Semantic Web Modeling Languages Part I: RDF

Markus Krötzsch & Sebastian Rudolph

ESSLLI 2009 Bordeaux

slides available at http://semantic-web-book.org/page/ESSLLI09_lecture

Outline

- A Brief Motivation
- RDF
- Simple Semantics for RDF
- RDF Schema
- Semantics for RDF(S)

Why Semantic Web Modelling?

- Initially, the Web was made for humans reading webpages.
- But there's too much information out there to be entirely checked by a human with a specific information need.
- Machines can process large amounts of data.
- Normal Web data (such as HTML) is not suitable for content-sensitive machine processing (ambiguous, relies on background knowledge, etc.)
- Semantic Web is concerned with representing information distributed across the Web in a machine-interpretable way.

- So, why not use XML?

Shortcomings of (Pure) XML

- Task: express ”The Book ‘Foundations of Semantic Web Technologies’ is published by CRC Press.”
- Many options:

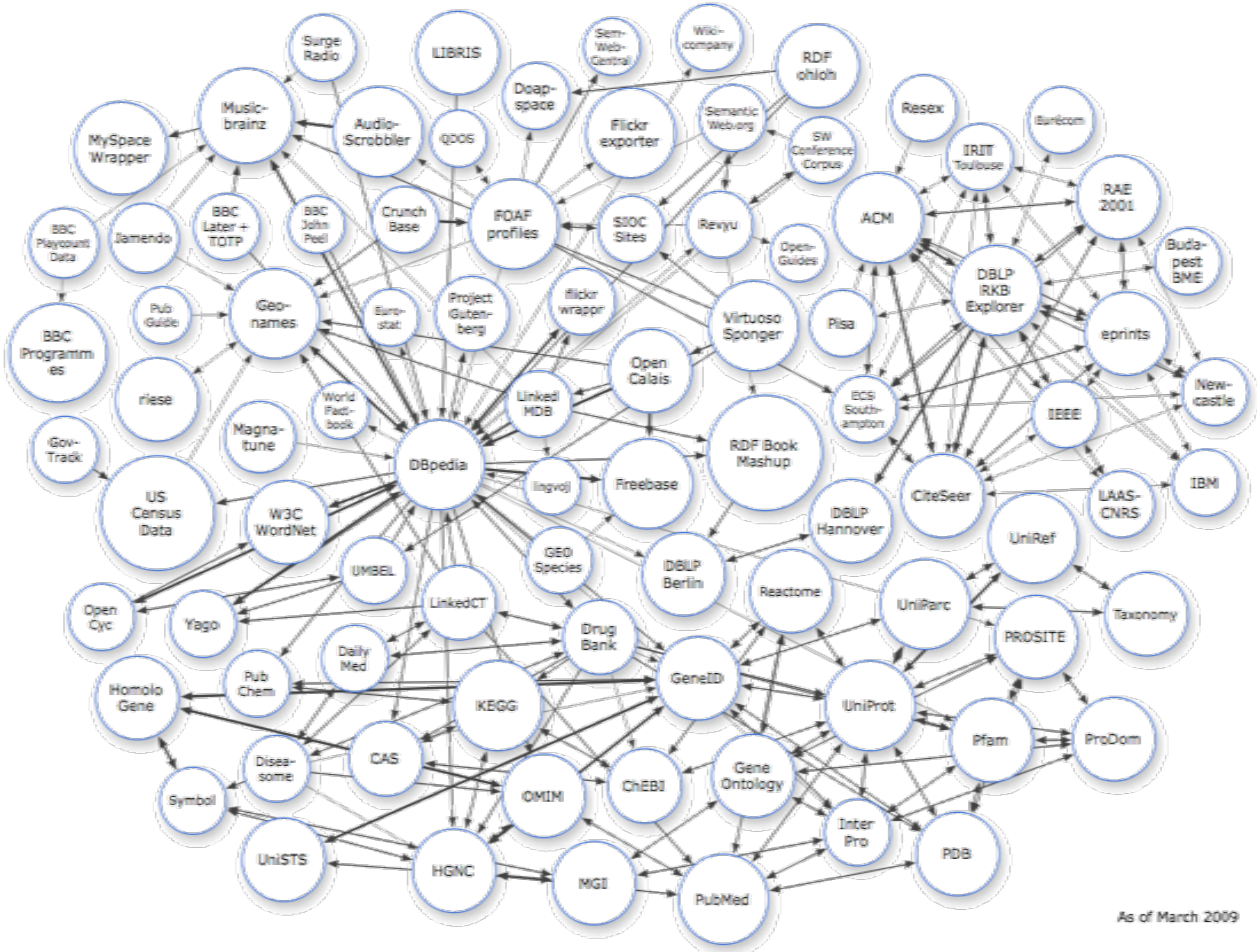
```
<published>
<publisher>CRC Press</publisher>
<book>Foundations of Semantic Web Technologies</book>
</published>
```

```
<publisher name="CRC Press">
<published book=”Foundations of Semantic Web Technologies/>
</publisher>
```

```
<book name="Foudations of Semantic Web Technologies">
<published publisher="CRC Press”/>
</book>
```

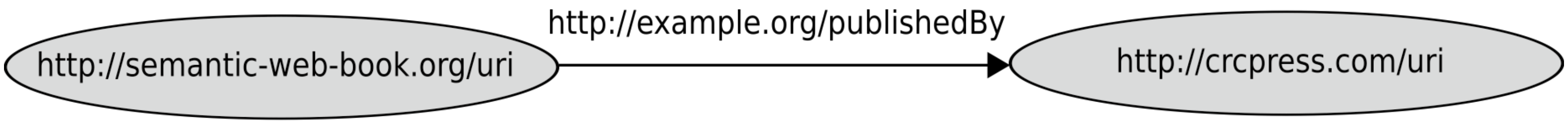
- ambiguity and tree structure inappropriate for intended purpose

Web-Wide Linked Open Data – The Vision Becoming True



RDF: Graphs instead of Trees

- Solution: representation by directed graphs

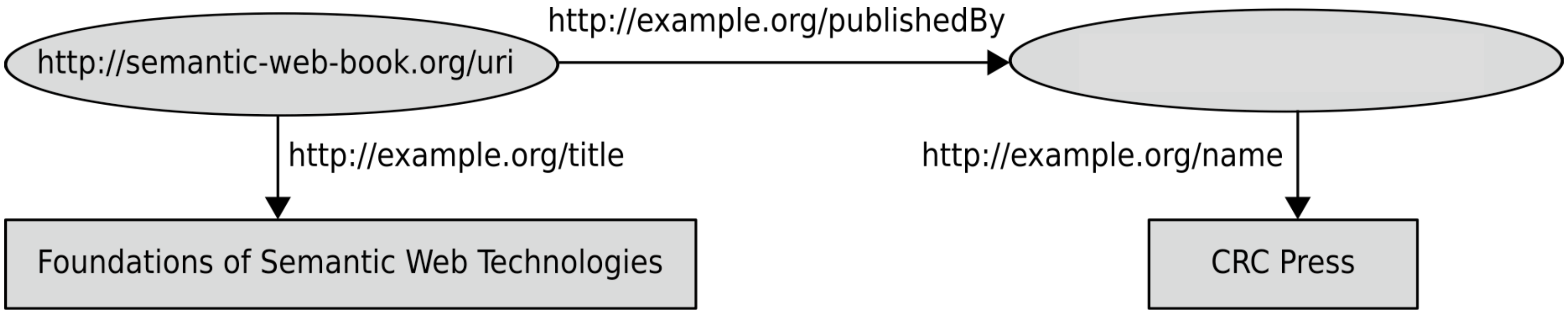


RDF

- "Resource Description Framework"
- W3C Recommendation (http://www.w3.org/RDF)
- RDF is a data model (not one specific syntax)
  - originally designed for providing metadata for Web resources, later used for more general purposes
  - encodes structured information
  - universal machine-readable exchange format

Building blocks for RDF Graphs

- URIs
- literals
- blank nodes (aka: empty nodes, bnodes)



URIs - Idea

- URI = Uniform Resource Identifier
- allow for denoting resources in a world-wide unambiguous way
- resources can be any object that possesses a clear identity (within the context of a given application)
- Examples: books, cities, humans, publishers, but also relations between those, abstract concepts, etc.
- already realized in some domains: e.g., ISBN for books

URIs - Syntax

- Builds on concept of URLs but not every URI refers to a Web document
  (but often the URL of a document is used as its URI)
- URI starts with so-called URI schema separated from the following part by ":"
  (e.g, http, ftp, mailto)
- mostly hierarchically organized

