Knowledge Representation and Semantic Technologies

Ontologies and OWL

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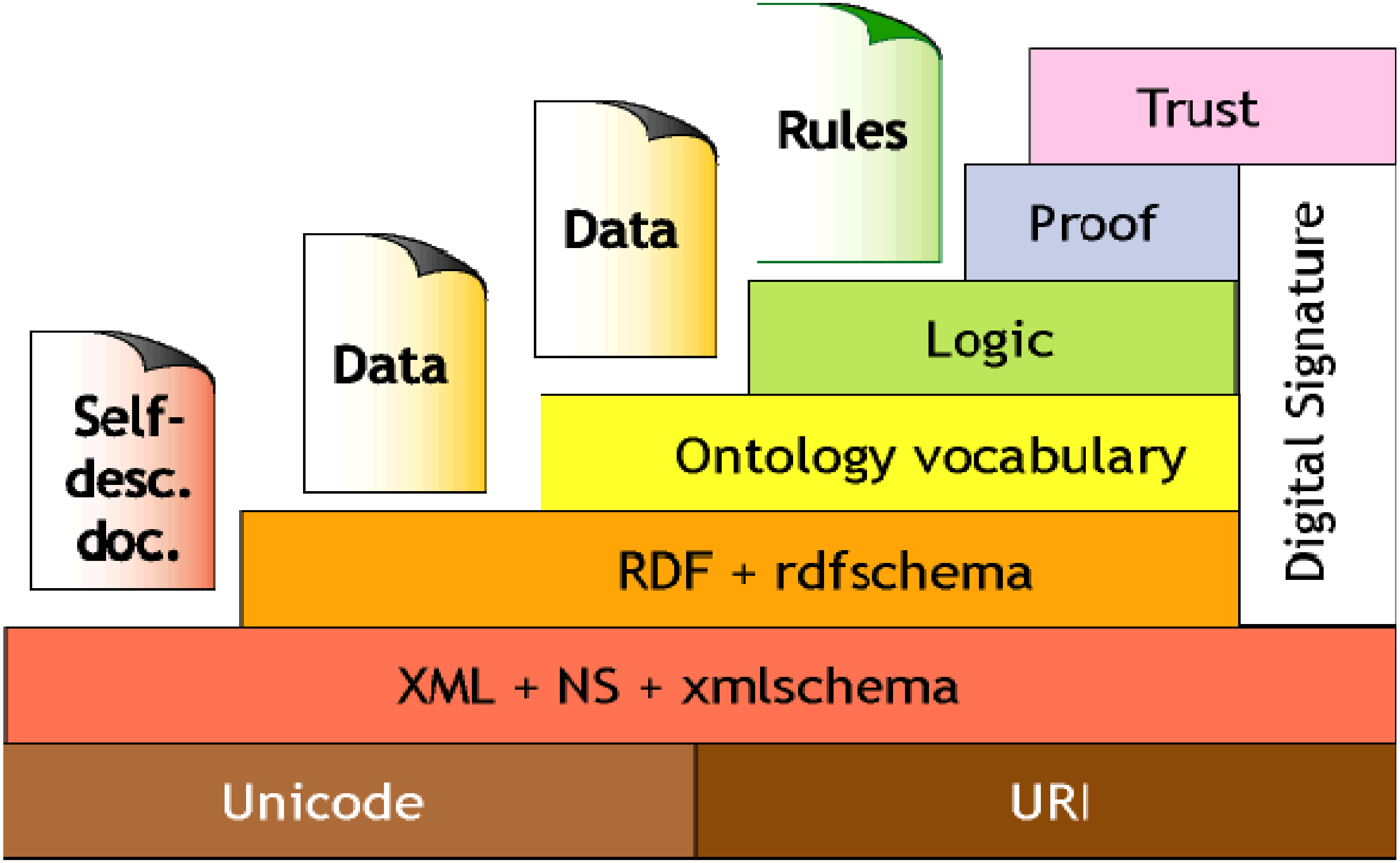
The Semantic Web Tower



Ontology in computer science

- ontology = shared conceptualization of a domain of interest (Gruber, 1993)
- shared vocabulary (set of terms)
  - ⇒ simple (shallow) ontology
- (complex) relationships between terms
  - ⇒ deep ontology
- AI view:
  - ontology = logical theory (knowledge base)
- DB view:
  - ontology = conceptual data model

