DAML+OIL: a Reason-able Web Ontology Language

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Talk Outline

- The Semantic Web
- Web Ontology Languages
- DAML+OIL Language
- Reasoning with DAML+OIL
    - OilEd Demo
- Description Logic Reasoning
- Research Challenges
- Summary

The Semantic Web

The Semantic Web Vision

- Web made possible through established **standards**
  - **TCP/IP** for transporting bits down a wire
  - **HTTP & HTML** for transporting and rendering hyperlinked text
- **Applications** able to exploit this common infrastructure
  - Result is the WWW as we know it
- **1st generation** web mostly handwritten HTML pages
- **2nd generation** (current) web often machine generated/active
- Both intended for direct human processing/interaction
- In **next generation** web, **resources** should be more accessible to automated processes
  - To be achieved via **semantic markup**
  - **Metadata** annotations that describe content/function
- Coincides with Tim Berners-Lee's vision of a **Semantic Web**

Realising the Semantic Web

- Semantic web vision is **extremely ambitious**
- Even partial realisation will be a **major undertaking**
- Input will be required from **many communities** (inc. AI and Database)
- Topics covered at **ISWC** include:

Agents	Multimedia data
Database technologies	Natural language
Digital libraries	Ontologies
e-business	Searching and querying
e-science and the Grid	Services and service description
Integration, mediation and storage	Trust and meaning
Knowledge representation and reasoning	User interfaces
Languages and infrastructure	Visualisation and modelling
Metadata (inc. generation and authoring)	Web mining

Ontologies

- Semantic markup must be **meaningful** to automated processes
- Ontologies will play a key role
  - Source of **precisely defined** terms (vocabulary)
  - Can be **shared** across applications (and humans)
- Ontology typically consists of:
  - **Hierarchical** description of important **concepts** in domain
  - Descriptions of the **properties** of each concept
- Degree of formality can be quite variable (NL–logic)
- Increased formality and regularity facilitates machine understanding
- Ontologies can be used, e.g.:
  - To facilitate buyer–seller communication in **e-commerce**
  - In semantic based **search**
  - To provide richer **service descriptions** that can be more flexibly interpreted by intelligent agents

Web Ontology Languages

Web Languages

- Web languages already extended to facilitate **content description**
  - XML Schema (XMLS)
  - RDF and RDF Schema (RDFS)
- RDFS recognisable as an **ontology language**
  - Classes and properties
  - Range and domain
  - Sub/super-classes (and properties)
- But RDFS not a suitable foundation for Semantic Web
  - **Too weak** to describe resources in sufficient detail
- Requirements for web ontology language:
  - **Compatible** with existing Web standards (XML, RDF, RDFS)
  - **Easy to understand** and use (based on common KR idioms)
  - **Formally specified** and of “adequate” expressive power
  - Possible to provide **automated reasoning** support

History: OIL and DAML-ONT

- Two languages developed to satisfy above requirements
  - **OIL**: developed by group of (largely) European researchers (several from OntoKnowledge project)
  - **DAML-ONT**: developed by group of (largely) US researchers (in DARPA DAML programme)
- Efforts merged to produce DAML+OIL
  - Development was overseen by **joint EU/US committee**
  - Now **submitted to W3C** as basis for standardisation
  - **WebOnt working group** developing language standard
  - New standard may be called **OWL** (Ontology Web Language)

DAML+OIL

- DAML+OIL **layered** on top of RDFS
  - RDFS based **syntax**
  - **Inherits** RDFS ontological primitives (subclass, range, domain)
  - Provides **much** richer set of primitives (equality, cardinality, . . .)
- DAML+OIL designed to describe **structure** of domain (**schema**)
  - **Object oriented**: classes (concepts) and properties (roles)
  - DAML+OIL ontology consists of set of **axioms** asserting characteristics of classes and properties
  - E.g., Person is **kind of** Animal whose parents are Persons
- RDF used for class/property membership assertions (**data**)
  - E.g., John is an **instance of** Person; $\langle \text{John}, \text{Mary} \rangle$ is an instance of parent

