Introduction to Ontology Engineering

with emphasis on Semantic Web Technologies

C. Maria Keet

KRDB Research Center
Free University of Bozen-Bolzano, Italy

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Housekeeping points

- This course consists of lectures and exercises
- Each lecture takes about 2.5 hours, labs 45 minutes
- Following the lectures will be easier when you have read the recommended reading beforehand and it is assumed the student is familiar with first order logic and conceptual data modelling, such as UML and ER
- The topics covered in this course are of an **introductory** nature and due to time constraints only a selection of core and elective topics will be addressed.
- These slides serve as a teaching aid, not as a neat summary
- Course webpage, with introduction, references, and schedule: `http://www.meteck.org/teaching/SA/MOWS10OntoEngCouse.html`

Outline

1. Introduction to ontologies
2. Ontology Languages: OWL and OWL2
3. Foundational and top-down aspects of ontology engineering
4. Bottom-up ontology development
5. Methods and methodologies
6. Extra topic
    Representation and reasoning challenges

Part I

Introduction to ontologies

Outline

1. What is an ontology?
2. What is the usefulness of an ontology?
3. Success stories
   - The GO and data integration
   - Exploiting the classification reasoning services

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Background

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

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

What then, is this engineering artifact?

(Guarino, 2002)

A few definitions

- Most quoted: "An ontology is a specification of a conceptualization" (by Tom Gruber, 1993)
- "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*?

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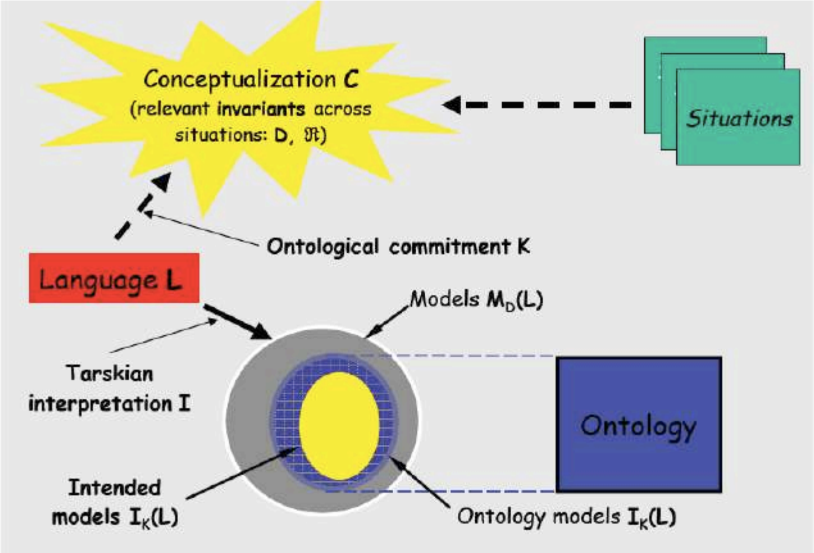
Ontologies and meaning



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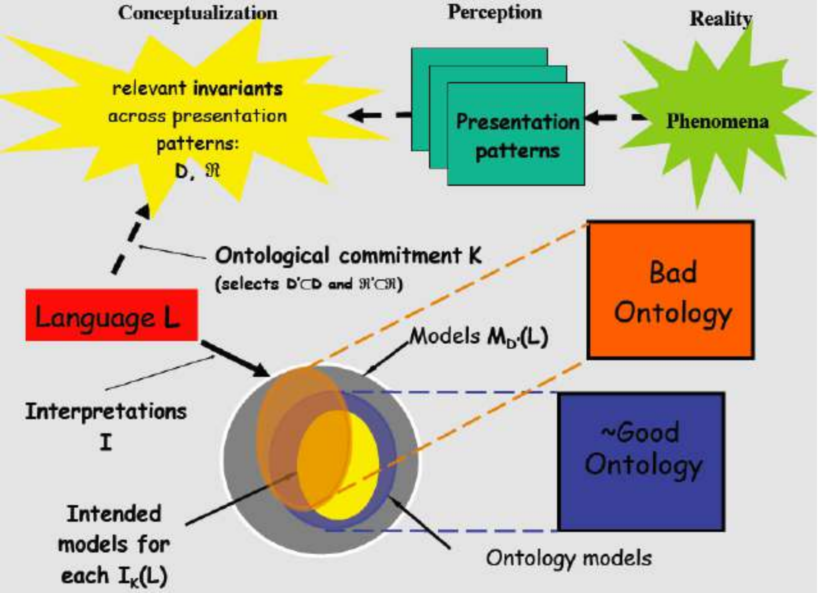
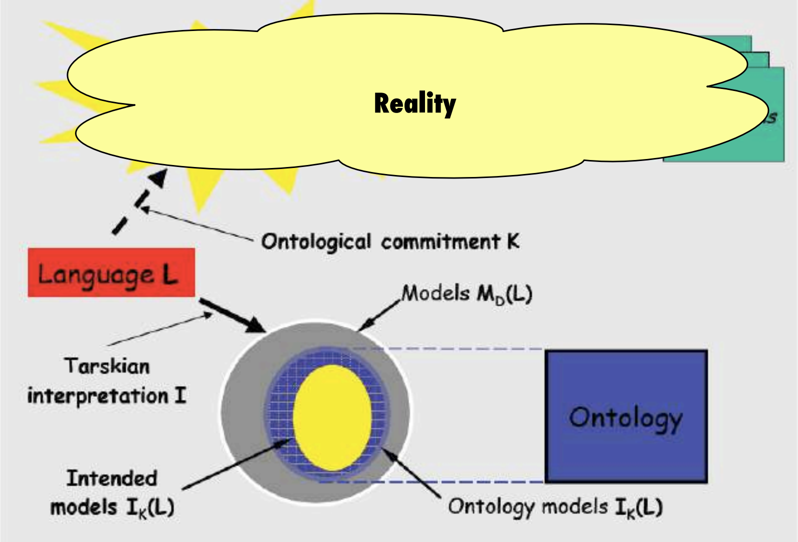


Ontologies and reality



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

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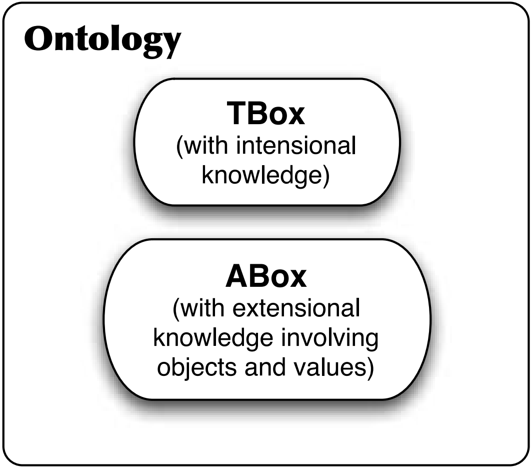
Description Logic knowledge base



From logical to ontological level

- Logical level (no structure, no constrained meaning[1]):
  - $\exists x(Apple(x) \wedge Red(x))$
- Epistemological level (structure, no constrained meaning):
  - $\exists x : apple.\ Red(x)$ (many-sorted logics)
  - $\exists x : red.\ Apple(x)$
  - $Apple(a)$ and $hasColor(a, red)$ (description logics[2])
  - $Red(a)$ and $hasShape(a, apple)$
- Ontological level (structure, constrained meaning):
  - Some structuring choices are excluded because of ontological constraints
  - *Apple* carries an identiy condition (and is a sortal), *Red* does not (is a qualia ['value'] of the quality ['attribute'] *hasColor* that a thing has)

adapted from (Guarino, 2008)

[1] well, meaning in the sense of subject domain semantics

[2] Likewise, DL has a formal, (model-theoretic) semantics, so the axioms have a meaning in that sense of 'meaning/semantics'

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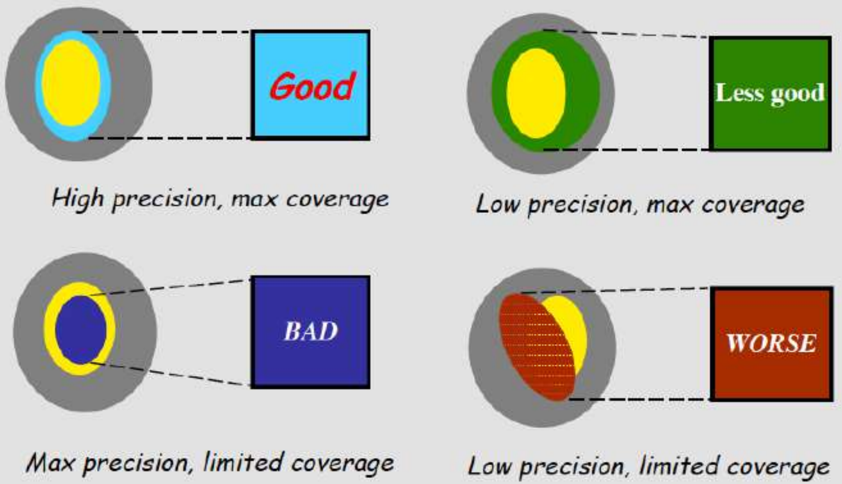

(Guarino, 2002)

Quality of the ontology

- "Bad ontologies are (inter alia) those whose general terms lack the relation to corresponding universals in reality, and thereby also to corresponding instances." $\Rightarrow$ need for grounding
- "Good ontologies are reality representations, and the fact that such representations are possible is shown by the fact that, as is documented in our scientific textbooks, very many of them have already been achieved, though of course always only at some specific level of granularity and to some specific degree of precision, detail and completeness."

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Initial Ontology Dimensions that have Evolved

- Semantic
  - Degree of Formality and Structure
  - Expressiveness of the Knowledge Representation Language
  - Representational Granularity
- Pragmatic
  - Intended Use
  - Role of Automated Reasoning
  - Descriptive vs. Prescriptive
  - Design Methodology
  - Governance

slide from, and more details available in: http://ontolog.cim3.net/file/work/OntologySummit2007/symposium/

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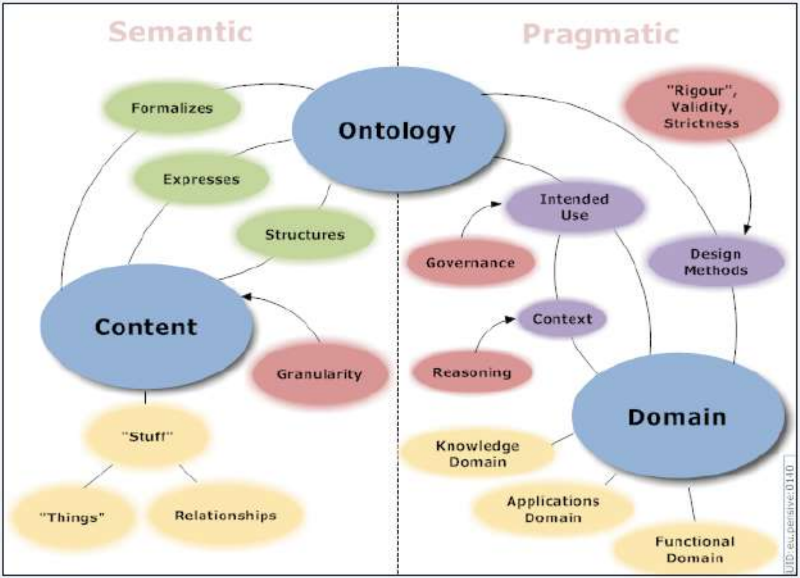
And graphically



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3. Success stories
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- Making, more or less precisely, the (dis-)agreement among people explicit
- Enrich software applications with the additional semantics
- Thus, practically, improving: computer-computer, computer-human, and human-human communication

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Examples in different application areas, using different features

- **Data(base) integration** (example today)
- Instance classification (example today)
- 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)
- Orchestrating the components in semantic scientific workflows, e-learning, etc.

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Success?

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  - How much "semantics" (with ontologies)?
  - SemWeb stack, technologies
- Absolute measures? e.g.,
  - Usage of Amazon's recommender system with and without ontologies
  - Information retrieval: compare precision and recall between a statistics-based and a ontologies-mediated document system
  - Feasibility and performance of a set of user queries posed to a RDBMS and its RDF-ised version
- Relative measures
  - According to whom is it a success?
    - philosopher, logician, engineer, domain expert, CEO...
  - What was taken as baseline material? e.g.,
    - from string search in a digital library to ontology-annotated sorting of query answer
    - from no or clustering-based instance classification to one with OWL-based knowledge bases

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Early bioinformatics

- Advances in technologies to sequence genomes in the late '80s-early'90s, as well as more technologies for proteins
- Need to store the data: in databases ('90s)
- Several 'model organism' databases with genes (and genomes) of the fruitfly, yeast, mouse, a flowering plant, flatworm, zebrafish
- Compare genes and genomes
  - One observation (of many): About 12% (some 18,000) of the worm genes encode proteins whose biological roles could be inferred from their similarity to their (putative) orthologues in yeast, comprising about 27% of the yeast genes (about 5,700)
  - *What else can we infer from comparing genes and genomes (across species)?*
  - *What about the possibility of automated transfer of biological annotations from the model organisms to less 'fancy' organisms based on gene and protein sequence similarity, to use to improve human health or agriculture?*

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Scope and requirements

- Need: a mainly computational system for comparing or transferring annotation among different species
- Methods for sequence comparison existed
- Main requirements:
  - One needs a shared, controlled, vocabulary for annotation of the gene products, the *location* where they are active, the *function* they perform
  - To take on board and be compatible with existing terminologies, like gene and protein keyword databases such as UniProt, GenBank, Pfam, ENZYME etc.
  - Database interoperability among, at least, the model organism databases
  - Organize, describe, query and visualize biological knowledge at vastly different stages of completeness
  - Any system must be flexible and tolerant of this constantly changing level of knowledge and allow updates on a continuing basis

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How to meet such requirements?

- Two main strands in activities:
  - Very early adopters from late 1990s (by sub-cellular bio), i.e., starting *without* Semantic Web Technologies
  - Early adopters from mid 2000s (e.g., eco and agri), starting *with* Semantic Web Technologies
- The Gene Ontology Consortium
  - Initiated by fly, yeast and mouse database curators[3] and others came on board (see http://ww.geneontology.org for a full list)
  - In the beginning, there was the flat file format .obo to store the ontologies, definitions of terms and gene associations
  - Several techniques on offer for data(base) integration that could be experimented with

[3] more precisely: FlyBase (http://www.flybase.bio.indiana.edu), Berkeley Drosophila Genome Project (http://fruitfly.bdgp.berkeley.edu), Saccharomyces Genome Database (http://genome-www.stanford.edu), and Mouse Genome Database and Gene Expression Database (http://www.informatics.jax.org)

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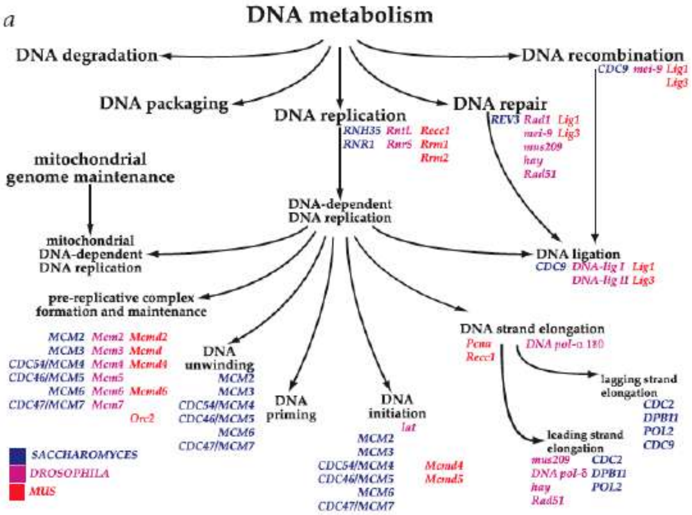
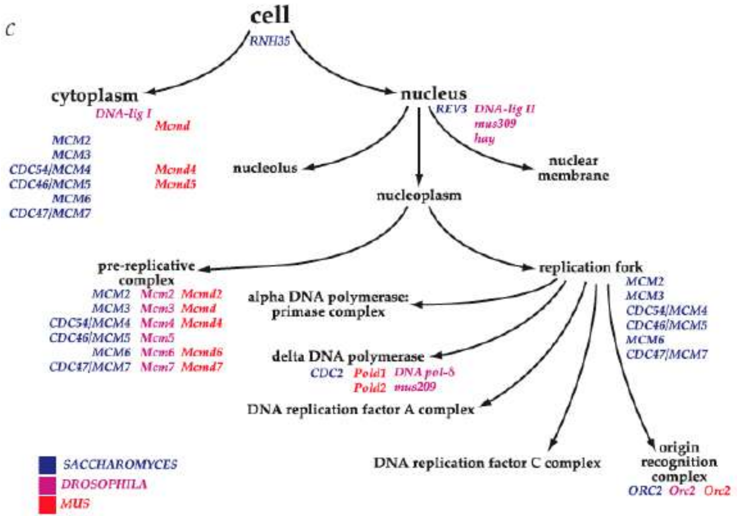
GO contents example (process)



GO contents example (cellular component)



from GOC, 2000

Progress

- Tool development, e.g. to:
  - add and query its contents
  - annotate genes (semi-automatically)
  - link the three GO ontologies
  - mine the literature (NLP)
- Content development: more in the GO, extensions to the GO (e.g., rice traits), copy of the principle to other subject domains (e.g., zebrafish anatomy)
- The GO and its approach went well beyond the initial scope (which does not imply that all requirements were met fully)

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- Problems:
  - one can infer very little knowledge from the obo-based bio-ontologies (mainly where there are errors, but not *new* insights)—but note that that was not it's original aim
  - semantics of the relations overloaded
  - mushrooming of obo-based bio-ontologies by different communities, which makes interoperation of the ontologies difficult
  - greater needs for collaborative ontology development, maintenance, etc.
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OBO Foundry

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  - open,
  - orthogonal,
  - same syntax,
  - common space for identifiers
- ... to one for the **O**pen **B**iological and Biomedical **O**ntologies:
  - developed in a collaborative effort
  - usage of common relations that are unambiguously defined (*in casu*: the Relation Ontology)
  - provide procedures for user feedback and for identifying successive versions
  - has to have a clearly bounded subject-matter ("so that an ontology devoted to cell components, for example, should not include terms like 'database' or 'integer' " ...)

More info in Smith et al, 2007, and `http://www.obofoundry.org`

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OBO Foundry coverage (canonical ontologies)

GRANULARITY / RELATION TO TIME	CONTINUANT				OCCURRENT
	INDEPENDENT		DEPENDENT		
ORGAN AND ORGANISM	Organism (NCBI Taxonomy?)	Anatomical Entity (FMA, CARO)	Organ Function (FMP, CPRO)	Phenotypic Quality (PaTO)	Organism-Level Process (GO)
CELL AND CELLULAR COMPONENT	Cell (CL)	Cellular Component (FMA, GO)	Cellular Function (GO)		Cellular Process (GO)
MOLECULE	Molecule (ChEBI, SO, RnaO, PrO)		Molecular Function (GO)		Molecular Process (GO)

OBO Foundry

- Sorting out the ontologies we have; e.g.,
    - harmonizing the four cell type ontologies into one (CL)
    - coordinating the anatomy ontologies of the various model organisms through a Common Aanatomy Reference Ontology
    - modularization of the subject domain by granularity, continuants, and occurents
- Adding ontologies to fill the gaps
- making OBO and OWL ontologies interoperable
- "Our long-term goal is that the data generated through biomedical research should form a single, consistent, cumulatively expanding and algorithmically tractable whole"
- "The result is an expanding family of ontologies designed to be interoperable and logically well formed and to incorporate accurate representations of biological reality"
- Aimed at "coordinated evolution of ontologies to support biomedical data integration"

OBO Foundry

- Sorting out the ontologies we have; e.g.,
  - harmonizing the four cell type ontologies into one (CL)
  - coordinating the anatomy ontologies of the various model organisms through a Common Aanatomy Reference Ontology
  - modularization of the subject domain by granularity, continuants, and occurents
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Instance classification with protein phosphatases (Wolstencroft et al, 2007)

- The setting:
  - Lots of sequence data in data silos that needs to be enriched with biological knowledge
  - Need to organise and classify genes and proteins into functional groups to compare typical properties across species
- The problems:
  - There is no proper, real life, use case that demonstrates the benefits of DL reasoning services such as taxonomic and instance classification
  - Limitations of traditional similarity methods, and automated protein motif and domain matching
  - Automation of p-domain analysis, but not for its interpretation (i.e., detects presence but not consequences for sub-family membership)

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Idea

- Maybe OWL reasoning can help with the interpretation of the analysis results:
  - That it does the classification of the (family of) proteins as good as a human expert for organisms x (in casu, human)
  - That the approach is 'transportable' to classification of the (family of) proteins in another organism of which much less is known (in casu, *Aspergillus fumigatus*), hence make predictions for those instances by means of classifying them
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How it can be done

- Develop ontology for the subject domain, in OWL
  - Extract knowledge from peer-reviewed literature
  - Protein phosphatases; e.g.

