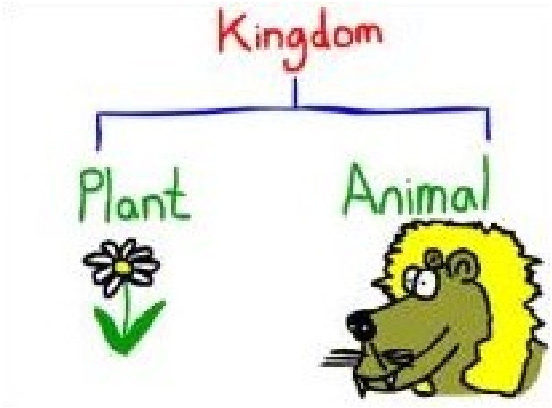

Ontologies and the Semantic Web

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Information Management Group
School of Computer Science
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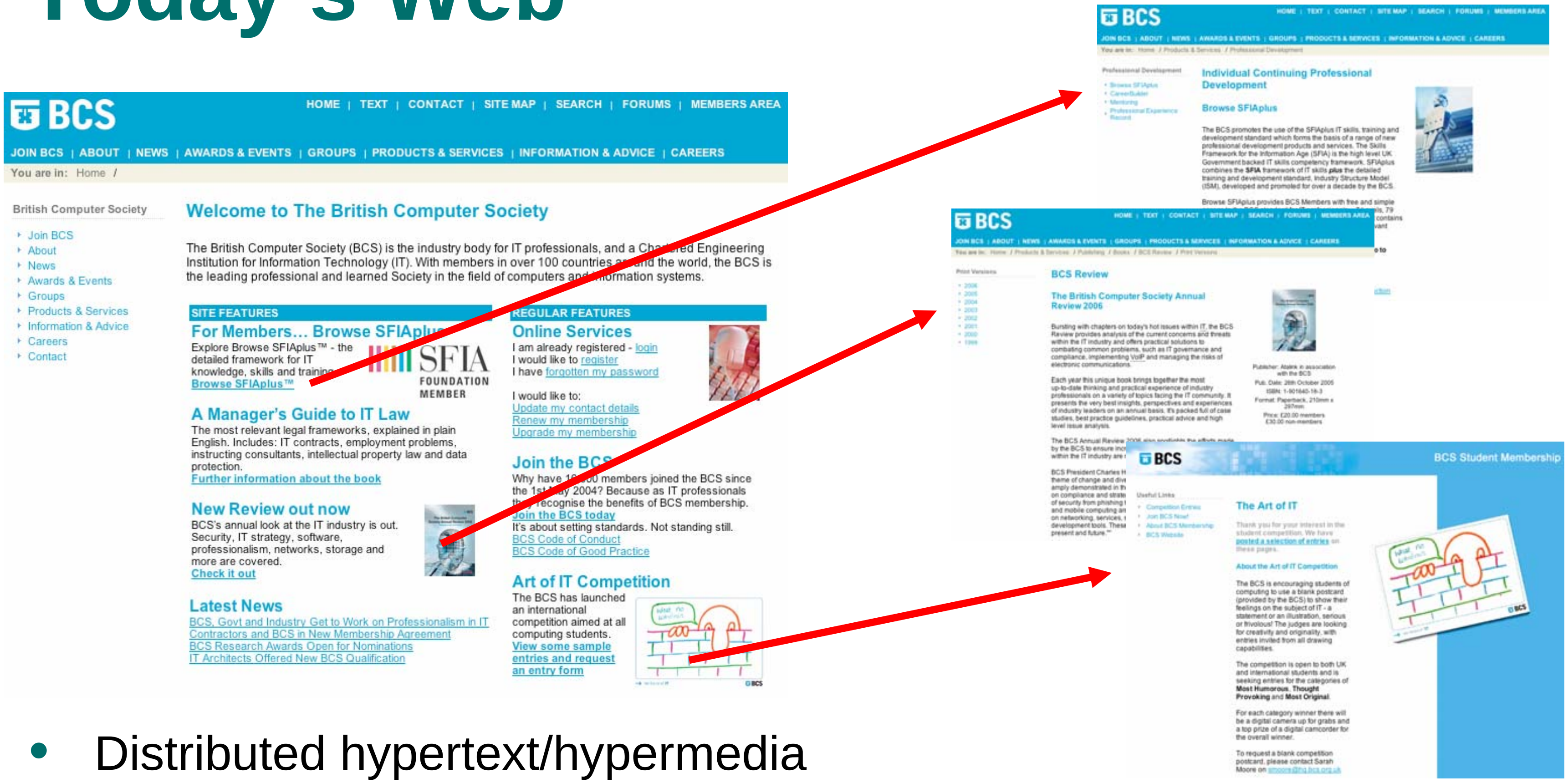
The Semantic Web

Today’s Web



- Distributed hypertext/hypermedia
- Information accessed via (keyword based) search and browse
- Browser tools render information for **human consumption**

What is the Semantic Web?

- Web was "invented" by **Tim Berners-Lee** (amongst others), a physicist working at CERN
- His vision of the Web was much more ambitious than the reality of the existing (syntactic) Web:

"… a set of **connected applications** … forming a **consistent logical web of data** …"

"… an extension of the current web in which information is given **well-defined meaning**, better enabling computers and people to work in cooperation …"

- This vision of the Web has become known as the **Semantic Web**

Hard Work using “Syntactic Web”

Find images of Peter Patel-Schneider, Frank van Harmelen and Alan Rector…

Rev. Alan M. Gates, Associate Rector of the Church of the Holy Spirit, Lake Forest, Illinois

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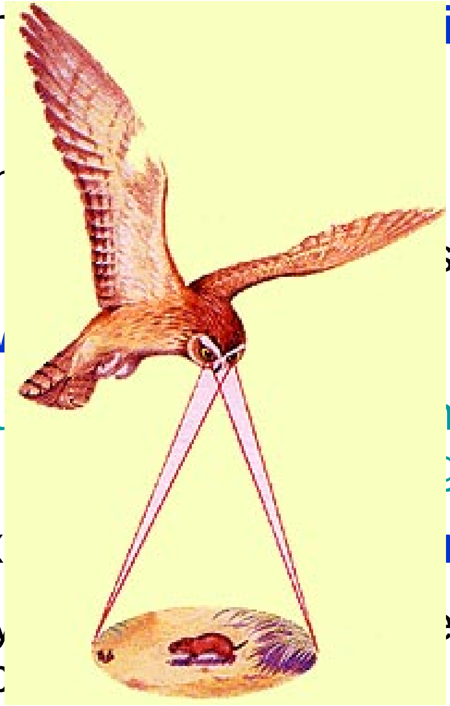
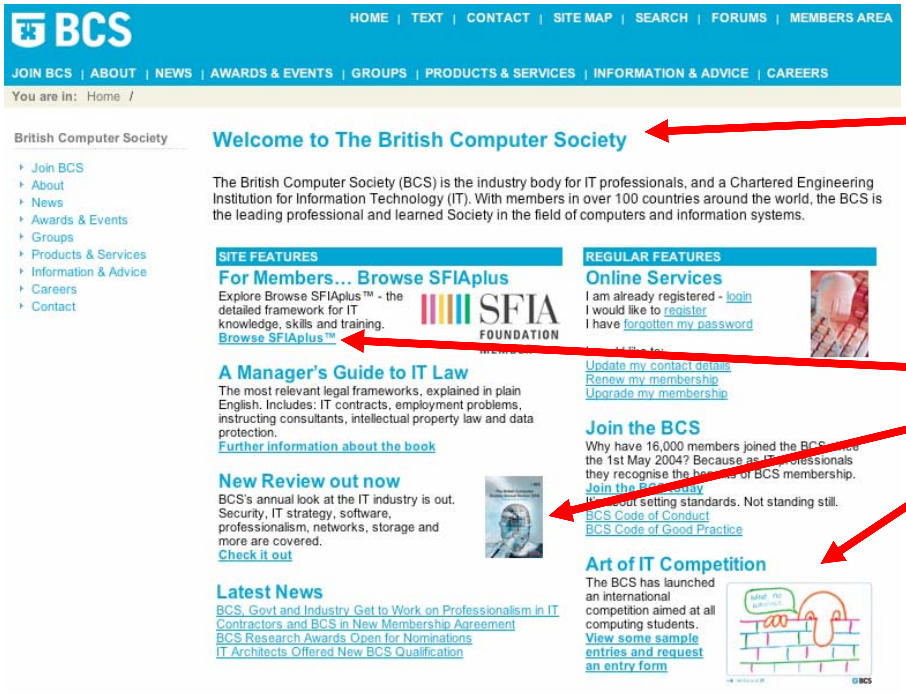
Impossible (?) using "Syntactic Web"