Self-defined URIs

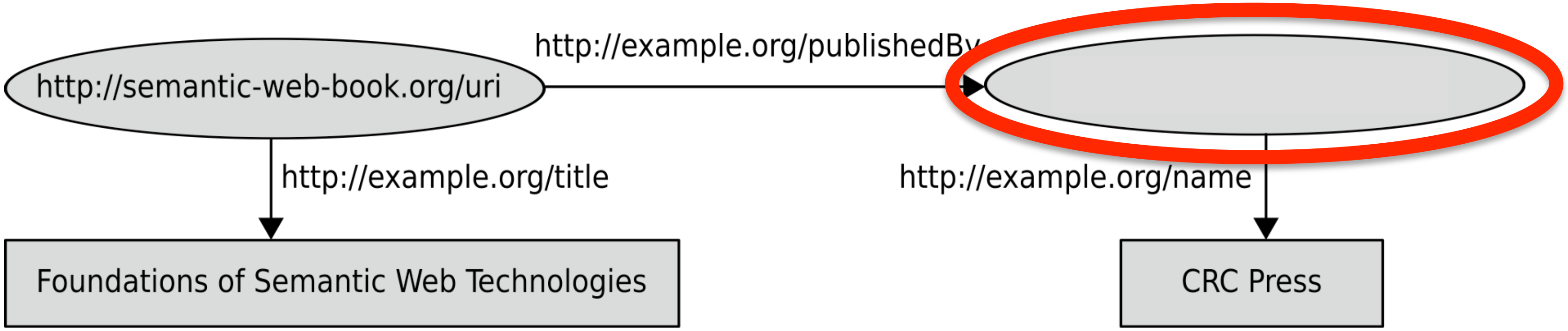
- necessary if no URI exists (yet) for a resource (or it is not known)
- strategy for avoiding unwanted clashes: use `http` URIs of webspace you control
- this also allows you to provide some documentation about the URI
- How to distinguish URI of a resource from URI of the associated documents describing it?
- Example: URI for "Othello”
  - don’t use: `http://de.wikipedia.org/wiki/Othello`
  - rather use: `http://de.wikipedia.org/wiki/Othello#URI`

Literals

- used for representing data values
- written down as strings
- interpreted via assigned *datatype*
- literals without explicitly associated datatype are treated like strings

Bnodes

- used to state existence of an entity the reference of which is not known
- from a logic perspective: existentially quantified variables



Graphs as Triple Sets

- there are several ways for representing graphs
- in RDF we see graphs as set of vertex-edge-vertex triples

Graphs as Triple Sets

- there are several ways for representing graphs
- in RDF we see graphs as set of vertex-edge-vertex triples

Graphs as Triple Sets

- there are several ways for representing graphs
- in RDF we see graphs as set of vertex-edge-vertex triples

RDF Triples

- constitutents of an RDF triple

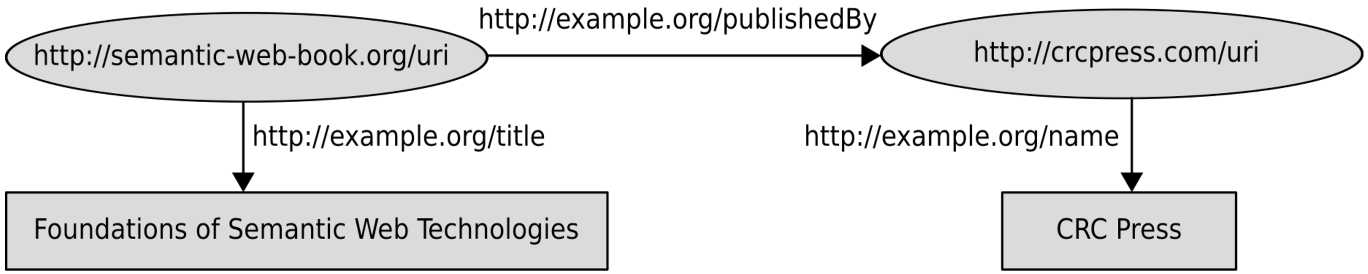
- terms inspired by linguistics but doesn’t always coincide
- eligible instantiations:
  subject : URI or bnode
  predicate : URI
  objekt : URI or bnode or literal

Turtle - An Easy Syntax for RDF

Turtle notation:

- unabbreviated URIs in <…>
- literals in "…"
- period at the end of each triple
- extra spaces and linebreaks outside of names irrelevant

```
<http://semantic-web-book.org/uri>  <http://example.org/publishedBy>  <http://crcpress.com/uri> .
<http://semantic-web-book.org/uri>  <http://example.org/title>        "Foundations of Semantic Web Technologies" .
<http://crcpress.com/uri>           <http://example.org/name>         "CRC Press" .
```

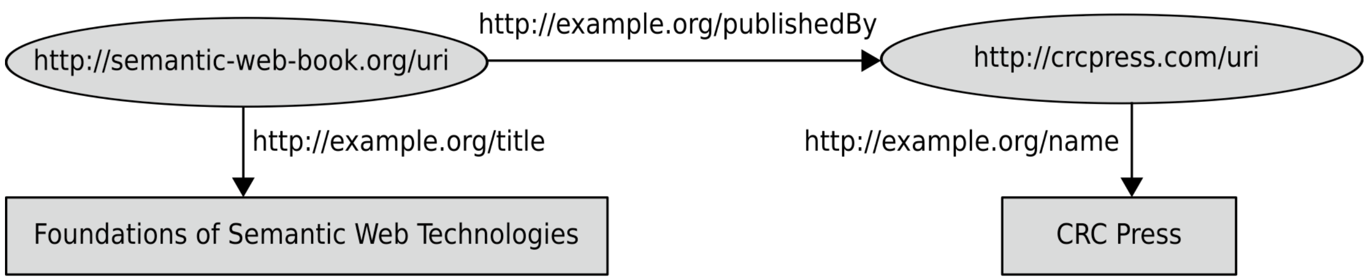


Turtle - An Easy Syntax for RDF

Turtle notation:

- unabbreviated URIs in <…> but can be abbreviated by namespaces
- literals in "…"
- period at the end of each triple
- extra spaces and linebreaks outside of names irrelevant

```
@prefix book: <http://semantic-web-book.org/> .
@prefix ex: <http://example.org/> .
@prefix crc: <http://crcpress.com/> .
book:uri     ex:publishedBy     crc:uri .
book:uri     ex:title           "Foundations of Semantic Web Technologies" .
crc:uri      ex:name            "CRC Press" .
```



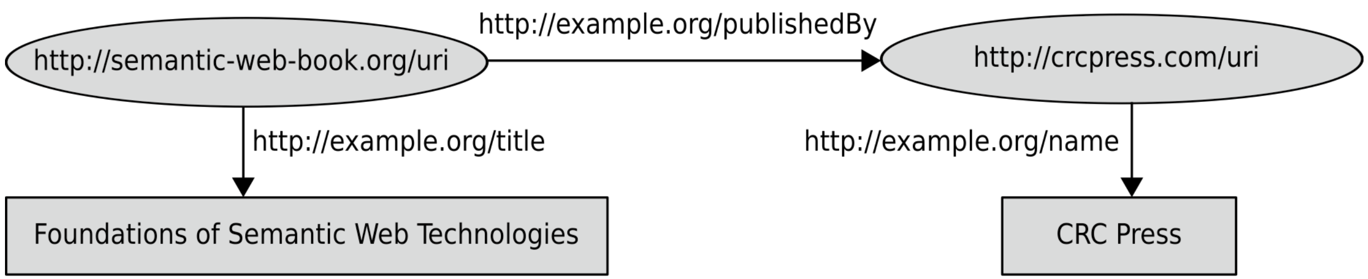
Turtle - An Easy Syntax for RDF

Turtle notation:

- unabbreviated URIs in <…> but can be abbreviated by namespaces
- literals in "…"
- period at the end of each triple
- extra spaces and linebreaks outside of names irrelevant

```
@prefix book: <http://semantic-web-book.org/> .
@prefix ex: <http://example.org/> .
@prefix crc: <http://crcpress.com/> .
book:uri     ex:publishedBy     crc:uri ;
             ex:title           "Foundations of Semantic Web Technologies" .
crc:uri      ex:name            "CRC Press" .
```

repeated subjects may be left out



Turtle - An Easy Syntax for RDF

Turtle notation:

