Scalable Ontology Systems

Ian Horrocks
<ian.horrocks@comlab.ox.ac.uk>
Information Systems Group
Oxford University Computing Laboratory

What is an Ontology?

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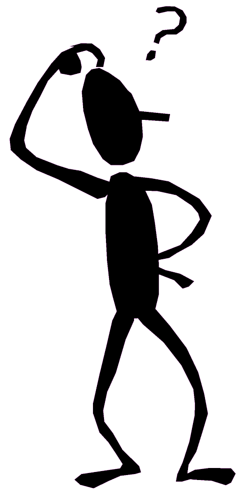

"A specification of a conceptualization" [Gruber]

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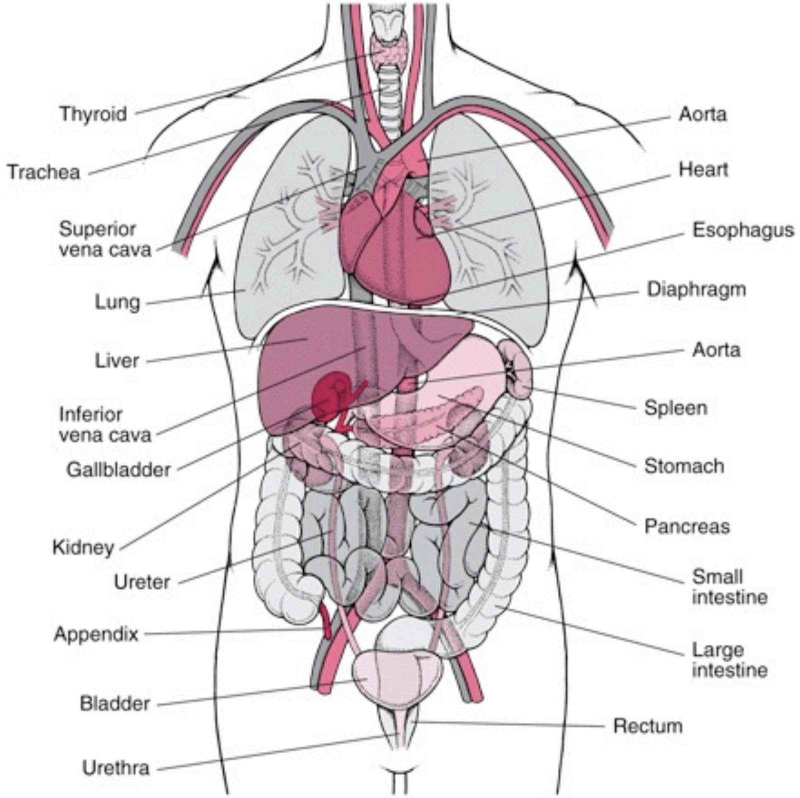

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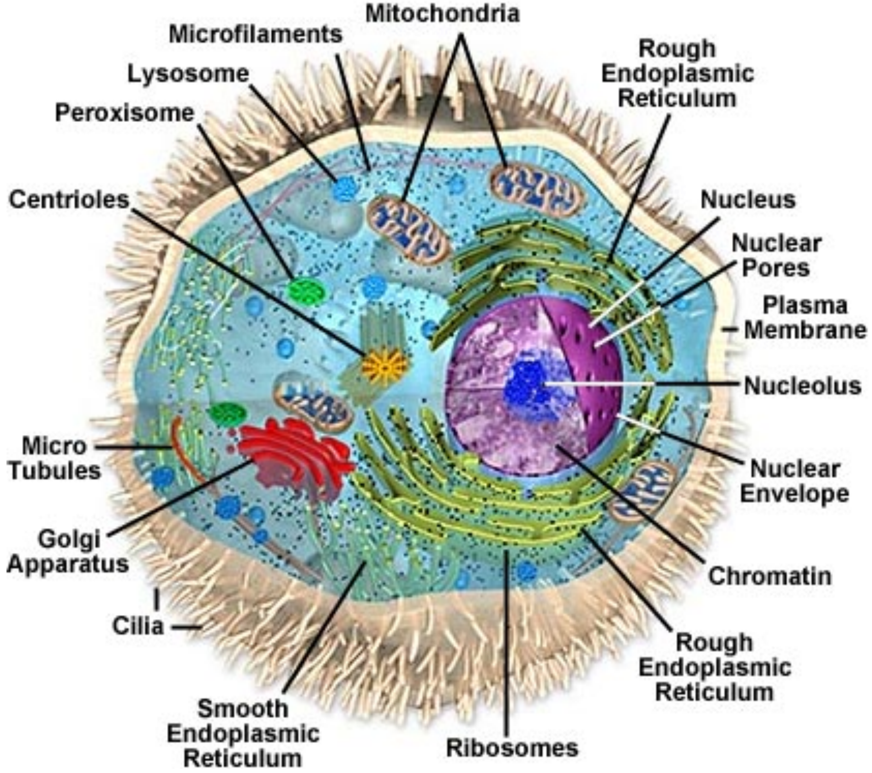

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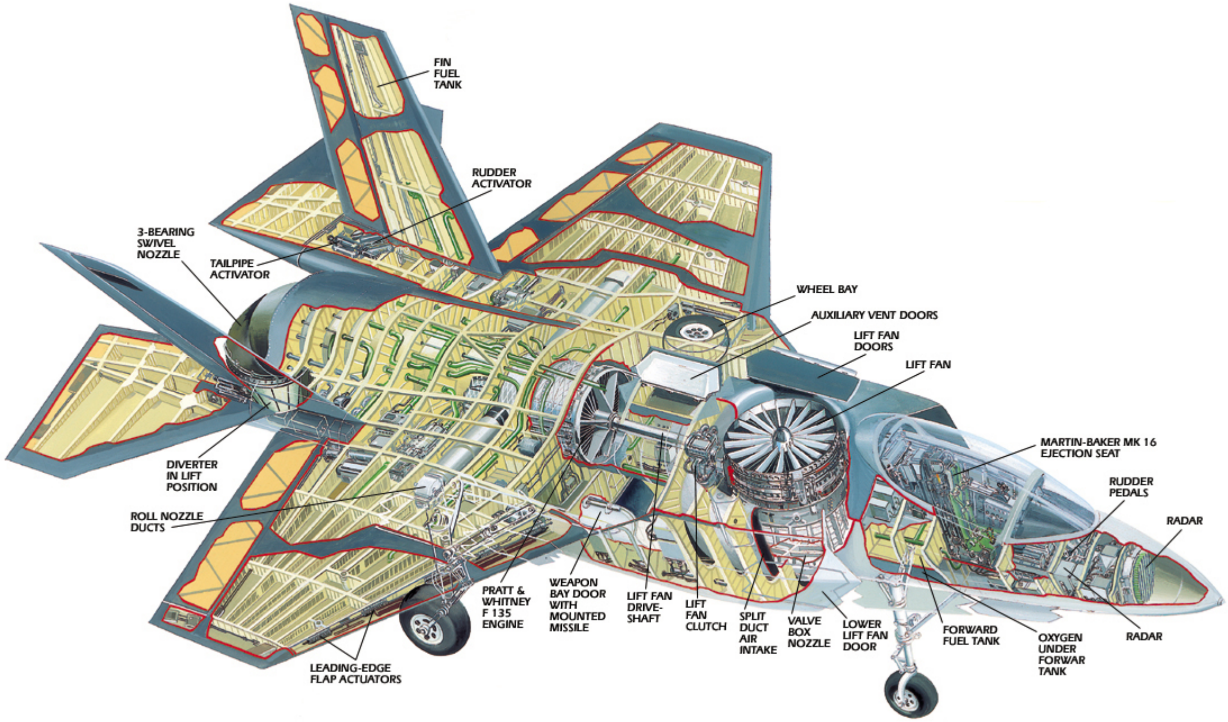

