Ontologies and the Semantic Web

The Story So Far

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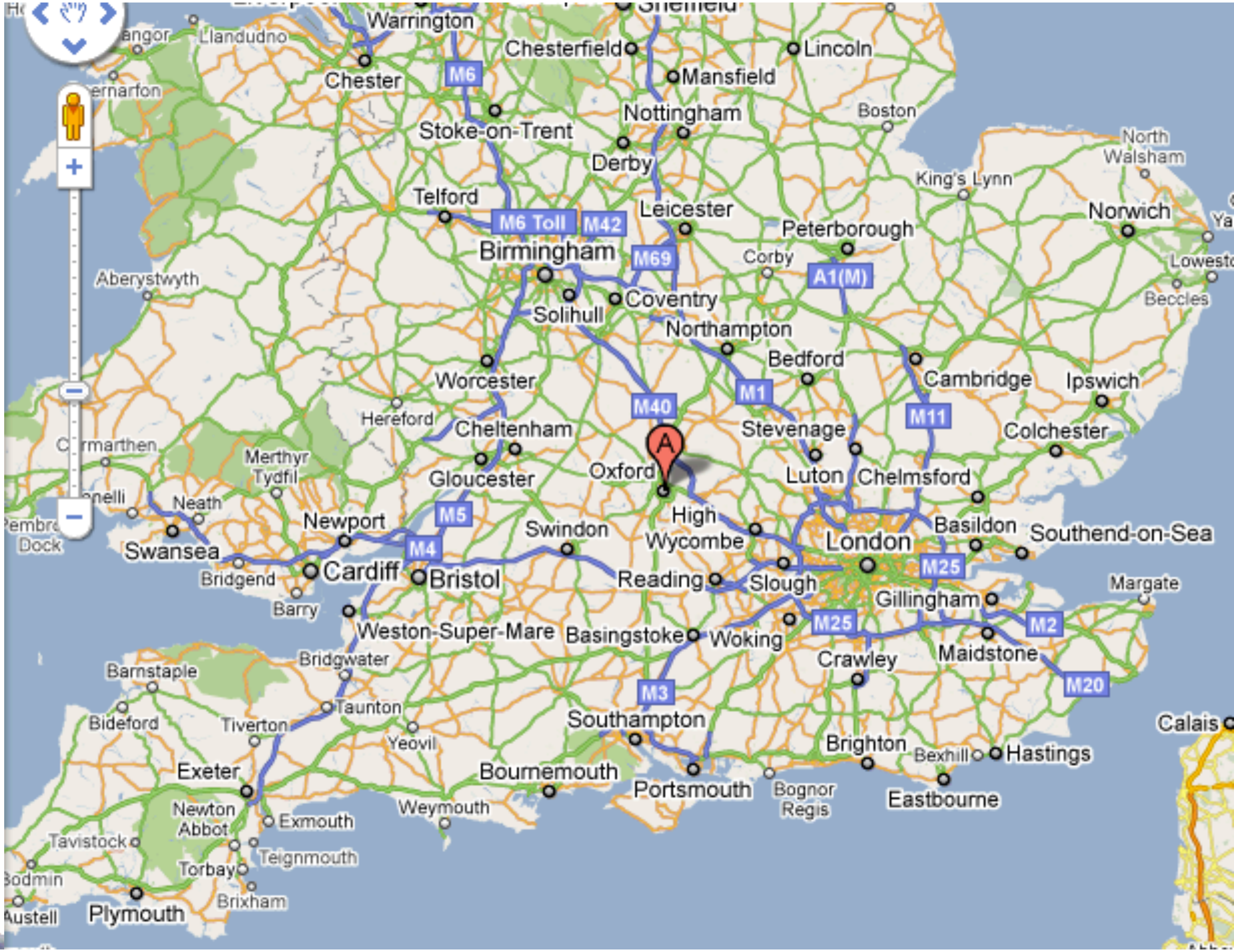
Information Systems Group
Oxford University Computing Laboratory

but first ...

University of Oxford



University of Oxford

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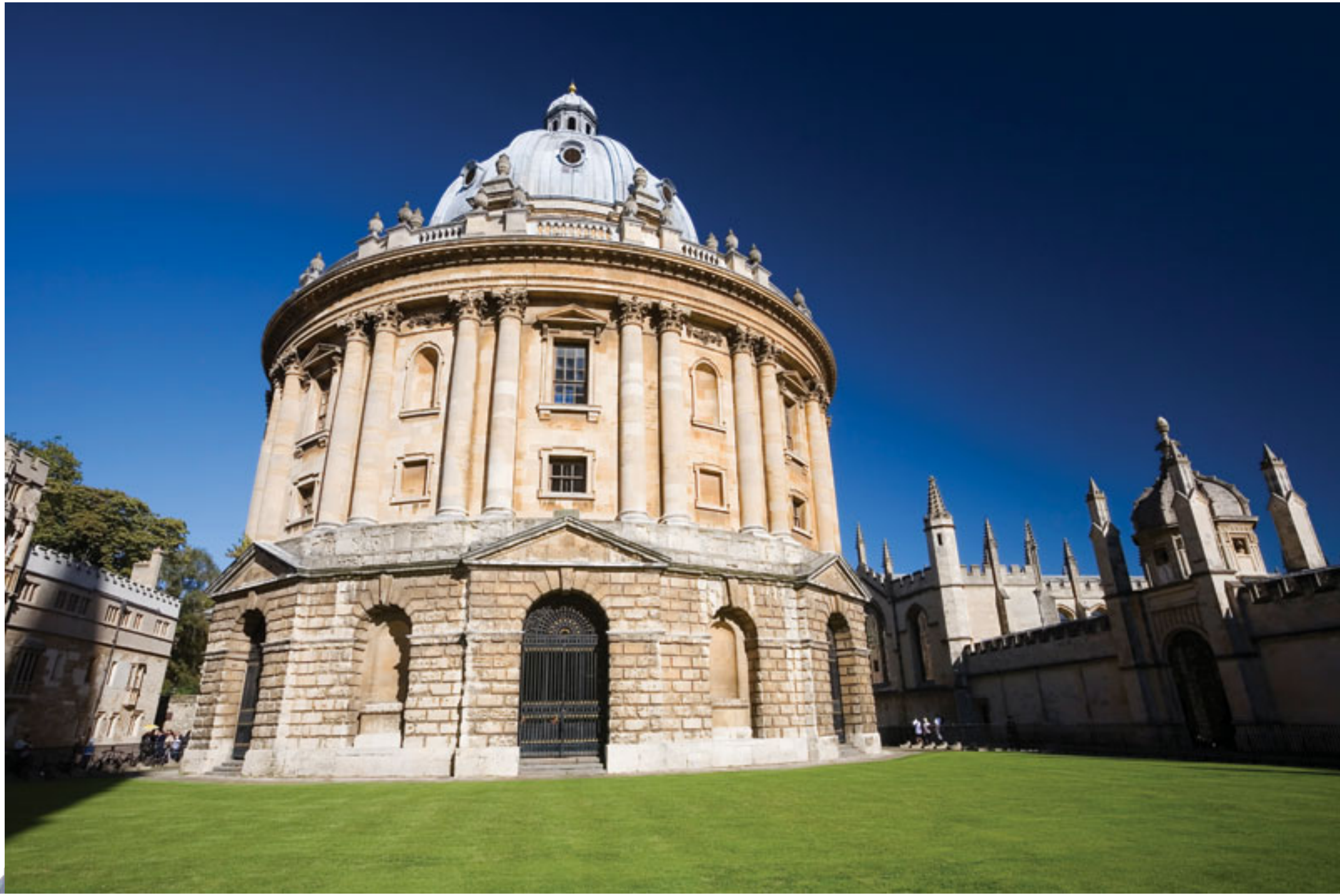