- unabbreviated URIs in <…> but can be abbreviated by namespaces
- literals in "…"
- period at the end of each triple
- extra spaces and linebreaks outside of names irrelevant

```
@prefix book: <http://semantic-web-book.org/> .
@prefix ex: <http://example.org/> .
@prefix crc: <http://crcpress.com/> .
book:uri     ex:publishedBy    crc:uri ;
             ex:title          "Foundations of Semantic Web Technologies“ ;
             ex:author         book:Hitzler, book:Krötzsch, book:Rudolph .
crc:uri      ex:name           "CRC Press" .
```

repeated subjects may be left out

several objects can be assigned to the same subject-predicate pairs

XML-Syntax of RDF

- there is also an XML syntax for RDF
- it’s for machines, so we don’t deal with it here

```
<rdf:Description rdf:about="http://semantic-web-book.org/uri">
    <ex:title>Foundations of Semantic Web Technologies</ex:title>
    <ex:publishedBy>
        <rdf:Description rdf:about="http://crcpress.com/uri">
            <ex:name>CRC Press</ex:name>
        </rdf:Description>
    </ex:publishedBy>
</rdf:Description>
```

Datatypes in RDF

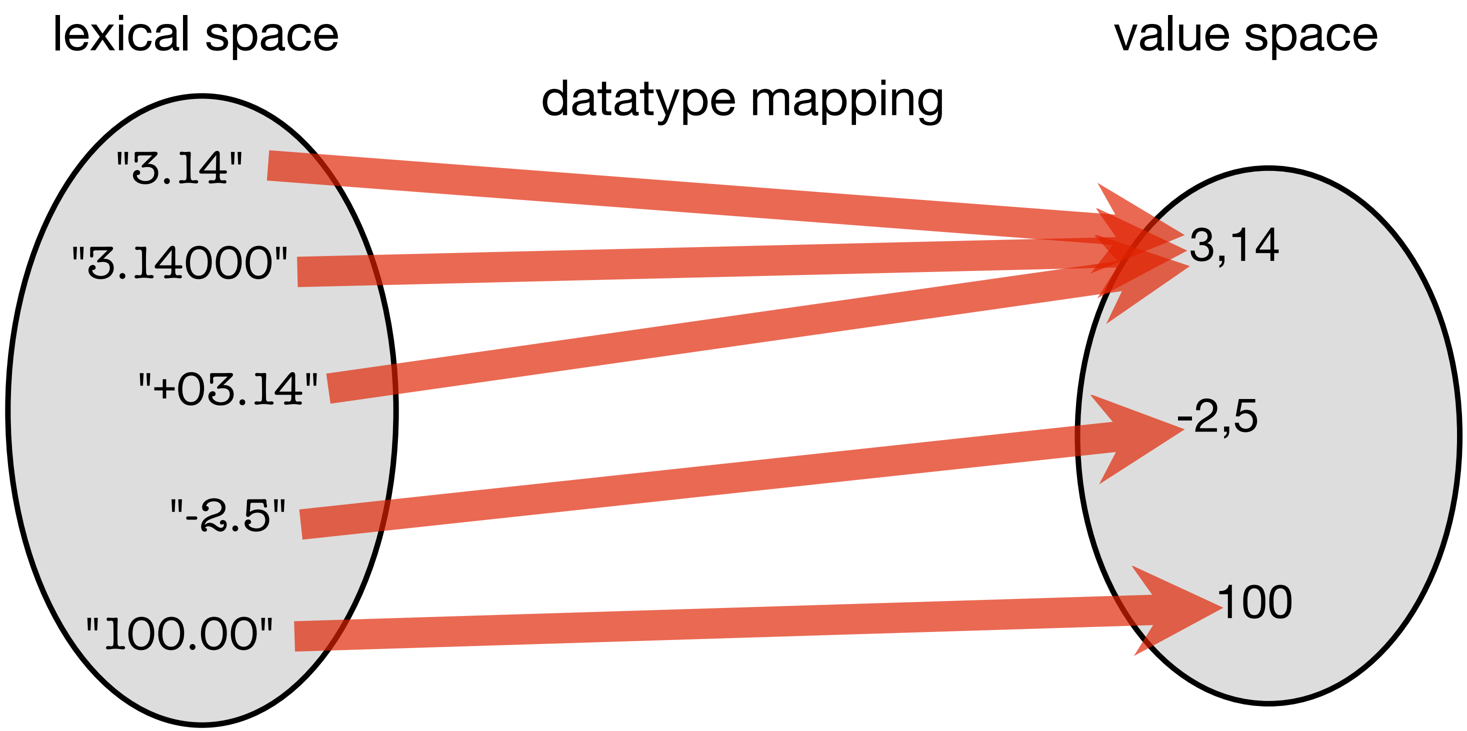
- by now: literals were untyped, interpreted as strings (making e.g. "02", "2", "2.0" all different)
- typing literals with datatypes allows for more adequate (semantic = meaning-appropriate) treatment of values
- datatypes denoted by URIs and can be freely chosen
- frequently: xsd datatypes from XML
- syntax of typed literal:

  "datavalue"^^datatype-URI

- rdf:XMLLiteral is the only datatype that is part of the RDF standard
- denotes arbitrary balanced XML "snippets"

Datatypes – the Abstract View

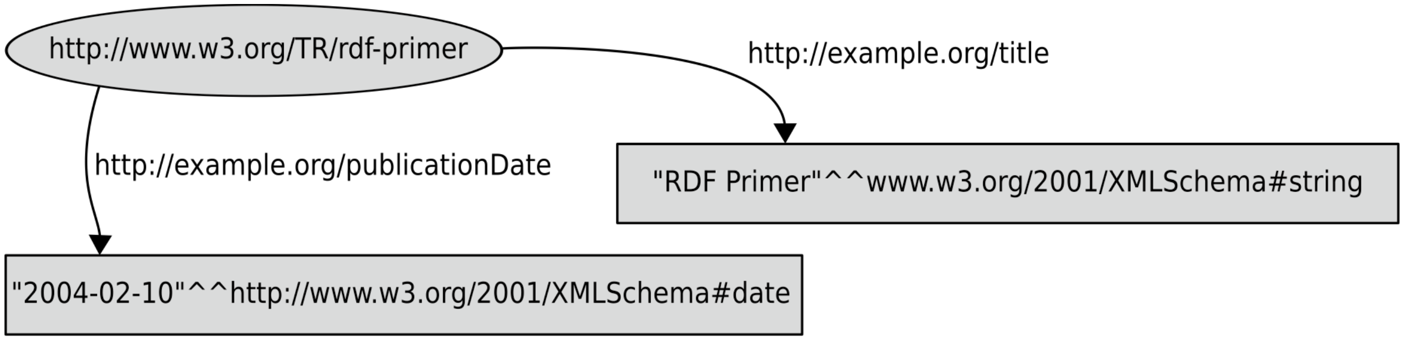
- Example: xsd:decimal



"3.14"="+03.14" holds for xsd:decimal but not for xsd:string

Datatypes in RDF – Example

- Graph:



- Turtle:

```
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
<http://www.w3.org/TR/rdf-primer>
    <http://example.org/title> "RDF Primer"^^xsd:string ;
    <http://example.org/publicationDate> "2004-02-10"^^xsd:date .
```

Language Settings and Datatypes

- language settings only applicable to untyped literals

```
<http://www.w3.org/TR/rdf-primer>
    <http://example.org/title>
    "Initiation à RDF"@fr, "RDF Primer"@en .
```

- distinct types or language settings – distinct literals

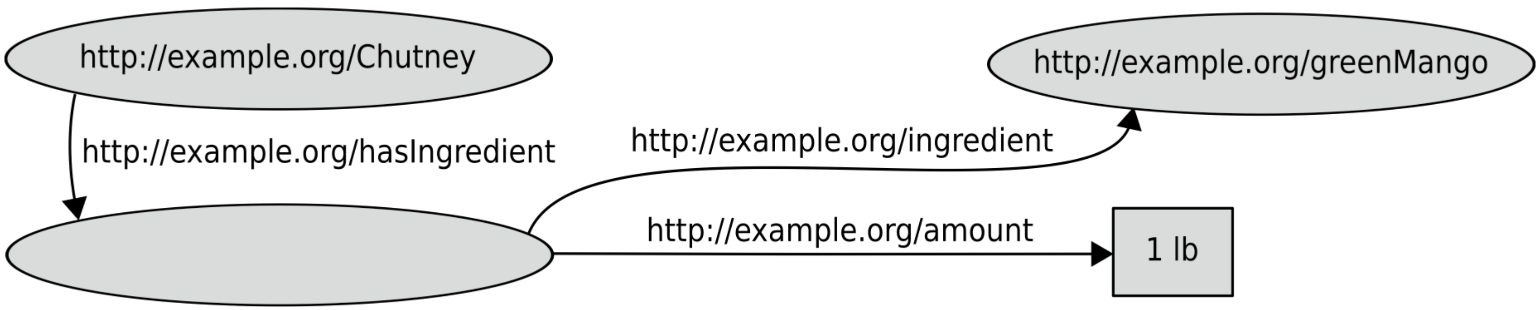
```
<http://crcpress.com/uri> <http://example.org/Name>
                          "CRC Press" ,
                          "CRC Press"@en ,
                          "CRC Press"^^xsd:string .
```

n-ary Relationships

- Cooking with RDF:
  "For the preparation of Chutney, we need the following: 1 lb green mango, 1 tsp. Cayenne pepper, ..."

dish	ingredient	amount
chutney	green mango	1 lb
chutney	cayenne pepper	1 tsp.