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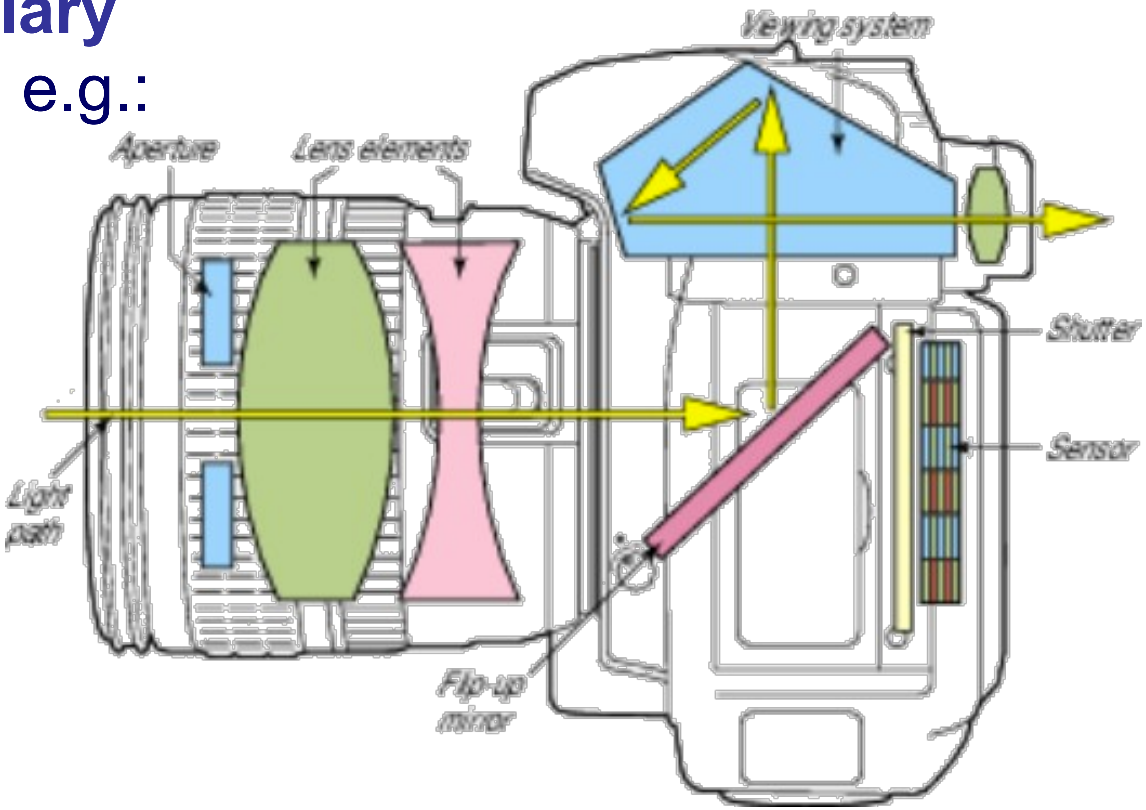

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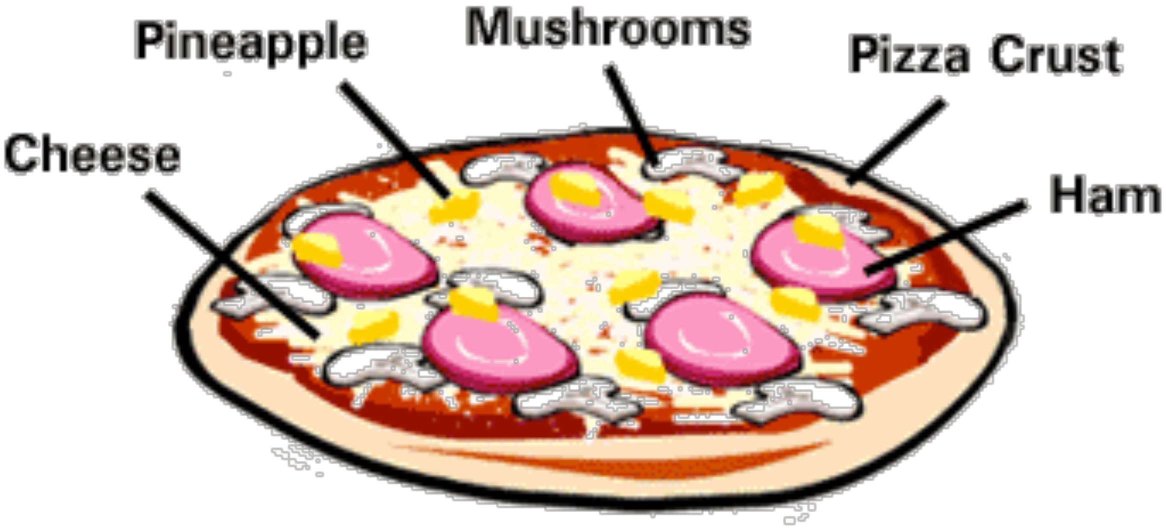
  - Pizzas
  - …



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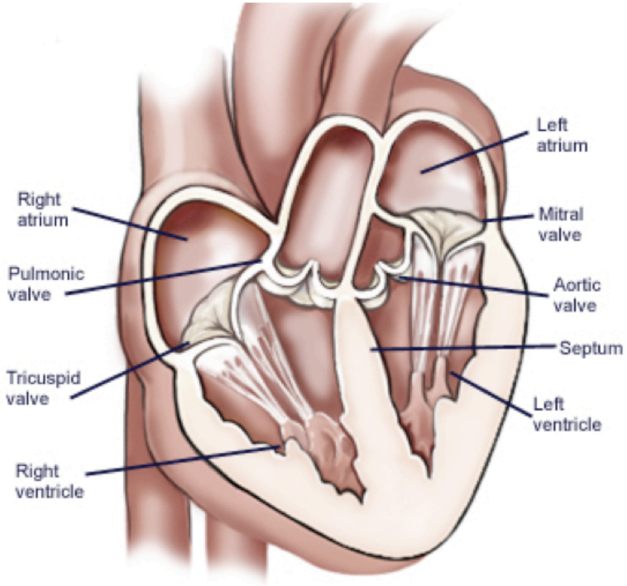
- Specifies **meaning** (semantics) of terms

Heart is a muscular organ that is part of the circulatory system



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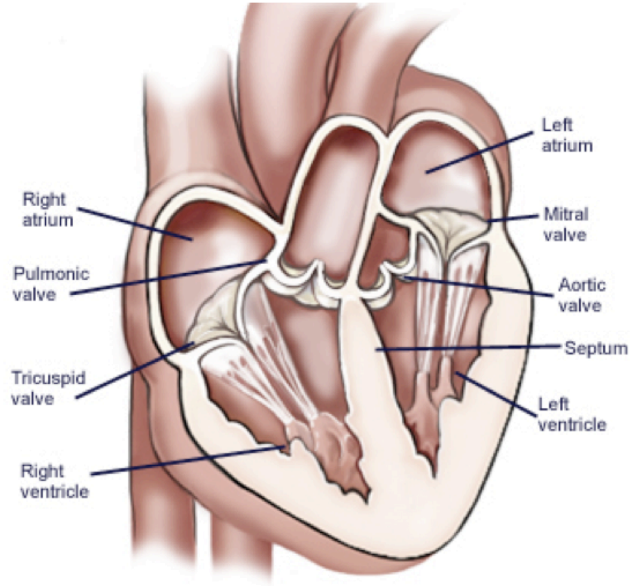
  Heart is a muscular organ that is part of the circulatory system

- **Formalised** using suitable logic

$$\forall x.[\mathsf{Heart}(x) \rightarrow \mathsf{MuscularOrgan}(x) \wedge \exists y.[\mathsf{isPartOf}(x,y) \wedge \mathsf{CirculatorySystem}(y)]]$$



Description Logics (DLs)

- Fragments of **first order logic** designed for KR
- Useful computational properties
  - **Decidable** (essential)
  - Low complexity (desirable)
- Succinct and **variable free syntax**

$$\forall x.[\mathsf{Heart}(x) \rightarrow \mathsf{MuscularOrgan}(x) \wedge \exists y.[\mathsf{isPartOf}(x,y) \wedge \mathsf{CirculatorySystem}(y)]]$$

$$\mathsf{Heart} \sqsubseteq \mathsf{MuscularOrgan} \sqcap \exists \mathsf{isPartOf}.\mathsf{CirculatorySystem}$$

Description Logics (DLs)

DL **Knowledge Base** (KB) consists of two parts:

– Ontology (aka **TBox**) axioms define terminology (schema)

$$\begin{aligned} \mathsf{Heart} &\sqsubseteq \mathsf{MuscularOrgan} \sqcap \\ &\quad \exists \mathsf{isPartOf}.\mathsf{CirculatorySystem} \\ \mathsf{HeartDisease} &\equiv \mathsf{Disease} \sqcap \\ &\quad \exists \mathsf{affects}.\mathsf{Heart} \\ \mathsf{VascularDisease} &\equiv \mathsf{Disease} \sqcap \\ &\quad \exists \mathsf{affects}.(\exists \mathsf{isPartOf}.\mathsf{CirculatorySystem}) \end{aligned}$$

– Ground facts (aka **ABox**) use the terminology (data)

$$\begin{aligned} \mathsf{John} : \mathsf{Patient} &\sqcap \\ &\exists \mathsf{suffersFrom}.\mathsf{HeartDisease} \end{aligned}$$

Ontology Applications

THE SEMANTIC WEB

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  "... a **consistent logical web of data** ..." in which
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  – **RDF** provides uniform syntactic structure for data
  – **Ontologies** provide machine readable schemas