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Class R5Phosphatase Complete
  (Protein and
    (hasDomain two TyrosinePhosphataseCatalyticDomain) and
    (hasDomain some TransmembraneDomain) and
    (hasDomain some FibronectinDomain) and
     (hasDomain some CarbonicAnhydraseDomain) and
     hasDomain only (TyrosinePhosphataseCatalyticDomain and
      TransmembraneDomain and
      CarbonicAnhydraseDomain))
```

- Obtain instance data
  - Process protein sequences by InterProScan
  - Transform into OWL
- Put it together in some system with a reasoner
  - InstanceStore
  - Racer reasoner

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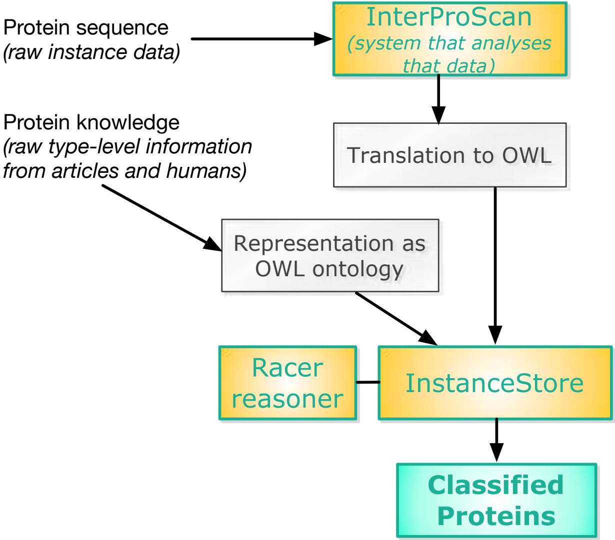
Sequence of activities and architecture



Results

- Human phosphatases:
  - The reasoner as good as human expert classification
  - Identification of additional p-domains, refined the classification into further subtypes
- *A. fumigatus* phosphatates:
  - Some phosphatases did not fit in any class, representing differences between the human and *A. fumigatus* protein families
  - Identification of a novel type of calcineurin phosphatase (has extra domain, like in other pathogenic fungi)
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Part II

Ontology Languages: OWL and OWL2

Outline

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4 Introduction
- Limitations of RDFS

5 OWL
- Design of OWL
- OWL and Description Logics
- OWL Syntaxes

6 Limitations

7 OWL 2
- OWL 2 DL

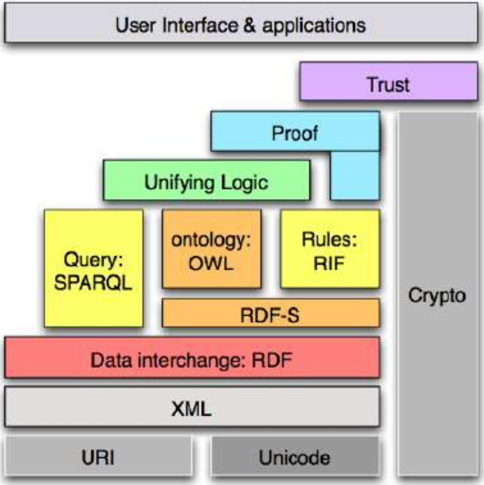
8 OWL 2 profiles
- OWL 2 EL
- OWL 2 QL
- OWL 2 RL

9 Reasoning

Toward one ontology language

- Plethora of ontology languages; e.g., KIF, KL-ONE, LOOM, F-logic, DAML, OIL, DAML+OIL, ...
- Lack of a lingua franca; hence, ontology interoperation problems even on the syntactic level
- Advances in expressive DL languages and, more importantly, in automated reasoners for expressive DL languages (mainly: FaCT++, then Racer)
- Limitations of RDF(S) as Semantic Web ‘ontology language’

The place of RFDS in the layer cake



RDFS as an Ontology Language

- Classes
- Properties
- Class hierarchies
- Property hierarchies
- Domain and range restrictions

Expressive limitations of RDF(S)

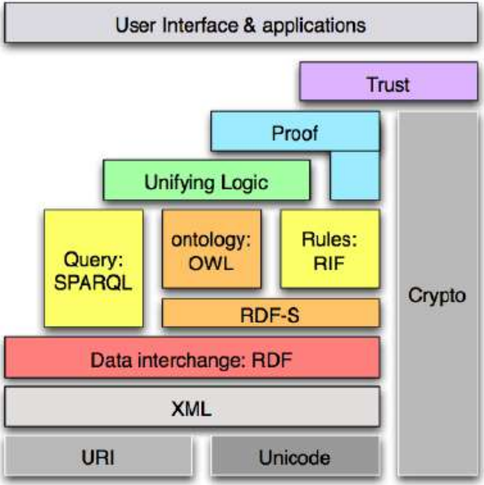
- Only binary relations
- Characteristics of Properties (e.g. inverse, transitive, symmetric)
- Local range restrictions (e.g. for Class Person, the property hasName has range xsd:string)
- Complex concept descriptions (e.g. Person is defined by Man and Woman)
- Cardinality restrictions (e.g. a Person may have at most 1 name)
- Disjointness axioms (e.g. nobody can be both a Man and a Woman)

Layering issues

- Syntax
  - Only binary relations in RDF
  - Verbose Syntax
  - No limitations on graph in RDF
    - Every graph is valid
- Semantics
  - Malformed graphs
  - Use of vocabulary in language
    - e.g. ⟨rdfs:Class,rdfs:subClassOf,ex:a⟩
  - Meta-classes
    - e.g. ⟨ex:a,rdf:type,ex:a⟩

Outline

The place of OWL in the layer cake



Stack of Languages

- XML
  - Surface syntax, no semantics
- XML Schema
  - Describes structure of XML documents
- RDF
  - Datamodel for “relations” between “things”
- RDF Schema
  - RDF Vocabulary Definition Language
- OWL
  - A more expressive Vocabulary Definition Language

Design Goals for OWL

- **Shareable**
- **Changing** over time
- **Interoperability**
- **Inconsistency** detection
- Balancing **expressivity and complexity**
- **Ease of use**
- Compatible with **existing standards**
- **Internationalization**

Requirements for OWL

- Ontologies are **object on the Web**
- with **their own meta-data**, versioning, etc...
- Ontologies are **extendable**
- They contain **classes, properties, data-types, range/domain, individuals**
- **Equality** (for classes, for individuals)
- **Classes as instances**
- **Cardinality** constraints
- **XML** syntax

Objectives for OWL

Objectives:

- layered language
- complex datatypes
- digital signatures
- decidability (in part)
- local unique names (in part)

Disregarded:

- default values
- closed world option
- property chaining
- arithmetic
- string operations
- partial imports
- view definitions
- procedural attachments

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Extending RDF Schema

- Leveraging experiences with OWL's predecessors SHOE, OIL, DAML-ONT, and DAML+OIL (frames, OO, DL)
- OWL extends RDF Schema to a full-fledged knowledge representation language for the Web
  - Logical expressions (and, or, not)
  - (in)equality
  - local properties
  - required/optional properties
  - required values
  - enumerated classes
  - symmetry, inverse

Species of OWL

- OWL Lite
  - Classification hierarchy
  - Simple constraints
- OWL DL
  - Maximal expressiveness
  - While maintaining tractability
  - Standard formalization in a DL
- OWL Full
  - Very high expressiveness
  - Losing tractability
  - All syntactic freedom of RDF (self-modifying)

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Features of OWL languages

- OWL Lite
  - (sub)classes, individuals
  - (sub)properties, domain, range
  - conjunction
  - (in)equality
  - (unqualified) cardinality 0/1
  - datatypes
  - inverse, transitive, symmetric properties
  - someValuesFrom
  - allValuesFrom
- OWL DL
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OWL Full

- **No restriction on use of vocabulary** (as long as legal RDF)
  - Classes as instances (and much more)
- **RDF style model theory**
  - Reasoning using FOL engine
  - Semantics should correspond to OWL DL for restricted KBs

OWL DL

- Use of vocabulary restricted
  - Cannot be used to do "nasty things" (e.g., modify OWL)
  - No classes as instances (this will be discussed in a later lecture)
  - Defined by abstract syntax
- Standard DL-based model theory
  - Direct correspondence with a DL
  - Automated reasoning with DL reasoners (e.g., Racer, Pellet, FaCT^{++})

OWL Lite

- No explicit negation or union
- Restricted cardinality (0/1)
- No nominals (oneOf)
- DL-based semantics
  - Automated reasoning with DL reasoners (e.g., Racer, Pellet, FaCT^{++})

More on OWL species

- OWL Full is *not* a Description Logic
- OWL Lite has strong syntactic restrictions, but only limited semantics restrictions cf. OWL DL
  - Negation can be encoded using disjointness
  - With negation an conjunction, you can encode disjunction
- For instance:

```
Class(C complete unionOf(B C))
```

is equivalent to:

```
DisjointClasses(notB B)
DisjointClasses(notC C)
Class(notBandnotC complete notB notC)
DisjointClasses(notBandnotC BorC)
Class(C complete notBandnotC)
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More on layering and OWL flavours

- For an OWL DL-restricted KB, OWL Full semantics is **not** equivalent to OWL DL semantics

```
John friend Susan .
```

OWL Full entails:

```
John rdf:type owl:Thing .  Susan rdf:type owl:Thing .  friend
rdf:type owl:ObjectProperty .

John rdf:type _:x .  _:x owl:onProperty friend .  _:x
owl:minCardinality "1"^^xsd:nonNegativeInteger .
```

OWL and Description Logics

- OWL Lite corresponds to the DL $\mathcal{SHIF}(\mathbf{D})$
  - Named classes (A)
  - Named properties (P)
  - Individuals ($C(o)$)
  - Property values ($P(o, a)$)
  - Intersection ($C \sqcap D$)
  - Union ($C \sqcup D$)
  - Negation ($\neg C$)
  - Existential value restrictions ($\exists P.C$)
  - Universal value restrictions ($\forall P.C$)
  - Unqualified (0/1) number restrictions ($\geq nP$, $\leq nP$, $= nP$), $0 \leq n \leq 1$
- OWL DL corresponds to the DL $\mathcal{SHOIN}(\mathbf{D})$
  - Arbitrary number restrictions ($\geq nP$, $\leq nP$, $= nP$), $0 \leq n$
  - Property value ($\exists P.\{o\}$)
  - Enumeration ($\{o_1, ..., o_n\}$)

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OWL constructs

OWL Construct	DL	Example
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	$Human \sqcap Male$
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	$Doctor \sqcup Lawyer$
complementOf	$\neg C$	$\neg Male$
oneOf	$\{o_1, \ldots, o_n\}$	$\{john, mary\}$
allValuesFrom	$\forall P.C$	$\forall hasChild.Doctor$
someValuesFrom	$\exists P.C$	$\exists hasChild.Lawyer$
value	$\exists P.\{o\}$	$\exists citizenOf.USA$
minCardinality	$\geq nP.C$	$\geq 2hasChild.Lawyer$
maxCardinality	$\leq nP.C$	$\leq 1hasChild.Male$
cardinality	$= nP.C$	$= 1hasParent.Female$

+ XML Schema datatypes: int, string, real, etc...

OWL axioms

OWL Axiom	DL	Example
SubClassOf	$C_1 \sqsubseteq C_2$	$Human \sqsubseteq Animal \sqcap Biped$
EquivalentClasses	$C_1 \equiv ... \equiv C_n$	$Man \equiv Human \sqcap Male$
SubPropertyOf	$P_1 \sqsubseteq P_2$	$hasDaughter \sqsubseteq hasChild$
EquivalentProperties	$P_1 \equiv ... \equiv P_n$	$cost \equiv price$
SameIndividual	$o_1 = ... = o_n$	$President\_Bush = G\_W\_Bush$
DisjointClasses	$C_i \sqsubseteq \neg C_j$	$Male \sqsubseteq \neg Female$
DifferentIndividuals	$o_i \neq o_j$	$john \neq peter$
inverseOf	$P_1 \equiv P_2^-$	$hasChild \equiv hasParent^-$
Transitive	$P^+ \sqsubseteq P$	$ancestor^+ \sqsubseteq ancestor$
Symmetric	$P \equiv P^-$	$connectedTo \equiv connectedTo^-$

DL-based OWL species as Semantic Web languages vs DLs

⇒ OWL uses URI references as names (like used in RDF, e.g., `http://www.w3.org/2002/07/owl#Thing`)

⇒ OWL gathers information into ontologies stored as documents written in RDF/XML, things like `owl:imports`

⇒ RDF data types and XML schema data types for the ranges of data properties (attributes) (`DataPropertyRange`)

- OWL-DL and OWL-Lite with a frame-like abstract syntax, whereas RDF/XML is the official exchange syntax for OWL
- Annotations

Syntaxes of OWL

- RDF
  - Official exchange syntax
  - Hard for humans
  - RDF parsers are hard to write!
- XML
  - Not the RDF syntax
  - Still hard for humans, but more XML than RDF tools available
- Abstract syntax
  - Not defined for OWL Full
  - To some, considered human readable
- User-usable ones
  - e.g., Manchester syntax, informal and limited matching with UML

OWL in RDF/XML

Example from [OwlGuide]:

```
<!ENTITY vin
"http://www.w3.org/TR/2004/REC-owl-guide-20040210/wine#" >
<!ENTITY food
"http://www.w3.org/TR/2004/REC-owl-guide-20040210/food#" > ...
<rdf:RDF
xmlns:vin="http://www.w3.org/TR/2004/REC-owl-guide-20040210/wine#"
xmlns:food="http://www.w3.org/TR/2004/REC-owl-guide-20040210/food#"
 ... >

<owl:Class rdf:ID="Wine"> <rdfs:subClassOf
rdf:resource="&food;PotableLiquid"/> <rdfs:label
xml:lang="en">wine</rdfs:label> <rdfs:label
xml:lang="fr">vin</rdfs:label> ...  </owl:Class>

<owl:Class rdf:ID="Pasta"> <rdfs:subClassOf
rdf:resource="#EdibleThing" /> ... </owl:Class> </rdf:RDF>
```

OWL Abstract syntax

Class(professor partial) Class(associateProfessor partial academicStaffMember)

DisjointClasses (associateProfessor assistantProfessor)
DisjointClasses (professor associateProfessor)

Class(faculty complete academicStaffMember)

In DL syntax:

$\text{associateProfessor} \sqsubseteq \text{academicStaffMember}$
$\text{associateProfessor} \sqsubseteq \neg\ \text{assistantProfessor}$
$\text{professor} \sqsubseteq \neg\ \text{associateProfessor}$

$\text{faculty} \equiv \text{academicStaffMember}$

More examples

DatatypeProperty(age range(xsd:nonNegativeInteger))
ObjectProperty(lecturesIn)

ObjectProperty(isTaughtBy domain(course) range(academicStaffMember))
SubPropertyOf(isTaughtBy involves)

ObjectProperty(teaches inverseOf(isTaughtBy)
domain(academicStaffMember) range(course))

EquivalentProperties (lecturesIn teaches)

ObjectProperty(hasSameGradeAs Transitive Symmetric domain(student)
range(student))

More examples

In DL syntax:

$\top \sqsubseteq \forall age.xsd : nonNegativeInteger$
$\top \sqsubseteq \forall isTaughtBy^{-}.course$
$\top \sqsubseteq \forall isTaughtBy.academicStaffMember$
$isTaughtBy \sqsubseteq involves$
$teaches \equiv isTaughtBy^{-}$
$\top \sqsubseteq \forall teaches^{-}.academicStaffMember$
$\top \sqsubseteq \forall teaches.course$
$lecturesIn \equiv teaches$
$hasSameGradeAs^{+} \sqsubseteq hasSameGradeAs$
$hasSameGradeAs \equiv hasSameGradeAs^{-}$
$\top \sqsubseteq \forall hasSameGradeAs^{-}.student$
$\top \sqsubseteq \forall hasSameGradeAs.student$

More examples

Individual (949318 type(lecturer))

Individual (949352 type(academicStaffMember) value(age "39"^^&xsd;integer))

ObjectProperty(isTaughtBy Functional)

Individual (CIT1111 type(course) value(isTaughtBy 949352) value(isTaughtBy 949318))

DifferentIndividuals (949318 949352) DifferentIndividuals (949352 949111 949318)

More examples

In DL syntax:

$949318 : lecturer$
$949352 : academicStaffMember$
$\langle 949352, "39"\hat{}\hat{}\&xsd; integer\rangle : age$
$\top \sqsubseteq \leq 1 isTaughtBy$
$CIT1111 : course$
$\langle CIT1111, 949352\rangle : isTaughtBy$
$\langle CIT1111, 949318\rangle : isTaughtBy$
$949318 \neq 949352$
$949352 \neq 949111$
$949111 \neq 949318$
$949352 \neq 949318$

More examples

Class(firstYearCourse partial restriction (isTaughtBy allValuesFrom (Professor)))

Class(mathCourse partial restriction (isTaughtBy hasValue (949352)))

Class(academicStaffMember partial restriction (teaches someValuesFrom (undergraduateCourse)))

Class(course partial restriction (isTaughtBy minCardinality (1)))

Class(department partial restriction (hasMember minCardinality(10)) restriction (hasMember maxCardinality(30)))

More examples

In DL syntax:

$$
\begin{aligned}
&\mathit{firstYearCourse} \sqsubseteq \forall \mathit{isTaughtBy}.\mathit{Professor} \\
&\mathit{mathCourse} \sqsubseteq \exists \mathit{isTaughtBy}.\{949352\} \\
&\mathit{academicStaffMember} \sqsubseteq \exists \mathit{teaches}.\mathit{undergraduateCourse} \\
&\mathit{course} \sqsubseteq \geq 1 \mathit{isTaughtBy} \\
&\mathit{department} \sqsubseteq \geq 10 \mathit{hasMember} \sqcap \leq 30 \mathit{hasMember}
\end{aligned}
$$

More examples

Class(course partial complementOf(staffMember))

Class(peopleAtUni complete unionOf(staffMember student))

Class(facultyInCS complete intersectionOf(faculty
restriction (belongsTo hasValue (CSDepartment))))

Class(adminStaff complete intersectionOf(staffMember
complementOf(unionOf(faculty techSupportStaff))))

In DL syntax:

$course \sqsubseteq \neg staffMember$
$peopleAtUni \equiv staffMember \sqcup student$
$facultyInCS \equiv faculty \sqcap \exists belongsTo.\{CSDepartment\}$
$adminStaff \equiv staffMember \sqcap \neg(faculty \sqcup techSupportStaff)$

Layering on top of RDF(S)

- RDF(S) bottom layer in Semantic Web stack
- Higher languages *layer* on top of RDFS

Syntactic Layering

- *Every valid RDF statement is a valid statement in a higher language*
- This *includes* triples containing keywords of these languages(!)

Semantic Layering

For RDFS graph G and higher-level language L:

If $G \models_{RDFS} G'$ then $G \models_L G'$, and *ideally*

if $G \models_L G'$ then $G \models_{RDFS} G'$

Syntactically layering OWL on RDF(S)

OWL Lite, OWL DL

- OWL Lite, OWL DL subsets of RDF
- Allowed triples defined through mapping from abstract syntax
- *Partial* layering:
  - *every* OWL Lite/DL ontology is an RDF graph
  - *some* RDF graphs are OWL Lite/DL ontologies

OWL Full

- OWL Full encompasses RDF
- *Complete* layering:
  - *every* OWL Full is an RDF graph
  - *all* RDF graphs are OWL Full ontologies

Semantically layering OWL on RDF(S)

OWL Lite, OWL DL

- OWL Lite/DL semantics *not* related to RDFS semantics
- Redefine semantics of RDFS keywords, e.g., `rdfs:subClassOf`
- Work ongoing to describe correspondence between subset of RDFS and OWL Lite/DL

OWL Full

- OWL Full semantics is *extension* of RDFS semantics
- OWL Full is undecidable
- OWL Full semantics hard to understand

OWL Lite/DL vs. RDF

- RDF Graph defined through translation from Abstract Syntax
- Example:

```
Class(Human partial Animal
        restriction(hasLegs cardinality(2))
        restriction(hasName allValuesFrom(xsd:string)))
```

Human	rdf:type	owl:Class
Human	rdfs:subClassOf	Animal
Human	rdfs:subClassOf	_:X1
_:X1	rdf:type	owl:Restriction
_:X1	owl:onProperty	hasLegs
_:X1	owl:cardinality	"2"8sd:nonNegativeInteger
Human	rdfs:subClassOf	_:X2
_:X2	rdf:type	owl:Restriction
_:X2	owl:onProperty	hasName
_:X2	owl:allValuesFrom	xsd:string

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OWL Lite/DL vs. RDF

- Not every RDF graph is OWL Lite/DL ontology
- Example:

  A rdf:type A

- How to check whether an RDF graph G is OWL DL?
  1. Construct an OWL ontology O in Abstract Syntax
  2. Translate to RDF graph G'
  3. If G=G', then G is OWL DL
     - Otherwise, go to step (1)

OWL Lite/DL vs. RDF

- Not every RDF graph is OWL Lite/DL ontology
- Example:

  A rdf:type *A*

- How to check whether an RDF graph *G* is OWL DL?

