Semantic Web reasoning

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Outline

• Summary
  – Logics
  – Semantic Web Languages
  – Reasoning

• Web-based reasoning techniques
• Reasoning using SemWeb languages expressivity
• General aspects of reasoning and calculability
• Reasoning on dynamic KBs
• Conclusion
Summary

• Formal logics

La logique est à l'origine la recherche de règles générales et formelles permettant de distinguer un raisonnement concluant de celui qui ne l'est pas. [Wikipedia-Fr](http://www.wikipedia.org)

– First Order Logic
– Propositional Logic
– Predicate logic
– Modal Logic
– Description logics
– Fuzzy logic...
Summary

• Description Logics (DL)

DL is a family of formal knowledge representation languages. Many DLs are more expressive than propositional logic but less expressive than first-order predicate logic. In contrast to the latter, the core reasoning problems for DLs are (usually) decidable, and efficient decision procedures have been designed and implemented for these problems. Wikipédia-En

– DLs model concepts, roles and individuals, and their relationships

– The fundamental modeling concept of a DL is the axiom - a logical statement relating roles and/or concepts.
Summary

• Description Logics (DL)
  – DLs provide various characteristics, corresponding to different types of *expressivity*
  – Each feature indicates “what you can say” with it
  – 3 basic logics:
    • Attributive Language (used in ontologies)
    • Frame based description language
    • Existential language
  – A set of extensions that provide specific constructs
Summary

• The Semantic Web
  – RDF
    • Triple: subject, predicate, object
    • Nodes
      – Subject, object
      – Possible types: IRI, literal, blank node
    • Predicate: link

Dogs eat Meat
Summary

• The Semantic Web
  – RDF
    • Graph: set of (possibly interrelated) triples

```
Dogs eat Meat
Cows eat Meat
```
Summary

• The Semantic Web
  – RDF
    • Blank node: resource without a definite IRI

![Diagram of RDF relationships]

- ? hasSpecies Cows
- ? hasSpecies Dogs
- Meat eats ?

Summary

• The Semantic Web
  – RDF
    • Containers (Bag, Seq, Alt): provide access to a set of similar resources

![Diagram](https://via.placeholder.com/150)
Summary

• The Semantic Web
  – RDF
    • Resource: basically anything in RDF
Summary

• The Semantic Web
  – RDF
    • Statement: talking about a triple
Summary

• The Semantic Web
  – Structured Graph: RDF-S
    • Schema: Class, Property, hierarchy, data
    • Constraints: domain, range

![Diagram of RDF-Schema with classes and properties including Cow, Meat, Dog, Animal, eats, ruminates, devours, subClassOf, subPropertyOf, rdf:type, and data sources](attachment:image.png)
Summary

• The Semantic Web
  – Ontologies: OWL
    • Web Ontology Language
    • 2 versions
      – OWL (1), February 2004: Lite, DL, Full
      – OWL2, December 2012: 3 profiles → EL, RL, QL
    • Adds expressivity to the couple RDF-S + RDF
    • Allows defining vocabularies
    • Based on Description Logics
The Semantic Web

Ontologies: OWL

- Terminology (TBox): domain vocabulary
- Assertions (ABox): to store actual data
- Roles (RBox): term articulation

Vocabulary components

- Classes
- Individuals
- Literals
- Roles
- Object properties
- Data properties
Summary

• The Semantic Web
  – Ontologies: OWL
    • Supplementary semantic constructs
      – Expressions
        » Object Property
        » Data ranges
        » Class expressions
      – Axioms
        » Class expression axioms
        » Object properties
        » Data properties
        » Datatypes
        » Keys
        » Data assertions

An OWL 2 ontology \(O\) is satisfied in an interpretation \(I\) if all axioms in the axiom closure of \(O\) are satisfied in \(I\).
Summary

• The Semantic Web
  – Ontologies: OWL
    • Cheatsheet reference for OWL 2 DL
      – Summary of OWL constructs: https://www.w3.org/TR/owl-quick-reference/
      – Detailed definitions: https://www.w3.org/TR/owl2-syntax/
      – Formal definitions: https://www.w3.org/TR/owl-direct-semantics/
      – DLs names vs. expressivity levels: https://en.wikipedia.org/wiki/Description_logic#Nomenclature
Summary