- **A wide ranging research effort:**
  – aimed at extracting "useful information" from web content
  – with KR (in particular ontologies) playing a key role

Web Ontology Languages

- RDF extended to **RDFS**, a primitive ontology language
  - classes and properties; sub/super-classes (and properties); range and domain (of properties)
- But RDFS **lacks** important **features**, e.g.:
  - existence/cardinality constraints; transitive/inverse properties; localised range and domain constraints, …
- And RDF(S) has “higher order flavour” with no (later **non-standard**) **formal semantics**
  - difficult to understand
  - difficult to provide reasoning support

From RDFS to OWL

- **OIL** language developed in **On-To-Knowledge** project



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- **OIL** language developed in **On-To-Knowledge** project
- **DAML-ONT** language later developed in **DAML** program
- Efforts soon merged to produce **DAML+OIL**
  - Further development carried out by “Joint EU/US Committee”



From RDFS to OWL

- **OIL** language developed in **On-To-Knowledge** project
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- Efforts soon merged to produce **DAML+OIL**
  - Further development carried out by “Joint EU/US Committee”
- DAML+OIL submitted to W3C as basis for standardisation
- **WebOnt** Working Group formed
  - WebOnt developed OWL language based on DAML+OIL
  - OWL became a W3C recommendation
  - “Web-friendly” syntax for $\mathcal{SHOIN}$

Why (Description) Logic?

- OWL exploits results of 20+ years of DL research
  - Well defined (model theoretic) **semantics**

Constructor	DL Syntax	Example	FOL Syntax
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	Human $\sqcap$ Male	$C_1(x) \wedge \ldots \wedge C_n(x)$
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	Doctor $\sqcup$ Lawyer	$C_1(x) \vee \ldots \vee C_n(x)$
complementOf	$\neg C$	$\neg$Male	$\neg C(x)$
oneOf	$\{x_1\} \sqcup \ldots \sqcup \{x_n\}$	{john} $\sqcup$ {mary}	$x = x_1 \vee \ldots \vee x = x_n$
allValuesFrom	$\forall P.C$	$\forall$hasChild.Doctor	$\forall y.P(x,y) \rightarrow C(y)$
someValuesFrom	$\exists P.C$	$\exists$hasChild.Lawyer	$\exists y.P(x,y) \wedge C(y)$
maxCardinality	$\leqslant nP$	$\leqslant$1hasChild	$\exists^{\leqslant n} y.P(x,y)$
minCardinality	$\geqslant nP$	$\geqslant$2hasChild	$\exists^{\geqslant n} y.P(x,y)$

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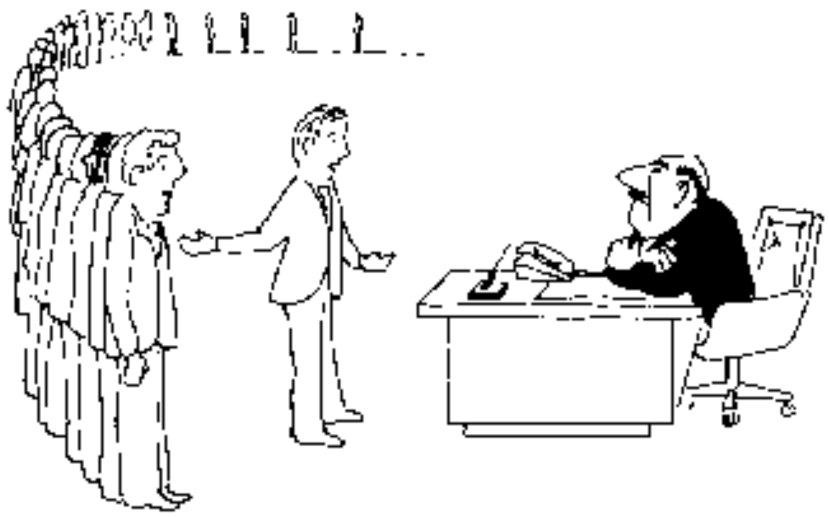
  - **Formal properties** well understood (complexity, decidability)



I can't find an efficient algorithm, but neither can all these famous people.

[Garey & Johnson. Computers and Intractability: A Guide to the Theory of NP-Completeness. Freeman, 1979.]

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  - Known **reasoning algorithms**

$\sqcap$-rule	if 1. $(C_1 \sqcap C_2) \in \mathcal{L}(v)$, v is not indirectly blocked, and 2. $\{C_1, C_2\} \not\subseteq \mathcal{L}(v)$ then $\mathcal{L}(v) \longrightarrow \mathcal{L}(v) \cup \{C_1, C_2\}$.
$\sqcup$-rule	if 1. $(C_1 \sqcup C_2) \in \mathcal{L}(v)$, v is not indirectly blocked, and 2. $\{C_1, C_2\} \cap \mathcal{L}(v) = \emptyset$ then $\mathcal{L}(v) \longrightarrow \mathcal{L}(v) \cup \{E\}$ for some $E \in \{C_1, C_2\}$
$\exists$-rule	if 1. $\exists r.C \in \mathcal{L}(v_1)$, v_1 is not blocked, and 2. v_1 has no safe r-neighbour v_2 with $C \in \mathcal{L}(v_1)$, then create a new node v_2 and an edge $\langle v_1, v_2 \rangle$ with $\mathcal{L}(v_2) = \{C\}$ and $\mathcal{L}(\langle v_1, v_2 \rangle) = \{r\}$.
$\forall$-rule	if 1. $\forall r.C \in \mathcal{L}(v_1)$, v_1 is not indirectly blocked, and 2. there is an r-neighbour v_2 of v_1 with $C \notin \mathcal{L}(v_2)$ then $\mathcal{L}(v_2) \longrightarrow \mathcal{L}(v_2) \cup \{C\}$.
$\forall_+$-rule	if 1. $\forall r.C \in \mathcal{L}(v_1)$, v_1 is not indirectly blocked, and 2. there is some role r' with Trans(r') and $r' \mathrel{\underline{\circledast}} r$ 3. there is an r'-neighbour v_2 of v_1 with $\forall r'.C \notin \mathcal{L}(v_2)$ then $\mathcal{L}(v_2) \longrightarrow \mathcal{L}(v_2) \cup \{\forall r'.C\}$.
choose-rule	if 1. $\leqslant n\, r.C \in \mathcal{L}(v_1)$, v_1 is not indirectly blocked, and 2. there is an r-neighbour v_2 of v_1 with $\{C, \dot{\neg} C\} \cap \mathcal{L}(v_2) = \emptyset$ then $\mathcal{L}(v_2) \longrightarrow \mathcal{L}(v_2) \cup \{E\}$ for some $E \in \{C, \dot{\neg} C\}$.
$\geqslant$-rule	if 1. $\geqslant n\, r.C \in \mathcal{L}(v)$, v is not blocked, and 2. there are not n safe r-neighbours $v_1, \ldots, v_n$ of v with $C \in \mathcal{L}(v_i)$ and $v_i \neq v_j$ for $1 \leqslant i < j \leqslant n$

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  - Well defined (model theoretic) **semantics**
  - **Formal properties** well understood (complexity, decidability)
  - Known **reasoning algorithms**
  - **Scalability** demonstrated by **implemented systems**

