ulm university universität uulm

# OWL
## The Web Ontology Language

## part II: beyond the basics

Pavel Klinov

# Next

Quickly about (decidable) reasoning

OWL and RDF

- OWL DL and OWL Full
- global restrictions

Modeling trickiness

- N-ary predicates
- meta-modeling
- OWA, UNA, and integrity constraints
- pain points: time and uncertainty

# Why reasoning?

Important for:

- quality assurance during ontology design
  - detects false entailments and non-entailments
  - esp. in case of multiple authors
- semantic integrations
  - errors during ontology re-use (remember imports)?
  - errors during ontology mapping and alignment
- deployment
  - any schema violations in my data?
  - is my data under-described?

# Reasoning

Typical reasoning problems given an ontology O:

- is O consistent?
- does O entail an axiom?
- classification: all class inclusions for named classes
- query answering
  - DL query (querying with arbitrary class expressions)

    ObjectIntersectionOf(:Person
    ObjectSomeValue(:hasParent :Peter))
  - conjunctive queries (tomorrow)

Reduces to consistency

(as you know from DLs)

# On decidability

OWL is based on 20+ years of DL research

- largely about finding practical decision procedures
- decidability means restrictions on the language
- do we care?

Well, sort of yes

- optimizations are typically easier to develop
- semi-decidability insufficient!
  - O entails $\alpha$ iff O $\cup$ {$\alpha$} is inconsistent
  - if consistency is semi-decidable, entailment is not

# OWL and RDF

What does "*OWL is based on RDF*" mean?

- each OWL axiom maps to a set of RDF triples
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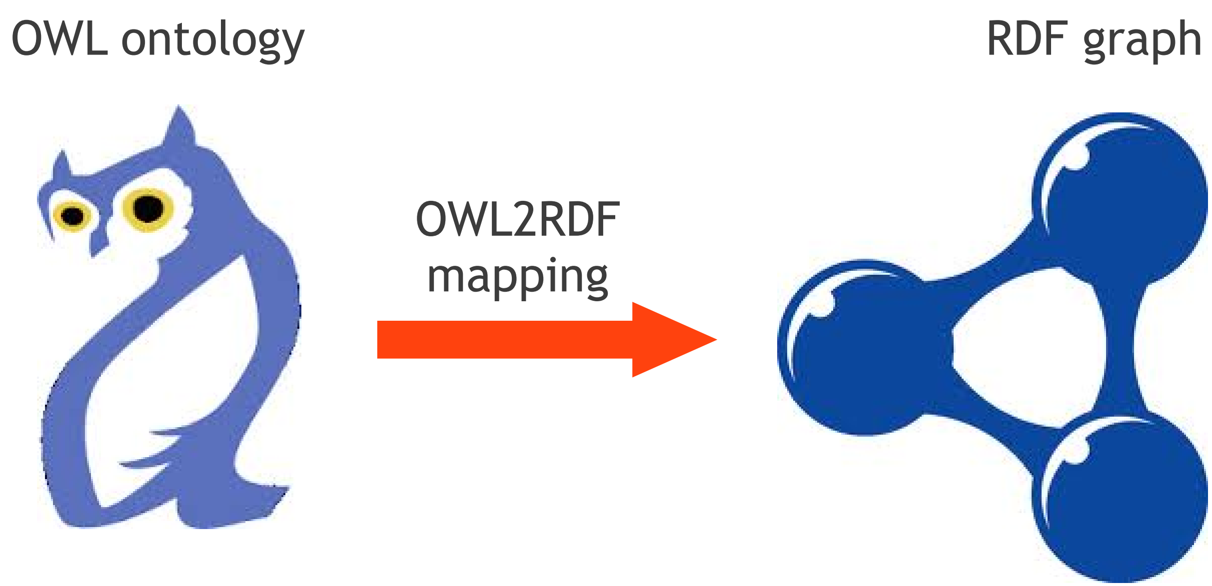

# The OWL to RDF Mapping

Entities are mapped to RDF resources

Data values become literals

Expressions and axioms are mapped to sets of triples

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Class expression example:

- OWL: ObjectAllValuesFrom( :hasRelative :Griffins )
- RDF:

  _:x rdf:type owl:Restriction

  _:x owl:onProperty :hasRelative

  _:x owl:allValuesFrom :Griffins

# What about semantics?

RDF(S) has its own model-theoretic semantics

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RDF graph


Interpretation

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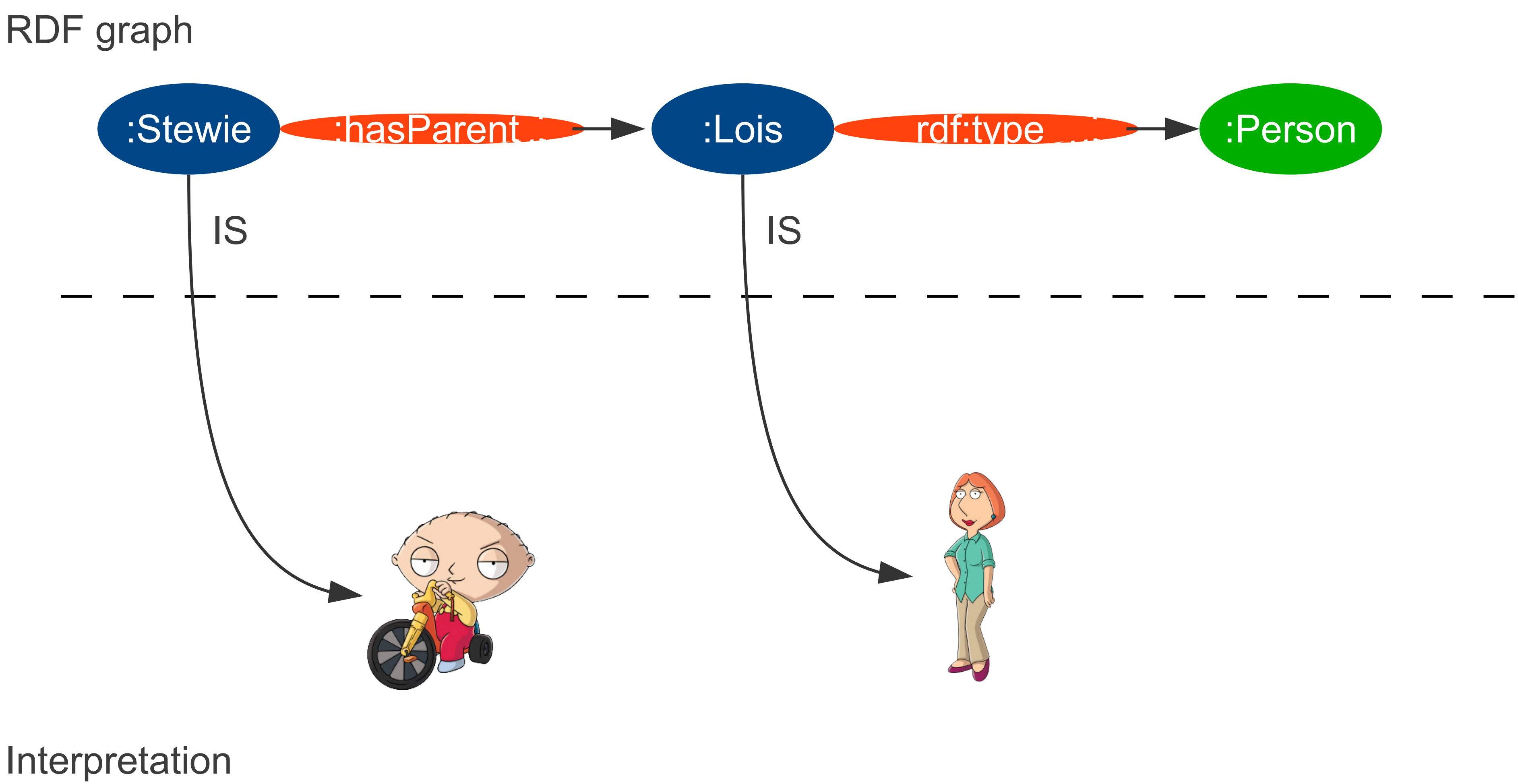