- Complex queries involving **background knowledge**
  - Find information about "animals that use sonar but are neither bats nor dolphins" **, e.g., Barn Owl**
- Locating information ... **ies**
  - Travel enquiries
  - Prices of goods ar...
  - Results of human ... s
- Finding and using "**w**...
  - Given a DNA sequ... es, determine the proteins they can produce, ... gical processes they control
- Delegating complex ... **nts**"
  - Book me a holiday ... ewhere warm, not too far away, and where they sp... English



What is the Problem?

Consider a typical web page:



- Markup consists of:
  - rendering information (e.g., font size and colour)
  - Hyper-links to related content
- Semantic content is accessible to humans, but not (easily) to computers…

What is the (Proposed) Solution?

- Add semantic annotations to web resources

Dr. Alan Rector, Professor of Computer Science, University of Manchester

<Person>Alan Rector</Person>, <Job>Professor of Computer Science</Job>, University of Manchester

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<Person>Alan M. Gates</Person>, <Job>Associate Rector</Job> of the Church of the Holy Spirit, Lake Forest, Illinois

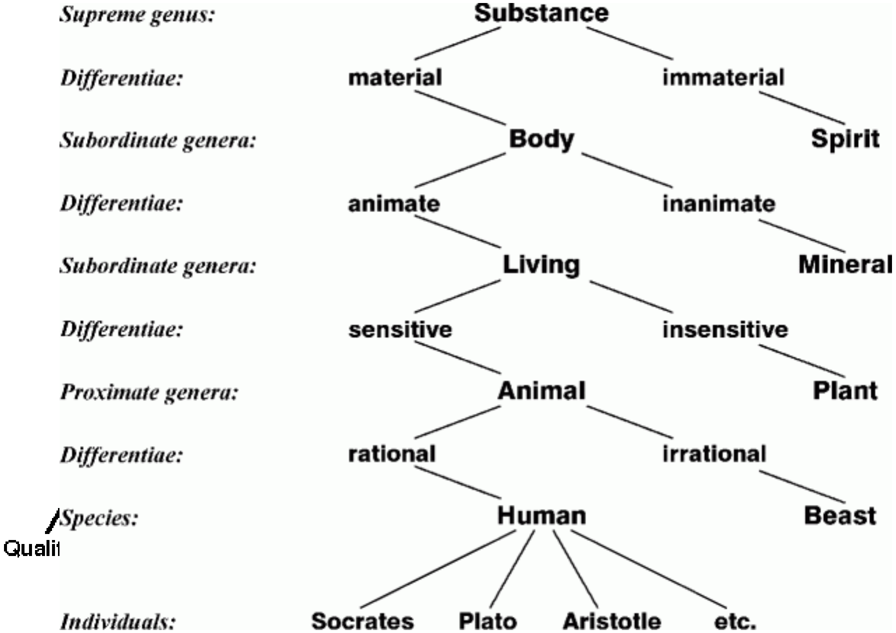
Giving Semantics to Annotations

- External agre… …notations
  - **Agree on m…** …tags
    - E.g., Dub…
  - Limited flexi…
  - Limited num… …d
- Use Ontologi… …annotations
  - **Agree on la…** …ning
  - Meanings o… …y ontologies
    - New term… …isting ones
    - Meaning … …ally specified
    - Can combine/relate terms in multiple ontologies

Ontologies

Ontology: Origins and History

- In Philosophy, fundamental branch of metaphysics
  - Studies "being" or "existence" and their **basic categories**
  - Aims to find out what **entities** and **types of entities** exist