- solved by auxiliary nodes (may be blank)



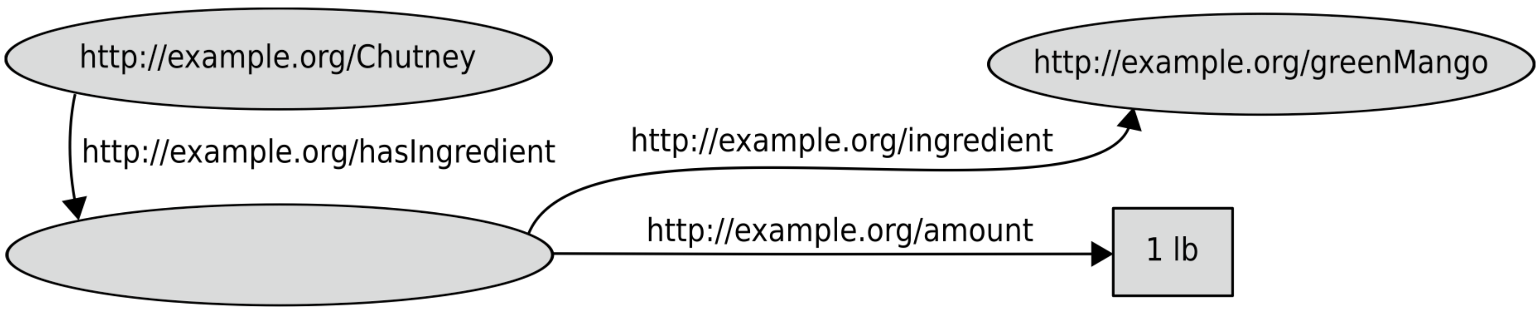
n-ary Relationships

- Turtle version 1:

```
@prefix ex: <http://example.org/> .
ex:Chutney ex:hasIngredient _:id1 .
_:id1 ex:ingredient ex:greenMango; ex:amount "1lb" .
```

- Turtle version 2:

```
@prefix ex: <http://example.org/> .
ex:Chutney ex:hasIngredient
      [ ex:ingredient ex:greenMango; ex:amount "1lb" ] .
```

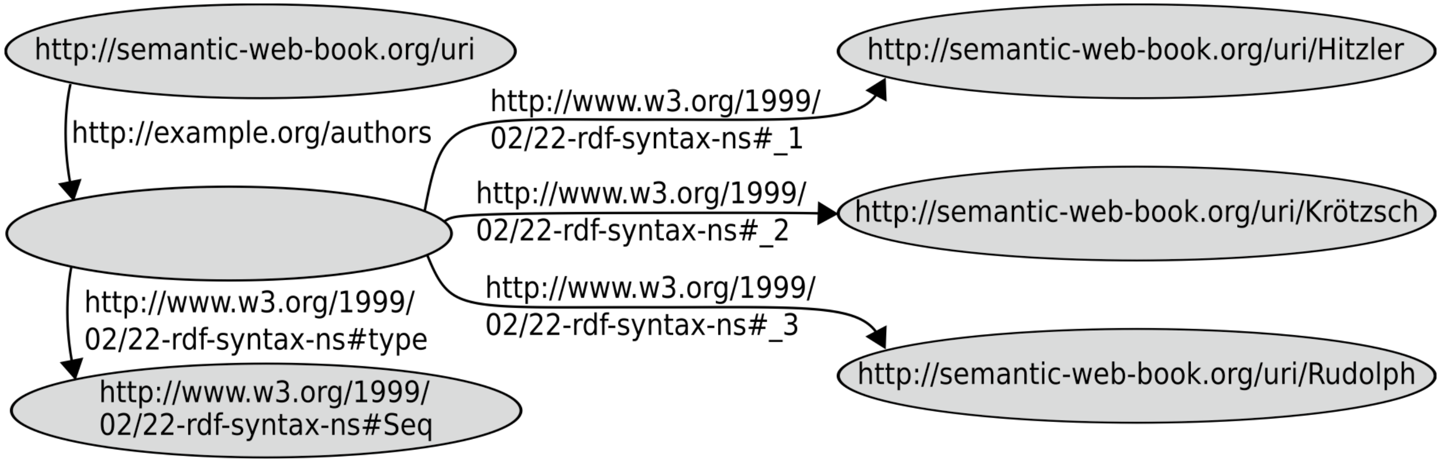


Special Datastructures in RDF

- open lists (containers)
- closed lists (collections)
- reified triples

Open Lists (Container)

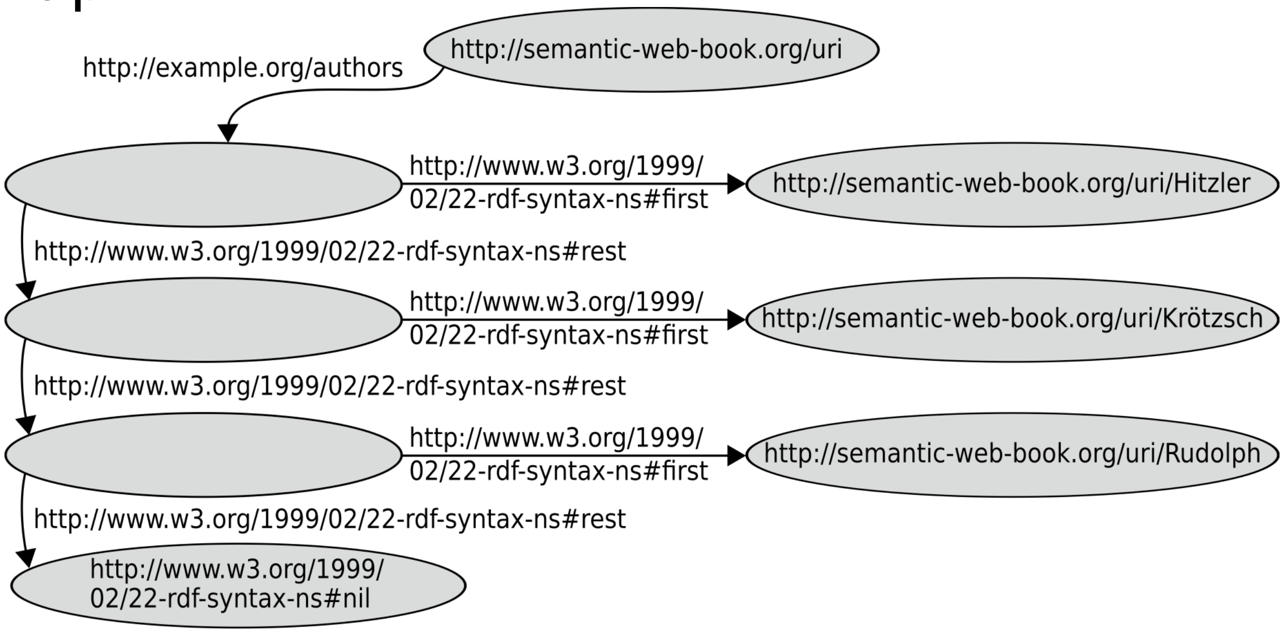
- Graph:



- by rdf:type we assign a list type to the root node
  - rdf:Seq – ordered liste (sequence)
  - rdf:Bag – unordered list
  - rdf:Alt – set of alternatives or choices

Closed Lists (Collections)

- Graph:

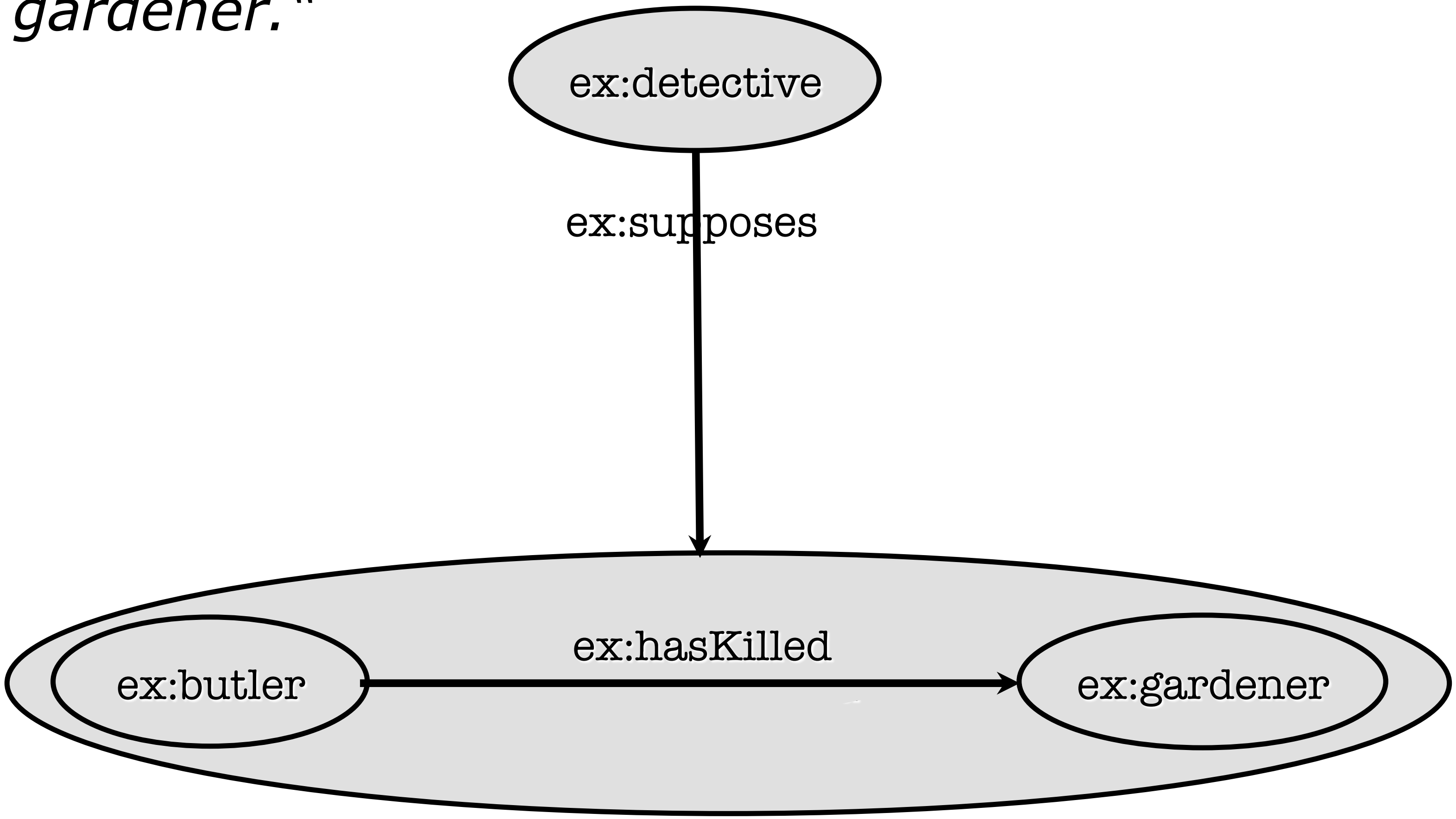


- Abbreviation for Turtle:

```
@prefix book: <http://semantic-web-book.org/> .
book:uri <http://example.org/authors>
   ( book:uri/Hitzler book:uri/Krötzsch book:uri/Rudolph ) .
```

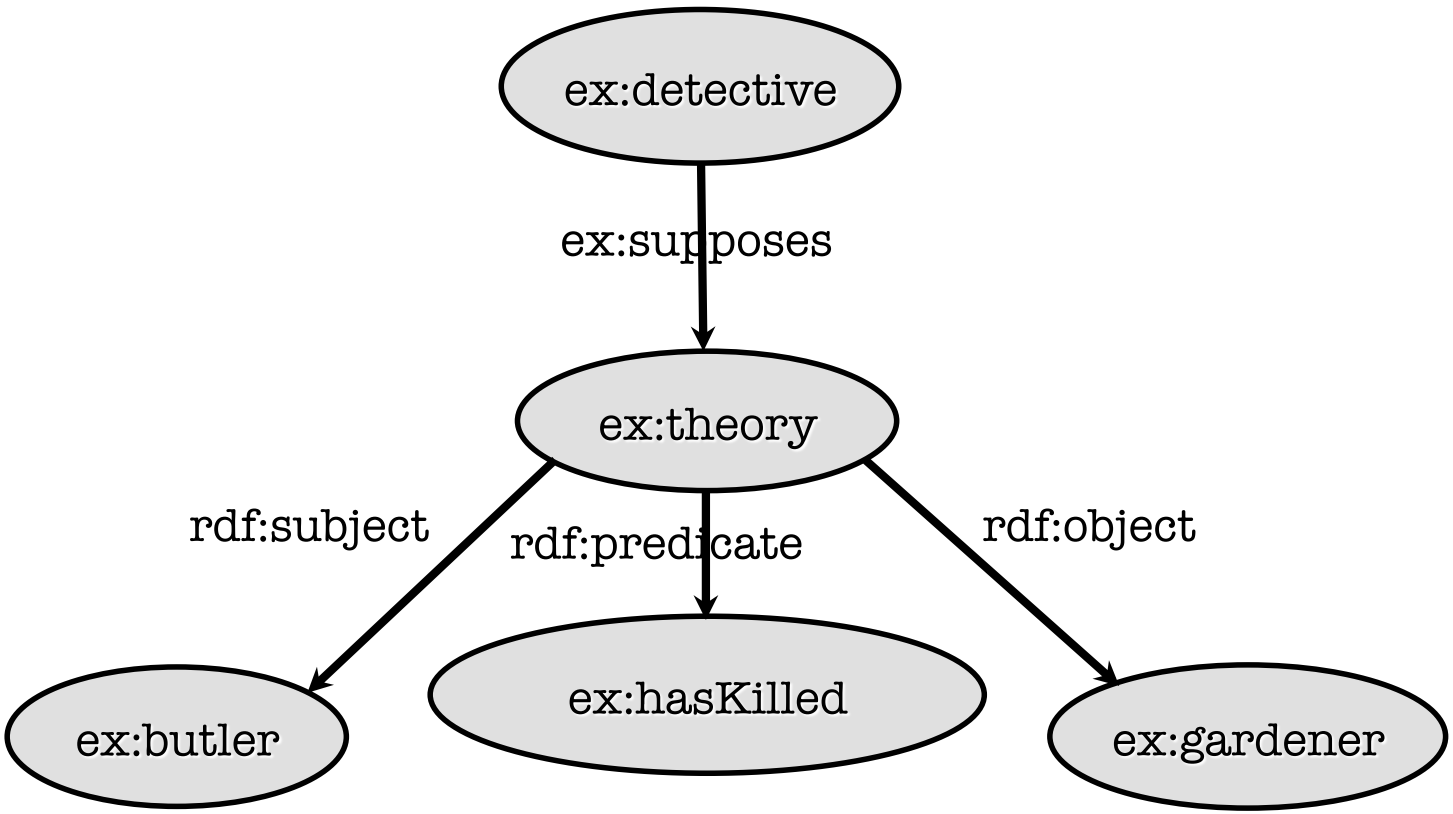
Reification

- How to model propositions about propositions such as:
  „The Detective supposes that the butler killed the gardener.“