Structure of an ontology

- Terms = names for important concepts in the domain
  - Elephant is a concept whose members are a kind of animal
  - Herbivore is a concept whose members are exactly those animals who eat only plants or parts of plants
  - Adult_Elephant is a concept whose members are exactly those elephants whose age is greater than 20 years
- Relationships between terms = background knowledge/constraints on the domain
  - Adult_Elephants weigh at least 2,000 kg
  - All Elephants are either African_Elephants or Indian_Elephants
  - No individual can be both a Herbivore and a Carnivore

Ontology languages

Kinds of potential ontology languages:

- Graphical notations
- Logic-based languages
- Object-oriented languages
- Web schema languages

Ontology languages

- Graphical notations:
    - Semantic networks
    - Topic Maps
    - UML
    - RDF

Ontology languages

- Logic based languages:
    - Description Logics
    - Rules (e.g., RuleML, Logic Programming/Prolog)
    - First Order Logic (e.g., KIF)
    - Conceptual graphs
    - (Syntactically) higher order logics (e.g., LBase)
    - Non-classical logics (e.g., F-logic, Non-Monotonic Logics, Modal Logics)

Obect-oriented languages

many languages use object-oriented models based on:

- Objects/Instances/Individuals
  - Elements of the domain of discourse
  - Equivalent to constants in FOL
- Types/Classes/Concepts
  - Sets of objects sharing certain characteristics
  - Equivalent to unary predicates in FOL
- Relations/Properties/Roles
  - Sets of pairs (tuples) of objects
  - Equivalent to binary predicates in FOL

Web schema languages

- Existing Web languages extended to facilitate content description
  - XML → XML Schema (XMLS)
  - RDF → RDF Schema (RDFS)
- XMLS *not* an ontology language
  - Changes format of DTDs (document schemas) to be XML
  - Adds an extensible type hierarchy
    - Integers, Strings, etc.
    - Can define sub-types, e.g., positive integers
- RDFS *is* recognizable as an ontology language
  - Classes and properties
  - Sub/super-classes (and properties)
  - Range and domain (of properties)

Limitations of RDFS

- RDFS too weak to describe resources in sufficient detail
  - No localised range and domain constraints
    - Can’t say that the range of hasChild is person when applied to persons and elephant when applied to elephants
  - No existence/cardinality constraints
    - Can’t say that all *instances* of person have a mother that is also a person, or that persons have exactly 2 parents
  - No transitive, inverse or symmetrical properties
    - Can’t say that isPartOf is a transitive property, that hasPart is the inverse of isPartOf or that touches is symmetrical
  - …

Web ontology language requirements

Desirable features identified for Web Ontology Language:

- Extends existing Web standards (XML, RDF, RDFS)
- Easy to understand and use (should be based on familiar KR idioms)
- Formally specified
- Of "adequate" expressive power
- Possible to provide automated reasoning support

Two languages developed to satisfy above requirements: DAML and OIL

The OWL language (based on DAML+OIL) became a W3C recommendation in 2004

OWL

- OWL = Web Ontology Language
- the OWL family is constituted by 3 different languages (with different expressive power):
  - OWL Full
    - union of OWL syntax and RDF
  - OWL-DL
    - "DL fragment" of OWL Full
  - OWL-Lite
    - "easier to implement" subset of OWL DL

OWL

- OWL standards and technology:
  - first version of OWL standardized in 2004
  - reasoning techniques and tools are recent
  - “optimization” of reasoning not fully explored
  - 2009: W3C standardization of OWL 2

OWL class constructors

Constructor	DL Syntax	Example	Modal Syntax
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	Human $\sqcap$ Male	$C_1 \wedge \ldots \wedge C_n$
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	Doctor $\sqcup$ Lawyer	$C_1 \vee \ldots \vee C_n$
complementOf	$\neg C$	¬Male	$\neg C$
oneOf	$\{x_1\} \sqcup \ldots \sqcup \{x_n\}$	{john} $\sqcup$ {mary}	$x_1 \vee \ldots \vee x_n$
allValuesFrom	$\forall P.C$	∀hasChild.Doctor	$[P]C$
someValuesFrom	$\exists P.C$	∃hasChild.Lawyer	$\langle P \rangle C$
maxCardinality	$\leqslant nP$	⩽1hasChild	$[P]_{n+1}$
minCardinality	$\geqslant nP$	⩾2hasChild	$\langle P \rangle_n$