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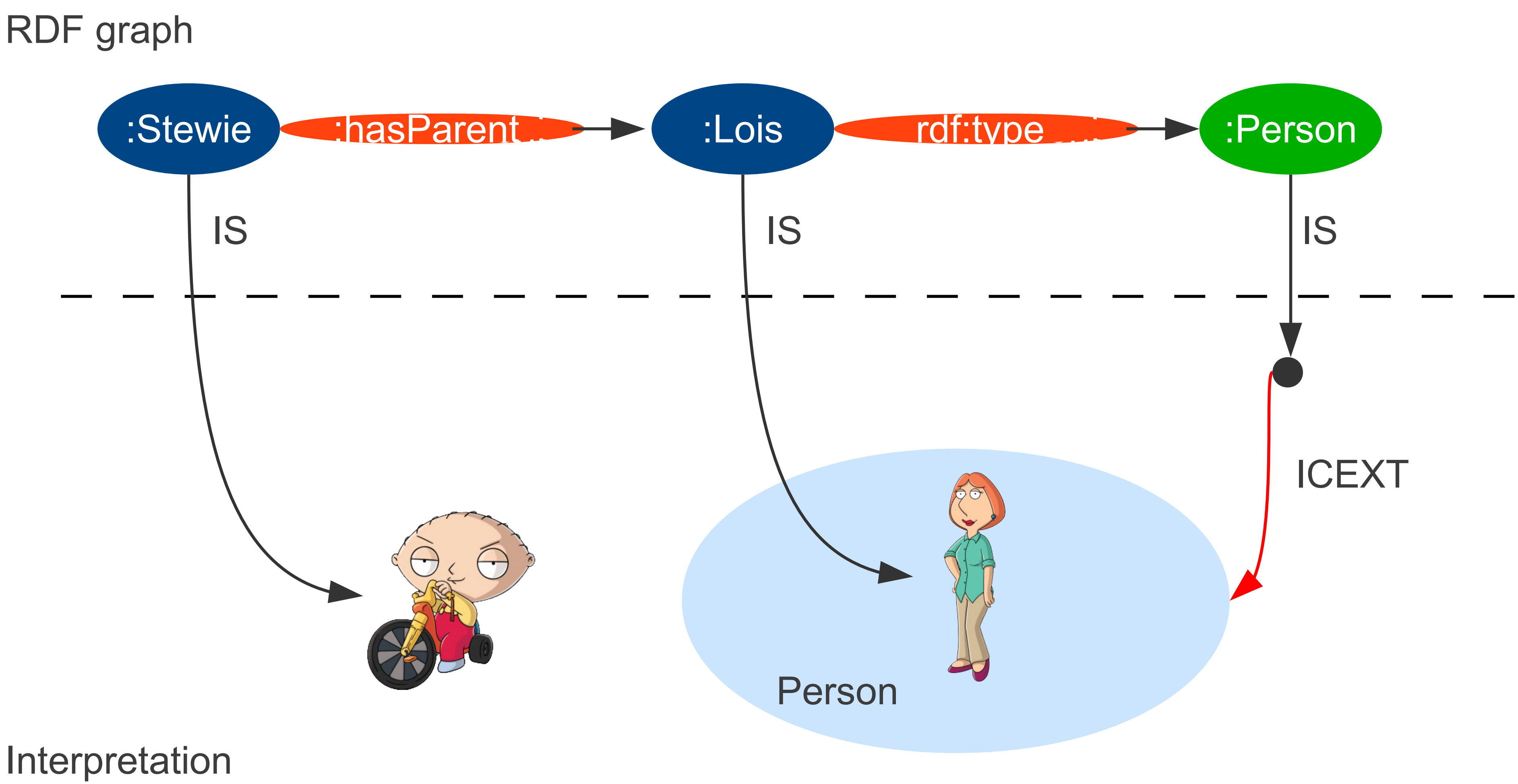