Tools, Tools, Tools

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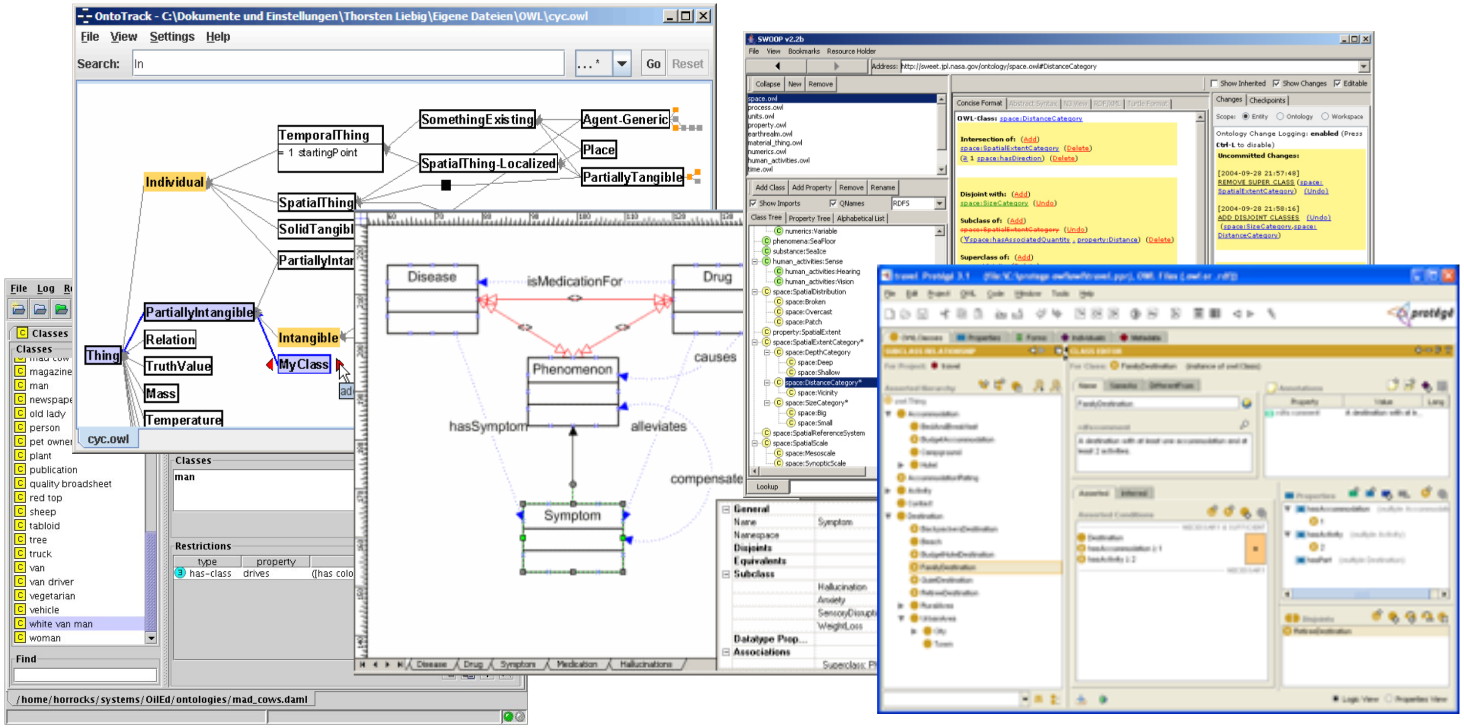

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- Reasoners

Hermit

FaCT++

Racer

MINDSWAP Pellet

KAON2

CEL

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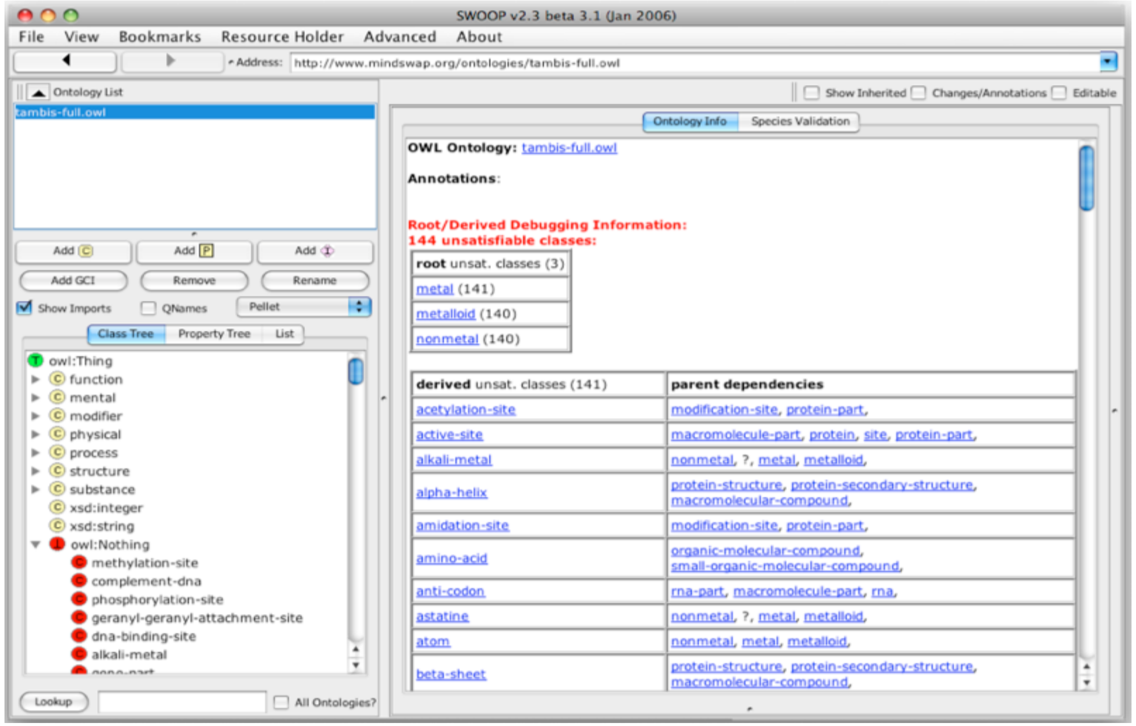

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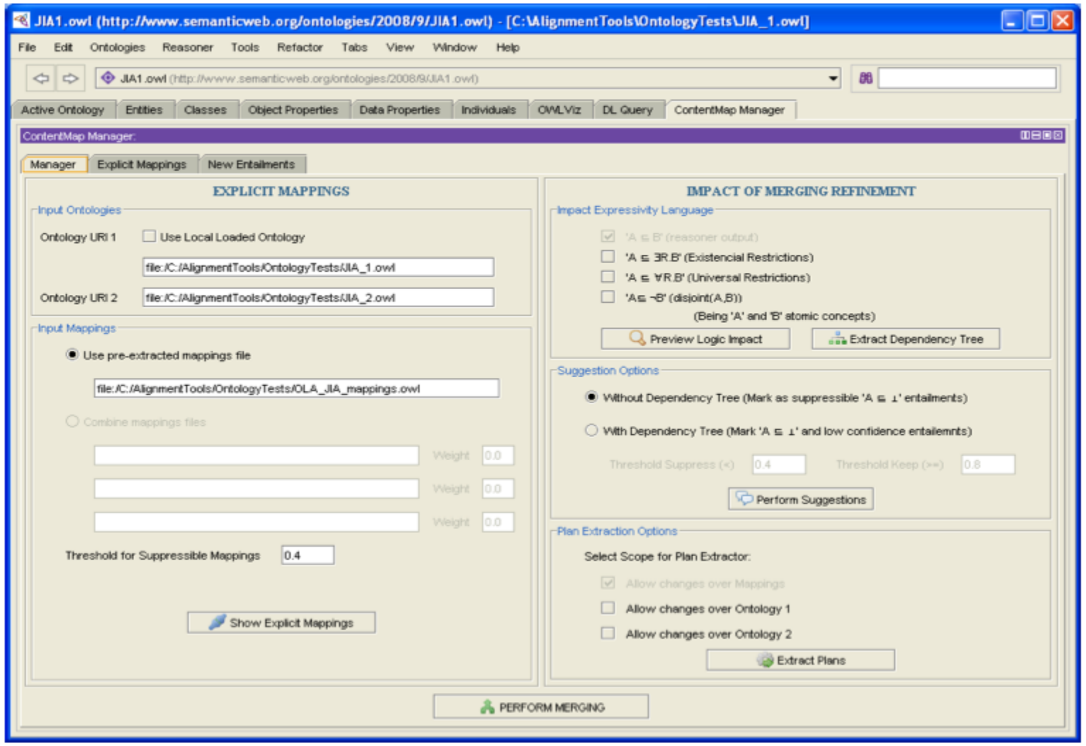

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- Integration and modularisation
- APIs, in particular the [OWL API]

