Symbolic Artificial Intelligence

Natalia Díaz Rodríguez

Sept. 2018

ENSTA ParisTech and INRIA Flowers `flowers.inria.fr` `http://asr.ensta-paristech.fr/`
`natalia.diaz@ensta-paristech.fr`

IA301 Logique et IA - 3A - Master (2018/2019)
`https://perso.telecom-paristech.fr/bloch/OptionIA/Logics-SymbolicAI.html`

Course: Logics and Symbolic AI

Course summary:

This course aims at providing the bases of symbolic AI, along with a few selected advanced topics. It includes courses on formal logics, ontologies, symbolic learning, typical AI topics such as revision, merging, etc., with illustrations on preference modelling and image understanding.

This 3 units: Ontologies, Knowledge Representation, Reasoning

Skills:

At the end of the course students will be able to understand different kinds of logic families, formulate reasoning in such formal languages, and manipulate tools to represent knowledge and its adaptation to imprecise and incomplete domains through the use of OWL, Protégé and fuzzyDL.

Prerequisites:

Basic knowledge in computer science and algebra

Syllabus by day sessions (8 total):

- 1- Reminder on bases on logics (syntax, semantics...) and overview of several logics (propositional, first order, modal...) - Isabelle Bloch
- 2,3 - Description Logics, Ontologies, Knowledge Graphs and Fuzzy Ontologies - Natalia Díaz
- 4 - Symbolic learning: formal concept analysis, decision trees - Isabelle Bloch
- 5 - Tutorial on ontology engineering and design. Building your own ontologies using (Fuzzy) OWL, Protégé and fuzzyDL for real life knowledge graph problems- (practical work, including a report at the end of the course) - Natalia Díaz
- 6,7 - Some typical examples in AI: revision, merging, abduction, with illustrations on preference modeling and image understanding - Isabelle Bloch
- 8 - Written exam

Practical Info

Dates 2018, Telecom ParisTech, Paris

September: 21, 28 (Natalia)

October: 5 (Natalia + Guest Seminar *Ontologies in Industry* by Juan Gomez Romero from Univ. of Granada), 12, 19 (Natalia), 26

November: 9, 16

Course evaluation:

The course will be evaluated based on a written exam (50%) and a report handed 2 weeks after, which will require to create an ontology as part of a decision support system of a freely elected domain problem (50%).

Practical Info

Dates 2018, Telecom ParisTech, Paris Télécom ParisTech (46 rue Barrault, dans le 13e), Friday - 8h30 - 11h45. Classrooms:

- 21/9 - C48
- 28/9 - C48
- 5/10 - B559
- 12/10 - F900
- 19/10 - TP en C124
- 26/10 - Amphi Estaunié
- 9/11 - F900
- 16/11 - Exam in F900

Evaluation: Ontology and Report

Send 1 single (max. 5 pages) pdf report (in couples, due 2 weeks after practical session: 2 Nov 2018) to natalia.diaz@ensta-paristech.fr including:

- A link to a repository/cloud with your designed ontology solution for an ideally daily problem that you describe and can support someone's decision making (transport choices, sustainability good practices, car buying -see examples [6] on matchmaking[1] [32]) using Protégé desktop editor.
- Only as many *Ontology facts worth reporting* as possible (indicate concrete -nr, letter, title- from those labelled *MUST* or *OPTIONAL* in MIRO repo[2][28] you are reporting).
- Justifications for your ontology design decisions[3]
- Optional: Experiment with OOPS! [31][4]: report nr. of ontology pitfalls you can fix in your ontology.

[1] FuzzyDL www.umbertostraccia.it/cs/software/fuzzyDL/fuzzyDL.html

[2] The Minimal Information for Reporting an Ontology (MIRO) Guidelines https://github.com/owlcs/miro/blob/master/miro.md

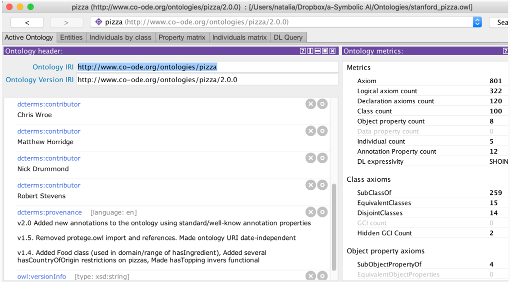
[3] If you lack inspiration, read OntoClean http://semanticweb.org/wiki/OntoClean.html tool to justify ontology building decisions or Ontology Engineering Methodologies (Ch. 9) [16] http://read.pudn.com/downloads77/ebook/293072/Semantic%20Web%20Technologies%20-%20Trends%20and%20Research%20in%20Ontology-based%20Systems(2006).pdf

[4] Online OOPS! - OntOlogy Pitfall Scanner! http://oops.linkeddata.es/

Evaluation: Ontology and Report

Evaluation will be based on:

- Nr of MIRO facts reported
- Nr of axioms, classes, and properties defined in the ontology -Report all ontology metrics values as below:



- How many of the concepts and relations above are consistent
- Coverage of a particular domain problem tackled[5]

[5] How many and which concepts are defined, how many instances/properties the dataset has, comparisons with a corpus, comprehensibility/consumability by the humans that will use it, connectivity to provide flexible queries and ambiguity evaluation (common identifiers and labels prone to miss-comprehension)[30].

Symbolic AI: Description Logics and Ontologies

Why study Symbolic AI?

Because:

- Deep learning-based AI is unable to reason, yet
- Neural models are black boxes, hard to interpret
- There is more to predict than what is visible or readable (CV, NLP):
  - Concepts, abstraction, embodiment, ...$\rightarrow$ context
- Eventually, decision support AI systems need to be told what the rules are (policies, ethics, laws) $\rightarrow$ requires knowledge representation (KR) and knowledge reasoning (KR)
  - If inference interpretation is wrong, decisions will be wrong as well
  - *The integration of both data-driven learning and knowledge-driven learning is probably what human learning is all about* [15, 19].

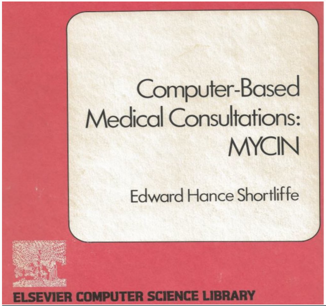
Knowledge Representation (KR)

- Goal: develop formalisms for providing high-level descriptions of the world that can be effectively used to build intelligent applications [3].
- KR languages need a well-defined syntax and a formal, unambiguous semantics -not always true for predecessor KR approaches-:
  - Semantic Networks [Quillian'67] (Semantic Memory Model, labeled directed graph)
  - Frames paradigm [Minsky'74] (A frame represents a concept and is characterized by a number of attributes (*slots*) that members of its class can have)
- High-level descriptions: concentrate on representing relevant aspects for a given application, while ignoring irrelevant details.

Knowledge Representation: The origins

MYCIN [33] (1976): influential in the development of expert systems, esp. rule-based approaches. One of the first programs to create a reasoning network for representing and utilizing judgmental knowledge, model inexact reasoning that typify real-world problems[6].

Later: NELL (Never Ending Language Learning, 2010) [12],...



[6] MYCIN's aim: give advice regarding antimicrobial selection, making it acceptable to physicians. 3 goals: ability to 1) give good **advice**, 2) **explain** the basis for its advice, 3) **acquire** new knowledge easily so advice can improve over time.

Description Logics (DL)

- A family of formal logic-based knowledge representation formalisms tailored towards representing terminological knowledge of a domain in a structured and well-understood way.
- Notions (classes, relations, objects) of the domain are modelled using (atomic) concepts -unary predicates-, (atomic) roles -binary preds-, and individuals to:
  - state *constraints* so that these notions can be interpreted
  - *deduce* consequences (*subclass* and *instance* relationships from definitions and constraints).

...rather than general first-order predicate logic?

- Because is a decidable[7] fragment of FOL, therefore, amenable for automated reasoning
- Because generating justifications for entailment[8] is possible[9]
- **Ex.**

A-BOX

$\boxed{\text{human(Aristotle)}}$

T-BOX

$\boxed{\text{human} \sqsubseteq \text{mortal}}$

Aristotle $\in$ mortal ?