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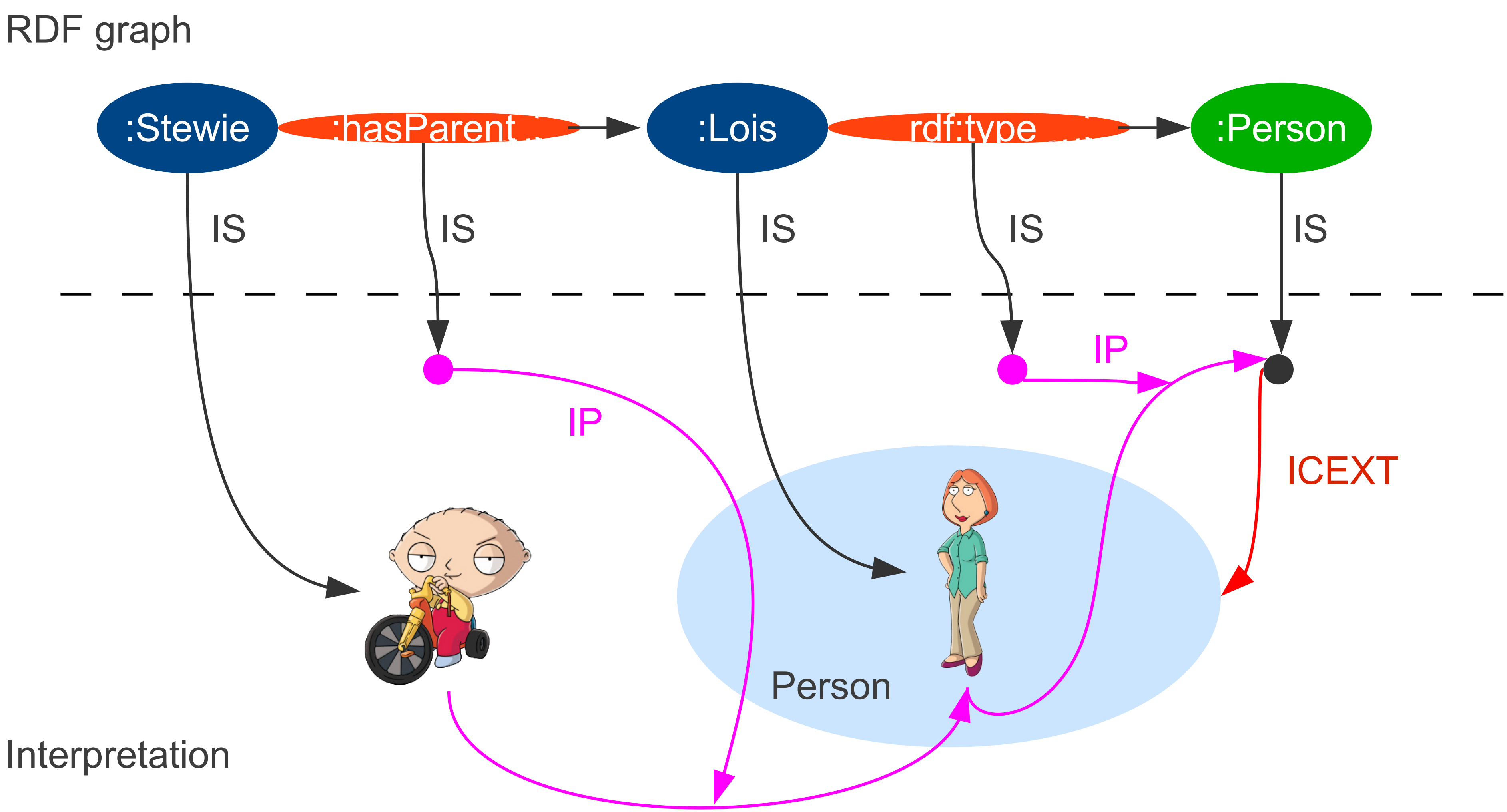

# Extra semantic conditions

For RDFS resources:

(c1, c2) $\in$ IEXT(IS(rdfs:subClassOf)), then

c1, c2 are classes, ICEXT(c1) $\subseteq$ ICEXT(c2)

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Similar for all OWL resources

- (z, c) ∈ IEXT(IS(owl:someValuesFrom)) and (z, p) ∈ IEXT(IS(owl:onProperty)), then ICEXT(z) = {x | ∃ y : (x,y) ∈ IEXT(p) and y ∈ ICEXT(c)} essentially encodes "$z \sqsubseteq \exists p.c$"

# Semantic correspondence

Ontology O can be interpreted in two ways:

- directly, via the DL model theory
- indirectly, as an RDF graph via the RDF model theory

Natural question: are the semantics equivalent?

# Semantic correspondence

Ontology O can be interpreted in two ways:

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Natural question: are the semantics equivalent?

- by means of entailment
- well, mostly yes: *the OWL 2 correspondence theorem*

  let G1 and G2 be RDF graphs s.t.

  F(G1) and F(G2) are corresponding ontologies in FS*

  F(G1) entails F(G2) under the DL semantics, then

  G1 entails G2 under the RDF semantics

  * which meet the OWL 2 DL global restrictions

# OWL 2 DL and OWL 2 Full

So every OWL ontology maps to an RDF graph

What about the other way?

- is every RDF graph an OWL ontology?

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- not in the DL sense
  - can make statements about the standard vocabulary

    <rdf:type rdf:type rdf:type> is a valid RDF triple!
  - too expressive (not in a decidable fragment of FOL)

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    <rdf:type rdf:type rdf:type> is a valid RDF triple!
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The decidable fragment is called OWL 2 DL

What's beyond is OWL 2 Full – the dark side,
an undecidable, very expressive ontology language

# OWL 2 DL syntactic restrictions

Can't use terms from owl:, rdf: etc. as entities

SubObjectPropertyOf (rdf:type :typeOf)

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Restrictions on datatypes

- no datatype occurs on LHS of two or more definitions
- datatype definitions are acyclic

(all value spaces are exact, datatypes are unfoldable)

```
DatatypeDefinition( :TaxNumber
        DatatypeRestriction( xsd:string xsd:pattern "[0-9]{11}")
DatatypeDefinition( :AlternativeTaxNumber
        DatatypeRestriction( xsd:string xsd:pattern "[0-9]{3}-[0-9]{7}")
DatatypeDefinition( :ID
        DataUnionOf( :TaxNumber :AlternativeTaxNumber ) )
```

# Complex object properties

Property is complex if its assertions can be derived from other property assertions

- this includes owl:topObjectProperty
- properties on the RHS of a chain

Otherwise it is simple

- Examples

```
SubObjectPropertyOf(ObjectPropertyChain(
                    :hasParent :hasBrother) :hasUncle)
SubObjectPropertyOf(:hasUncle :hasRelative)
```

# Restrictions on complex properties

Complex properties can't occur in cardinality restrictions

- ObjectMinCardinality
- ObjectMaxCardinality
- ObjectExactCardinality
- ObjectHasSelf