Revision 1403 - (download) (annotate)
Fri Dec 18 17:14:37 2009 UTC (4 months, 2 weeks ago) by matthewhorridge
File size: 4711 byte(s)

```
package org.coode.owlapi.examples;

import org.semanticweb.owlapi.apibinding.OWLManager;
import org.semanticweb.owlapi.model.*;
import org.semanticweb.owlapi.util.DefaultPrefixManager;
/*
 * Copyright (C) 2009, University of Manchester
 *
 * Modifications to the initial code base are copyright of their
 * respective authors, or their employers as appropriate.  Authorship
 * of the modifications may be determined from the ChangeLog placed at
 * the end of this file.
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```

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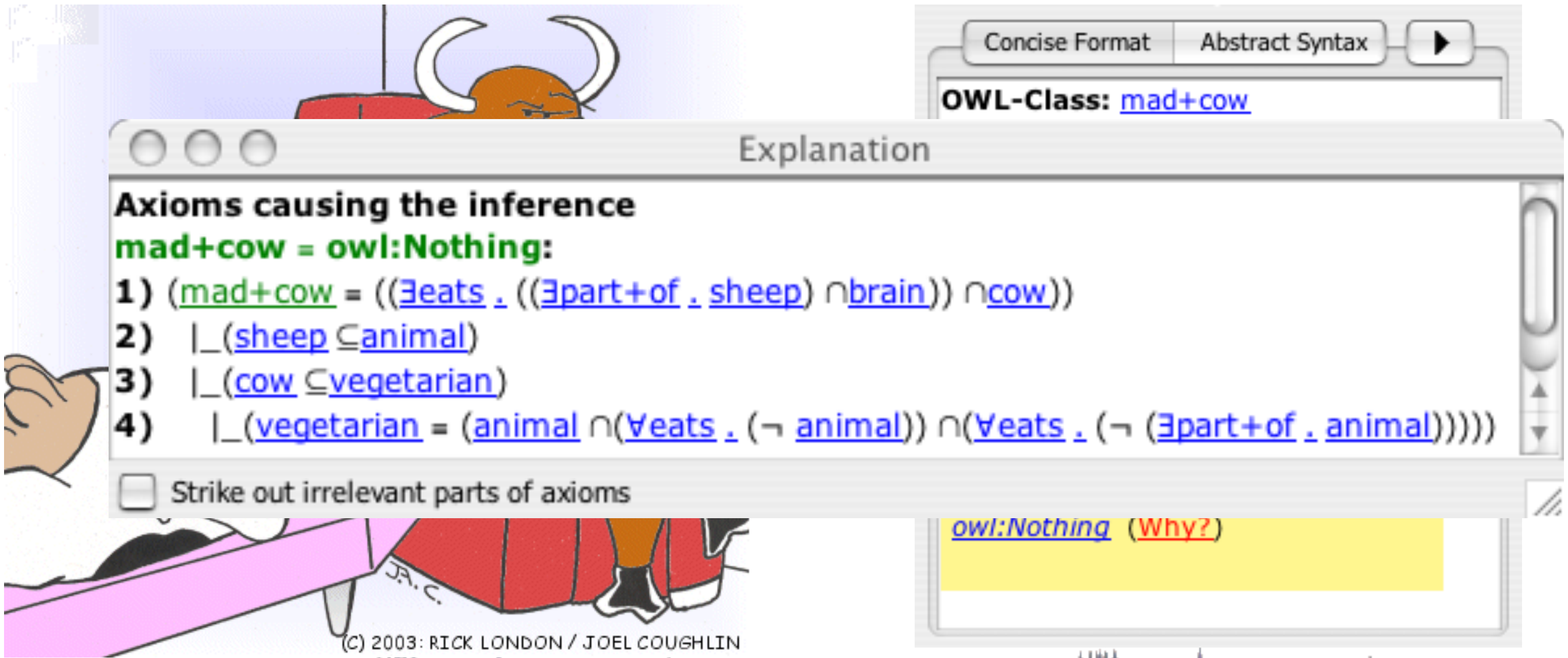

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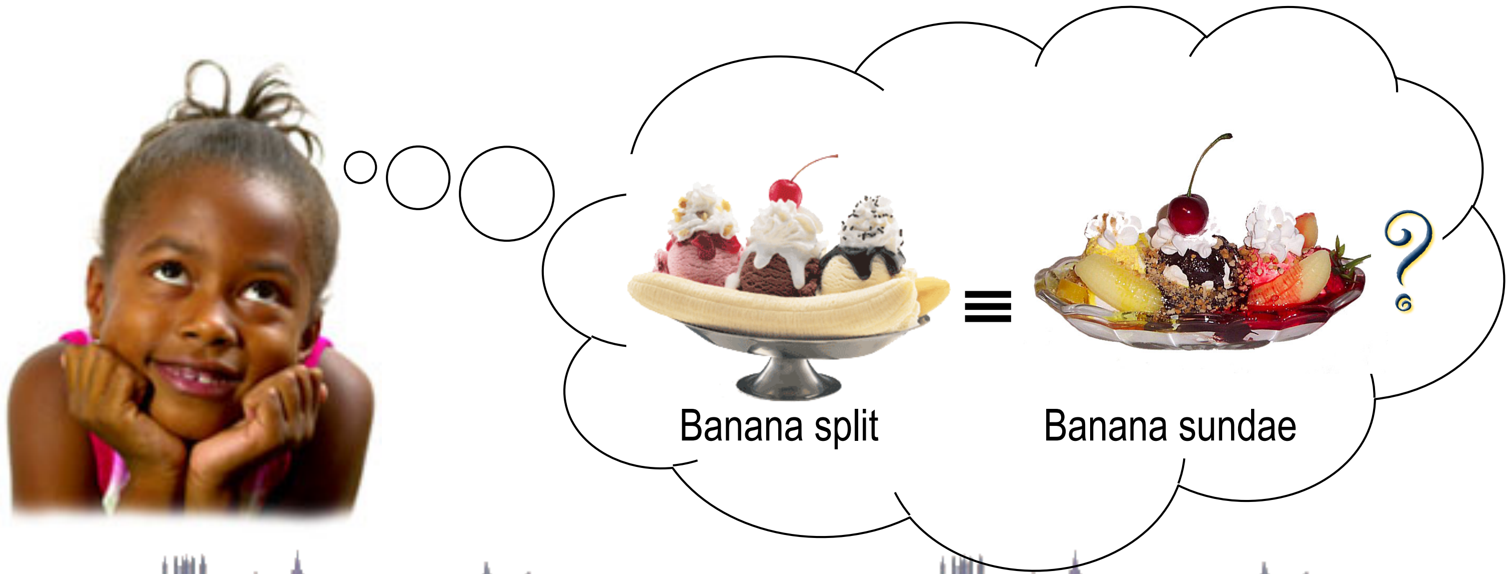
  - unexpected equivalences hold (unintended synonyms)



Ontology Applications

- OWL ontologies being **deployed** in increasing number and range of applications
  - eScience, eCommerce, geography, engineering, defence, …
  - major impact in healthcare and life sciences
- Now a mainstream technology supported by, e.g., **Oracle 11g**
  - Increasing impact in business applications

Ontology Applications

Designing and Building Business Ontologies

An Intensive 4-DAY SEMINAR with Workshops and Demonstrations, on Semantically Enabling the Enterprise led by Dave McComb and Simon Robe

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Seminar Objectives

Participants will:

- Gain an understanding of what an ontology is and what it can be used for.
- Understand how representing information in an ontology goes beyond a conceptual model or a simple taxonomy
- Understand the difference between frame based/ declarative classes and description logic based/ derivable classes.
- Understand the difference between open world and closed world models.
- Understand the basic principles for designing Ontologies for corporate applications.

Tuition Fee: $2,450

Healthcare and Life Sciences

- **OBO foundry** includes more than 100 biological and biomedical ontologies
- **Siemens** "actively building OWL based clinical solutions"
- OWL tools used to find and repair critical errors in ontology used at **Columbia Presbyterian**
- **SNOMED-CT** (Clinical Terms) ontology
  - used in healthcare systems of more than 15 countries, including Australia, Canada, Denmark, Spain, Sweden and the UK
  - also used by major US providers, e.g., Kaiser Permanente
  - ontology provides common vocabulary for recording clinical data

Case Study: SNOMED

It's **BIG** – over **400,000 concepts**

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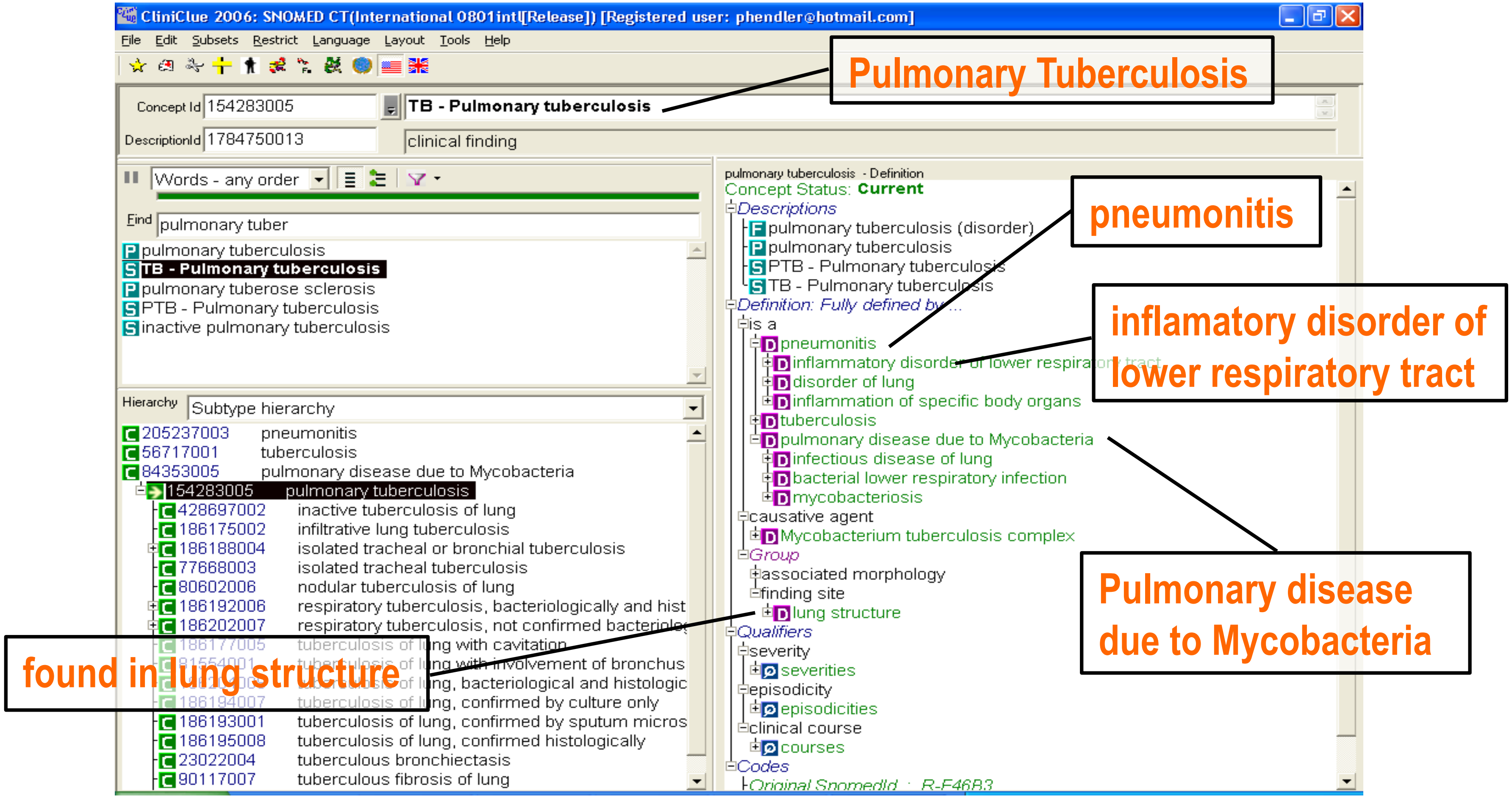

Case Study: SNOMED

- **Kaiser Permanente** extending SNOMED to express, e.g.:
  - *non-viral pneumonia* (negation)
  - *infectious pneumonia* is caused by a *virus* or a *bacterium* (disjunction)
  - *double pneumonia* occurs in two *lungs* (cardinalities)
- This is easy in **SNOMED-OWL**
  - but reasoner failed to find expected subsumptions, e.g., that *bacterial pneumonia* is a kind of *non-viral pneumonia*
- Ontology highly **under-constrained**: need to add disjointness axioms (at least)
  - *virus* and *bacterium* must be disjoint

Case Study: SNOMED

- Adding disjointness led to **surprising results**
  - many classes become inconsistent, e.g., *percutanious embolization of hepatic artery using fluoroscopy guidance*
- Cause of **inconsistencies** identified as class *groin*
  - *groin* asserted to be subclass of both *abdomen* and *leg*
  - *abdomen and leg* are disjoint
  - modelling of *groin* (and other similar “junction” regions) identified as incorrect

Case Study: SNOMED

- Correct modelling of groin is quite complex, e.g.:
  - groin has a part that is part of the abdomen, and has a part that is part of the leg (***inverse properties***)

    $$\mathsf{Groin} \sqsubseteq \exists \mathsf{hasPart}.(\exists \mathsf{isPartOf}.\mathsf{Abdomen}))$$
    $$\mathsf{Groin} \sqsubseteq \exists \mathsf{hasPart}.(\exists \mathsf{isPartOf}.\mathsf{Leg})$$
    $$\mathsf{hasPart} \equiv \mathsf{isPartOf}^{-}$$

  - all parts of the groin are part of the abdomen or the leg (**disjunction**)

    $$\mathsf{Groin} \sqsubseteq \forall \mathsf{hasPart}.(\exists \mathsf{isPartOf}.(\mathsf{Abdomen} \sqcup \mathsf{Leg}))$$

  - ...

Case Study: SNOMED

What we learned:

- Ontology engineering is **error prone**
  - errors of omission (e.g., disjointness) and commission (e.g., modelling of groin)
- **Expressive features** of OWL are sometimes needed
- Sophisticated tool support is **essential**
  - handling ontologies of this size is challenging
  - domain experts (and logicians!) often need help to understand the (root) cause of both inconsistencies and non-subsumptions
  - surprising and unexplained (non-) inferences are frustrating for users and may cause them to lose faith in the reasoner

What About Scalability?

- Tools only **useful in practice** if they can deal with large ontologies and/or large data sets