[7] A logic is decidable if computations/algorithms based on it will terminate in a finite time

[8] R: set of clauses, γ: a ground atom; $R \models \gamma$ if every model satisfying R also satisfies γ

[9] `https://github.com/matthewhorridge/owlexplanation`

Description Logics: ABox, TBox and KB

- TBox (Terminological): The vocabulary used to describe concept hierarchies and roles in the KB (the world's rules, the *schema* in a DB setting). Can contain two kinds of axioms asserting that:
  - An individual is an instance of a given concept
  - A pair of individuals is an instance of a given role [4].
- ABox (Assertional): States properties of individuals in the KB (the data)
- Statements in TBox and ABox can be interpreted with DL rules and axioms[10] to enable reasoning and inference (including satisfiability, subsumption, equivalence, instantiation, disjointness, and consistency).

[10] *Axioms* (logical assertions) together comprise the overall theory that the ontology describes in its domain

Description Logics: ABox, TBox and KB

Examples TBox concept definitions [4][11]:

- *Men that are married to a doctor and all of whose children are either doctors or professors*: $\texttt{HappyMan} \equiv \texttt{Human} \sqcap \neg\ \texttt{Female} \sqcap (\exists\ \texttt{married.Doctor}) \sqcap (\forall\ \texttt{hasChild.(Doctor} \sqcup \texttt{Professor))}.$
- *Only humans can have human children:* $\exists\ \texttt{hasChild.Human} \sqsubseteq \texttt{Human}$

Ex. ABox:

- $\texttt{HappyMan(BOB)},\ \texttt{hasChild(BOB, MARY)},\ \neg\ \texttt{Doctor(MARY)}$

[11] The variable-free syntax of DL makes TBox statements *easier to read* than the corresponding first-order formulae.

Ex. $\texttt{HappyMan}$: men that have between 2-4 children

$\texttt{HappyMan} \equiv \texttt{Human} \sqcap \neg\ \texttt{Female} \sqcap (\exists\ \texttt{married.Doctor}) \sqcap (\forall\ \texttt{hasChild.(Doctor} \sqcup \texttt{Professor))} \sqcap \geqslant 2\ \texttt{hasChild} \sqcap \leqslant 4\ \texttt{hasChild}.$

How to modify $\texttt{HappyMan}$ with "has at least 2 children who are doctors"?

Description Logics: ABox, TBox and KB

Ex. HappyMan: men that have between 2-4 children, etc:

$\texttt{HappyMan} \equiv \texttt{Human} \sqcap \neg\ \texttt{Female} \sqcap (\exists\ \texttt{married.Doctor}) \sqcap (\forall\ \texttt{hasChild.(Doctor} \sqcup \texttt{Professor))} \sqcap \geqslant 2\ \texttt{hasChild} \sqcap \leqslant 4\ \texttt{hasChild}.$

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Description Logics: ABox, TBox and KB Examples[12]

What can we do with a Knowledge Base (KB = Ontology + instances)?

A-BOX

man(john)	loves(john,mary)
woman(mary)	loves(mary,sam)
man(sam)	married(sam,sue)
woman(sue)	happy(sam)

Some assertions...

T-BOX

...and some rules:

bachelor $\doteq \neg\, \exists$married.$\top \sqcap$ man	*„bachelors are unmarried men“*
married $\doteq$ married^{-1}	(being married to so. is reflexive)
$\exists$married.$\top \sqsubseteq$ happy	*„all married people are happy“*
$\exists_{\geqq 2}$ love $\sqsubseteq \bot$	*„you can love at most one person“*
$\exists$married.woman $\sqsubseteq \exists$love.woman	*„someone married to a woman also loves a woman“*

[12][Resources for Comp' Linguists. Regneri & Wolska'07]

Description Logics: ABox, TBox and KB[13]

A Knowledge Base $\mathcal{K}$ is a pair $(\mathcal{T}, \mathcal{A})$, where $\mathcal{T}$ is a TBox and $\mathcal{A}$ is an ABox.

An interpretation $\mathcal{I}$ is a model of a KB $\mathcal{K} = (\mathcal{T}, \mathcal{A})$ if $\mathcal{I}$ is a model of $\mathcal{T}$ and $\mathcal{I}$ is a model of $\mathcal{A}$.

$\mathcal{AL}$ (attribute language) logic: the minimal logic with a practically usable vocabulary.

If $\mathcal{A}$ and $\mathcal{B}$: atomic concepts; $\mathcal{C}$ and $\mathcal{D}$: concept descriptions; $\mathcal{R}$: atomic role, semantics defined using interpretation $\mathcal{I}$ consist of:

- non-empty set $\Delta^{\mathcal{I}}$ (the domain of interpretation)
- an interpretation function that assigns:
  a set $\mathcal{A}^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}}$ to every atomic concept $\mathcal{A}$
  a binary relation $\mathcal{R}^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$ to every atomic role $\mathcal{R}$.

Concepts $\mathcal{C}$ and $\mathcal{D}$ are equivalent ($\mathcal{C} \equiv \mathcal{D}$), if $\mathcal{C}^{\mathcal{I}} \equiv \mathcal{D}^{\mathcal{I}}$ for all interpretations $\mathcal{I}$.

[13] http://www.obitko.com/tutorials/ontologies-semantic-web/syntax-and-semantics.html

Description Logics[14]: $\mathcal{AL}$ (Attributive Language) logic syntax and semantics

Syntax	Semantics	Comment
A	$A^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}}$	atomic concept
R	$R^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$	atomic role
$\top$	$\Delta^{\mathcal{I}}$	top (most general) concept
$\bot$	$\emptyset$	bottom (most specific) concept
$\neg A$	$\Delta^{\mathcal{I}} \setminus A^{\mathcal{I}}$	atomic negation
$C \sqcap D$	$C^{\mathcal{I}} \cap D^{\mathcal{I}}$	intersection
$\forall R.C$	$\{a \in \Delta^{\mathcal{I}} \mid \forall b.(a,b) \in R^{\mathcal{I}} \Rightarrow b \in C^{\mathcal{I}}\}$	value restriction
$\exists R.\top$	$\{a \in \Delta^{\mathcal{I}} \mid \exists b.(a,b) \in R^{\mathcal{I}}\}$	limited existential quantification

[14] http://www.obitko.com/tutorials/ontologies-semantic-web/syntax-and-semantics.html

The name of the logic is formed from the string $\mathcal{AL}[\mathcal{U}][\mathcal{E}][\mathcal{N}][\mathcal{C}]$[15].

Name	Syntax	Semantics	Comment
$\mathcal{U}$	$C \sqcup D$	$C^{\mathcal{I}} \cup D^{\mathcal{I}}$	union of two concepts
$\mathcal{E}$	$\exists R.C$	$\{a \in \Delta^{\mathcal{I}} \mid \exists b.(a,b) \in R^{\mathcal{I}} \wedge b \in C^{\mathcal{I}}\}$	full quantification
$\mathcal{N}$	$\geqslant nR$ $\leqslant nR$	$\{a \in \Delta^{\mathcal{I}} \mid \quad \lvert\{b \mid (a,b) \in R^{\mathcal{I}}\}\rvert \geq n\}$ $\{a \in \Delta^{\mathcal{I}} \mid \quad \lvert\{b \mid (a,b) \in R^{\mathcal{I}}\}\rvert \leq n\}$	number restriction
$\mathcal{C}$	$\neg C$	$\Delta^{\mathcal{I}} \setminus C^{\mathcal{I}}$	negation of arbitrary concept

[15] $\mathcal{ALEN}$: $\mathcal{AL}$ extended with full existential quantification and number restrictions
[16] http://www.obitko.com/tutorials/ontologies-semantic-web/syntax-and-semantics.html

Description Logics[17]: $\mathcal{AL}$ logic - extensions of interest

:

- $\mathcal{S}$: role transitivity: `hasAncestor`
- $\mathcal{H}$: role hierarchy: `hasParent` subrole of `hasAncestor`.
- $\mathcal{I}$: role inverse: `hasChild` and `hasParent`
- $\mathcal{F}$: functional role in concept creation
- $\mathcal{O}$: nominals $a_1, ..., a_n$ (concept declared by enumeration)

[17] http://www.obitko.com/tutorials/ontologies-semantic-web/syntax-and-semantics.html

Description Logics Families (increasing comput. complexity):

- $\mathcal{EL}$: A prominent tractable DL
- $\mathcal{ALC}$: A basic DL which corresponds to multimodal logic K_n[18].
- $\mathcal{SHIQ}$: Very expressive DL basis of the OWL family

DL	concept and role expressions	TBox axioms
$\mathcal{EL}_\perp$	$C ::= A \mid \perp \mid C_1 \sqcap C_2 \mid \exists P.C$ $R ::= P$	$C_1 \sqsubseteq C_2$
$\mathcal{ALC}$	$C ::= A \mid C_1 \sqcap C_2 \mid \neg C \mid \exists P.C$ $R ::= P$	$C_1 \sqsubseteq C_2$
$\mathcal{SHIQ}$	$C ::= A \mid \neg C \mid C_1 \sqcap C_2 \mid (\geq n\, R\, C)$ $R ::= P \mid P^-$	$C_1 \sqsubseteq C_2$ $R_1 \sqsubseteq R_2$ $\mathrm{Trans}(R)$

[18] Important extensions: inverse roles, number restrictions, and concrete domains

Description Logics Applications

- NLP, DB, and biomedicine[19], healthcare (activity recognition [21, 20], lifestyle profiling [18, 22], rehabilitation [23]), fashion [9, 8],...
- Most notable success: adoption of DL-based OWL as SW std[20].

