Data with Semantics – RDF(S)

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October 3, 2019

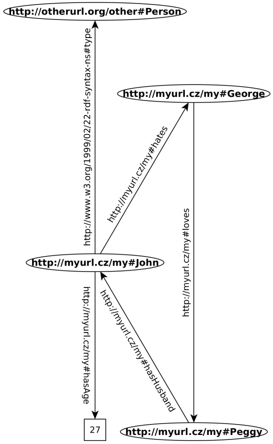
Outline

RDF(S)

Core RDF

RDF Basics

- RDF 1.0 – W3C Recommendation in 2004,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http://myurl.cz/my#hates
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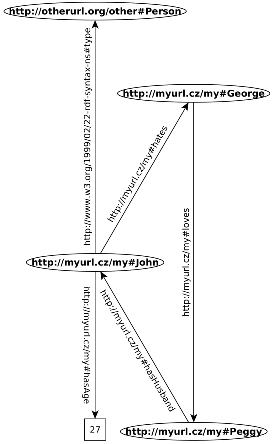
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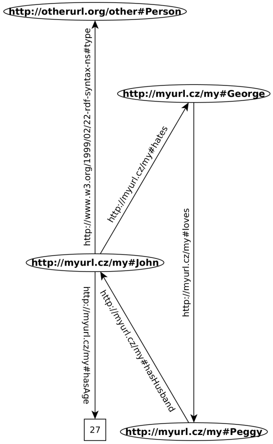
- Intuitivelly, RDF document is a graph, where each node is either an IRI (ellipse), a literal (rectangle), or a blank node (blank ellipse)
- RDF document is a set of statements about resources in expression of triples (Subject, Predicate, Object)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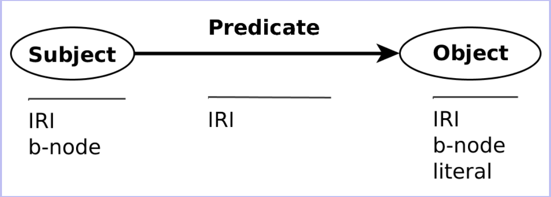
Main Definitions

Definitions

RDF Graph	is a set of RDF triples,
RDF Triple	is an ordered triple of the form (*Subject*, *Predicate*, *Object*):



RDF Term	is either an *IRI*, a *blank node*, or a *literal*
RDF Source	is a mutable source of RDF graphs (e.g. RDF4J Graph store)

IRIs

- IRI = Internationalized 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 = backwards-compatibility

Note

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

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 $\{"0", "01", \ldots\}$ of strings made of numbers 0-9.

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

lexical-to-value mapping $L2V$, e.g.

$$L2V(\text{datatype for } \mathtt{xsd:integer}) = \{\langle "01", 1\rangle, \ldots\}.$$

- most XML Schema built-in datatypes:
  - `xsd:string`,`xsd:boolean`, `xsd:integer`, `xsd:decimal`, `xsd:dateTimeStamp`,`xsd:base64Binary`, ...
- `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, ...

Namespaces

In many RDF syntaxes, namespaces can be abbreviated by means of prefixes for the sake of readability, e.g. `rdf:type` denotes the IRI `http://www.w3.org/1999/02/22-rdf-syntax-ns#type`. But `rdf:type` is not itself an IRI.

- **rdf:** represents the vocabulary of RDF `http://www.w3.org/1999/02/22-rdf-syntax-ns#`. This vocabulary defines basic resources, like `rdf:type`, `rdf:Property`.
- **rdfs:** represents the RDFS vocabulary `http://www.w3.org/2000/01/rdf-schema#` for metamodeling, like `rdfs:Class`, or `rdfs:subPropertyOf`.
- **xsd:** represents the XML Schema vocabulary `http://www.w3.org/2001/XMLSchema#`, for referencing datatypes reused by RDF, like `xsd:integer`, or `xsd:string`.

Note

We will slightly abuse syntax and use shortened versions of IRIs (e.g. `rdf:type`) in place of IRIs (`http://www.w3.org/1999/02/22-rdf-syntax-ns#type`). 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.

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

Blank Nodes (b-nodes)

- denote existentially quantified variables,

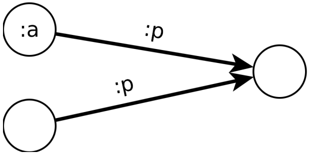
Definition

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

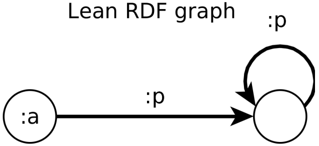
Instance of RDF Graph G_1 is an RDF Graph in which some b-nodes are be replaced by an arbitrary RDF Term.