- Unfortunately, many ontology languages are highly intractable
  - OWL 2 satisfiability is **2NExpTime-complete** w.r.t. schema
  - and **NP-Hard** w.r.t. data (upper bound open)
- Problem addressed in practice by
  - Algorithms that work well in **typical cases**
  - Highly **optimised implementations**
  - Use of **tractable fragments**

Reasoning Algorithms

Most OWL reasoners based on (hyper-) **tableau**

- Reasoning tasks reducible to (un)**satisfiability**
  - E.g., $\mathcal{O} \models \mathsf{HeartDisease} \sqsubseteq \mathsf{VascularDisease}$ iff $\mathcal{O} \cup \{x : (\mathsf{HeartDisease} \sqcap \neg \mathsf{VascularDisease})\}$ is *not* satisfiable
- Algorithm tries to **construct** (abstraction of) a **model**
- Success trivially proves **non-subsumption**
  - we have constructed a counter-model
- Model search designed such that failure proves non-existence of model, and hence **subsumption**

Highly Optimised Implementations

- Lazy unfolding
- Simplification and rewriting
- Search optimisations
- Caching
- Optimised blocking
- Heuristics
- Fast semi-decision procedures
- Algebraic methods
- Nominal absorption
- Individual reuse
- ...

Computationally **sub-optimal**, but **highly effective** in practice

Problem Solved?

Implementation of ExpTime algorithms is futile!

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Develop new ontologies

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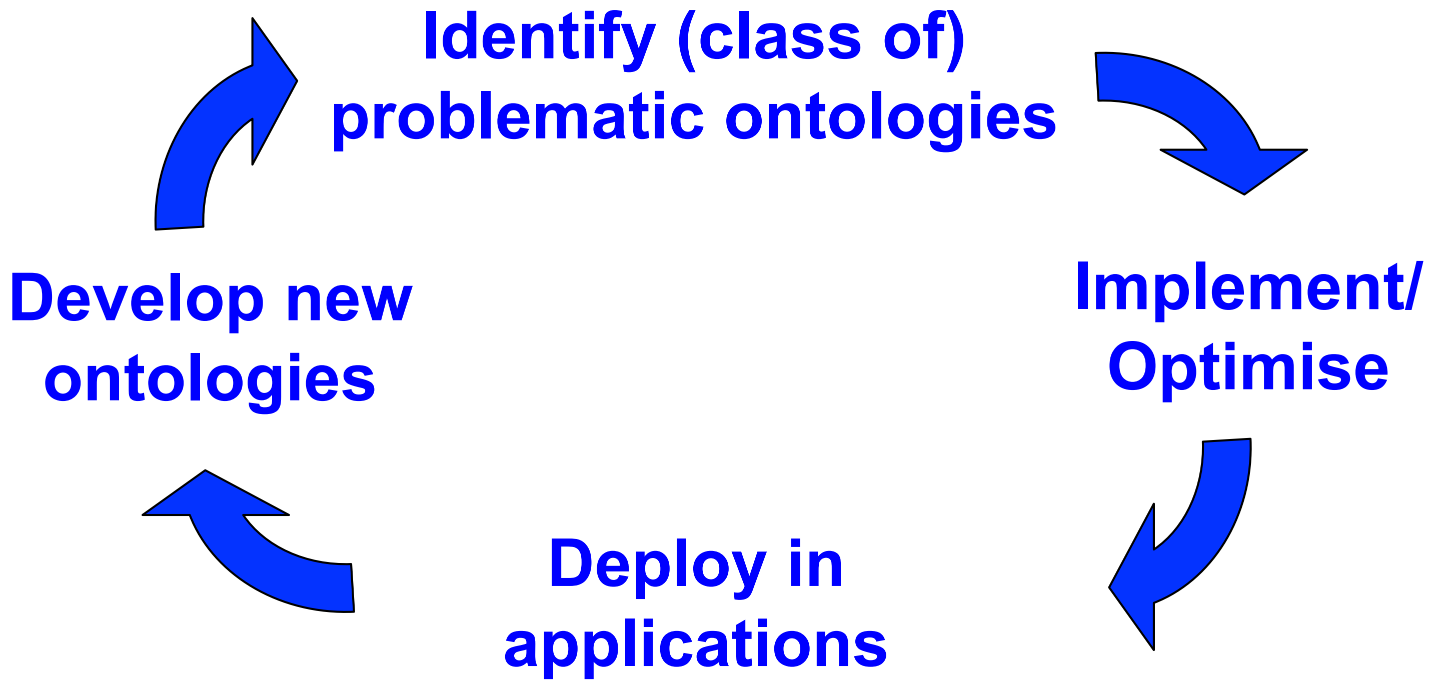
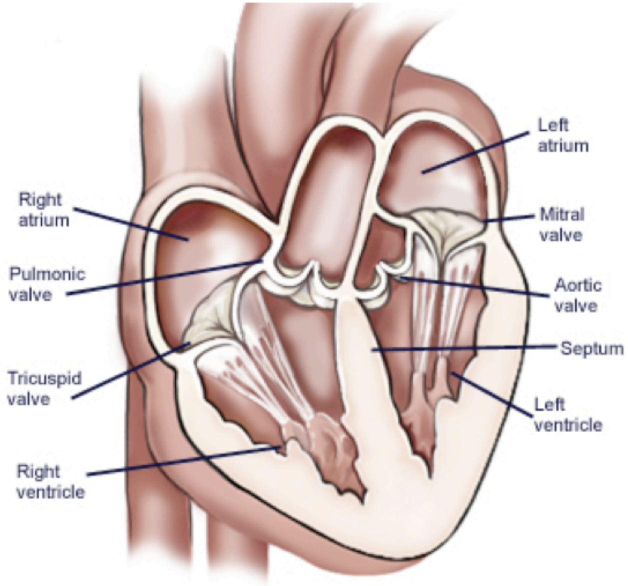


Scalability Issues

- Problems with very **large and/or cyclical ontologies**



$$\begin{aligned}
\mathsf{LeftSide} &\sqsubseteq \exists \mathsf{hasComponent}.\mathsf{AorticValve} \\
\mathsf{LeftSide} &\sqsubseteq \exists \mathsf{hasComponent}.\mathsf{MitralValve} \\
\mathsf{AorticValve} &\sqsubseteq \exists \mathsf{hasConnection}.\mathsf{LeftVentircle} \\
\mathsf{MitralValve} &\sqsubseteq \exists \mathsf{hasConnection}.\mathsf{LeftVentircle} \\
\mathsf{LeftVentricle} &\sqsubseteq \exists \mathsf{isDivisionOf}.\mathsf{LeftSide}
\end{aligned}$$

- Ontologies may define 10s/100s of thousands of terms
- Can lead to construction of *very* large models

Scalability Issues

- Problems with **large data sets** (ABoxes)
  - Main reasoning problem is (conjunctive) query answering, e.g., retrieve all patients suffering from vascular disease:
    $Q(x) \leftarrow \mathsf{Patient}(x) \wedge \mathsf{suffersFrom}(x, y) \wedge \mathsf{VascularDisease}(y)$
  - Decidability still open for OWL, although minor restrictions (on cycles in non-distinguished variables) restore decidability
  - Query answering reduced to standard decision problem, e.g., by checking for each individual x if $\mathcal{O} \models Q(x)$
  - Model construction starts with *all* ground facts (data)
- Typical applications may use data sets with **10s/100s of millions** of individuals (or more)

OWL 2

- **New version** of OWL became a rec in October 2009
- **Extends OWL** with a small but useful set of features
  - That are needed in applications
  - For which semantics and reasoning techniques well understood
  - That tool builders are willing and able to support
- Adds **profiles**
  - Language subsets with useful computational properties

New Language Features

Four kinds of new feature:

- **Increased expressive power**
  - qualified cardinality restrictions, e.g.:
    - persons having two friends who are republicans
  - property chains, e.g.:
    - the brother of your parent is your uncle
  - local reflexivity restrictions, e.g.:
    - narcissists love themselves
  - reflexive, irreflexive, and asymmetric properties, e.g.:
    - nothing can be a proper part of itself (irreflexive)
  - disjoint properties, e.g.:
    - you can't be both the parent of and child of the same person
  - keys, e.g.:
    - country + license plate constitute a unique identifier for vehicles

New Language Features

Four kinds of new feature:

- **Extended Datatypes**
  - Much wider range of XSD Datatypes supported, e.g.:

    Integer, string, boolean, real, decimal, float, datatime, …
  - User-defined datatypes using facets, e.g.:

max weight of an airmail letter:
xsd:integer maxInclusive ”20"^^xsd:integer

format of Italian registration plates:
xsd:string xsd:pattern "[A-Z]{2} [0-9]{3}[A-Z]{2}

New Language Features

Four kinds of new feature:

- **Metamodelling and annotations**
  - Restricted form of metamodelling via “punning”, e.g.:

    SnowLeopard subClassOf BigCat (i.e., a class)

    SnowLeopard type EndangeredSpecies (i.e., an individual)
  - Annotations of axioms as well as entities, e.g.:

    SnowLeopard type EndangeredSpecies (“source: WWF”)
  - Even annotations of annotations

New Language Features

Four kinds of new feature:

- **Syntactic sugar**
  - Disjoint unions, e.g.:

    Element is the DisjointUnion of Earth Wind Fire Water

    i.e., Element is equivalent to the union of Earth Wind Fire Water

    Earth Wind Fire Water are pair-wise disjoint
  - Negative assertions, e.g.:

    Mary is not a sister of Ian

    21 is not the age of Ian

Alternative Syntaxes

- Normative exchange syntax is **RDF/XML**

