DAML+OIL: a Reason-able Web Ontology Language

Ian Horrocks

horrocks@cs.man.ac.uk

University of Manchester

Manchester, UK

Talk Outline

Talk Outline

The Semantic Web

Talk Outline

- The Semantic Web
- Web Ontology Languages

Talk Outline

- The Semantic Web
- Web Ontology Languages
- DAML+OIL Language

Talk Outline

- The Semantic Web
- Web Ontology Languages
- DAML+OIL Language
- Reasoning with DAML+OIL
    - OilEd Demo

Talk Outline

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

Talk Outline

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

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

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

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

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

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

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

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

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

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

Realising the Semantic Web

- ☞ Semantic web vision is **extremely ambitious**

Realising the Semantic Web

- Semantic web vision is **extremely ambitious**
- Even partial realisation will be a **major undertaking**

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**

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**
- E.g., 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

Ontologies

- Semantic markup must be **meaningful** to automated processes

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)

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

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)

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

- 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

- Web languages already extended to facilitate **content description**
  - XML Schema (XMLS)
  - RDF and RDF Schema (RDFS)

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)

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

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

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)

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

- DAML+OIL **layered** on top of RDFS
  - RDFS based **syntax**
  - **Inherits** RDFS ontological primitives (subclass, range, domain)
  - Adds **much** richer set of primitives (transitivity, cardinality, . . .)

DAML+OIL

- DAML+OIL **layered** on top of RDFS
  - RDFS based **syntax**
  - **Inherits** RDFS ontological primitives (subclass, range, domain)
  - Adds **much** richer set of primitives (transitivity, 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

DAML+OIL

- DAML+OIL **layered** on top of RDFS
  - RDFS based **syntax**
  - **Inherits** RDFS ontological primitives (subclass, range, domain)
  - Adds **much** richer set of primitives (transitivity, 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; $\langle \mathrm{John}, \mathrm{Mary} \rangle$ is an instance of parent

DAML+OIL Language

Foundations

Foundations

- ☞ DAML+OIL equivalent to very expressive **Description Logic**

Foundations

- DAML+OIL equivalent to very expressive **Description Logic**
  - But don't tell anyone!

Foundations

- DAML+OIL equivalent to very expressive **Description Logic**
  - But don't tell anyone!
- More precisely, DAML+OIL is (extension of) $\mathcal{SHIQ}$ DL

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)

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

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

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

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

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)