What we can't say:

- ObjectMinCardinality(2 :hasRelative owl:Thing)
- TranstitiveObjectProperty(:loves)

  ObjectHasSelf(:loves)

# Restrictions on property hierarchies

Object property hierarchies must be regular

- let $\rightarrow^*$ be the reflexive-transitive closure on properties
- must exist strict linear order < on properties

  s.t. :p1 < :p2 means :p2 $\rightarrow^*$ :p1 doesn't hold

# Restrictions on property hierarchies

Object property hierarchies must be regular

- let → * be the reflexive-transitive closure on properties
- must exist strict linear order < on properties

  s.t. $:p_1 < :p_2$ means $:p_2 \rightarrow^* :p_1$ doesn't hold
- each SubObjectPropertyOf ( ObjectPropertyChain( $:p_1 \ldots :p_n$) :p) axiom meets the following
  - SubObjectPropertyOf(ObjectPropertyChain(:p :p) :p ), or
  - :p is owl:topObjectProperty, or
  - **$:p_i < :p$ for all i = 1 … n, or**
  - SubObjectPropertyOf(ObjectPropertyChain(:p $:p_1 \ldots :p_n$) :p), or
  - SubObjectPropertyOf(ObjectPropertyChain($:p_1 \ldots :p_n$ :p) :p)

# Regular and irregular hierarchies

SubObjectPropertyOf (

ObjectPropertyChain( :hasFather :hasBrother ) :hasUncle )

SubObjectPropertyOf (

ObjectPropertyChain( :hasUncle :hasWife ) :hasAuntInLaw )

:hasFather < :hasBrother < :hasUncle < :hasWife < :hasAuntInLaw

# Regular and irregular hierarchies

SubObjectPropertyOf ( ObjectPropertyChain

(:hasParent :hasSpouse :hasParent ) :hasGrandparent )

:hasParent < :hasSpouse < :hasGrandparent

# Regular and irregular hierarchies

SubObjectPropertyOf ( ObjectPropertyChain

(:hasFather :hasBrother ) :hasUncle )

SubObjectPropertyOf ( ObjectPropertyChain

( :hasChild :hasUncle ) :hasBrother )

no linear order between :hasUncle and :hasBrother

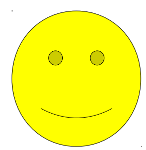
SubObjectPropertyOf ( ObjectPropertyChain (:p :s :r) :s)

(:s, :s) can't be in <

# How're you feeling?

The OWL 2 DL vs. OWL 2 Full is tricky

- the OWL API will check the profile!
- and point to where you violate it

The rest is easier 

- modeling issues
- where the Full stuff matters

# OWL can't represent everything

It can't represent what FOL can't (naturally) represent

- temporal knowledge
- various sorts of uncertainty
- higher-order knowledge

It has troubles with knowledge beyond the 2-var FOL

- n-ary relationships of sorts

# N-ary stuff is problematic

OWL (and RDF) are 2-variable logics

- schema restrictions and properties are binary

    ObjectExactCardinalityFrom(2 :hasParent :Person)

    ObjectAllValuesFrom(:hasChild :Person)

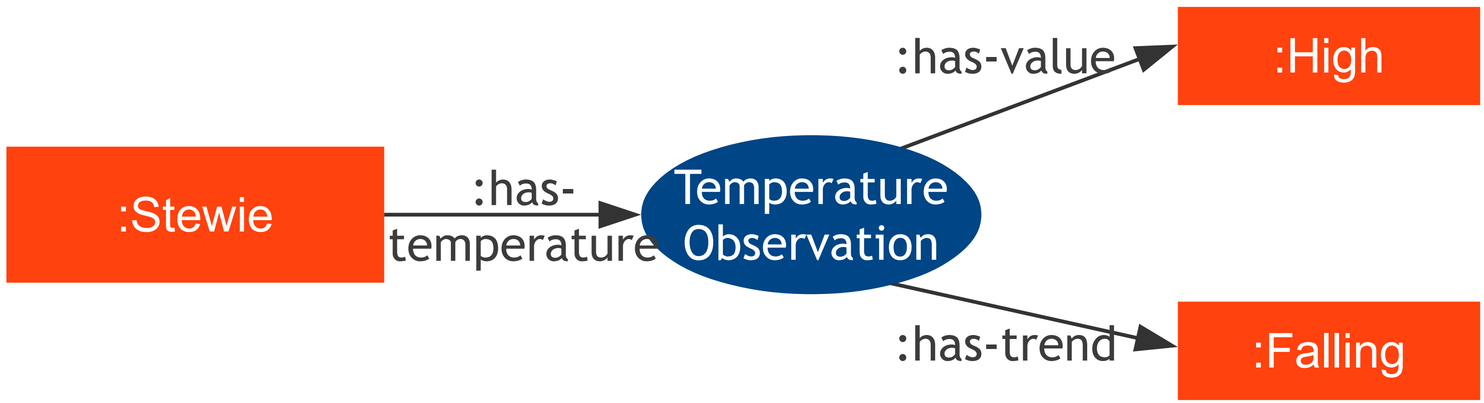
- assertions are binary

How do we say:

- Stewie has a high (but falling) temperature?
- Megan bought a book A from store B?
- Lois visited LAX, JFK, and BOS on a single trip?

# Workarounds

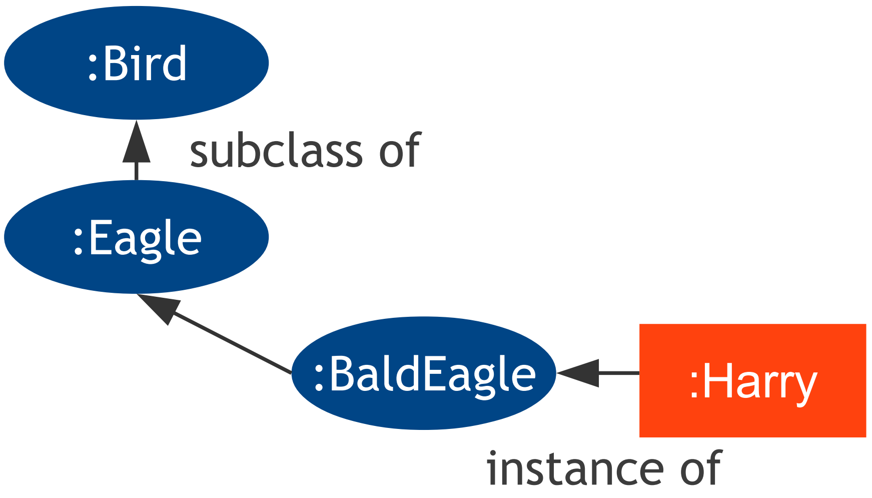
Via classes that work like reified properties