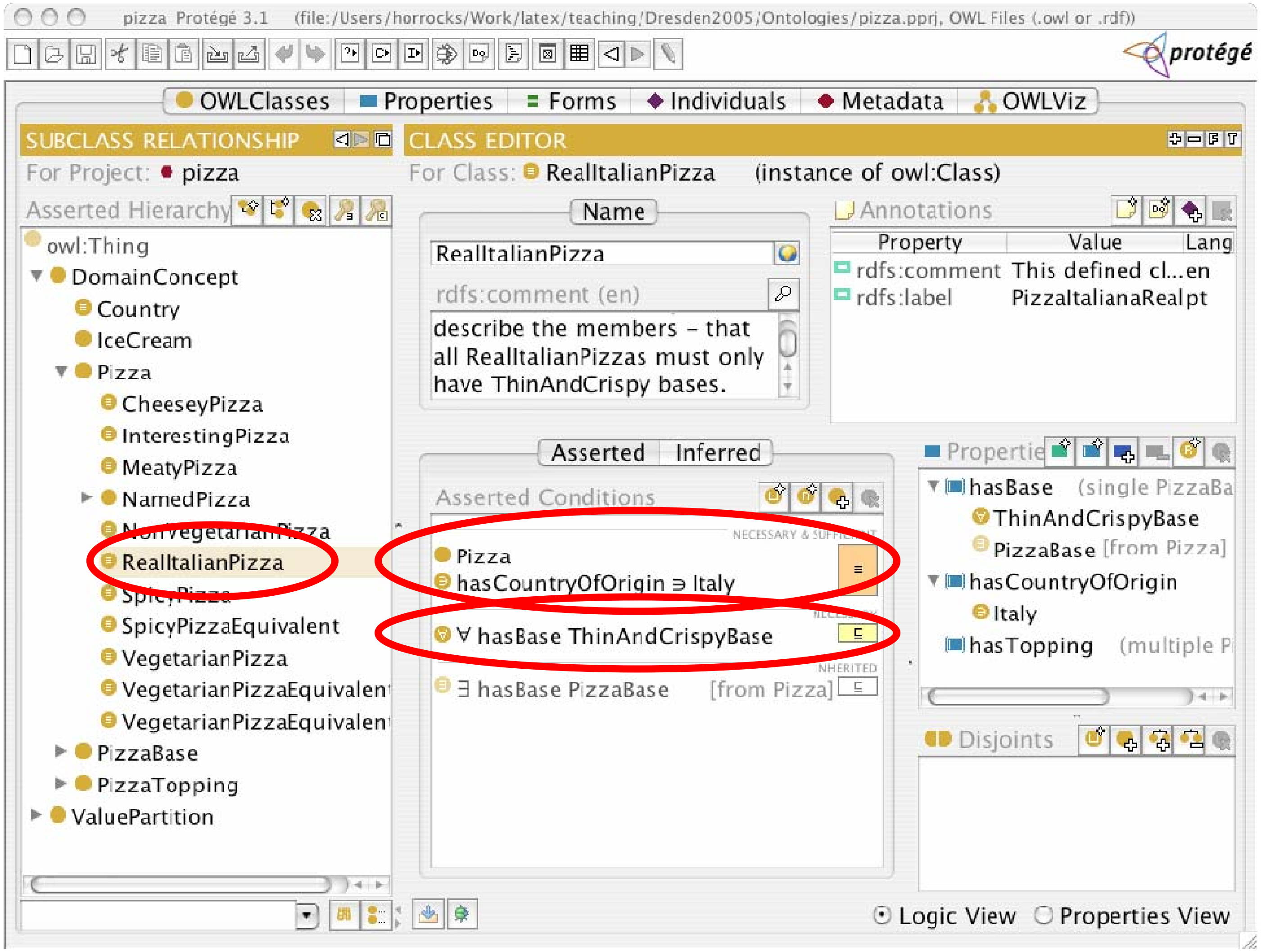


Ontology in Information Science

- An ontology is an engineering artefact consisting of:
  - A **vocabulary** used to describe (a particular view of) some domain
  - An **explicit specification** of the **intended meaning** of the vocabulary.
    - Often includes classification based information
  - Constraints capturing **background knowledge** about the domain

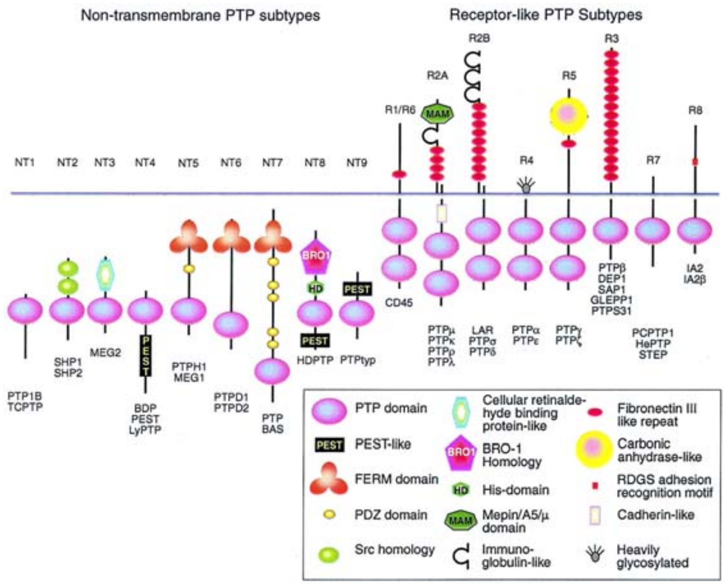
- Ideally, an ontology should:
  - Capture a **shared understanding** of a domain of interest
  - Provide a **formal** and **machine manipulable** model

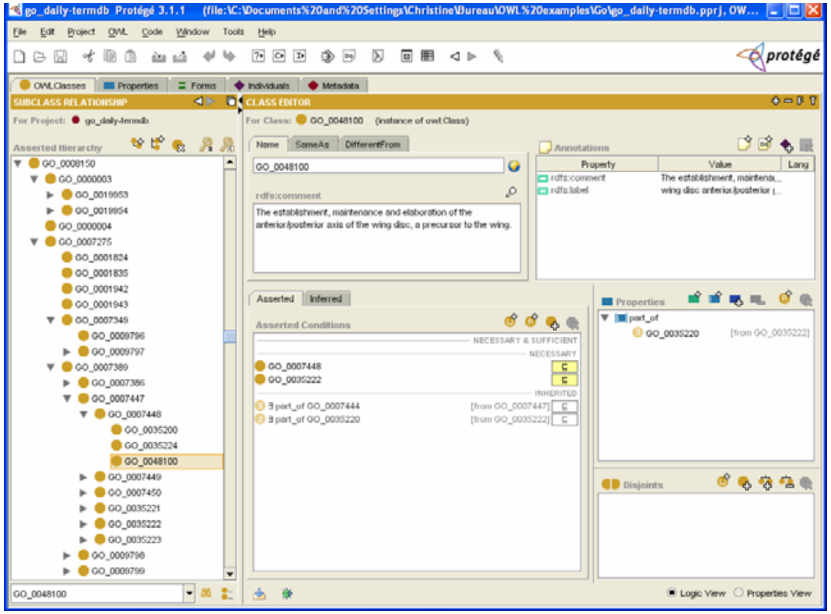
Example Ontology (Protégé)



Applications of Ontologies

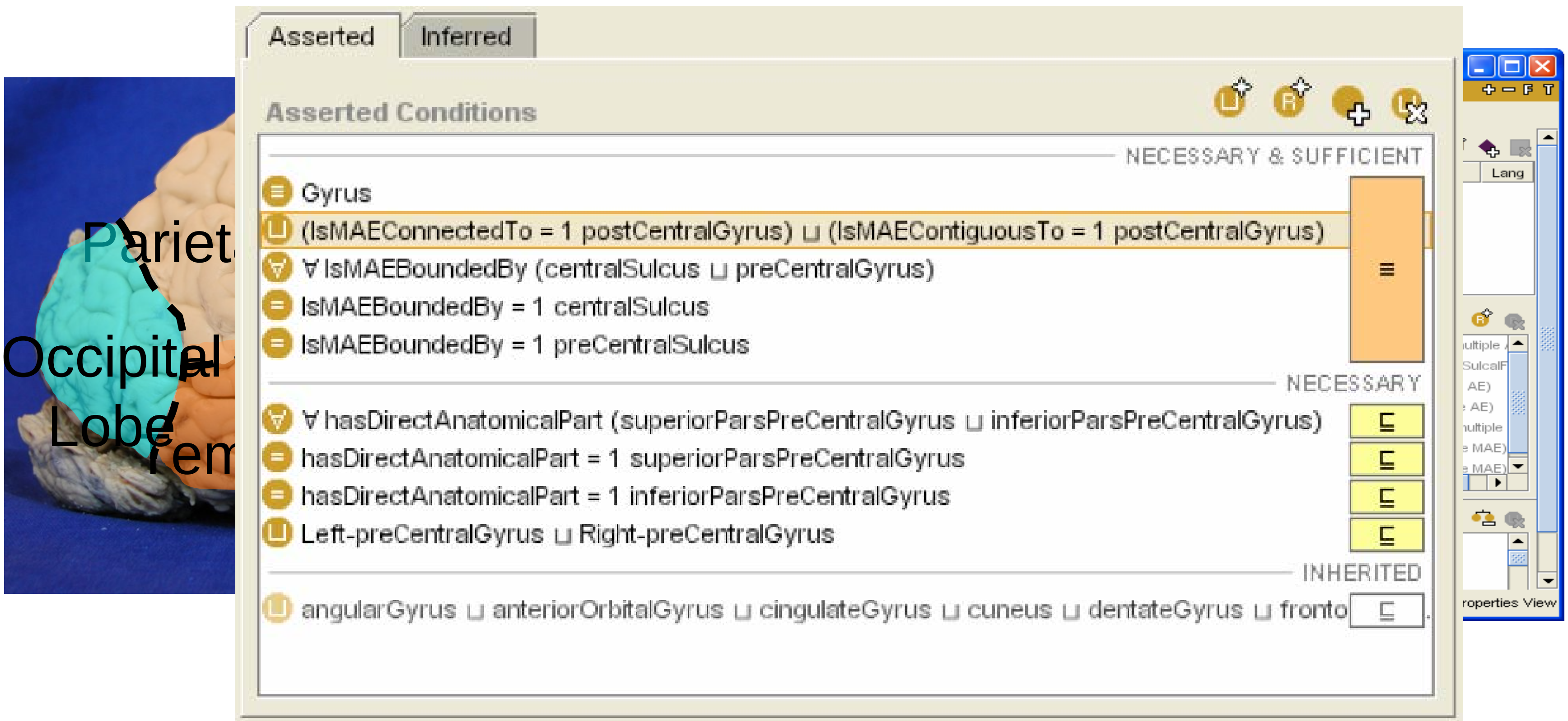
- e-Science, e.g., Bioinformatics
  - Open Biomedical Ontologies Consortium (GO, MGED)
  - Used e.g., for “in silico” investigations relating theory and data
    - E.g., relating data on phosphatases to (model of) biological knowledge





