Université Claude Bernard Lyon 1

Semantic reasoning for dynamic knowledge bases

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M2IA – Knowledge Dynamics

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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.
Wikipédia-Fr

  - First Order Logic
  - Propositional Logic
  - Predicate logic
  - Modal Logics
  - 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

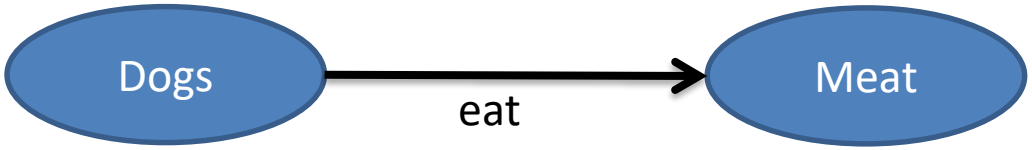
  - DLs model concepts, roles and individuals, and their relationships
  - The fundamental modeling concept of a DL is the axiom - a logical statement relating roles and/or concepts.

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
  - Ref: https://en.wikipedia.org/wiki/Description_logic

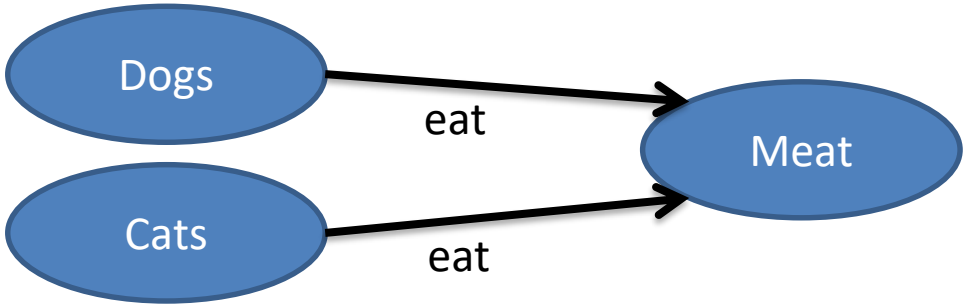
Summary

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



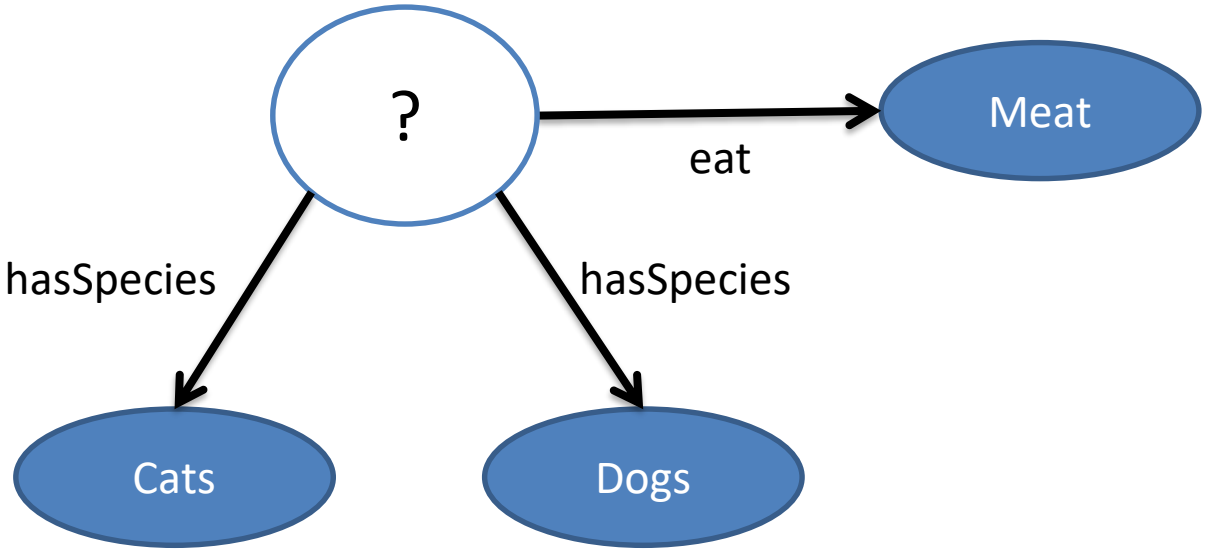
Summary

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



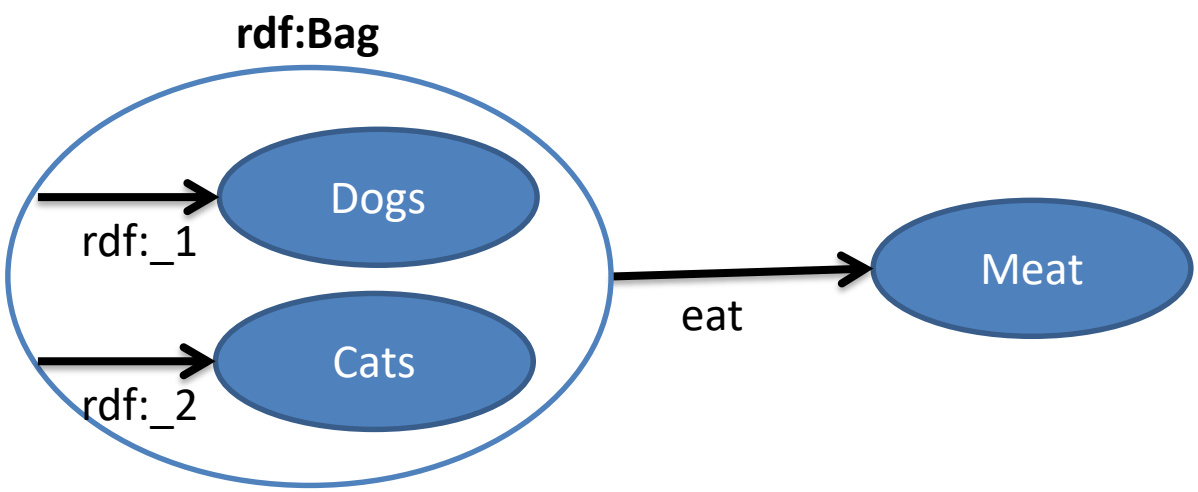
Summary

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



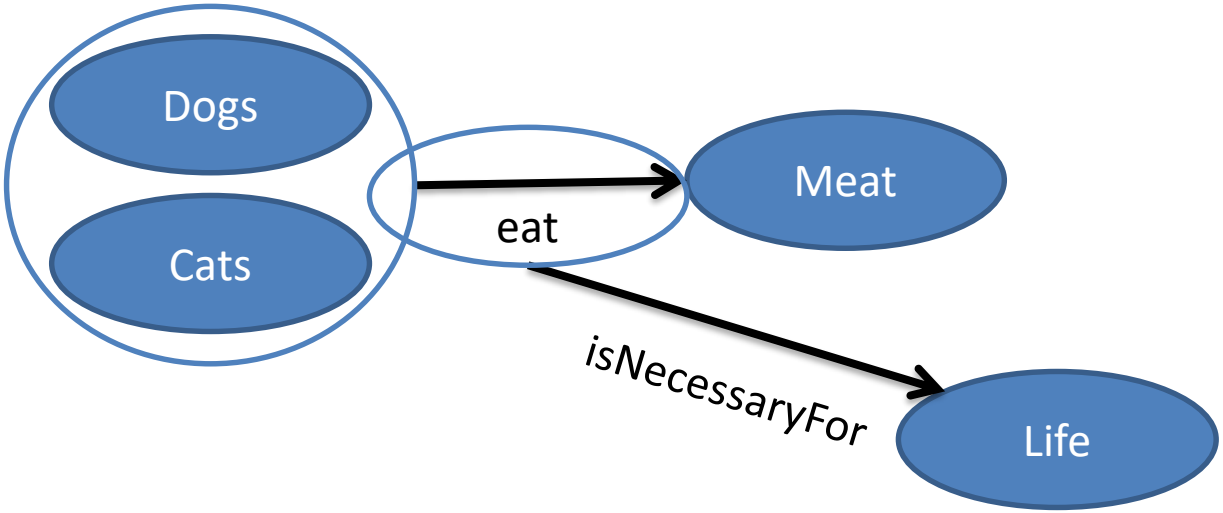
Summary