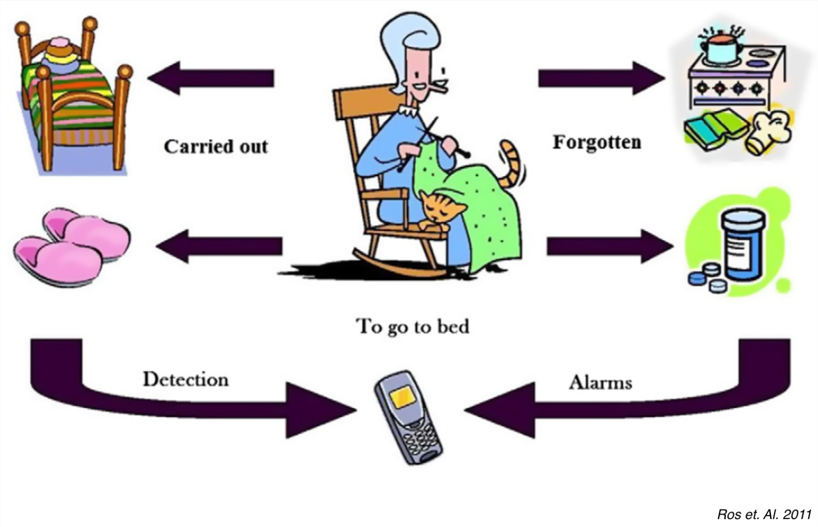
Why adopting DLs as ontology languages?

- For a formal, unambiguous semantics of FOL easy to describe and comprehend
- To provide *expressiveness* for constructing concepts and roles, *constraining* their interpretations and instantiating concepts and roles with individuals;
- To provide optimized *inference* procedures (deducing *implicit* knowledge from *explicit* one).

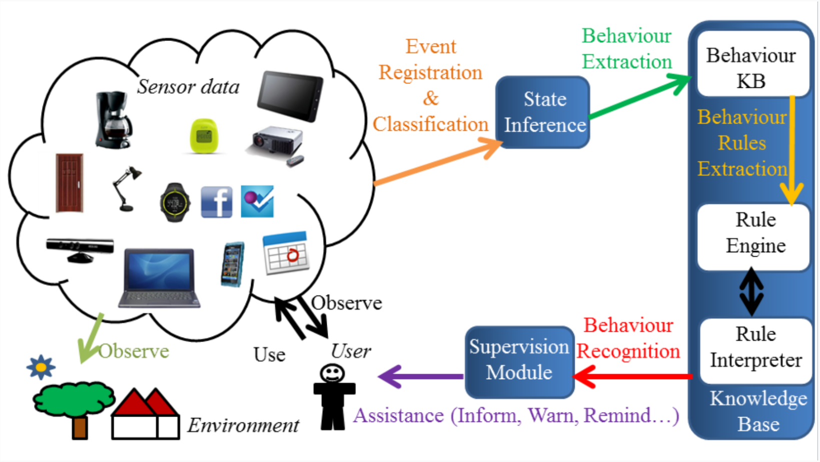
[19] `geneontology.org`

[20] `http://www.w3.org/TR/owl-features/`

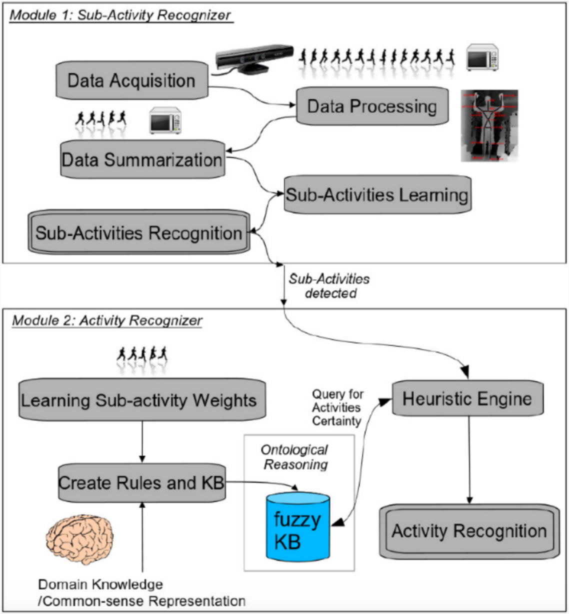
Description Logics Applications: Human activity recognition (HAR)[17]



Description Logics Applications: Human activity recognition [17]



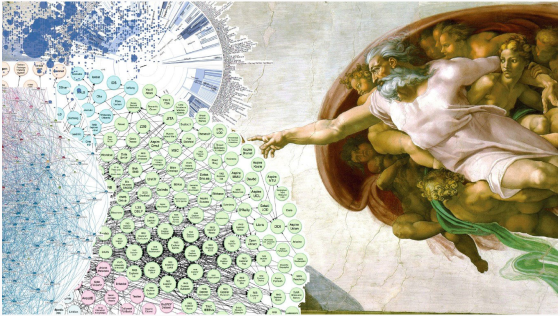
Description Logics Applications: HAR: the big picture [17]



The Semantic Web

The Semantic Web (SW) [5][21]

- *An extension of the web in which information is given well-defined meaning, better enabling computers and people to work in cooperation*
- W3C standard for defining data on the Web.
- XML tags conform to RDF and OWL formats.
- Refers to *things* in the world as resources



[21] http://www.cs.rpi.edu/academics/courses/fall07/semantic/CH1.pdf

RDF: The Resource Description Framework

- Set of tools that use concepts from *graph theory* to add relationships and semantics to *unstructured* data such as the WWW.
- Aim: machine interoperation of cross-domain data and merging info. from different sources as effortless as possible.
- RDF *triple*: foundation of the RDF data model: a subject, predicate and object resource that form a statement. Triples consisting of matching subjects and objects can be linked together to form an *RDF graph* hosted in an RDF store.
- SPARQL[22]: W3C std query language for RDF.

[22] '*sparkle*', SPARQL (Simple Protocol and RDF Query Language) Protocol and RDF Query Language

RDF example: Namespaces, URIs and Identity[24]

RDFS: RDF Schema, vocabulary[23]

QUESTION?: How to know when a node in one graph the same as a node in another graph?

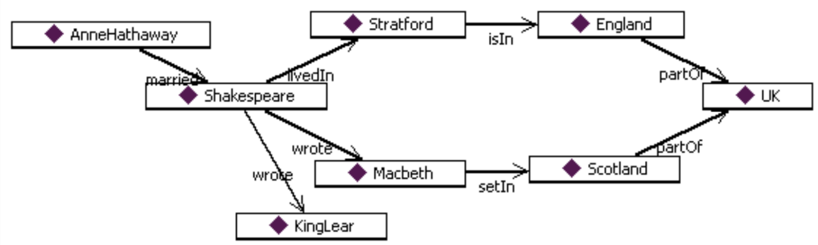
Subject		Predicate	Object
Shakespeare	Wrote		King Lear
Shakespeare	Wrote		Macbeth
Anne Hathaway	Married		Shakespeare
Shakespeare	Lived In		Stratford
Stratford	Is in		England
Macbeth	Set in		Scotland
England	Part of		The UK
Scotland	Part of		The UK

[23] *Intensional* (logic): Not extensional. Allows distinct entities with the same extension. *Extensional* (logic): A set-based theory or logic of classes, in which classes are considered to be sets, properties considered to be sets of <object, value> pairs, and so on. A theory which admits no distinction between entities with the same extension.

