

1.1 RDF(S)

```
@prefix qb:     <http://purl.org/linked-data/cube#> .
@prefix cssz-measure: <https://data.cssz.cz/ontology/measure/> .
@prefix rdf:    <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix y-onto: <https://data.cssz.cz/ontology/years/> .
@prefix xsd:    <http://www.w3.org/2001/XMLSchema#> .
@prefix skos:   <http://www.w3.org/2004/02/skos/core#> .
@prefix cssz:   <https://data.cssz.cz/ontology/> .
@prefix rdfs:   <http://www.w3.org/2000/01/rdf-schema#> .
@prefix cssz-dimension: <https://data.cssz.cz/ontology/dimension/> .

<https://data.cssz.cz/resource/observation/invalidita/2011/pk_id/t/60-64>
  rdf:type qb:Observation ;
  qb:dataSet <https://data.cssz.cz/resource/dataset/invalidita> ;
  cssz-dimension:druh-duchodu
    <https://data.cssz.cz/resource/pension-kind/PK_ID_2010> ;
  cssz-dimension:pohlavi
    <https://data.cssz.cz/ontology/sdmx/code/sex-T> ;
  cssz-dimension:refPeriod
    <https://data.cssz.cz/resource/reference.data.gov.uk/id/gregorian-year/2011> ;
  cssz-dimension:skupina-diagnoz-dle-who
    <https://data.cssz.cz/resource/icd-10/chapter/C_T> ;
  cssz-dimension:vekova-kategorie
    <https://data.cssz.cz/generated/resource/age/Y60T64> ;
  cssz-measure:pocet-nove-priznanych-duchodu 234.0 .
```

