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
University of Oxford
University of Oxford
University of Oxford
University of Oxford
University of Oxford
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
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
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Jeff Pan
Semantic Web Challenge Chairs
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Diana Maynard
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Proceedings Chair
Birte Glimm
Sponsor Chairs
Kendall Clark
Anand Ranganathan
Local Organization
Dingyi Han
Gui-Rong Xue
Haifen Wang
Lei Zhang

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
What is an Ontology?
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A model of (some aspect of) the world
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A model of (some aspect of) the world

• Introduces **vocabulary** relevant to domain, e.g.:
  – Anatomy
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• Introduces **vocabulary** relevant to domain, e.g.:
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  - Cellular biology
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- Introduces **vocabulary** relevant to domain, e.g.:
  - Anatomy
  - Cellular biology
  - Aerospace
  - Dogs
What is an Ontology?

A model of (some aspect of) the world

• Introduces *vocabulary* relevant to domain, e.g.:
  – Anatomy
  – Cellular biology
  – Aerospace
  – Dogs
  – Hotdogs
  – …
What is an Ontology?

A model of (some aspect of) the world

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

Heart is a muscular organ that is part of the circulatory system
What is an Ontology?

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- Introduces **vocabulary** relevant to domain
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  Heart is a muscular organ that is part of the circulatory system

- **Formalised** using suitable logic
  
  \[
  \forall x. [\text{Heart}(x) \rightarrow \text{MuscularOrgan}(x) \land \\
  \exists y. [\text{isPartOf}(x, y) \land \\
  \text{CirculatorySystem}(y)]]
  \]
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** (SHOIN / 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**

\[
\forall x. [\text{Heart}(x) \rightarrow \text{MuscularOrgan}(x) \land \\
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\text{CirculatorySystem}(y)]]
\]

\[
\text{Heart} \sqsubseteq \text{MuscularOrgan} \sqcap \\
\exists \text{isPartOf}. \text{CirculatorySystem}
\]
Description Logics (DLs)

DL Knowledge Base (KB) consists of two parts:

- Ontology (aka TBox) axioms define terminology (schema)
  
  \[
  \text{Heart} \sqsubseteq \text{MuscularOrgan} \sqcap
  \exists \text{isPartOf.CirculatorySystem}
  
  \text{HeartDisease} \equiv \text{Disease} \sqcap
  \exists \text{affects.Heart}
  
  \text{VascularDisease} \equiv \text{Disease} \sqcap
  \exists \text{affects.} (\exists \text{isPartOf.CirculatorySystem})
  \]

- Ground facts (aka ABox) use the terminology (data)
  
  \[
  \text{John} : \text{Patient} \sqcap
  \exists \text{suffersFrom.HeartDisease}
  \]
Why Care About Semantics?
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Why should I 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.
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.

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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\]

\[
\text{HeartDisease} \equiv \text{Disease} \\n\exists \text{affects.Heart}
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\text{VascularDisease} \equiv \text{Disease} \\n\exists \text{affects.}(\exists \text{isPartOf.CirculatorySystem})
\]

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\text{John} : \text{Patient} \\n\exists \text{suffersFrom.HearthDisease}
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What are Ontologies Good For?

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• 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”
  – Query expansion/navigation/refinement
  – Incomplete and semi-structured data
  – Integration of heterogeneous sources

Now... *that* should clear up a few things around here
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
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
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  - E.g., KB \models HeartDisease \sqsubseteq VascularDisease iff
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- Algorithm tries to construct (an abstraction of) a model:

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  \( x : \text{HeartDisease} \)
  \( x : \neg\text{VascularDisease} \)
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\[
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x & : \text{HeartDisease} \quad \neg \text{VascularDisease} \\
x & : \text{HeartDisease} \\
x & : \text{Disease} \\
x & : \exists \text{affects. Heart}
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  x & : \text{Disease} \\
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  (x, y) & : \text{affects} \\
  y & : \text{Heart}
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  (x, y) &: \text{affects} \\
  y &: \text{Heart} \\
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– Algorithm tries to construct (an abstraction of) a model:

\begin{align*}
x &: \text{HeartDisease} \land \neg\text{VascularDisease} & x &: \neg\text{VascularDisease} \\
x &: \text{HeartDisease} \\
x &: \text{Disease} \\
x &: \exists \text{affects. Heart} \\
(x, y) &: \text{affects} \\
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x & : \text{HeartDisease} & x & : \neg\text{Disease} \\
x & : \text{Disease} & -\exists\text{affects.}(\exists\text{isPartOf.CirculatorySystem}) \\
x & : \exists\text{affects.Heart} \\
(x, y) & : \text{affects} \\
y & : \text{Heart} \\
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  – Algorithm tries to construct (an abstraction of) a model:

```plaintext
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 : ¬Disease
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  - E.g., \( \text{KB} \not\models \text{HeartDisease} \sqsubseteq \text{VascularDisease} \) iff
    \[ \text{KB} \cup \{ x : (\text{HeartDisease} \land \neg \text{VascularDisease}) \} \] is *not* satisfiable
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\begin{align*}
x &: \text{HeartDisease} \land \neg \text{VascularDisease} & x &: \neg \text{VascularDisease} \\
x &: \text{HeartDisease} & x &: \neg \text{Disease} \\
x &: \text{Disease} & \neg \exists \text{affects. (}\exists \text{isPartOf. CirculatorySystem}) \\
x &: \exists \text{affects. Heart} & x &: \neg \text{Disease} \\
(x, y) &: \text{affects} & y &: \text{Heart} \\
& & y &: \text{Muscular Organ} \\
& & y &: \exists \text{isPartOf. CirculatorySystem} \\
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x &: \exists \text{affects.} \text{Heart} \\
(x, y) &: \text{affects} \\
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x : & \text{HeartDisease} & x : & \neg \text{Disease} \\
x : & \text{Disease} & \neg \exists \text{affects} . (\exists \text{isPartOf. CirculatorySystem}) \\
x : & \exists \text{affects} . \text{Heart} & x : & \neg \exists \text{affects} . (\exists \text{isPartOf. CirculatorySystem}) \\
(x, y) : & \text{affects} & x : & \forall \text{affects} . (\forall \text{isPartOf.} \neg \text{CirculatorySystem}) \\
y : & \text{Heart} & y : & \text{MuscularOrgan} \\
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y: \text{MuscularOrgan} \\
y: \exists \text{isPartOf. CirculatorySystem} \\
(y, z): \text{isPartOf} \\
z: \text{CirculatorySystem} \\
x: \neg \text{VascularDisease} \\
x: \neg \text{Disease} \\
\neg \exists \text{affects. (}\exists \text{isPartOf. CirculatorySystem}\text{)} \\
x: \neg \exists \text{affects. (}\exists \text{isPartOf. CirculatorySystem}\text{)} \\