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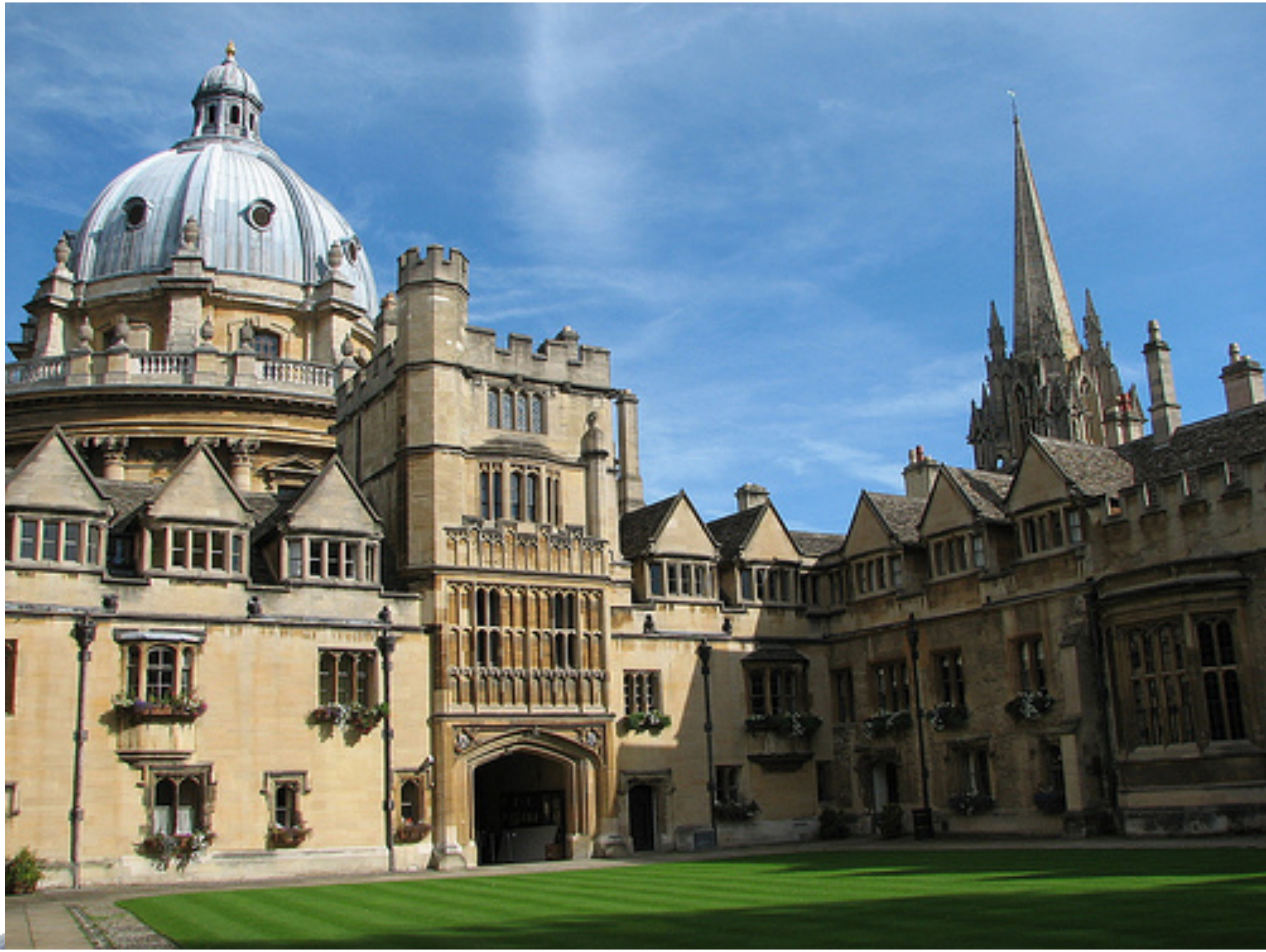

University of Oxford

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Computing Laboratory

Research Groups

Theory and Automated Verification
Foundations; semantics; concurrency and security; computer-aided reasoning

Program Development and Tools
Programming tools; algebra of programming

Applications and Algorithms
Algorithms; computational biology; computational linguistics; constraints; machine learning; spatial reasoning

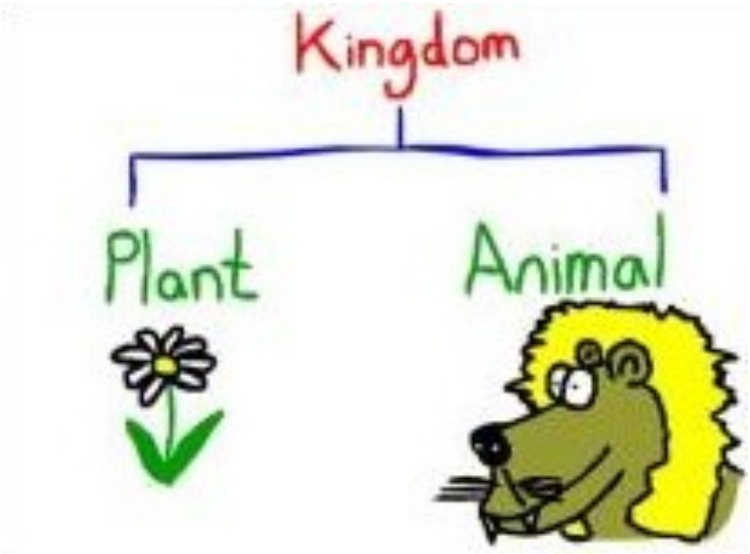
Software Engineering
Software engineering; requirements analysis; security; eScience and Grid computing

Numerical Analysis
Numerical solution of partial differential equations; numerical linear algebra; optimisation

Information Systems
Databases, knowledge representation and reasoning, computational linguistics

oerc
Oxford e-Research Centre

Knowledge Representation and Reasoning (sub-) Group



Who are we?