1.1.1 Core RDF

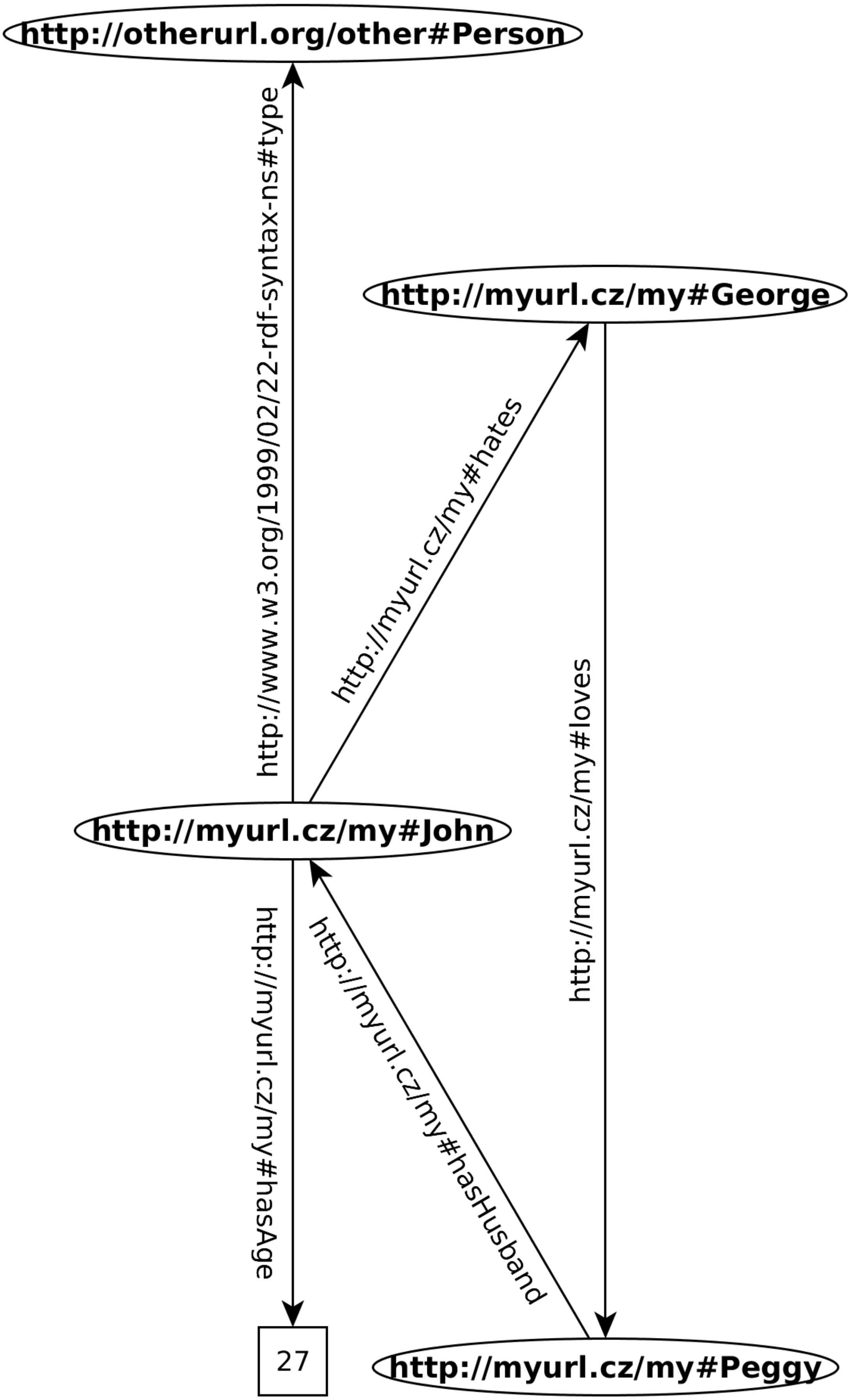
RDF

- RDF = **R**esource **D**escription **F**ramework
- RDF 1.0 – W3C Recommendation in 2004,

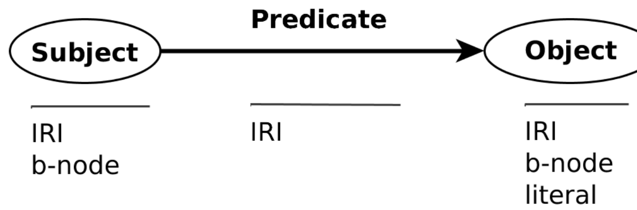
RDF Document
is a graph, where each

node is either an IRI (ellipse), a literal (rectangle), or a blank node (blank ellipse)

edge is labeled with IRI


http://otherurl.org/other#Person
http://www.w3.org/1999/02/22-rdf-syntax-ns#type
http://myurl.cz/my#George
http://myurl.cz/my#hates
http://myurl.cz/my#loves
http://myurl.cz/my#John
http://myurl.cz/my#hasAge
http://myurl.cz/my#hasHusband
27
http://myurl.cz/my#Peggy

RDF Triple



is an ordered triple of the form $(Subject, Predicate, Object)$:

Definitions

RDF Graph is a set of RDF triples

RDF Term is either an *IRI*, a *blank node*, or a *literal*

IRIs

- IRI = International Resource Identifier
- denotes a *document*, or a real *thing*

  `<http://myurl.cz/my#Peggy>`
  `<http://myurl.cz/my/document-about-peggy>`

- using hash (#) or slash (/) for delimiting particular entities in a namespace
- mapped to URIs = backward-compatibility

  Note

  - Two IRIs are equal iff their string representations are equal.
  - No IRI is equal to any blank node, or literal.

Namespaces

can be abbreviated using prefixes to improve readability

`rdf:type` (can be also abbreviated as `a`) instead of `http://www.w3.org/1999/02/22-rdf-syntax-ns#ty`

rdf: `http://www.w3.org/1999/02/22-rdf-syntax-ns#`. This namespace defines basic resources, like `rdf:type`, `rdf:Property`.

rdfs: `http://www.w3.org/2000/01/rdf-schema#`. This namespace is used for metamodeling, like `rdfs:Class`, or `rdfs:subPropertyOf`.

xsd: `http://www.w3.org/2001/XMLSchema#`, for referencing XML Schema datatypes reused by RDF, like `xsd:integer`, or `xsd:string`.

Note
Often, a shortened IRI with empty prefix (e.g. `:x`) is used in examples. In such cases, the namespace is fixed, but unimportant for the example, if not stated otherwise.

Literals

- denote basic data values, like strings, integers, or calendar data.

  Definition

  A literal consists of:

  a lexical form , being a Unicode string,

  a datatype IRI , being an IRI identifying a datatype,

  a language tag , iff the datatype IRI is `http://www.w3.org/1999/02/22-rdf-syntax-ns#langString`.

  Two literals are equal iff their 1) lexical forms, 2) datatypes, 3) language tags equal.

- $\underbrace{\texttt{"dolphin"}}_{\text{lex. form}}\underbrace{\texttt{@en}}_{\text{lang. tag}}$

- $\underbrace{\texttt{"dolphin"}}_{\text{lex. form}}\underbrace{\texttt{\^{}\^{}xsd:string}}_{\text{datatype IRI}}$

other examples:

```
"128"^^xsd:integer
"2010-01-19T16:00:00Z"
   ^^xsd:dateTime
```

Datatypes

- reused from XML Schema (e.g. `xsd:string`) plus `rdf:HTML` and `rdf:XMLLiteral`

  Definition

  A datatype consists of:

  lexical space , e.g. a set {"0", "01", . . .} of strings made of numbers 0-9.

  value space , e.g. a set of integers $\{0, 1, \dots, \infty\}$,

  lexical-to-value mapping $L2V$, e.g. $L2V(\text{datatype for } \texttt{xsd:integer}) = \{\langle \text{"01"}, 1\rangle, \dots\}$.

- most XML Schema built-in datatypes:
  - `xsd:string`,`xsd:boolean`, `xsd:integer`, `xsd:decimal`, `xsd:dateTimeStamp`,`xs`
    . . .