In OWL 2 property chains help

$$:\text{has-temperature} \circ :\text{has-trend} \sqsubseteq :\text{has-temperature-trend}$$

# Meta-modeling



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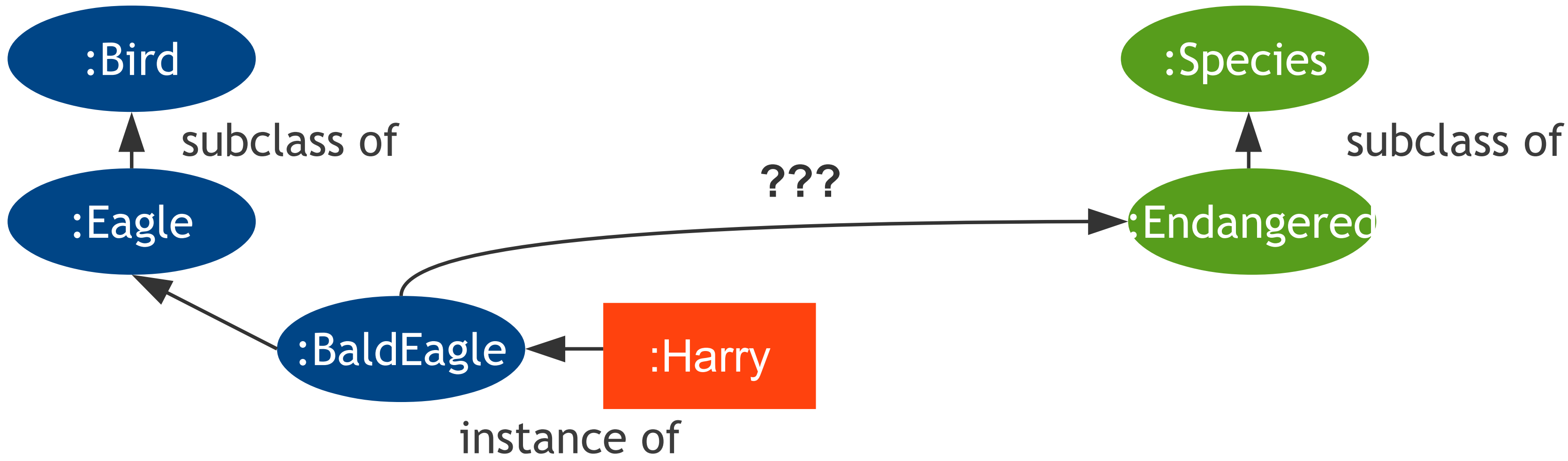


:BaldEagle subclass of :Endangered would imply :Harry is a :Species

:Species and :Endangered are meta-classes

# Meta-modeling in DL and Full

OWL 2 Full

- supports meta-modeling!

  ClassAssertion(:BaldEagle :EndangeredSpecies)

OWL 2 DL

- limited support of meta-modeling

In contrast to DL, OWL 2 Full:

i. can use the built-in vocabulary

ii. don't separate out classes, properties, and individuals

iii. has no decidability restrictions

# Can it work in OWL 2 DL?

OWL Full is trivially undecidable due to iii.

which isn't very useful for meta-modeling

Is OWL 2 DL with i. and ii. decidable?

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Is OWL 2 DL with i. and ii. decidable?

- bad news: no
- good news: it's due to i. while we really want ii.

  who wants ClassAssertion(owl:allValuesFrom :X)?!

Main question: how to allow ii. and still be first-order?

- semantic extensions (B. Motik, 2007)
- axiomatization (S. Rudolph and B. Glimm, 2010)

# Semantic extensions to OWL 2 DL

Contextual semantics (or punning with entities)

- each name :n treated as $:n_{class}$, $:n_{ind}$, $:n_{obj}$, $:n_{data}$ depending on syntactic occurrence
- simple: ClassAssertion(:BaldEagle :EndangeredSpecies)
- no interaction between $:BaldEagle_{class}$, $:BaldEagle_{ind}$

  → no useful entailments

How about something more in the OWL 2 Full spirit?