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x & : \neg \exists \text{affects. (} & \exists \text{isPartOf. CirculatorySystem)} \\
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x &: \neg \text{VascularDisease} \\
x &: \neg \text{Disease} \\
x &: \neg \exists \text{affects.}(\exists \text{isPartOf.CirculatorySystem}) \\
x &: \neg \exists \text{affects.}(\exists \text{isPartOf.CirculatorySystem}) \\
x &: \forall \text{affects.}(\forall \text{isPartOf.} \neg \text{CirculatorySystem}) \\
y &: \text{VisPartOf.} \neg \text{CirculatorySystem} \\
z &: \neg \text{CirculatorySystem}
\end{align*}
\]
Highly Optimised Implementations

• Lazy unfolding
• Simplification and rewriting,
  e.g., \( A \cap B \subseteq C \rightarrow A \subseteq C \cup \neg B \)
• 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
Scalability Issues

• Problems with large data sets (ABoxes)
  – Main reasoning problem is (conjunctive) query answering, e.g., retrieve all patients suffering from vascular disease:
    \[ Q(x) \leftarrow \text{Patient}(x) \land \text{suffersFrom}(x, y) \land \text{VascularDisease}(y) \]
  – 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 \( \text{KB} \models Q(x) \)
  – 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 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:
  \[ A \subseteq B \quad A \cap B \subseteq C \quad A \subseteq \exists R.B \quad \exists R.B \subseteq C \]

• Saturate using inference rules:
  \[
  \frac{A \subseteq B \quad B \subseteq C}{A \subseteq C} \quad \frac{A \subseteq B \quad A \subseteq C \quad B \cap C \subseteq D}{A \subseteq D}
  \]
  \[
  \frac{A \subseteq \exists R.B \quad B \subseteq C \quad \exists R.C \subseteq D}{A \subseteq D}
  \]

• Extension to Horn fragment requires (many) more rules
Saturation-based Technique (basics)

Example:

\[
\text{Organ Transplant} \equiv \text{Transplant} \land \exists \text{site. Organ}
\]
\[
\text{Heart Transplant} \equiv \text{Transplant} \land \exists \text{site. Heart}
\]
\[
\text{Heart} \subseteq \text{Organ}
\]
Saturation-based Technique (basics)

Example:

\[ \text{OrganTransplant} \equiv \text{Transplant} \land \exists \text{site.Organ} \]
\[ \text{HeartTransplant} \equiv \text{Transplant} \land \exists \text{site.Heart} \]
\[ \text{Heart} \subseteq \text{Organ} \]
Saturation-based Technique (basics)

Example:

\[ \text{OrganTransplant} \equiv \text{Transplant} \land \exists \text{site.Organ} \]
\[ \text{HeartTransplant} \equiv \text{Transplant} \land \exists \text{site.Heart} \]
\[ \text{Heart} \subseteq \text{Organ} \]

\[ \text{OrganTransplant} \subseteq \text{Transplant} \]
\[ \text{OrganTransplant} \subseteq \exists \text{site.Organ} \]
Saturation-based Technique (basics)

Example:

\[
\text{OrganTransplant} \equiv \text{Transplant} \sqcap \exists \text{site. Organ} \\
\text{HeartTransplant} \equiv \text{Transplant} \sqcap \exists \text{site. Heart} \\
\quad \text{Heart} \sqsubseteq \text{Organ}
\]

\[
\text{OrganTransplant} \sqsubseteq \text{Transplant} \\
\text{OrganTransplant} \sqsubseteq \exists \text{site. Organ} \\
\quad \exists \text{site. Organ} \sqsubseteq \text{SO} \\
\text{Transplant} \sqcap \text{SO} \sqsubseteq \text{OrganTransplant}
\]
Saturation-based Technique (basics)

Example:

\[ \text{OrganTransplant} \equiv \text{Transplant} \sqcap \exists \text{site.Organ} \]
\[ \text{HeartTransplant} \equiv \text{Transplant} \sqcap \exists \text{site.Heart} \]
\[ \text{Heart} \sqsubseteq \text{Organ} \]