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



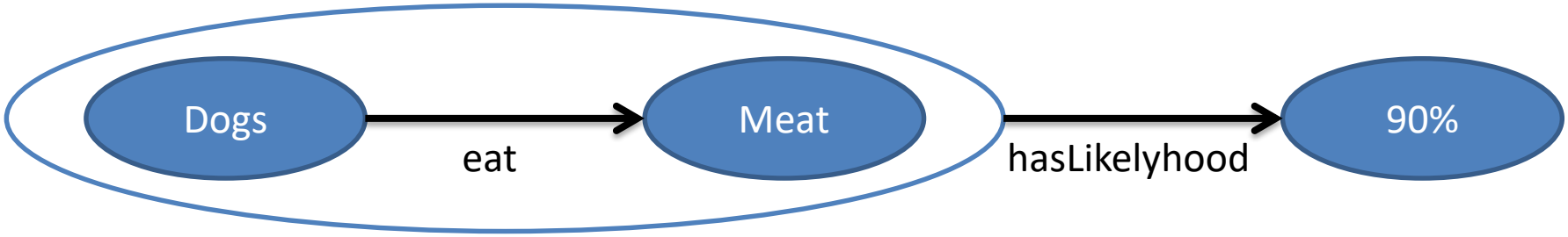
Summary

- The Semantic Web
  - RDF
    - Resource: basically anything in RDF



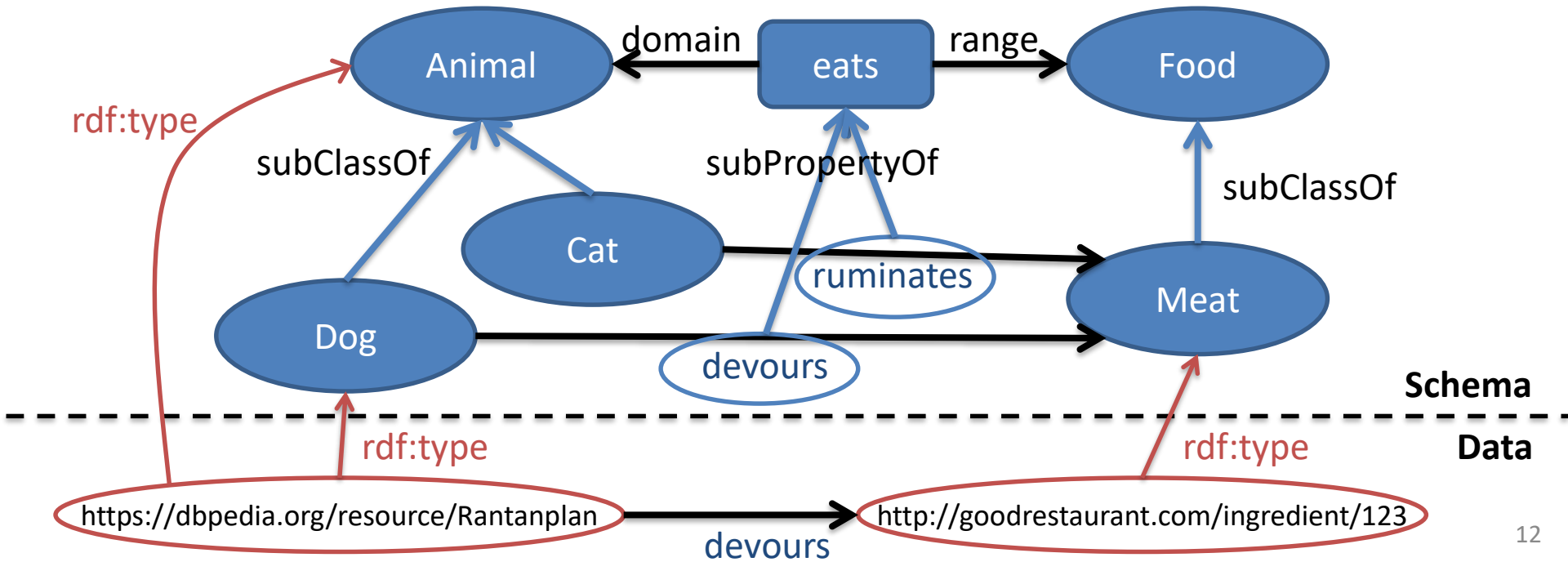
Summary

- 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



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*

Summary

- The Semantic Web
  - Ontologies: OWL
    - OWL ontology components
      - Terminology (TBox): domain vocabulary
      - Assertions (ABox): to store actual data
      - Roles (RBox): term articulation
    - Vocabulary components

