Logical Foundations for the Semantic Web

Reasoning with Expressive Description Logics: Theory and Practice

Ian Horrocks

horrocks@cs.man.ac.uk

University of Manchester

Manchester, UK

Talk Outline

Talk Outline

Introduction to Description Logics

Talk Outline

- Introduction to Description Logics
- The Semantic Web

Talk Outline

- Introduction to Description Logics
- The Semantic Web
- Web Ontology Languages

Talk Outline

Introduction to Description Logics

The Semantic Web

Web Ontology Languages

DAML+OIL and OWL Languages

Talk Outline

- Introduction to Description Logics
- The Semantic Web
- Web Ontology Languages
- DAML+OIL and OWL Languages
- Reasoning with OWL
    - OilEd Demo

Talk Outline

- Introduction to Description Logics
- The Semantic Web
- Web Ontology Languages
- DAML+OIL and OWL Languages
- Reasoning with OWL
  - OilEd Demo
- Research Challenges

Introduction to Description Logics

What are Description Logics?

What are Description Logics?

- A family of logic based Knowledge Representation formalisms
  - Descendants of **semantic networks** and **KL-ONE**
  - Describe domain in terms of **concepts** (classes), **roles** (relationships) and **individuals**

What are Description Logics?

- A family of logic based Knowledge Representation formalisms
  - Descendants of **semantic networks** and **KL-ONE**
  - Describe domain in terms of **concepts** (classes), **roles** (relationships) and **individuals**
- Distinguished by:
  - **Formal semantics** (model theoretic)
    - Decidable fragments of FOL
    - Closely related to Propositional Modal & Dynamic Logics
  - Provision of **inference services**
    - Sound and complete decision procedures for key problems
    - Implemented systems (highly optimised)

Short History of Description Logics

Short History of Description Logics

Phase 1:

- ☞ Incomplete systems (Back, Classic, Loom, . . .)
- ☞ Based on **structural algorithms**

Short History of Description Logics

Phase 1:

- ☞ Incomplete systems (Back, Classic, Loom, . . .)
- ☞ Based on **structural algorithms**

Phase 2:

- ☞ Development of **tableau algorithms** and **complexity results**
- ☞ Tableau-based systems (Kris, Crack)
- ☞ Investigation of optimisation techniques

Short History of Description Logics

Phase 1:

- ☞ Incomplete systems (Back, Classic, Loom, . . .)
- ☞ Based on **structural algorithms**

Phase 2:

- ☞ Development of **tableau algorithms** and **complexity results**
- ☞ Tableau-based systems (Kris, Crack)
- ☞ Investigation of optimisation techniques

Phase 3:

- ☞ Tableau algorithms for **very expressive** DLs
- ☞ **Highly optimised** tableau systems (FaCT, DLP, Racer)
- ☞ Relationship to modal logic and decidable fragments of FOL

Latest Developments

Phase 4:

Latest Developments

Phase 4:

- Mature **implementations**

Latest Developments

Phase 4:

☞ Mature **implementations**

☞ Mainstream **applications** and Tools

- Databases
  - Consistency of conceptual schemata (EER, UML etc.)
  - Schema integration
  - Query subsumption (w.r.t. a conceptual schema)
- Ontologies and **Semantic Web** (and **Grid**)
  - Ontology engineering (design, maintenance, integration)
  - Reasoning with ontology-based markup (meta-data)
  - Service description and discovery

Latest Developments

Phase 4:

- ☞ Mature **implementations**
- ☞ Mainstream **applications** and Tools
  - Databases
    - Consistency of conceptual schemata (EER, UML etc.)
    - Schema integration
    - Query subsumption (w.r.t. a conceptual schema)
  - Ontologies and **Semantic Web** (and **Grid**)
    - Ontology engineering (design, maintenance, integration)
    - Reasoning with ontology-based markup (meta-data)
    - Service description and discovery
- ☞ **Commercial** implementations
  - Cerebra system from Network Inference Ltd

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

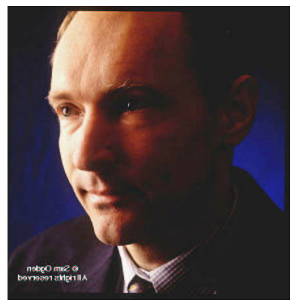
- Web made possible through established **standards**
  - **TCP/IP** for transporting bits down a wire
  - **HTTP & HTML** for transporting and rendering hyperlinked text
- **Applications** able to exploit this common infrastructure
  - Result is the WWW as we know it
- **1st generation** web mostly 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**

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**



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 **properties** of instances 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 **properties** of instances of each concept
- Degree of formality can be quite variable (NL–logic)