- `rdf:HTML` – for embedding HTML as literals

- `rdf:XMLLiteral` – for embedding XML as literals

- custom datatypes can be defined on different levels – XML Schema, OWL 2, . . .

Blank Nodes (b-nodes)

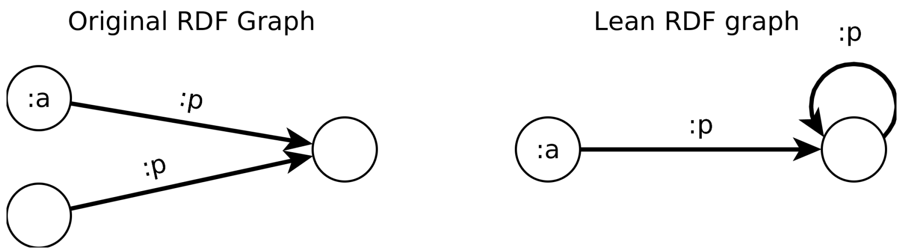
- denote existential variables,
- are local to the RDF document (cannot be reused outside),
- in Turtle/N-TRIPLES/SPARQL have `_:` prefix, e.g. `_:x`,

Definition

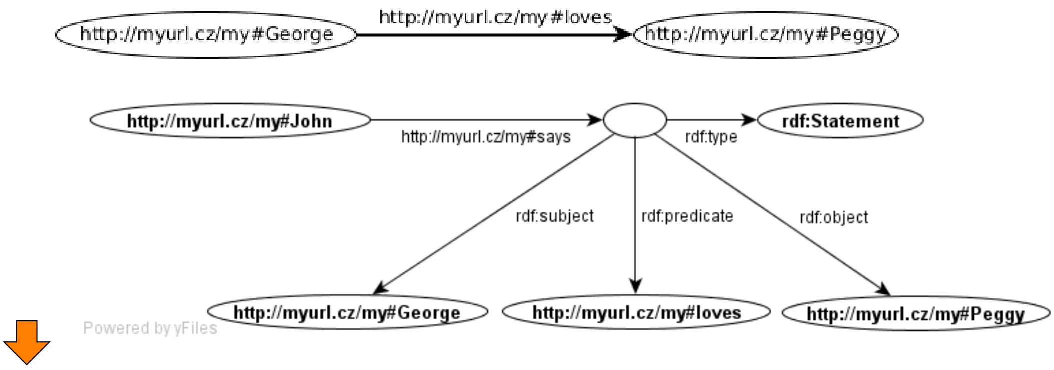
Ground RDF Graph is an RDF Graph containing no b-nodes.

Instance of RDF Graph G_1 is an RDF Graph in which some b-nodes are be replaced by an arbitrary RDF Term.

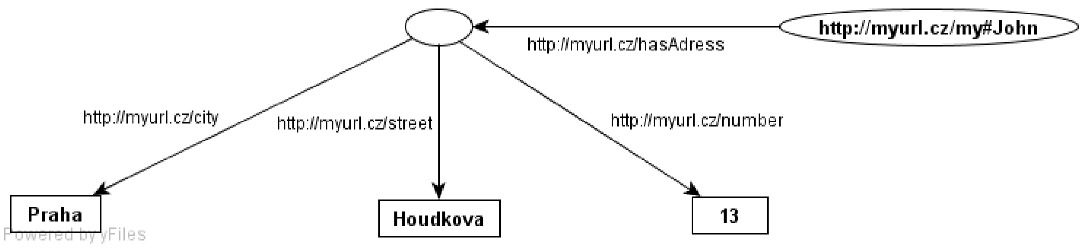
Lean RDF Graph G_1 has no instance G_2 which is a proper subgraph of G_1.



Blank Nodes for statement reification



Blank Nodes for expressing complex values

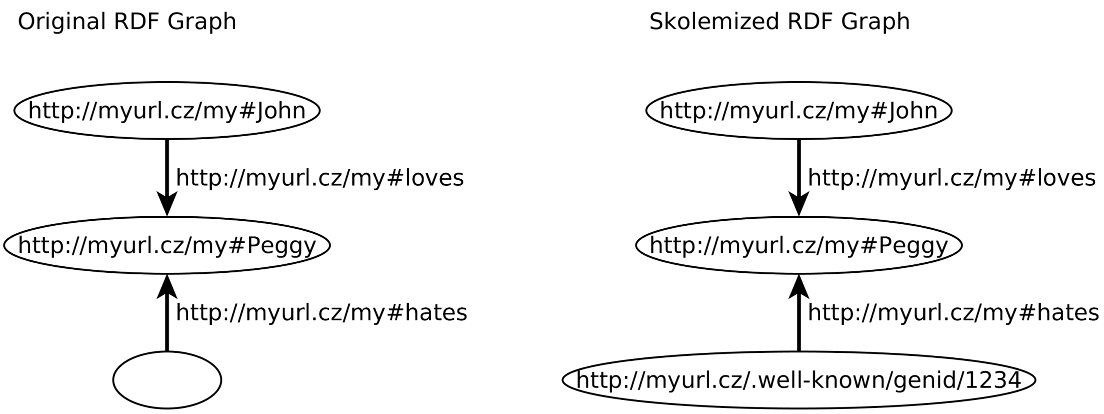


Blank Nodes for other use-cases

- container description – multisets, sequences, alternatives
- modeling n-ary relations (e.g. `birth`)