# Semantic extensions to OWL 2 DL

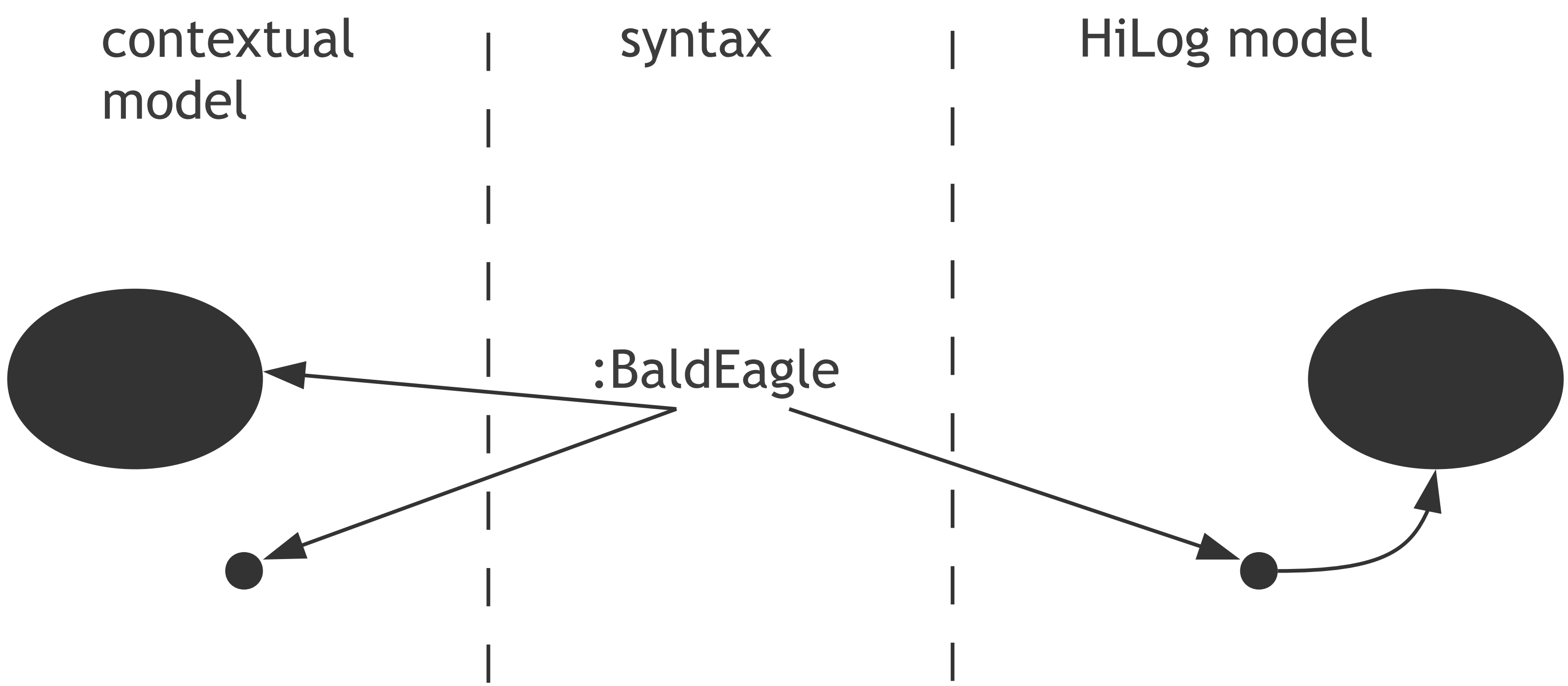
HiLog semantics

- Δ - the domain
- I – maps all entities to elements of Δ
- $C^I: \Delta \rightarrow 2^{\Delta}$ atomic class extension
- $R^I: \Delta \rightarrow 2^{\Delta \times \Delta}$

Each entity has its identity, a dedicated domain element which is then extended to interpret the entity

Can be encoded in FOL

# Contextual vs. HiLog



# Direct axiomatization in OWL 2 DL

Extend the vocabulary

- classes: :Inst, :Class
- properties: :type, :subClassOf, :Rinst
- individuals: $:o_C$ for each normal class C

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- classes: :Inst, :Class
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And restrict it

- DisjointClasses(:Inst :Class)
- ClassAssertion($o_C$ :C), ClassAssertion(:i :Inst) for each :i, :C
- EquivalentClasses(:C ObjectSomeValuesFrom(:type :C))
- ObjectPropertyDomain(:R :Inst) for each :R
  ObjectPropertyDomain(:R :Inst)
- etc.-etc.

# Direct encoding in OWL 2 DL

So we

- conceptualize the meta-layer
- make sure it doesn't interfere with ontology layer
- no unwanted entailments due to the extra stuff

(could be hidden behind a reasonable API/GUI)

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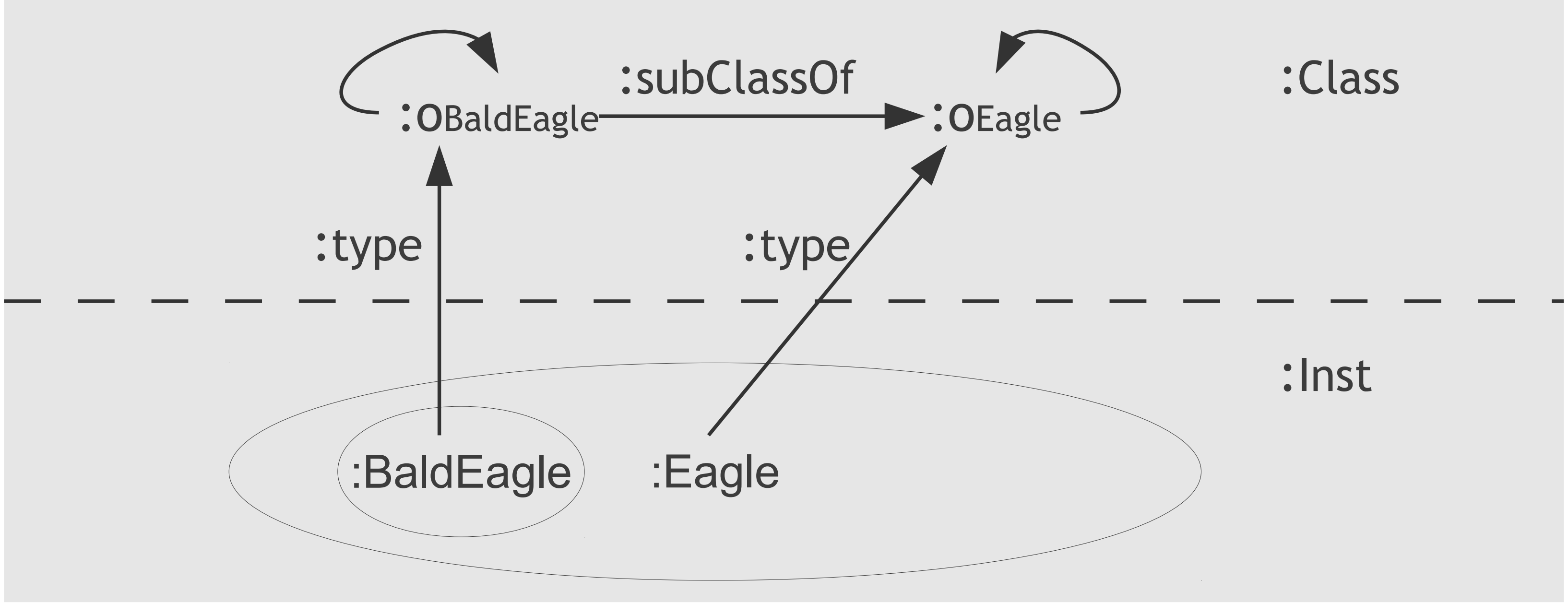

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Endangered → cannot be hunted, don't hunt Harry!

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HiLog semantics

- need language extensions:

  $\text{Endangered}(P) \land P(i) \rightarrow \text{CantHunt}(i)$
- entails cantHunt(:Harry)

# Meta-reasoning

Endangered → cannot be hunted, don't hunt Harry!