• The Semantic Web
  – OWL 2: building blocks

Source: https://www.w3.org/TR/owl-overview/
Summary

• The Semantic Web
  – OWL 2 : building blocks
    • Ontologies (conceptual structure): the structural elements, their roles and functionalities
      https://www.w3.org/TR/owl2-primer/
    • Concrete syntaxes: Functional-style, Manchester, RDF/XML, OWL/XML, Turtle...
    • Semantics: define the meaning of OWL 2 ontologies
      https://www.w3.org/TR/owl2-direct-semantics/
      https://www.w3.org/TR/owl2-rdf-based-semantics/
Summary

• The Semantic Web
  – **OWL2 profiles**
    • Expression Language (EL)
      – For classification tasks
      – Different expressivity levels
      – Query rewriting (SPARQL -> SPARQL)
    • Query Language (QL)
      – For querying large datasets
      – Relies on an internal RDB
      – Query rewriting (SPARQL -> SQL)
    • Rule Language (RL)
      – For entailing facts using rules
      – More to come...
Summary

• Ontology limitations
  – Made by non-experts
    • inconsistent
  – Automatically generated
    • Not very useful without domain knowledge
  – Heterogeneous
  – Too high complexity
Summary

• The Semantic Web
  – Finally, what is it good for?
    • Describing domain vocabularies
    • Querying structured data sources (aka knowledge bases)
    • Agreeing on a common meaning of types of information
    • Interlinking data sources
  
  – But can’t we do better?...
Web-based reasoning

• Reasoning
  – The process of logically determining information that has not been explicitly been stated
  – Examples
    • Calculus
    • Syntactic analysis
    • Proofs
    • Verification
    • Inferences
    • Science?...
Web-based reasoning

• Inference
  – The process of entailing a fact based on rules
  – Basis of a reasoning process

Condition (head) (I finished my homework) AND (the weather is nice) \(\rightarrow\) conclusion (body) (I can go for a walk)
Web-based reasoning

- Examples of inductive (logical) reasoning
  - Satisfiability (SAT)
  - Backward chaining (Prolog)
  - Forward chaining (rules)
  - Saturation (tableaux)
Outline

• Summary

• **Web-based reasoning techniques**
  – Rule-based reasoning
  – Tableaux-based reasoning
  – Comparison

• Reasoning using SemWeb languages expressivity

• General aspects of reasoning and calculability

• Reasoning on dynamic KBs

• Conclusion
Rule-based reasoning

• Reasoning type
  – Inductive reasoning
  – Forward chaining

• Principles
  – Rules are applied to a set of facts
    • At the beginning: explicit facts
  – May infer new facts
    • Implicit facts
  – On which the rules are applied
  – Loop until nothing more happens
Rule-based reasoning

• Functioning with RDF graphs
  – Facts = triples
  – Order of rule application must not be relevant

• Usages
  – Datalog: query language for deductive DBs
  – View materialization: data duplication for creating views in DBs
Rule-based reasoning

• Use conjunctive rules
  – Only conjunctions in head clauses
  – To ensure commutativity

• Separate non-commutative operations in different queries
  – Deletions
  – Insertions
Tableaux-based algorithms

• Explore all possible Aboxes (« tableaux »)
• Apply rules to search for unsatisfiabilities
  – Start: tableau is open
  – Apply rules (recursively)
  – If a clash is found: tableau is closed
  – If no clash is found and no more rule can be applied: tableau is complete
• If there is a complete tableau, the Tbox is satisfiable
Tableaux-based algorithms

- Tableaux calculus (aka truth tree)
  - Objective: explore all possible solutions for finite sets of formulas of various logics
    - Propositional Logic
    - First order predicate logic
    - Clause tableaux
  - Based on algorithms that break formulas into pieces
  - Close branches when a contradiction is found
  - Derivation process
    - Assess the derivation is complete
    - Store the derivation history
Hyper tableaux
(Baumgartner, Furbach, Niemelä 1996)

