Ontology Engineering

Lecture 1: Foundations of ontology engineering

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Foundations and recent trends on ontology engineering
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Outline

Administrivia (1/2)

- This course consists of two lectures of four hours, exercises, and a mini-project assignment in small groups
- Labs&self study about 4-6 hours
- Mini-project [100%], 8 hours (rough timeframe)
  - Topics will be distributed after this lecture
  - Need to from groups of 2-3 people and choose topic by next lecture
  - Deadline hand-in: 14 June
- Following the lectures will be easier and beneficial when you have read the recommended and required reading beforehand, and at least the 10-20 pages/chapter of the lecture notes

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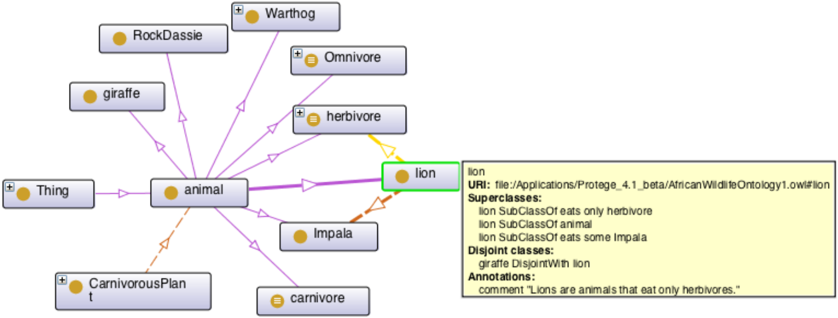
- ... there are lecture notes (though you still have to read some scientific literature)

Outline

An ontology (very informally)

- classes, relationships between them, and constraints that hold between/for them, with possibly individuals and their relations
- as a representation of a particular subject domain

'pretty' picture of a section of the AWO



¡ there's a lot going on behind the scenes !

Conceptual data models vs ontologies

- Main differences:
  - Information needs for one application vs. representing the knowledge of a subject domain (regardless the particular application)
  - Formalization in a logic language (though one could do that for conceptual models as well)

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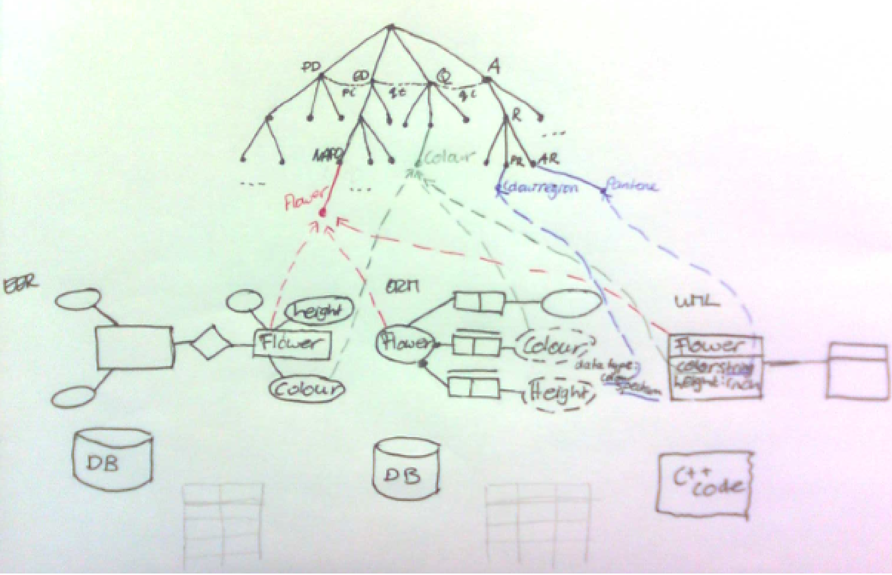
- An ontology as a layer on top of conceptual data models
  - To improve the quality of a conceptual data model (hence, the software)
  - To facilitate database integration, or prevent the usual data integration problems


PD
ED
Q
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NAPO
Colour
PR
AR
Flower
EER
ORM
UML
Height
Flower
Colour
Flower
Colour
Height
Flower
DB
DB
C++ code

Databases vs. Knowledge bases

- Main differences:
  - Representation of the knowledge
  - Rules
  - Reasoning to infer new or implicit knowledge, detect inconsistencies of the knowledge base
  - Open World Assumption (vs. Closed World Assumption in databases)

What is the usefulness of an ontology?