\[ \text{OrganTransplant} \sqsubseteq \text{Transplant} \]
\[ \text{OrganTransplant} \sqsubseteq \exists \text{site.Organ} \]
\[ \exists \text{site.Organ} \sqsubseteq \text{SO} \]
\[ \text{Transplant} \sqcap \text{SO} \sqsubseteq \text{OrganTransplant} \]
Saturation-based Technique (basics)

Example:

\[
\begin{align*}
\text{OrganTransplant} & \equiv \text{Transplant} \sqcap \exists \text{site. Organ} \\
\text{HeartTransplant} & \equiv \text{Transplant} \sqcap \exists \text{site. Heart} \\
\text{Heart} & \subseteq \text{Organ} \\
\end{align*}
\]

\[
\begin{align*}
\text{OrganTransplant} & \subseteq \text{Transplant} \\
\text{OrganTransplant} & \subseteq \exists \text{site. Organ} \\
\exists \text{site. Organ} & \subseteq \text{SO} \\
\text{Transplant} \sqcap \text{SO} & \subseteq \text{OrganTransplant} \\
\text{HeartTransplant} & \subseteq \text{Transplant} \\
\text{HeartTransplant} & \subseteq \exists \text{site. Heart} \\
\exists \text{site. Heart} & \subseteq \text{SH} \\
\text{Transplant} \sqcap \text{SH} & \subseteq \text{HeartTransplant} \\
\end{align*}
\]
Saturation-based Technique (basics)

Example:

\[\text{OrganTransplant} \equiv \text{Transplant} \sqcap \exists \text{site.Organ}\]
\[\text{HeartTransplant} \equiv \text{Transplant} \sqcap \exists \text{site.Heart}\]
\[\text{Heart} \sqsubseteq \text{Organ}\]

\[\text{OrganTransplant} \sqsubseteq \text{Transplant}\]
\[\text{OrganTransplant} \sqsubseteq \exists \text{site.Organ}\]
\[\exists \text{site.Organ} \sqsubseteq \text{SO}\]
\[\text{Transplant} \sqcap \text{SO} \sqsubseteq \text{OrganTransplant}\]
\[\text{HeartTransplant} \sqsubseteq \text{Transplant}\]
\[\text{HeartTransplant} \sqsubseteq \exists \text{site.Heart}\]
\[\exists \text{site.Heart} \sqsubseteq \text{SH}\]
\[\text{Transplant} \sqcap \text{SH} \sqsubseteq \text{HeartTransplant}\]
Saturation-based Technique (basics)

Example:

\[
\text{OrganTransplant} \equiv \text{Transplant} \sqcap \exists \text{site.Organ}
\]
\[
\text{HeartTransplant} \equiv \text{Transplant} \sqcap \exists \text{site.Heart}
\]
\[
\text{Heart} \subseteq \text{Organ}
\]

\[
\text{OrganTransplant} \subseteq \text{Transplant}
\]
\[
\text{OrganTransplant} \subseteq \exists \text{site.Organ}
\]
\[
\exists \text{site.Organ} \subseteq \text{SO}
\]
\[
\text{Transplant} \sqcap \text{SO} \subseteq \text{OrganTransplant}
\]
\[
\text{HeartTransplant} \subseteq \text{Transplant}
\]
\[
\text{HeartTransplant} \subseteq \exists \text{site.Heart}
\]
\[
\exists \text{site.Heart} \subseteq \text{SH}
\]
\[
\text{Transplant} \sqcap \text{SH} \subseteq \text{HeartTransplant}
\]
\[
\text{Heart} \subseteq \text{Organ}
\]
Saturation-based Technique (basics)

Example:

\[
\begin{align*}
\text{OrganTransplant} & \equiv \text{Transplant} \sqcap \exists \text{site.Organ} \\
\text{HeartTransplant} & \equiv \text{Transplant} \sqcap \exists \text{site.Heart} \\
\text{Heart} & \sqsubseteq \text{Organ}
\end{align*}
\]

\[
\begin{align*}
\text{OrganTransplant} & \sqsubseteq \text{Transplant} \\
\text{OrganTransplant} & \sqsubseteq \exists \text{site.Organ} \\
\exists \text{site.Organ} & \sqsubseteq \text{SO} \\
\text{Transplant} \sqcap \text{SO} & \sqsubseteq \text{OrganTransplant} \\
\text{HeartTransplant} & \sqsubseteq \text{Transplant} \\
\exists \text{site.Heart} & \sqsubseteq \text{Heart} \\
\exists \text{site.Heart} & \sqsubseteq \text{SH} \\