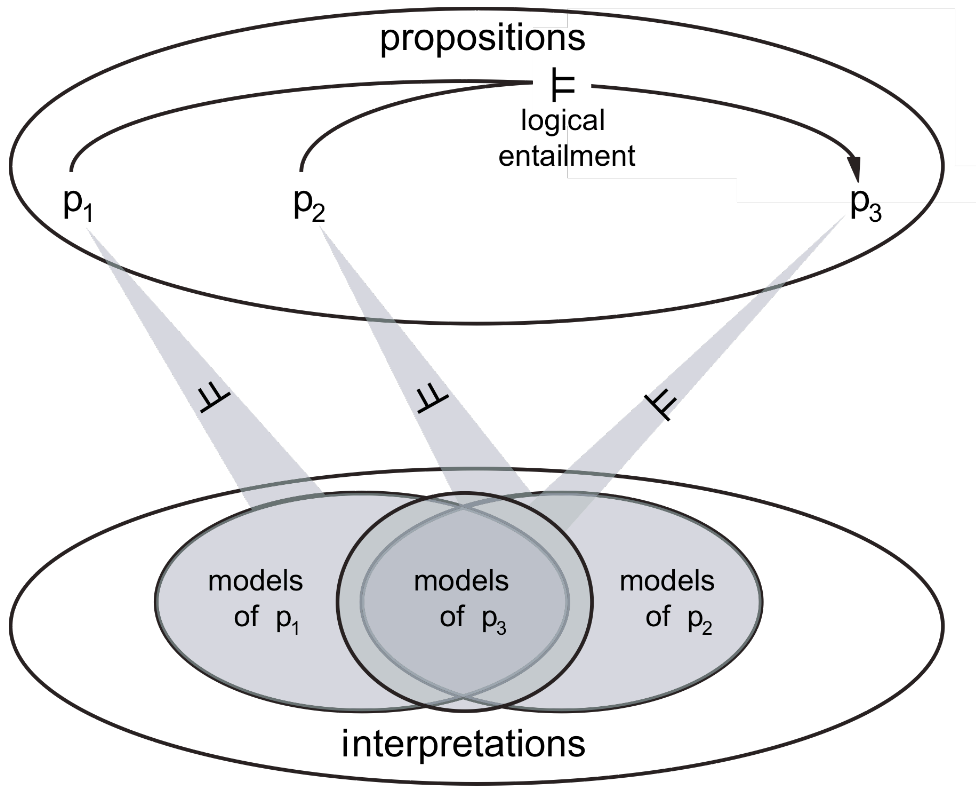
Reification

- Solution: auxiliary node for nested proposition



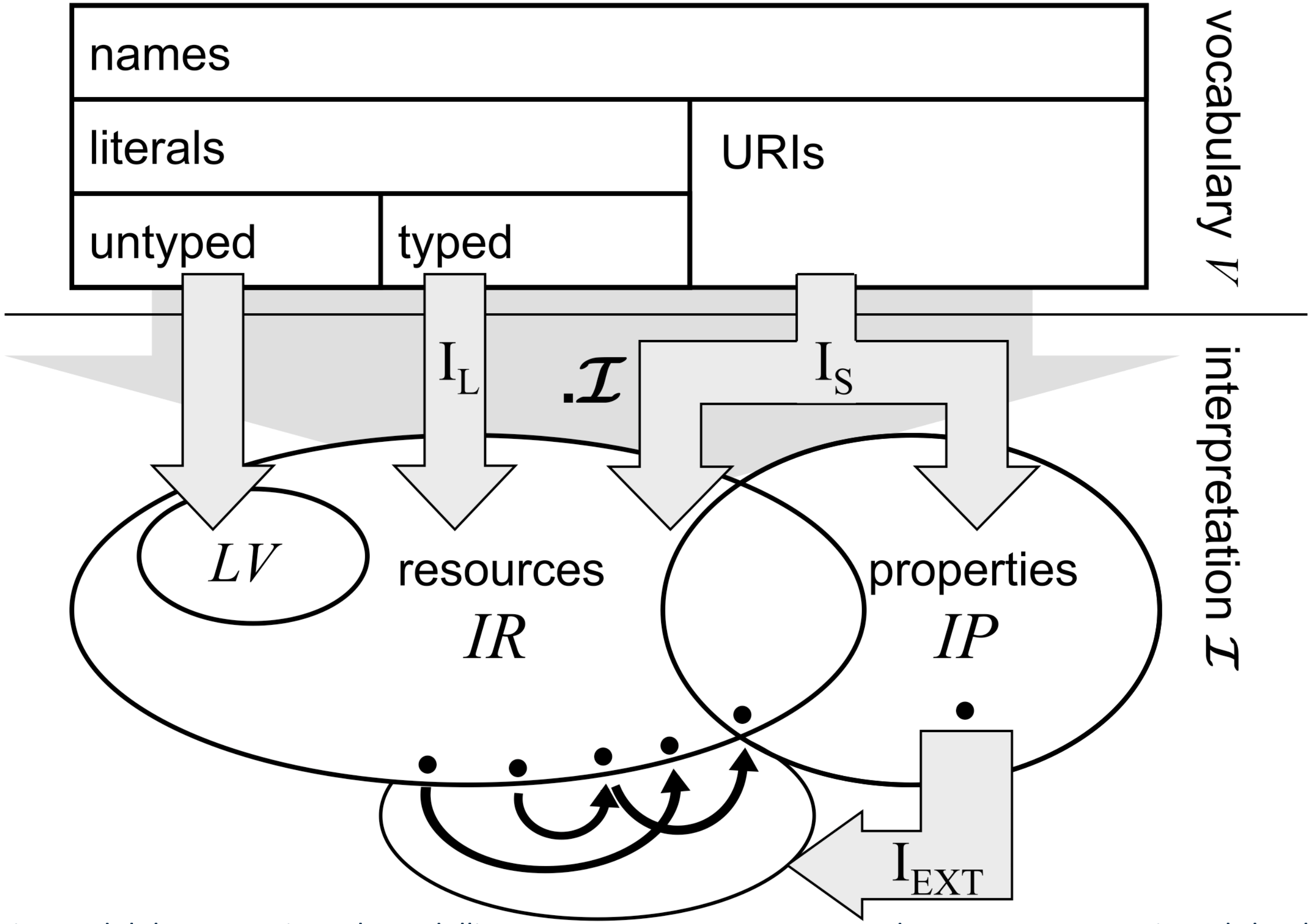
Simple Semantics

- RDF is focused on information exchange and interoperability
- answers of RDF tools to entailment queries should coincide
- therefore, formal semantics needed
- defined in a model-theoretic way, i.e. we start by defining interpretations



Simple Semantics

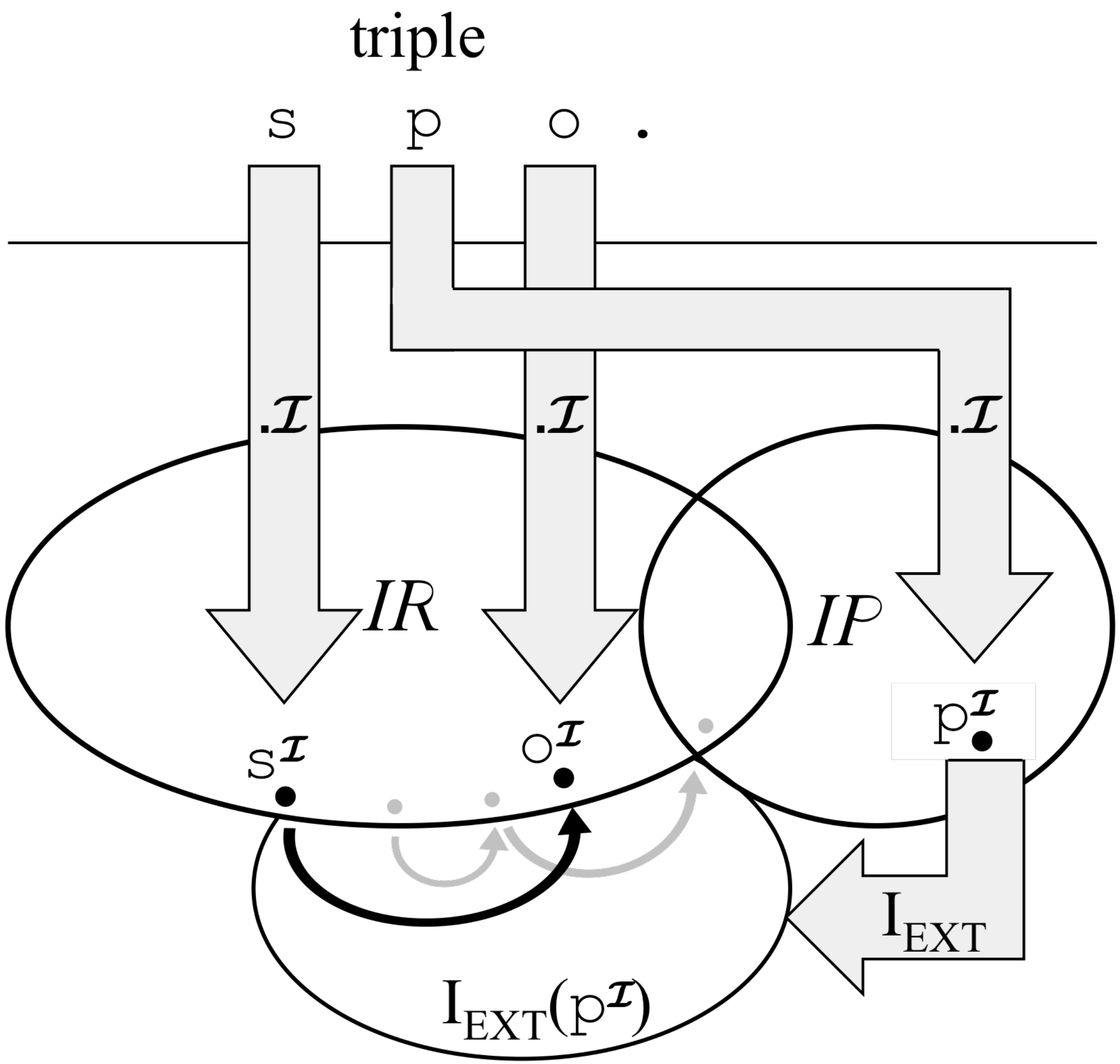
- Interpretations in RDF:



Simple Semantics

- when is a triple valid in an interpretation?