Blank Node Skolemization

- replacing the blank nodes with fresh IRIs (*Skolem IRI*) to allow stronger identification of those resources
- the meaning of the RDF graph remains the same as before skolemization
- skolemized IRIs `http://.../.well-known/genid/xxx`, where `xxx` is a placeholder for a generated identifier.



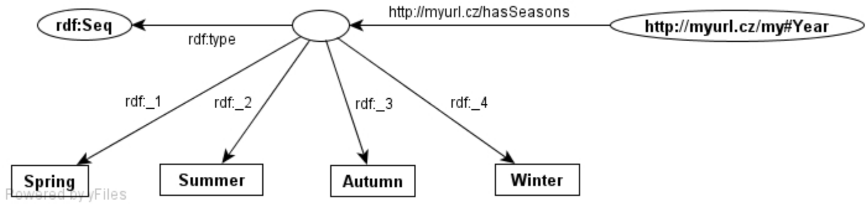
Vocabularies

Various predefinied vocabularies can be reused in your data, e.g.:

- schema.org – `http://schema.org/docs/schemas.html`
- Dublin Core – `http://dublincore.org/documents/dc-rdf/`. `https://www.dublincore.org/specifications/dublin-core/dcmi-terms/`
- FOAF – `http://www.foaf-project.org/`
- VOID – `http://www.w3.org/TR/void/`
- ... and many others

1.1.2 RDF features

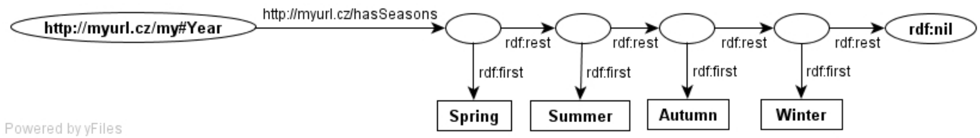
RDF containers



- rdf:Bag denotes an unordered sets of possibly repeating elements (multiset),
- rdf:Seq denotes an ordered seequence,
- rdf:Alt denotes an alternative choice from given resources/literals

- Container elements can be addressed by means of the **rdf** : _x property, where 'x' is a positive number,
- Containers are **not closed** – someone else can assert statements adding elements to our container,
- Containers can be modeled by means of blank nodes.

RDF collections



- represent **closable** containers, similarly as LISP/Prolog lists
- rdf:List represents a list; the list head is available through rdf:first and the property is available through rdf:rest. The list can be closed by means of an empty list rdf:nil.

RDF Model – Axiomatic Triples

RDF 1.1

- RDF 1.1 Primer – W3C Working Group Note [**Schreiber:13:RP**]
- a set of W3C Recommendations in February 2014
- main differences to RDF 1.0:

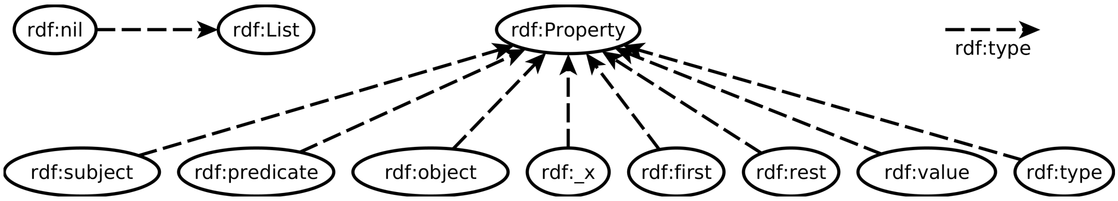


Figure 1.1: Visualization of axiomatic triples of RDF. Precise definition can be found in [**Patel-Schneider:14:RS**]

- identification of resources by IRIs
- all literals are *typed*, new datatypes introduced:

```
rdf:langString
rdf:HTML
rdf:XMLLiteral
```

  The last two are non-normative in RDF 1.1
- additional XSD datatypes

```
xsd:duration,
xsd:dayTimeDuration,
xsd:yearMonthDuration,
xsd:dateTimeStamp
```

- additional serialization – JSON-LD, Turtle, TriG, N-Quads

RDF*

- extending RDF 1.1 to support more efficient reification
- `https://arxiv.org/pdf/1406.3399.pdf`
- statement `:man :hasSpouse :woman`.
- reified statement `<<:man :hasSpouse :woman>> :startDate "2020-02-11" .`