  Construct an OWL ontology *O* in Abstract Syntax
  Translate to RDF graph *G'*
  If *G*=*G'*, then *G* is OWL DL

  - Otherwise, go to step (1)

Outline

Expressivity limitations

- Qualified cardinality restrictions (e.g., no Bicycle $\sqsubseteq \geq 2$ hasComponent.Wheel)
- Relational properties (no reflexivity, irreflexivity)
- Data types
  - restrictions to a subset of datatype values (ranges)
  - relationships between values of data properties on one object
  - relationships between values of data properties on different objects
  - aggregation functions
- Other things like annotations, imports, versioning, species validation (see p315 of the paper)

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- Other things like annotations, imports, versioning, species validation (see p315 of the paper)

Syntax problems

- Having both frame-based legacy (Abstract syntax) and axioms (DL) was deemed confusing
- Type of ontology entity. e.g.,

```
Class(A partial
   restriction(hasB someValuesFrom(C))
```

  - `hasB` is data property and `C` a datatype?
  - `hasB` an object property and `C` a class?

OWL-DL has a strict separation of the vocabulary, but the specification does not precisely specify how to enforce this separation at the syntactic level

More syntax problems

- RDF's triple notation, difficult to read and process
- OWL 1 provides mapping from the Abstract Syntax into OWL RDF, but not the converse:
  - an RDF graph G is an OWL-DL ontology if there exists an ontology $\mathcal{O}$ in Abstract Syntax s.t. the result of the normative transformation of $\mathcal{O}$ into triples is precisely G, which makes checking whether G is an OWL-DL ontology very hard in practice:
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Problems with the semantics

- RDF's blank nodes, but unnamed individuals not directly available in $\mathcal{SHOIN}(D)$
- Frames and axioms

Outline

Aims

- Address as much as possible of the identified problems (previous slides and "the next steps for OWL 2" paper)
- Task: compare this with the possible "future extensions" of the "the making of an ontology language" paper

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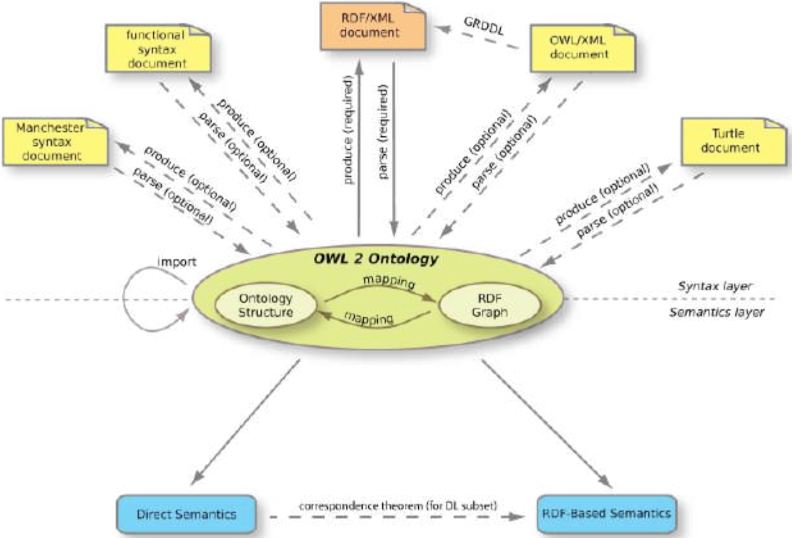
Some general points

- OWL 2 a W3C recommendation since 27-10-'09
- Any OWL 2 ontology can also be viewed as an RDF graph (The relationship between these two views is specified by the Mapping to RDF Graphs document)
- Direct, i.e. model-theoretic, semantics ($\Rightarrow$ OWL 2 DL) and an RDF-based semantics ($\Rightarrow$ OWL 2 full)
- Primary exchange syntax for OWL 2 is RDF/XML, others are optional
- Three profiles, which are sub-languages of OWL 2 (syntactic restrictions)

The Structure of OWL 2



Overview

- Based on $\mathcal{SROIQ}(D)$, which is 2NExpTime-complete
- More expressive than OWL-DL
- Fancier metamodelling and annotations
- Improved ontology publishing, imports and versioning control
- Variety of syntaxes, RDF serialization (but no RDF-style semantics)

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The language: properties of properties

- property chains (`ObjectPropertyChain`), e.g.:
  ```
  SubObjectPropertyOf( ObjectPropertyChain(
    a:hasMother a:hasSister ) a:hasAunt )
  ```
  with having Lois as the mother of Stewie, and Carol a sister of Lois, the ontology entails that Stewie has Carol as aunt
- ObjectMinCardinality, ObjectMaxCardinality, ObjectExactCardinality, ObjectHasSelf, FunctionalObjectProperty, InverseFunctionalObjectProperty, IrreflexiveObjectProperty, AsymmetricObjectProperty, and DisjointObjectProperties **only on simple object properties** (i.e., has no direct or indirect subproperties that are either transitive or are defined by means of property chains—so we still can't represent parthood fully)

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The language: other extensions

- qualified cardinality restrictions
- The `HasKey` 'key' that are **not** keys like in conceptual models and databases
  - Alike inverse functional only (i.e., merely 1:n instead of 1:1) but applicable only to individuals that are explicitly named in an ontology
  - No unique name assumption, hence inferences are different from that expected of keys in databases
  - "relevant mainly for query answering" [Cuenca Grau et al, 2008, p316], which does not go well with OWL 2 DL in non-toy applications anyway
- Richer datatypes, data ranges; e.g., `DatatypeRestriction( xsd:integer xsd:minInclusive "5"8sd:integer xsd:maxExclusive "10"8sd:integer )`

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Partial table of features

Language ⇒ **Feature** ⇓	OWL 1 **Lite**	OWL 1 **DL**	OWL 2 **DL**	OWL 2 Profiles EL	OWL 2 Profiles QL	OWL 2 Profiles RL
Role hierarchy	+	+	+	.	+	.
N-ary roles (where $n \geq 2$)	–	–	–	.	?	.
Role chaining	–	–	+	.	–	.
Role acyclicity	–	–	–	.	–	.
Symmetry	+	+	+	.	+	.
Role values	–	–	–	.	–	.
Qualified number restrictions	–	–	+	.	–	.
One-of, enumerated classes	?	+	+	.	–	.
Functional dependency	+	+	+	.	?	.
Covering constraint over concepts	?	+	+	.	–	.
Complement of concepts	?	+	+	.	+	.
Complement of roles	–	–	+	.	+	.
Concept identification	–	–	–	.	–	.
Range typing	–	+	+	.	+	.
Reflexivity	–	–	+	.	–	.
Antisymmetry	–	–	–	.	–	.
Transitivity	+	+	+	.	–	.
Asymmetry	?	?	+	–	+	+
Irreflexivity	–	–	+	.	–	.
.	.	.	.	.	.	.

Exercise: verify the question marks in the table (tentatively all "–") and fill in the dots (any "±" should be qualified at to what the restriction is)

Outline

Rationale

- Computational considerations
  - Consult "OWL profiles" page *Table 10. Complexity of the Profiles*
- Robustness of implementations w.r.t. *scalable* applications
- Already enjoy 'substantial' user base

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/`

Supported class restrictions

- 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

- class inclusion, equivalence, disjointness
- object property inclusion (w. or w.o. property chains), and data property inclusion
- property equivalence
- transitive object properties
- reflexive object properties
- domain and range restrictions
- assertions
- functional data properties
- keys

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

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*)

Supported Axioms in OWL 2QL, 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

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

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 $\sqsubseteq$

Another section on speculation about future extensions

- The 'leftover' from OWL 1's "Future extensions" (UNA, CWA, defaults), parthood relation (primarily: antisymmetry, restrictions on current usage of properties)
- New "future of OWL", a.o.:
  - Syntactic sugar: 'macros', 'n-aries'
  - Query languages: EQL-lite and nRQL w.r.t. SPARQL
  - Integration with rules: RIF, DL-safe rules, SBVR
  - Orthogonal dimensions: temporal, fuzzy, rough, probabilistic

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Outline

Reasoning services for DL-based OWL ontologies

- OWL ontology is a first-order logical theory ⇒ verifying the formal properties of the ontology corresponds to reasoning over a first-order theory
- Main ('standard') reasoning tasks for the OWL ontologies:
  - consistency of the ontology
  - concept (and role) consistency
  - concept (and role) subsumption
  - instance checking
  - instance retrieval
  - query answering
- Non-standard reasoning services, such as explanation, repair, least common subsumer, ...
- Note: Not all OWL languages are equally suitable for all these reasoning tasks

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Reasoning services for DL-based OWL ontologies

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- Concept (and role) consistency
  - is there a model of T in which C (resp. R) has a nonempty extension?
- Concept (and role) subsumption
  - i.e., is the extension of C (resp. R) contained in the extension of D in every model of T?
- Instance checking
  - is a a member of concept C in K, i.e., is the fact $C(a)$ satisfied by every interpretation of K?
- Instance retrieval
  - find all members of C in K, i.e., compute all individuals a s.t. $C(a)$ is satisfied by every interpretation of K
- Query answering
  - compute all tuples of individuals t s.t. query $q(x)$ is entailed by K, i.e., $q(t)$ is satisfied by every interpretation

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Example

Which alumni do not have a PhD?

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Peter	MSc in Informatics
Dalila	PhD in politics

- Query under CWA says "Peter"
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Summary

Part III

Foundational and top-down aspects of ontology engineering

Outline

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10 Foundational ontologies
- DOLCE
- BFO
- More foundational ontologies

11 Part-whole relations
- Parts, mereology, meronymy
- Taxonomy of types of part-whole relations
- Mereotopology and other extensions

12 Ontology Design Patterns
- Types of patterns
- Developing and using an ODP

General notion

- Provide a top-level with basic categories of kinds of things
- Principal choices
  - Endurantist vs. Perdurantist
  - Universals vs. Particulars
- Formal...
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- Strong cognitive/linguistic bias:
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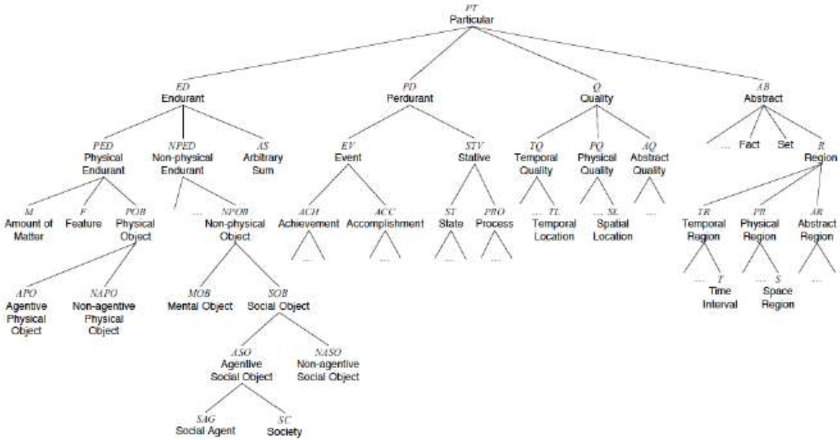
Outline of DOLCE categories



DOLCE's basic relations

- Parthood
  - Between quality regions (immediate)
  - Between arbitrary objects (temporary)
- Constitution
- Participation
- Representation
- Dependence: Specific/generic constant dependence
- Inherence (between a quality and its host)
- Quale
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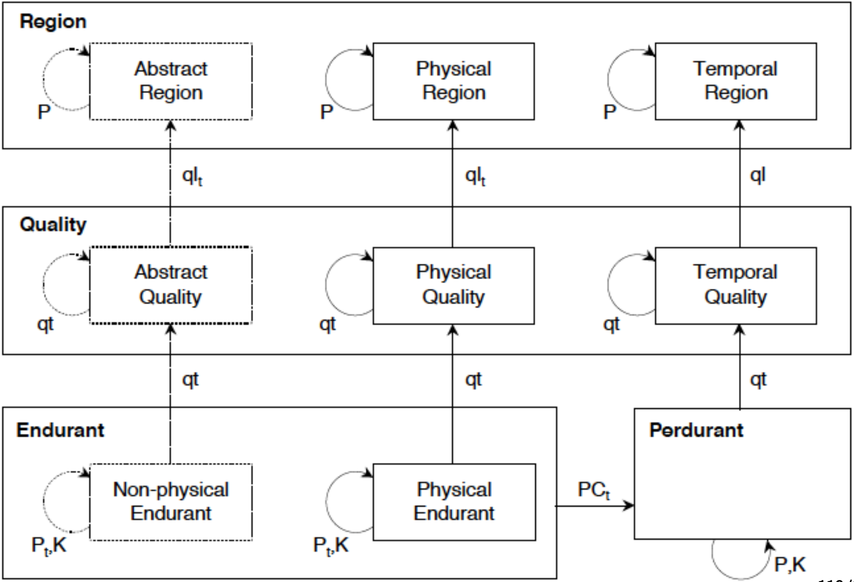
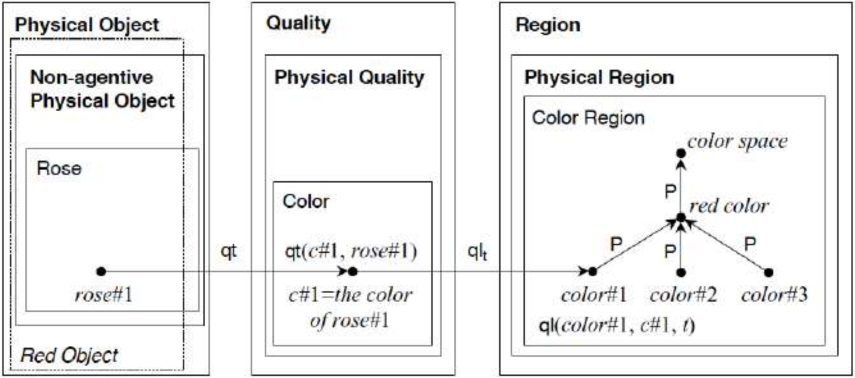
DOLCE's primitive relations between basic categories



DOLCE's basic relations w.r.t. qualities



Various commitments regarding ‘attributes’

- DOLCE: [*PerDurant*/*EnDurant*] –*qt*– *Quality* –*ql*– *Region*
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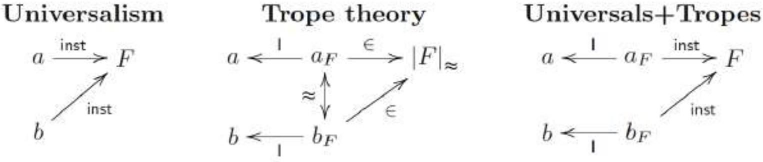

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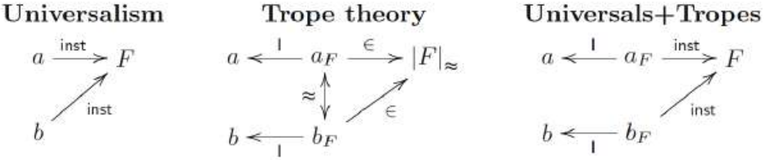

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DOLCE's basics on universals

(Dd1)	$\mathsf{RG}(\phi) \triangleq \Box\forall x(\phi(x) \rightarrow \Box\phi(x))$	(ϕ *is Rigid*)
(Dd2)	$\mathsf{NEP}(\phi) \triangleq \Box\exists x(\phi(x))$	(ϕ *is Non-Empty*)
(Dd3)	$\mathsf{DJ}(\phi,\psi) \triangleq \Box\neg\exists x(\phi(x) \wedge \psi(x))$	(ϕ *and* ψ *are Disjoint*)
(Dd4)	$\mathsf{SB}(\phi,\psi) \triangleq \Box\forall x(\psi(x) \rightarrow \phi(x))$	(ϕ *Subsumes* ψ)
(Dd5)	$\mathsf{EQ}(\phi,\psi) \triangleq \mathsf{SB}(\phi,\psi) \wedge \mathsf{SB}(\psi,\phi)$	(ϕ *and* ψ *are Equal*)
(Dd6)	$\mathsf{PSB}(\phi,\psi) \triangleq \mathsf{SB}(\phi,\psi) \wedge \neg\mathsf{SB}(\phi,\psi)$	(ϕ *Properly Subsumes* ψ)
(Dd7)	$\mathsf{L}(\phi) \triangleq \Box\forall\psi(\mathsf{SB}(\phi,\psi) \rightarrow \mathsf{EQ}(\phi,\psi))$	(ϕ *is a Leaf*)
(Dd8)	$\mathsf{SBL}(\phi,\psi) \triangleq \mathsf{SB}(\phi,\psi) \wedge \mathsf{L}(\psi)$	(ψ *is a Leaf Subsumed by* ϕ)
(Dd9)	$\mathsf{PSBL}(\phi,\psi) \triangleq \mathsf{PSB}(\phi,\psi) \wedge \mathsf{L}(\psi)$	(ψ *is a Leaf Properly Subsumed by* ϕ)

....

DOLCE's characterisation of categories

Physical Object

(Ad32)* $\mathsf{GK}(SC, SAG)$

(Ad30)* $\mathsf{GK}(NAPO, M)$

(Ad70)* $\mathsf{OGD}(F, NAPO)$

(Ad71)* $\mathsf{OSD}(MOB, APO)$

(Ad72)* $\mathsf{OGD}(SAG, APO)$

Feature

(Ad70)* $\mathsf{OGD}(F, NAPO)$

Non-physical Endurant

(Ad12)* $\mathsf{P}(x,y,t) \rightarrow (NPED(x) \leftrightarrow NPED(y))$

(Ad22)* $\mathsf{K}(x,y,t) \rightarrow (NPED(x) \leftrightarrow NPED(y))$

(Ad41)* $\mathsf{qt}(x,y) \rightarrow (AQ(x) \leftrightarrow (AQ(y) \vee NPED(y)))$

(Ad48)* $AQ(x) \rightarrow \exists! y(\mathsf{qt}(x,y) \wedge NPED(y))$

(Ad51)* $NPED(x) \rightarrow \exists \phi, y(\mathsf{SBL}(AQ, \phi) \wedge \mathsf{qt}(\phi, y, x))$

(Ad74)* $\mathsf{OD}(NPED, PED)$

... etc...

Can all that be used?