- Making, more or less precisely, the (dis-)agreement among people explicit
- Enrich software applications with the additional semantics ⇒ *ontology-driven information systems*
- Thus, practically, improving computer-computer, computer-human, and human-human communication

Outline

Examples ontologies in information systems

- **e-learning** with *Inquire Biology* [Chaudhri et al., 2013]: textbook annotated with terms of the ontology, generates questions and answers.
- **data integration, cultural heritage**: combining resources of data and querying them, on the ever interesting topic of food [Calvanese et al., 2016]
- **publishing** of scientific papers, books: enable navigation and understanding of scholarly documents [Di Iorio et al., 2014]
- **semantic meta-mining of data mining experiments** (sections 1 and 5 of [Keet et al., 2015]): mine the (ontology-based) annotations of the data mining experiments, reason over that to have it propose the optimal data mining experiment

More Examples

- **For science** Inside the scientific method: Outperforming humans (ontology+reasoner): classification of protein phosphatases [Wolstencroft et al., 2007]
- **Deep Question-Answering** with Watson beating human top-performers in 'Jeopardy!'; uses over 100 techniques, including ontologies for integration
- **Ontology-driven conceptual data modelling**: being more precise than just drawing diagrams, e.g., on those 'shared' and 'composite' aggregations in UML Class diagrams [Keet & Artale, 2008], finding contradictions.

The Semantic Web – Introduction (some motivations for ontologies and knowledge bases)

- AI put to the test in the (uncontrollable?) very large field
- Adding meaning to plain HTML pages and Web 2.0 by using theory and technologies of KBs and ontologies

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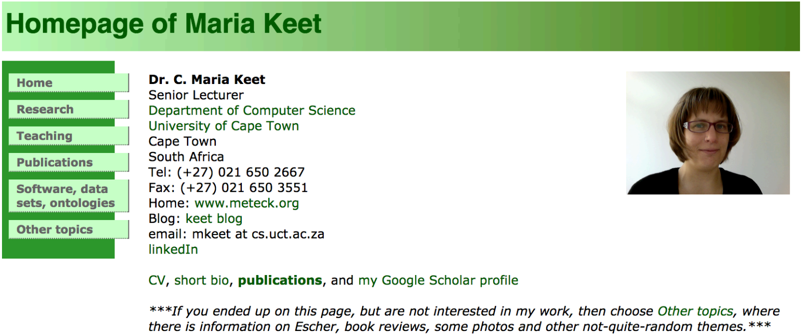

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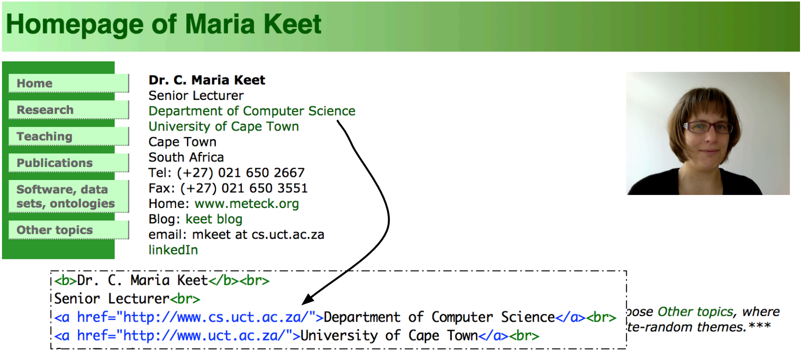

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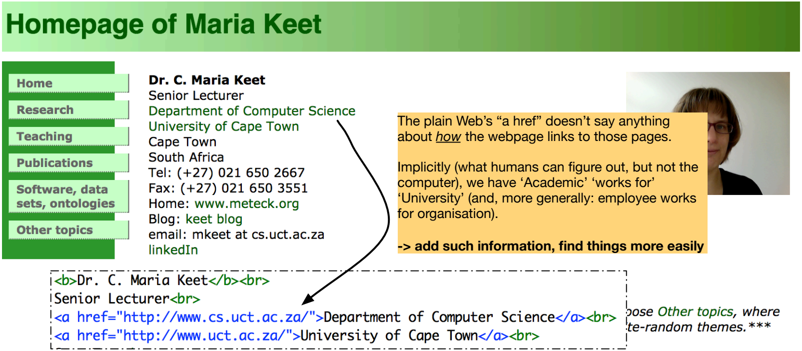


Generalising from the examples, ontologies are used for:

- Data(base) linking and integration
- Instance classification
- Matchmaking and services
- Querying, information retrieval
  - Ontology-Based Data Access
  - Ontologies to improve NLP
- Bringing more quality criteria into conceptual data modelling to develop a better model (hence, a better quality software system)

Outline

Background

– Aristotle and colleagues: **O**ntology
– Engineering: ontolog**ies** (count noun)

– Investigating reality, representing it
– Putting an engineering artefact to use

What then, is this engineering artefact?

(Guarino, 2002)

First, let's look at an artefact: a text file....