Contextual semantics: can't do logically

HiLog semantics

- need language extensions:

  Endangered(P) ∧ P(i) → CantHunt(i)

- entails cantHunt(:Harry)

Axiomatization

ObjectPropertyAssertion(:subClassOf :OBaldEagle :OEndangered)

SubClassOf(ObjectSomeValue(:type :OEndangered) :CantHunt)

entails ClassAssertion(:Harry :CantHunt)

# Meta-modeling in OWL 2 DL

Some limited support is available:

- annotations (:isEndangered could be semantic-free)
- punning (BaldEagle-as-class vs. BaldEagle-as-instance)

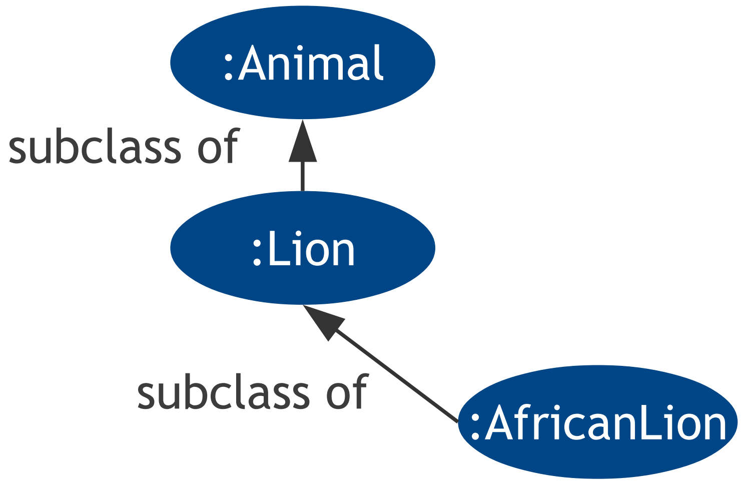
  but not for properties

What's often done:

- parallel hierarchy of meta-classes and extra-logical linking
- OWL Full

# Classes as property values

## Another example of meta-modeling



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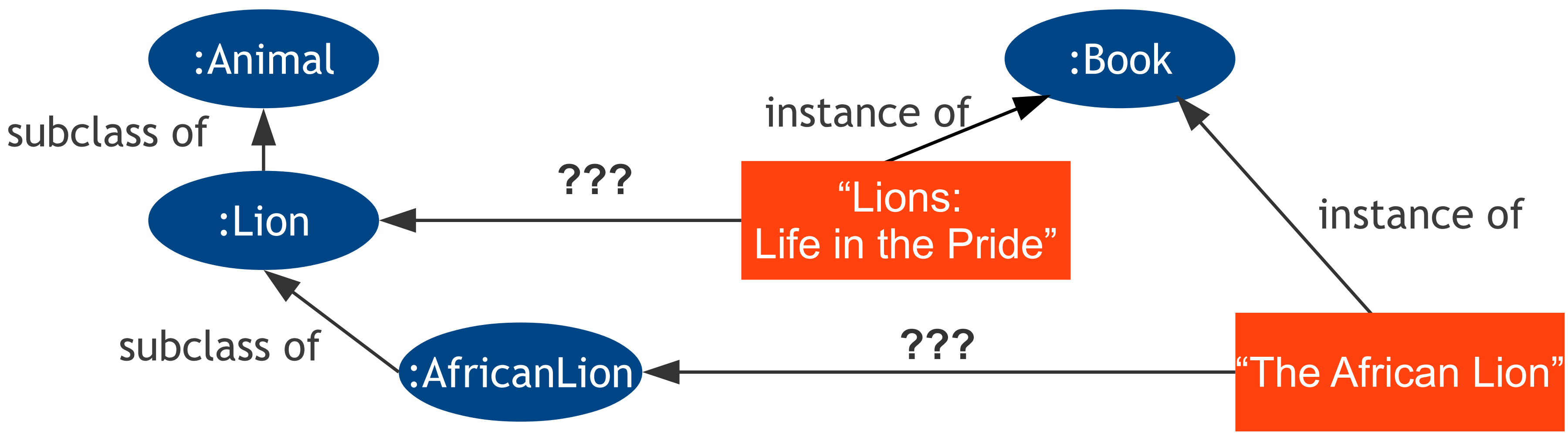
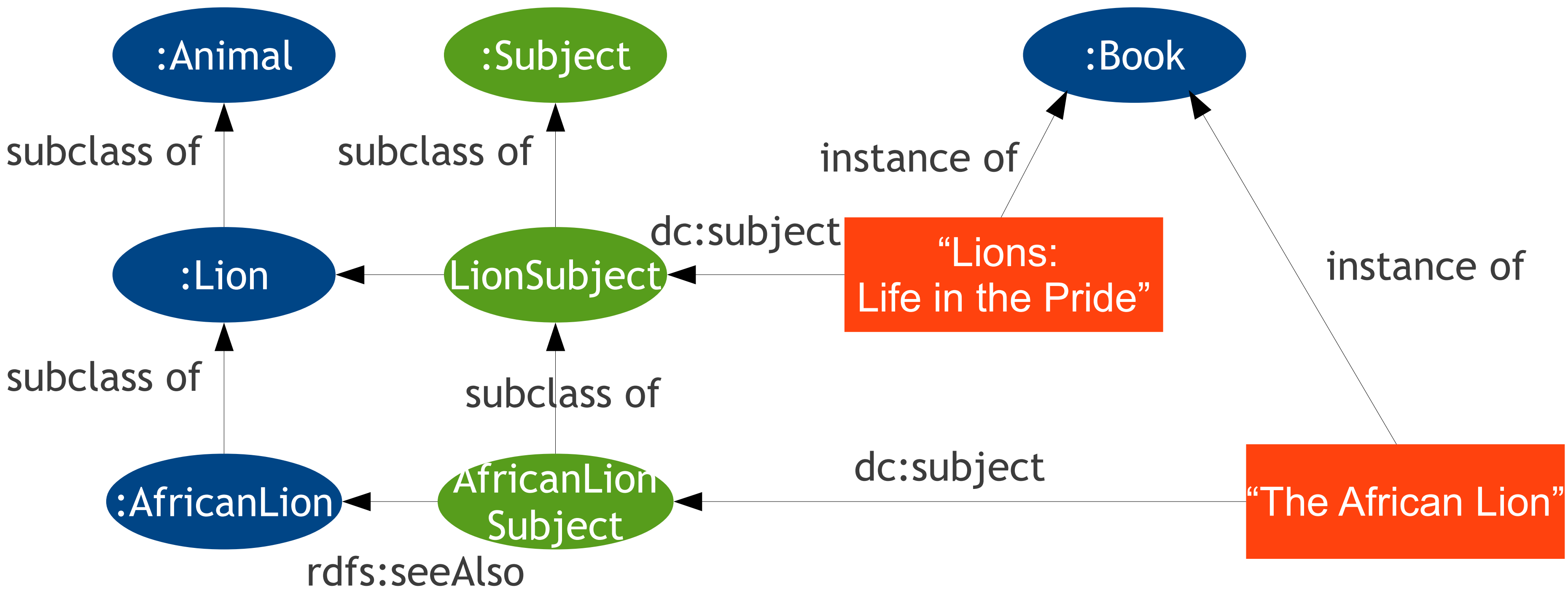