DAML+OIL Language

Foundations

- DAML+OIL equivalent to very expressive **Description Logic**
  - But don't tell anyone!
- More precisely, DAML+OIL is (extension of) $\mathcal{SHIQ}$ DL
- DAML+OIL benefits from many years of DL research
  - Well defined **semantics**
  - **Formal properties** well understood (complexity, decidability)
  - Known **reasoning algorithms**
  - **Implemented systems** (highly optimised)
- DAML+OIL classes can be names (URI's) or **expressions**
  - Various **constructors** provided for building class expressions
- **Expressive power** determined by
  - Kinds of constructor provided
  - Kinds of axiom allowed

DAML+OIL Class Constructors

Constructor	DL Syntax	Example
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	Human $\sqcap$ Male
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	Doctor $\sqcup$ Lawyer
complementOf	$\neg C$	$\neg$Male
oneOf	$\{x_1 \ldots x_n\}$	{john, mary}
toClass	$\forall P.C$	$\forall$hasChild.Doctor
hasClass	$\exists P.C$	$\exists$hasChild.Lawyer
hasValue	$\exists P.\{x\}$	$\exists$citizenOf.{USA}
minCardinalityQ	$\geqslant n P.C$	$\geqslant 2$hasChild.Lawyer
maxCardinalityQ	$\leqslant n P.C$	$\leqslant 1$hasChild.Male
cardinalityQ	$= n\, P.C$	$=1$ hasParent.Female

- XMLS **datatypes** as well as classes
- Arbitrarily complex **nesting** of constructors
  - E.g., Person $\sqcap$ $\forall$hasChild.(Doctor $\sqcup$ $\exists$hasChild.Doctor)

DAML+OIL Axioms

Axiom	DL Syntax	Example
subClassOf	$C_1 \sqsubseteq C_2$	Human $\sqsubseteq$ Animal $\sqcap$ Biped
sameClassAs	$C_1 \equiv C_2$	Man $\equiv$ Human $\sqcap$ Male
subPropertyOf	$P_1 \sqsubseteq P_2$	hasDaughter $\sqsubseteq$ hasChild
samePropertyAs	$P_1 \equiv P_2$	cost $\equiv$ price
sameIndividualAs	$\{x_1\} \equiv \{x_2\}$	{President_Bush} $\equiv$ {G_W_Bush}
disjointWith	$C_1 \sqsubseteq \neg C_2$	Male $\sqsubseteq \neg$Female
differentIndividualFrom	$\{x_1\} \sqsubseteq \neg\{x_2\}$	{john} $\sqsubseteq \neg${peter}
inverseOf	$P_1 \equiv P_2^-$	hasChild $\equiv$ hasParent$^-$
transitiveProperty	$P^+ \sqsubseteq P$	ancestor$^+ \sqsubseteq$ ancestor
uniqueProperty	$\top \sqsubseteq \leqslant 1P$	$\top \sqsubseteq \leqslant 1$hasMother
unambiguousProperty	$\top \sqsubseteq \leqslant 1P^-$	$\top \sqsubseteq \leqslant 1$isMotherOf$^-$

☞ Axioms (mostly) **reducible to subClass/PropertyOf**

RDFS Syntax

```
<daml:Class>
  <daml:intersectionOf rdf:parseType="daml:collection">
    <daml:Class rdf:about="#Person"/>
    <daml:Restriction>
      <daml:onProperty rdf:resource="#hasChild"/>
      <daml:toClass>
        <daml:unionOf rdf:parseType="daml:collection">
          <daml:Class rdf:about="#Doctor"/>
          <daml:Restriction>
            <daml:onProperty rdf:resource="#hasChild"/>
            <daml:hasClass rdf:resource="#Doctor"/>
          </daml:Restriction>
        </daml:unionOf>
      </daml:toClass>
    </daml:Restriction>
  </daml:intersectionOf>
</daml:Class>
```