\text{Transplant} \sqcap \text{SH} & \sqsubseteq \text{HeartTransplant} \\
\text{Heart} & \sqsubseteq \text{Organ}
\end{align*}
\]
Saturation-based Technique (basics)

Example:

\[
\begin{align*}
\text{OrganTransplant} & \equiv \text{Transplant} \sqcap \exists \text{site.Organ} \\
\text{HeartTransplant} & \equiv \text{Transplant} \sqcap \exists \text{site.Heart} \\
& \quad \text{Heart} \sqsubseteq \text{Organ}
\end{align*}
\]

\[
\begin{align*}
\text{OrganTransplant} & \sqsubseteq \text{Transplant} \\
\text{OrganTransplant} & \sqsubseteq \exists \text{site.Organ} \\
& \quad \exists \text{site.Organ} \sqsubseteq \text{SO} \\
\text{Transplant} \sqcap \text{SO} & \sqsubseteq \text{OrganTransplant} \\
\text{HeartTransplant} & \sqsubseteq \text{Transplant} \\
\text{HeartTransplant} & \sqsubseteq \exists \text{site.Heart} \\
& \quad \exists \text{site.Heart} \sqsubseteq \text{SH} \\
\text{Transplant} \sqcap \text{SH} & \sqsubseteq \text{HeartTransplant} \\
& \quad \text{Heart} \sqsubseteq \text{Organ}
\end{align*}
\]

\[
\begin{align*}
A & \sqsubseteq \exists R.B \\
B & \sqsubseteq C \\
\exists R.C & \sqsubseteq D \\
A & \sqsubseteq D
\end{align*}
\]

\[
\text{HeartTransplant} \sqsubseteq \text{SO}
\]
Saturation-based Technique (basics)

Example:

\[
\begin{align*}
\text{OrganTransplant} & \equiv \text{Transplant} \land \exists \text{site. Organ} \\
\text{HeartTransplant} & \equiv \text{Transplant} \land \exists \text{site. Heart} \\
\text{Heart} & \subseteq \text{Organ}
\end{align*}
\]

\[
\begin{align*}
A & \subseteq B \\
A & \subseteq C \\
B \land C & \subseteq D \\
A & \subseteq D
\end{align*}
\]

\[
\begin{align*}
\text{OrganTransplant} & \subseteq \text{Transplant} \\
\text{OrganTransplant} & \subseteq \exists \text{site. Organ} \\
\exists \text{site. Organ} & \subseteq \text{SO} \\
\text{Transplant} \land \text{SO} & \subseteq \text{OrganTransplant} \\
\text{HeartTransplant} & \subseteq \text{Transplant} \\
\text{HeartTransplant} & \subseteq \exists \text{site. Heart} \\
\exists \text{site. Heart} & \subseteq \text{SH} \\
\text{Transplant} \land \text{SH} & \subseteq \text{HeartTransplant} \\
\text{Heart} & \subseteq \text{Organ}
\end{align*}
\]

\[\text{HeartTransplant} \subseteq \text{SO}\]
Saturation-based Technique (basics)

Example:

\[
\begin{align*}
\text{OrganTransplant} & \equiv \text{Transplant} \sqcap \exists \text{site.Organ} \\
\text{HeartTransplant} & \equiv \text{Transplant} \sqcap \exists \text{site.Heart} \\
& \quad \text{Heart} \sqsubseteq \text{Organ}
\end{align*}
\]

\[
\begin{align*}
A \sqsubseteq B & \quad A \sqsubseteq C \\
B \sqcap C & \sqsubseteq D \\
& \quad A \sqsubseteq D
\end{align*}
\]

\[
\begin{align*}
\text{OrganTransplant} & \sqsubseteq \text{Transplant} \\
\text{OrganTransplant} & \sqsubseteq \exists \text{site.Organ} \\
& \quad \exists \text{site.Organ} \sqsubseteq \text{SO} \\
\text{Transplant} \sqcap \text{SO} & \sqsubseteq \text{OrganTransplant} \\
\text{HeartTransplant} & \sqsubseteq \text{Transplant} \\
\text{HeartTransplant} & \sqsubseteq \exists \text{site.Heart} \\
& \quad \exists \text{site.Heart} \sqsubseteq \text{SH} \\
\text{Transplant} \sqcap \text{SH} & \sqsubseteq \text{HeartTransplant} \\
& \quad \text{Heart} \sqsubseteq \text{Organ}
\end{align*}
\]

\[
\begin{align*}
\text{HeartTransplant} & \sqsubseteq \text{SO} \\
\text{HeartTransplant} & \sqsubseteq \text{OrganTransplant}
\end{align*}
\]