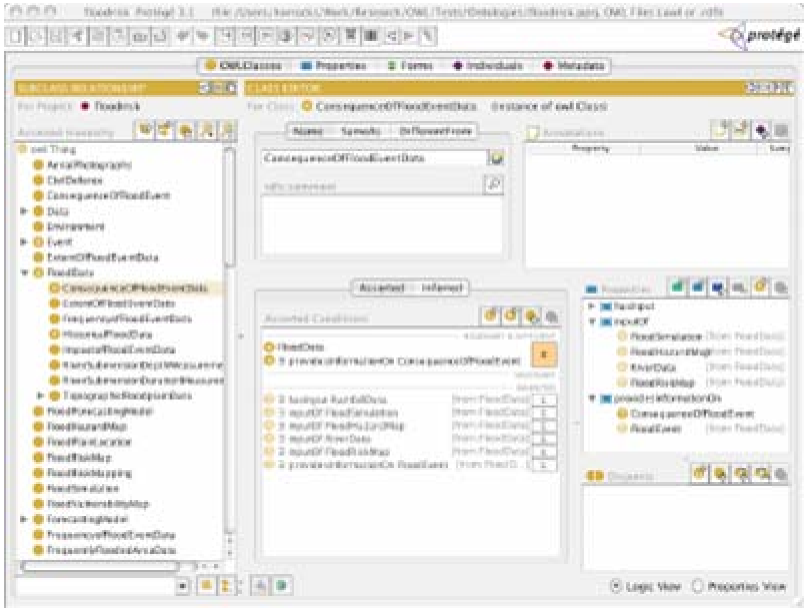
Applications of Ontologies

- Medicine
  - Building/maintaining terminologies such as Snomed, NCI & Galen



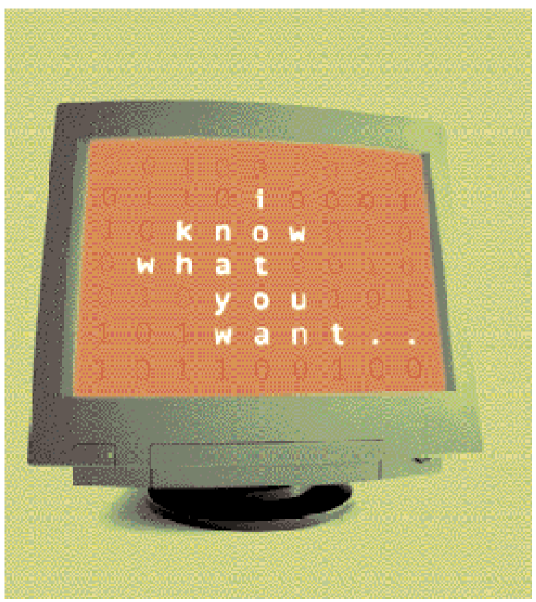
Applications of Ontologies

- Organising complex and semi-structured information
  - UN-FAO, NASA, Ordnance Survey, General Motors, Lockheed Martin, …



Applications of Ontologies

- Military/Government
  - DARPA, NIST, SAIC, Department of Homeland Security, …
- The Semantic Web and so-called Semantic Grid



THE SEMANTIC WEB

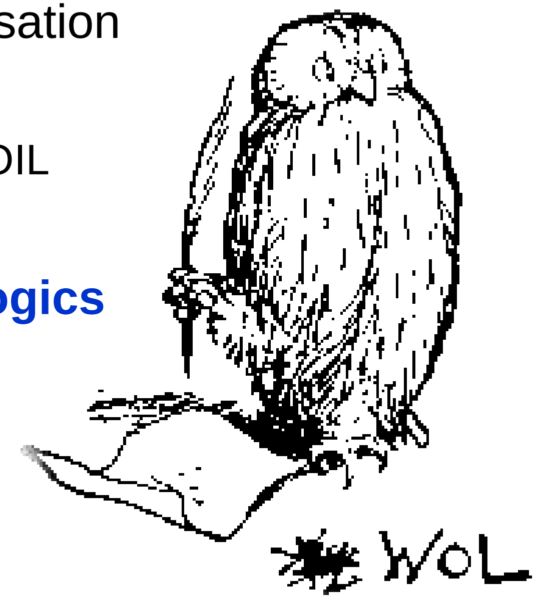
Ontology Languages

Ontology Languages for the Web

- Semantic Web effort led to development of "resource description" language(s)
  - E.g., **RDF**, and later RDF Schema (**RDFS**)
- RDFS is recognisable as an ontology language
  - **Classes** and **properties**
  - **Sub/super-classes** (and properties)
  - **Range** and **domain** (of properties)
- But RDFS **too weak** to describe resources in sufficient detail, e.g.:
  - No **existence/cardinality** constraints
  - No **transitive, inverse or symmetrical** properties
  - No **localised range and domain** constraints
  - …
- And RDF(S) has "higher order flavour" with non-standard semantics
  - Difficult to provide **reasoning support**

From RDFS to OWL

- Two languages developed to address deficiencies & problems of RDFS:
  - **OIL**: developed by group of (largely) European researchers
  - **DAML-ONT**: developed by group of (largely) US researchers
- Efforts merged to produce **DAML+OIL**
  - Development carried out by “Joint EU/US Committee on Agent Markup Languages”
- DAML+OIL submitted to W3C as basis for standardisation
  - Web-Ontology (**WebOnt**) Working Group formed
  - WebOnt developed **OWL** language based on DAML+OIL
  - OWL now a W3C **recommendation** (i.e., a standard)
- OIL, DAML+OIL and OWL based on **Description Logics**
  - OWL is effectively a “Web-friendly” syntax for **SHOIN**