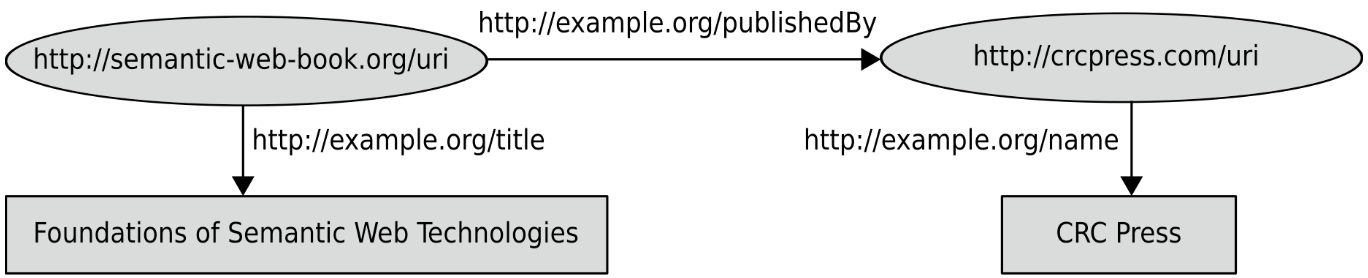
- a graph is valid, if all its triples are
- this settles the case for „grounded" graphs
- graph with blank nodes is valid if they can be mapped to elements such that the condition on the right is satisfied



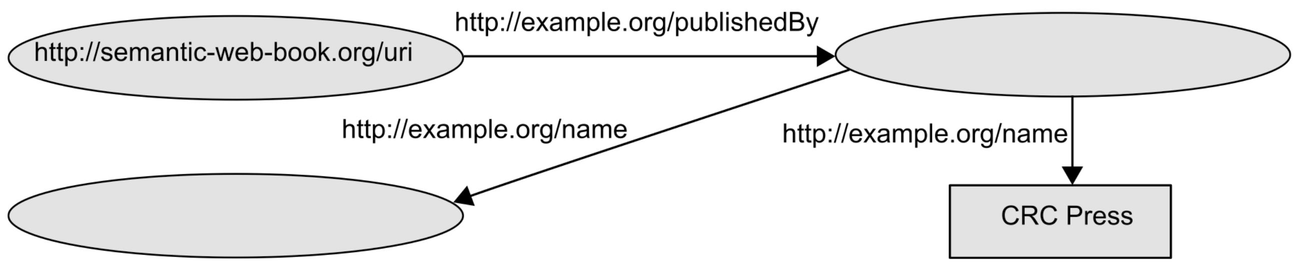
Simple Entailment

- this model theory defines simple entailment
- this is essentially graph matching with bnodes being wildcards (more precisely: graph homomorphism)

Example: the graph

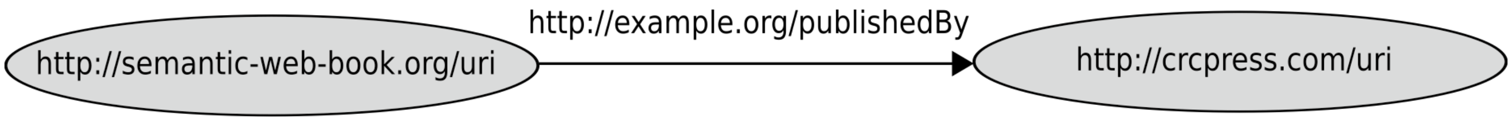


simply entails the graph



Schema Knowledge with RDF(S)

- RDF allows for specification of factual data



- = propositions about single resources (individuals) and their relationships
- desirable: propositions about generic groups of individuals, such as the class of publishers, of organizations, or of persons
- in database terminology: *schema knowledge*
- RDF Schema (RDFS): part of the RDF W3C recommendation

Classes and Instances

```
book:uri  rdf:type  ex:Textbook .
```

- characterizes the specific book as an instance of the (self-defined) class of textbooks

- class-membership not exclusive:

```
book:uri  rdf:type  ex:Enjoyable .
```

- URIs can be typed as class-identifiers:

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

Subclasses

- we want to express that every textbook is a book, e.g., that every instance of the class ex:Textbook is “automatically” an instance of the class ex:Book
- realized by rdfs:subClassOf property:

  ex:Textbook rdfs:subClassOf ex:Book .

- rdfs:subClassOf is defined to be transitive and reflexive
- rule of thumb:

rdf:type	means	$\in$
rdfs:subClassOf	means	$\subseteq$

Properties

- technical term for Relations, Correspondencies
- Property names usually occur in predicate position in factoid RDF triples
- characterize, how two resources are related
- mathematically: set of pairs:
  married_with = {(Adam,Eva),(Brad,Angelina),...}
- URI can be marked as property name by typing it accordingly:

```
ex:publishedBy  rdf:type  rdf:Property  .
```

Subproperties

- in analogy to subclass relationships
- representation in RDFS via rdfs:subPropertyOf e.g.:

  ex:happilyMarriedWith rdf:subPropertyOf rdf:marriedWith .

- then, given

  ex:Markus ex:happilyMarriedWith ex:Anja .

  we can deduce

  ex:Markus ex:marriedWith ex:Anja .

Property Restrictions

- properties may give hints what types the linked resources have, e.g. we know that ex:publishedBy connects publications with publishers

- i.e., for all URIs a, b where we know

  a ex:publishedBy b .

  we want to automatically follow:

  a rdf:type ex:Publication .
  b rdf:type ex:Publisher .

- this generic correspondency can be encoded in RDFS:

  ex:publishedBy rdfs:domain ex:Publication .
  ex:publishedBy rdfs:range ex:Publisher .

Property Restrictions

- with property restrictions, semantic interdependencies between properties and classes can be specified
- Caution: property restrictions are interpreted globally and conjunctively, e.g.

  ```
  ex:authorOf  rdfs:range  ex:Cookbook  .
  ex:authorOf  rdfs:range  ex:Storybook  .
  ```

  means: everything which is authored by somebody is both a cookbook and a storybook
- thus: always use most generic classes for domain/range statements

Additional Information

- used to add human-readable information (comments or names)
- for compatibility reasons graph-based representation recommended; set of properties for that purpose:
  - rdfs:label assigns an alternative name (encoded as literal) to an arbitrary ressource
  - rdfs:comment assigns a more comprehensive comment (also literal)
  - rdfs:seeAlso, rdfs:definedBy refer to resources (URIs!) containing further information about the subject resource

RDFS Entailment

- RDFS interpretations take care of RDF(S)-specific vocabulary by imposing additional conditions on simple interpretations:
  - all URIs and bnodes are of type rdf:Resource
  - triple predicates are of type rdf:Property
  - all well-typed and untyped literals are of type rdf:Literal
  - types of triple subjects/objects correspond to rdfs:domain/rdfs:range statements
  - rdfs:subClassOf and rdfs:subPropertyOf are interpreted reflexive and transitive and "inheriting"
  - well-formed XML-Literals are mapped into LV, ill-formed ones go somewhere else
  - ...and many more