1.1.3 Metamodeling in RDFS

RDFS Basics

- RDFS = RDF Schema
- simple metamodeling language
- `rdfs` being shortcut for `http://www.w3.org/2000/01/rdf-schema#`
- `rdf` being shortcut for `http://www.w3.org/1999/02/22-rdf-syntax-ns#`

- RDF Schema 1.0 – W3C Recommendation in 2004 [**Brickley:04:RVD**]
- basic metamodeling vocabulary:

```
rdf:type,
rdfs:Class,
rdfs:subClassOf,
rdf:Property,
rdfs:subPropertyOf,
rdfs:domain,
rdfs:range
```

Classes

- define instances :

```
ex:John rdf:type ex:Person .
```

- define classes (class `rdfs:Class`) :

```
ex:Person rdf:type rdfs:Class .
```

- create class hierarchies (property `rdfs:subClassOf`) :

```
ex:Woman rdfs:subClassOf ex:Person .
```

- multiple inheritance :

```
ex:Woman rdfs:subClassOf ex:Person .
ex:Woman rdfs:subClassOf ex:Female.
```

Properties

- property definitions (resource `rdf:Property`) :

```
ex:hasParent rdf:type rdf:Property .
```

- creation of property hierarchies (property `rdfs:subPropertyOf`) :

```
ex:hasMother rdfs:subPropertyOf ex:hasParent.
```

- multiple inheritance
- domain and range definition :

```
ex:hasMother rdfs:domain ex:Person .
ex:hasMother rdfs:range ex:Woman
```

- domains/ranges considered as conjunction :

```
ex:hasMother rdfs:range ex:Person .
ex:hasMother rdfs:range ex:Female .
```

RDFS Model – Axiomatic Triples

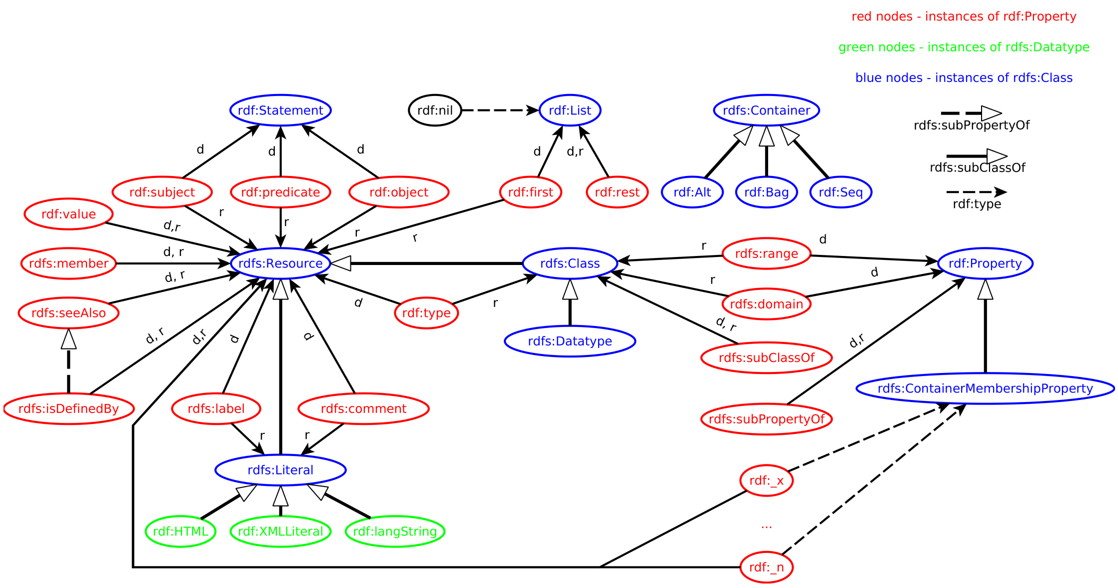


Figure 1.2: Visualization of axiomatic triples of RDFS. Precise definition can be found in [**Patel-Schneider:14:RS**]

1.1.4 RDF Syntaxes

Syntaxes
Turtle family

N-TRIPLES , simple triples, for batch processing

TURTLE , well-readable, compact

TriG , extension of TURTLE for multiple graphs (RDF datasets)

N-QUADS , extension of N-TRIPLES for multiple graphs (RDF datasets)

RDF/XML , a frame-based syntax

JSON-LD , JSON syntax for RDF 1.1

RDF-A , syntax for embedding RDF 1.1 into HTML

N-TRIPLES
suitable for loading large data volumes

```
<http://www.myurl.cz/my#George> <http://www.myurl.cz/my#loves> <http://www.myurl.cz/my#Peggy> .
<http://www.myurl.cz/my#Peggy> <http://www.myurl.cz/my#hasHusband> <http://www.myurl.cz/my#John> .
<http://www.myurl.cz/my#John> <http://www.myurl.cz/my#hates> <http://www.myurl.cz/my#George> .
<http://www.myurl.cz/my#John> <http://www.w3.org/1999/02/22-rdf-syntax-ns#type>
    <http://www.otherurl.org/other#Person> .
<http://www.myurl.cz/my#John> <http://www.myurl.cz#hasAge>
    "27"^^<http://www.w3.org/2001/XMLSchema#integer> .
```