- DOLCE in KIF
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DLP3971

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- Still rather complex to understand (aside from using OWL-DL): Full DOLCE-Lite-Plus with 208 classes, 313 object properties, etc (check the "Active ontology" tab in Protégé) and basic DOLCE-Lite 37 classes, 70 object properties etc (in $\mathcal{SHI}$)
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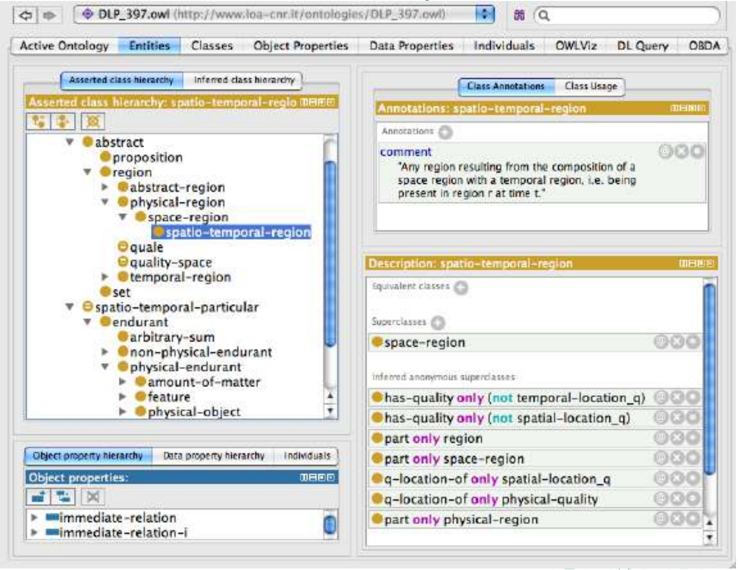
DLP_397.owl (http://www.loa-cnr.it/ontologies/DLP_397.owl)
Active Ontology
Entities
Classes
Object Properties
Data Properties
Individuals
OWLViz
DL Query
OBDA
Asserted class hierarchy
Inferred class hierarchy
Asserted class hierarchy: spatio-temporal-regio
abstract
proposition
region
abstract-region
physical-region
space-region
spatio-temporal-region
quale
quality-space
temporal-region
set
spatio-temporal-particular
endurant
arbitrary-sum
non-physical-endurant
physical-endurant
amount-of-matter
feature
physical-object
Object property hierarchy
Data property hierarchy
Individuals
Object properties:
immediate-relation
immediate-relation-i
Class Annotations
Class Usage
Annotations: spatio-temporal-region
Annotations
comment
"Any region resulting from the composition of a space region with a temporal region, i.e. being present in region r at time t."
Description: spatio-temporal-region
Equivalent classes
Superclasses
space-region
Inferred anonymous superclasses
has-quality only (not temporal-location_q)
has-quality only (not spatial-location_q)
part only region
part only space-region
q-location-of only spatial-location_q
q-location-of only physical-quality
part only physical-region

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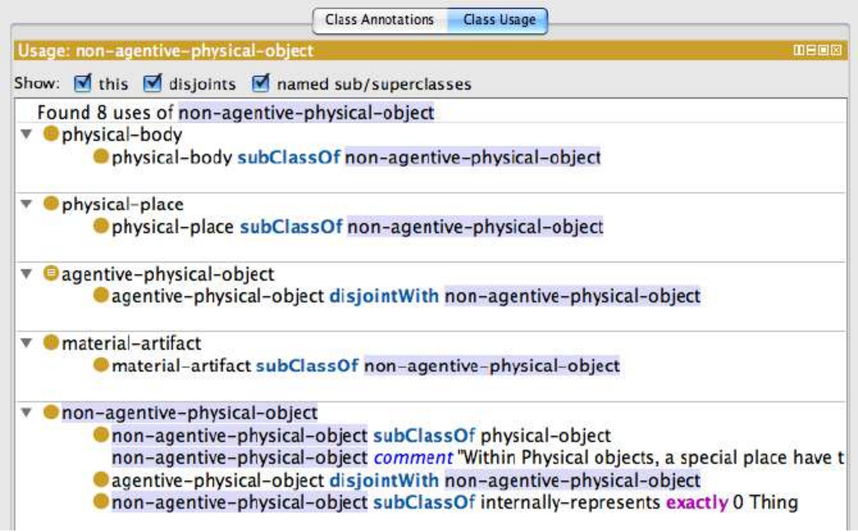
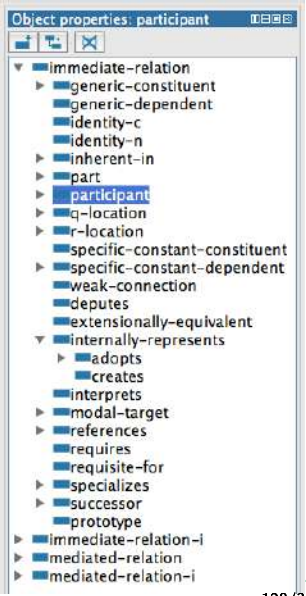

Class Annotations
Class Usage
Usage: non-agentive-physical-object
Show: this disjoints named sub/superclasses
Found 8 uses of non-agentive-physical-object
physical-body
physical-body subClassOf non-agentive-physical-object
physical-place
physical-place subClassOf non-agentive-physical-object
agentive-physical-object
agentive-physical-object disjointWith non-agentive-physical-object
material-artifact
material-artifact subClassOf non-agentive-physical-object
non-agentive-physical-object
non-agentive-physical-object subClassOf physical-object
non-agentive-physical-object comment "Within Physical objects, a special place have t
agentive-physical-object disjointWith non-agentive-physical-object
non-agentive-physical-object subClassOf internally-represents exactly 0 Thing

Comment: "The immediate relation holding between endurants and perdurants (e.g. in 'the car is running').Participation can be constant (in all parts of the perdurant, e.g. in 'the car is running'), or temporary (in only some parts, e.g. in 'I'm electing the president').A 'functional' participant is specialized for those forms of participation that depend on the nature of participants, processes, or on the intentionality of agentive participants. Traditional 'thematic role' should be mapped to functional participation.For relations holding between participants in a same perdurant, see the co-participates relation."



BFO Overview

- Ontology as reality representation
- Aims at reconciling the so-called three-dimensionalist and four-dimensionalist views
  - A Snap ontology of endurants which is reproduced at each moment of time and is used to characterize static views of the world
  - Span ontology of happenings and occurrents and, more generally, of entities which persist in time by perduring
  - Endurants (Snap) or perdurants (Span)
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- BFO 1.1 in OWL with 39 classes, no object or data properties, in $\mathcal{ALC}$.
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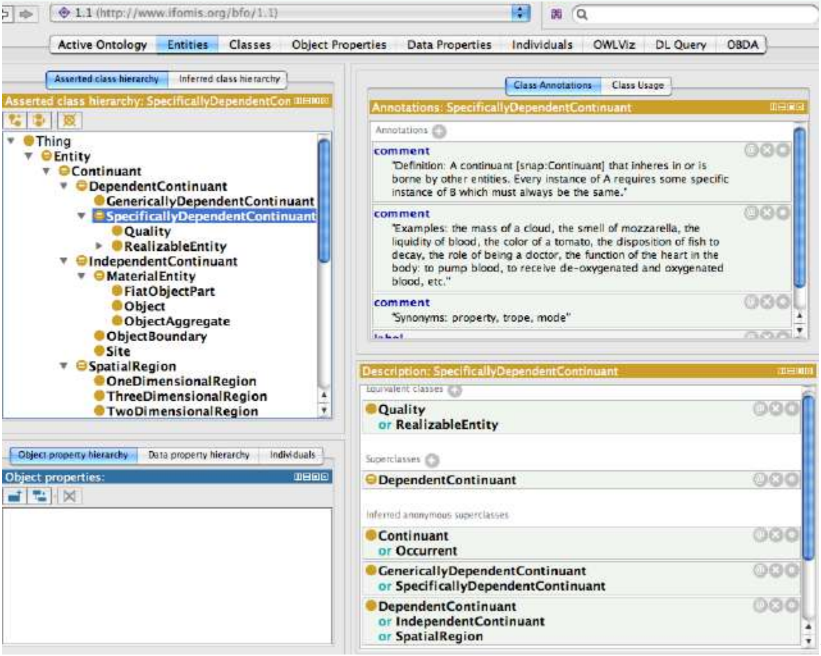
BFO Taxonomy

```
bfo:Entity
  snap:Continuant
    snap:DependentContinuant
      snap:GenericalyDependentContinuant
      snap:SpecificalyDependentContinuant
        snap:Quality
        snap:RealizableEntity
          snap:Disposition
          snap:Function
          snap:Role
    snap:IndependentContinuant
      snap:MaterialEntity
          snap:Object
          snap:FiatObjectPart
          snap:ObjectAggregate
      snap:ObjectBoundary
      snap:Site
    snap:SpatialRegion
      snap:ZeroDimensionalRegion
      snap:OneDimensionalRegion
      snap:TwoDimensionalRegion
      snap:ThreeDimensionalRegion
```

```
span:Occurrent
  span:ProcessualEntity
    span:Process
    span:ProcessBoundary
    span:FiatProcessPart
    span:ProcessAggregate
    span:ProcessualContext
  span:SpatiotemporalRegion
    span:ConnectedTemporalRegion
      span:SpatiotemporalInstant
      span:SpatiotemporalInterval
    span:ScatteredSpatiotemporalRegion
  span:TemporalRegion
    span:ConnectedSpatiotemporalRegion
      span:TemporalInstant
      span:TemporalInterval
    span:ScatteredTemporalRegion
```


1.1 (http://www.ifomis.org/bfo/1.1)
Active Ontology
Entities
Classes
Object Properties
Data Properties
Individuals
OWLViz
DL Query
OBDA
Asserted class hierarchy
Inferred class hierarchy
Asserted class hierarchy: SpecificallyDependentCon
Thing
Entity
Continuant
DependentContinuant
GenericallyDependentContinuant
SpecificallyDependentContinuant
Quality
RealizableEntity
IndependentContinuant
MaterialEntity
FiatObjectPart
Object
ObjectAggregate
ObjectBoundary
Site
SpatialRegion
OneDimensionalRegion
ThreeDimensionalRegion
TwoDimensionalRegion
Object property hierarchy
Data property hierarchy
Individuals
Object properties:
Class Annotations
Class Usage
Annotations: SpecificallyDependentContinuant
Annotations
comment
"Definition: A continuant [snap:Continuant] that inheres in or is borne by other entities. Every instance of A requires some specific instance of B which must always be the same."
comment
"Examples: the mass of a cloud, the smell of mozzarella, the liquidity of blood, the color of a tomato, the disposition of fish to decay, the role of being a doctor, the function of the heart in the body: to pump blood, to receive de-oxygenated and oxygenated blood, etc."
comment
"Synonyms: property, trope, mode"
Description: SpecificallyDependentContinuant
Equivalent classes
Quality
or RealizableEntity
Superclasses
DependentContinuant
Inferred anonymous superclasses
Continuant
or Occurrent
GenericallyDependentContinuant
or SpecificallyDependentContinuant
DependentContinuant
or IndependentContinuant
or SpatialRegion

BFO Core

- A non-extensional temporal mereology with collections, sums, and universals
- BFO as a collection of smaller theories
  - EMR, QSizeR, RBG, QDiaSizeR, ..., Adjacency, Collections, SumsPartitions, Universals, Instantiation, ExtensionsOfUniversals, PartonomicInclusion, UniversalParthood
- Reference material `http://www.ifomis.org/bfo/fol` and `http://www.acsu.buffalo.edu/~bittner3/Theories/BFO/`

Section of one of the sub-theories in BFO Core

theory *UniversalParthood*

imports *ExtensionsOfUniversals PartonomicInclusion*

begin

consts

```
UPt1 :: Un => Un => Ti => o
UPt2 :: Un => Un => Ti => o
UPt12 :: Un => Un => Ti => o

UP1 :: Un => Un => o
UP2 :: Un => Un  => o
UP12 :: Un => Un  => o
```