- XMLS datatypes as well as classes in ∀P.C and ∃P.C
  - E.g., ∃hasAge.nonNegativeInteger
- Arbitrarily complex nesting of constructors
  - E.g., Person ⊓ ∀hasChild.Doctor ⊔∃hasChild.Doctor

RDFS syntax

E.g., concept $\text{Person} \sqcap \forall\text{hasChild.Doctor} \sqcup \exists\text{hasChild.Doctor}$:

```
<owl:Class>
  <owl:intersectionOf rdf:parseType=" collection">
    <owl:Class rdf:about="#Person"/>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#hasChild"/>
      <owl:toClass>
        <owl:unionOf rdf:parseType=" collection">
          <owl:Class rdf:about="#Doctor"/>
          <owl:Restriction>
            <owl:onProperty rdf:resource="#hasChild"/>
            <owl:hasClass rdf:resource="#Doctor"/>
          </owl:Restriction>
        </owl:unionOf>
      </owl:toClass>
    </owl:Restriction>
  </owl:intersectionOf>
</owl:Class>
```

OWL axioms

Axiom	DL Syntax	Example
subClassOf	$C_1 \sqsubseteq C_2$	$\mathsf{Human} \sqsubseteq \mathsf{Animal} \sqcap \mathsf{Biped}$
equivalentClass	$C_1 \equiv C_2$	$\mathsf{Man} \equiv \mathsf{Human} \sqcap \mathsf{Male}$
disjointWith	$C_1 \sqsubseteq \neg C_2$	$\mathsf{Male} \sqsubseteq \neg \mathsf{Female}$
sameIndividualAs	$\{x_1\} \equiv \{x_2\}$	$\{\mathsf{President\_Bush}\} \equiv \{\mathsf{G\_W\_Bush}\}$
differentFrom	$\{x_1\} \sqsubseteq \neg\{x_2\}$	$\{\mathsf{john}\} \sqsubseteq \neg\{\mathsf{peter}\}$
subPropertyOf	$P_1 \sqsubseteq P_2$	$\mathsf{hasDaughter} \sqsubseteq \mathsf{hasChild}$
equivalentProperty	$P_1 \equiv P_2$	$\mathsf{cost} \equiv \mathsf{price}$
inverseOf	$P_1 \equiv P_2^-$	$\mathsf{hasChild} \equiv \mathsf{hasParent}^-$
transitiveProperty	$P^+ \sqsubseteq P$	$\mathsf{ancestor}^+ \sqsubseteq \mathsf{ancestor}$
functionalProperty	$\top \sqsubseteq \leqslant 1 P$	$\top \sqsubseteq \leqslant 1 \mathsf{hasMother}$
inverseFunctionalProperty	$\top \sqsubseteq \leqslant 1 P^-$	$\top \sqsubseteq \leqslant 1 \mathsf{hasSSN}^-$

Axioms (mostly) reducible to inclusion ($\sqsubseteq$)

$\mathbf{C} \equiv \mathbf{D}$ iff both $\mathbf{C} \sqsubseteq \mathbf{D}$ and $\mathbf{D} \sqsubseteq \mathbf{C}$

XML Schema datatypes in OWL

- OWL supports XML Schema primitive datatypes
  - E.g., integer, real, string, …
- Strict separation between “object” classes and datatypes
  - Disjoint interpretation domain Δ_D for datatypes
    - For a datavalue d, $d^{\mathcal{I}} \subseteq \Delta_D$
    - And $\Delta_D \cap \Delta^{\mathcal{I}} = \emptyset$
  - Disjoint “object” and datatype properties
    - For a datatype propterty P, $P^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta_D$
    - For object property S and datatype property P, $S^{\mathcal{I}} \cap P^{\mathcal{I}} = \emptyset$
- Equivalent to the “(D_n)” in $\mathcal{SHOIN}(D_n)$