- Variant of the clausal normal form tableaux
  - Applies derivation in an efficient minimal model reasoning (hyper derivation)
  - Subsumption-based pruning and decision procedure
  - Resolve away all negative literals of a clause in a single inference step
- Allows avoiding backtracking in reasoning mechanisms
  ➔ More “reasonably implementable” than regular clausal algorithms

Source:
Reasoning algorithms:
Rule-based vs. Tableaux

• Rule-based instantiate variables (if they can)
• Tableaux make assumptions on all possibilities

• Example:

→ Do I know a woman who knows a man?
• Summary
• Web-based reasoning techniques
• **Reasoning using SemWeb languages expressivity**
  – RDF
  – RDF-S
  – OWL
• General aspects of reasoning and calculability
• Reasoning on dynamic KBs
• Conclusion
RDF reasoning

• Only about facts, triple structure and datatypes
• RDF entailments
  – Simple entailments: structural matching by renaming blank nodes
  – RDF entailments: interpret RDF vocabulary
RDF reasoning

- **Simple entailment rules**

<table>
<thead>
<tr>
<th>Rule name</th>
<th>If E contains</th>
<th>then add</th>
</tr>
</thead>
<tbody>
<tr>
<td>se1</td>
<td>uuu aaa xxx .</td>
<td>uuu aaa _:nnn . where _:nnn identifies a blank node allocated to xxx by rule se1 or se2.</td>
</tr>
<tr>
<td>se2</td>
<td>uuu aaa xxx .</td>
<td>_:nnn aaa xxx . where _:nnn identifies a blank node allocated to uuu by rule se1 or se2.</td>
</tr>
<tr>
<td>lg</td>
<td>uuu aaa lll .</td>
<td>uuu aaa _:nnn . where _:nnn identifies a blank node allocated to the literal lll by this rule.</td>
</tr>
<tr>
<td>gl</td>
<td>uuu aaa _:nnn . where _:nnn identifies a blank node allocated to the literal lll by rule lg.</td>
<td>uuu aaa lll .</td>
</tr>
</tbody>
</table>

Source: Corno & Farinetti: Logic and Reasoning in the Semantic Web
RDF reasoning

• RDF entailment rules

<table>
<thead>
<tr>
<th>Rule name</th>
<th>If E contains</th>
<th>then add</th>
</tr>
</thead>
<tbody>
<tr>
<td>rdf1</td>
<td>uuu aaa yyy .</td>
<td>aaa rdf:type rdf:Property .</td>
</tr>
</tbody>
</table>
| rdf2      | uuu aaa lll .  
where lll is a well-typed XML literal . | _:nnn rdf:type rdf:XMLLiteral .  
where _:nnn identifies a blank node allocated to lll by rule lg. |
RDF reasoning

- RDF axiomatic triples

<table>
<thead>
<tr>
<th>rdf:type</th>
<th>rdf:type</th>
<th>rdf:Property .</th>
</tr>
</thead>
<tbody>
<tr>
<td>rdf:subject</td>
<td>rdf:type</td>
<td>rdf:Property .</td>
</tr>
<tr>
<td>rdf:predicate</td>
<td>rdf:type</td>
<td>rdf:Property .</td>
</tr>
<tr>
<td>rdf:object</td>
<td>rdf:type</td>
<td>rdf:Property .</td>
</tr>
<tr>
<td>rdf:first</td>
<td>rdf:type</td>
<td>rdf:Property .</td>
</tr>
<tr>
<td>rdf:rest</td>
<td>rdf:type</td>
<td>rdf:Property .</td>
</tr>
<tr>
<td>rdf:value</td>
<td>rdf:type</td>
<td>rdf:Property .</td>
</tr>
<tr>
<td>rdf:_1</td>
<td>rdf:type</td>
<td>rdf:Property .</td>
</tr>
<tr>
<td>rdf:_2</td>
<td>rdf:type</td>
<td>rdf:Property .</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rdf:nil</td>
<td>rdf:type</td>
<td>rdf:List .</td>
</tr>
</tbody>
</table>