```
<owl:Class rdf:about="#Heart">
    <owl:equivalentClass>
        <owl:Class>
            <owl:intersectionOf rdf:parseType="Collection">
                <rdf:Description rdf:about="#MuscularOrgan"/>
                <owl:Restriction>
                    <owl:onProperty rdf:resource="#isPartOf"/>
                    <owl:someValuesFrom rdf:resource="#CirculatorySystem"/>
                </owl:Restriction>
            </owl:intersectionOf>
        </owl:Class>
    </owl:equivalentClass>
    <rdfs:subClassOf rdf:resource="&owl;Thing"/>
</owl:Class>
```

Alternative Syntaxes

- Normative exchange syntax is **RDF/XML**
- **Functional syntax** mainly intended for language spec

```
EquivalentClasses(Heart
   ObjectIntersectionOf(ObjectSomeValuesFrom(isPartOf CirculatorySystem)
      MuscularOrgan))
```

Alternative Syntaxes

- Normative exchange syntax is **RDF/XML**
- **Functional syntax** mainly intended for language spec
- **XML syntax** for interoperability with XML toolchain

```
<EquivalentClasses>
    <Class URI="Heart"/>
    <ObjectIntersectionOf>
        <Class URI="MuscularOrgan"/>
        <ObjectSomeValuesFrom>
            <ObjectProperty URI="isPartOf"/>
            <Class URI="CirculatorySystem"/>
        </ObjectSomeValuesFrom>
    </ObjectIntersectionOf>
</EquivalentClasses>
```

Alternative Syntaxes

- Normative exchange syntax is **RDF/XML**
- **Functional syntax** mainly intended for language spec
- **XML syntax** for interoperability with XML toolchain
- **Manchester syntax** for better readability