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>
```

DAML+OIL Axioms

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	$\top \sqsubseteq \leqslant 1 P$	$\top \sqsubseteq \leqslant 1$hasMother
unambiguousProperty	$\top \sqsubseteq \leqslant 1 P^-$	$\top \sqsubseteq \leqslant 1$isMotherOf$^-$

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	$\top \sqsubseteq \leqslant 1 P$	$\top \sqsubseteq \leqslant 1$hasMother
unambiguousProperty	$\top \sqsubseteq \leqslant 1 P^-$	$\top \sqsubseteq \leqslant 1$isMotherOf$^-$

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

XML Datatypes in DAML+OIL

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)

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

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

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: $\text{John}^{\mathcal{I}} \neq (\text{int } 5)^{\mathcal{I}}$
  - 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

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: $\text{John}^{\mathcal{I}} \neq (\text{int } 5)^{\mathcal{I}}$
  - 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?

Why Provide Reasoning Services?

☞ **Understanding** closely related to reasoning

- Semantic Web aims at machine understanding

Why Provide Reasoning Services?

- **Understanding** closely related to reasoning
  - Semantic Web aims at machine understanding
- Reasoning useful at all stages of ontology life-cycle

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

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

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?

Why Decidable Reasoning?

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

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

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**

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

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 $\mathcal{O}$

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 $\mathcal{O}$

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 $\mathcal{O}$

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 $\mathcal{O}$

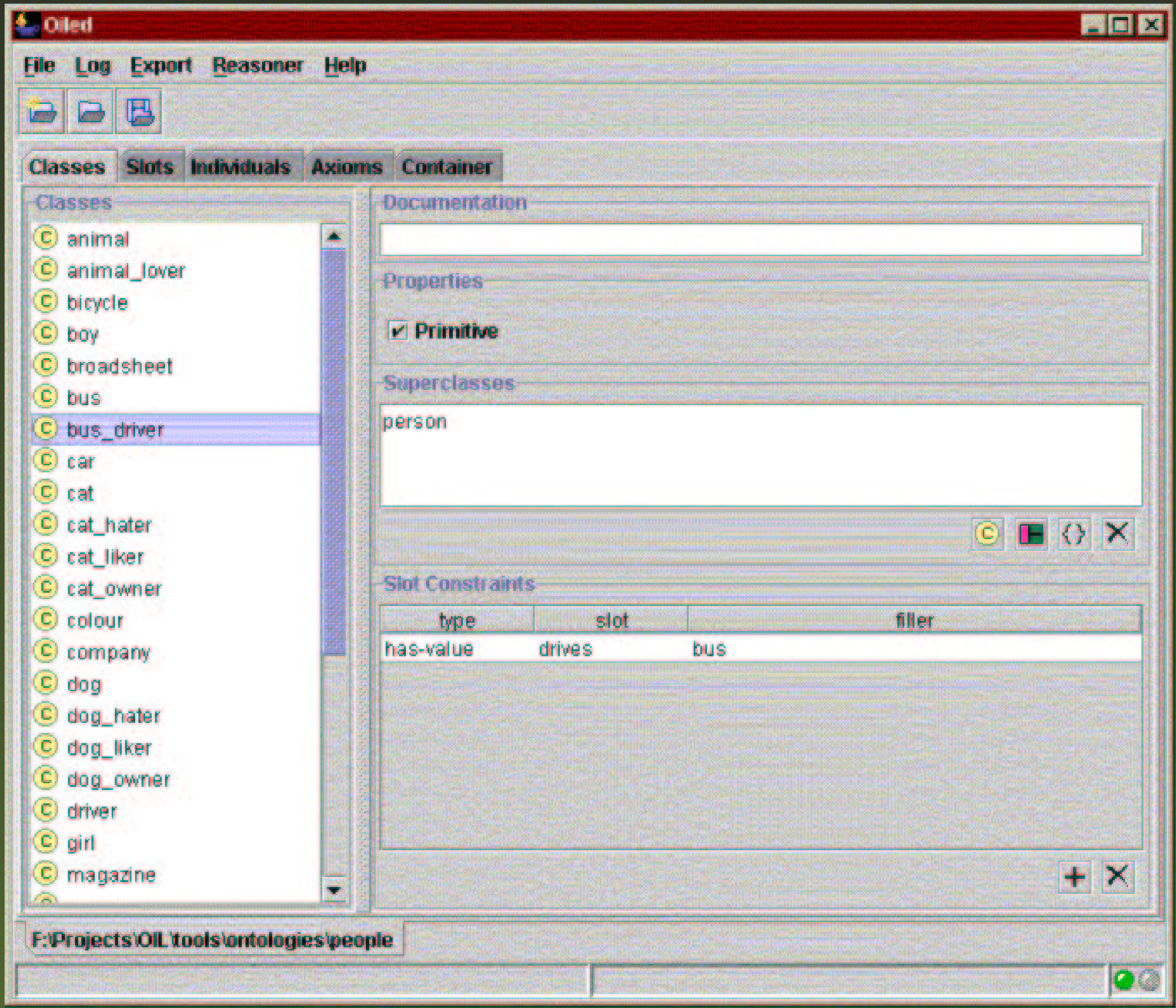
Basic Inference Problems

- **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 $\mathcal{O}$

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

Highly Optimised Implementation

- ☞ Naive implementation $\longrightarrow$ effective non-termination

Highly Optimised Implementation

- ☞ Naive implementation $\longrightarrow$ effective non-termination
- ☞ Modern systems include **MANY** optimisations

Highly Optimised Implementation

- Naive implementation $\longrightarrow$ effective non-termination
- Modern systems include **MANY** optimisations
- Optimised **classification** (compute partial ordering)
  - Use enhanced traversal (exploit information from previous tests)
  - Use structural information to select classification order

Highly Optimised Implementation

- Naive implementation $\longrightarrow$ effective non-termination
- Modern systems include **MANY** optimisations
- Optimised **classification** (compute partial ordering)
  - Use enhanced traversal (exploit information from previous tests)
  - Use structural information to select classification order
- Optimised **subsumption** testing (search for models)
  - 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

Research Challenges

☞ **Increased expressive power**

- Existing DL systems implement (at most) $\mathcal{SHIQ}$
- DAML+OIL extends $\mathcal{SHIQ}$ with datatypes and nominals

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

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
- $\ldots$

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

Increased Expressive Power: Datatypes

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

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”)

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 (?)

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

Increased Expressive Power: Nominals

- DAML+OIL **oneOf** constructor equivalent to hybrid logic **nominals**
  - Extensionally defined concepts, e.g., EU $\equiv \{\text{France}, \text{Italy}, \ldots\}$

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: $\{Spy\} \sqsubseteq \leqslant n R^-$

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

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: $\{Spy\} \sqsubseteq \leqslant n R^{-}$
  - 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

Scalability

- Reasoning **hard** — even without nominals (i.e., $\mathcal{SHIQ}$)

Scalability

- ☞ Reasoning **hard** — even without nominals (i.e., $\mathcal{SHIQ}$)
- ☞ Web ontologies may grow **very large**

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

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)

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

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

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]

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