Ontologies

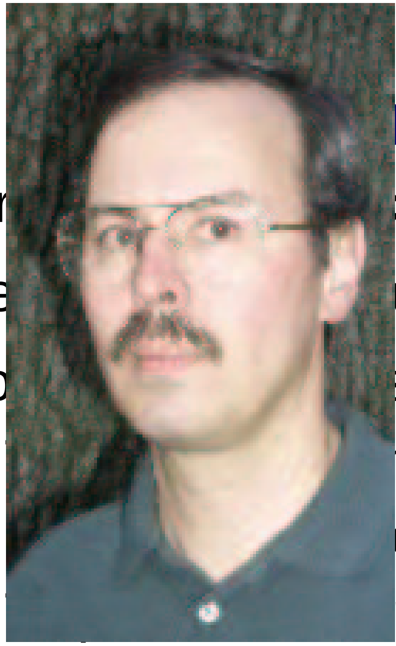
- Semantic markup must be **meaningful** to automated processes
- Ontologies will play a key role
  - Source of **precisely defined** terms (vocabulary)
  - Can be **shared** across applications (and humans)
- Ontology typically consists of:
  - **Hierarchical** description of important **concepts** in domain
  - Descriptions of **properties** of instances 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 **properties** of instances 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 agent-agent communication in **e-commerce**
  - In semantic based **search**
  - To provide richer **service descriptions** that can be more flexibly interpreted by intelligent agents

Ontologies

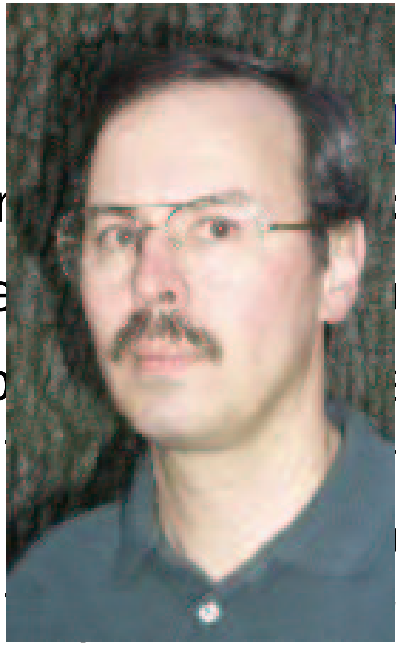
- Semantic markup must be **meaningful** to automated processes
- Ontologies will play a key role
  - Source of **precisely defined** terms (vocabulary)
  - Can be **shared** across applications (and humans)
- Ontology typically consists of:

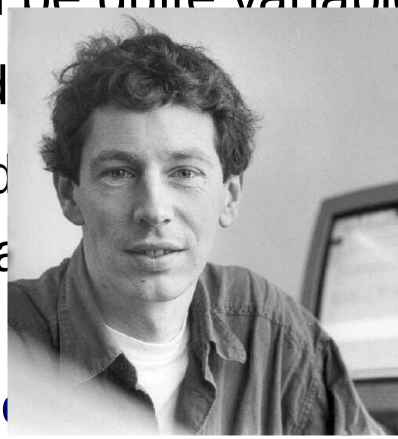


  - scription of important **concepts** in domain
  - **properties** of instances of each concept
- Degr can be quite variable (NL–logic)
- Incre and regularity facilitates machine understanding
- Onto sed, e.g.:
  - nt-agent communication in **e-commerce**
  - ed **search**
  - r **service descriptions** that can be more flexibly interpreted by intelligent agents

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:
  - scription of important **concepts** in domain
  - **properties** of instances of each concept

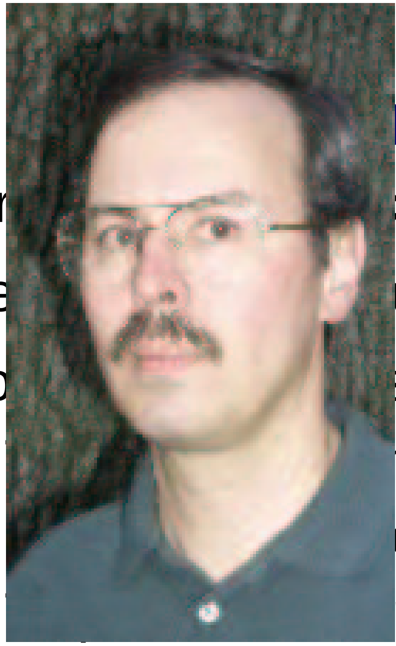


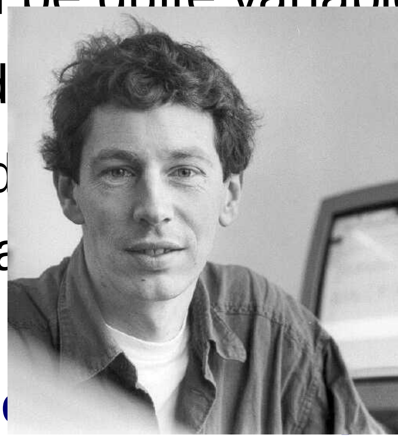


- Degr can be quite variable (NL–logic)
- Incre and ates machine understanding
- Onto sed
  - nt-a ation in **e-commerce**
  - ed
  - r **s ions** that can be more flexibly interpreted by intelligent agents