[24] http://www.cs.rpi.edu/academics/courses/fall07/semantic/CH3.pdf

RDF example: Namespaces, URIs and Identity[25]

When they share the Uniform Resource Identifier (URI) in RDF.



[25] http://www.cs.rpi.edu/academics/courses/fall07/semantic/CH3.pdf

Reasoning (Rule) Engine[29]

→ software able to infer logical consequences from asserted facts/ axioms

Logic Programming:

- Backward chaining[26]
- From goal to facts, applying rules backwards
- Conservative
- Unification[27].
- Backtracking

Rule-based (Prod. Rule) Systems:

- Forward chaining[28]
- Facts activate rules that generate new facts
- Potentially destructive
- Pattern matching
- Parallelism

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[26] To test if $R \models \gamma$, we work backwards from γ, looking for rules in R whose head unifies with γ. Tree root: node containing γ; search terminates when a node with no atoms remaining to be proved [25] is found.

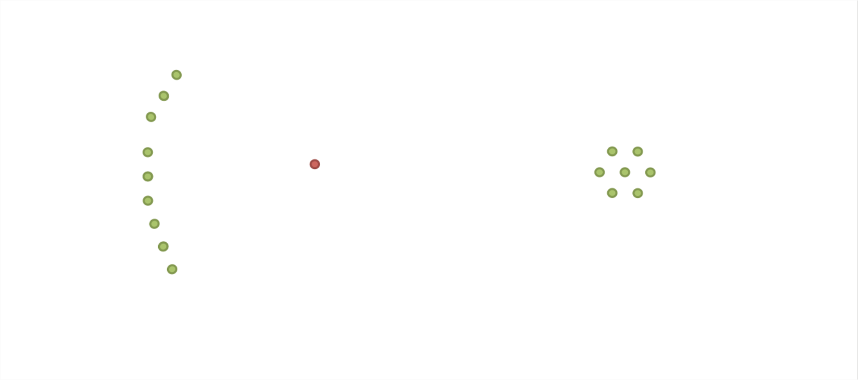
[27] Solves equations among symbolic expressions by computing a complete and minimal substitution set covering all solutions and no redundant members.

[28] To test if $R \models \gamma$, we check if $\gamma \in \mathit{consequences}(R)$ [25].

[29] [Sistemi a Regole di Produzione, S. Bragaglia'13]

Logic Programming VS Rule-based Systems (Production rules)[30]:

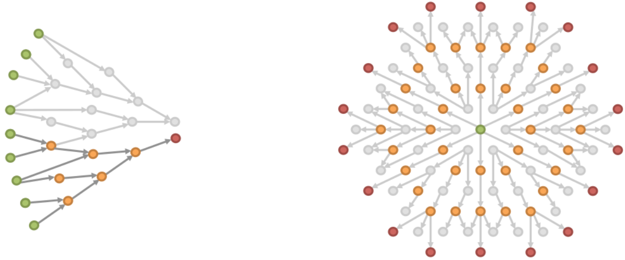
Backward vs Forward chaining - at the start:



[30] [Sistemi a Regole di Produzione, S. Bragaglia'13]

Logic Programming VS Rule-based Systems (Production rules):[31]:

Backward vs Forward chaining - at the end:



[31] [Sistemi a Regole di Produzione, S. Bragaglia'13]

What can a DL reasoner[36] do?

More than classification!: Discover (infer) implicit information (e.g., using necessary and sufficient conditions. **Ex**. `CheesyPizza`)

- (Class) Consistency checking (**Ex**.: `MeatyVegetableTopping`)[32] and Equivalence checking
- Instantiation checking (e.g., determine *domain* and *fillers* of a role[33])
- Retrieval tasks: all individuals of a concept, all concepts of an individual
- Subsumption checking (compute classification hierarchy, find parent concepts[34], predecessors[35] (/successors). **Ex**. "Are *cities* `locations?`")

[32] In Protégé inconsistent classes turn red (cannot possibly contain any individual)
[33] Fillers of R: all f s.t. $\exists x.R(x, f)$
[34] Parents of C: the most specific C‘ s.t. $C \sqsubseteq C$‘ (children analogously)
[35] Predecessors of C: all C‘ s.t. $C \sqsubseteq^* C$‘ (successors analogously)
[36] Ex. reasoners: **Pellet**, RACER, FaCT, DROOLs. Rule (engine) production systems: JBoss Drools, OPS5, CLIPS, Jess, ILOG, JRules, BizTalk.

So, What can a DL reasoner do? e.g., RACER[37]

Example queries:

Is Sue happy?
(Does ‚happy‘ contain Sue?)

Can Mary love John?
(loves(mary, john) -> consistent?)

What properties does Mary have?
(Concepts containing mary)

A-BOX

man(john)	loves(john,mary)
woman(mary)	loves(mary,sam)
man(sam)	married(sam,sue)
woman(sue)	happy(sam)

T-BOX

$$\text{bachelor} \doteq \neg \exists \text{married}.\top \sqcap \text{man}$$

$$\text{married} \doteq \text{married}^{-1}$$

$$\exists \text{married}.\top \sqsubseteq \text{happy}$$

$$\exists_{\geq 2}\, \text{love} \sqsubseteq \bot$$

$$\exists \text{married}.\text{woman} \sqsubseteq \exists \text{love}.\text{woman}$$

[37] [Resources for Comp' Linguists. Regneri & Wolska'07]

Common Operators in Description Logics [2]

Constructor	Syntax	Semantics
concept name	C	$C^{\mathcal{I}}$
top	$\top$	$\Delta^{\mathcal{I}}$
negation ($\mathcal{C}$)	$\neg C$	$\Delta^{\mathcal{I}} \setminus C^{\mathcal{I}}$
conjunction	$C_1 \sqcap C_2$	$C_1^{\mathcal{I}} \cap C_2^{\mathcal{I}}$
disjunction ($\mathcal{U}$)	$C_1 \sqcup C_2$	$C_1^{\mathcal{I}} \cup C_2^{\mathcal{I}}$
universal quant.	$\forall R.C$	$\{d_1 \mid \forall d_2 \in \Delta^{\mathcal{I}}.(R^{\mathcal{I}}(d_1, d_2) \rightarrow d_2 \in C^{\mathcal{I}})\}$
existential quant. ($\mathcal{E}$)	$\exists R.C$	$\{d_1 \mid \exists d_2 \in \Delta^{\mathcal{I}}.(R^{\mathcal{I}}(d_1, d_2) \wedge d_2 \in C^{\mathcal{I}})\}$
number restr. ($\mathcal{N}$)	$(\geq n\ R)$	$\{d_1 \mid \lvert\{d_2 \mid R^{\mathcal{I}}(d_1, d_2)\}\rvert \geq n\}$
	$(\leq n\ R)$	$\{d_1 \mid \lvert\{d_2 \mid R^{\mathcal{I}}(d_1, d_2)\}\rvert \leq n\}$
one-of ($\mathcal{O}$)	$\{a_1, \ldots, a_n\}$	$\{d \mid d = a_i^{\mathcal{I}}$ for some $a_i\}$
role filler ($\mathcal{B}$)	$\exists R.\{a\}$	$\{d \mid R^{\mathcal{I}}(d, a^{\mathcal{I}})\}$
role name	R	$R^{\mathcal{I}}$
role conjunction ($\mathcal{R}$)	$R_1 \sqcap R_2$	$R_1^{\mathcal{I}} \cap R_2^{\mathcal{I}}$
inverse roles ($\mathcal{I}$)	R^{-1}	$\{(d_1, d_2) \mid R^{\mathcal{I}}(d_2, d_1)\}$

Reasoning tasks [2]

- $\{C_1, C_2, ...\}$ atomic concepts
- $\{R_1, R_2 ...\}$ atomic roles
- $\{a_1, a_2, ...\}$ individuals
- Σ a Knowledge Base (KB)

- *Subsumption*, $\Sigma \models C_1 \sqsubseteq C_2$.
  Check whether for all interpretations $\mathcal{I}$ such that $\mathcal{I} \models \Sigma$ we have $C_1^{\mathcal{I}} \subseteq C_2^{\mathcal{I}}$.
- *Instance Checking*, $\Sigma \models a : C$.
  Check whether for all interpretations $\mathcal{I}$ such that $\mathcal{I} \models \Sigma$ we have $a^{\mathcal{I}} \in C^{\mathcal{I}}$.
- *Relation Checking*, $\sigma \models (a, b) : R$.
  Check whether for all interpretations $\mathcal{I}$ such that $\mathcal{I} \models \Sigma$ we have $(a^{\mathcal{I}}, b^{\mathcal{I}}) \in R^{\mathcal{I}}$.
- *Concept Consistency*, $\Sigma \not\models C \doteq \bot$.
  Check whether for some interpretation $\mathcal{I}$ such that $\mathcal{I} \models \Sigma$ we have $C^{\mathcal{I}} \neq \{\}$.
- *Knowledge Base Consistency*, $\Sigma \not\models \bot$.
  Check whether there exists $\mathcal{I}$ such that $\mathcal{I} \models \Sigma$.