Classes	Roles
Individuals	Object properties
Literals	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

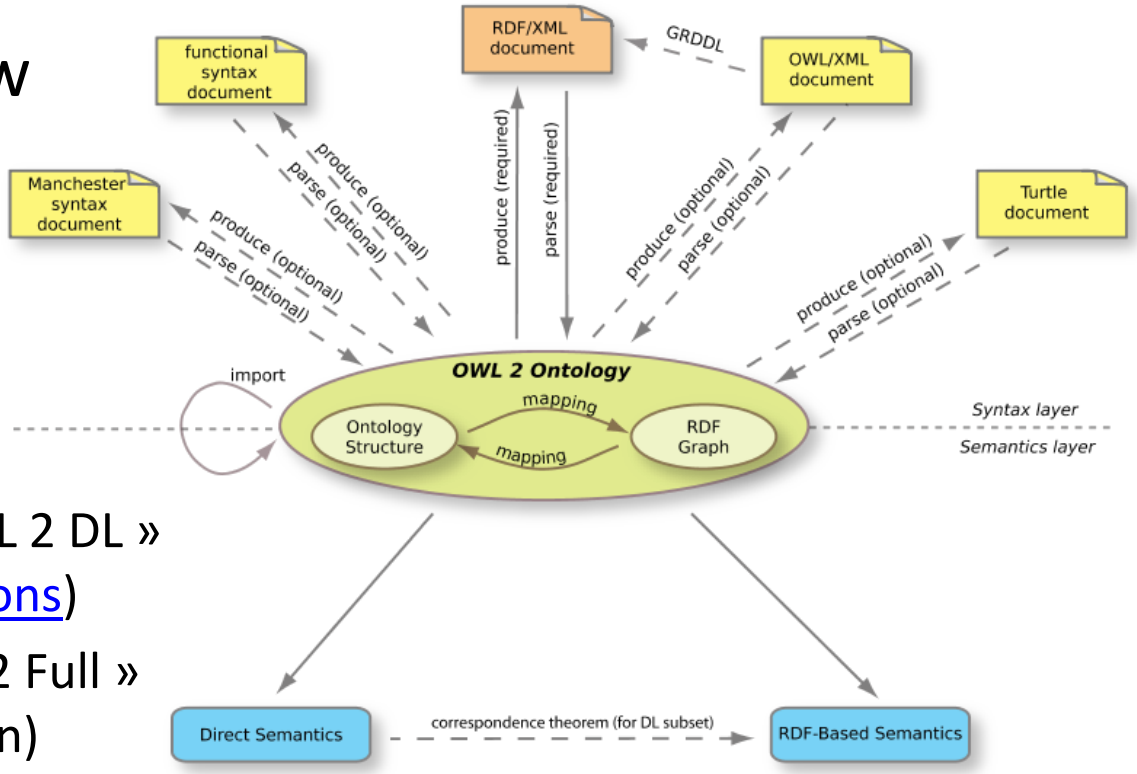
An OWL 2 ontology *O* is *satisfied* in an interpretation *I* if all axioms in the axiom closure of *O* are satisfied in *I*.

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 definitons: 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 overview
    - 5 serialization syntaxes
    - 2 semantics
      - Direct: « OWL 2 DL » (see restrictions)
      - RDF: « OWL 2 Full » (no restriction)



Source: https://www.w3.org/TR/owl2-overview/

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)	→	conclusion (body)
(I finished my homework) AND (the weather is nice)	→	**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
  - Deductive 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
  - 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

Condition (head)	→	conclusion (body)
(I finished my homework) AND (the weather is nice)	→	**I can go for a walk**