XML Datatypes in DAML+OIL

- DAML+OIL supports the full range of **XML Schema** datatypes
  - Primitive (e.g., decimal) and derived (e.g., integer sub-range)
- Clean **separation** between “object” classes and datatypes
  - Disjoint interpretation domains: John$^{\mathcal{I}} \neq$ (int 5)$^{\mathcal{I}}$
  - Object properties disjoint from datatype properties
- Philosophical reasons:
  - Datatypes structured by **built-in predicates**
  - Not appropriate to form new datatypes using ontology language
- Practical reasons:
  - Ontology language remains **simple and compact**
  - **Semantic integrity** of ontology language not compromised
  - **Implementability** not compromised—can use hybrid reasoner
- In practice, DAML+OIL implementations can choose to support **subset** of XML Schema datatypes.

Reasoning with DAML+OIL

Why Provide Reasoning Services?

- **Understanding** closely related to reasoning
  - Semantic Web aims at machine understanding
- Reasoning useful at all stages of ontology life-cycle
- Ontology **design and maintenance**
  - Check class consistency and (unexpected) implied relationships
  - Particularly important with large ontologies/multiple authors
- Ontology **integration**
  - Assert inter-ontology relationships
  - Reasoner computes integrated class hierarchy/consistency
- Ontology **deployment**
  - Determine if set of facts are consistent w.r.t. ontology
  - Determine if individuals are instances of ontology classes

Why Decidable Reasoning?

☞ DAML+OIL constructors/axioms restricted so reasoning is **decidable**

☞ Consistent with Semantic Web's **layered architecture**

- XML provides syntax **transport layer**
- RDF(S) provides basic **relational language** and simple ontological primitives
- DAML+OIL provides powerful but still decidable **ontology language**
- Further layers (e.g., **rules**) will extend DAML+OIL
- **Extensions** will almost certainly be undecidable

☞ Facilitates provision of **reasoning services**

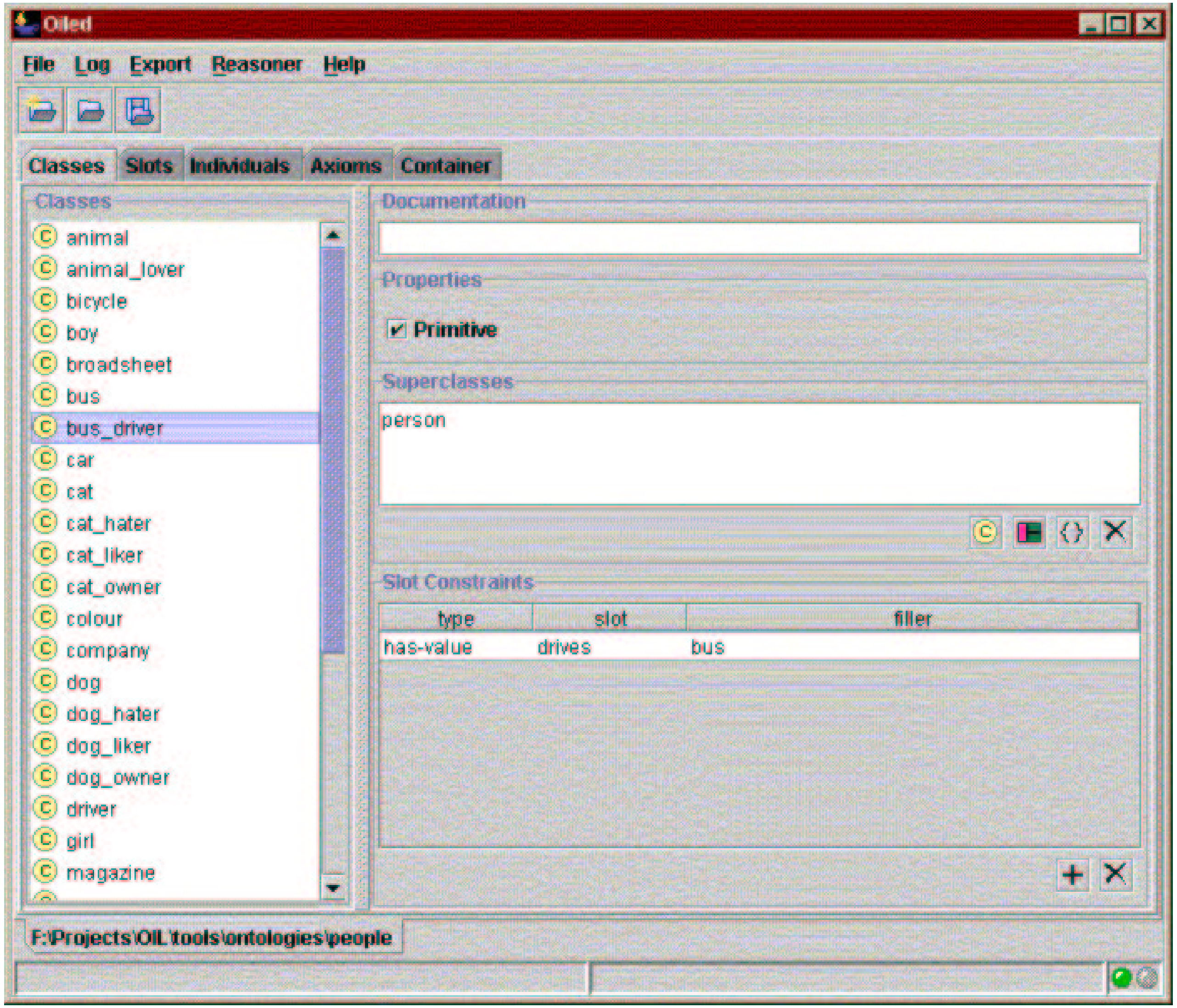
- Known "practical" **algorithms**
- Several implemented **systems**
- Evidence of **empirical tractability**