TURTLE

extension of N-TRIPLES, allowing shortcuts

```
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix my: <http://www.myurl.cz/my#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
my:George my:loves my:Peggy .
my:Peggy my:hasHusband my:John .
my:John rdf:type <http://www.otherurl.org/other#Person> ;
        my:hates my:George ;
        my:hasAge "27"^^xsd:integer.
```

```
:a :p1 :o1 ;
   :p2 :o2 .
```

```
:a :p1 :o1 .
:a :p2 :o2 .
```

```
:a :p :o1, :o2 .
```

```
:a :p :o1 .
:a :p :o2 .
```

TURTLE

extension of N-TRIPLES, allowing shortcuts

```
:a :p1 [
   :p2 :o2 ;
   :p3 :o3 .
]
```

```
:a :p1 _:x .
_:x :p2 :o2 .
_:x :p3 :o3 .
```

```
:a :p (:o1 :o2 :o3).
```

```
:a :p _:a .
_:a rdf:first :o1 .
_:a rdf:rest _:b .
_:b rdf:first :o2 .
_:b rdf:rest _:c .
_:c rdf:first :o3 .
_:c rdf:rest rdf:nil .
```

RDF/XML

readable, expressive, plenty of syntactic sugar

```
<rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
         xmlns:base="http://myurl.cz/my#"
         xmlns:my="http://myurl.cz/my#"
         xmlns:other="http://otherurl.org/other#">
<rdf:Description rdf:ID="George">
  <my:loves rdf:about="http://myurl.cz/my#Peggy"/>
</rdf:Description>
<rdf:Description rdf:ID="Peggy">
  <my:hasHusband rdf:about="http://myurl.cz/my#John"/>
</rdf:Description>
<other:Person rdf:ID="John">
  <my:hates rdf:about="http://myurl.cz/my#George"/>
  <my:hasAge rdf:datatype="http://www.w3.org/2001/XMLSchema#integer">
    27
  </my:hasAge>
</other:Person>
</rdf:RDF>
```

1.1.5 RDF Datasets

Definition

RDF dataset is a collection of RDF graphs:

$$DS = \{DG, (i_1, G_1), \ldots, (i_n, G_n)\}$$

consisting of a **default (unnamed) RDF graph** DG and zero or more **named RDF graphs** G_k identified by their IRI/blank node i_k.

- Default graphs might be independent on named graphs (in RDF4J they are not – default graph contains union of all named graphs).
- Blank nodes can be reused between different graphs in a single RDF dataset.
- For SPARQL 1.1, RDF dataset cannot use blank nodes as graph names.

RDF Merge

- **Merge** of RDF graphs G_1 and G_2 is an RDF graph created as follows:
  - rename b-nodes in G_1, so that no b-node label occur in both G_1 and G_2.
  - union G_1 and G_2.
- Example:
  - G_1 :

```
@prefix : <http://www.myurl.cz/my#> .
:a :p _:b .
:a :q _:c .
```

– G_2 :

```
@prefix : <http://www.myurl.cz/my#> .
:a :s _:c .
:a :t _:d .
```

– merge of G_1 and G_2 :

```
@prefix : <http://www.myurl.cz/my#> .
:a :p _:b .
:a :q _:c .
:a :s _:e .
:a :t _:d .
```

1.1.6 Semantics of RDF(S)

Entailment Regimes and Semantic Extension

Precise definition of RDF semantics can be found in [**Patel-Schneider:14:RS**]

Definition

Semantic Extension is a set of semantic constraints on an RDF graph.

Entailment Regime is a set of entailments defined by the corresponding *semantic extension.*

- Four entailment regimes are predefined in RDF specs:

  Simple entailment provides only structural matching of graphs with possible b-node renaming

  RDF entailment interprets RDF vocabulary

  RDFS entailment interprets RDF and RDFS vocabularies

  D entailment additionally interprets datatypes

- All entailment regimes must be *monotonic* extensions of simple entailment

Simple Interpretation

Definition

A finite interpretation $I = (IR, IP, IEXT, IS, IL)$ w.r.t. vocabulary $N = (N_{IRI}, N_{lit})$ is defined as follows:

- IR is a set of *resources*
- IP is a set of *properties* (often $IP \subseteq IR$)
- $IEXT$ is a mapping $IEXT : IP \rightarrow IR \times IR$
- IS is a mapping $IS : N_{IRI} \rightarrow IR \cup IP$
- IL is a partial mapping $IL : N_{lit} \rightarrow IR$

Simple Interpretation Example

```
@prefix : <http://www.myurl.cz/my#> .
:John :loves :Mary .
:John :childcount 2 .
```

- $IR = \{John, Mary, 2\}$ (real resources)
- $IP = \{loves, childcount\}$ (real properties)
- $IEXT = \{(loves, \langle John, Mary\rangle),$
  $(childcount, \langle John, 2\rangle)\}$
- $IS = \{\langle \texttt{http://www.myurl.cz/my\#John}, John\rangle,$
  $\langle \texttt{http://www.myurl.cz/my\#Mary}, Mary\rangle,$
  $\langle \texttt{http://www.myurl.cz/my\#loves}, loves\rangle,$
  $\langle \texttt{http://www.myurl.cz/my\#childcount}, childcount\rangle\}$
- $IL = \{\langle \text{"2"\^{}\^{}}\texttt{http://www.w3.org/2001/XMLSchema\#integer}, 2\rangle\}$

Simple Entailment

Simple entailment is just a "structural matching with b-node rewriting."