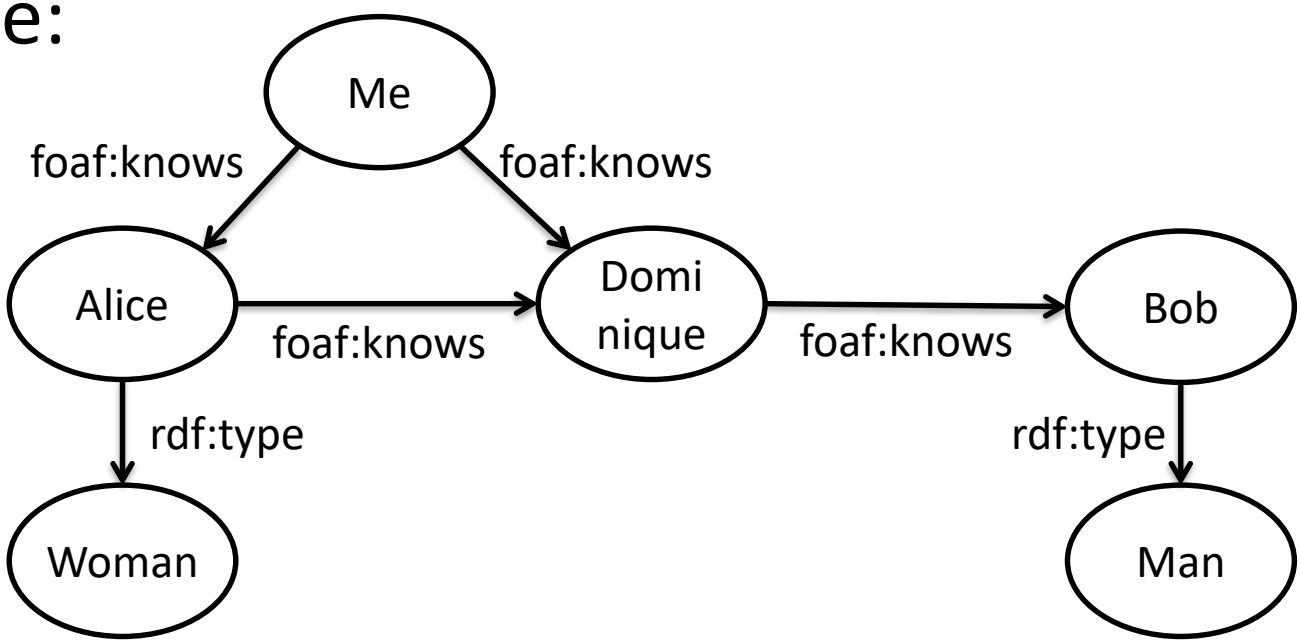
- Separate non-commutative operations in different queries
  - Deletions
  - Insertions

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

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?

Outline

- 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 and graph structures, and datatypes
- RDF entailments
  - Simple entailments: structural matching by renaming blank nodes
  - RDF entailments: interpret RDF vocabulary

RDF reasoning

- Simple entailment rules

Rule name	If E contains	then add
se1	`uuu aaa xxx .`	`uuu aaa _:nnn .` where _:nnn identifies a blank node allocated to xxx by rule se1 or se2.
se2	`uuu aaa xxx .`	`_:nnn aaa xxx .` where _:nnn identifies a blank node allocated to uuu by rule se1 or se2.
lg	`uuu aaa lll .`	`uuu aaa _:nnn .` where _:nnn identifies a blank node allocated to the literal lll by this rule.
gl	`uuu aaa _:nnn .` where _:nnn identifies a blank node allocated to the literal lll by rule lg.	`uuu aaa lll .`

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

RDF reasoning

- RDF entailment rules

Rule name	If E contains	then add
rdf1	`uuu aaa yyy .`	`aaa rdf:type rdf:Property .`
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.