AfricanWildlifeOntology1.owl

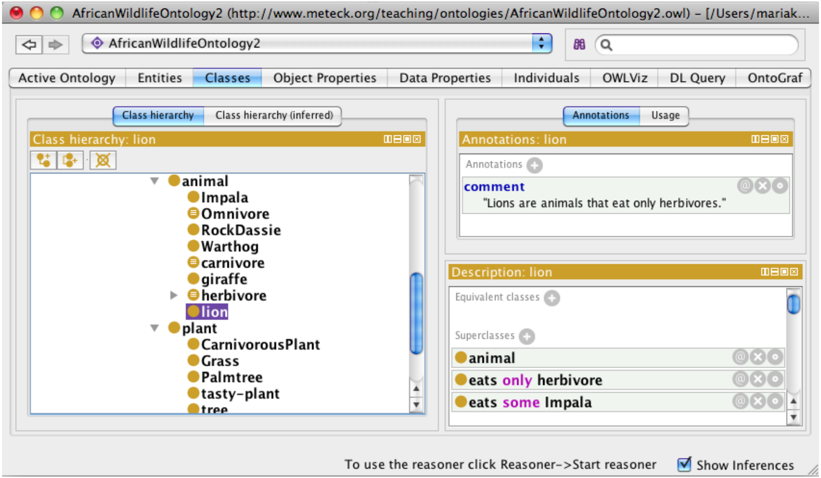
```
<owl:Class rdf:about="&AfricanWildlifeOntology1;lion">
    <rdfs:subClassOf rdf:resource="&AfricanWildlifeOntology1;animal"/>
    <rdfs:subClassOf>
        <owl:Restriction>
            <owl:onProperty rdf:resource="&AfricanWildlifeOntology1;eats"/>
            <owl:allValuesFrom rdf:resource="&AfricanWildlifeOntology1;herbivore"/>
        </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:subClassOf>
        <owl:Restriction>
            <owl:onProperty rdf:resource="&AfricanWildlifeOntology1;eats"/>
            <owl:someValuesFrom rdf:resource="#Impala"/>
        </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:comment>Lions are animals that eat only herbivores.</rdfs:comment>
</owl:Class>



<!-- file:/Applications/Protege_4.1_beta/AfricanWildlifeOntology1.owl#plant -->

<owl:Class rdf:about="&AfricanWildlifeOntology1;plant">
    <rdfs:comment>Plants are disjoint from animals.</rdfs:comment>
</owl:Class>
```

… and rendered in an ontology editor



A few definitions on what the text in the file is supposed to stand for

- Most cited (but very inadequate definition): "An ontology is a specification of a conceptualization" (by Tom Gruber, 1993)
- "a formal specification of a shared conceptualization" (by Borst, 1997)
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- "a formal specification of a shared conceptualization" (by Borst, 1997)
- "An ontology is a formal, explicit specification of a shared conceptualization" (Studer et al., 1998)
- What is a *conceptualization*, and a *formal, explicit specification*? Why *shared*?

More definitions

- More detailed: "An ontology is a logical theory accounting for the *intended meaning* of a formal vocabulary, i.e. its *ontological commitment* to a particular *conceptualization* of the world. The intended models of a logical language using such a vocabulary are constrained by its ontological commitment. An ontology indirectly reflects this commitment (and the underlying conceptualization) by approximating these intended models." (Guarino, 1998)

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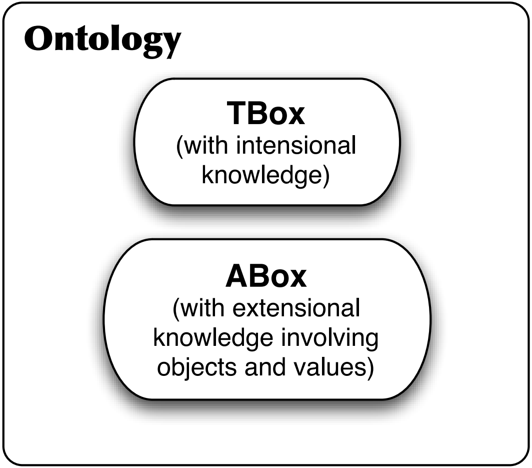
- And back to a simpler definition: "with an ontology being equivalent to a Description Logic knowledge base" (Horrocks et al, 2003)

Description Logic knowledge base



From logical to ontological level (1/2)

- Logical level (no structure, no constrained meaning[1]):
  - $\exists x (Apple(x) \wedge Green(x))$
  - "there exists an object that is an apple and it is green"

adapted from (Guarino, 2008)

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  - ~~$Green(a)$ and $hasShape(a, apple)$~~
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- Put differently: one way of representing things turn out to be *better* than others.