defs

```
UPt1-def: UPt1(c,d,t) == (ALL x. (Inst(x,c,t) --> (EX y. (Inst(y,d,t) & P(x,y,t)))))
UPt2-def: UPt2(c,d,t) == (ALL y. (Inst(y,d,t) --> (EX x. (Inst(x,c,t) & P(x,y,t)))))
UPt12-def: UPt12(c,d,t) == UPt1(c,d,t) & UPt2(c,d,t)

UP1-def: UP1(c,d) == (ALL t. UPt1(c,d,t))
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UP12-def: UP12(c,d) == (ALL t. UPt12(c,d,t))
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A relation ontology

- What are the ‘core’ and primitive relations necessary to develop a domain ontology?
- Do we need a *separate* ontology for relations, or integrated in a foundational ontology?
- Philosophers do not agree on the answers, but the modellers and engineers need agreement to facilitate interoperability among ontologies

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The Relation Ontology

- Definitions for *is_a*, *part_of*, *integral_part_of*, *proper_part_of*, *located_in*, *contained_in*, *adjacent_to*, *transformation_of*, *derives_from*, *preceded_by*, *has_participant*, *has_agent*, *instance_of*
- Proposed extensions under consideration, among others:
  - Relations between generically dependent continuants and specifically dependent continuants (a.o., concretizes, *has_quality*, *has_function*, ...)
  - A relation between a process and a process or quality (*regulates*)
  - Refinements on *derived_from*
  - Measurements (*has_value*, *of_dimension*, ...)

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Ontologies and choices

- Other more or less used foundational ontologies, a.o.:
  - GFO
  - SUMO
  - OCHRE
  - ...
- Within WonderWeb project: a (future) aim to develop a library of foundational ontologies with mappings between them: choose your pet ontology and be interoperable with the others
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Outline

Some questions and problems (not exhaustive...)[4]

- Is a tunnel part of the mountain?
- What is the difference, if any, between how `Cell nucleus` and `Cell` are related and how `Receptor` and `Cell wall` are related?
- And w.r.t. `Brain part of Human` and/versus `Hand part of Boxer`? (assuming boxers must have their own hands)
- A classical example: hand is part of musician, musician part of orchestra, but clearly, the musician's hands are not part of the orchestra. Is part-of then not transitive, or is there a problem with the example?

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Analysis of the issues from diverse angles

- Mereological theories (Varzi, 2004), usage & extensions (e.g. mereotopology, relation with granularity, set theory)
- Early attempts with direct parthood, SEP triples, and other outstanding issues, some still remaining
- Cognitive & linguistic issues from meronymy
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Ground Mereology

Reflexivity (everything is part of itself)

$$\forall x(part\_of(x, x)) \quad (1)$$

Antisymmetry (two distinct things cannot be part of each other, or: if they are, then they are the same thing)

$$\forall x, y((part\_of(x, y) \land part\_of(y, x)) \rightarrow x = y) \quad (2)$$

Transitivity (if x is part of y and y is part of z, then x is part of z)

$$\forall x, y, z((part\_of(x, y) \land part\_of(y, z)) \rightarrow part\_of(x, z)) \quad (3)$$

Proper parthood

$$\forall x, y(proper\_part\_of(x, y) \equiv part\_of(x, y) \land \neg part\_of(y, x)) \quad (4)$$

Ground Mereology

Proper parthood

$$\forall x, y(proper\_part\_of(x, y) \equiv part\_of(x, y) \land \neg part\_of(y, x)) \quad (5)$$

Asymmetry (if x is part of y then y is not part of x)

$$\forall x, y(part\_of(x, y) \rightarrow \neg part\_of(y, x)) \quad (6)$$

Irreflexivity (x is not part of itself)

$$\forall x \neg(part\_of(x, x)) \quad (7)$$

Defining other relations with *part_of*

Overlap (x and y share a piece z)

$$\forall x, y(overlap(x, y) \equiv \exists z(part\_of(z, x) \wedge part\_of(z, y))) \quad (8)$$

Underlap (x and y are both part of some z)

$$\forall x, y(underlap(x, y) \equiv \exists z(part\_of(x, z) \wedge part\_of(y, z))) \quad (9)$$

Over- & undercross (over/underlap but not part of)

$$\forall x, y(overcross(x, y) \equiv overlap(x, y) \wedge \neg part\_of(x, y)) \quad (10)$$

$$\forall x, y(undercross(x, y) \equiv underlap(x, y) \wedge \neg part\_of(y, x)) \quad (11)$$

Proper overlap & Proper underlap

$$\forall x, y(p\_overlap(x, y) \equiv overcross(x, y) \wedge overcross(y, x)) \quad (12)$$

$$\forall x, y(p\_underlap(x, y) \equiv undercross(x, y) \wedge undercross(y, x)) \quad (13)$$

- With x as part, what to do with the remainder that makes up y?
  - Weak supplementation: every proper part must be supplemented by another, disjoint, part. **MM**
  - Strong supplementation: if an object fails to include another among its parts, then there must be a remainder. **EM**
- Problem with EM: non-atomic objects with the same proper parts are identical, because of this (extensionality principle), but sameness of parts may not be sufficient for identity E.g.: two objects can be distinct purely based on arrangement of its parts, differences statue and its marble (multiplicative approach)

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General Extensional Mereology

- Strong supplementation [EM]

$$\neg part\_of(y,x) \rightarrow \exists z(part\_of(z,y) \land \neg overlap(z,x)) \quad (14)$$

- And add unrestricted fusion [GEM]. Let ϕ be a property or condition, then for every satisfied ϕ there is an entity consisting of all entities that satisfy ϕ. [5] Then:

$$\exists x\phi \rightarrow \exists z \forall y(overlap(y,z) \leftrightarrow \exists x(\phi \land overlap(y,x))) \quad (15)$$

- Note that in EM and upward we have identity, from which one can prove acyclicity for ppo
- There are more mereological theories, and the above is not uncontested (more about that later)

[5] Need to refer to classes, but desire to stay within FOL. Solution: axiom schema with only predicates or open formulas

Relations between common mereological theories

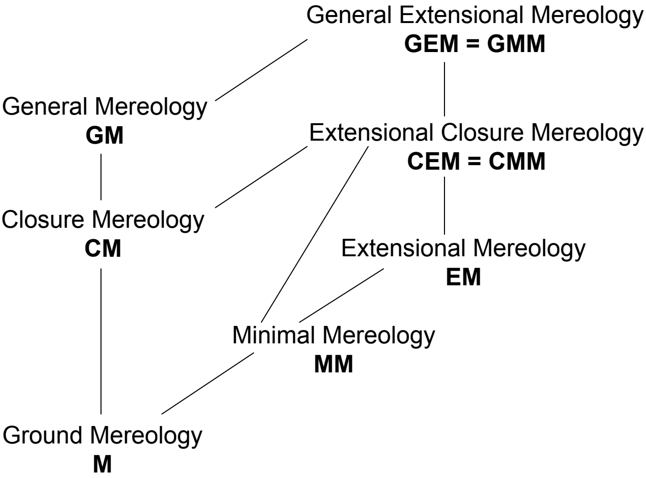

Fig. 1: Hasse diagram of mereological theories; from weaker to stronger, going uphill (after [44]).

Can any of this be represented in a decidable fragment of first order logic for use in ontologies and (scalable) software implementations?

Things are improving...

- Early days (90s) and simplest options: DL-role `R` as `partof`, or `has-part` added as primitive role as $\succeq$, model it as the transitive closure of a parthood relation (16) and define e.g. `Car` as having wheels that in turn have tires (17):

$$\succeq \doteq (\texttt{primitive-part})* \qquad (16)$$

$$\texttt{Car} \doteq \exists \succeq .(\texttt{Wheel} \sqcap \exists \succeq .\texttt{Tire}) \qquad (17)$$

  Then $\texttt{Car} \sqsubseteq \exists \succeq .\texttt{Tire}$

- SEP triples with $\mathcal{ALC}$
- What $\mathcal{SHIQ}$ fixes cf. $\mathcal{ALC}$: Transitive roles, Inverse roles (to have both part-of and has-part), Role hierarchies (e.g. for subtypes of part-of), qualified Number restrictions (e.g. to represent that a bycicle has-part 2 wheels)
- Build-your-own DL-language

What we can(not) implement now with DL-based ontology languages

Table: Properties of parthood and proper parthood compared to their support in $\mathcal{DLR}_\mu$, $\mathcal{SHOIN}$ and $\mathcal{SROIQ}$. *: properties of the parthood relation (in M); ‡: properties of the proper parthood relation (in M).

Language ⇒ **Feature** ⇓	$\mathcal{DLR}_\mu$	$\mathcal{SHOIN}$ (∼ OWL-DL)	$\mathcal{SROIQ}$ (∼ OWL 2 DL)	DL-Lite$_A$ (∼ OWL 2 QL)
Reflexivity *	+	–	+	–
Antisymmetry *	–	–	–	–
Transitivity * ‡	+	+	+	–
Asymmetry ‡	+	+	+	+
Irreflexivity ‡	+	–	+	–
Acyclicity	+	–	–	–

Definitions in OBO Relations Ontology

- Instance-level relations
  - c **part_of** c_1 at t - a primitive relation between two continuant instances and a time at which the one is part of the other
  - p **part_of** p_1, r **part_of** r_1 - a primitive relation of parthood, holding independently of time, either between process instances (one a subprocess of the other), or between spatial regions (one a subregion of the other)
  - c **contained_in** c_1 at $t \triangleq c$ **located_in** c_1 at t and not c **overlap** c_1 at t
  - c located_in r at t - a primitive relation between a continuant instance, a spatial region which it occupies, and a time

Definitions in OBO Relations Ontology

- Class-level relations
  - C *part_of* $C_1 \triangleq$ for all c, t, if Cct then there is some c_1 such that $C_1 c_1 t$ and c **part_of** c_1 **at** t.
  - P *part_of* $P_1 \triangleq$ for all p, if Pp then there is some p_1 such that: $P_1 p_1$ and p **part_of** p_1.
  - C *contained_in* $C_1 \triangleq$ for all c, t, if Cct then there is some c_1 such that: $C_1 c_1 t$ and c **contained_in** c_1 at t
- Need to commit to a foundational ontology. Recently, linked to BFO http://obofoundry.org/ro/#mappings (test release)
- Same labels, different relata and only a textual constraint: Label the relations differently

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- Class-level relations
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  - P *part_of* $P_1 \triangleq$ for all p, if Pp then there is some p_1 such that: $P_1 p_1$ and p **part_of** p_1.
  - C *contained_in* $C_1 \triangleq$ for all c, t, if Cct then there is some c_1 such that: $C_1 c_1 t$ and c **contained_in** c_1 at t
- Need to commit to a foundational ontology. Recently, linked to BFO http://obofoundry.org/ro/#mappings (test release)
- Same labels, different relata and only a textual constraint: Label the relations differently

Linguistic use of part-whole relations (meronymy)

- Part of?
  - ⋆ Centimeter part of Decimeter
  - ⋆ Decimeter part of Meter
  - — *therefore* Centimeter part of Meter
  - ⋆ Meter part of SI
  - — but *not* Centimeter part of SI
- Transitivity?
  - ⋆ Person part of Organisation
  - ⋆ Organisation located in Bolzano
  - — therefore Person located in Bolzano?
  - — but *not* Person part of Bolzano

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Linguistic use of part-whole relations

- Which part of?
  - ⋆ CellMembrane structural part of RedBloodCell
  - ⋆ RedBloodCell part of Blood
  - — but *not* CellMembrane structural part of Blood
  - ⋆ Receptor structural part of CellMembrane
  - — *therefore* Receptor structural part of RedBloodCell

Linguistic use of part-whole relations

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  - ⋆ CellMembrane structural part of RedBloodCell
  - ⋆ RedBloodCell contained in? Blood
  - — but *not* CellMembrane structural part of Blood
  - ⋆ Receptor structural part of CellMembrane
  - — *therefore* Receptor structural part of RedBloodCell

Addressing the issues

- Efforts to disambiguate this confusion; e.g. an informal taxonomy by Winston et al (1987), list of 6 types motivated by UML conceptual modeling (Odell) ontology-inspired conceptual modelling (Guizzardi)
- Location, containment, membership of a collective, quantities of a mass
- Relatively well-settled debate on transitivity, or not

Overview

- Mereological *part_of* (and subtypes) versus 'other' part-whole relations
- Categories of object types of the part-whole relation changes
- Structure these relations by (non/in)transitivity and kinds of relata
- Simplest mereological theory, **M**.
- Commit to a foundational ontology: DOLCE (though one also could choose, a.o., BFO, OCHRE, GFO, ...)

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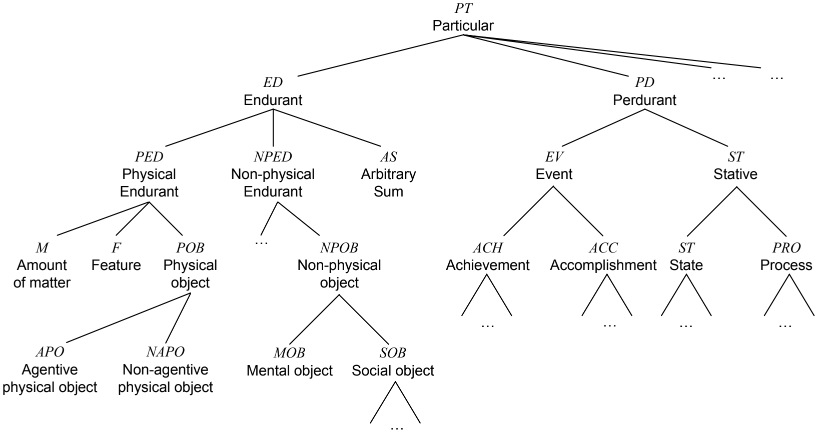
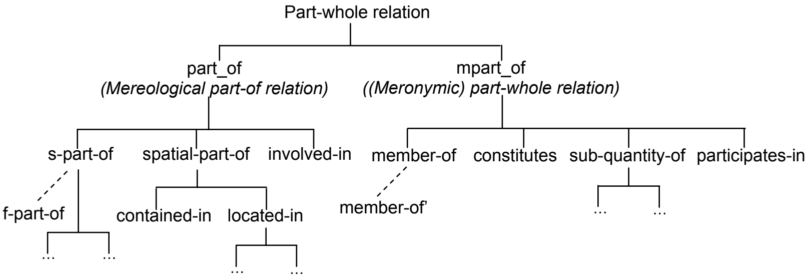
DOLCE categories



Part-whole relations



Part-whole relations

"member-bunch", collective nouns (e.g. `Herd`, `Orchestra`) with their members (`Sheep`, `Musician`)

$$\forall x, y(member\_of_n(x, y) \triangleq mpart\_of(x, y) \land (POB(x) \lor SOB(x)) \land SOB(y))$$

"material-object", that what something is made of (e.g., `Vase` and `Clay`)

$$\forall x, y(constitutes_{it}(x, y) \equiv constituted\_of_{it}(y, x) \triangleq mpart\_of(x, y) \land POB(y) \land M(x))$$

Part-whole relations

"quantity-mass", "portion-object", relating a smaller (or sub) part of an amount of matter to the whole. Two issues (glass of wine & bottle of wine vs. `Salt` as subquantity of `SeaWater`)

$$\forall x, y(sub\_quantity\_of_n(x, y) \triangleq mpart\_of(x, y) \wedge M(x) \wedge M(y))$$

"noun-feature/activity", entity participates in a process, like `Enzyme` that participates in `CatalyticReaction`

$$\forall x, y(participates\_in_{it}(x, y) \triangleq mpart\_of(x, y) \wedge ED(x) \wedge PD(y))$$

Part-whole relations

processes and sub-processes (e.g. `Chewing` is involved in the grander process of `Eating`)

$$\forall x, y(involved\_in(x, y) \triangleq part\_of(x, y) \land PD(x) \land PD(y))$$

Object and its 2D or 3D region, such as `contained_in(John's address book, John's bag)` and `located_in(Pretoria, South Africa)`

$$\forall x, y(contained\_in(x, y) \triangleq part\_of(x, y) \land R(x) \land R(y) \land \exists z, w(has\_3D(z, x) \land has\_3D(w, y) \land ED(z) \land ED(w)))$$

$$\forall x, y(located\_in(x, y) \triangleq part\_of(x, y) \land R(x) \land R(y) \land \exists z, w(has\_2D(z, x) \land has\_2D(w, y) \land ED(z) \land ED(w)))$$

$$\forall x, y(s\_part\_of(x, y) \triangleq part\_of(x, y) \land ED(x) \land ED(y))$$

Using the taxonomy of part-whole relations

- Representing it correctly in ontologies and conceptual data models
  - Decision diagram
  - Using the categories of the foundational ontology
  - Examples
  - *Software application* that simplifies all that
- Reasoning with a taxonomy of relations
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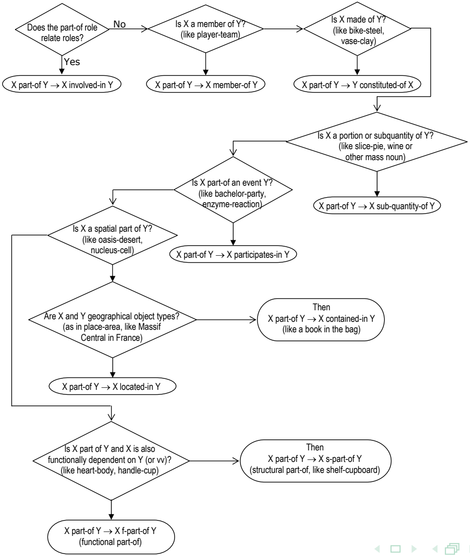
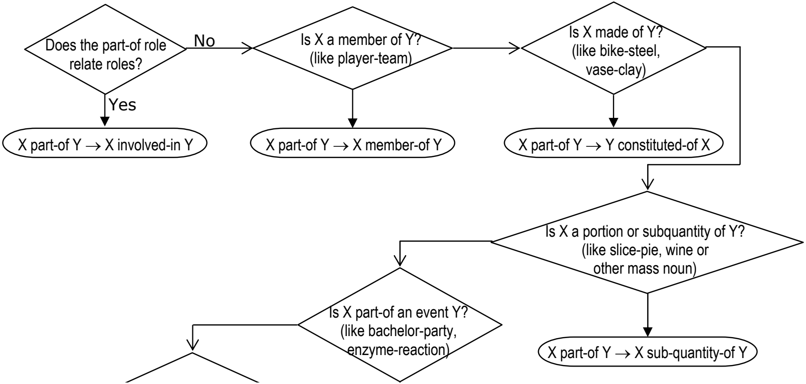
Decision diagram



Decision diagram



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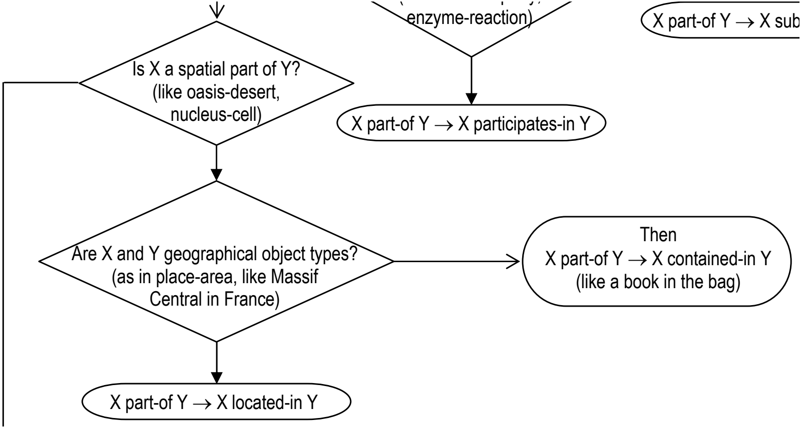


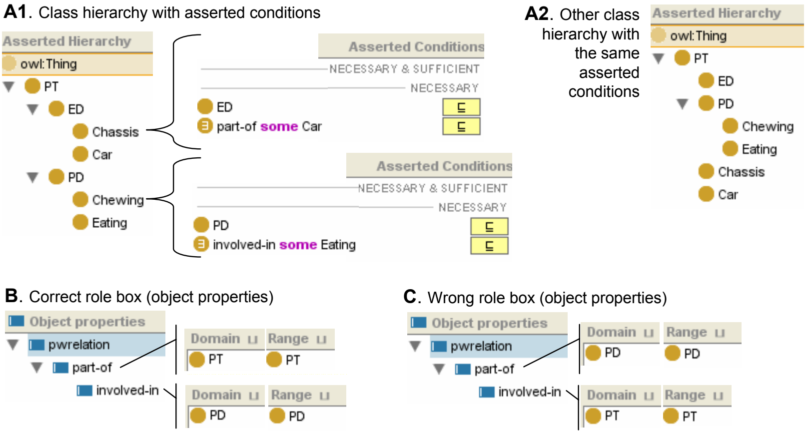
Using DOLCE's categories

- The participating objects instantiate some category (*ED*, *PD*, etc)
- Given the formalization, one immediately can exclude/identify appropriate relations, taking a shortcut in the decision diagram
  - E.g.: *Chewing* and *Eating* are both a kind of (a subtype of) *PD*, hence *involved_in*
  - E.g.: *Alcohol* and *Wine* are both mass nouns, or *M*, hence *sub_quantity_of*
- Demo of ONTOPARTS

Requirements for reasoning over the hierarchy

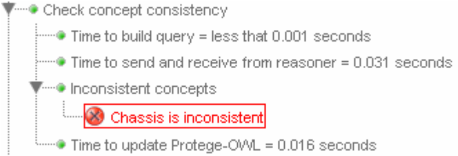
- Represent at least Ground Mereology,
- Express ontological categories and their taxonomic relations,
- Having the option to represent transitive and intransitive relations, and
- Specify the domain and range restrictions (/relata/entity types) for the classes participating in a relation.

Current behaviour of reasoners

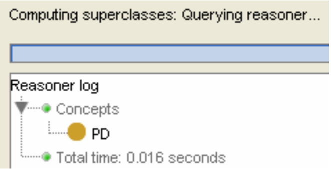


Current behaviour of reasoners

1. A1+B+racer: *ontology OK*
2. A2+B+racer: *ontology OK*
3. A1+C+racer: class hierarchy is inconsistent



4. A2+C+racer: Chassis reclassified as PD



The *RBox Compatibility* service – definitions

Definition (Domain and Range Concepts)

Let R be a role and $R \sqsubseteq C_1 \times C_2$ its associated Domain & Range axiom. Then, with the symbol D_R we indicate the *User-defined Domain* of R—i.e., $D_R = C_1$—while with the symbol R_R we indicate the *User-defined Range* of R—i.e., $R_R = C_2$.

Definition (RBox Compatibility)

For each pair of roles, R, S, such that $\langle \mathcal{T}, \mathcal{R} \rangle \models R \sqsubseteq S$, check:

Test 1. $\langle \mathcal{T}, \mathcal{R} \rangle \models D_R \sqsubseteq D_S$ and $\langle \mathcal{T}, \mathcal{R} \rangle \models R_R \sqsubseteq R_S$;

Test 2. $\langle \mathcal{T}, \mathcal{R} \rangle \not\models D_S \sqsubseteq D_R$;

Test 3. $\langle \mathcal{T}, \mathcal{R} \rangle \not\models R_S \sqsubseteq R_R$.

An RBox is said to be compatible iff *Test 1* and (*2* or *3*) hold for all pairs of role-subrole in the RBox.

The *RBox Compatibility* service – behaviour

- If `Test 1` does not hold: warning that domain & range restrictions of either R or S are in conflict with the role hierarchy proposing either
  - (i) To change the role hierarchy or
  - (ii) To change domain & range restrictions or
  - (iii) If the test on the domains fails, then propose a new axiom $R \sqsubseteq D'_R \times R_R$, where $D'_R \equiv D_R \sqcap D_S$[6], which subsequently has to go through the RBox compatibility service (and similarly when `Test 1` fails on range restrictions).

[6] The axiom $C_1 \equiv C_2$ is a shortcut for the axioms: $C_1 \sqsubseteq C_2$ and $C_2 \sqsubseteq C_1$.

The *RBox Compatibility* service – behaviour

- If `Test 2` and `Test 3` fail: warn that R cannot be a proper subrole of S but that the two roles can be equivalent. Then, either:
  (a) Accept the possible equivalence between the two roles or
  (b) Change domain & range restrictions.
- Ignoring all warnings is allowed, too

Extensions in various directions

- Mereotopology, with location, GIS, Region Connection Calculus (http://www.comp.leeds.ac.uk/qsr/rcc.html)
- Mereogeometry
- Mereology and/vs granularity
- Temporal aspects of part-whole relations

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Mereology with spatial notions

- Another primitive: *C*onnected, which is reflexive and symmetric
- More and more expressive theories, e.g.:
  - T: $C(x,x)$ and $C(x,y) \rightarrow C(y,x)$
  - MT: T and $P(x,y) \rightarrow E(x,y)$ where E is enclosure ($E(x,y) =_{def} \forall z(C(z,x) \rightarrow C(z,y))$)
- Two primitives, P and C, or *part* in terms of C?
  - $P =_{def} \forall z(C(z,x) \rightarrow C(z,y))$
- or perhaps "x and y are connected parts of z" as primitive, $CP(x,y,z)$, then:
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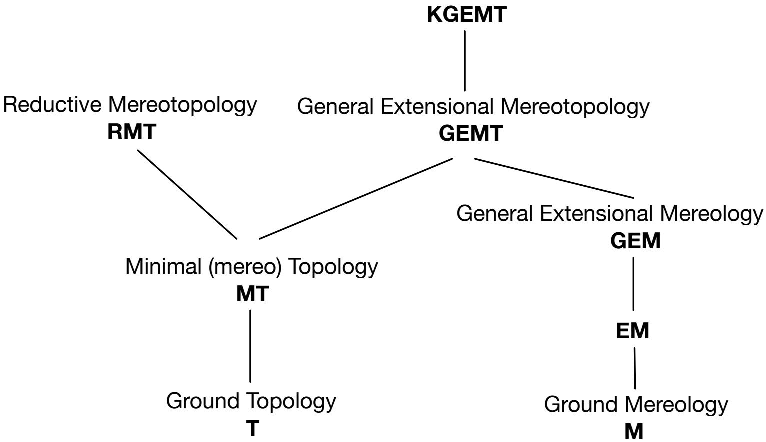
Some of the mereo- and topological theories



Note: one can add explicit variations with Atom/Atomless and Boundary/Boundaryless

Outline

Rationale

- It is hard to reuse only the "useful pieces" of a comprehensive (foundational) ontology, and the cost of reuse may be higher than developing a new ontology from scratch
- Need for small (or cleverly modularized) ontologies with explicit documentation of design rationales, and best reengineering practices
- Hence, in analogy to software design patterns: **ontology design patterns**
- ODPs summarize the good practices to be applied within design solutions
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content of slides based on Presutti et al, 2008

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ODP definition

- An ODP is an information object
- A design pattern schema is the description of an ODP, including the roles, tasks, and parameters needed in order to solve an ontology design issue
- *An ODP is a modeling solution to solve a recurrent ontology design problem. It is an Information Object that expresses a Design Pattern Schema (or skin) that can only be satisfied by DesignSolutions. Design solutions provide the setting for Ontology Elements that play some ElementRole(s) from the schema.* (Presutti et al, 2008)

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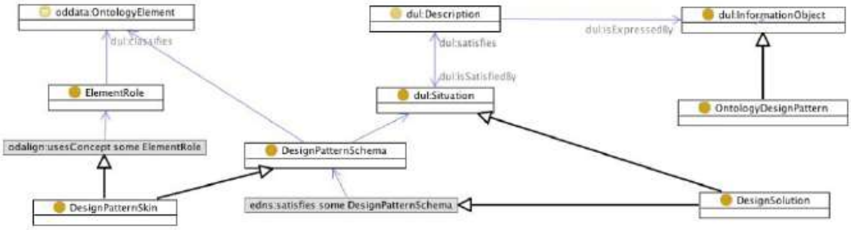
oddata:OntologyElement
dul:classifies
ElementRole
odalign:usesConcept some ElementRole
DesignPatternSkin
DesignPatternSchema
edns:satisfies some DesignPatternSchema
dul:Description
dul:satisfies
dul:isSatisfiedBy
dul:Situation
dul:InformationObject
dul:isExpressedBy
OntologyDesignPattern
DesignSolution

Types of Patterns

- Six families of ODPs: Structural OPs, Correspondence OPs, Content OPs (CPs), Reasoning OPs, Presentation OPs, and Lexico-Syntactic OPs
- CPs can be distinguished in terms of the domain they represent
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- Logical OPs:
  - Are compositions of logical constructs that solve a problem of expressivity in OWL-DL (and, in cases, also in OWL 2 DL)
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  - Independent from a specific domain of interest
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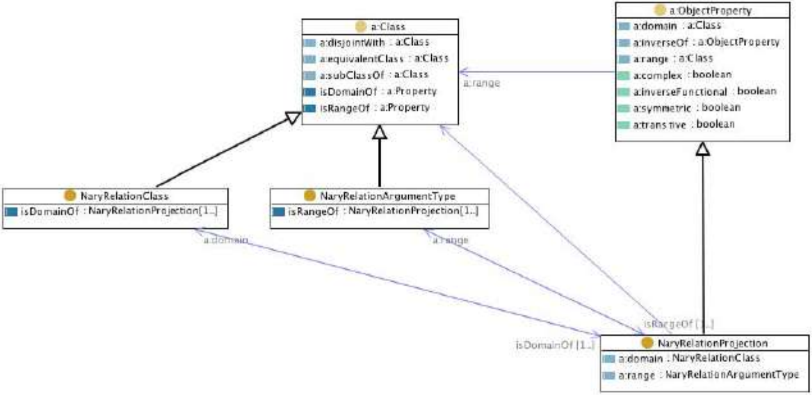
Example: n-ary relation Logical OP



Architectural OPs

- Architectural OPs are defined in terms of composition of Logical OPs that are used in order to affect the overall shape of the ontology; i.e., an Architectural OP identifies a composition of Logical OPs that are to be exclusively used in the design of an ontology
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- linguistic structures or schemas that consist of certain types of words following a specific order and that permit to generalize and extract some conclusions about the meaning they express; *verbalisation* patterns
- E.g., "subClassOf" relation, NP<subclass> be NP<superclass>, a Noun Phrase should appear before the verb—represented by its basic form or lemma, be in this example—and the verb should in its turn be followed by another Noun Phrase
- Other Lexical OPs provided for OWL's equivalence between classes, object property, subpropertyOf relation, datatype property, existential restriction, universal restriction, disjointness, union of classes
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- See chapter 3 of (Presutti et al., 2008)