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

Tools and Infrastructure

Tools and Infrastructure

- Ontology **design and maintenance**
  - Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
  - Need integrated **environments** supporting modularity, versioning, visualisation, explanation, high-level languages, . . .

Tools and Infrastructure

- Ontology **design and maintenance**
  - Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
  - Need integrated **environments** supporting modularity, versioning, visualisation, explanation, high-level languages, . . .
- Ontology **Integration**
  - Some tools available, e.g., Chimera (Stanford)
  - Need integrated **environments** . . .
  - Can learn from DB integration work [Lenzerini, Calvanese et al]

Tools and Infrastructure

- ☞ Ontology **design and maintenance**
  - Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
  - Need integrated **environments** supporting modularity, versioning, visualisation, explanation, high-level languages, . . .
- ☞ Ontology **Integration**
  - Some tools available, e.g., Chimera (Stanford)
  - Need integrated **environments** . . .
  - Can learn from DB integration work [Lenzerini, Calvanese et al]
- ☞ **Reasoning** engines
  - Several DL systems available
  - Need for improved usability/connectivity

Tools and Infrastructure

- Ontology **design and maintenance**
  - Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
  - Need integrated **environments** supporting modularity, versioning, visualisation, explanation, high-level languages, . . .
- Ontology **Integration**
  - Some tools available, e.g., Chimera (Stanford)
  - Need integrated **environments** . . .
  - Can learn from DB integration work [Lenzerini, Calvanese et al]
- **Reasoning** engines
  - Several DL systems available
  - Need for improved usability/connectivity
- . . .

Summary

☞ **Semantic Web** aims to make web resources accessible to automated processes

Summary

- ☞ **Semantic Web** aims to make web resources accessible to automated processes
- ☞ **Ontologies** will play key role by providing vocabulary for semantic markup

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

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

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
  - Development of (high quality) tools and infrastructure

Acknowledgements

- ☞ Members of the OIL and DAML+OIL development teams, in particular Dieter Fensel and Frank van Harmelen (Amsterdam) and Peter Patel-Schneider (Bell Labs)

Acknowledgements

- ☞ Members of the OIL and DAML+OIL development teams, in particular Dieter Fensel and Frank van Harmelen (Amsterdam) and Peter Patel-Schneider (Bell Labs)
- ☞ Franz Baader, Uli Satler and Stefan Tobies (Dresden — formerly Aachen)

Acknowledgements

- Members of the OIL and DAML+OIL development teams, in particular Dieter Fensel and Frank van Harmelen (Amsterdam) and Peter Patel-Schneider (Bell Labs)
- Franz Baader, Uli Satler and Stefan Tobies (Dresden — formerly Aachen)
- Members of the Information Management, Medical Informatics, Formal Methods and Artificial Intelligence Groups at the University of Manchester

Resources

Slides from this talk

`http://www.cs.man.ac.uk/~horrocks/Slides/caise02.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/`

I.COM (CASE tool with reasoning support)

`www.cs.man.ac.uk/~franconi/icom/`

Select Bibliography

F. Baader, S. Brandt, and R. Küsters. Matching under side conditions in description logics. In B. Nebel, editor, *Proc. of IJCAI-01*, pages 213–218, Seattle, Washington, 2001. Morgan Kaufmann.

F. Baader and P. Hanschke. A scheme for integrating concrete domains into concept languages. In *Proceedings of the 12th International Joint Conference on Artificial Intelligence (IJCAI-91)*, pages 452–457, 1991.

A. Borgida, E. Franconi, and I. Horrocks. Explaining $\mathcal{ALC}$ subsumption. In *Proc. of ECAI 2000*, pages 209–213. IOS Press, 2000.

D. Calvanese, G. De Giacomo, M. Lenzerini, D. Nardi, and R. Rosati. A principled approach to data integration and reconciliation in data warehousing. In *Proceedings of the International Workshop on Design and Management of Data Warehouses (DWDM'99)*, 1999.

I. Horrocks and U. Sattler. Ontology reasoning in the $\mathcal{SHOQ}(\mathbf{D})$ description logic. In B. Nebel, editor, *Proc. of IJCAI-01*, pages 199–204. Morgan Kaufmann, 2001.

Select Bibliography

I. Horrocks and S. Tessaris. A conjunctive query language for description logic aboxes. In *Proc. of AAAI 2000*, pages 399–404, 2000.

R. Küsters and R. Molitor. Approximating most specific concepts in description logics with existential restrictions. In *Proc. of the Joint German Austrian Conference on AI*, number 2174 in Lecture Notes in Artificial Intelligence, pages 33–47. Springer-Verlag, 2001.

C. Lutz. *The Complexity of Reasoning with Concrete Domains*. PhD thesis, Teaching and Research Area for Theoretical Computer Science, RWTH Aachen, 2001.

D. L. McGuinness. *Explaining Reasoning in Description Logics*. PhD thesis, Rutgers, The State University of New Jersey, 1996.