Reasoning tasks for concepts [3]

Satisfiability: A concept C is *satisfiable* with respect to $\mathcal{T}$ if there exists a model $\mathcal{I}$ of $\mathcal{T}$ such that $C^{\mathcal{I}}$ is nonempty. In this case we say also that $\mathcal{I}$ is a *model* of C.

Subsumption: A concept C is *subsumed* by a concept D with respect to $\mathcal{T}$ if $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ for every model $\mathcal{I}$ of $\mathcal{T}$. In this case we write $C \sqsubseteq_{\mathcal{T}} D$ or $\mathcal{T} \models C \sqsubseteq D$.

Equivalence: Two concepts C and D are *equivalent* with respect to $\mathcal{T}$ if $C^{\mathcal{I}} = D^{\mathcal{I}}$ for every model $\mathcal{I}$ of $\mathcal{T}$. In this case we write $C \equiv_{\mathcal{T}} D$ or $\mathcal{T} \models C \equiv D$.

Disjointness: Two concepts C and D are *disjoint* with respect to $\mathcal{T}$ if $C^{\mathcal{I}} \cap D^{\mathcal{I}} = \emptyset$ for every model $\mathcal{I}$ of $\mathcal{T}$.

The Curry-Howard-Voevodsky correspondence [38]

type theory	set theory	logic	homotopy theory
A	set	proposition	space
$x : A$	element	proof	point
$\emptyset, 1$	$\emptyset, \{\emptyset\}$	$\bot, \top$	$\emptyset, *$
$A \times B$	set of pairs	A and B	product space
$A + B$	disjoint union	A or B	coproduct
$A \to B$	set of functions	A implies B	function space
$x : A \vdash B(x)$	family of sets	predicate	fibration
$x : A \vdash b : B(x)$	fam. of elements	conditional proof	section
$\prod_{x:A} B(x)$	product	$\forall x.B(x)$	space of sections
$\sum_{x:A} B(x)$	disjoint sum	$\exists x.B(x)$	total space
$p : x =_A y$	$x = y$	proof of equality	path from x to y
$\sum_{x,y:A} x =_A y$	diagonal	equality relation	path space for A

[38] [Riehl'18] `http://www.math.jhu.edu/~eriehl/Voevodsky.pdf`

Ontologies

Ontologies

In *Philosophy*: (*Ontological*) Concerned with what kinds of things really exist [Parmenides: not only what exists, but what can exist].

In *AI*: *A explicit (formal) specification of a (shared) conceptualization* [26, 10]; defines concepts, individuals, relationships and constraints (functions, attributes) within a domain.

Why Ontologies?

- The power of representation (separate declarative & procedural knowledge)
- Logical reasoning capabilities: deduction, abduction, and subsumption
- Explainability: to extract a minimal set of covering models of interpretation from a KB based on a set of observed actions, which could explain the observations [14].
- To represent and share knowledge by using a common vocabulary
- To promote interoperability, knowledge reuse, and info. integration with automatic validation

Ontologies

- **Facilitate** KB *modularity* [6], allow machine-readability by agents [24]
- Among semantic technologies, the most used formalism to represent and reason with knowledge.
- **Applications**: Information retrieval, search, question answering, m-Government emergency response services [1] or detecting information system conflicts [27]
  $\rightarrow$ and transport infraction detection in Paris!

Semantic Web (SW) Family of Languages [35]

3 main streams:[39]:

- Triple languages (RDF, RDFS). **Ex.** RDF:
  Subject Predicate Object
  ```
  metro:item0 rdf:type metro:Metro
  metro:item0 dc:title ''Allen Station''
  metro:item0 simile:address "395 N. Allen Av., Pasadena 91106"
  ```
- Ontology (conceptual) languages (OWL2): family that relates to DLs
- Rule-based languages (SWRL[40], RIF[41]). **Ex.** RIF:
  ```
  Forall ?Buyer ?Item ?Seller
  buy(?Buyer ?Item ?Seller) :- sell(?Seller ?Item ?Buyer)
  ```

---

[39] http://www.umbertostraccia.it/cs/download/papers/SUM11/SUMSlidesStraccia11.pdf
[40] Semantic Web Rule Lang.: High-level abstract syntax for Horn-like rules in both OWL DL and OWL Lite sub-languages of OWL.
[41] Rule Interchange Format, family relating to the Logic Programming (LP) paradigm [34][11])

Web Ontology Language (OWL)

- W3C std based on the KR formalism of DL [4]
  - Most used language to model formal ontologies
  - DL reasoning supports incremental inference
- Models concepts, roles and individuals.
  - Concepts: define aggregation of things
  - Individuals: instances of concepts
  - Properties (relationships): link individuals from the domain to individuals from the range

OWL Properties Restrictions:

→ *Anonymous* class definitions that group individuals together based on at least one object prop.

Ex.: "class of individuals that have at least one `hasTopping` relationship to individuals member of `MozzarellaTopping`".

- Existential restrictions ($\exists$): An individual of the class *Pizza* must have (at least one) `PizzaBase`:
  `Pizza and hasBase` *`some`* `PizzaBase`
  Should paraphrase: "Among other things..."
- Universal Restriction ($\forall$): individuals from the class `VegetarianPizza` can *only* have toppings that are vegetarian toppings. (`owl:AllValuesFrom` restriction).
  `Pizza and hasTopping only VegetarianTopping`
  Should paraphrase: "All and only values from"
- Necessary conditions: {Class} $\Rightarrow$ {[conditions]} (called superclasses, *Subclass Of* Protégé slot)
- Necessary and sufficient conditions: {Class} $\Leftrightarrow$ {[conditions]} (called equivalent classes, *Equivalent To* Protégé slot)

Conceptual languages (OWL, OWL 2) and OWL 2 **profiles**:

- OWL EL: instance/subsumption checking decided in polynomial time. Useful: large size of properties and/or classes.
- OWL QL: (relates to the DL family DL-Lite): Useful: very large instance data volumes[42].
- OWL RL[43] Useful for scalable reasoning without sacrificing much expressive power.

[42] conjunctive query answering via query rewriting and SQL
[43] Maps to Datalog, same complexity: polyn. in size of the data, exp. t., wrt. KB size

Web Ontology Language (OWL) [7]

OWL comprises 3 **sub-languages**[44] of increasing expressive power (all sublanguages of OWL2-DL, as itself, tractable):

- OWL Lite: Lowest complexity (only 0/1 card. constr., no disjointness nor enumerated classes).
- OWL DL: (based on DL, our focus, OWL DL $\subseteq$ OWL Full): Decidable, permits inconsistency checking
- OWL Full: Max. expressiveness with syntactic freedom of RDF[45]

Which sub-language to use?[46]

- Are OWL-Lite constructs sufficient?
- OWL-DL vs OWL-Full? Carrying out automated reasoning vs using highly expressive and powerful modelling (e.g. classes of classes)?

[44] Our focus: OWL 2 and OWL DL.