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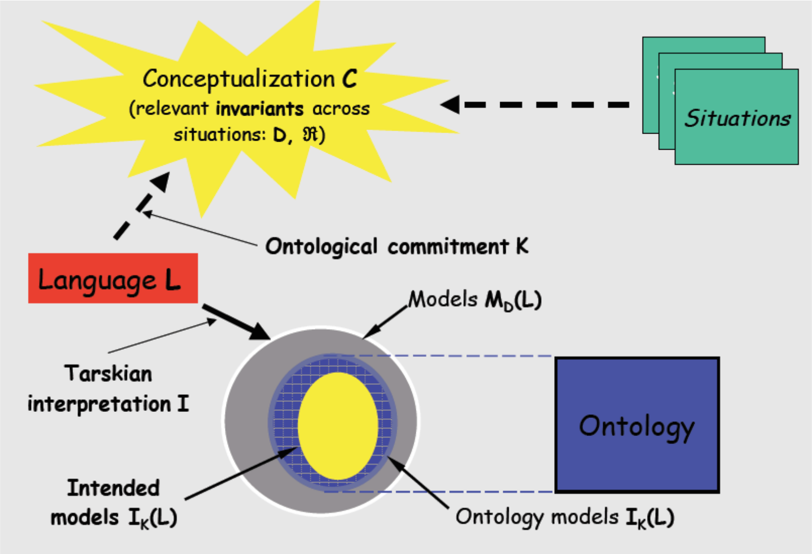
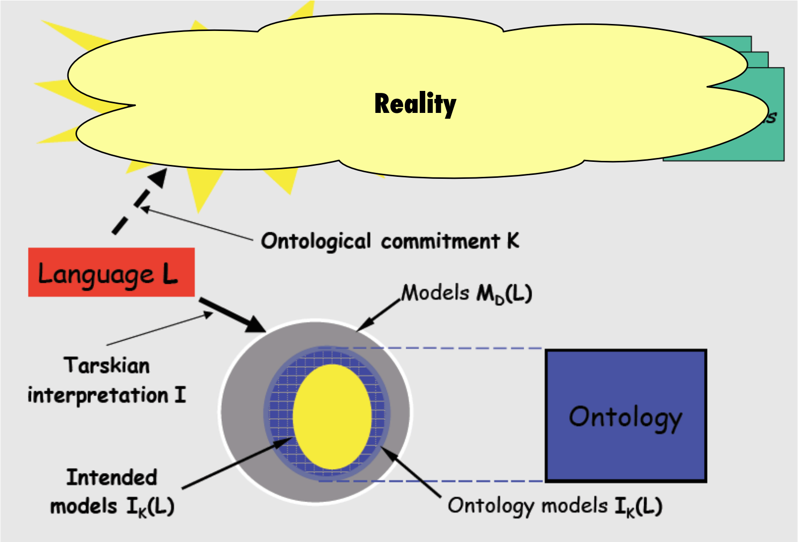
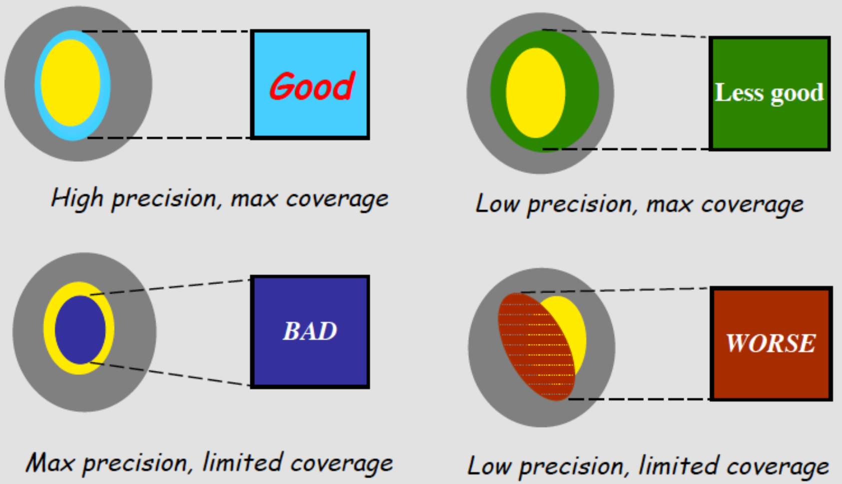
Ontologies and meaning



Ontologies and reality



Quality of the ontology



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Outline

Preliminary note

- There are only a few core concepts to get the general idea
- There are very many details
- Here we focus on the core concepts and some details and how that works out in computing
- More logic and details in the lecture notes

How to formalise it?