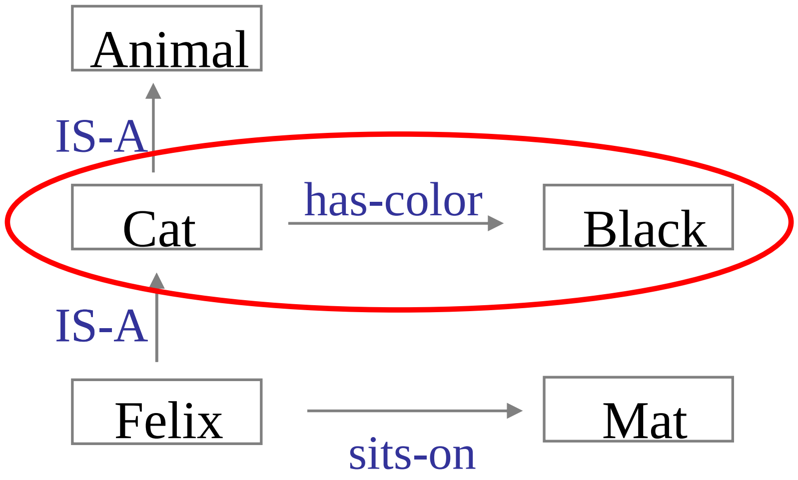
What Are Description Logics?

- A family of logic based Knowledge Representation formalisms
  - Descendants of **semantic networks** and **KL-ONE**
  - Describe domain in terms of **concepts** (classes), **roles** (properties, relationships) and **individuals**
  - **Operators** allow for composition of complex concepts
  - **Names** can be given to complex concepts, e.g.:

HappyParent ´ Parent u 8hasChild.(Intelligent t Athletic)

Semantics and Reasoning

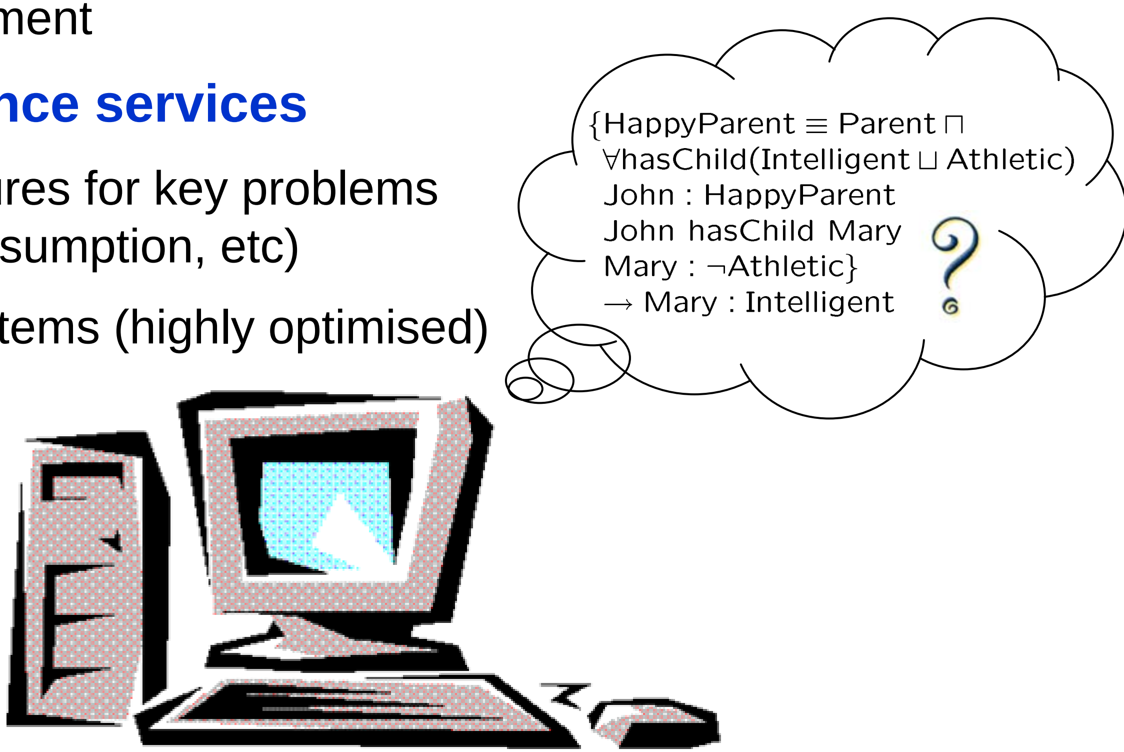
- Distinguished by:
  - **Formal semantics** (typically model theoretic)
    - Decidable fragments of FOL (often contained in C_2)
    - Closely related to Propositional Modal & Dynamic Logics, and to Guarded Fragment



[Quillian, 1967]

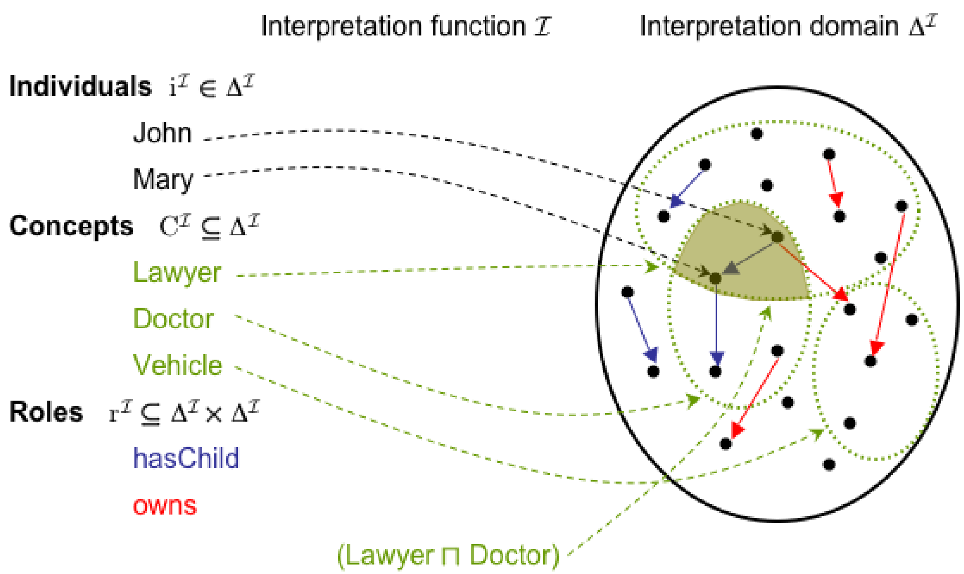
Semantics and Reasoning

- Distinguished by:
  - **Formal semantics** (typically model theoretic)
    - Decidable fragments of FOL (often contained in C_2)
    - Closely related to Propositional Modal & Dynamic Logics, and to Guarded Fragment
  - Provision of **inference services**
    - Decision procedures for key problems (satisfiability, subsumption, etc)
    - Implemented systems (highly optimised)



Why Description Logic?