- Where do ODPs come from (section 3.4—in part: legacy sources, which we deal with in the next lecture)
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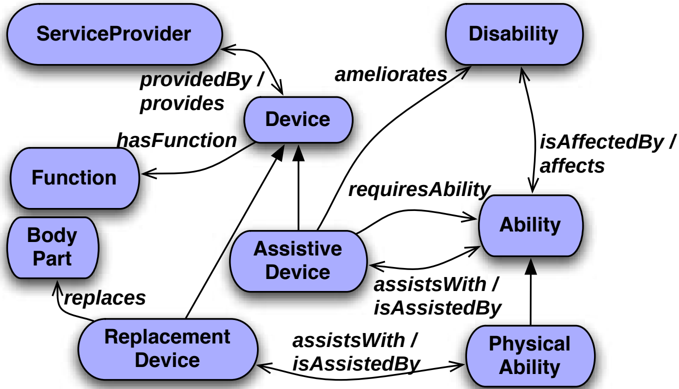
Sample exercise: an ODP for the ADOLENA ontology?

- Novel Abilities and Disabilities OntoLogy for ENhancing Accessibility: ADOLENA
- Can this be engineered into an ODP? If so, which type(s), how, what information is needed to document an ODP?



Summary

10 Foundational ontologies
- DOLCE
- BFO
- More foundational ontologies

11 Part-whole relations
- Parts, mereology, meronymy
- Taxonomy of types of part-whole relations
- Mereotopology and other extensions

12 Ontology Design Patterns
- Types of patterns
- Developing and using an ODP

Part IV

Bottom-up ontology development

Outline

13 RDBMSs and other 'legacy KR'
- Example: manual and automated extractions

14 Natural language
- Introduction
- Ontology learning
- Ontology population

15 Biological models and thesauri
- Models in biology
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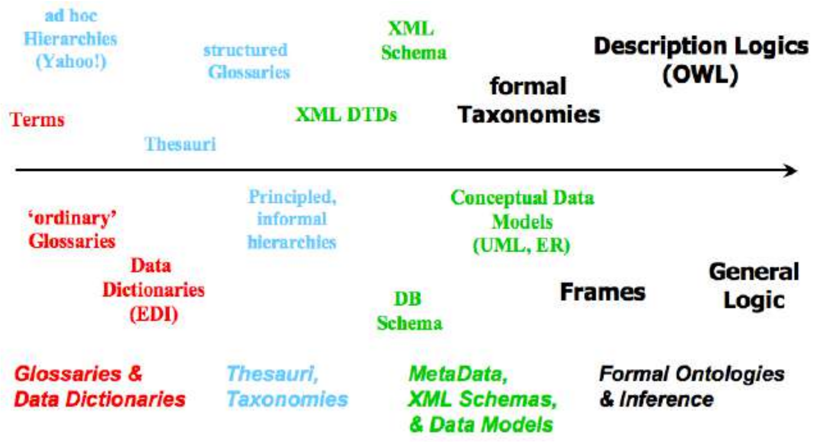
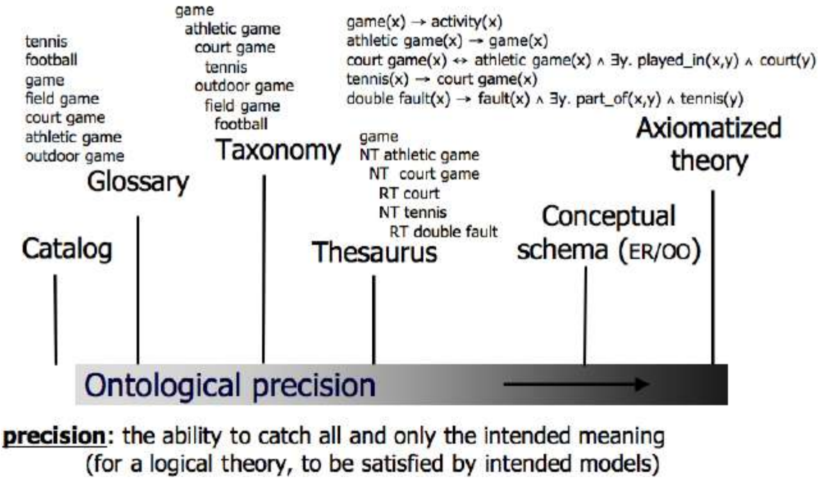
Bottom-up

- From *some* seemingly suitable legacy representation to an OWL ontology
  - Database reverse engineering
  - Conceptual model (ER, UML)
  - Frame-based system
  - OBO format
  - Thesauri
  - Formalizing biological models
  - Excel sheets
  - Text mining, machine learning, clustering
  - etc...

A few languages



Levels of ontological precision



(from Gangemi, 2004)

Outline

Examples: OBO and Protégé-frames

- OBO in OWL 2 DL
  - OBO is a Directed Acyclic Graph (with is_a, part_of, etc. relationships)
  - with some extras (a.o., date, saved by, remark)
  - and 'work-arounds' (not-necessary and inverse-necessary) and non-mappable things (antisymmetry)
  - There are several OBO-in-OWL mappings, some more comprehensive than others
  - e.g. FMA-Lite

Examples: OBO and Protégé-frames

- Frames (as in Protégé) into OWL-DL (see Zhang & Bodenreider, 2004), and its problems doing that to the FMA
  - Not a formal transformation
  - Slot values generally correspond to necessary conditions—so they took a first guess to define an anatomical entity as the sum of its parts
  - Global axioms dropped (with an eye on the reasoner)
  - After the conversion of the 39,337 classes and 187 slots from FMA in Protégé (ignoring laterality distinctions), FMAinOWL contains 39,337 classes, 187 properties and 85 individuals
  - Additional optimizations: optimizing domains and subClassOf axioms
  - But still caused Racer to fail to reason over the whole file; restricting properties further obtained results

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- Set aside of data duplication, violations of integrity constraints, hacks, outdated imports from other databases, outdated conceptual data models
- Some data in the DB—mathematically instances—actually assumed to be concepts/universals/classes
- 'impedance mismatch' DB values and ABox objects
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- Reuse conceptual data model (in ER, EER, UML, ORM, ...)
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  - Denormalization steps to flatten the database structure, which, if simply reverse engineered, ends up in the ontology as a class with umpteen attributes
  - Minimal (if at all) automated reasoning with it
- Redo the normalization steps to try to get some structure back into the conceptual view of the data?
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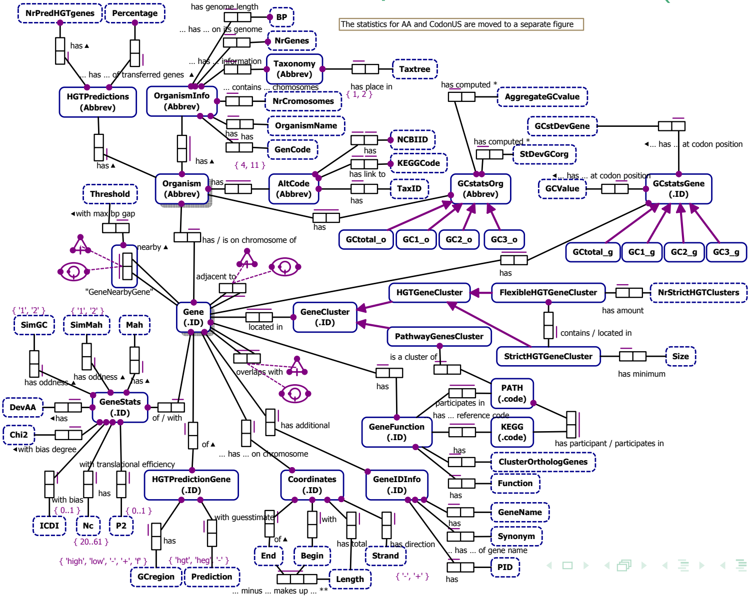
Section of the HGT conceptual data model (in ORM 2)



Manual mapping to *DL-Lite*$_{\mathcal{A}}$

- Basic statistics:
  - 38 classes
  - 34 object properties of which 17 functional
  - 55 data properties of which 47 functional
  - 102 subclass axioms
- Subsequently used for Ontology-Based Data Access

Automatic Extraction of Ontologies

- Examples
  - Lina Lubyte & Sergio Tessaris's presentation of the DEXA'09 paper
  - Reverse engineering from DB to ORM model with, e.g., VisioModeler v3.1 or NORMA

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  - To enhance precision and recall of queries
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A few notes on the nature of relations

- Early ideas were put forward by Williamson85 and have been elaborated on and structured in Fine00, Inwagen06, Leo08, and Cross02[7]
- Three different ontological commitments[8] about relations and relationships, which are, in Fine's terminology, the *standard view*, the *positionalist*, and the *anti-positionalist* commitment

[7] Full references in Keet, C.M. Positionalism of relations and its consequences for fact-oriented modelling. *Proc. of ORM'09, OTM Workshops*, Springer, LNCS 5872, 735-744.

[8] well, different people are convinced about the nature of the relation in reality; it does not exclude the possibility that maybe the corresponding different formalisations have equivalence-preserving transformations between them and admit the exact same models (if on assumes a model-theoretic semantics)).

The 'standard view' commitment

- Relies on linguistics and the English language in particular
- Take the fact *John loves Mary*, then one could be led to assume that *loves* is the name of the relation and *John* and *Mary* are the objects participating in the relation
- Then *Mary loves John* is not guaranteed to have the same truth value as the former fact—changing the verb does, i.e., *Mary is loved by John*
- We (seem to) have two relations, *loves* and its inverse *is loved by*

Problems with the 'standard view' (1/2)

- First, generally, for names *a* and *b*, *a loves b* holds iff what *a* denotes (in the reality we aim to represent) loves what *b* denotes.
- *John loves Mary* is not about language but about John loving Mary, so John and Mary are non-linguistic; cf. *'cabeza' translates into 'head'*
- Then, that John loves Mary and Mary is being loved by John refer to only one state of affairs between John and Mary
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Toward the 'positionalist' commitment

- Designate the two aforementioned facts to be relational expressions and not to let the verb used in the fact automatically also denote the name of the relation
- Then we can have many relational expressions standing in for the single relation that captures the state of affairs between John and Mary
- In analogy, we can have many relational expressions for one relationship at the type level

Problems with the 'standard view' (2/2)

- Second, the specific order of the relation: changing the order does not mean the same for verbs that indicate an asymmetric relation; different for some other languages.
- Consider *John kills the dragon*. In Latin we have:
  Johannus anguigenam caedit, or
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- The order of the argument places is not relevant for the relation itself
- English without such declensions that change the terms so as to disambiguate the meaning of a relational expression
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Toward the 'positionalist' commitment

- A linguistic version of *argument places* (roles) thanks to the nominative and the accusative that are linguistically clearly indicated
- The order of the argument places is not relevant for the relation itself
- English without such declensions that change the terms so as to disambiguate the meaning of a relational expression
- *Inverses for seemingly asymmetrical relations necessarily exist in reality and descriptions of reality in English, but not in other languages even when they represent the same state of affairs???*
- Asymmetric **relational expressions**, but this does not imply that the **relation** it verbalises is asymmetric

The 'positionalist' commitment

- Binary relation *killing* and identify the argument places—"argument positions" [Fine00] to have "distinguishability of the slots" [Cross02]—*killer* and *deceased* (loosely, a place for the nominative and a place for the accusative), assign *John* to *killer* and *the dragon* to *deceased* and order the three elements in any arrangement
- Relation(ship) and several distinguishable 'holes' and we put each object in its suitable hole.
- There are no asymmetrical relations, because a relationship R and its inverse R^{-}, or their instances, say, r and r', are *identical*, i.e., the same thing [Williamson85,Fine00,Cross02]

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The 'positionalist' commitment

- Ingredients
  - (i) an n-ary relationship R with $A_1, \ldots, A_m$ participating object types ($m \leq n$),
  - (ii) n argument places $\pi_1, \ldots, \pi_n$, and
  - (iii) n assignments $\alpha_1, \ldots, \alpha_n$ that link each object $o_1, \ldots, o_n$ (each object instantiating an A_i) to an argument place ($\alpha \mapsto \pi \times o$)
- R, π_1, π_2, π_3, $r \in R$, $o_1 \in A_1$, $o_2 \in A_2$, $o_3 \in A_3$, then any of $\forall x, y, z(R(x, y, z) \rightarrow A_1(x) \wedge A_2(y) \wedge A_3(z))$ and its permutations with corresponding argument places—i.e., $R[\pi_1, \pi_2, \pi_3]$, and e.g., $R[\pi_2, \pi_1, \pi_3]$, and $[\pi_2\pi_3]R[\pi_1]$—all denote the same SoA under the same assignment o_1 to π_1, o_2 to π_2, and o_3 to π_3 for the extension
- Thus, $r(o_1, o_2, o_3)$, $r(o_2, o_1, o_3)$, and $o_2 o_3 r o_1$ are different representations of the same SoA where objects o_1, o_2, and o_3 are related to each other by means of relation r.

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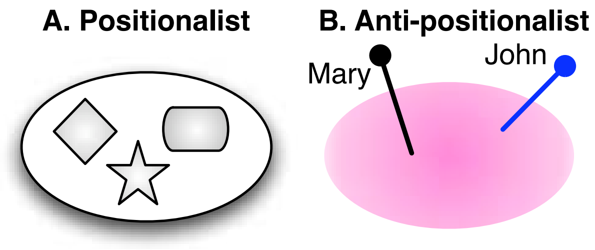
Graphical depictions



Problems with the 'positionalist' commitment

- From an ontological viewpoint, it requires identifiable argument positions to be part of the fundamental furniture of the universe.
- Practically, it requires something to finger-point to, i.e, to reify the argument places, and use it in the signature of the formal language, which is not clean and simple
- Symmetric relations, such as *adjacent to*, and relationships are problematic:
    i. Take π_a and π_b of a symmetric binary relation r, assign o_1 to position π_a and o_2 to π_b in state s.
    ii. One can do a reverse assignment of o_1 to position π_b and o_2 to π_a in state s'
    iii. But then o_1 and o_2 do not occupy the same positions as they did in s, so s and s' must be different, which should not be the case.

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- No argument positions, but just a relation and objects that yield states by "combining" into "a single complex" [Fine00]
- Solves the problems with the standard view
- Solves the positionalist's problem with symmetric relations
- (How to formalise this idea in a KR language is another problem)

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Example

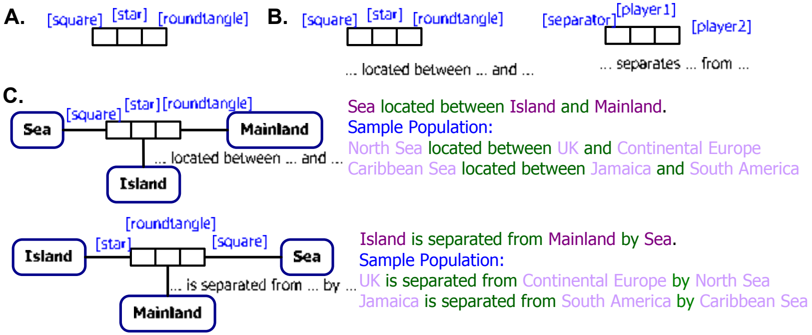
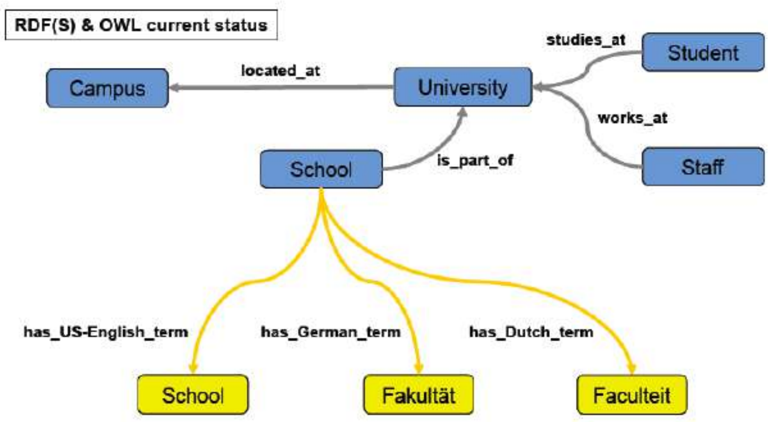


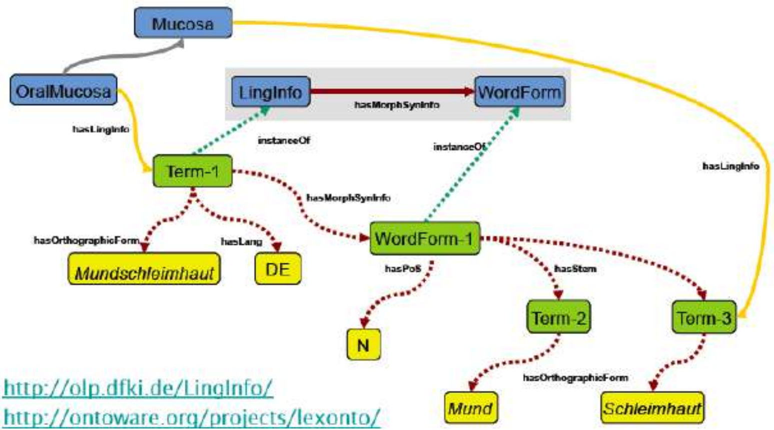
Figure: Positionalist examples in ORM. A: an ORM diagram rendering of Fig. 10-A; B: a reading added and a possible generalization of it, naming the relationship, e.g. *betweenness*; C: sample fact types and populations.

Ontologies in practice: Semantic Tagging—Classes, Terms



http://www.deri.ie/fileadmin/documents/teaching/tutorials/DERI-Tutorial-NLP.final.pdf

Ontologies in practice: Semantic Tagging—Lexicalized Ontologies



http://olp.dfki.de/LingInfo/
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Examples (out of many)

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  - Layer over PubMed, which indexes ± 19mln articles in the bio(medical) domain; pre-processing of the abstracts (advanced semantic tagging)
  - Results of the PubMed query are sorted according to terms in the ontology
- Question answer system AliQAn for agriculture (Vila and Ferrández, 2009)
  - Question assignment task too difficult for specialised domains
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Background

- Ontology development is time consuming
- Bottom-up ontology development strategies, of which one is to use NLP
- Where, if anywhere, can NLP make life easier for ontology development, and how?
- Current results are mostly discouraging, and depend on the approach, technique, and ontological commitment
  - We take a closer look at ontology learning limited to finding terms for a domain ontology

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Bottom-up ontology development with NLP

- Usual parameters, such as purpose (in casu, document retrieval), formal language (an OWL species)
- A standard kind of ontology (not a comprehensive lexicalised ontology)
- Additional considerations for "text-mining ontologies"
  - Level of granularity of the terms to include (hypo/hypernyms)
  - How to deal with synonyms ('LDL I' and 'large LDL')
  - Handle term variations (e.g., 'LDL-I' and 'LDL I', 'Tangiers' disease' and 'Tangier's Disease')
  - Disambiguation; e.g. w.r.t. abbreviations

Method to test automated term recognition

- Compare the terms of a manually constructed ontology with the terms obtained from text mining a suitable corpus
- Build an ontology manually
  - Lipoprotein metabolism (LMO), 223 classes with 623 synonyms
- Create a corpus
  - 3066 review article abstract from PubMed, obtained with a 'lipoprotein metabolism' search
- Automatic Term Recognition (ATR) tools
  - Text2Onto: relative term frequency, TFIDF, entropy, hypernym structure of WordNet, Hearst patterns
  - Termine: statistics of candidate term, such as total frequency of occurrence, frequency of the term as part of other longer candidate terms, length of term
  - OntoLearn: linguistic processor and syntactic parser, Domain relevance and domain consensus
  - RelFreq: relative frequency of a term in a corpus
  - TFIDF: RelFreq + doc. frequency derived from all phrases in PubMed

Results

- OntoLearn excluded form analysis because it regenerated few terms
- Text2Onto only included in analysis for up to 300 abstracts (could not process all 3066)
- Precision for LMO 17-35% for top 50 terms, and 4-8% for top 1000 terms
- Precision for LMO + expert analysis of the automatically generated terms: up to 75% for top 50 terms, and up to 29% for top 1000 terms
- Termine good for the longer terms, RelFreq and TFIDF for the shorter terms

Results (cont'd)

Table 3: Coverage of LMO terminology in selected document sets. The table sets the upper limit of terms that can be found with text-mining: Even a large text base with 50,000 documents contains only 71% of LMO terms. TFIDF can predict up to 38% of LMO terms.

	LMO terminology predicted by TFIDF		*LMO terminology literally contained*
	1000	**all**	
300 review abstracts for "lipoprotein metabolism"	8.75%	15.35%	20.98%
3,066 abstracts for "lipoprotein metabolism"	14.99%	38.25%	53.00%
50,000 abstracts containing "lipoprotein"			71.22%

from Alexopoulou et al, 2008

What went wrong with some of the terms?

- LMO terms that were not in the 50k abstracts grouped into:
  - Rarely occurring terms: occur rarely even in the whole of PubMed
  - Rarely occurring variants of terms: e.g., 'free chol' (0, instead of 2622 for 'free cholesterol')
  - Very long terms; e.g, 'predominance of large low-density lipoprotein particles', which can be decomposed into smaller terms
  - Combinations of terms/variants; e.g., 'increased total chol' (0, instead of 116 for 'increased total cholesterol'),
  - Terms that should normally be easily found; e.g., 'diabetes type I' (126) and 'acetyl-coa c-acyltransferase', probably due to limited corpus
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- Entity normalization; e.g., different strings refer to the same thing (full and abbreviated name, or single letter amino acid, three-letter aminoacid and full name: W, Trp, Tryptophan)
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- Text model, concerns with classes such as *sentence*, *text position* and locations like *abstract*, *intorduction*
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MutationMiner use case

- See Witte et al. book chapter for details
- Ontology in OWL, in Protégé; with class name, textual definition and example instances
- Species info from the NCBI taxonomy; note the management of central *scientific name* and its synonyms, common variants and misspellings
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- Benefits:
  - Standardizes data exchange, consolidate disparate resources
  - Detecting inconsistencies (caused by, e.g., a pronoun with an incompatible relation to another textual entity)
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Outline

Overview

- Pure and applied life sciences use many diagrams
- Some diagram hand drawn, but more and more with software
- Come with their own 'icon vocabulary' and many diagrams
- Exploit such informal but structured representation of information to develop automatically (a preliminary version of) a domain ontology
- Formalize the 'icon vocabulary' in a suitable logic language, choose a foundational ontology (taxonomy, relations), categorise the formalised icons accordingly, load each diagram into the ontology, verify with the domain expert

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Example of a PathwayAssist diagram

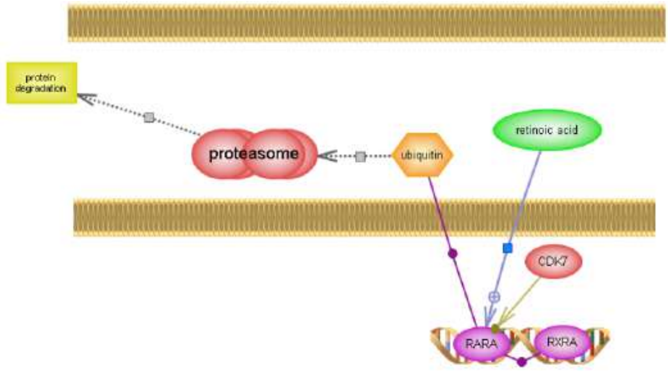
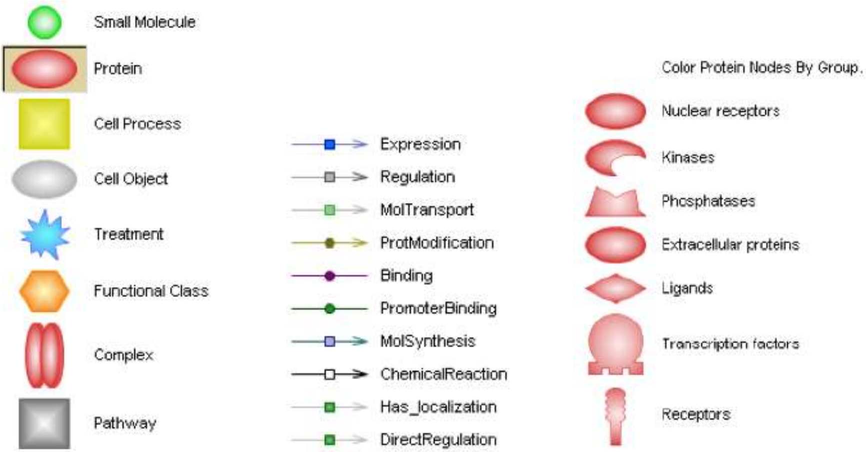


Figure: **Node** description: red: proteins, green: small molecules, orange: functional classes, yellow: cell processes, violet: nuclear receptors. **Link** description: grey dotted: regulation, violet solid: binding, yellow-green solid: protein modification, blue solid: expression.

Kindly provided by Kristina Hettne

PathwayAssist vocabulary



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Case study motivation

- Experiment in 2005 (Keet, 2005), but progress made in ecology (Madin et al, 2008; MTSR'09 proceedings)
- Extensive use of modelling in ecology, but not much shared (depending on sub-discipline)
- Models used with independent software tools (DB and other applications)
- 'Legacy code' (procedural), moving toward more OO, and ontologies
- Requirement for (re-)analysis to upgrade legacy SW, develop new SW to meet increasing complexities and rising demands
- **use the opportunity to create a more durable, yet computationally usable, shared, agreed upon representation of the knowledge about reality**

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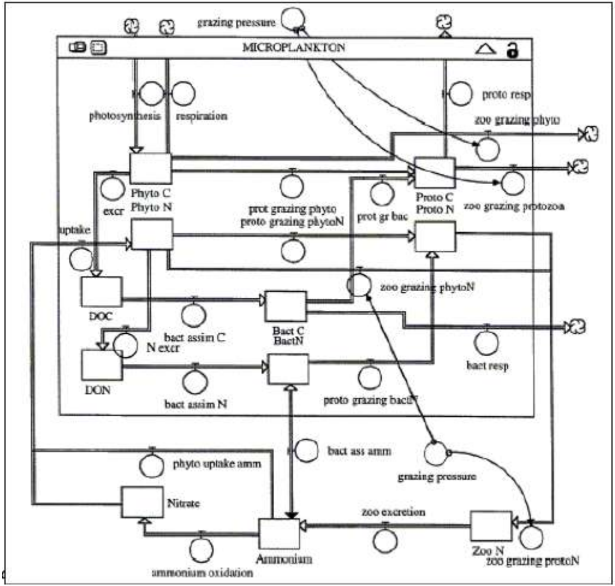
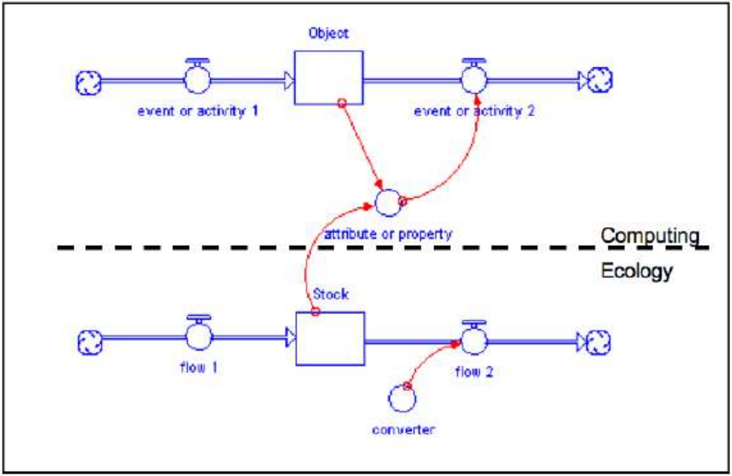
Example: the Microbial Loop [Tett&Wilson04]



Key aspects in the ecological model: Flow, Stock, Converter, Action Connector



Informal 'Translation'

- A `Stock` correspond to a noun (particular or universal)
- `Flow` to verb
- `Converter` to attribute related to Flow or Stock
- `Action Connector` relates the former
- Object is candidate for an *Endurant*
- Event_or_activity for a method or *Perdurant*
- Converter maps to *Attribute_or_property*
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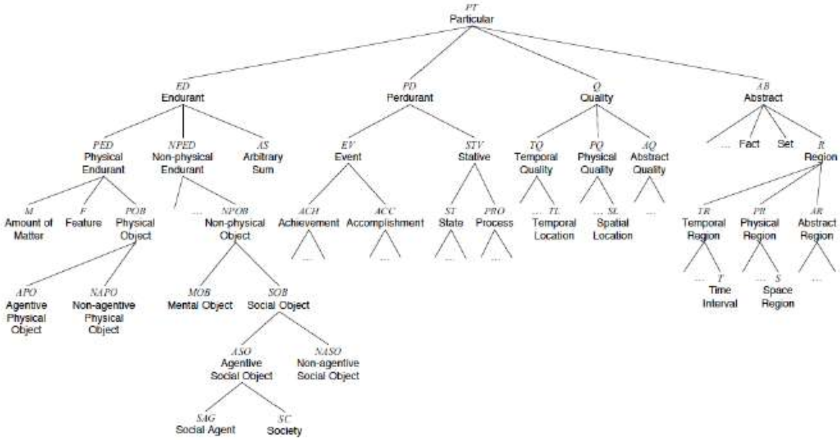
'Translation' w.r.t. DOLCE categories

- Basic mapping to DOLCE categories:
  - $\forall x((Stock(x) \leftrightarrow Entity(x)) \rightarrow ED(x))$
  - $\forall x((Flow(x) \leftrightarrow Entity(x)) \rightarrow PD(x))$
  - $\forall x((Converter(x) \leftrightarrow Entity(x)) \rightarrow (Q(x) \lor ST(x)))$
  - $\forall x(ActionConnector(x, y) \rightarrow Relationship(x, y))$

DOLCE categories



ML to Microbial Loop domain ontology

- Aim: to test translations with a real STELLA model
- ML's initial mapping to ontological categories contain 38 STELLA elements: 11 Stock/ED, 21 Flow/PD, 2 Converters/ST, 4 Action Connectors/Relationships
- The MicrobialLoop ontology has 59 classes and 10 properties
- Increase due to including DOLCE categories and implicit knowledge of ML that is explicit in MicrobialLoop

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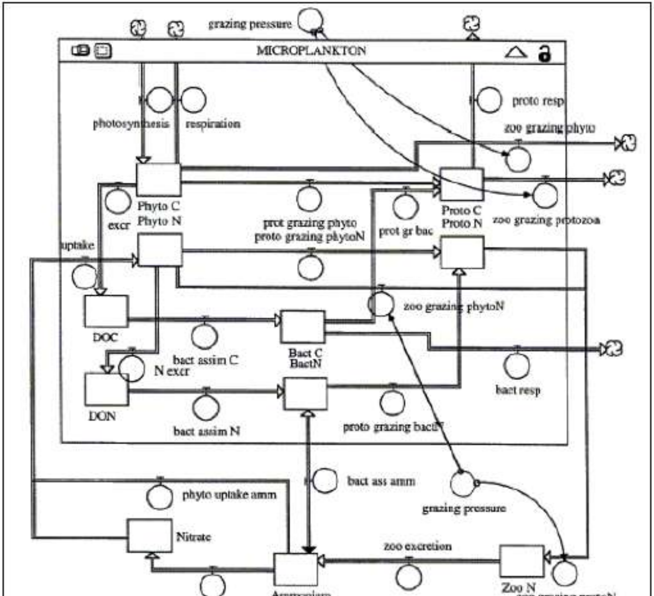
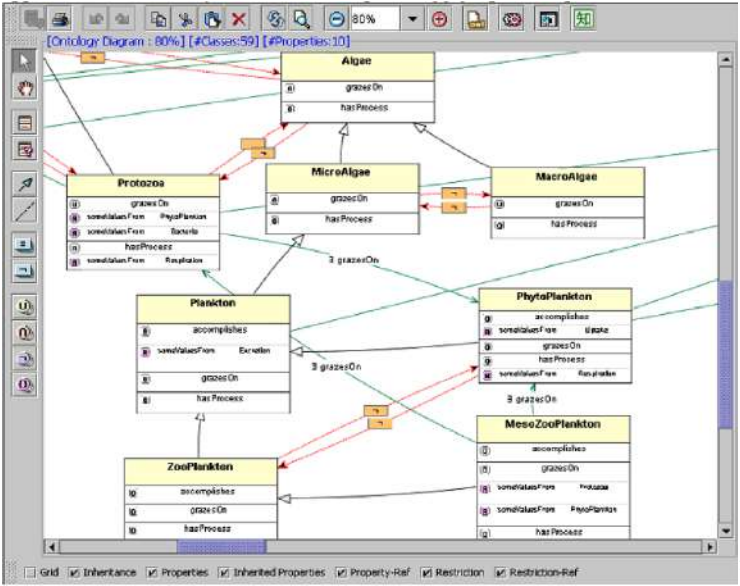


Section of more refined mapping to DOCLE categories

Phyto C	**NAPO**	**Phyto C = phytoplankton organic carbon. Phytoplankton is an APO, but 'phyto C' is *part* of the APO: only the organic carbon of the phytoplankton, not the organism as an active agent as such**
Phyto N	NAPO	Phyto N = phytoplankton nitrogen
DOC	NAPO	DOC = detrital organic carbon. Detritus is an ED with no unity, thus an amount of matter (M), but here, like with the organisms, there is focus on only a *part* of the NAPO
Nitrate	NAPO	Dissolved nitrate. Molecules are non agentive physical objects.
Flow		
Photosynthesis	PRO	To phytoplankton N
Respiration	PRO	From phytoplankton N
Prot gr bac	**PRO**	**Protozoa that are grazing on the Bacterial C**
Converter		
Grazing pressure	**ST**	**Acts on a PRO affecting the process of grazing; 'grazing pressure' is there (might reach zero), hence a ST.**
Action connector		
"1"	Yes	Acts on the mesozooplankton grazing on the protozoa, and acts on the mesozooplankton grazing on the phytoplankton: relation *hasGrazingPressure*

more mappings at http://www.meteck.org/supplDILS.html

Section in ezOWL



The serialized version of the ontology (section)