- Faculty
  - Ian Horrocks
  - Boris Motik
- DPhil Students
  - Héctor Pérez-Urbina
  - Rob Shearer
  - Frantisek Simancik
  - Despoina Magka
- Research Staff
  - Bernardo Cuenca Grau
  - Birte Glimm
  - Yevgeny Kazakov
  - Rob Shearer
  - Giorgos Stoilos
  - Mikalai Yatskevich

What Do We Do?

- Knowledge representation (obviously)
- Semantic Web
- Ontologies and ontology languages
- Description logics
- Reasoning problems and algorithms
- Implementation and optimisation of reasoning systems
- Ontology based information systems

Currently Funded Projects

- LOGO: Logic for Ontologies (EPSRC)
- RInO: Reasoning Infrastructure for Ontologies (EPSRC)
- HermiT: Reasoning with Large Ontologies (EPSRC)
- ConDOR: Consequence Driven Ontology Reasoning (EPSRC)
- SEALS: Developing and Testing Ontology Infrastructure (EU)
- Privacy in Ontology Information Systems (Royal Society)

The 9th International Semantic Web Conference
Shanghai International Convention Center, Shanghai, China
Nov 7th -11th, 2010
http://iswc2010.semanticweb.org
ISWC 2010
Semantics for a Better Web!
General Chair
Ian Horrocks
Program Chairs
Peter F. Patel-Schneider
Yue Pan
Local Chair
Yong Yu
Workshop & Tutorial Chairs
Philippe Cudré-Mauroux
Bijan Parsia
Poster & Demo Chairs
Huajun Chen
Axel Polleres
Industry & Semantic Web in Use Chairs
Pascal Hitzler
Peter Mika
Doctoral Consortium Chair
Jeff Pan
Semantic Web Challenge Chairs
Chris Bizer
Diana Maynard
Publicity Chair
Sebastian Rudolph
Metadata Chair
Jie Bao
Proceedings Chair
Birte Glimm
Sponsor Chairs
Kendall Clark
Anand Ranganathan
Local Organization
Dingyi Han
Gui-Rong Xue
Haofen Wang
Lei Zhang
EXPO
SHANGHAI CHINA
Stunning Venue
Great Time
Fascinating City
Excellent Food
SWSA
Semantic Web Science Association
上海交通大學
SHANGHAI JIAO TONG UNIVERSITY
IBM
Research

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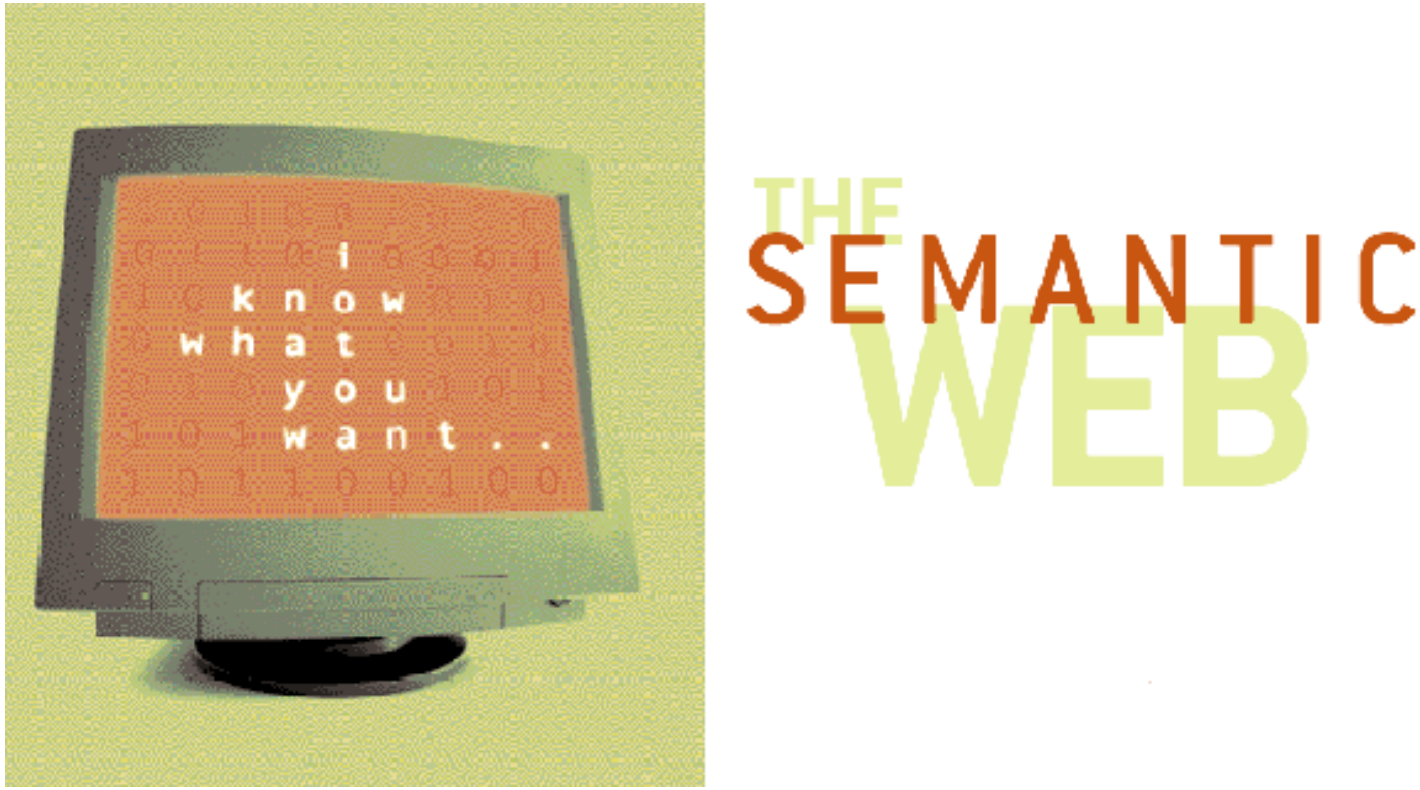
Semantic Web



Semantic Web

- According to **W3C**
  - "an evolving extension of the World Wide Web in which web content can be … read and used by software agents, thus permitting them to find, share and integrate information more easily"
- Data will use uniform syntactic structure (**RDF**)
- **Ontologies** will provide
  - Schemas for data
  - Vocabulary for annotations
- Ultimate goal is to transform web into a platform for distributed applications and sharing (linking) of data

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A model of (some aspect of) the world