- OWL exploits results of 15+ years of DL research
  - Well defined (model theoretic) **semantics**



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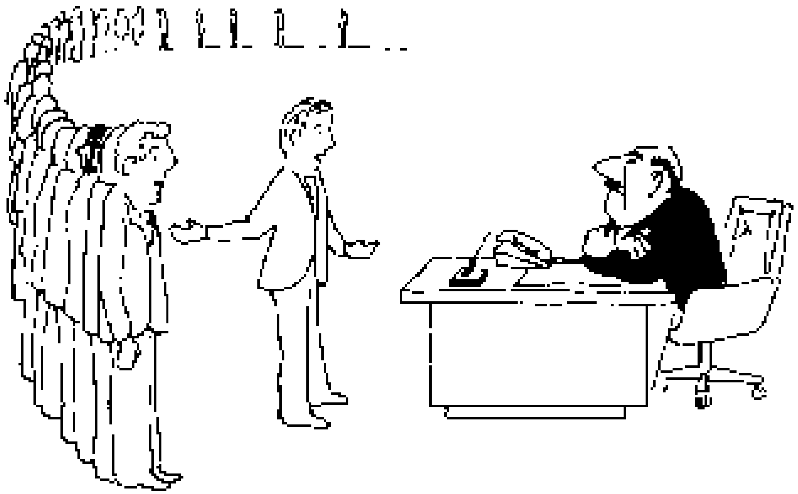
  - **Formal properties** well understood (complexity, decidability)



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.]

Why Description Logic?

- OWL exploits results of 15+ years of DL research
  - Well defined (model theoretic) **semantics**
  - **Formal properties** well understood (complexity, decidability)
  - 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 $\mathcal{L}(v) \to \mathcal{L}(v) \cup \{C_1, C_2\}$.
$\sqcup$-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 $\mathcal{L}(v) \to \mathcal{L}(v) \cup \{E\}$ 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 $\mathcal{L}(v_2) \to \mathcal{L}(v_2) \cup \{C\}$.
$\forall_+$-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 $\mathsf{Trans}(r')$ and $r' \sqsubseteq\!\!\!* \, r$ 3. there is an r'-neighbour v_2 of v_1 with $\forall r'.C \notin \mathcal{L}(v_2)$ then $\mathcal{L}(v_2) \to \mathcal{L}(v_2) \cup \{\forall r'.C\}$.
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 $\mathcal{L}(v_2) \to \mathcal{L}(v_2) \cup \{E\}$ 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 $1 \leqslant i < j \leqslant n$

Why Description Logic?

- OWL exploits results of 15+ years of DL research
  - Well defined (model theoretic) **semantics**
  - **Formal properties** well understood (complexity, decidability)
  - Known **reasoning** **algorithms**
  - **Implemented systems** (highly optimised)

Cerebra® FaCT++

Racer MINDSWAP Pellet

Why Description Logic?

- Foundational research was **crucial** to design of OWL
  - Informed Working Group decisions at every stage, e.g.:
    - "Why not extend the language with feature **x**, which is clearly harmless?"

    - "Adding **x** would lead to undecidability - see proof in […]"

Why the Strange Names?

- Description Logics are a **family** of KR formalisms
  - Mainly distinguished by available operators
- **Available operators** indicated by letters in name, e.g.,
  - **S** : basic DL (ALC) plus transitive roles (e.g., ancestor $\in R_+$)
  - **H** : role hierarchy (e.g., hasDaughter **v** hasChild)
  - **O** : nominals/singleton classes (e.g., {Italy})
  - **I** : inverse roles (e.g., isChildOf ´ hasChild⁻)
  - **N** : number restrictions (e.g., **>**2hasChild, **6**3hasChild)
- Basic DL + role hierarchy + nominals + inverse + NR = **SHOIN**
  - SHOIN is the basis for W3C's **OWL** Web Ontology Language
- SHOIN is very expressive, but still decidable (just)

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Class/Concept Constructors

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	$\exists^{\geqslant n} y.P(x,y)$

C is a concept (class); P is a role (property); x is an individual name

Knowledge Base / Ontology

- A TBox is a set of "schema" axioms (sentences), e.g.:

> {Parent v Person u >1hasChild,
> HappyParent ´ Parent u 8hasChild.(Intelligent t Athletic)}

- An ABox is a set of "data" axioms (ground facts), e.g.:

> {John:HappyParent,
> John hasChild Mary}

- An OWL ontology is just a **SHOIN** KB

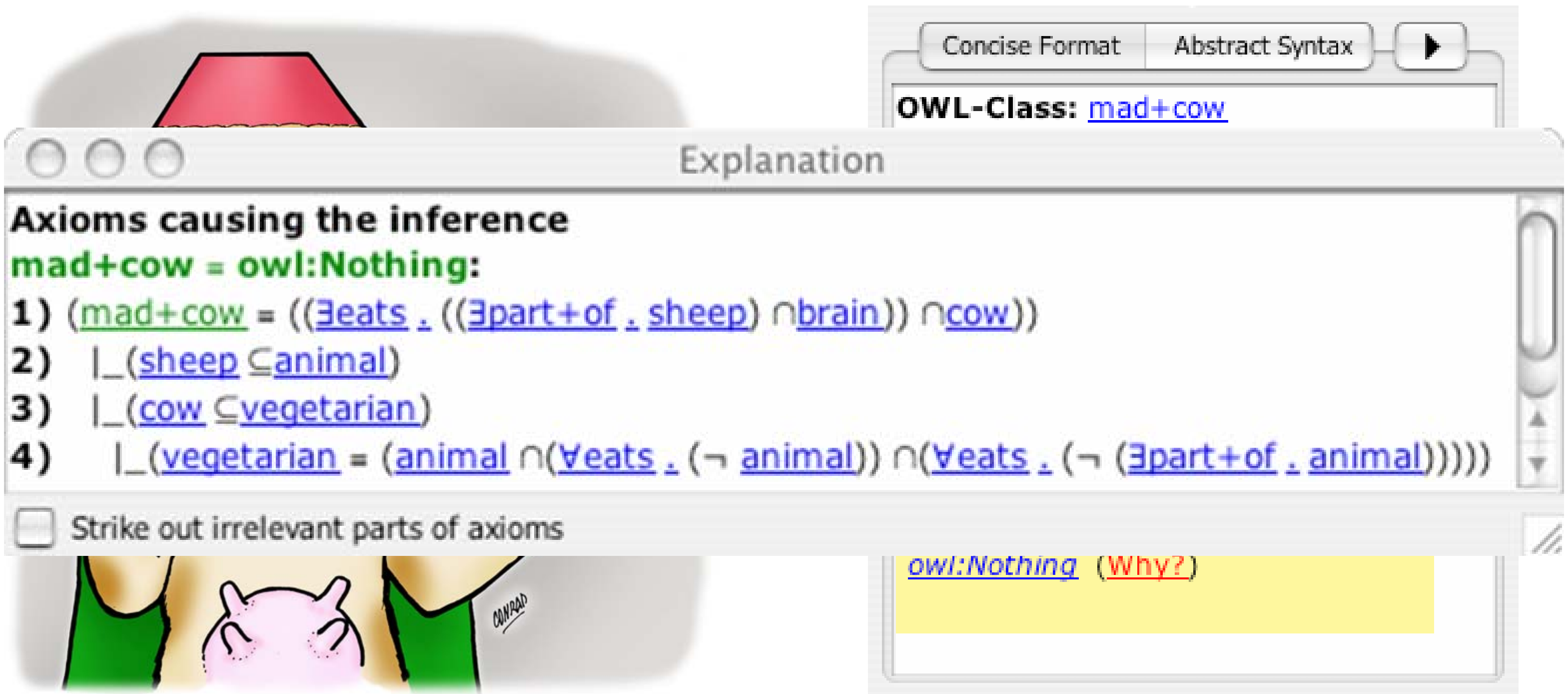
OWL RDF/XML Exchange Syntax

E.g., Parent u 8hasChild.(Intelligent t Athletic):

```
<owl:Class>
  <owl:intersectionOf rdf:parseType=" collection">
    <owl:Class rdf:about="#Parent"/>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#hasChild"/>
      <owl:allValuesFrom>
        <owl:unionOf rdf:parseType=" collection">
          <owl:Class rdf:about="#Intelligent"/>
          <owl:Class rdf:about="#Athletic"/>
        </owl:unionOf>
      </owl:allValuesFrom>
    </owl:Restriction>
  </owl:intersectionOf>
</owl:Class>
```

Why Ontology Reasoning?

- Given key role of ontologies in many applications, it is essential to provide **tools** and **services** to help users:
  - Design and maintain high quality ontologies, e.g.:
    - **Meaningful** — all named classes can have instances



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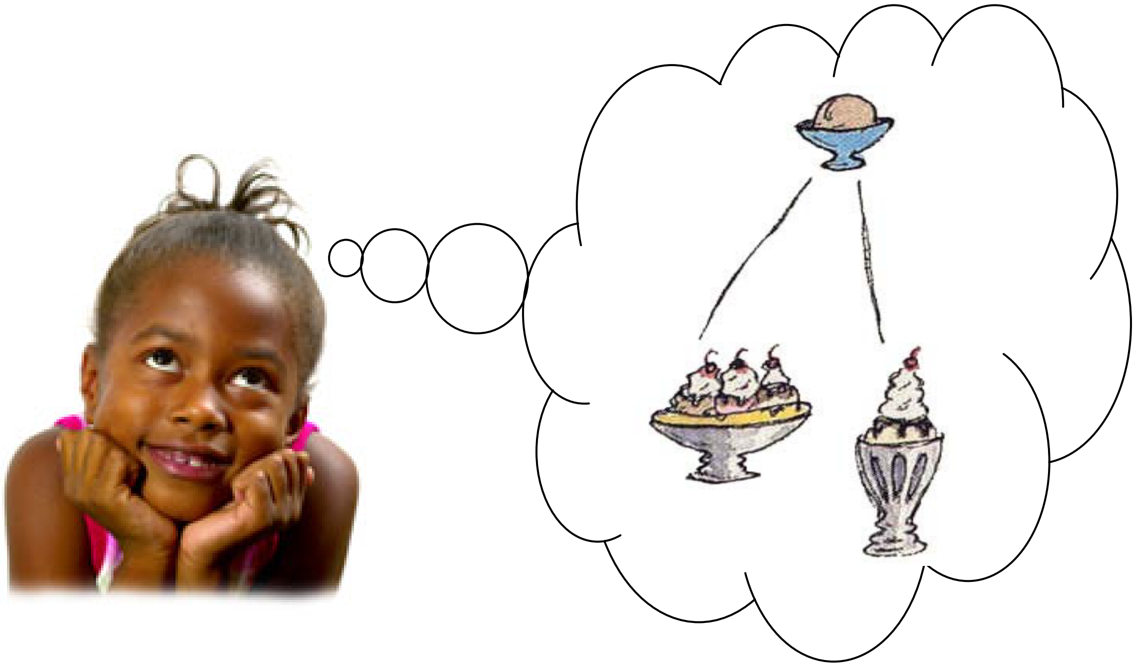

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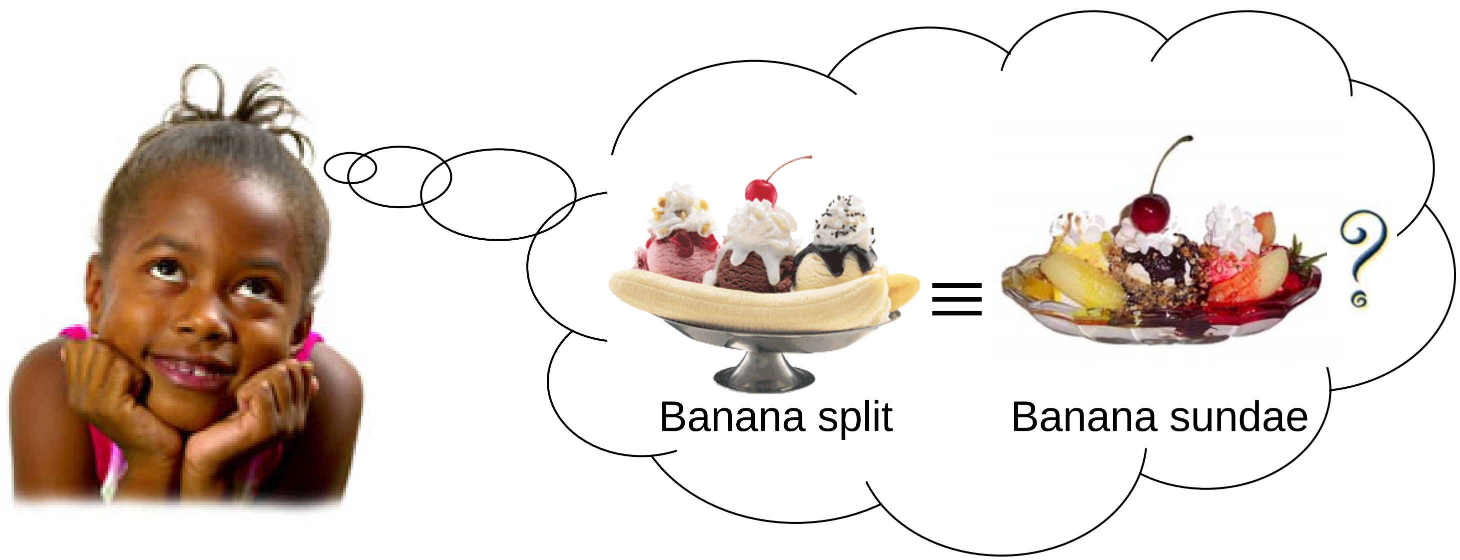

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    - **Correct** — captures intuitions of domain experts
    - **Minimally redundant** — no unintended synonyms
  - Answer **queries** over ontology classes and instances, e.g.:
    - Find more general/specific classes
    - Retrieve individuals/tuples matching a given query