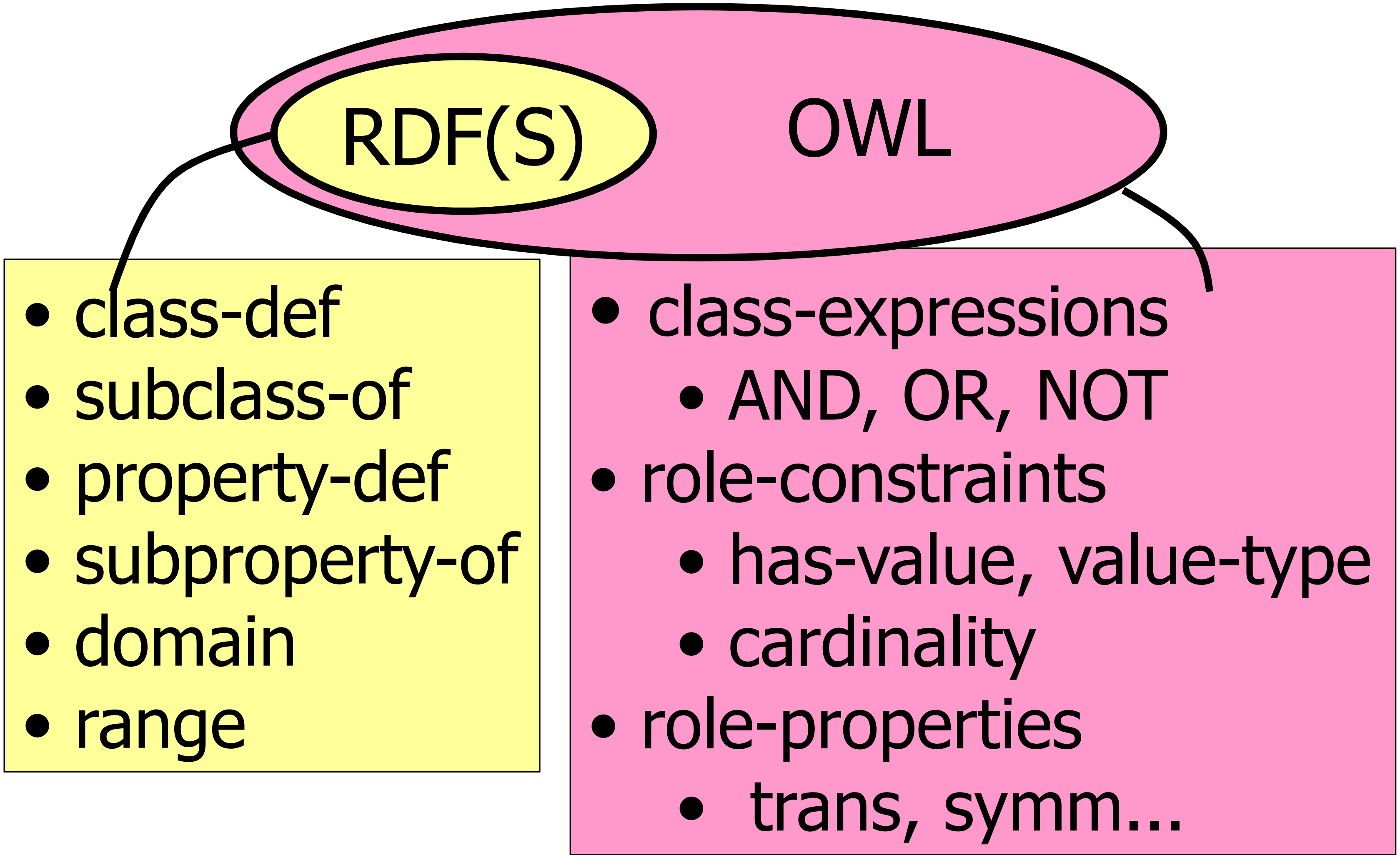
OWL DL semantics

- Mapping OWL to equivalent DL ($\mathcal{SHOIN}(D_n)$):
  - Facilitates provision of reasoning services (using DL systems)
  - Provides well defined semantics
- DL semantics defined by interpretations: $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$, where
  - $\Delta^{\mathcal{I}}$ is the domain (a non-empty set)
  - $\cdot^{\mathcal{I}}$ is an interpretation function that maps:
    - Concept (class) name A → subset $A^{\mathcal{I}}$ of $\Delta^{\mathcal{I}}$
    - Role (property) name R → binary relation $R^{\mathcal{I}}$ over $\Delta^{\mathcal{I}}$
    - Individual name i → $i^{\mathcal{I}}$ element of $\Delta^{\mathcal{I}}$