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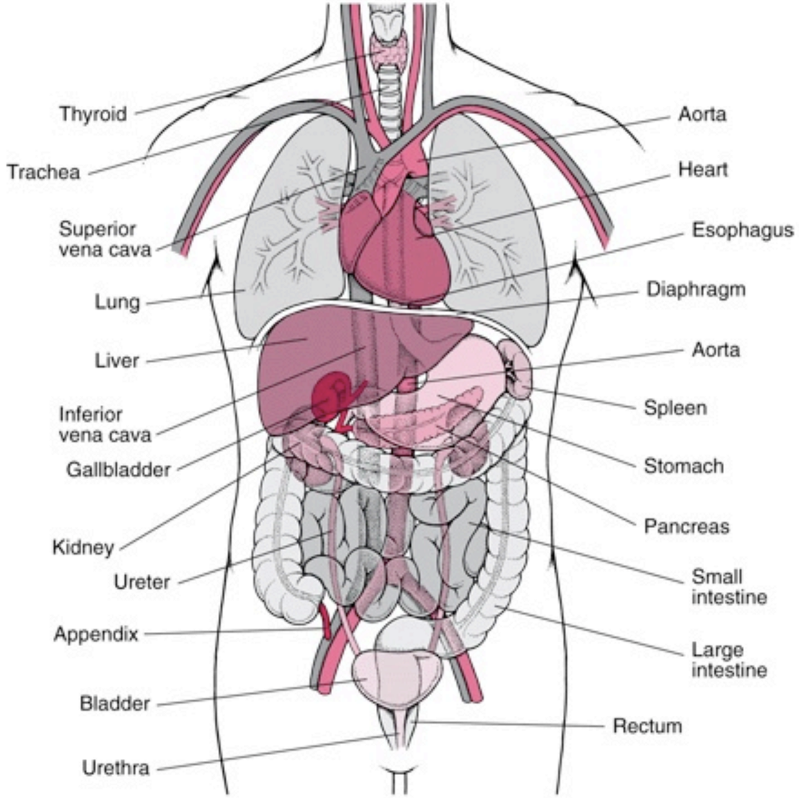
  - Anatomy



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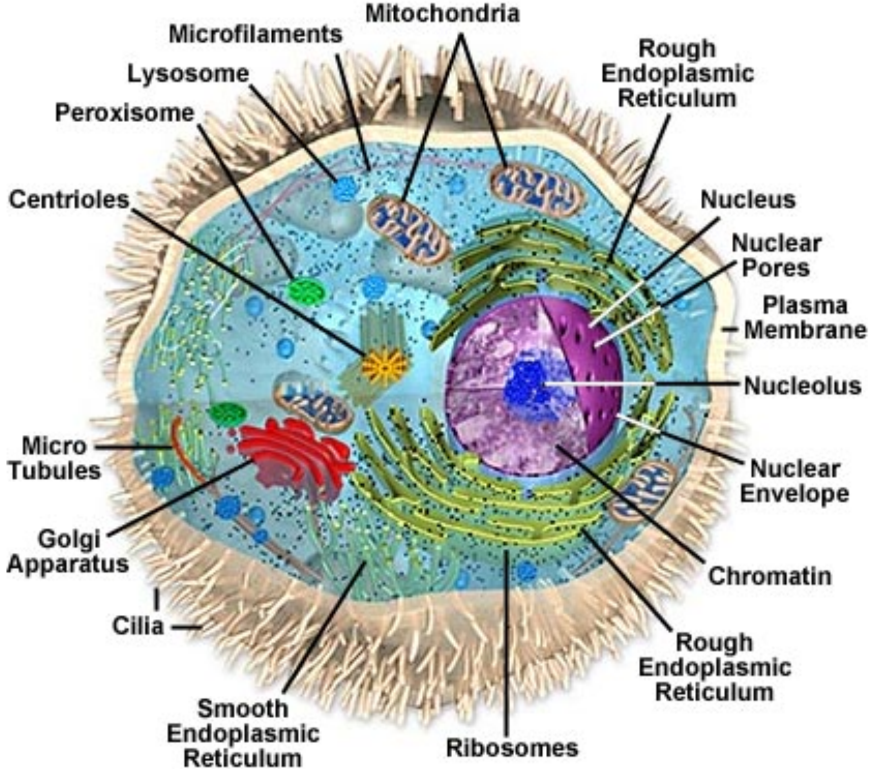
  - Cellular biology



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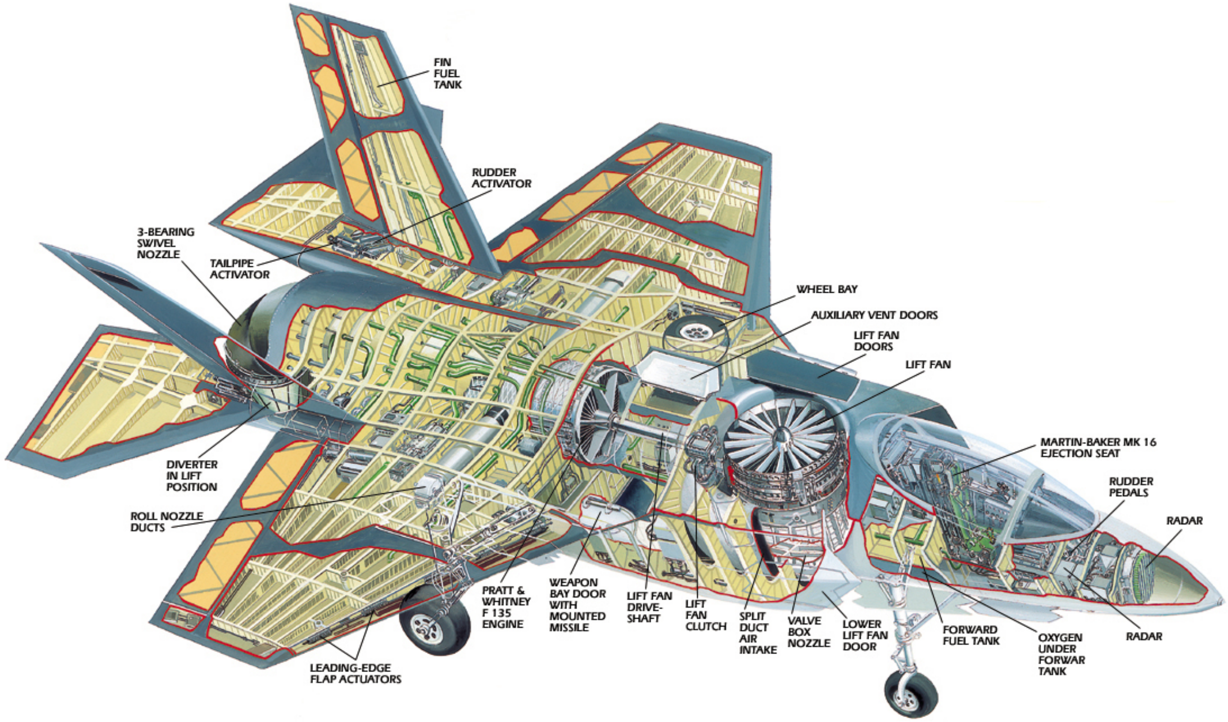