Saturation-based Technique

Performance with large bio-medical ontologies:

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<tr>
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<td>1.61X</td>
<td>143X</td>
<td>∞</td>
<td>13.15X</td>
</tr>
</tbody>
</table>
OWL 2 QL

• A (near maximal) fragment of OWL 2 such that
  – Data complexity of conjunctive query answering in $\text{AC}^0$
• 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 $\text{AC}^0$) by delegating query answering to a Datalog engine
Query Rewriting Technique (basics)

• Given ontology $\mathcal{O}$ and query $Q$, use $\mathcal{O}$ to rewrite $Q$ as $Q'$ s.t., for any set of ground facts $\mathcal{A}$:
  \[ \text{ans}(Q, \mathcal{O}, \mathcal{A}) = \text{ans}(Q', \emptyset, \mathcal{A}) \]
Query Rewriting Technique (basics)

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

• Use (GAV) mapping $\mathcal{M}$ to map $Q'$ to SQL query
Query Rewriting Technique (basics)

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

• Use (GAV) mapping $\mathcal{M}$ to map $Q'$ to SQL query

\[Q \xrightarrow{\text{Rewrite}} Q' \xrightarrow{\text{Map}} \mathcal{A} \xrightarrow{\text{Ans}}\]
Query Rewriting Technique (basics)

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

• Use (GAV) mapping $M$ to map $Q'$ 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:

\[
\text{Doctor} \sqsubseteq \exists \text{treats.Patient} \\
\text{Consultant} \sqsubseteq \text{Doctor} \\
\]

\[
Q(x) \leftarrow \text{treats}(x, y) \land \text{Patient}(y)
\]
Query Rewriting Technique (basics)

- Example:

\[
\begin{align*}
\text{Doctor} & \sqsubseteq \exists \text{treats}.\text{Patient} \\
\text{Consultant} & \sqsubseteq \text{Doctor} \\
\text{treats}(x, f(x)) & \leftarrow \text{Doctor}(x) \\
\text{Patient}(f(x)) & \leftarrow \text{Doctor}(x) \\
\text{Doctor}(x) & \leftarrow \text{Consultant}(x)
\end{align*}
\]
Query Rewriting Technique (basics)

• Example:

\[ \text{Doctor} \subseteq \exists \text{treats}. \text{Patient} \]
\[ \text{Consultant} \subseteq \text{Doctor} \]

\[ \text{treats}(x, f(x)) \leftarrow \text{Doctor}(x) \]
\[ Q(x) \leftarrow \text{treats}(x, y) \land \text{Patient}(y) \]
\[ \text{Patient}(f(x)) \leftarrow \text{Doctor}(x) \]
\[ \text{Doctor}(x) \leftarrow \text{Consultant}(x) \]
Query Rewriting Technique (basics)

• Example:

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\begin{align*}
\text{Doctor} &\subseteq \exists \text{treats. Patient} \\
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\text{treats}(x, f(x)) &\leftarrow \text{Doctor}(x) \\
\text{Patient}(f(x)) &\leftarrow \text{Doctor}(x) \\
\text{Doctor}(x) &\leftarrow \text{Consultant}(x) \\
Q(x) &\leftarrow \text{treats}(x, y) \land \text{Patient}(y) \\
Q(x) &\leftarrow \text{Doctor}(x) \land \text{Patient}(f(x))
\end{align*}
\]
Query Rewriting Technique (basics)

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Q(x) & \leftarrow \text{treats}(x, y) \land \text{Patient}(y) \\
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\text{Doctor}(x) & \leftarrow \text{Consultant}(x) \\
Q(x) & \leftarrow \text{treats}(x, y) \land \text{Patient}(y) \\
Q(x) & \leftarrow \text{Doctor}(x) \land \text{Patient}(f(x)) \\
Q(x) & \leftarrow \text{treats}(x, f(x)) \land \text{Doctor}(x)
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Query Rewriting Technique (basics)