RDFS Entailment – Automation

- RDFS entailment can be decided via rule-like deduction calculus (NP-complete)

$$\frac{}{u\ a\ x}\ \text{rdfsax}$$

$$\frac{u\ a\ \_{:}n\ .}{u\ a\ l\ .}\ \text{gl}$$

$$\frac{u\ a\ l\ .}{\_{:}n\ \texttt{rdf:type rdfs:Literal}\ .}\ \text{rdfs1}$$

$$\frac{a\ \texttt{rdfs:domain}\ x\ . \qquad u\ a\ y\ .}{u\ \texttt{rdf:type}\ x\ .}\ \text{rdfs2}$$

$$\frac{a\ \texttt{rdfs:range}\ x\ . \qquad u\ a\ v\ .}{v\ \texttt{rdf:type}\ x\ .}\ \text{rdfs3}$$

$$\frac{u\ a\ x\ .}{u\ \texttt{rdf:type rdfs:Resource}\ .}\ \text{rdfs4a}$$

$$\frac{u\ a\ v\ .}{v\ \texttt{rdf:type rdfs:Resource}\ .}\ \text{rdfs4b}$$

$$\frac{u\ \texttt{rdfs:subPropertyOf}\ v\ . \qquad v\ \texttt{rdfs:subPropertyOf}\ x\ .}{u\ \texttt{rdfs:subPropertyOf}\ x\ .}\ \text{rdfs5}$$

$$\frac{u\ \texttt{rdf:type rdf:Property}\ .}{u\ \texttt{rdfs:subPropertyOf}\ u\ .}\ \text{rdfs6}$$

$$\frac{a\ \texttt{rdfs:subPropertyOf}\ b\ . \qquad u\ a\ y\ .}{u\ b\ y\ .}\ \text{rdfs7}$$

$$\frac{u\ \texttt{rdf:type rdfs:Class}\ .}{u\ \texttt{rdfs:subClassOf rdfs:Resource}\ .}\ \text{rdfs8}$$

$$\frac{u\ \texttt{rdfs:subClassOf}\ x\ . \qquad v\ \texttt{rdf:type}\ u\ .}{v\ \texttt{rdf:type}\ x\ .}\ \text{rdfs9}$$

$$\frac{u\ \texttt{rdf:type rdfs:Class}\ .}{u\ \texttt{rdfs:subClassOf}\ u\ .}\ \text{rdfs10}$$

$$\frac{u\ \texttt{rdfs:subClassOf}\ v\ . \qquad v\ \texttt{rdfs:subClassOf}\ x\ .}{u\ \texttt{rdfs:subClassOf}\ x\ .}\ \text{rdfs11}$$

$$\frac{u\ \texttt{rdf:type rdfs:ContainerMembershipProperty}\ .}{u\ \texttt{rdfs:subPropertyOf rdfs:member}\ .}\ \text{rdfs12}$$

$$\frac{u\ \texttt{rdf:type rdfs:Datatype}\ .}{u\ \texttt{rdfs:subClassOf rdfs:Literal}\ .}\ \text{rdfs13}$$

Semantics of RDFS via Translation into FOL

- other option for defining RDF(S) semantics: embedding into first order logic
- 2 Problems:
  - FOL doesn‘t provide literals/datatypes
    - can be tackled by „built-in“ predicates
  - straight forward translation `s p o .` ➔ `p(s,o)` does not work, as `p` might also occur in subject or object position
    - solved by alternative translation with one ternary predicate: `s p o .` ➔ `triple(s,p,o)`

Semantics of RDFS via Translation into FOL

- RDF graph is translated into FOL theory by introducing statement triple(s,p,o) for every triple `s p o .`
- for every blank node, one distinct variable is used (whereas URIs and literals are treated as constants)
- the final translation is obtained by conjunctively combining all the obtained statements and then existentially quantifying over all variables

Semantics of RDFS via Translation into FOL

- RDFS semantics can then be implemented by axiomatising the deduction calculus:

rdfs2:
$$\forall x.\forall y.\forall u.\forall v.\mathtt{triple}(x,\mathtt{rdfs:domain},y) \wedge \mathtt{triple}(u,x,v) \rightarrow \mathtt{triple}(u,\mathtt{rdf:type},y)$$

rdfs3:
$$\forall x.\forall y.\forall u.\forall v.\mathtt{triple}(x,\mathtt{rdfs:range},y) \wedge \mathtt{triple}(u,x,v) \rightarrow \mathtt{triple}(v,\mathtt{rdf:type},y)$$

rdfs4a, *rdfs4b*:
$$\forall x.\mathtt{triple}(x,\mathtt{rdf:type},\mathtt{rdfs:Resource})$$

rdfs5:
$$\forall x.\forall y.\forall z.\mathtt{triple}(x,\mathtt{rdfs:subPropertyOf},y) \wedge \mathtt{triple}(y,\mathtt{rdfs:subPropertyOf},z) \rightarrow \mathtt{triple}(x,\mathtt{rdfs:subPropertyOf},z)$$

rdfs6:
$$\forall x.\mathtt{triple}(x,\mathtt{rdf:type},\mathtt{rdf:Property}) \rightarrow \mathtt{triple}(x,\mathtt{rdfs:subPropertyOf},x)$$

rdfs7:
$$\forall x.\forall y.\forall u.\forall v.\mathtt{triple}(x,\mathtt{rdfs:subPropertyOf},y) \wedge \mathtt{triple}(u,x,v) \rightarrow \mathtt{triple}(u,y,v)$$

rdfs8:
$$\forall x.\mathtt{triple}(x,\mathtt{rdf:type},\mathtt{rdf:Class}) \rightarrow \mathtt{triple}(x,\mathtt{rdfs:subClassOf},\mathtt{rdfs:Resource})$$

rdfs9:
$$\forall x.\forall y.\forall z.\mathtt{triple}(x,\mathtt{rdfs:subClassOf},y) \wedge \mathtt{triple}(z,\mathtt{rdf:type},x) \rightarrow \mathtt{triple}(z,\mathtt{rdf:type},y)$$

rdfs10:
$$\forall x.\mathtt{triple}(x,\mathtt{rdf:type},\mathtt{rdf:Class}) \rightarrow \mathtt{triple}(x,\mathtt{rdfs:subClassOf},x)$$

rdfs11:
$$\forall x.\forall y.\forall z.\mathtt{triple}(x,\mathtt{rdfs:subClassOf},y) \wedge \mathtt{triple}(y,\mathtt{rdfs:subClassOf},z) \rightarrow \mathtt{triple}(x,\mathtt{rdfs:subClassOf},z)$$

rdfs12:
$$\forall x.\mathtt{triple}(x,\mathtt{rdf:type},\mathtt{rdfs:ContainerMembershipProperty}) \rightarrow \mathtt{triple}(x,\mathtt{rdfs:subPropertyOf},\mathtt{rdfs:member})$$

rdfs13:
$$\forall x.\mathtt{triple}(x,\mathtt{rdf:type},\mathtt{rdfs:Datatype}) \rightarrow \mathtt{triple}(x,\mathtt{rdfs:subClassOf},\mathtt{rdfs:Literal})$$

Deployment of RDF

- today there is a variety of RDF tools
- software libraries for virtually every programming language
- freely available systems for handling large sets of RDF data (so-called RDF stores or triple stores)
- increasingly supported by commercial actors (e.g. Oracle)
- basis for several data formats: RSS 1.0, XMP (Adobe), SVG (vector graphics format)

RDF(S) as Ontology Language?

- RDFS language features allow for modeling certain semantic aspects of a domain of interest
- hence, RDFS can be seen as a *lightweight* ontology language

RDF(S) as Ontology Language?

Shortcomings of RDF(S):

- “weak” semantics:

ex:speaksWith	rdfs:domain	ex:Homo .
ex:Homo	rdfs:subClassOf	ex:Primates .

does not entail

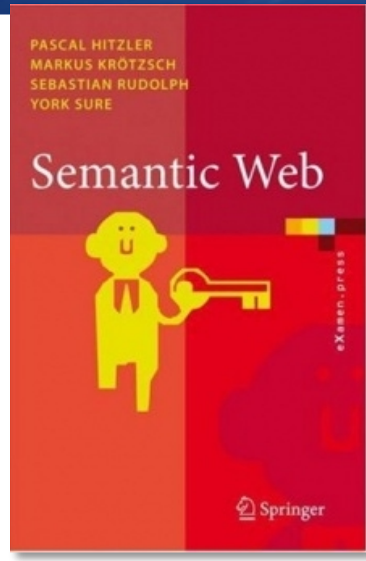
ex:speaksWith	rdfs:domain	ex:Primates .

- expressivity: no negative information can be specified, no cardinality, no disjunction…

References

- W3C Specification: http://www.w3.org/RDF/

- Pascal Hitzler, Markus Krötzsch,
  Sebastian Rudolph, York Sure,
  Semantic Web – Grundlagen.
  Springer, 2008.
  http://www.semantic-web-grundlagen.de/
  (In German.)



- Pascal Hitzler, Markus Krötzsch,
  Sebastian Rudolph,
  Foundations of Semantic Web Technologies.
  Chapman & Hall/CRC, 2009.
  http://www.semantic-web-book.org/wiki/FOST
  (Grab a flyer from us.)