- Logics have a:
  - Syntax
    - Alphabet
    - Languages constructs
    - Sentences to assert knowledge
  - Semantics
    - Formal meaning

Several ontology languages

- W3C-standardised Web Ontology Language OWL, comes in many ‘species’
  - Description Logics-based OWL species
  - OWL full and OWL 2 full (RDF-based semantics)
- Common logic, CLIF
- First order logic
- Fuzzy and temporal extensions and variants

DLs are structured fragments of FOL

- Recall that full FOL is undecidable
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- Recall that full FOL is undecidable
- This is unpleasant for automated reasoning
- Approach: find a fragment—a *sublanguage*—of FOL that is decidable
- Take some features, prove the computational complexity of some problem

DLs are structured fragments of FOL

- We end up with *trade-offs* of features in a DL
- Some features always will make the language undecidable (e.g., true role composition, $R \circ S \equiv T$)
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  - $\exists R$ only on the rhs of the inclusion but not on the lhs
- There are *many* DLs, and most combinations have been investigated over the past 25 years
- Roughly: the fewer features and the more restrictions, the more 'computationally well-behaved' the language is

On those OWL ‘species’

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    - OWL 2 EL
    - OWL 2 QL
    - OWL 2 RL
  - OWL 2 DL
  - OWL 2 full

OWL 2 DL Overview

- Has more features than OWL DL
- Computationally more ‘costly’ (N2EXPTIME-complete cf EXPTIME-complete)
- Based on the DL language $\mathcal{SROIQ}$
- Main novelty especially w.r.t. modelling practices: qualified cardinality constraints, more ‘characteristics’ of object properties

OWL 2 EL Overview

- Intended for large ‘simple’ ontologies
- Focussed on type-level knowledge (TBox)
- Better computational behaviour than OWL 2 DL (polynomial vs. exponential/open)
- Based on the DL language $\mathcal{EL}^{++}$ (PTime complete)
- Reasoner: e.g. CEL `http://code.google.com/p/cel/`
- $\sqcap \exists \top \bot \quad \sqsubseteq \quad \sqcap \exists \top \bot$

OWL 2 QL Overview

- Query answering over a large amount of instances with same kind of performance as relational databases (Ontology-Based Data Access)
- Expressive features cover several used features of UML Class diagrams and ER models ('COnceptual MOdel-based Data Access')
- Based on *DL-Lite*$_{\mathcal{R}}$ (*more is possible with UNA and in some implementations*)

OWL 2 RL Overview

- Development motivated by: what fraction of OWL 2 DL can be expressed by rules (with equality)?
- Scalable reasoning in the context of RDF(S) application
- Rule-based technologies (forward chaining rule system, over *instances*)
- Inspired by Description Logic Programs and pD*
- Reasoning in PTime
- No $\forall$ and $\neg$ on lhs, and $\exists$ and $\sqcup$ on rhs of $\sqsubseteq$

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- RDF/XML
  - Official exchange syntax
  - Hard for humans to read (and RDF parsers are hard to write)
- OWL/XML
  - Not the RDF syntax
  - Still hard for humans, but more XML than RDF tools available
- Abstract syntax
  - To some, considered human readable
- "User-usable" ones
  - e.g., Manchester syntax, informal and limited matching with UML, pseudo-NL verbalisations

Example correspondences

- ‘Each C is a D’ / ‘All Cs are Ds’
  - `SubClassOf(C D)`
  - $C \sqsubseteq D$
  - $\forall x(C(x) \rightarrow D(x))$

e.g.: $Giraffe \sqsubseteq Animal$

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- ‘Each C R at least one D’ / ‘Each C R some D’
  - `SubClassOf(C ObjectSomeValueFrom(R D))`
  - $C \sqsubseteq \exists R.D$
  - $\forall x(C(x) \rightarrow \exists y(R(x, y) \wedge D(y))$

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- ‘C and D are disjoint’ / ‘each C is not a D’
  - `DisjointClasses(C D)` / `SubClassOf(C ObjectComplementOf(D))`
  - $C \sqcap D \sqsubseteq \bot$ (disj.) / $C \sqsubseteq \neg D$ (complement)
  - $\forall x(C(x) \rightarrow \neg D(x))$

  e.g.: $Herbivore \sqsubseteq \neg Carnivore$

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- Interpretation: $\cdot^{\mathcal{I}}$ is the *interpretation function*, domain $\Delta^{\mathcal{I}}$
  - $\cdot^{\mathcal{I}}$ maps every concept name A to a subset $A^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}}$
  - $\cdot^{\mathcal{I}}$ maps every role name R to a subset $R^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$
  - $\cdot^{\mathcal{I}}$ maps every individual name a to elements of $\Delta^{\mathcal{I}}$: $a^{\mathcal{I}} \in \Delta^{\mathcal{I}}$
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- Note: $\top^{\mathcal{I}} = \Delta^{\mathcal{I}}$ and $\bot^{\mathcal{I}} = \emptyset$
- An interpretation $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$ is a model of a knowledge base $\mathcal{KB}$ if every axiom of $\mathcal{KB}$ is satisfied by $\mathcal{I}$
- A knowledge base $\mathcal{KB}$ is said to be satisfiable if it admits a model

Essential to automated reasoning (Ch2 of LN)

- The choice of the class of problems the software program has to solve
- The formal language in which to represent the problems
- The way how the program has to compute the solution
- How to do this efficiently

Reasoning services for DL-based OWL ontologies

- Concept (and role) satisfiability ($\mathcal{KB} \not\models C \sqsubseteq \bot$)
  - is there a model of $\mathcal{KB}$ in which C (resp. R) has a nonempty extension?