[45] When expressiveness is more important than being able to guarantee the decidability /computational completeness/ complete reasoning of the language

[46] See `http://www.cs.rpi.edu/academics/courses/fall07/semantic/CH3.pdf` and comparative table `https://ragrawal.wordpress.com/2007/02/20/difference-between-owl-lite-dl-and-full/` and `http://www2.cs.man.ac.uk/~raym8/comp38212/main/node187.html`

OWL constructors and axioms

Constructor	DL Syntax	Example
`intersectionOf`	$C_1 \sqcap \ldots \sqcap C_n$	$\mathsf{Human} \sqcap \mathsf{Male}$
`unionOf`	$C_1 \sqcup \ldots \sqcup C_n$	$\mathsf{Doctor} \sqcup \mathsf{Lawyer}$
`complementOf`	$\neg C$	$\neg\mathsf{Male}$
`oneOf`	$\{x_1 \ldots x_n\}$	$\{\mathsf{john}, \mathsf{mary}\}$
`allValuesFrom`	$\forall P.C$	$\forall\mathsf{hasChild}.\mathsf{Doctor}$
`someValuesFrom`	$\exists r.C$	$\exists\mathsf{hasChild}.\mathsf{Lawyer}$
`hasValue`	$\exists r.\{x\}$	$\exists\mathsf{citizenOf}.\{\mathsf{USA}\}$
`minCardinality`	$(\geqslant n\ r)$	$(\geqslant 2\ \mathsf{hasChild})$
`maxCardinality`	$(\leqslant n\ r)$	$(\leqslant 1\ \mathsf{hasChild})$
`inverseOf`	r^-	$\mathsf{hasChild}^-$

OWL constructors and axioms

Axiom	DL Syntax	Example
`subClassOf`	$C_1 \sqsubseteq C_2$	Human $\sqsubseteq$ Animal $\sqcap$ Biped
`equivalentClass`	$C_1 \equiv C_2$	Man $\equiv$ Human $\sqcap$ Male
`subPropertyOf`	$P_1 \sqsubseteq P_2$	hasDaughter $\sqsubseteq$ hasChild
`equivalentProperty`	$P_1 \equiv P_2$	cost $\equiv$ price
`disjointWith`	$C_1 \sqsubseteq \neg C_2$	Male $\sqsubseteq$ $\neg$Female
`sameAs`	$\{x_1\} \equiv \{x_2\}$	{Pres_Bush} $\equiv$ {G_W_Bush}
`differentFrom`	$\{x_1\} \sqsubseteq \neg\{x_2\}$	{john} $\sqsubseteq$ $\neg${peter}
`TransitiveProperty`	P transitive role	hasAncestor is a transitive role
`FunctionalProperty`	$\top \sqsubseteq (\leqslant 1\ P)$	$\top \sqsubseteq (\leqslant 1$ hasMother$)$
`InverseFunctionalProperty`	$\top \sqsubseteq (\leqslant 1\ P^-)$	$\top \sqsubseteq (\leqslant 1$ isMotherOf$^-)$
`SymmetricProperty`	$P \equiv P^-$	isSiblingOf $\equiv$ isSiblingOf$^-$

Learning OWL through Protégé examples

Reminder: Why building an ontology?[29]

1. To share common understanding of the info. structure among people/ agents
2. To enable reuse of domain knowledge
3. To make domain assumptions explicit
4. To separate domain knowledge from the operational knowledge
5. To analyze domain knowledge

What does it mean "developing" an ontology?[29]

1. Defining classes in the ontology
2. Arranging them in a taxonomic hierarchy
3. Refining slots and describing its allowed values, filling in the values for slots for instances.

$\rightarrow$ 1st step: Determining domain and scope!

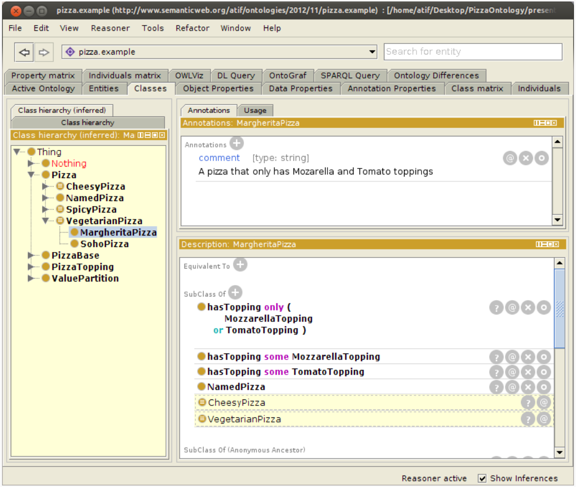
Protégé

A useful ontology IDE for managing large ontologies and discovering existing ones

- edit
- visualize
- validate KBs

Download: `https://protege.stanford.edu/`

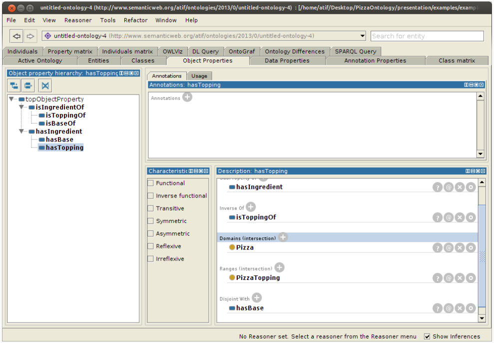
- *Inverse* (object) property: *a pizza has a topping of anchovies* ≡ anchovies is a topping of a pizza
- *Disjoint* concepts: `Calzone` and `Napolitana`. `PizzaTopping` and `PizzaBase`.



Terminology: OWL Property Restrictions

OWL primitives to enrich property definitions. Can you think of examples of ...?:

- *Functional*: `hasAge(A, x)`, `hasBirthMother(A,B)`
- *Inverse functional*: `isBirthModerOf(A,B)`
- *Transitive*: `hasAncestor(A,B)`, `containsIngredient(A,B)`
- *Symmetric*: `married(A, B)` *Anti-symmetric*: `hasFavouriteFlavor(A,B)`
- *Reflexive*: `preparesBreakfast(A, A)`, `dresses(A,A)`
- *Irreflexive*: `isMotherOf(A, B)`



OWL Property Restrictions Exercise: The Simpsons!

	Irreflexive	Asymmetric	Symmetric	Transitive
hasRelationshipTo				
hasSibling				
hasBrother				
hasSister				
hasParent				
hasMother				
hasFather				
hasAunt				
hasUncle				
hasChild				
hasSon				
hasDaugther				
hasGrandParent				
hasSpouse				
hasHusband				
hasWife				

OWL Property Restrictions Exercise: The Simpsons!

See wikipedia for explanations of the characteristics asymmetric[3] , reflexive and irreflexive[4] .

Assuming all relationships have Person as both domain and range, the following is an arguably common interpretation of their characteristics.

	Irreflexive	Asymmetric	Symmetric	Transitive
hasRelationshipTo	X		X	
hasSibling	x		X	X
hasBrother	x			X
hasSister	x			X
hasParent	x	X		
hasMother	x	X		
hasFather	x	X		
hasAunt	x	X		
hasUncle	x	X		
hasChild	x			
hasSon	x			
hasDaugther	x			
hasGrandParent	x			
hasSpouse	x		X	
hasHusband	x	X †)		
hasWife	x	X †)		

Notes:

- x: hasRelationshipTo is irreflexive, so all subproperties of it must also be.
- †) Assuming heteronormativity.

OWL Property Restrictions

- *Number restrictions*: describe the nr of relationships of a particular type that individuals can participate in. **Ex**: $\texttt{Person} \sqsubseteq \leqslant 1\ \texttt{married}$
- *Qualified Nr restrictions*: the type of individuals that are counted by a given number restriction. **Ex**. `HappyMan`: men that have between 2-4 children $\texttt{HappyMan} \equiv \texttt{Human} \sqcap \neg\ \texttt{Female} \sqcap (\exists\ \texttt{married.Doctor}) \sqcap (\forall\ \texttt{hasChild.(Doctor} \sqcup \texttt{Professor))} \sqcap \geqslant 2\ \texttt{hasChild} \sqcap \leqslant 4\ \texttt{hasChild}.$