☞ Understanding dependent on **reliable & consistent** reasoning

Basic Inference Problems

- **Consistency** — check if knowledge is meaningful
  - Is $\mathcal{O}$ consistent? There exists some model $\mathcal{I}$ of $\mathcal{O}$
  - Is C consistent? $C^{\mathcal{I}} \neq \emptyset$ in some model $\mathcal{I}$ of $\mathcal{O}$
- **Subsumption** — structure knowledge, compute taxonomy
  - $C \sqsubseteq_{\mathcal{O}} D$? $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ in all models $\mathcal{I}$ of $\mathcal{O}$
- **Equivalence** — check if two classes denote same set of instances
  - $C \equiv_{\mathcal{O}} D$? $C^{\mathcal{I}} = D^{\mathcal{I}}$ in all models $\mathcal{I}$ of $\mathcal{O}$
- **Instantiation** — check if individual i instance of class C
  - $i \in_{\mathcal{O}} C$? $i \in C^{\mathcal{I}}$ in all models $\mathcal{I}$ of $\mathcal{O}$
- **Retrieval** — retrieve set of individuals that instantiate C
  - set of i s.t. $i \in C^{\mathcal{I}}$ in all models $\mathcal{I}$ of $\mathcal{O}$
- Problems all **recucible** to consistency (satisfiability):
  - $C \sqsubseteq_{\mathcal{O}} D$ iff $D \sqcap \neg C$ not consistent w.r.t. $\mathcal{O}$
  - $i \in_{\mathcal{O}} C$ iff $\mathcal{O} \cup \{i \in \neg C\}$ is **not** consistent

Reasoning Support for Ontology Design: OilEd



Description Logic Reasoning

Highly Optimised Implementation

- Naive implementation $\longrightarrow$ effective non-termination
- Modern systems include **MANY** optimisations
- Optimised **classification**
  - Use enhanced traversal (exploit information from previous tests)
  - Use structural information to select classification order
- Optimised **subsumption** testing
  - Normalisation and simplification of concepts
  - Absorption (simplification) of general axioms
  - Davis-Putnam style semantic branching search
  - Dependency directed backtracking
  - Caching of satisfiability results and (partial) models
  - Heuristic ordering of propositional and modal expansion
  - . . .