```
- <owl:Class rdf:ID="Protozoa">
    <owl:disjointWith rdf:resource="#Algae" />
    <owl:disjointWith rdf:resource="#Bacteria" />
  - <rdfs:subClassOf>
    - <owl:Restriction>
        <owl:onProperty rdf:resource="#hasProcess" />
        <owl:someValuesFrom rdf:resource="#Respiration" />
      </owl:Restriction>
    </rdfs:subClassOf>
  - <rdfs:subClassOf>
    - <owl:Restriction>
      - <owl:onProperty>
          <owl:ObjectProperty rdf:about="#grazesOn" />
        </owl:onProperty>
        <owl:someValuesFrom rdf:resource="#PhytoPlankton" />
      </owl:Restriction>
    </rdfs:subClassOf>
  - <rdfs:subClassOf>
    - <owl:Restriction>
        <owl:someValuesFrom rdf:resource="#Bacteria" />
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  </owl:Class>
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Discussion

- Formalising ecological natural, functional and integrative concepts
  - aids comparison of scientific theories
  - makes the implicit explicit, and more expressive than other modelling practices, therefore useful:
    - points to ambiguous sections,
    - part of/extra tool for doing science,
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To summarize

- Taxonomies insufficiently expressive compared to existing ecological modelling techniques
- Perspective of flow in ecological models cannot be represented adequately in a taxonomy
- More comprehensive semantics of formal ontologies
- Formalised mapping between STELLA and ontology elements facilitates bottom-up ontology development and has excellent potential for semi-automated ontology development
- STELLA as intermediate representation, widely used by ecologists and is translatable to a representation usable for ontologists

Overview

- Thesauri galore in medicine, education, agriculture, ...
- Core notions of **BT** broader term, **NT** narrower term, and **RT** related term (and auxiliary ones UF/USE)
- E.g. the Educational Resources Information Center thesaurus:

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reading ability
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- Low ontological precision
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- Lacks basic categories alike those in DOLCE and BFO (ED, PD, SDC, etc.)

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Simple Knowledge Organisation System(s): SKOS

- W3C standard intended for converting Thesauri, Classification Schemes, Taxonomies, Subject Headings etc into one interoperable syntax
  - Concept-based search instead of text-based search
  - Reuse each others concept definitions
  - Search across (institution) boundaries
  - Standard software
- Limitations:
  - ‘unusual’ concept schemes do not fit into SKOS (original structure too complex)
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- A possible re-engineering procedure:
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  - Edit manually using an ontology editor:
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see (Soergel et al, 2004)

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    - automation of discovered patterns (rules-as-you-go); e.g.
      - observation: *cow* NT *cow milk* should become *cow <hasComponent> cow milk*
      – pattern: *animal <hasComponent> milk* (or, more generally *animal <hasComponent> body part*)
      — derive automatically: *goat* NT *goat milk* should become *goat <hasComponent> goat milk*
      other pattern examples, e.g., *plant <growsIn> soil type* and *geographical entity <spatiallyIncludedIn> geographical entity*

Summary

13 RDBMSs and other 'legacy KR'
- Example: manual and automated extractions

14 Natural language
- Introduction
- Ontology learning
- Ontology population

15 Biological models and thesauri
- Models in biology
- Thesauri

Part V

Methods and methodologies

Outline

16 Parameters and dependencies

17 Example methods: OntoClean and Debugging
- Guidance for modelling: OntoClean
- Debugging ontologies

18 Methodologies and tools

The landscape

- Difference between *method* and *methodology*
- Difference between writing down what you did (to make it a 'guideline') vs. experimentally validating a methodology
- Isn't ontology development just like conceptual data model development?
  - yes: e.g., interaction with the domain expert, data analysis
  - no: e.g., logic, automated reasoning, using (parts of) other ontologies, different scopes/purposes, specific isolated application scenario vs. general knowledge
- There are many methods for ontology development, but no up-to-date methodology

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- Multiple modelling issues in ontology development for the applied life sciences (e.g., part-of, uncertainty, prototypes, multilingual), methodological issues, highly specialised knowledge
- W3C's incubator group on modelling uncertainty, mushrooming of bio-ontologies, ontology design patterns, W3C standard OWL, etc.
- Solving the early-adopter issues moves the goal-posts
  - Which ontologies are reusable for one's own ontology?
  - What are the consequences choosing one ontology over the other?
  - The successor of OWL, draft OWL 2, has 5 languages: which one should be used for what and when?

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  - What are the consequences choosing one ontology over the other?
  - The successor of OWL, draft OWL 2, has 5 languages: which one should be used for what and when?