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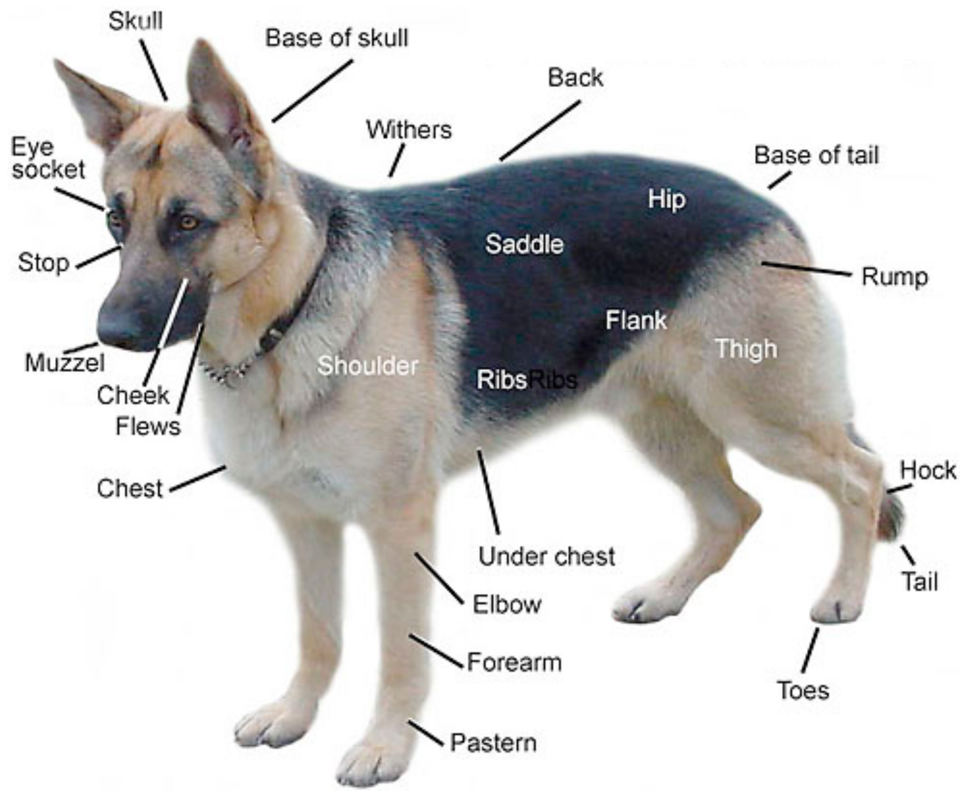

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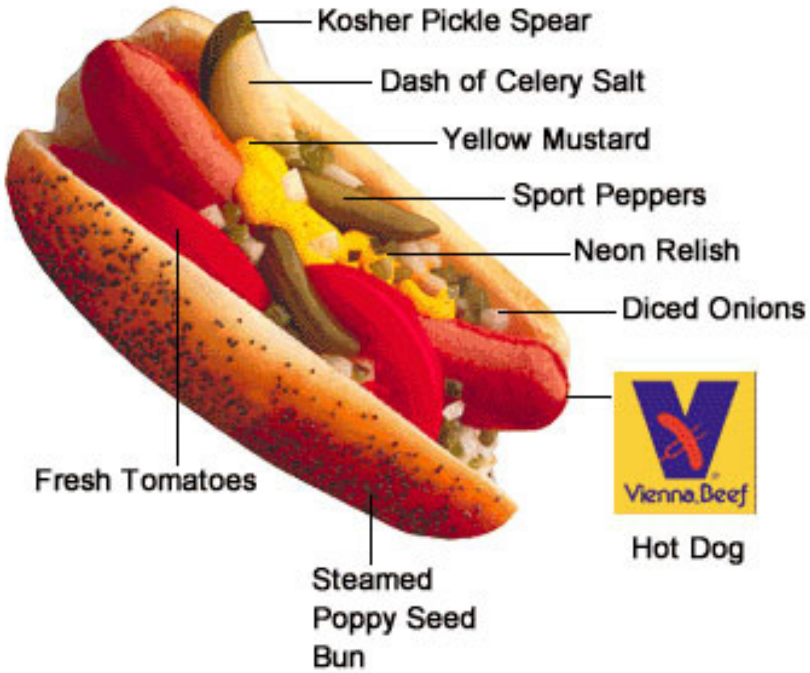
  - Aerospace
  - Dogs
  - Hotdogs
  - …



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- Introduces **vocabulary** relevant to domain
- Specifies **meaning** (semantics) of terms

Heart is a muscular organ that
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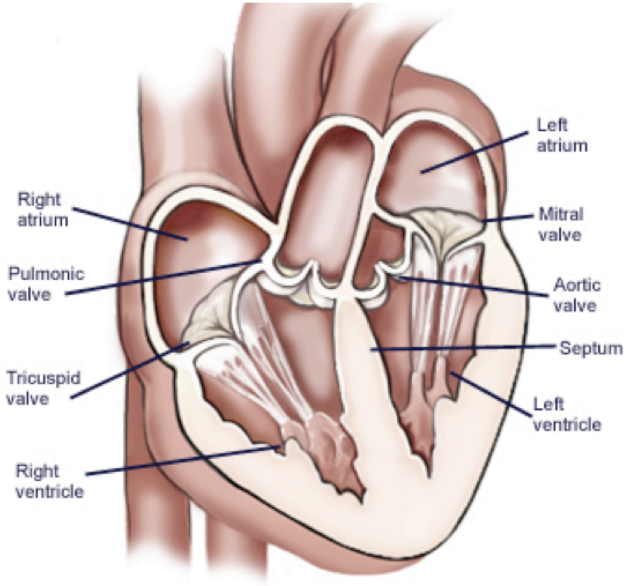

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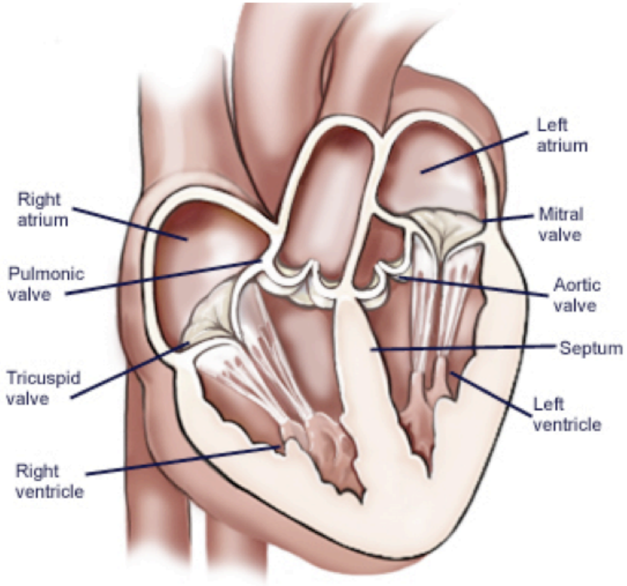
- **Formalised** using suitable logic

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



Web Ontology Language OWL (2)

- W3C **recommendation(s)**
- Motivated by **Semantic Web** activity

  Requirement for standardised
  "web ontology language"

- Supported by **tools and infrastructure**
  - APIs (e.g., OWL API, Thea, OWLink)
  - Development environments
    (e.g., Protégé, Swoop, TopBraid Composer, Neon)
  - Reasoners & Information Systems
    (e.g., Pellet, Racer, HermiT, Quonto, …)
- Based on **Description Logics** ($\mathcal{SHOIN}$ / $\mathcal{SROIQ}$)

Description Logics (DLs)

- Fragments of **first order logic** designed for KR
- Desirable 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)

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

Why Care About Semantics?