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

RDF reasoning

- RDF axiomatic triples

```
rdf:type          rdf:type          rdf:Property .
rdf:subject       rdf:type          rdf:Property .
rdf:predicate     rdf:type          rdf:Property .
rdf:object        rdf:type          rdf:Property .
rdf:first         rdf:type          rdf:Property .
rdf:rest          rdf:type          rdf:Property .
rdf:value         rdf:type          rdf:Property .
rdf:_1            rdf:type          rdf:Property .
rdf:_2            rdf:type          rdf:Property .
...
rdf:nil           rdf:type          rdf:List .
```

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 → recommendation
  - Comparison → adaptation

RDF-S reasoning

- Deduce new information on
  - Hierarchy (subclassOf, subPropertyOf)
  - Individuals (rdf-type)

RDF-S reasoning

- RDF-S entailment rules (1/2)

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

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

RDF-S reasoning

- RDF-S entailment rules (2/2)

Rule name	If E contains	then add
rdfs6	uuu rdf:type rdf:Property .	uuu rdfs:subPropertyOf uuu .
rdfs7	aaa rdfs:subPropertyOf bbb uuu aaa yyy .	uuu bbb yyy .
rdfs8	uuu rdf:type rdfs:Class .	uuu rdfs:subClassOf rdfs:Resource .
rdfs9	uuu rdfs:subClassOf xxx . vvv rdf:type uuu .	vvv rdf:type xxx .
rdfs10	uuu rdf:type rdfs:Class .	uuu rdfs:subClassOf uuu .
rdfs11	uuu rdfs:subClassOf vvv . vvv rdfs:subClassOf xxx .	uuu rdfs:subClassOf xxx .
rdfs12	uuu rdf:type rdfs:ContainerMembershipProperty .	uuu rdfs:subPropertyOf rdfs:member .
rdfs13	uuu rdf:type rdfs:Datatype	uuu rdfs:subClassOf rdfs:Literal .

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

RDF-S reasoning

- RDF-S axiomatic triples (1/3)

```
rdf:type              rdfs:domain     rdfs:Resource .
rdfs:domain           rdfs:domain     rdf:Property .
rdfs:range            rdfs:domain     rdf:Property .
rdfs:subPropertyOf    rdfs:domain     rdf:Property .
rdfs:subClassOf       rdfs:domain     rdfs:Class .
rdf:subject           rdfs:domain     rdf:Statement .
rdf:predicate         rdfs:domain     rdf:Statement .
rdf:object            rdfs:domain     rdf:Statement .
rdfs:member           rdfs:domain     rdfs:Resource .
rdf:first             rdfs:domain     rdf:List .
rdf:rest              rdfs:domain     rdf:List .
rdfs:seeAlso          rdfs:domain     rdfs:Resource .
rdfs:isDefinedBy      rdfs:domain     rdfs:Resource .
rdfs:comment          rdfs:domain     rdfs:Resource .
rdfs:label            rdfs:domain     rdfs:Resource .
rdf:value             rdfs:domain     rdfs:Resource .
```

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

RDF-S reasoning

- RDF-S axiomatic triples (2/3)

```
rdf:type              rdfs:range      rdfs:Class .
rdfs:domain           rdfs:range      rdfs:Class .
rdfs:range            rdfs:range      rdfs:Class .
rdfs:subPropertyOf    rdfs:range      rdf:Property .
rdfs:subClassOf       rdfs:range      rdfs:Class .
rdf:subject           rdfs:range      rdfs:Resource .
rdf:predicate         rdfs:range      rdfs:Resource .
rdf:object            rdfs:range      rdfs:Resource .
rdfs:member           rdfs:range      rdfs:Resource .
rdf:first             rdfs:range      rdfs:Resource .
rdf:rest              rdfs:range      rdf:List .
rdfs:seeAlso          rdfs:range      rdfs:Resource .
rdfs:isDefinedBy      rdfs:range      rdfs:Resource .
rdfs:comment          rdfs:range      rdfs:Literal .
rdfs:label            rdfs:range      rdfs:Literal .
rdf:value             rdfs:range      rdfs:Resource .
```