Source: Corno & Farinetti: Logic and Reasoning in the Semantic Web
RDF reasoning

• Interpolation Lemma

  A set of graphs $S$ entails a graph $E$ if and only if every subgraph of $S$ is an instance of $E$
  
  – Syntactic description of entailment
  
  – Satisfied by simple entailment rules
RDF reasoning

• RDF entailment lemma

S rdf-entails E if and only if there exists a graph

• that can be derived
  – from S and the RDF axiomatic triples
  – by the application of rule lg and the RDF entailment rules

• that entails E
  – Describes reasoning completeness
  – Satisfied by RDF entailment rules
RDF reasoning

• Usage
  – Structural graph mapping
  – Assertions about assertions (reification)

• Examples
  – Trust $\rightarrow$ recommendation
  – Comparison $\rightarrow$ adaptation
RDF-S reasoning

• Deduce new information on
  – Hierarchy (subclassOf, subPropertyOf)
  – Individuals (rdf-type)
### RDF-S reasoning

#### RDF-S entailment rules (1/2)

<table>
<thead>
<tr>
<th>Rule name</th>
<th>If E contains</th>
<th>then add</th>
</tr>
</thead>
<tbody>
<tr>
<td>rdfs1</td>
<td>uuu aaa lll.</td>
<td>_:nnn rdf:type rdfs:Literal . where _:nnn identifies a blank node allocated to lll by rule rule lg.</td>
</tr>
<tr>
<td></td>
<td>where lll is a plain literal (with or without a language tag)</td>
<td></td>
</tr>
<tr>
<td>rdfs2</td>
<td>aaa rdfs:domain xxx . uuu aaa yyy .</td>
<td>uuu rdf:type xxx .</td>
</tr>
<tr>
<td>rdfs3</td>
<td>aaa rdfs:range xxx . uuu aaa vvv .</td>
<td>vvv rdf:type xxx .</td>
</tr>
<tr>
<td>rdfs4a</td>
<td>uuu aaa xxx .</td>
<td>uuu rdf:type rdfs:Resource .</td>
</tr>
<tr>
<td>rdfs4b</td>
<td>uuu aaa vvv .</td>
<td>vvv rdf:type rdfs:Resource .</td>
</tr>
<tr>
<td>rdfs5</td>
<td>uuu rdfs:subPropertyOf vvv . vvv rdfs:subPropertyOf xxx .</td>
<td>uuu rdfs:subPropertyOf xxx .</td>
</tr>
</tbody>
</table>

Source: Corno & Farinetti: Logic and Reasoning in the Semantic Web
RDF-S reasoning

- **RDF-S entailment rules (2/2)**

<table>
<thead>
<tr>
<th>Rule name</th>
<th>If E contains</th>
<th>then add</th>
</tr>
</thead>
<tbody>
<tr>
<td>rdfs6</td>
<td>uuu rdf:type rdf:Property .</td>
<td>uuu rdfs:subPropertyOf uuu .</td>
</tr>
<tr>
<td>rdfs7</td>
<td>aaa rdfs:subPropertyOf bbb uuu aaa yyy .</td>
<td>uuu bbb yyy .</td>
</tr>
<tr>
<td>rdfs8</td>
<td>uuu rdf:type rdfs:Class .</td>
<td>uuu rdfs:subClassOf rdfs:Resource .</td>
</tr>
<tr>
<td>rdfs9</td>
<td>uuu rdfs:subClassOf xxx . vvv rdf:type uuu .</td>
<td>vvv rdf:type xxx .</td>
</tr>
<tr>
<td>rdfs10</td>
<td>uuu rdf:type rdfs:Class .</td>
<td>uuu rdfs:subClassOf uuu .</td>
</tr>
<tr>
<td>rdfs11</td>
<td>uuu rdfs:subClassOf vvv . vvv rdfs:subClassOf xxx .</td>
<td>uuu rdfs:subClassOf xxx .</td>
</tr>
<tr>
<td>rdfs12</td>
<td>uuu rdf:type rdfs:ContainerMembershipProperty .</td>
<td>uuu rdfs:subPropertyOf rdfs:member .</td>
</tr>
<tr>
<td>rdfs13</td>
<td>uuu rdf:type rdfs:Datatype</td>
<td>uuu rdfs:subClassOf rdfs:Literal .</td>
</tr>
</tbody>
</table>