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Well, from a philosophical POV, we need to specify the relationship between statements in the logic and the existential phenomena they describe.

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That's OK, but I don't get paid for philosophy.

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Well, from a philosophical POV, we need to specify the relationship between statements in the logic and the existential phenomena they describe.

That's OK, but I don't get paid for philosophy.

From a practical POV, in order to specify and test (ontology-based) information systems we need to precisely define their intended behaviour

What are Ontologies Good For?

- Coherent **user-centric view** of domain
  - Help identify and resolve disagreements
- Ontology-based **Information Systems**
  - View of data that is independent of logical/ physical schema
  - Answers reflect schema & data, e.g.:

    “Patients suffering from Vascular Disease”

Now... *that* should clear up a few things around here

What are Ontologies Good For?

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  - View of data that is independent of logical/ physical schema
  - Answers reflect schema & data, e.g.:

    "Patients suffering from Vascular Disease"
  - Query expansion/navigation/refinement
  - Incomplete and semi-structured data
  - Integration of heterogeneous sources

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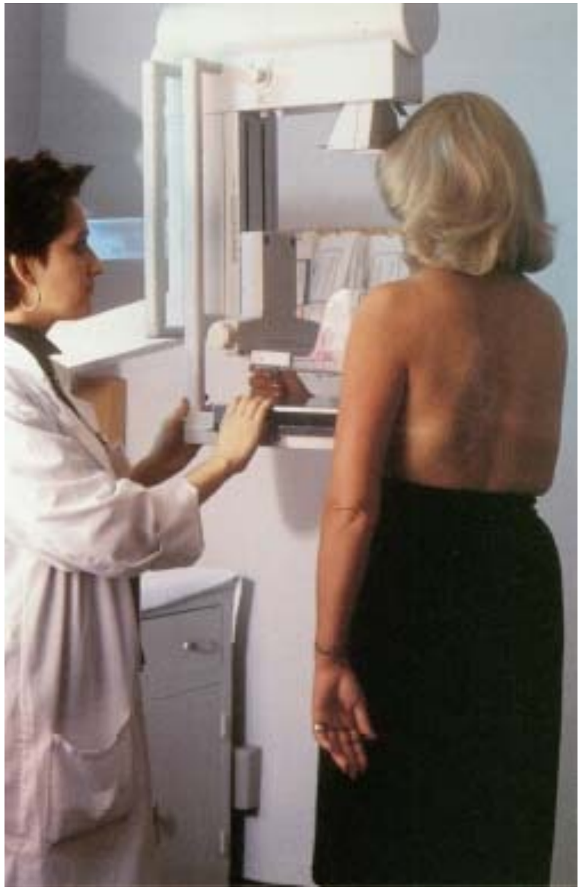
Information-Based Decisions

Increasingly critical in many areas:

- In Healthcare industry, e.g., selecting patients for screening
  - Too much screening harms patients and wastes money
  - Too little screening costs lives



Information-Based Decisions

Increasingly critical in many areas:

- In Oil and Gas industry, e.g., selecting production parameters
  - Better quality information could add €1B/year net value to Statoil production
  - Poorer quality information and analysis costs €6M/weekend!

Information-Based Decisions

Increasingly critical in many areas:

- In IT industry, e.g., facilitating tech support
  - SAP deals with 80,000 queries/month at a cost of approx. €16M
  - SAP estimate 50% of support staff time spent searching for relevant information

Healthcare

- UK NHS **£10 billion** "Connecting for Health" IT programme
- Key component is **Care Records Service** (CRS)
  - "Live, interactive patient record service accessible 24/7"
  - Patient **data distributed** across local centres in 5 regional clusters, and a national DB
  - **SNOMED-CT** ontology provides common **vocabulary** for data
    - Clinical data uses terms drawn from this ontology
    - The ontology defines more than 400,000 different terms!

What About Scalability?

- Only **useful in practice** if we 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 (aka **profiles**)

Tableau Reasoning Algorithms

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Standard technique based on (hyper-) **tableau**

– Reasoning tasks reducible to (un)**satisfiability**

  - E.g., KB ⊨ HeartDisease ⊑ VascularDisease iff
    KB ∪ {x:(HeartDisease ⊓ ¬VascularDisease)} is *not* satisfiable

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x &: \mathsf{HeartDisease}\\
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x &: \exists\mathsf{affects}.\mathsf{Heart}\\
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\end{aligned}
$$

$$
\begin{aligned}
x &: \neg\mathsf{VascularDisease}\\
x &: \neg\mathsf{Disease} \sqcup\\
&\quad \neg\exists\mathsf{affects}.(\exists\mathsf{isPartOf}.\mathsf{CirculatorySystem})\\
x &: \neg\exists\mathsf{affects}.(\exists\mathsf{isPartOf}.\mathsf{CirculatorySystem})\\
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x : $\exists$affects.Heart
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y : MuscularOrgan
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(y, z) : isPartOf
z : CirculatorySystem

x : $\neg$VascularDisease
x : $\neg$Disease $\sqcup$ $\neg\exists$affects.($\exists$isPartOf.CirculatorySystem)
x : $\neg\exists$affects.($\exists$isPartOf.CirculatorySystem)
x : $\forall$affects.($\forall$isPartOf.$\neg$CirculatorySystem)
y : $\forall$isPartOf.$\neg$CirculatorySystem

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x &: \neg\mathsf{VascularDisease} \\
x &: \neg\mathsf{Disease} \sqcup \\
&\quad \neg\exists \mathsf{affects}.(\exists \mathsf{isPartOf}.\mathsf{CirculatorySystem}) \\
x &: \neg\exists \mathsf{affects}.(\exists \mathsf{isPartOf}.\mathsf{CirculatorySystem}) \\
x &: \forall \mathsf{affects}.(\forall \mathsf{isPartOf}.\neg\mathsf{CirculatorySystem}) \\
y &: \forall \mathsf{isPartOf}.\neg\mathsf{CirculatorySystem} \\
z &: \neg\mathsf{CirculatorySystem}
\end{aligned}
$$

Tableau Reasoning Algorithms

Standard technique based on (hyper-) **tableau**

– Reasoning tasks reducible to (un)**satisfiability**

  • E.g., KB ⊨ HeartDisease ⊑ VascularDisease iff KB ∪ {x:(HeartDisease ⊓ ¬VascularDisease)} is *not* satisfiable