OWL DL ontologies are DL knowledge bases

- An OWL ontology maps to a DL Knowledge Base $\mathcal{K} = \langle \mathcal{T}, \mathcal{A} \rangle$
  - $\mathcal{T}$(Tbox) is a set of axioms of the form:
    - $C \sqsubseteq D$ (concept inclusion)
    - $C \equiv D$ (concept equivalence)
    - $R \sqsubseteq S$ (role inclusion)
    - $R \equiv S$ (role equivalence)
    - $R^+ \sqsubseteq R$ (role transitivity)
  - $\mathcal{A}$(Abox) is a set of axioms of the form
    - $x \in D$ (concept instantiation)
    - $\langle x,y \rangle \in R$ (role instantiation)

OWL vs. RDFS



RDF(S)

OWL

- class-def
- subclass-of
- property-def
- subproperty-of
- domain
- range

- class-expressions
  - AND, OR, NOT
- role-constraints
  - has-value, value-type
  - cardinality
- role-properties
  - trans, symm...

OWL vs. First-Order Logic

- in general, DLs correspond to decidable subclasses of first-order logic (FOL)
- DL KB = first-order theory
- OWL Full is NOT a FOL fragment!
    - reasoning in OWL Full is undecidable
- OWL-DL and OWL-Lite are decidable fragments of FOL

OWL vs. First-Order Logic

let $\mathcal{K} = \langle \mathcal{T}, \mathcal{A} \rangle$ be an ontology about persons where:

- $\mathcal{T}$ contains the following inclusion assertions:

  $\mathbf{MALE} \sqsubseteq \mathbf{PERSON}$

  $\mathbf{FEMALE} \sqsubseteq \mathbf{PERSON}$

  $\mathbf{MALE} \sqsubseteq \neg\, \mathbf{FEMALE}$

  $\mathbf{PERSON} \sqsubseteq \exists \mathbf{Father}^{-}.\mathbf{MALE}$

- $\mathcal{A}$ contains the following instance assertions:

  MALE(Bob)

  PERSON (Mary)

  PERSON(Paul)

OWL vs. First-Order Logic

- $\mathcal{T}$ corresponds to the following FOL sentences:

  $\forall$ x. MALE(x) → PERSON(x)

  $\forall$ x. FEMALE(x) → PERSON(x)

  $\forall$ x. MALE(x) → ¬FEMALE(x)

  $\forall$ x. PERSON(x) → $\exists$y. Father(y,x) and MALE(y)

- $\mathcal{A}$ corresponds to the following FOL ground atoms:

  MALE(Bob)

  PERSON (Mary)

  PERSON(Paul)

Inference tasks in OWL

- Ontology consistency (corresponds to KB consistency in DL)
- Concept/role consistency (same as DL)
- Concept/role subsumption and equivalence (same as DL)
- Instance checking (same as DL)
- …

Inference tasks

- OWL-DL ontology = first-order logical theory
- verifying the formal properties of the ontology corresponds to **reasoning** over a first-order theory

Inference tasks

- OWL-DL ontology = first-order logical theory
- verifying the formal properties of the ontology corresponds to **reasoning** over a first-order theory
- main reasoning tasks over ontologies:
  - consistency of the ontology
  - concept (and role) consistency
  - concept (and role) subsumption
  - instance checking
  - instance retrieval
  - query answering

Consistency of the ontology

- Is the ontology K=(T,A) consistent (non-self-contradictory)?
- i.e., is there at least a model for K?
- intensional + extensional reasoning task
- fundamental formal property:
- inconsistent ontology => there is a semantic problem in K!
- K must be repaired

Consistency of the ontology

Example TBox:

$\text{MALE} \sqsubseteq \text{PERSON}$

$\text{FEMALE} \sqsubseteq \text{PERSON}$

$\text{MALE} \sqsubseteq \neg\, \text{FEMALE}$

$\text{PERSON} \sqsubseteq \exists \text{hasFather}.\text{MALE}$

$\text{PERSON} \sqsubseteq \exists \text{hasMother}.\text{FEMALE}$

$\text{hasMother} \sqsubseteq \text{hasParent}$

$\text{hasFather} \sqsubseteq \text{hasParent}$

$\exists \text{hasParent}.\text{BLACK-EYES} \sqsubseteq \text{BLACK-EYES}$

Consistency of the ontology

Example ABox:

MALE(Bob)
MALE(Paul)
FEMALE(Ann)
hasFather(Ann,Paul)
hasMother(Paul,Mary)
BLACK-EYES(Mary)

¬ BLACK-EYES(Ann)

⇒ TBox + ABox **inconsistent** (Ann should have black eyes)

Concept consistency

- is a concept definition C consistent in a TBox T?
- i.e., is there a model of T in which C has a non-empty extension?
- intensional (schema) reasoning task
- detects a fundamental modeling problem in T:
    - if a concept is not consistent, then it can never be populated!