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- Consistency of the knowledge base ($\mathcal{KB} \not\models \top \sqsubseteq \bot$)
  - Is the $\mathcal{KB} = (\mathcal{T}, \mathcal{A})$ consistent (non-selfcontradictory), i.e., is there at least a model for $\mathcal{KB}$?

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  - Is the $\mathcal{KB} = (\mathcal{T}, \mathcal{A})$ consistent (non-selfcontradictory), i.e., is there at least a model for $\mathcal{KB}$?
- Concept (and role) subsumption ($\mathcal{KB} \models C \sqsubseteq D$)
  - i.e., is the extension of C (resp. R) contained in the extension of D (resp. S) in every model of $\mathcal{T}$?

Reasoning services for DL-based OWL ontologies

- Concept (and role) satisfiability ($\mathcal{KB} \not\models C \sqsubseteq \bot$)
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- Instance checking ($\mathcal{KB} \models C(a)$ or $\mathcal{KB} \models R(a, b)$)
  - is a (resp. (a, b)) a member of concept C (resp. R) in $\mathcal{KB}$, i.e., is the fact $C(a)$ (resp. $R(a, b)$) satisfied by every interpretation of $\mathcal{KB}$?

Reasoning services for DL-based OWL ontologies

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  - is a (resp. (a, b)) a member of concept C (resp. R) in $\mathcal{KB}$, i.e., is the fact $C(a)$ (resp. $R(a, b)$) satisfied by every interpretation of $\mathcal{KB}$?
- Instance retrieval ($\{a \mid \mathcal{KB} \models C(a)\}$)
  - find all members of C in $\mathcal{KB}$, i.e., compute all individuals a s.t. $C(a)$ is satisfied by every interpretation of $\mathcal{KB}$

Logical implication

- $\mathcal{KB} \models \phi$ if every model of $\mathcal{KB}$ is a model of ϕ

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- Example:
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  ABox: $\mathtt{TEACHES}(\mathtt{John}, \mathtt{cs101})$, $\mathtt{Course}(\mathtt{cs101})$, $\mathtt{Undergrad}(\mathtt{John})$

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- $\mathcal{KB} \models \mathtt{Professor}(\mathtt{John})$

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  ABox: $\mathtt{TEACHES(John, cs101)}$, $\mathtt{Course(cs101)}$, $\mathtt{Undergrad(John)}$
- $\mathcal{KB} \models \mathtt{Professor(John)}$
- What if:
  TBox: $\exists \mathtt{TEACHES.Course} \sqsubseteq \mathtt{Undergrad} \sqcup \mathtt{Professor}$
  ABox: $\mathtt{TEACHES(John, cs101)}$, $\mathtt{Course(cs101)}$, $\mathtt{Undergrad(John)}$
- $\mathcal{KB} \models \mathtt{Professor(John)}$? or perhaps $\mathcal{KB} \models \neg\mathtt{Professor(John)}$?

Automated reasoning techniques

- How do we compute, say, satisfiability?

Automated reasoning techniques

- How do we compute, say, satisfiability?
- Truth tables are too cumbersome
- Several techniques are more efficient
- Current ‘winner’ is *tableau reasoning*

The idea, same as for FOL

- A sound and complete procedure deciding satisfiability is all we need, and the **tableaux method is a decision procedure which checks the existence of a model**
- It exhaustively looks at all the possibilities, so that it can eventually prove that no model could be found for unsatisfiable formulas.
- $\phi \models \psi$ iff $\phi \land \neg\psi$ is NOT satisfiable—if it is satisfiable, we have found a counterexample
- Decompose the formula in top-down fashion

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- $\phi \models \psi$ iff $\phi \wedge \neg\psi$ is NOT satisfiable—if it is satisfiable, we have found a counterexample
- Decompose the formula in top-down fashion
- Following slide *simplified* process (thanks to Markus Krötzsch & Sebastian Rudolph ESSLLI 2009 Bordeaux)

Automated reasoning

Knowledge Base

ex:Healthy rdfs:subClassOf [owl:complementOf ex:Dead] .
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ex:HappyCatOwner

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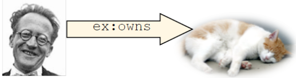

ex:HappyCatOwner
[owl:intersectionOf (,)]

ex:Cat

Automated reasoning

Knowledge Base

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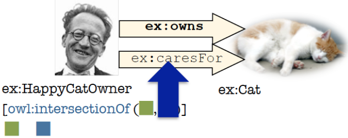