– Algorithm tries to construct (an abstraction of) a model

x : HeartDisease ⊓ ¬VascularDisease
x : HeartDisease
x : Disease
x : ∃affects.Heart
(x, y) : affects
y : Heart
y : MuscularOrgan
y : ∃isPartOf.CirculatorySystem
(y, z) : isPartOf
z : CirculatorySystem

x : ¬VascularDisease
x : ¬Disease ⊔ ¬∃affects.(∃isPartOf.CirculatorySystem)
x : ¬∃affects.(∃isPartOf.CirculatorySystem)
x : ∀affects.(∀isPartOf.¬CirculatorySystem)
y : ∀isPartOf.¬CirculatorySystem
z : ¬CirculatorySystem

Highly Optimised Implementations

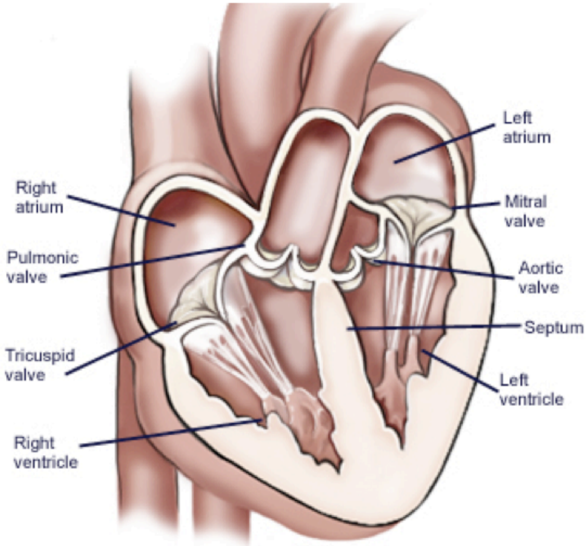
- Lazy unfolding
- Simplification and rewriting,

  e.g., $A \sqcap B \sqsubseteq C \quad \longrightarrow \quad A \sqsubseteq C \sqcup \neg B$
- HyperTableau (reduces non-determinism)
- Fast semi-decision procedures
- Search optimisations
- Reuse of previous computations
- Heuristics

Not computationally optimal,
but effective with many realistic ontologies

Scalability Issues

- Problems with very **large and/or cyclical ontologies**
  - Ontologies may define 10s/100s of thousands of terms
  - Potentially vast number (n^2) of tests needed for classification
  - Each test can lead to construction of *very* large models



$$\mathrm{LeftSide} \sqsubseteq \exists \mathrm{hasComponent}.\mathrm{AorticValve}$$
$$\mathrm{LeftSide} \sqsubseteq \exists \mathrm{hasComponent}.\mathrm{MitralValve}$$
$$\mathrm{AorticValve} \sqsubseteq \exists \mathrm{hasConnection}.\mathrm{LeftVentircle}$$
$$\mathrm{MitralValve} \sqsubseteq \exists \mathrm{hasConnection}.\mathrm{LeftVentircle}$$
$$\mathrm{LeftVentricle} \sqsubseteq \exists \mathrm{isDivisionOf}.\mathrm{LeftSide}$$

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 KB $\models \mathcal{Q}(x)$
  - 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 Profiles

- OWL recommendation now updated to **OWL 2**
- OWL 2 defines several **profiles** – fragments with desirable computational properties
  - **OWL 2 EL** targeted at very large ontologies
  - **OWL 2 QL** targeted at very large data sets

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
- Can exploit **saturation** based reasoning techniques
  - Computes complete classification in “one pass”
  - Computationally optimal (PTime for EL)
  - Can be extended to Horn fragment of OWL DL

Saturation-based Technique (basics)

- Normalise ontology axioms to standard form:

$$A \sqsubseteq B \quad A \sqcap B \sqsubseteq C \quad A \sqsubseteq \exists R.B \quad \exists R.B \sqsubseteq C$$

- Saturate using inference rules:

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

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

- Extension to Horn fragment requires (many) more rules

Saturation-based Technique (basics)

Example:

$$\mathsf{OrganTransplant} \equiv \mathsf{Transplant} \sqcap \exists \mathsf{site}.\mathsf{Organ}$$
$$\mathsf{HeartTransplant} \equiv \mathsf{Transplant} \sqcap \exists \mathsf{site}.\mathsf{Heart}$$
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$$\exists \mathsf{site}.\mathsf{Organ} \sqsubseteq \mathsf{SO}$$

$$\mathsf{Transplant} \sqcap \mathsf{SO} \sqsubseteq \mathsf{OrganTransplant}$$

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Saturation-based Technique

Performance with large bio-medical ontologies:

	GO	NCI	Galen v.0	Galen v.7	SNOMED
Concepts:	20465	27652	2748	23136	389472
FaCT++	15.24	6.05	465.35	—	650.37
HermiT	199.52	169.47	45.72	—	—
Pellet	72.02	26.47	—	—	—
CEL	1.84	5.76	—	—	1185.70
CB	1.17	3.57	0.32	9.58	49.44
Speed-Up:	1.57X	1.61X	143X	∞	13.15X

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
- Can exploit **query rewriting** based reasoning technique
  - Computationally optimal
  - Data storage and query evaluation can be delegated to standard RDBMS
  - Can be extended to more expressive languages (beyond AC^0) by delegating query answering to a Datalog engine

Query Rewriting Technique (basics)

- Given ontology $\mathcal{O}$ and query $\mathcal{Q}$, use $\mathcal{O}$ to rewrite $\mathcal{Q}$ as $\mathcal{Q}'$ s.t., for any set of ground facts $\mathcal{A}$:
  - ans($\mathcal{Q}$, $\mathcal{O}$, $\mathcal{A}$) = ans($\mathcal{Q}'$, $\emptyset$, $\mathcal{A}$)