Research Challenges

Research Challenges

- **Increased expressive power**
  - Existing DL systems implement (at most) $\mathcal{SHIQ}$
  - DAML+OIL extends $\mathcal{SHIQ}$ with datatypes and nominals
- **Scalability**
  - Very large KBs
  - Reasoning with (very large numbers of) individuals
- **Other reasoning tasks**
  - Querying
  - Matching
  - Least common subsumer
  - ...
- **Tools and Infrastructure**

Increased Expressive Power: Datatypes

☞ **DAML+OIL** has simple form of datatypes
  - Unary predicates plus disjoint object-class/datatype domains

☞ Well understood **theoretically**
  - Existing work on **concrete domains** [Baader & Hanschke, Lutz]
  - Algorithm already known for $\mathcal{SHOQ}(\mathbf{D})$ [Horrocks & Sattler]
  - Can use **hybrid reasoning** (DL reasoner + datatype “oracle”)

☞ May be **practically** challenging
  - All XMLS datatypes supported (?)

☞ Already seeing some (partial) **implementations**
  - Cerebra system (Network Inference), Racer system (Hamburg)

Increased Expressive Power: Nominals

☞ DAML+OIL **oneOf** constructor equivalent to hybrid logic **nominals**

- Extensionally defined concepts, e.g., EU $\equiv \{$France, Italy, $\ldots\}$

☞ Theoretically **very challenging**

- Resulting logic has known **high complexity** (NExpTime)
- No known “practical” algorithm
- Not obvious how to extend tableaux techniques in this direction
  - Loss of tree model property
  - Spy-points: $\top \sqsubseteq \exists R.\{Spy\}$
  - Finite domains: $\{Spy\} \sqsubseteq \leqslant nR^-$
- Promising research on **automata** based algorithms

☞ **Standard solution** is weaker semantics for nominals

- Treat nominals as (disjoint) primitive classes
- Loose some inferential power, e.g., w.r.t. max cardinality

Scalability

- Reasoning **hard** — even without nominals (i.e., $\mathcal{SHIQ}$)
- Web ontologies may grow **very large**
- Good **empirical evidence** of scalability/tractability for DL systems
  - E.g., 5,000 (complex) classes – 100,000+ (simple) classes
- But evidence mostly w.r.t. $\mathcal{SHF}$ (no inverse)
- **Problems** can arise when $\mathcal{SHF}$ extended to $\mathcal{SHIQ}$
  - Important **optimisations** no longer (fully) work
- Reasoning with **individuals**
  - **Deployment** of web ontologies will mean reasoning with (possibly very large numbers of) individuals/tuples
  - Unlikely that standard **Abox** techniques will be able to cope
  - Necessary to employ **database** technology

Other Reasoning Tasks

- **Querying**
  - Retrieval and instantiation wont be sufficient
  - Minimum requirement will be **conjunctive query language** [Tessaris & Horrocks]
  - May also need “what can I say about x?” style of query [Bechhofer & Horrocks]
- **Explanation** [McGuinness, Borgida et al]
  - To support ontology design
  - Justifications and proofs
- **LCS** and/or **matching** [Baader, Küsters & Molitor]
  - To support ontology integration
  - To support “bottom up” design of ontologies

Summary

- ☞ **Semantic Web** aims to make web resources accessible to automated processes
- ☞ **Ontologies** will play key role by providing vocabulary for semantic markup
- ☞ **DAML+OIL** is an ontology language designed for the web
  - Exploits existing standards: XML, RDF(S)
  - Formal rigor of Description Logic
  - KR idioms from object oriented and frame systems
- ☞ **Popular** combination of features—already being widely adopted
- ☞ **Challenges** remain
  - Reasoning with full language
  - Demonstration of scalability

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Resources

Slides from this talk

`http://www.cs.man.ac.uk/~horrocks/Slides/edbt02.pdf`

FaCT system (open source)

`http://www.cs.man.ac.uk/FaCT/`

OilEd (open source)

`http://oiled.man.ac.uk/`

OIL

`http://www.ontoknowledge.org/oil/`

DAML+OIL

`http://www.w3c.org/Submission/2001/12/`