OWL Property Restrictions

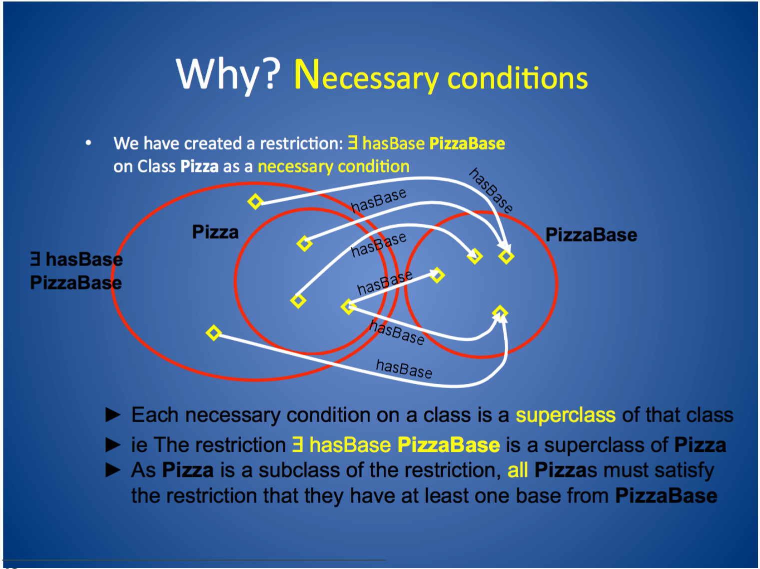
- *Number restrictions*: describe the nr of relationships of a particular type that individuals can participate in. **Ex**: $\texttt{Person} \sqsubseteq \leqslant 1\ \texttt{married}$
- *Qualified Nr restrictions*: the type of individuals that are counted by a given number restriction. **Ex**. `HappyMan`: men that have between 2-4 children, etc:
  $\texttt{HappyMan} \equiv \texttt{Human} \sqcap \neg\ \texttt{Female} \sqcap (\exists\ \texttt{married.Doctor}) \sqcap (\forall\ \texttt{hasChild.(Doctor} \sqcup \texttt{Professor))} \sqcap \geqslant 2\ \texttt{hasChild} \sqcap \leqslant 4\ \texttt{hasChild}.$

Key to Remember! A simple modelling pipeline

- Start building disjoint tree of primitive concepts. Recall:
  - Classes: Asserted vs Inferred (Pre/post reasoner)
  - Primitive class: Only has necessary conditions, i.e., superclasses.
  - Defined class[47]: has necessary and sufficient conditions, i.e., equivalent classes (**Ex**. `Parent`: the set of all persons that have at least one child). They are rarely disjoint.
- (Most often) asserting *polyhierarchies* is bad
  $\rightarrow$ let the reasoner do it!
  Ex.: `CheesyPizza`: can be `VegetarianPizza`, `SpicyPizza`.
  1. Asserting subclass manually: We lose some encapsulation of knowledge and self-explanation (*Why is this class a subclass of that one?*)
  2. Difficult to maintain (all subclasses may need to be updated)

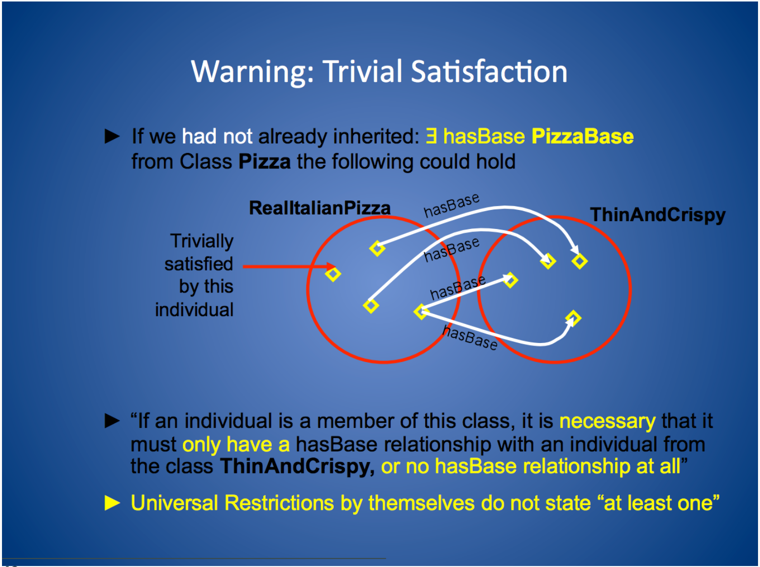
[47] *Declares* the named class to be equivalent to the *anonymous* class
`https://protegewiki.stanford.edu/wiki/ProtegeOWL_API_Advanced_Class_Definitions`

Key to Remember! Learning to model Existential vs Universal restrictions[48]



[48] [C. Lagoze, Cornell]

Key to Remember! Learning to model Existential vs Universal restrictions[49]



[49] [C. Lagoze, Cornell]

Take home message: A simple knowledge engineering methodology [29]

- There is no single *correct* way to model a domain ontology-design methodology[50]
  $\rightarrow$ depends on application and future extensions
- Concepts in the ontology should be close to objects (*physical* or *logical*)
- Ontology development: necessarily *iterative*

[50] but many ideas + good practices found useful from experience

Logical Reasoning Capabilities: Subsumption

The task of computing the task hierarchy (*is-a* super/sub class relationship):

- *A* subsumes *B* if *A* is a superclass of *B*
- Defined explicitly (*asserted*), or *inferred* by a reasoner
- Superclass of all OWL Classes: `owl:Thing`

Logical Reasoning Capabilities: Classification and Disjointness!

Detecting inconsistencies in DL (unsatisfiable axioms):

- OWL assumes that classes overlap! → means an individual could be both a `MeatTopping` and a `VegetableTopping` at the same time!
  → We must state disjointness explicitly in the interface

Open vs Closed World Assumption in ML

A Closed World Assumption "closes" the interpretation by assuming that every fact not explicitly stated to be true is actually **false**.

Open World Assumption (OWA)

What it means: missing information is **not** confirmation of negation. Must state that a description is **complete** (we need `closure` for the given property).

Ex. `MargheritaPizza` toppings must be explicitly limited to their toppings:

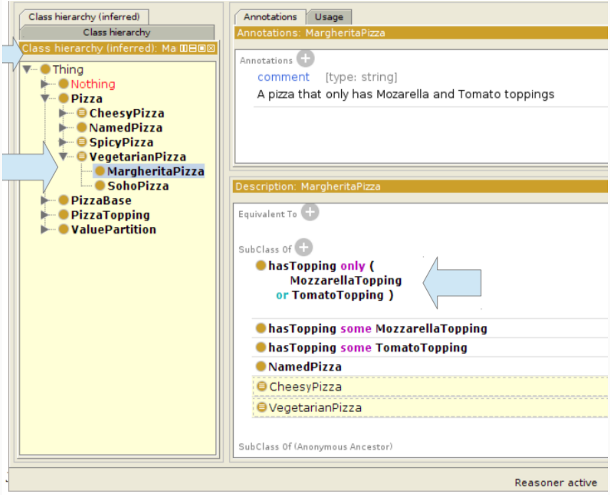
`MargheritaPizza: hasTopping only (MozzarellaTopping or TomatoTopping)`

All `MargheritaPizzas` must have:

- at least 1 topping from `MozzarellaTopping` (Existential restr.)
- at least 1 topping from `TomatoTopping`
- **only** toppings from `MozzarellaTopping` or `TomatoTopping` $\rightarrow$ no other toppings; The union **closes** the `hasTopping` property on `MargheritaPizza`

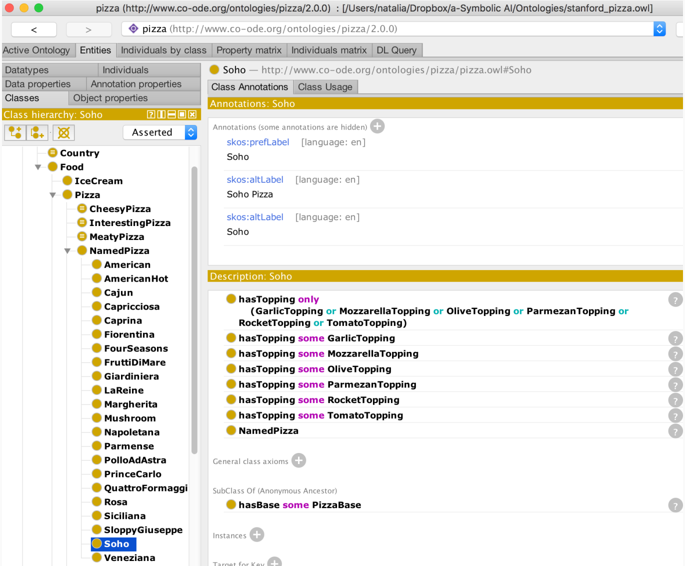
OWA and Universal Restrictions in Protégé