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\text{Doctor} &\subseteq \exists \text{treats. Patient} \\
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\text{Patient}(f(x)) &\leftarrow \text{Doctor}(x) \\
\text{Doctor}(x) &\leftarrow \text{Consultant}(x) \\
\end{align*}
\]

\[
\begin{align*}
Q(x) &\leftarrow \text{treats}(x, y) \land \text{Patient}(y) \\
Q(x) &\leftarrow \text{Doctor}(x) \land \text{Patient}(f(x)) \\
Q(x) &\leftarrow \text{treats}(x, f(x)) \land \text{Doctor}(x)
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\text{Q}(x) & \leftarrow \text{treats}(x, y) \land \text{Patient}(y) \\
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Q(x) & \leftarrow \text{Doctor}(x) \land \text{Patient}(f(x)) \\
Q(x) & \leftarrow \text{treats}(x, f(x)) \land \text{Doctor}(x) \\
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Q(x) \leftarrow \text{treats}(x, y) \land \text{Patient}(y) \\
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Q(x) & \leftarrow \text{treats}(x, y) \land \text{Patient}(y) \\
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\]

\[
\begin{align*}
\text{treats}(x, f(x)) & \leftarrow \text{Doctor}(x) \\
\text{Patient}(f(x)) & \leftarrow \text{Doctor}(x) \\
\text{Doctor}(x) & \leftarrow \text{Consultant}(x)
\end{align*}
\]

\[
\begin{align*}
Q(x) & \leftarrow \text{treats}(x, y) \land \text{Patient}(y) \\
Q(x) & \leftarrow \text{Doctor}(x) \land \text{Patient}(f(x)) \\
Q(x) & \leftarrow \text{treats}(x, f(x)) \land \text{Doctor}(x) \\
Q(x) & \leftarrow \text{Doctor}(x) \\
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\end{align*}
\]

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

\[
Q(x) \leftarrow (\text{treats}(x, y) \land \text{Patient}(y)) \lor \text{Doctor}(x) \lor \text{Consultant}(x)
\]
Query Rewriting Technique (basics)

- Data can be stored/left in **RDBMS**
- Relationship between ontology and DB defined by **mappings**, e.g.:
  
  | Doctor  | SELECT Name FROM Doctor |
  | Patient | SELECT Name FROM Patient |
  | treats  | SELECT DName, PName FROM Treats |
Query Rewriting Technique (basics)

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

  Doctor \iff \text{SELECT Name FROM Doctor}
  
  Patient \iff \text{SELECT Name FROM Patient}
  
  treats \iff \text{SELECT DName, PName FROM Treats}

- UCQ translated into SQL query:

  \[ Q(x) \leftarrow (\text{treats}(x, y) \land \text{Patient}(y)) \lor \text{Doctor}(x) \lor \text{Consultant}(x) \]

  ⌄

  \text{SELECT Name FROM Doctor UNION}
  
  \text{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.:
Problems & Research Challenges

• Open questions w.r.t. query rewriting
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  – Currently only for very weak ontology languages
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  – Even for these languages, queries can get very large (order \(|O| \cdot |Q|^{|O|}\)), and existing RDBMSs may behave poorly
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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
Problems & Research Challenges

• Infrastructure
  – Standardised query language
    • SPARQL standard for RDF
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  – ...

Thanks To

• Boris Motik
• Yevgeny Kazakov
• Héctor Pérez-Urbina
• Rob Shearer
• Bernardo Cuenca Grau
• Birte Glimm
Thank you for listening
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Any questions?
Select Bibliography