Concept subsumption

- is a concept C subsumed by another concept D in T?
- i.e., is the extension of C contained in the extension of D in every model of T?
- intensional (schema) reasoning task
- allows to do classification of concepts (i.e., to construct the concept ISA hierarchy)

Instance checking

- is an individual a a member of concept C in K?
- i.e., is the fact C(a) satisfied by every interpretation of K?
- intensional + extensional reasoning task
- basic “instance-level query” (tell me if object a is in class C)

Instance retrieval

- find all members of concept C in K
- i.e., compute all individuals a such that C(a) is satisfied by every interpretation of K
- intensional + extensional reasoning task
- (slight) generalization of instance checking

Query answering

- compute the answers to a **query** q in K (expressed in some query language)
- i.e., compute all tuples of individuals t such that q(t) is entailed by K (= q(t) is satisfied by every interpretation of K)
- extensional + extensional reasoning task
- generalization of instance checking and instance retrieval
- e.g.: database queries (SQL-like) over ontologies (or SPARQL-like queries)

Queries over ontologies

classes of queries over DL ontologies considered:

- **conjunctive queries** = subclass of SQL queries
  - correspond to select-project-join queries
- **unions of conjunctive queries**
  - correspond to select-project-join-union queries
- **more expressive queries** (e.g., epistemic queries)
- **SPARQL queries**
  - restrictions/extensions of SPARQL

SPARQL 1.1

- SPARQL 1.1 is the W3C standard query language over OWL ontologies (released in 2013)
- SPARQL 1.1 has different associated **entailment regimes** that define the semantics of queries over different datasets (RDF models, RDFS+RDF graphs, OWL ontologies)
- the semantics of SPARQL queries for OWL is defined by two entailment regimes for SPARQL:
  - **OWL 2 RDF-based semantics** entailment regime
  - **OWL 2 direct semantics** entailment regime (corresponds to DL semantics)

Computational aspects of reasoning

- reasoning in OWL-DL is decidable (and the complexity is characterized)
- however: high computational complexity (EXPTIME)
- (optimized) reasoning algorithms developed
- OWL-DL reasoning tools implemented

Current OWL technology

two kinds of tools:

- OWL editors (“environments”)
- OWL reasoners

OWL editors

- allow for visualizing/browsing/editing OWL ontologies
- able to connect to an external OWL reasoner

  => OWL "environments"
- main current tools:
  - Protege
  - SWOOP
  - OWLed2

OWL reasoning tools

two categories:

- OWL-DL reasoners, e.g.:
  - Hermit
  - Pellet
  - Konclude
  - Racer, RacerPro
  - Fact++
- reasoners for “tractable fragments” of OWL-DL, e.g.:
  - ELK (OWL 2 EL)
  - Mastro, Ontop (OWL 2 QL)
  - RDFox (OWL 2 RL)

OWL-DL reasoning tools

- all tools support “standard” reasoning tasks, i.e.:
  - consistency of the ontology
  - concept consistency
  - concept subsumption and classification
  - instance checking and retrieval
  - query answering (SPARQL)

References

- OWL W3C Web site:

  `http://www.w3.org/2004/OWL/`
- OWL 2 overview:

  `http://www.w3.org/TR/owl2-overview/`
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- Web page on Description Logic reasoners:

  `http://owl.cs.manchester.ac.uk/tools/list-of-reasoners/`

- Protege (OWL ontology editor):

  `http://protege.stanford.edu/`

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  `http://hermit-reasoner.com/`

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  `http://www.cs.ox.ac.uk/isg/tools/ELK/`

- Stardog (OWL 2 profiles and OWL2 DL reasoner):

  `http://stardog.com/`

- RacerPro (OWL reasoning tool):

  `http://franz.com/agraph/racer/`

- Mastro (DL-Lite ontology-based data access system)

  `http://www.dis.uniroma1.it/~mastro/`