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

RDF-S reasoning

- RDF-S axiomatic triples (3/3)

```
rdf:Alt                    rdfs:subClassOf            rdfs:Container .
rdf:Bag                    rdfs:subClassOf            rdfs:Container .
rdf:Seq                    rdfs:subClassOf            rdfs:Container .
rdfs:ContainerMembershipProperty rdfs:subClassOf rdf:Property .

rdfs:isDefinedBy           rdfs:subPropertyOf         rdfs:seeAlso .

rdf:XMLLiteral             rdf:type                   rdfs:Datatype .
rdf:XMLLiteral             rdfs:subClassOf            rdfs:Literal .
rdfs:Datatype              rdfs:subClassOf            rdfs:Class .

rdf:_1                     rdf:type  rdfs:ContainerMembershipProperty .
rdf:_1                     rdfs:domain                rdfs:Resource .
rdf:_1                     rdfs:range                 rdfs:Resource .
rdf:_2                     rdf:type  rdfs:ContainerMembershipProperty .
rdf:_2                     rdfs:domain                rdfs:Resource .
rdf:_2                     rdfs:range                 rdfs:Resource .
...
```

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/#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

- Consistency
- Subsumption
  - Equivalence
- Instance retrieval

➔ 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/

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"

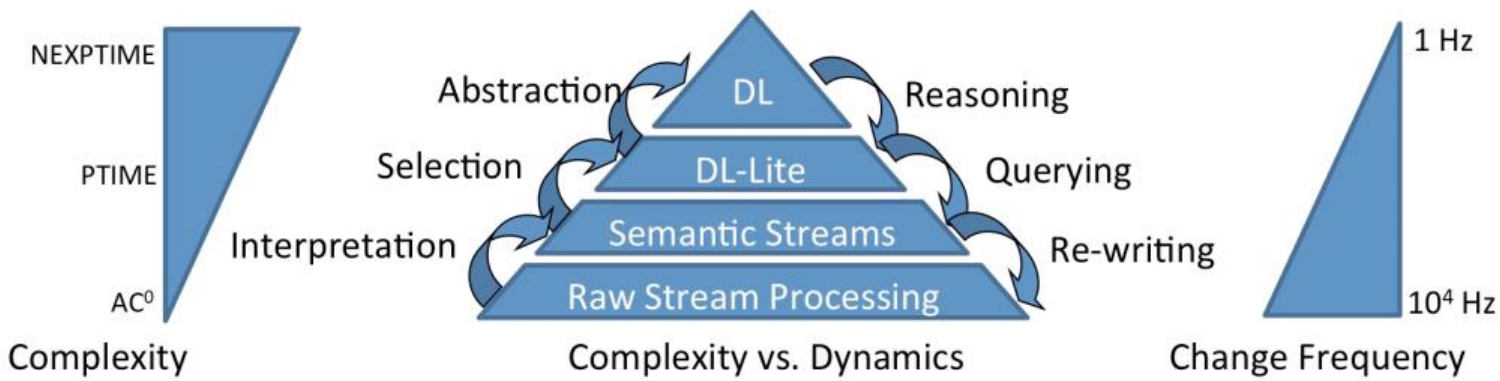
  ➔ minimizes storage space

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

Trade-offs between expressivity and complexity vs. speed of data processing



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

Source : https://www.w3.org/TR/owl2-profiles/#Computational_Properties

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

A note about complexity

- Practical considerations
  - ➔Restraining the set of used constructs to the necessary ones is a good practice
  - ➔Using **DL-safe rules** ensures all individuals are known beforehand

Example:

~~*parent(x, y) ∧ brother (y, z) → uncle(x, z)*~~

name(x), name(y), name(z), parent (x, y) ∧ brother(y, z) → uncle(x, z)

Where "name" is a class that "knows" all instances of the ontology

➔Reducing the size of requests can also help…

A note about complexity

- Practical considerations
  - A “tractable” reasoning process is polynomial
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  - In practice, polynomial reasoning is not necessarily achievable
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➔Restraining the set of used constructs to the necessary ones is a good practice