OWA (missing information is NOT confirmation of negation). `SohoPizza` and `MargheritaPizza` must be explicitly limited to their toppings



Open World Assumption (OWA): Inferring VegetarianPizzas

OWA (missing info is NOT confirmation of negation). SohoPizza and MargheritaPizza must be explicitly limited to their toppings



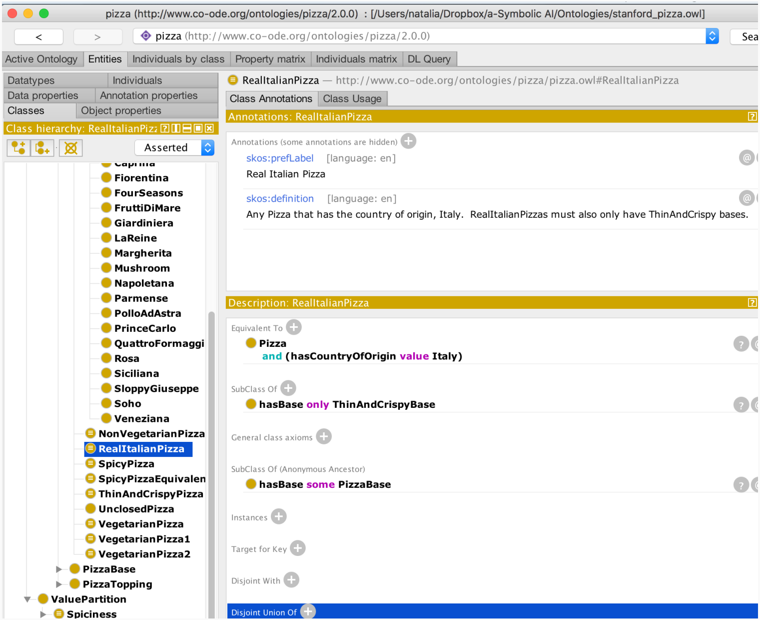
Existential Restrictions vs Universal Restrictions: In Protégé

Existential ($\exists$) Restrictions (*some* keyword). ["Among other things..."]

Universal ($\forall$) Restrictions (*only* keyword). [‘‘All and only values from’’]

$\rightarrow$ Both restrictions added same way but different restriction type:

Univ. Restr: `RealItalianPizzas` only have bases that are `ThinAndCrispy`



Homework: By next week:

1. Install and run Protégé (5.2 or 5.5 Beta, avoid WebProtégé until you consider yourself a Protégé expert ;))[51]
2. Find a pair! Think of a problem worth working on that requires an ontology
3. Protégé *Getting Started* and Protégé for *Pizzas in 10 min*[52]
4. Read THE Protégé Tutorial[53]. In the same page you can download the Pizza ontology[54] to play around with it at the same time.
5. Curious to learn more? Play with/extend some fun ontology (Wine [13][55] or Beer[56] ontologies :) → **When in doubt**: *Ontology development 101: A guide to creating your first ontology*[57] [29]. **When stuck**, see [58]

[51] Follow instructions from `https://protege.stanford.edu/` (if asked, choose version with Java Virtual Machine), If problems, see `https://tinyurl.com/ycs5msue`

[52] `https://protegewiki.stanford.edu/wiki/Protege4GettingStarted` and `https://protegewiki.stanford.edu/wiki/Protege4Pizzas10Minutes`

[53] `http://mowl-power.cs.man.ac.uk/protegeowltutorial/resources/ProtegeOWLTutorialP4_v1_3.pdf`

[54] `http://owl.cs.manchester.ac.uk/publications/talks-and-tutorials/protg-owl-tutorial/`

[55] `https://github.com/NataliaDiaz/Ontologies/blob/master/DidacticOntologies/FuzzyWineOntologyAppCarlsson10/Wine_ontology2.5.owl`

[56] `https://www.cs.umd.edu/projects/plus/SHOE/onts/beer1.0.html`

[57] `https://protege.stanford.edu/publications/ontology_development/ontology101.pdf`

[58] `http://www.cs.cornell.edu/courses/cs431/2008sp/Lectures/public/lecture-4-09-08.pdf`

Searching for stage/internship/superproject/PRe/PFE?

If interested in deep learning, reinforcement learning, symbolic AI, computer vision and NLP for

- robotics
- autonomous systems, e.g., driving, drones...

consider ENSTA ParisTech U2IS Lab:

- `flowers.inria.fr`
- `http://asr.ensta-paristech.fr/`

Send single pdf with grades, CV and github: natalia.diaz@ensta-paristech.fr

Lewis Carroll

'How do you know I'm mad?' said Alice.
'You must be,' said the Cat,
'or you wouldn't have come here.'

from "Alice's Adventures in Wonderland," Lewis Carroll

Useful Links

USEFUL LINKS I

1. W3C Glossary[59]
2. MIRO – Minimum Information for Reporting of an Ontology guidelines: a community-validated set of recommendations on what should be reported about an ontology and its development, most importantly in the context of ontology description papers intended for publishing in scientific journals or conferences [28]
3. THE Protégé Tutorial[60]
4. Building OWL Ontologies with Protégé. CS431 –Cornell Univ. 2008 C. Lagoze[61]
5. Resources for Comp‘ Linguists 07 Description Logics - M. Regneri & M. Wolska[62]
6. Tutorial on description logics. I. Horrocks and U. Sattler[63]
7. Probabilistic Logic Programming Languages, F. Riguzzi,[64]
8. Common Pitfalls creating ontologies[65]

USEFUL LINKS II

9. Building OWL Ontologies with Protégé CS431 –Cornell University, 2008 C. Lagoze[66]
10. Ontology Engineering Methodologies (Ch. 9) [16][67]
11. Resources for Comp' Linguists 07 Description Logics - M. Regneri & M. Wolska[68]
12. An introduction to Ontology Engineering. M. Keet[69].
13. Description Logic, Semantic Web and Ontology Development, S.Bragaglia[70]

[59] https://www.w3.org/TR/rdf-mt/#glossIntensional

[60] http://mowl-power.cs.man.ac.uk/protegeowltutorial/resources/ProtegeOWLTutorialP4_v1_3.pdf

[61] www.cs.cornell.edu/courses/cs431/2008sp/Lectures/public/lecture-4-09-08.pdf

[62] www.cse.iitd.ernet.in/~kkb/DL-1.pdf

[63] http://www.cs.man.ac.uk/~horrocks/Slides/IJCARtutorial/Display/

[64] mcs.unife.it/~friguzzi/chapter2.pdf

[65] http://www.cs.man.ac.uk/~rector/papers/common_errors_ekaw_2004.pdf

[66] www.cs.cornell.edu/courses/cs431/2008sp/Lectures/public/lecture-4-09-08.pdf

[67] http://read.pudn.com/downloads77/ebook/293072/Semantic%20Web%20Technologies%20-%20Trends%20and%20Research%20in%20Ontology-based%20Systems(2006).pdf

[68] www.cse.iitd.ernet.in/~kkb/DL-1.pdf

[69] http://www.meteck.org/teaching/OEbook/

[70] *Fondamenti di Intelligenza Artificiale*, Uni. of Bologna, Italy https://www.slideshare.net/StefanoBragaglia/ontology-development

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[8] Kurt Bollacker, Natalia Díaz-Rodríguez, and Xian Li. *Extending Knowledge Graphs with Subjective Influence Networks for Personalized Fashion*, pages 203–233. Springer International Publishing, Cham, 2019.

[9] Kurt Bollacker, Natalia Díaz Rodríguez, and Xian Li. Beyond clothing ontologies: Modeling fashion with subjective influence networks. In Vikas C. Raykar, Brad Klingenberg, Heng Xu, Raghavendra Singh, and Amrita Saha, editors, *Machine Learning meets fashion KDD Workshop*, page 1–7. ACM, 2016.

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[11] Stefano Bragaglia, Federico Chesani, Paola Mello, and Davide Sottara. A rule-based implementation of fuzzy tableau reasoning. In Mike Dean, John Hall, Antonino Rotolo, and Said Tabet, editors, *Semantic Web Rules*, pages 35–49, Berlin, Heidelberg, 2010. Springer Berlin Heidelberg.

[12] Andrew Carlson, Justin Betteridge, Bryan Kisiel, and Burr Settles. Toward an architecture for never-ending language learning. 2010.

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