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

Original RDF Graph



Lean RDF graph



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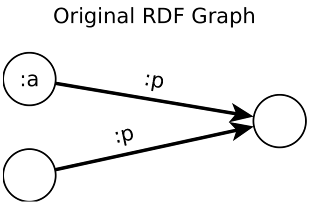

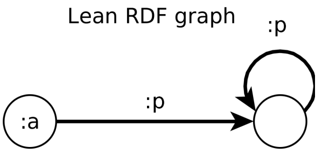

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- in Turtle/N-TRIPLES/SPARQL have `_:` prefix, e.g. `_:x`,

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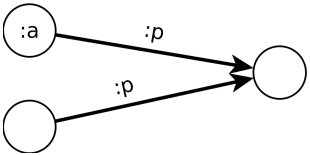

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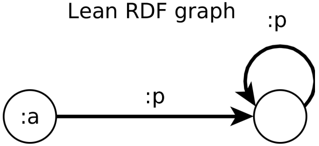
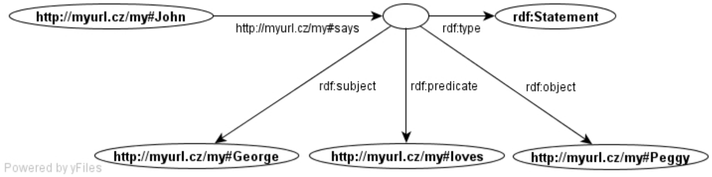


Blank Nodes Usage

- describing higher-order statements (reification)



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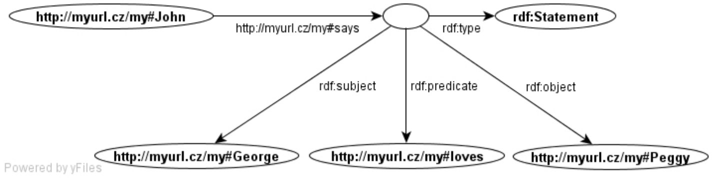

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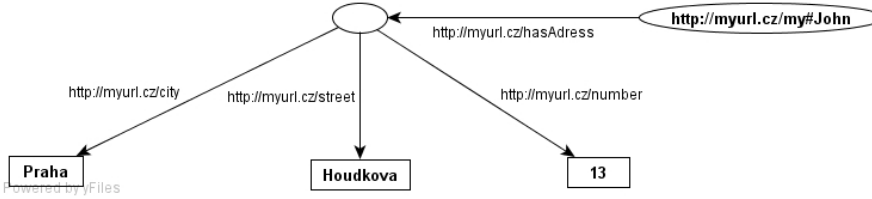

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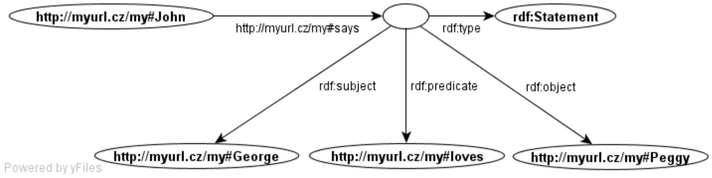

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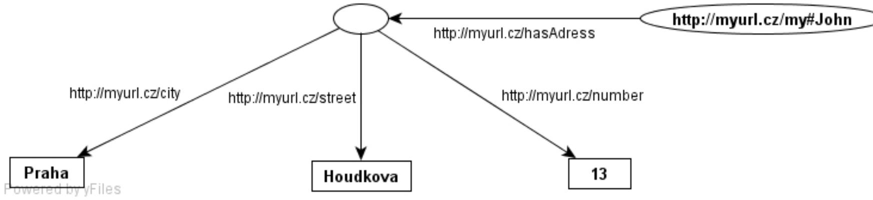

- container description – multisets, sequences, alternatives

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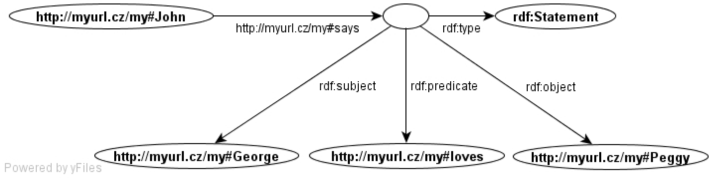

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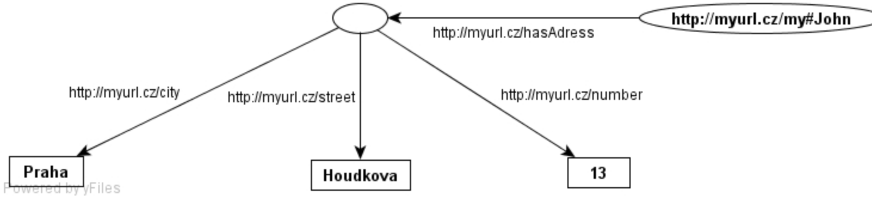

- container description – multisets, sequences, alternatives
- modeling n-ary relations (e.g. `birth`)

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.