Source: Corno & Farinetti: Logic and Reasoning in the Semantic Web
RDF-S reasoning

- RDF-S axiomatic triples (1/3)

<table>
<thead>
<tr>
<th>Property</th>
<th>Domain</th>
<th>Resource</th>
</tr>
</thead>
<tbody>
<tr>
<td>rdf:type</td>
<td>rdfs:domain</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdfs:domain</td>
<td>rdfs:domain</td>
<td>rdf:Property</td>
</tr>
<tr>
<td>rdfs:range</td>
<td>rdfs:domain</td>
<td>rdf:Property</td>
</tr>
<tr>
<td>rdfs:subPropertyOf</td>
<td>rdfs:domain</td>
<td>rdf:Property</td>
</tr>
<tr>
<td>rdfs:subClassOf</td>
<td>rdfs:domain</td>
<td>rdfs:Class</td>
</tr>
<tr>
<td>rdf:subject</td>
<td>rdfs:domain</td>
<td>rdf:Statement</td>
</tr>
<tr>
<td>rdf:predicate</td>
<td>rdfs:domain</td>
<td>rdf:Statement</td>
</tr>
<tr>
<td>rdf:object</td>
<td>rdfs:domain</td>
<td>rdf:Statement</td>
</tr>
<tr>
<td>rdfs:member</td>
<td>rdfs:domain</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdf:first</td>
<td>rdfs:domain</td>
<td>rdf:List</td>
</tr>
<tr>
<td>rdf:rest</td>
<td>rdfs:domain</td>
<td>rdf:List</td>
</tr>
<tr>
<td>rdfs:seeAlso</td>
<td>rdfs:domain</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdfs:isDefinedBy</td>
<td>rdfs:domain</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdfs:comment</td>
<td>rdfs:domain</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdfs:label</td>
<td>rdfs:domain</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdf:value</td>
<td>rdfs:domain</td>
<td>rdfs:Resource</td>
</tr>
</tbody>
</table>

Source: Corno & Farinetti: Logic and Reasoning in the Semantic Web
### RDF-S reasoning

- **RDF-S axiomatic triples (2/3)**

<table>
<thead>
<tr>
<th>rdf:type</th>
<th>rdfs:range</th>
<th>rdfs:Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>rdfs:domain</td>
<td>rdfs:range</td>
<td>rdfs:Class</td>
</tr>
<tr>
<td>rdfs:range</td>
<td>rdfs:range</td>
<td>rdfs:Class</td>
</tr>
<tr>
<td>rdfs:subPropertyOf</td>
<td>rdfs:range</td>
<td>rdf:Property</td>
</tr>
<tr>
<td>rdfs:subClassOf</td>
<td>rdfs:range</td>
<td>rdfs:Class</td>
</tr>
<tr>
<td>rdf:subject</td>
<td>rdfs:range</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdf:predicate</td>
<td>rdfs:range</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdf:object</td>
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<td>rdfs:Resource</td>
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<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdf:rest</td>
<td>rdfs:range</td>
<td>rdf:List</td>
</tr>
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<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdfs:isDefinedBy</td>
<td>rdfs:range</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdfs:comment</td>
<td>rdfs:range</td>
<td>rdfs:Literal</td>
</tr>
<tr>
<td>rdfs:label</td>
<td>rdfs:range</td>
<td>rdfs:Literal</td>
</tr>
<tr>
<td>rdf:value</td>
<td>rdfs:range</td>
<td>rdfs:Resource</td>
</tr>
</tbody>
</table>