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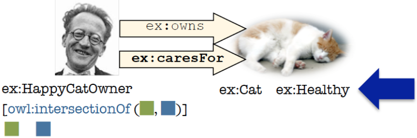

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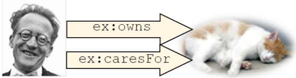

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ex:Cat ex:Healthy
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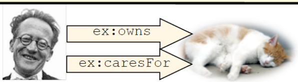

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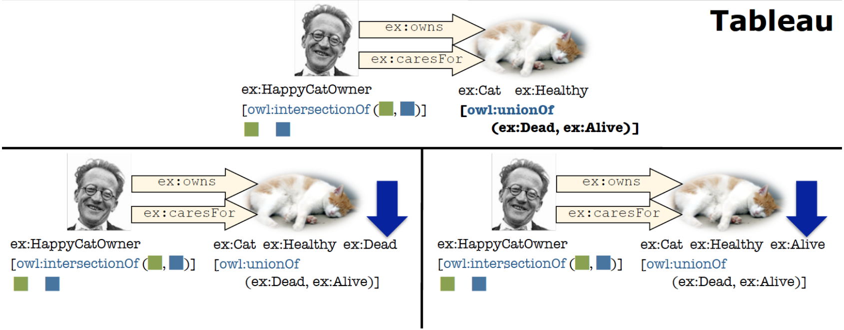

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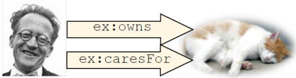
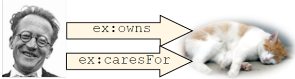


ex:HappyCatOwner
[owl:intersectionOf (,)]

ex:Cat ex:Healthy
[owl:unionOf
(ex:Dead, ex:Alive)]



ex:HappyCatOwner
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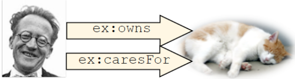
ex:Cat **ex:Healthy** ex:Dead
[owl:unionOf
(ex:Dead, ex:Alive)]
[owl:complementOf ex:Dead]



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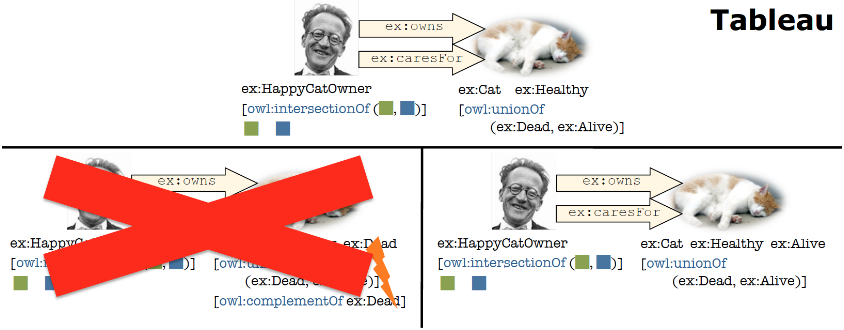

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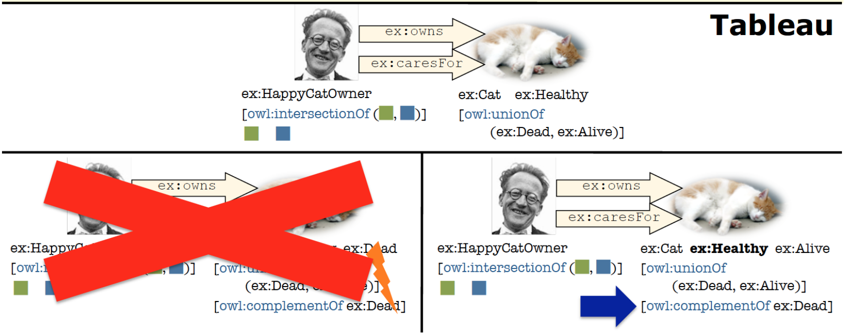

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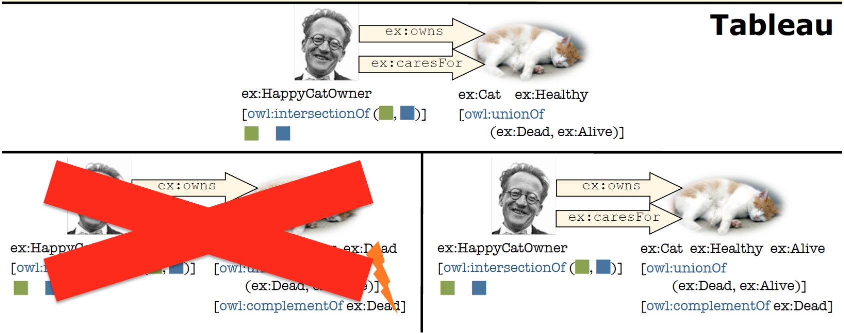