Semantic Conditions on Simple Entailment

- if E is a literal, then $I(E) = IL(E)$
- if E is an IRI, then $I(E) = IS(E)$
- if E is a ground triple (s, p, o), then $I(E) = true$ iff $I(p) \in IP$ and $\langle I(s), I(o)\rangle \in IEXT(I(p))$
- if E is a ground RDF graph, then $I(E) = true$ iff $I(E') = true$ for each triple $E' \in E$
- if E is an RDF graph, then $I(E) = true$ iff there exists a mapping $A : N_{bnode} \to IR$, such that $I(A(E)) = true$, where $A(E)$ is E, where each blank node B is replaced by $A(B)$.

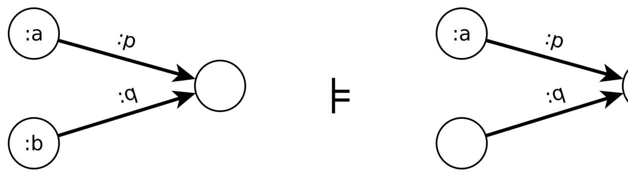
Simple Entailment

- graph G_1 (simply) entails graph G_2 (denoted $G_1 \models G_2$) if $I(G_2) = true$ whenever $I(G_1) = true$.
- if $G_1 \models G_2$ and $G_2 \models G_1$ then they are *logically equivalent*.

How to Check Simple Entailment ?

Interpolation lemma

Graph G_1 simply entails graph G_2 iff a subgraph of G_1 is an instance of G_2.



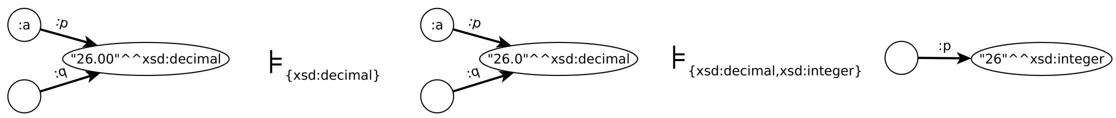
Simple entailment is NP in the size of G_1 and G_2.

D-Entailment

In addition to blank nodes, D-entailment ($\models_D$) interprets datatypes in the set D of recognized datatypes. Literals with non-recognized datatypes are treated as uninterpreted.

Semantic Conditions on D-Entailment

- if $\texttt{rdf}:\texttt{langString} \in D$, then for each literal $lex@lang$:, $IL(lex@lang) = \langle lex, lowercase(lang)\rangle$
- if $dIRI \in D$, then for each literal $lex\hat{}\hat{}dIRI$: $IL(lex\hat{}\hat{}dIRI) = L2V(I(dIRI))(lex)$, where
  - $I(dIRI)$ is a datatype identified by $dIRI$
  - $L2V(d)$ transforms a lexical value to the value space of d.



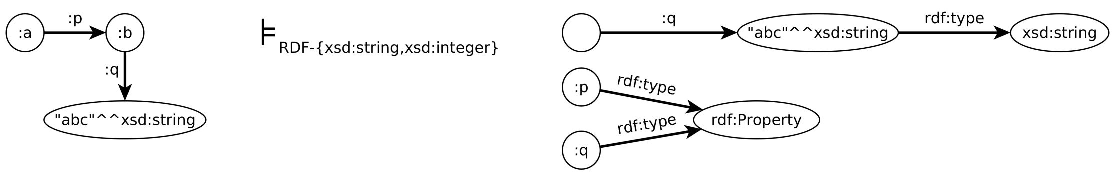
RDF-Entailment

In addition to D-entailment, RDF-entailment w.r.t D interprets properties in the RDF vocabulary.