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## RDF-S reasoning

### RDF-S axiomatic triples (3/3)

<table>
<thead>
<tr>
<th>RDF Term</th>
<th>RDFS Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>rdf:Alt</td>
<td>rdfs:subClassOf</td>
<td>rdfs:Container</td>
</tr>
<tr>
<td>rdf:Bag</td>
<td>rdfs:subClassOf</td>
<td>rdfs:Container</td>
</tr>
<tr>
<td>rdf:Seq</td>
<td>rdfs:subClassOf</td>
<td>rdfs:Container</td>
</tr>
<tr>
<td>rdfs:ContainerMembershipProperty</td>
<td>rdfs:subClassOf</td>
<td>rdf:Property</td>
</tr>
<tr>
<td>rdfs:isDefinedBy</td>
<td>rdfs:subPropertyOf</td>
<td>rdfs:seeAlso</td>
</tr>
<tr>
<td>rdf:XMLLiteral</td>
<td>rdf:type</td>
<td>rdfs:Datatype</td>
</tr>
<tr>
<td>rdf:XMLLiteral</td>
<td>rdfs:subClassOf</td>
<td>rdfs:Literal</td>
</tr>
<tr>
<td>rdfs:Datatype</td>
<td>rdfs:subClassOf</td>
<td>rdfs:Class</td>
</tr>
<tr>
<td>rdf:_1</td>
<td>rdf:type</td>
<td>rdfs:ContainerMembershipProperty</td>
</tr>
<tr>
<td>rdf:_1</td>
<td>rdfs:domain</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdf:_1</td>
<td>rdfs:range</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdf:_2</td>
<td>rdf:type</td>
<td>rdfs:ContainerMembershipProperty</td>
</tr>
<tr>
<td>rdf:_2</td>
<td>rdfs:domain</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>rdf:_2</td>
<td>rdfs:range</td>
<td>rdfs:Resource</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Corno & Farinetti: Logic and Reasoning in the Semantic Web
RDF-S reasoning

- RDF-S entailment lemma
  - S rdfs-entails E if and only if there is a graph
    - that can be derived
      - from S plus the RDF and RDFS axiomatic triples
      - by the application of rule lg, rule gl and the RDF and RDFS entailment rules
    - that either
      - simply entails E or
      - contains a clash
OWL reasoning

- **General principle**
  - Deducing new information from OWL axioms

- **(Most used) principle: applying rules to**
  - Enforce OWL constructors
  - Respond to queries

- In OWL2 RL, rules are specified in the spec:
  [https://www.w3.org/TR/owl2-profiles/](https://www.w3.org/TR/owl2-profiles/)
  #Reasoning_in_OWL_2_RL_and_RDF_Graphs_using_Rules
OWL reasoning

• Based on OWL language constructs
• Different levels of expressivity

However, computing all interesting logical conclusions of an OWL ontology can be a challenging problem, and reasoning is typically multi-exponential or even undecidable.

• OWL2 profiles were created to
  – Be *tractable* (polynomial for tasks they are designed for)
  – Be easier to understand for practitioners
  – Make it easier to develop reasoning algorithms
Outline

• Summary
• Web-based reasoning techniques
• Reasoning using SemWeb languages expressivity
• **General aspects of reasoning**
  – Inference problems
  – Complexity
• Reasoning on dynamic KBs
• Conclusion
Basic inference problems

• Subsumption
• Equivalence
• Consistency
• Instantiation

⇒ All these problems are reducible to KB satisfiability

Source: http://www.computational-logic.org/content/events/iccl-ss-2005/lectures/horrocks/part4b-tableaux.pdf
OWL inference problems

• Ontology Consistency
• Ontology Entailment
• Ontology Equivalence
• Ontology Equisatisfiability
• Class Expression Satisfiability
• Class Expression Subsumption
• Instance Checking
• Boolean Conjunctive Query Answering

Source: [http://www.w3.org/TR/owl2-direct-semantics/](http://www.w3.org/TR/owl2-direct-semantics/)
Closure and Reduction

• The closure of a graph $G$ is the graph containing $G$ and all triples that can be inferred from $G$ by a given reasoning algorithm.

• The reduction of a graph $G$ is the minimal subset of triples needed to compute $G$ (and therefore, its closure).