Automated reasoning

Knowledge Base

Satisfiable

ex:Healthy rdfs:subClassOf [owl:complementOf ex:Dead] .
ex:Cat rdfs:subClassOf [owl:unionOf (ex:Dead, ex:Alive)] .
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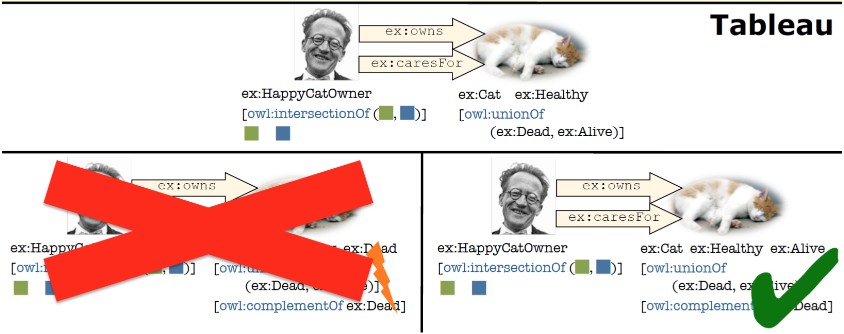
Tableau



Summary

1. Introduction
2. Where is it used?
3. What is an Ontology?
4. Logic and automated reasoning
   - Representation languages
   - Automated reasoning

Exercises

- Chapter 1: exercises 1 and 2
- Chapter 3: exercises 5 (optionally 6)
- Chapter 4: exercises 8, 10, 14-21
- Read the mini-project topics (optionally also looking up what some of those terms mean) and select one

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- Chapter 1: exercises 1 and 2
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- Read the mini-project topics (optionally also looking up what some of those terms mean) and select one
- The tutorial ontologies are available from `http://www.meteck.org/teaching/ontologies/`

Additional references

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Supported class restrictions OWL 2 EL

- existential quantification to a class expression or a data range
- existential quantification to an individual or a literal
- self-restriction
- enumerations involving a single individual or a single literal
- intersection of classes and data ranges

Supported axioms, restricted to allowed set of class expressions OWL 2 EL

- class inclusion, equivalence, disjointness
- object property inclusion and data property inclusion
- property equivalence
- transitive object properties
- reflexive object properties
- domain and range restrictions
- assertions
- functional data properties
- keys
- In short: $\sqcap\ \exists\ \top\ \bot\ \sqsubseteq\ \sqcap\ \exists\ \top\ \bot$

NOT supported in OWL 2 EL

- universal quantification to a class expression or a data range
- cardinality restrictions
- disjunction
- class negation
- enumerations involving more than one individual
- disjoint properties
- irreflexive, symmetric, and asymmetric object properties
- inverse object properties, functional and inverse-functional object properties

Supported Axioms in OWL 2 QL, restrictions

- Subclass expressions restrictions:
  - a class
  - existential quantification (ObjectSomeValuesFrom) where the class is limited to owl:Thing
  - existential quantification to a data range (DataSomeValuesFrom)
- Super expressions restrictions:
  - a class
  - intersection (ObjectIntersectionOf)
  - negation (ObjectComplementOf)
  - existential quantification to a class (ObjectSomeValuesFrom)
  - existential quantification to a data range (DataSomeValuesFrom)

Supported Axioms in OWL 2QL

- Restrictions on class expressions, object and data properties occurring in functionality assertions cannot be specialized
- subclass axioms
- class expression equivalence (involving subClassExpression), disjointness
- inverse object properties
- property inclusion (not involving property chains and SubDataPropertyOf)
- property equivalence
- property domain and range
- disjoint properties
- symmetric, reflexive, irreflexive, asymmetric properties
- assertions other than individual equality assertions and negative property assertions (DifferentIndividuals, ClassAssertion, ObjectPropertyAssertion, and DataPropertyAssertion)

NOT supported in OWL 2 QL

- existential quantification to a class expression or a data range in the subclass position
- self-restriction
- existential quantification to an individual or a literal
- enumeration of individuals and literals
- universal quantification to a class expression or a data range
- cardinality restrictions
- disjunction
- property inclusions involving property chains
- functional and inverse-functional properties
- transitive properties
- keys
- individual equality assertions and negative property assertions

Supported in OWL 2 RL

- More restrictions on class expressions (see table 2, e.g. no SomeValuesFrom on the right-hand side of a subclass axiom)
- All axioms in OWL 2 RL are constrained in a way that is compliant with the restrictions in Table 2.
- Thus, OWL 2 RL supports all axioms of OWL 2 apart from disjoint unions of classes and reflexive object property axioms.
- No $\forall$ and $\neg$ on lhs, and $\exists$ and $\sqcup$ on rhs of $\sqsubseteq$