```
         Class: Heart
  EquivalentTo: MuscularOrgan
                that isPartOf CirculatorySystem
```

Profiles

- OWL 2 defines three **profiles**:
  - **EL**: polynomial time reasoning for schema and data
  - **QL**: logspace query answering using RDBMs
  - **RL**: polynomial time query answering using rule-extended DBs
- OWL defined only one profile: **OWL Lite**
  - DL research not consulted in design of OWL Lite
  - resulting “fragment” not in fact very Lite (EXPTIME-complete)

OWL 2 EL

- A (near maximal) fragment of OWL 2 such that
  - satisfiability checking is in PTime (**PTime-Complete**)
  - data complexity of query answering also PTime-Complete

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OWL 2 EL

- A (near maximal) fragment of OWL 2 such that
  - satisfiability checking is in PTime (**PTime-Complete**)
  - data complexity of query answering also PTime-Complete
- Based on $\mathcal{EL}$ family of description logics
- Efficient **saturation** based algorithms
  - derive axioms rather than constructing models, e.g.:

$$\frac{A \sqsubseteq B \quad B \sqsubseteq C}{A \sqsubseteq C} \qquad \frac{A \sqsubseteq B \quad A \sqsubseteq C \quad B \sqcap C \sqsubseteq D}{A \sqsubseteq D}$$

$$\frac{A \sqsubseteq \exists R.B \quad B \sqsubseteq C \quad \exists R.C \sqsubseteq D}{A \sqsubseteq D}$$

OWL 2 QL

- A (near maximal) fragment of OWL 2 such that
  - data complexity of conjunctive query answering in **AC^0**
- Based on **DL-Lite** family of description logics
- Efficient **query rewriting** based algorithms
  - ontology axioms used as rewrite rules for query, e.g.:

$$Q(x) \leftarrow \mathsf{treats}(x,y) \wedge \mathsf{Patient}(y)$$
$$Q(x) \leftarrow \mathsf{Doctor}(x)$$
$$Q(x) \leftarrow \mathsf{Consultant}(x)$$

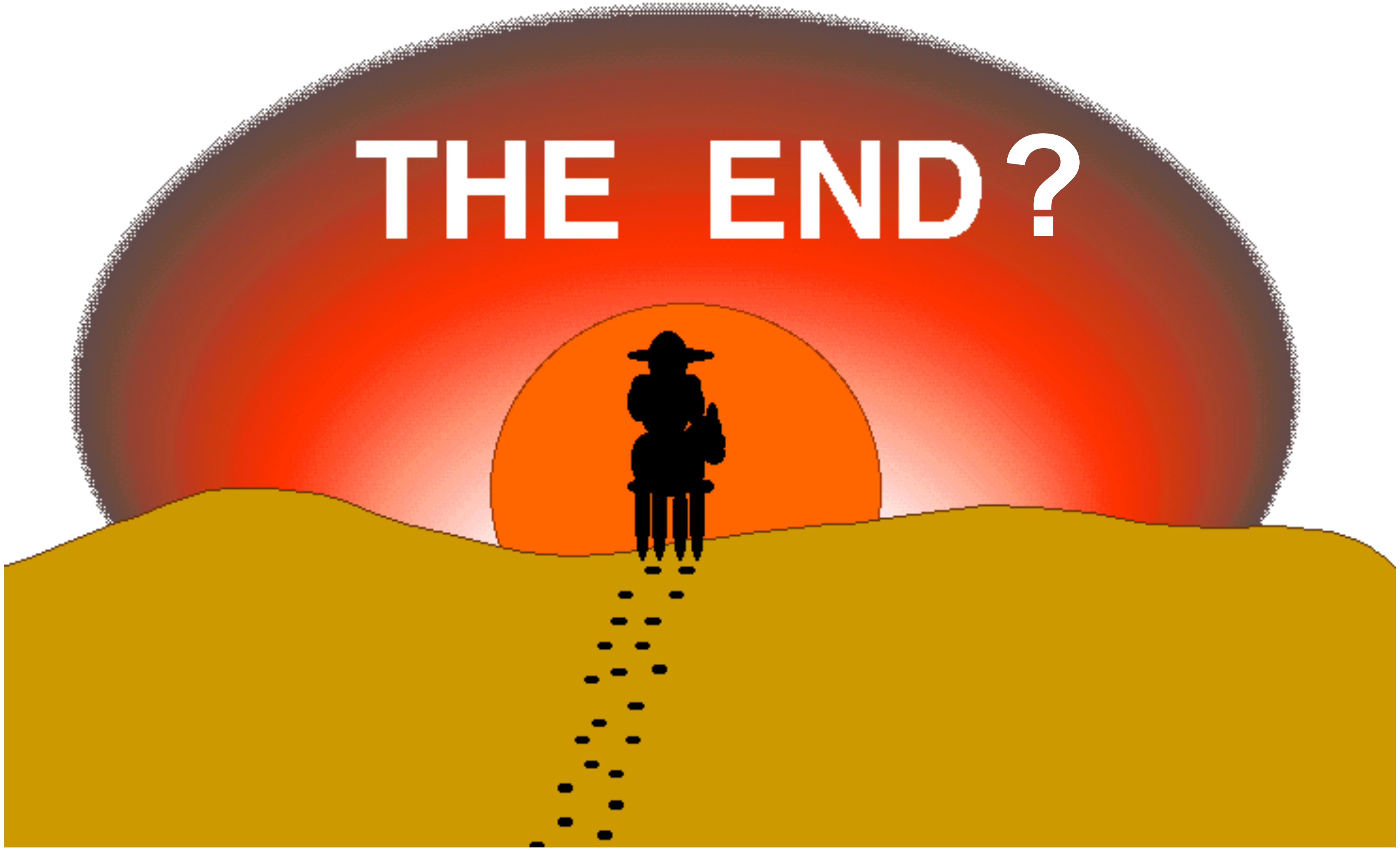
$$\mathsf{Doctor} \sqsubseteq \exists \mathsf{treats}.\mathsf{Patient}$$
$$\mathsf{Consultant} \sqsubseteq \mathsf{Doctor}$$

  - data storage & evaluation of resulting UCQ delegated to RDBMS

$$Q(x) \leftarrow (\mathsf{treats}(x,y) \wedge \mathsf{Patient}(y)) \vee \mathsf{Doctor}(x) \vee \mathsf{Consultant}(x)$$

Profiles as Optimisations

- **EL techniques** as optimisation for OWL classification
  - use saturation algorithm to classify part of ontology
  - use incremental reasoning techniques to add remaining axioms
  - similar optimisation already used to good effect in FaCT++ (can classify extended SNOMED-OWL in 24 minutes)
- **QL techniques** as optimisation for EL query answering
  - in “hybrid” approach, data first extended by partially materialising EL inferences
  - then use modified query rewriting with ontology and extended data


THE END?

Ongoing Research

- Query answering
  - [Kontchakov et al], [Konev et al], [Baader et al], [Glimm et al]
- Diagnosis and repair
  - [Peñaloza et al]
- Reasoning over hidden content
  - [Cuenca Grau et al]
- Probabilistic DLs
  - [Lutz et al]

Ongoing Research

- Optimisation
- Second order DLs
- Temporal DLs
- Fuzzy/rough concepts
- Modularity, alignment and integration
- Integrity constraints
- ...

Ongoing Standardisation Efforts

- Standardised query language
  - SPARQL standard for RDF
  - Currently being extended for OWL, see *http://www.w3.org/TR/sparql11-entailment/*
- RDF
  - Revision currently being considered, see *http://www.w3.org/2009/12/rdf-ws/*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- Birte Glimm






Thank you for listening

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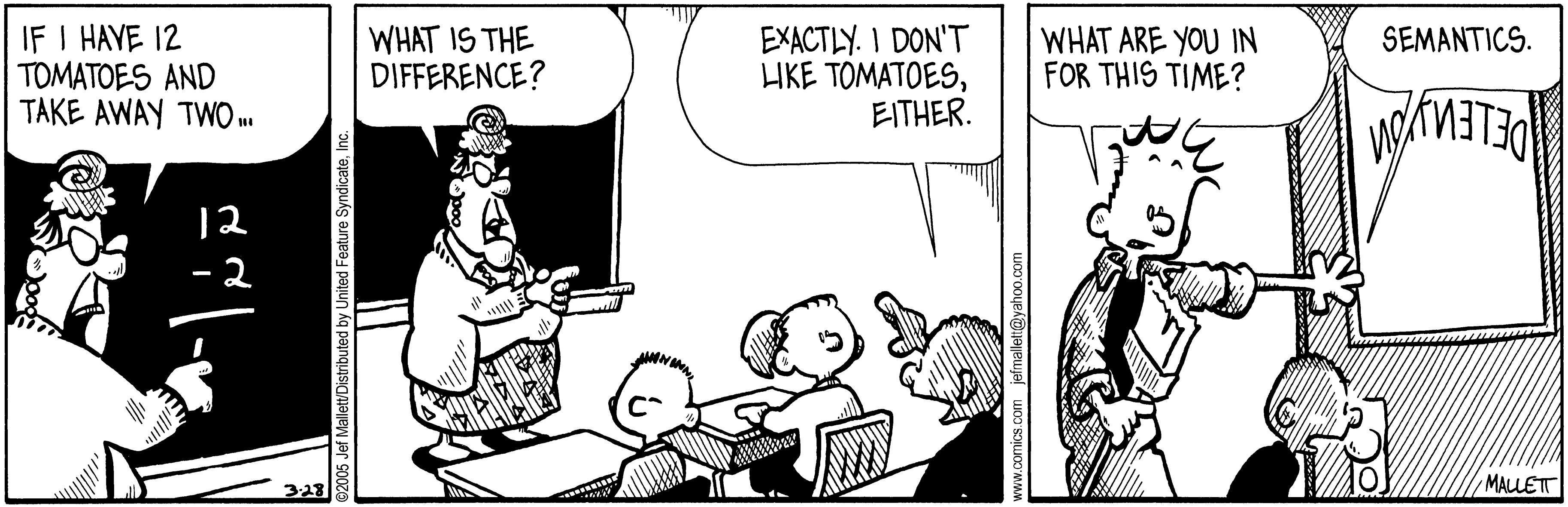

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Any questions?