⇒ What can they be used for?
Closure and Reduction

- Computing the closure of a graph
  - “pre-computes” query answers (view materialization)
    ➔ minimizes query processing time
- Computing the reduction of a graph
  - Produces a “light graph”
    ➔ minimizes storage space
Hardness of reasoning

It is very easy to compute some OWL entailments – the challenge is to compute all entailments of a certain kind. Markus Krötzsch

• Soundness
  – All computed inferences are really entailed
  – Necessary to be reliable

• Completeness
  – All computed inferences should actually be entailed
  – Not always necessary, if well documented
A note about complexity

• OWL 1 (OWL under RDF semantics)
  – OWL DL was NP complete
  – OWL Full was undecidable

• OWL 2 (OWL under direct semantics)
  – In general, reasoning is N2ExpTime-complete
  – EL, RL and QL profiles have been designed to be *tractable* (i.e. polynomial) in their most important tasks
A note about complexity

• Practical considerations
  – A tractable reasoning process is polynomial
    • In worst case, but worst case is not always the case
  – In practice, polynomial reasoning is not necessarily achievable
    • What’s the use of a $n^{100}$-complex algorithm?
    • Even $n^4$ can be too complex on big data sets

→ Restraining the set of used constructs to the necessary ones is a good practice
→ Reducing the size of requests can also help...
Outline

• Summary
• Web-based reasoning techniques
• Reasoning using SemWeb languages expressivity
• General aspects of reasoning
• Reasoning on dynamic KBs
  – Problem
  – Example of solution
• Conclusion
Reasoning on Dynamic Knowledge

• Problem position
  – Semantic reasoning can be a hard problem
  – What if the ontology changes?

• What can happen
  – Depending on the application, the KB can vary
    • Evolution of the domain knowledge
      → Graph structure (classes, properties)
    • Evolution of the application state
      → Individuals
    • Evolution of the model behavior
      → Inference rules
Reasoning on Dynamic Knowledge

• Problem position
  – Example on rule-based reasoning
  – What if:

  - E1 is removed
  - E5 is removed
  - E5 and E6 are removed
  - E5 and E6 are removed, and I3 is inserted as an explicit fact
Reasoning on Dynamic Knowledge

• Solution 1: « *tabula rasa* »
  – Erase all inferences and recompute everything
  – ...

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Reasoning on Dynamic Knowledge

- Solution 2: Incremental reasoning (Motik, Horrocks, Kim 2012)
  - Based on Gupta & Al. 1993, DRed
  - Only designed for conjunctive rules
  - Overdeletion
    - Evaluate the list of implicit facts inferred from explicit facts to suppress
  - Rederivation
    - Evaluate the list of implicit facts that could have been derived from other explicit facts
Reasoning on Dynamic Knowledge

• Incremental reasoning: example
  – E5 is removed

Overdeletion

Rederivation

E1
E2
E3
E4
E5
E6
I1
I2
I3
I4
I5
I6
E1
E2
E3
E4
E6
I1
I5
I6
Reasoning on Dynamic Knowledge

• Solution 3:
  Keep track of previous reasoning results
  – Ontology modules (Grau & al. 2007)
    • Split the ontology in atomic parts that do not interfere during reasoning
    • Apply IR technique only on modified modules
  – Tag-based reasoning (Terdjimi & al. 2018)
    • Tag all explicit facts "valid" at insertion and "invalid" at deletion
    • Store the explicit causes of each implicit fact
    • Filter implicit facts at response time according to the validity of their causes
  – ...

  ...
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Conclusion

• Reasoning results can depend on
  – Representation language expressivity
  – KB
    • Size
    • Class hierarchy
    • Number and complexity of (actually used) relations
    • Presence of instances
  – Reasoning engine type
Conclusion

• Problems due to reasoning on the Semantic Web
  – Scalability
  – Distribution
  – Heterogeneity
  – Data quality
  – Data velocity (streams)
Conclusion

• Reasoning algorithms are quite simple
  – Building a reasoner is easy
  – Optimizing it is harder

• Complexity is always computed in worst case
  ➔ Make sure the worst case never happens
  ➔ Use different algorithms for different problems
Conclusion

• In any case, logical reasoning is a means to retrieve information « hidden » in the KB

  – It can solve complex queries in a generic, elegant manner

  – But it cannot produce new « knowledge »

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