Research Challenges

Increasing Expressive Power

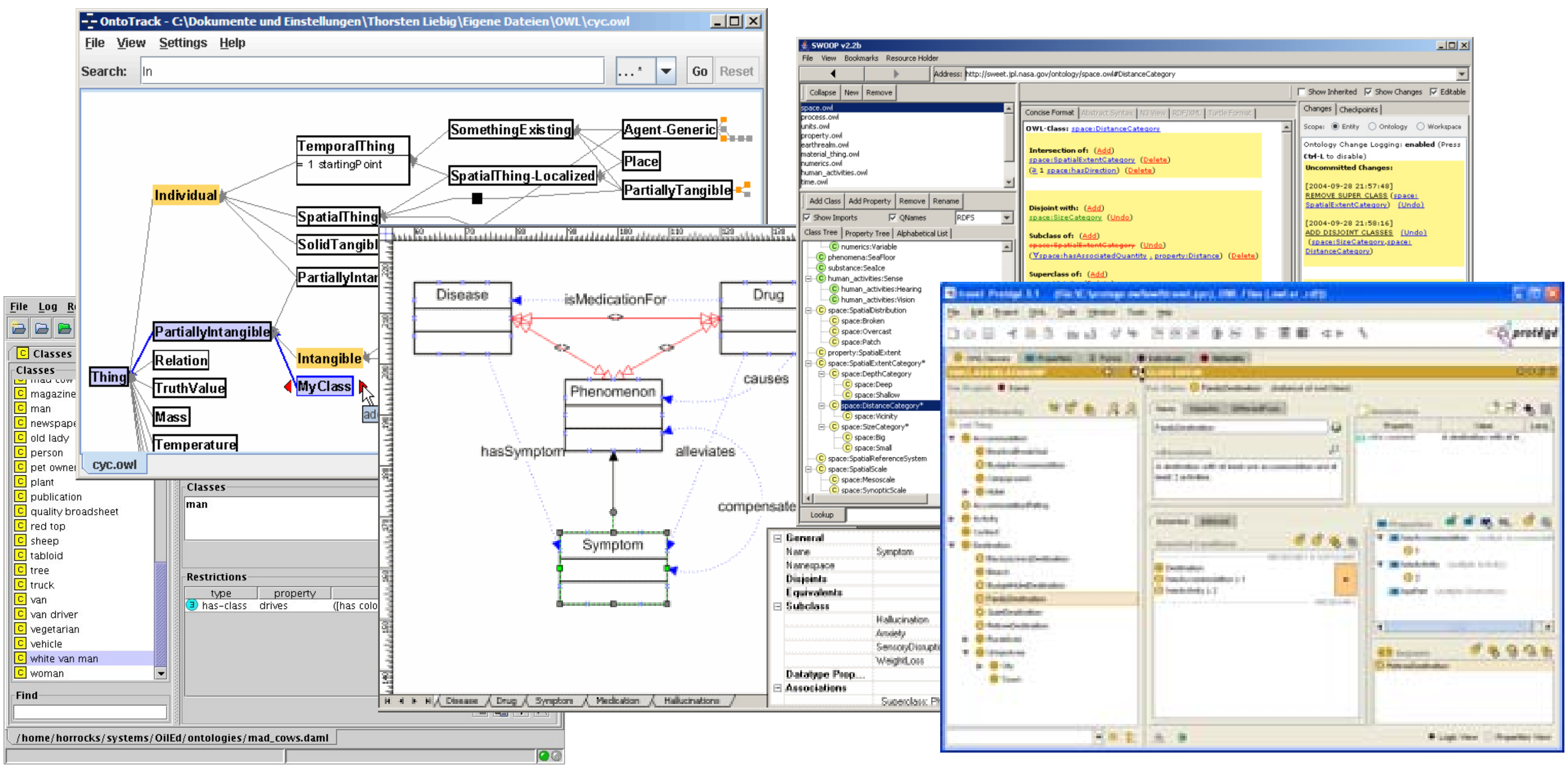
- **Complex role inclusion axioms** [Horrocks&Sattler, IJCAI-03]
  - E.g., hasLocation ± partOf **v** hasLocation
- **Concrete domains**/datatypes, e.g., [Lutz, IJCAI-99; Pan et al, ISWC-03]
  - E.g., value comparison (income > expenditure)
- **Database style keys** [Lutz et al, JAIR 2004]
  - E.g., make + model + chassis-number is a key for Vehicles
- **Rule language extensions**
  - First order extensions (e.g., SWRL) [Horrocks et al, JWS, 2005]
  - Hybrid language extensions, e.g., [Eiter et al, KR-04; Motik et al, ISWC-04]
  - LP/F-Logic/Common Logic [Chen et al, JLP, 1993; de Bruijn et al, WWW-05]

Improving Scalability

- **Optimisation techniques**
  - Improve performance of DL reasoners, e.g., [Sirin et al, KR-06]
- **Reduction to disjunctive Datalog** [Motik et at, KR-04]
  - Transform DL ontology to Datalogç rules
  - Use LP techniques to deal with large numbers of ground facts
- **Hybrid DL-DB systems** [Horrocks et al, CADE-05]
  - Use DB to store “Abox” (individual) axioms
  - Cache inferences and use DB queries to answer/scope logical queries
- **Polynomial time algorithms** for sub-ALC logics [Baader et al, IJCAI-05]
  - Graph based techniques for subsumption computation

Tools and Infrastructure

- Editors/environments
  - Oiled, Protégé, Swoop, Construct, Ontotrack, …



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- **Non-standard inferences**
  - Explanation, matching, least common subsumer, …

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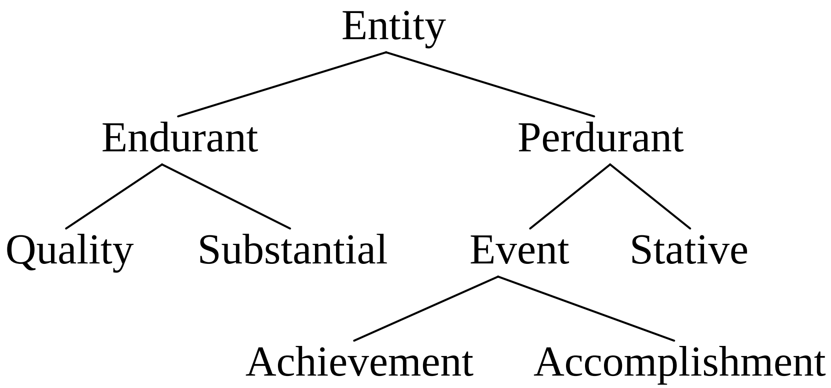
- **Non-standard inferences**
  - Explanation, matching, least common subsumer, …
- **Design methodologies**
  - Foundational ontologies, modularisation, etc.



Summary

- **Semantic Web** aims to make web content more accessible to automated processes
  - Adds semantic annotations to web resources
- **Ontologies** provide vocabulary for annotations
  - Terms have well defined meaning
- **OWL** ontology language based on (description) logic
  - Exploits results of basic research on complexity, reasoning, etc.
- Many **research challenges** remain
  - Including expressive power, scalability and tools

Acknowledgements

Thanks to my many friends in the DL and Semantic Web communities, in particular:

- Alan Rector
- Franz Baader
- Uli Sattler

Resources

- FaCT++ system (open source)
  - http://owl.man.ac.uk/factplusplus/
- Protégé
  - http://protege.stanford.edu/plugins/owl/
- W3C Web-Ontology (WebOnt) working group (OWL)
  - http://www.w3.org/2001/sw/WebOnt/
- DL Handbook, Cambridge University Press
  - http://books.cambridge.org/0521781760.htm


Thank you for listening
Any questions?
DL & KR, Windermere, 30th May – 5th June