Entailment rules

rule	G contains	t_i, s.t. $G \models_{RDF-D} t_i$
GrdfD1	$(s, p, lex\hat{}\hat{}d)$ $d \in D$	$(lex\hat{}\hat{}d, \texttt{rdf}:\texttt{type}, d)$
rdfD2	(s, p, o)	$(p, \texttt{rdf}:\texttt{type}, \texttt{rdf}:\texttt{Property})$

For example:



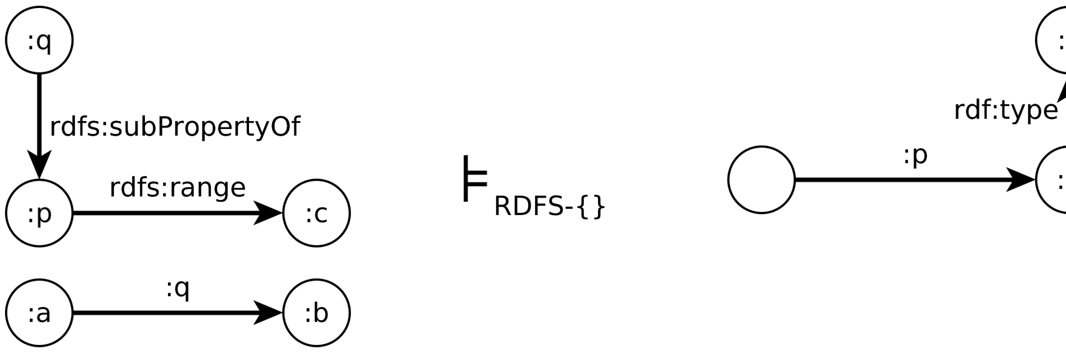
RDFS-Entailment

RDFS-entailment w.r.t D interprets most RDF and RDFS vocabulary.

Entailment rules

rule	G contains	t_i, s.t. $G \models_{RDFS-D} t_i$
rdfs1	any IRI $dIRI \in D$ in G	$(dIRI, \texttt{rdf:type}, \texttt{rdfs:Datatype})$
rdfs2	(s,p,o), $(p, \texttt{rdfs:domain}, w)$	$(s, \texttt{rdf:type}, w)$
rdfs3	(s,p,o), $(p, \texttt{rdfs:range}, w)$	$(o, \texttt{rdf:type}, w)$
rdfs4	(s,p,o)	$(s, \texttt{rdf:type}, \texttt{rdfs:Resource})$ $(o, \texttt{rdf:type}, \texttt{rdfs:Resource})$
rdfs5	$(p_1, \texttt{rdfs:subPropertyOf}, p_2)$ $(p_2, \texttt{rdfs:subPropertyOf}, p_3)$	$(p_1, \texttt{rdfs:subPropertyOf}, p_3)$
rdfs6	$(p, \texttt{rdf:type}, \texttt{rdf:Property})$	$(p, \texttt{rdfs:subPropertyOf}, p)$
rdfs7	$(p_1, \texttt{rdfs:subPropertyOf}, p_2)$ (s, p_1, o)	(s, p_2, o)
rdfs8	$(s, \texttt{rdf:type}, \texttt{rdfs:Class})$	$(s, \texttt{rdfs:subClassOf}, \texttt{rdfs:Resource})$
rdfs9	$(c_1, \texttt{rdfs:subClassOf}, c_2)$ $(s, \texttt{rdf:type}, c_1)$	$(s, \texttt{rdf:type}, c_2)$
rdfs10	$(c, \texttt{rdf:type}, \texttt{rdfs:Class})$	$(c, \texttt{rdfs:subClassOf}, c)$
rdfs11	$(c_1, \texttt{rdfs:subClassOf}, c_2)$ $(c_2, \texttt{rdfs:subClassOf}, c_3)$	$(c_1, \texttt{rdfs:subClassOf}, c_3)$
rdfs12	$(p, \texttt{rdf:type},$ $\texttt{rdfs:ContainerMembershipProperty})$	$(p, \texttt{rdfs:subPropertyOf},$ $\texttt{rdfs:member})$
rdfs13	$(d, \texttt{rdf:type}, \texttt{rdfs:Datatype})$	$(d, \texttt{rdfs:subClassOf}, \texttt{rdfs:Literal})$

RDFS-Entailment Example

For example: 

Entailment Checking

All discussed entailments can be checked by applying the entailment rules on *generalized RDF graphs*, i.e. **graphs that allow all RDF Terms in all positions – subject, predicate, object**.

Entailment checking procedure

$G_1 \models_X G_2$, iff $Clos_X(G_1)$ simply entails G_2, where $Clos_X(G_1)$ is constructed as follows:

1. Add to G_1 all axiomatic triples for $X \in$ {RDF-D,RDFS-D} (visualized in Figure 1.1, resp. Figure 1.2)

2. For each container membership property IRI p occuring in G_1, add to G_1 corresponding axiomatic triples for X containing p.

3. If no triples were added in the previous step, add axiomatic triples for X containing `rdf:_1`.

4. Apply rules for X (i.e. $\{GrdfD1, rdfD2\}$ for $X = RDF$, or $\{Grdf1, rdfD2, rdfs1, \ldots, rdfs13\}$ for $X = RDFS$) with $D = \{rdf : langString, xsd : string\}$, until exhaustion.

Entailment Checking Complexity

- the previous procedure is finite and polynomial
- simple entailment checking itself is NP
- the less blank nodes, the more efficient