The landscape

- Multiple modelling issues in ontology development for the applied life sciences (e.g., part-of, uncertainty, prototypes, multilingual), methodological issues, highly specialised knowledge
- W3C's incubator group on modelling uncertainty, mushrooming of bio-ontologies, ontology design patterns, W3C standard OWL, etc.
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- Querying data by means of an ontology (OBDA) through linking databases to an ontology
- Database integration, (GO, OBO Foundry)
- Structured controlled vocabulary to link data(base) records and navigate across databases on the Internet ('linked data')
- Using it as part of scientific discourse and advancing research at a faster pace, (including experimental ontologies)
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- Ontology in an ontology-driven information system destined for run-time usage, e.g., in scientific workflows, MASs, ontology-mediated data clustering, and user interaction in e-learning
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Reusing ontologies

- Foundational ontologies
- Reference ontologies
- Domain ontologies that have an overlap with the new ontology;
- For each of them, resource usage considerations, such as
  - Availability of the resource (open, copyright)
  - If the source is being maintained or abandoned one-off effort;
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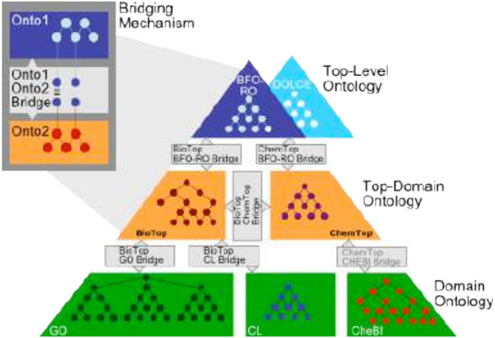

image from http://www.imbi.uni-freiburg.de/ontology/biotop/

Bottom-up development

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  - conceptual data models (UML diagrams, ER, and ORM)
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Languages – preliminary considerations

- Depending on the purpose(s) (and available resources), one ends up with either
  - (a) a large but simple ontology, i.e., mostly just a taxonomy without, or very few, properties (relations) linked to the concepts, where 'large' is, roughly, $>$ 10000 concepts, so that a simple representation language suffices;
  - (b) a large and elaborate ontology, which includes rich usage of properties, defined concepts, and, roughly, requiring OWL-DL; or
  - (c) a small and very complex ontology, where 'small' is, roughly, $<$ 250 concepts, and requiring at least OWL 2 DL
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Languages

- Older KR languages (frames, obo, conceptual graphs, etc.)
- Web Ontology Languages:
  - OWL: OWL-Lite, OWL-DL, OWL full
  - OWL 2 with 4 languages to tailor the choice of ontology language to fit best with the usage scope in the context of a *scalable* and *multi-purpose* SW:
    - OWL 2 DL is most expressive and based on the DL language $\mathcal{SROIQ}$
    - OWL 2 EL fragment to achieve better performance with larger ontologies (e.g., for use with SNOMED-CT)
    - OWL 2 QL fragment to achieve better performance with ontologies linked to large amounts of data in secondary storage (databases); e.g. DIG-QuOnto
    - OWL 2 RL has special features to handle rules
- Extensions (probabilistic, fuzzy, temporal, etc.)
- Differences between expressiveness of the ontology languages and their trade-offs

Reasoning services

- Description logics-based reasoning services
  - The standard reasoning services for ontology usage: satisfiability and consistency checking, taxonomic classification, instance classification;
  - 'Non-standard' reasoning services to facilitate ontology development: explanation/justification, glass-box reasoning, pin-pointing errors, least-common subsumer;
  - Querying functionalities, such as epistemic and (unions of) conjunctive queries;
- Ontological reasoning services (OntoClean, RBox reasoning service)
- Other technologies (e.g., Bayesian networks)

		OWL Language					Ontology reuse		
	SKOS	2 QL	2 EL	2 DL	DL	Extensions	foundational	reference	domain
Purpose ⇓									
1. Query data	−	+	−	−	−	+	−	−	±
2. Database integration	+	+	+	−	−	±	±	±	+
3. Integration / record navigation	+	+	+	−	−	−	−	±	+
4. Part of scientific discourse	−	−	−	+	+	+	+	+	+
5. Web services orchestration	−	−	+	±	+	−	±	+	+
6. ODIS	±	+	+	−	±	±	±	+	+
7. ontoNLP	+	+	+	−	±	−	±	+	+
8. Science	−	−	−	+	±	+	+	+	−
9. Tutorial ontology	−	−	−	+	+	±	−	−	+
Reasoning services ⇓									
1. Standard	−	±	±	+	+	+			
2. Non-standard	−	±	±	+	+	−			
3. Querying	−	+	+	−	−	±			
4. Ontological	+	+	+	+	+	+			
Bottom-up ⇓									
1. Other KR/CM	−	±	±	+	+	−			
2. DB reverse	−	±	±	+	+	−			
3. Textbook models	−	−	±	+	+	+			
4. Thesauri	+	±	+	−	−	−			
5. Other semi-structured	±	±	+	−	−	−			
6. Text mining	+	±	+	−	−	−			
7. Terminologies	+	±	+	−	−	−			
8. Tagging	+	±	+	−	−	−			
Ontology reuse ⇓									
1. Foundational	−	−	−	+	±	−			
2. Reference	−	±	±	+	+	−			
3. Domain	±	±	+	+	+	−			

Table 1 Basic cross-matching between realistic combinations of parameters. The more complex dependencies, such as the interaction between purpose, language, and reasoning service, can be obtained from traversing the table (*purpose* ↔

Outline

16 Parameters and dependencies

17 Example methods: OntoClean and Debugging
- Guidance for modelling: OntoClean
- Debugging ontologies

18 Methodologies and tools

OntoClean overview

- Problem: messy taxonomies on what subsumes what
- How to put them in the right order?
- OntoClean provides guidelines for this (see to Guarino & Welty, 2004 for an extended example)
- Based on philosophical principles, such as identity and rigidity (see Guarino & Welty's EKAW'00 and ECAI'00 papers for more information on the basics)

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Basics

- A property of an entity is *essential* to that entity if it must be true of it in every possible world, i.e. if it necessarily holds for that entity.
- Special form of essentiality is *rigidity*

Definition (+R)

A *rigid* property ϕ is a property that is essential to *all* its instances, i.e., $\forall x \phi(x) \rightarrow \Box \phi(x)$.

Definition (-R)

A *non-rigid* property ϕ is a property that is not essential to *some* of its instances, i.e., $\exists x \phi(x) \wedge \neg \Box \phi(x)$.

Basics

Definition (∼R)

An *anti-rigid* property ϕ is a property that is not essential to *all* its instances, i.e., $\forall x \phi(x) \rightarrow \neg \Box \phi(x)$.

Definition (¬R)

A *semi-rigid* property ϕ is a property that is non-rigid but not anti-rigid.

- Anti-rigid properties cannot subsume rigid properties

Basics

- *Identity*: being able to recognize individual entities in the world as being the same (or different)
- *Unity*: being able to recognize all the parts that form an individual entity; e.g., ocean carries unity (+U), legal agent carries no unity (-U), and amount of water carries anti-unity ("not necessarily wholes", ∼U)
- *Identity criteria* are the criteria we use to answer questions like, "is that my dog?"
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Basics

Definition

A non-rigid property carries an IC Γ iff it is subsumed by a rigid property carrying Γ.

Definition

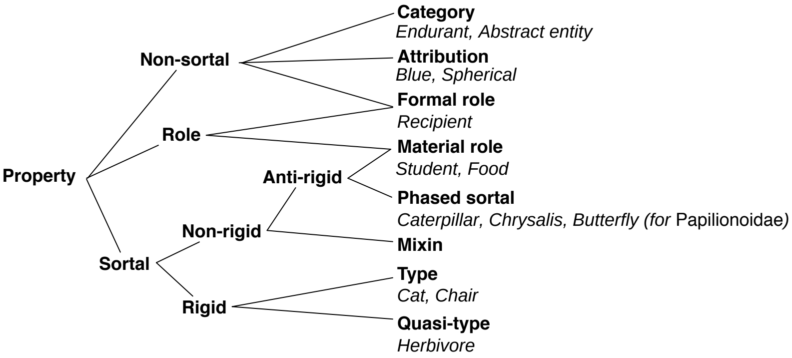
A property ϕ supplies an IC Γ iff i) it is rigid; ii) it carries Γ; and iii) Γ is not carried by all the properties subsuming ϕ. This means that, if ϕ inherits different (but compatible) ICs from multiple properties, it still counts as supplying an IC.

- Any property carrying an IC: $+$I (-I otherwise).
- Any property supplying an IC: $+$O (-O otherwise); "O" is a mnemonic for "own identity"
- $+$O implies $+$I and $+$R

Formal ontological property classifications

+O	+I	+R	+D	Type	Sortal
			-D		
-O	+I	+R	+D	Quasi-Type	
			-D		
-O	+I	~R	+D	Material role	
-O	+I	~R	-D	Phased sortal	
-O	+I	¬R	+D	Mixin	
			-D		
-O	-I	+R	+D	Category	Non-Sortal
			-D		
-O	-I	~R	+D	Formal role	
-O	-I	~R	-D	Attribution	
		¬R	+D		
			-D		

Formal ontological property classifications



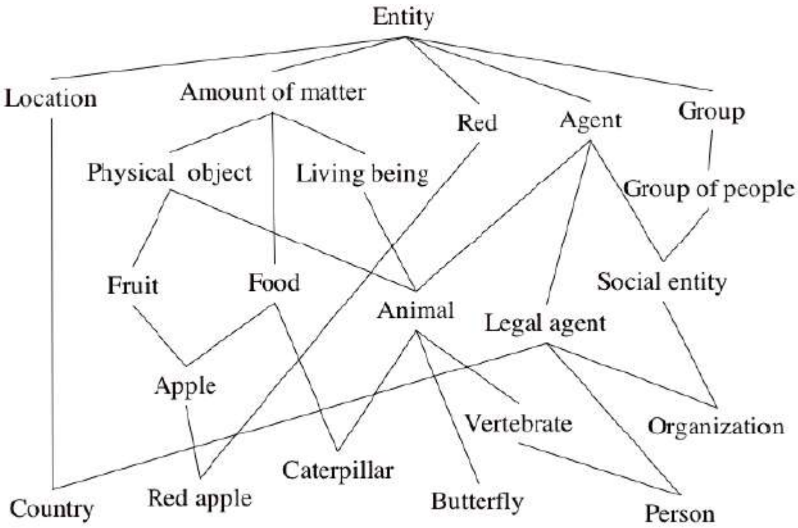
Basic rules

- Given two properties, p and q, when q subsumes p the following constraints hold:
    1. If q is anti-rigid, then p must be anti-rigid
    2. If q carries an IC, then p must carry the same IC
    3. If q carries a UC, then p must carry the same UC
    4. If q has anti-unity, then p must also have anti-unity

5. Incompatible IC's are disjoint, and Incompatible UC's are disjoint

- And, in shorthand:
    6. $+R \not\subset \sim R$
    7. $-I \not\subset +I$
    8. $-U \not\subset +U$
    9. $+U \not\subset \sim U$
    10. $-D \not\subset +D$

Example: before



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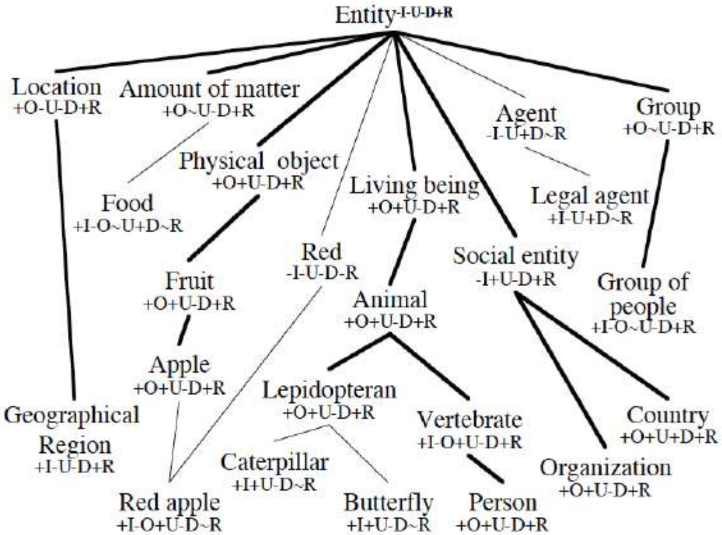

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- Domain experts are expert in their subject domain, which is not logic
- Modellers often do not understand the subject domain well
- The more expressive the language, the easier it is to make errors or bump into unintended entailments
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- In short: people make errors (w.r.t. their intentions) in the modelling task, and automated reasoners can help fix that

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Overview

- Using automated reasoners for 'debugging' ontologies, requires one to know about reasoning services
- Using standard reasoning services
- New reasoning services tailored to pinpointing the errors and explaining the entailments

Common errors

- Unsatisfiable classes
  - In the tools: the unsatisfiable classes end up as direct subclass of `owl:Nothing`
  - Sometimes one little error generates a whole cascade of unsatisfiable classes
- Satisfiability checking can cause rearrangement of the class tree and any inferred relationships to be associated with a class definition: 'desirable' vs. 'undesireable' inferred subsumptions
- Inconsistent ontologies: all classes *taken together* unsatisfiable

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Outline

Where are we?

- Parameters that affect ontology development, such as purpose, base material, language
- Methods, such as reverse engineering text mining to start, OntoClean to improve
- Tools to model, to reason, to debug, to integrate, to link to data
- Methodologies that are coarse-grained: they do not (yet) contain all the permutations at each step, i.e. *what* and *how* to do each step, given the recent developments;
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Example methodology: METHONTOLOGY

- Basic methodology:
  - specification: why, what are its intended uses, who are the prospective users
  - conceptualization, with intermediate representations
  - formalization (transforms the domain-expert understandable 'conceptual model' into a formal or semi-computable model)
  - implementation (represent it in an ontology language)
  - maintenance (corrections, updates, etc)
- Additional tasks (as identified by METHONTOLOGY)
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- MoKi is based on a **SemanticWiki**, which is used for collaborative and cooperative ontology development
- It enables actors with different expertise to develop an "enterprise model"[9]: use both *structural (formal) descriptions* and *more informal* and *semi-formal* descriptions of knowledge
- ⇒ access to the enterprise model **at different levels of formality**: informal, semi-formal and formal
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- Among others: ontology localization, -alignment, -formalization, -diagnosis, -enrichment etc.
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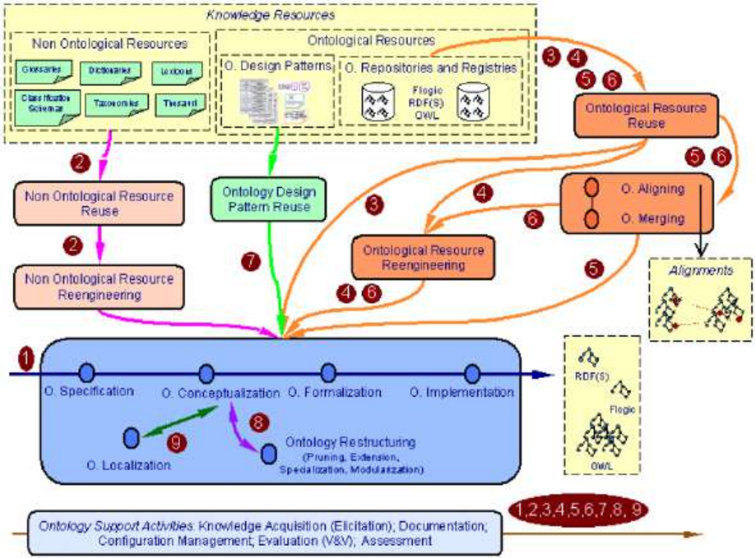
Scenarios for Building Ontology Networks



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    - NeOn toolkit aims to be a "open source multi-platform ontology engineering environment, which aims to provide comprehensive support for all activities in the ontology engineering life-cycle"; 45 plugins
    - RacerPro, RacerPorter. a.o.: sophisticated querying
    - KAON, SWOOP, etc.
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Summary

16 Parameters and dependencies

17 Example methods: OntoClean and Debugging

- Guidance for modelling: OntoClean
- Debugging ontologies

18 Methodologies and tools

Part VI

Extra topics

Outline

19 Challenges

- Modelling the subject domain
- Reasoning scenarios
- Social Aspects

Outline

SWT challenges or failures?

- Challenge: solution to problem y not possible yet (or very difficult to achieve) with current SWT, but in theory is (expected to be) feasible
- Failure: technology x claims to solve problem y but it does not and will not do so, or technology x is developed for a non-existing problem but does not solve real problems
  - Is y one that, at least in theory, can be solved with SWT?
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A few general issues

- RDF triple stores vs. RDBMSs vs OWL ABoxes in memory; more generally:
  - Making 'legacy' (operational) systems 'Semantic Web compliant'
  - Add a 'wrapper' over the legacy system so that from the outside it looks like it uses SWT
- How to integrate rules other than at instance level
- Modularization
- Semantics-based language transformations
- Coordination among tools with different functionalities

Language limitations considerations

- Known trade-offs between expressiveness and computational complexity
- Different ontology developers and their scopes (and purposes of the ontologies):
  - to some, there is more in OWL/OWL2 than needed and used
  - to some, there is not enough
- From a logician's perspective, language limitations are not failures per sé, only *challenge*s to find the more interesting and useful combinations of features
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Which language do we need?

- The (reflexive, antisymmetric, transitive) parthood relation
- Each Government has as members at least 10 Ministers
- A father is necessarily male
- Each plane passenger boards the aircraft after having checked in
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- The class of people who are young
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- *n*-ary relations, where $n > 2$
- “Hepatitis hasSymptom Fever in most but not all cases”
  - What about doing it with probabilistic default knowledge?
  - $(\psi \mid \phi)[l, u]$ as “generally, if an object belongs to ϕ, then it belongs to ψ with a probability in $[l, u]$”
  - e.g., (∃hasSymptom.Fever | Hepatitis)[illegible]
- “In 2000, worldwide prevalence of diabetes mellitus was 2.8%”
  - Probabilistic, or arithmetic, or what have we?
  - First, it assumes some class Human and a class HumanDiabetesMellitus, where some of the instances of the former have (are bearerOf) an instance of the latter.
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- ... Diabetes example continued
  - Authors' proposal to put it in the ABox with arithmetic operators, e.g. "$\frac{|DiabeticHuman|}{|Human|} = 0.028$"
  - Another option: put in TBox with a data property, e.g., `HumanDiabetesMellitus` $\sqsubseteq$ `∃hasPrevalence.real`
  - Yet another: represent the *probability* of a human having diabetes mellitus
  - What are the pros and cons of each option w.r.t. subject domain semantics, Ontology, and the ontology languages?
- Problems with Drug Abuse Prevention (in SNOMED CT)

  `DrugAbusePrevention` $\sqsubseteq$ `Procedure` $\sqcap$ `∃hasFocus.DrugAbuse`

  `DrugAbusePrevention` $\equiv$ `Procedure` $\sqcap$ `∃hasParticipant.Person` $\sqcap$ `∃causes.(State` $\sqcap$ `hasParticipant.(Person` $\sqcap$ `∃practicesIn-DrugAbuse))`

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- "Concussion of the brain without loss of consciousness", and the temporal aspects
- "aspirin prevents myocardial infarction"
  - Let us assume that is total prevention (though we could add a probability to it)
  - This only holds for humans actually ingesting aspirin, not for the substance itself
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Introduction on reasoning scenarios

- The standard reasoning services are obviously sorted out
- Performance issues for the ‘debugging’ and explanation reasoning, and how to provide the ‘best’ explanation
- Querying OWL 2 DL, and any ABox data
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Scenarios

1. Supporting the ontology development process
2. Classification
3. Model checking (violation)
4. Finding gaps in an ontology & discovering new relations
    - Deriving types and relations from instance-level data
    - Computing derived relations at the type level
5. Comparison of two ontologies ([logical] theories)
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- Usual model checking
- Model checking against *real* instances in the ABox/Database
  - For each DL-concept in the OWL-formalised ontology (representing a universal), there has to be at least one ABox instance (as representation of the entity in reality)
  - To spot "redundant" DL-concepts w.r.t. the data-needs
- Model violation
  - Reducing the amount of instances to only those that do not violate the TBox (or: the more inconsistencies, the better)
  - For instance, to find a few candidate molecules that satisfy a given set of properties, out of a large pool of possibly suitable molecules; e.g., for drug discovery in pharmainformatics, tyre production

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Discovering information

- The idea is that the combination of bio-ontologies, instances, and automated reasoning services somehow can find either the missing relations, or the types, or both
- How can one find what is, or may, not be in the ontology but ought to be there?
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  - computing derived relations (object properties)
  - find out where relations that are known by the developer have not yet been added to the ontology (finding 'known gaps')
  - add 'ontological' notions with top type 'whole' in a partonomy; e.g., 17 types of macrophage in the FMA each must be part of something
  - flag classes that have no relation (no or no is_a) to anything else in the ontology

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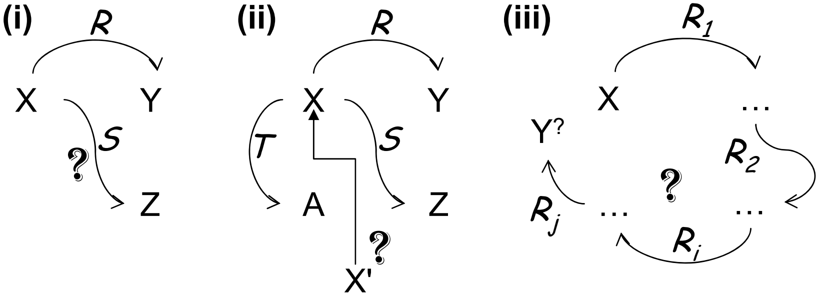
- For the TBox through querying the data (ABox, RDBMS)
  i. "for each x:X, y:Y, r:R, XRY, does there exist a z:Z, s:S, such that there exist ≥ 1 x and xsz?"
  ii. "for each x:X, y:Y, r:R, XRY, does there exist an xsz and an xta where z:Z, s:S, a:A, t:T hold?"
  iii. Find-me-anything-you-have: "for each x:X, return any $r_1, \ldots r_n$, their type of role and the concepts $Y_1, \ldots Y_n$ they are related to"



Building ontologies involves humans

- Building an ontology is, generally, an *interdisciplinary* (transdisciplinary?) endeavour
- Different disciplines with different mores, goals
- The collaboration requires patience, respect, capability to listen, compromise
- More slides in a separate file, time permitting