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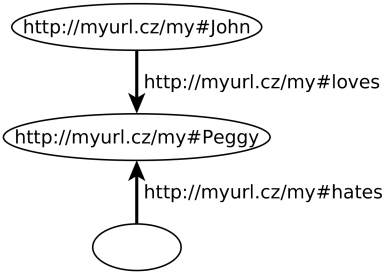
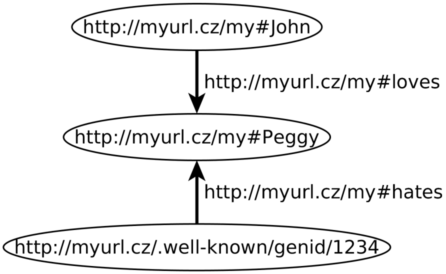


Skolemized RDF Graph



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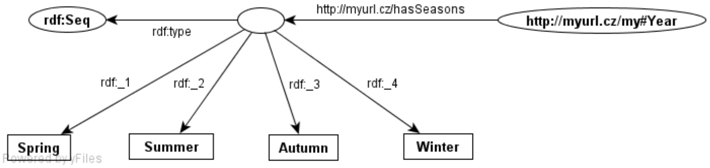

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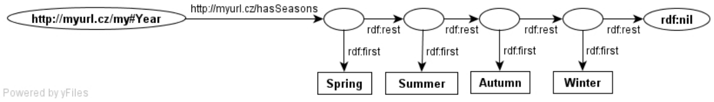
- `rdf:List` represents a list; the list head is available through `rdf:first` and the property is available through `rdf:rest`. The list can be closed by means of an empty list `rdf:nil`.



RDF Model – Axiomatic Triples

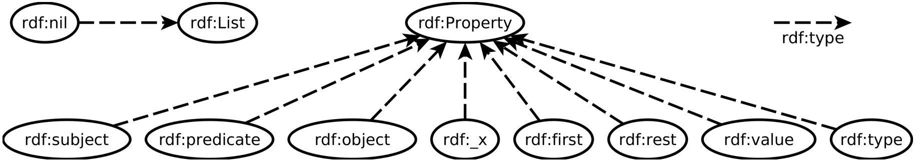


Figure: Visualization of axiomatic triples of RDF. Precise definition can be found in [**Patel-Schneider:14:RS**]

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  - all literals are *typed*, new datatypes introduced:

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  - additional XSD datatypes

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          xsd:duration,
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          xsd:dateTimeStamp
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    - additional XSD datatypes

```
xsd:duration,
xsd:dayTimeDuration,
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```

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

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 :

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

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```

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

```
        ex:Woman rdfs:subClassOf ex:Person .
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        ex:John rdf:type ex:Person .
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```

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```

- 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

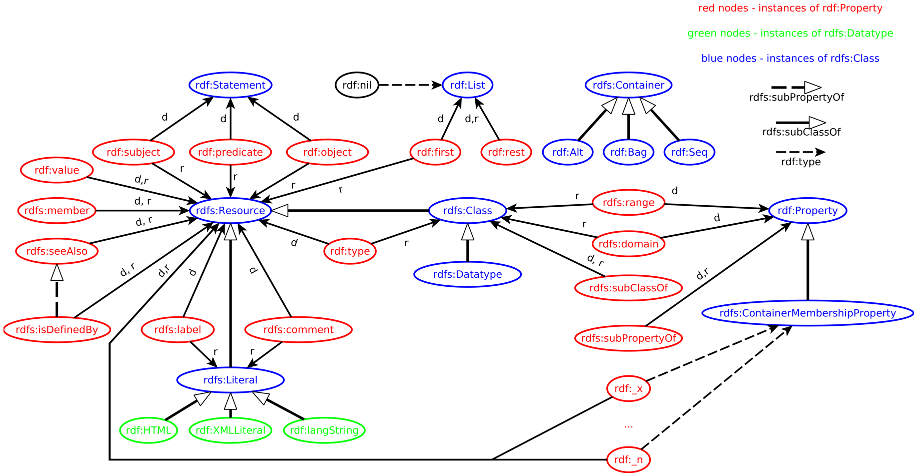


Figure: Visualization of axiomatic triples of RDFS. Precise definition can be found in [**Patel-Schneider:14:RS**]