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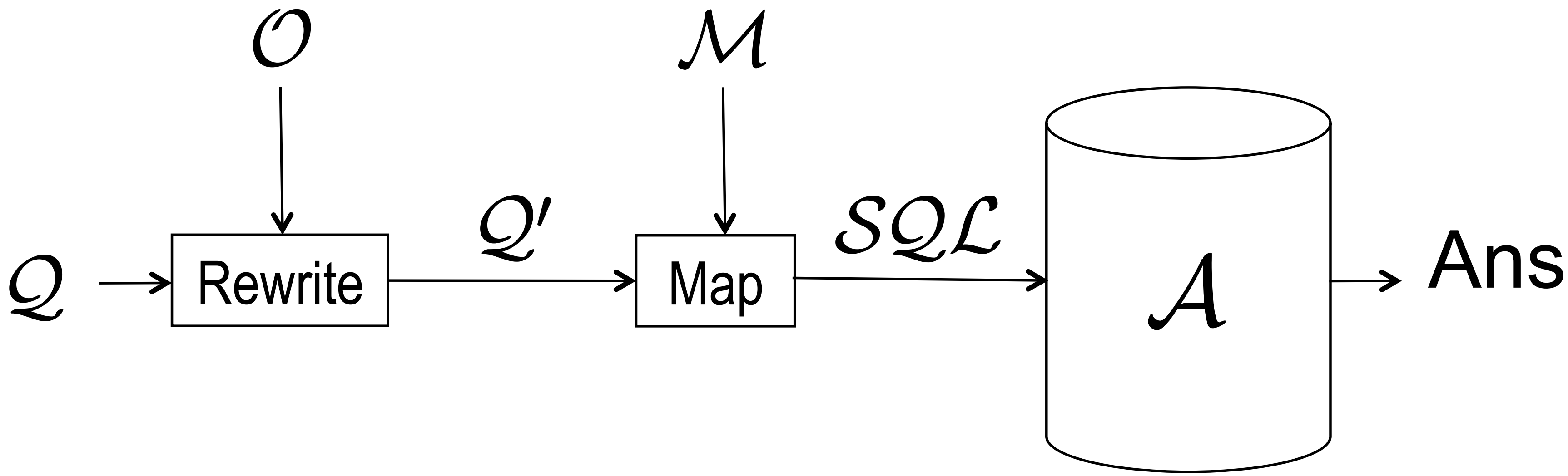

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- Use (GAV) mapping $\mathcal{M}$ to map $\mathcal{Q}'$ to SQL query
- Resolution based query rewriting
  - **Clausify** ontology axioms
  - **Saturate** (clausified) ontology and query using resolution
  - **Prune** redundant query clauses

Query Rewriting Technique (basics)

- Example:

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

$$\mathsf{Consultant} \sqsubseteq \mathsf{Doctor}$$

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

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$$Q(x) \leftarrow \text{Doctor}(x)$$

$$Q(x) \leftarrow \text{Consultant}(x)$$

- For DL-Lite, result is a union of conjunctive queries

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

Query Rewriting Technique (basics)

- Data can be stored/left in **RDBMS**
- Relationship between ontology and DB defined by **mappings**, e.g.:

Doctor	$\mapsto$	SELECT Name FROM Doctor
Patient	$\mapsto$	SELECT Name FROM Patient
treats	$\mapsto$	SELECT DName, PName FROM Treats

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$$\begin{aligned} \text{Doctor} &\mapsto \text{SELECT Name FROM Doctor} \\ \text{Patient} &\mapsto \text{SELECT Name FROM Patient} \\ \text{treats} &\mapsto \text{SELECT DName, PName FROM Treats} \end{aligned}$$

- UCQ translated into **SQL query**:

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

$$\Downarrow$$

SELECT Name FROM Doctor UNION
SELECT DName FROM Treats, Patient WHERE PName=Name

Problems & Research Challenges

- Combining best features of DLs & DBs
  - In particular, integrating OWA and CWA
- Hard to find a coherent semantic framework
  - Problems mainly due to existential quantifiers: should existentially implied objects be considered different?
    - Does a person owning a phone and an ipod own 2 things?
    - Does a person owning a phone and an iphone own 2 things?
    - Does a person owning a phone and a phone own 2 things?
- Interesting ideas emerging in DL & DB communities, e.g.:
  - *Calì et al. Datalog±: a unified approach to ontologies and integrity constraints. ICDT 2009.*
  - *Motik et al. Bridging the gap between OWL and relational databases. WWW 2007.*

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    - Not clear if this will be a problem in practice, see, e.g., *Savo et al. MASTRO at Work: Experiences on Ontology-based Data Access. DL 2010.*

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  - Larger fragments require (at least) Datalog engines and/or extension to technique (e.g., partial materialisation)
    - Promising new work in this area, see, e.g., *Lutz et al. Conjunctive Query Answering in the Description Logic EL Using a Relational Database System. IJCAI 2009.*

Problems & Research Challenges

- Infrastructure

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  - Standardised query language
    - SPARQL standard for RDF
    - Currently being extended for OWL, see *http://www.w3.org/2009/sparql/wiki/Main_Page*

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  - ...

Thanks To

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- Yevgeny Kazakov
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- Rob Shearer
- Bernardo Cuenca Grau
- Birte Glimm






Thank you for listening

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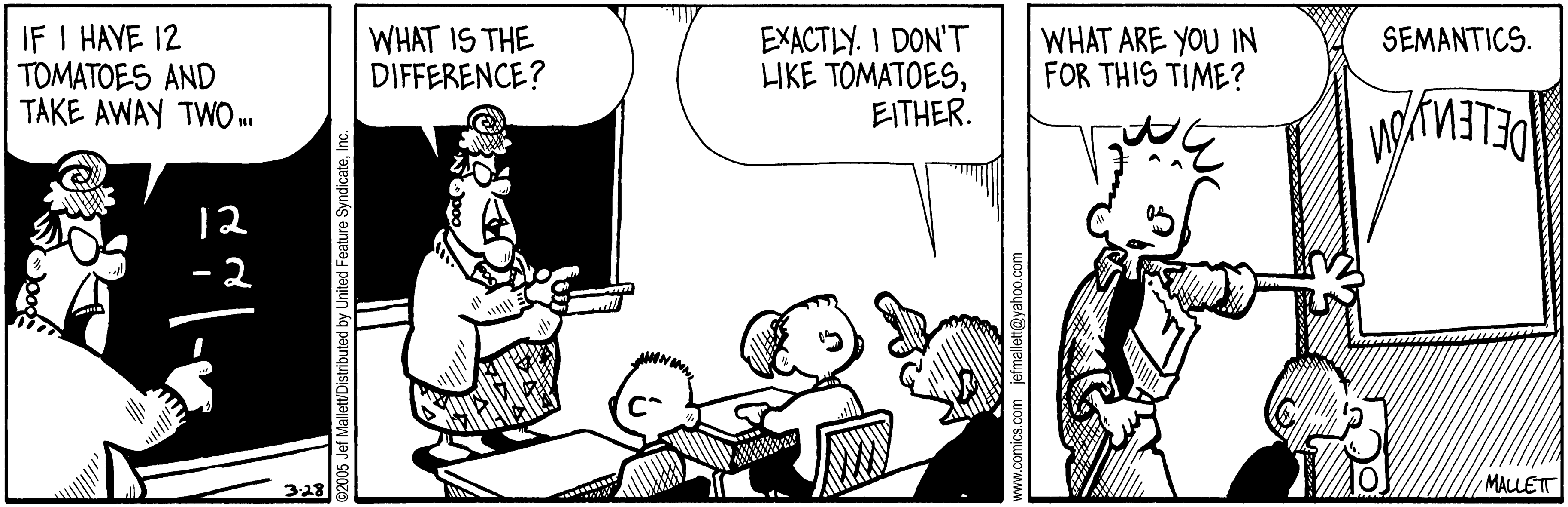

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Any questions?

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