The books are not about some specific lions but about (African)Lion as a class

# Workaround: parallel hierarchy




Obvious maintenance overhead for keeping the hierarchies in sync

Or (you guessed it!) OWL Full

# Integrity constraints

Popular idea: OWL as a constraint language for RDF

- take a Linked Data dataset
- describe ICs as OWL axioms
- validate!

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DOES NOT WORK

# IC failure example 1

Schema

SubClassOf(:Person ObjectSomeValuesFrom(:hasParent :Person))

Data

ClassAssertion(:Stewie :Person)

Valid?

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- yes!
- but Stewie is inferred to have a parent

# IC failure example 1

## Schema

SubClassOf(:Person
ObjectSomeValuesFrom(:hasParent :Person))

## Data

ClassAssertion(:Stewie :Person)

## Problem

Open World Assumption

Stewie is not known to have a parent

but he must, otherwise it's inconsistent

# IC failure example 2

Schema

SubClassOf(:Person

ObjectMaxCardinality(1 :hasMother :Woman)

Data

ClassAssertion(:Stewie :Person)

ObjectPropertyAssertion(:hasMother :Stewie :Lois)

ObjectPropertyAssertion(:hasMother :Stewie :Peter)

Valid?

# IC failure example 2

Schema

SubClassOf(:Person

ObjectMaxCardinality(1 :hasMother :Woman)

Data

ClassAssertion(:Stewie :Person)

ObjectPropertyAssertion(:hasMother :Stewie :Lois)

ObjectPropertyAssertion(:hasMother :Stewie :Peter)

Valid?

- yes!
- but :Lois and :Peter are inferred to be identical

# IC failure example 2

Schema

- SubClassOf(:Person
- ObjectMaxCardinality(1 :hasMother :Woman)

Data

- ClassAssertion(:Stewie :Person)
- ObjectPropertyAssertion(:hasMother :Stewie :Lois)
- ObjectPropertyAssertion(:hasMother :Stewie :Peter)

Problem

- Lack of the Unique Name Assumption
- Lois and Peter aren't known to be different

# OWL and ICs: proposals

Rules with DL-queries and NAF

- DL[Person(x)] ∧ DL[hasParent(x,y)] → P(x,y)
- DL[Person(x)] ∧ NAF[P(x,y)] → ⊥

Minimal model interpretation

- constraints checked in all minimal models

  ClassAssertion(:Stewie :Person)

  ClassAssertion(:Stewie ObjectSomeValuesFrom(:hasParent :Person))

  } still valid!

# Integrity constraints as queries

Instead of (non-recursive) rules we can use SPARQL

- a query language for RDF
- which can express NAF as OPTIONAL/FILTER/!BOUND
- (NOT EXISTS in SPARQL 1.1)

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- which can express NAF as OPTIONAL/FILTER/!BOUND
- (NOT EXISTS in SPARQL 1.1)

Check that every named person has a named parent

```
ASK WHERE { ?x rdf:type :Person .
OPTIONAL { ?x :hasParent ?y .
           ?y rdf:type :Person . }
FILTER(!BOUND(?y))}
```

"yes" means a violation

# Integrity constraints as queries

Can be implemented by RDF databases

- keep axioms separately from data
- run queries as data changes

Syntax does not matter

- OWL axioms → queries (Stardog)
- SPIN, queries as RDF triples (AllegroGraph)
  spinrdf.org

# Time

OWL doesn't support temporal concepts:

- class of people who were employed before the crisis
- everyone will be eventually dead
- A was true, will be true, will be true after B... etc.

Available out-of-the-box? XSD datatypes

- xsd:dateTime, xsd:dateTimeStamp
- Facts are expressible:

  DataPropertyAssertion ( :startTime

  :MeetingA "2002-09-24-06:00"^^xsd:dateTime )

# Time: “solutions”

OWL Time (formerly DAML Time)

- ontology on top of the existing logical model

  SubClassOf(:Process

  ObjectSomeValuesFrom(:hasDuration time:Interval)

- may help standardize temporal vocabulary
- very limited temporal reasoning

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Various extensions based on temporal logics

Rule built-ins

Patient(?p) ∧ hasTreatment(?p, ?t) ∧ hasDrug(?t, DDI) ∧

temporal:hasValidTime(?t, ?tVT) ∧ temporal:before(?tVT, “1999”)

→ TrialEligible(?p)

# Uncertainty

Similar to Time: first-order logical model provides very limited means to capture uncertainty:

- disjunction
- Open World Assumption
  - information may be legitimately missing
- no Unique Name Assumption
  - captures canonical name uncertainty
  - New York and The Big Apple
  - different from name ambiguity!
    - New York as a city vs. New York as a state

# The sad state of affairs

At least 30 yrs of the “uncertainty in AI” research

- combinations of logic and probability
  - very-very-VERY hard (computationally and cognitively)
  - ClassAssertion(:Stewie :Infant 0.7)
- Bayesian and Markov models
  - computationally tractable
  - but propositional!
  - … or, again, computationally impractical
- statistical black-box models (Breast Cancer Risk Calc)

No reusable modeling of uncertainty in SemWeb

# To summarize

OWL 2 isn't a silver bullet

But

- it's helpful in certain, reasonably understood scenarios
  - terminology management
  - data integration
- it matures fast
  - tool support is getting better
  - people accumulate experience

So

- you may try it for your next project
- and tell us about your experience! e.g. at OWLED!

Questions!