➔Reducing the size of requests can also help…

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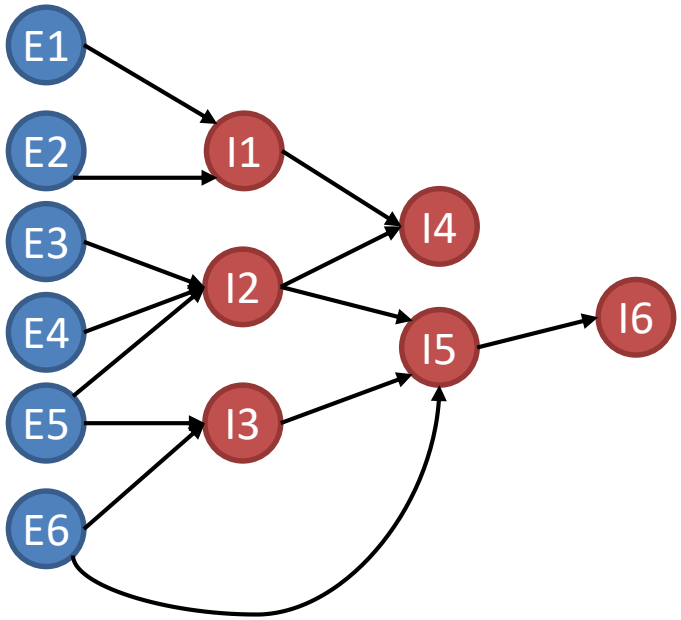
- Summary
- Web-based reasoning techniques
- Reasoning using SemWeb languages expressivity
- General aspects of reasoning
- **Reasoning on dynamic KBs**
  - Problem
  - Example of solution
- Conclusion

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
  - …

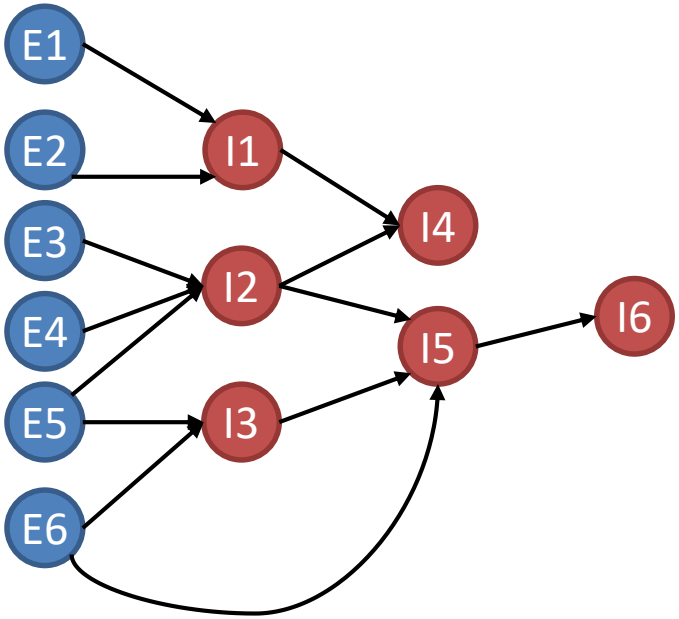
Reasoning on Dynamic Knowledge

- 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

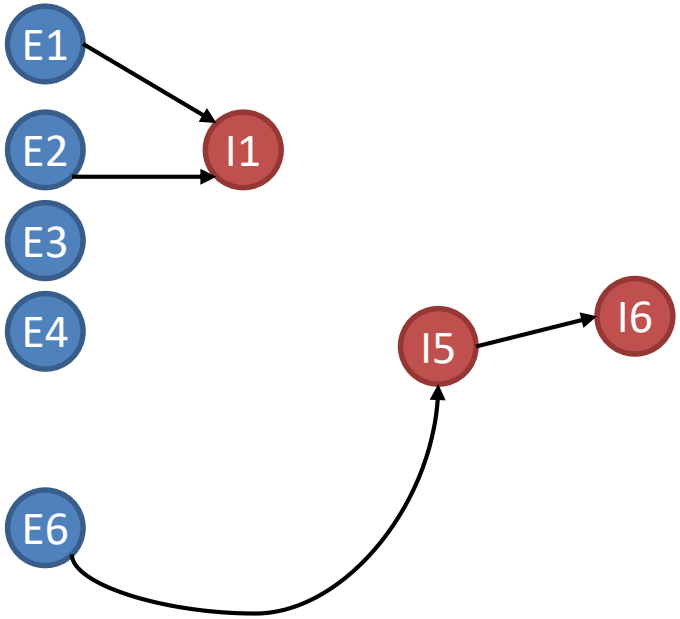
Reasoning on Dynamic Knowledge

- Incremental reasoning: example
  - E5 is removed

Overdeletion



Rederivation



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
  - …

Outline

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

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 (much) 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 mean 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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