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>
```

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 .
```

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)
- $IEXT = \{(loves, \langle John, Mary\rangle), (childcount, \langle John, 2\rangle)\}$
- $IS = \{\langle \mathtt{http://www.myurl.cz/my\#John}, John\rangle, \langle \mathtt{http://www.myurl.cz/my\#Mary}, Mary\rangle, \langle \mathtt{http://www.myurl.cz/my\#loves}, loves\rangle, \langle \mathtt{http://www.myurl.cz/my\#childcount}, childcount\rangle\}$
- $IL = \{\langle \mathtt{"2"\hat{}\hat{}http://www.w3.org/2001/XMLSchema\#integer}, 2\rangle\}$

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

Simple Entailment

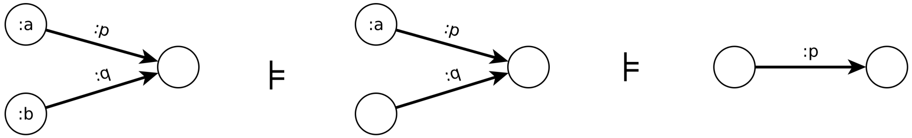
- graph G_1 (simply) entails graph G_2 (denoted $G_1 \models G_2$) if $I(G_2) = \mathit{true}$ whenever $I(G_1) = \mathit{true}$.
- if $G_1 \models G_2$ and $G_2 \models G_1$ then they are *logically equivalent*.

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.

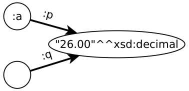


D-Entailment

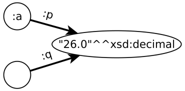
In addition to blank nodes, *D*-entailment ($\models_D$) interprets datatypes in the set *D* of recognized datatypes. Literals with non-recognized datatypes are treated as uninterpreted.

Semantic Conditions on D-Entailment

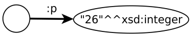
- if $\texttt{rdf:langString} \in D$, then for each literal *lex*@*lang*:, $IL(lex@lang) = \langle lex, lowercase(lang)\rangle$
- if $dIRI \in D$, then for each literal *lex*^^*dIRI*: $IL(lex\hat{}\hat{}dIRI) = L2V(I(dIRI))(lex)$, where
  - $I(dIRI)$ is a datatype identified by *dIRI*
  - $L2V(d)$ transforms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



$\models_{\{xsd:decimal\}}$



$\models_{\{xsd:decimal,xsd:integer\}}$



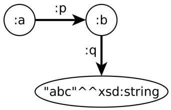
RDF-Entailment

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

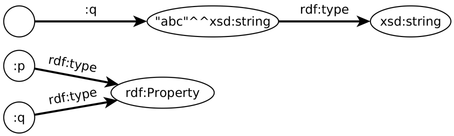
Entailment rules

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

For example:



$\models_{\text{RDF-\{xsd:string,xsd:integer\}}}$



RDFS-Entailment

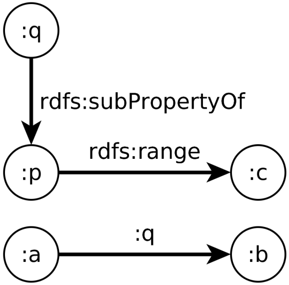
RDFS-entailment w.r.t D interprets most RDF and RDFS vocabulary.

Entailment rules

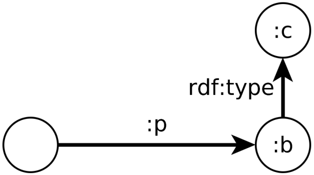
rule	G contains	t_i, s.t. $G \models_{RDFS-D} t_i$
rdfs1	any IRI $dIRI \in D$ in G	$(dIRI, \texttt{rdf:type}, \texttt{rdfs:Datatype})$
rdfs2	(s, p, o), $(p, \texttt{rdfs:domain}, w)$	$(s, \texttt{rdf:type}, w)$
rdfs3	(s, p, o), $(p, \texttt{rdfs:range}, w)$	$(o, \texttt{rdf:type}, w)$
rdfs4	(s, p, o)	$(s, \texttt{rdf:type}, \texttt{rdfs:Resource})$ $(o, \texttt{rdf:type}, \texttt{rdfs:Resource})$
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:



$\models_{\text{RDFS-}\{\}}$



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 $X \in \{\text{RDF-D,RDFS-D}\}$ (visualized in Figure 1, resp. Figure 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 $\{Grdf1, rdfD2, rdfs1, \dots, rdfs13\}$ 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