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:
  - scription of important **concepts** in domain
  - **properties** of instances of each concept
- Degr can be quite variable (
- Incre and ate rstanding
- Onto sed
  - nt-a atio **ce**
  - ed
  - r **s ion** ore 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 familiar KR idioms)
  - **Formally specified** and of "adequate" expressive power
  - Possible to provide **automated reasoning** support

OIL, DAML-ONT, DAML+OIL and OWL

OIL, DAML-ONT, DAML+OIL and OWL

☞ Two languages developed to satisfy above requirements

- **OIL**: developed by group of (largely) European researchers
- **DAML-ONT**: developed in DARPA DAML programme

OIL, DAML-ONT, DAML+OIL and OWL

- Two languages developed to satisfy above requirements
  - **OIL**: developed by group of (largely) European researchers
  - **DAML-ONT**: developed in DARPA DAML programme
- Efforts merged to produce **DAML+OIL**

OIL, DAML-ONT, DAML+OIL and OWL

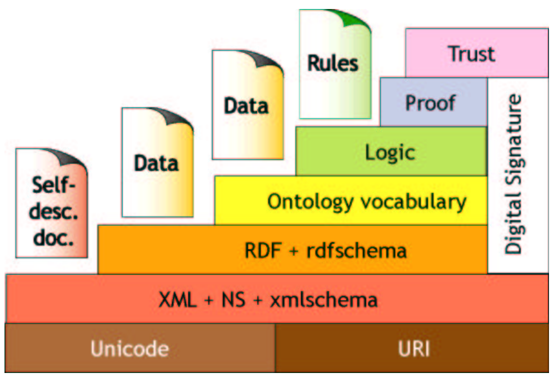
- Two languages developed to satisfy above requirements
  - **OIL**: developed by group of (largely) European researchers
  - **DAML-ONT**: developed in DARPA DAML programme
- Efforts merged to produce **DAML+OIL**
- **Submitted to W3C** as basis for standardisation
  - **WebOnt working group** developing **OWL** language standard

OIL, DAML-ONT, DAML+OIL and OWL

- Two languages developed to satisfy above requirements
  - **OIL**: developed by group of (largely) European researchers
  - **DAML-ONT**: developed in DARPA DAML programme
- Efforts merged to produce **DAML+OIL**
- **Submitted to W3C** as basis for standardisation
  - **WebOnt working group** developing **OWL** language standard
- DAML+OIL/OWL **“layered”** on top of RDFS
  - RDFS based **syntax** and ontological primitives (subclass etc.)
  - Adds **much** richer set of primitives (transitivity, cardinality, . . .)

OIL, DAML-ONT, DAML+OIL and OWL

- Two languages developed to satisfy above requirements
  - **OIL**: developed by group of (largely) European researchers
  - **DAML-ONT**: developed in DARPA DAML programme
- Efforts merged to produce **DAML+OIL**
- **Submitted to W3C** as basis for standardisation
  - **WebOnt working group** developing **OWL** language standard
- DAML+OIL/OWL **“layered”** on top of RDFS
  - RDFS based **syntax** and ontological primitives (subclass etc.)
  - Adds **much** richer set of primitives (transitivity, cardinality, . . .)



OIL, DAML-ONT, DAML+OIL and OWL

- Two languages developed to satisfy above requirements
  - **OIL**: developed by group of (largely) European researchers
  - **DAML-ONT**: developed in DARPA DAML programme
- Efforts merged to produce **DAML+OIL**
- **Submitted to W3C** as basis for standardisation
  - **WebOnt working group** developing **OWL** language standard
- DAML+OIL/OWL **“layered”** on top of RDFS
  - RDFS based **syntax** and ontological primitives (subclass etc.)
  - Adds **much** richer set of primitives (transitivity, cardinality, . . .)
- Describes **structure** of domain in terms of Classes and Properties
  - Ontology is set of **axioms** describing classes and properties
  - E.g., Person **subclass of** Animal whose parents are all Persons

OIL, DAML-ONT, DAML+OIL and OWL

- Two languages developed to satisfy above requirements
  - **OIL**: developed by group of (largely) European researchers
  - **DAML-ONT**: developed in DARPA DAML programme
- Efforts merged to produce **DAML+OIL**
- **Submitted to W3C** as basis for standardisation
  - **WebOnt working group** developing **OWL** language standard
- DAML+OIL/OWL **"layered"** on top of RDFS
  - RDFS based **syntax** and ontological primitives (subclass etc.)
  - Adds **much** richer set of primitives (transitivity, cardinality, . . .)
- Describes **structure** of domain in terms of Classes and Properties
  - Ontology is set of **axioms** describing classes and properties
  - E.g., Person **subclass of** Animal whose parents are all Persons
- Uses RDF for class/property membership assertions (ground facts)
  - E.g., john **instance of** Person; $\langle \text{john}, \text{mary} \rangle$ instance of parent

OWL Language

Foundations

Foundations

- Three species of OWL
  - OWL full is union of OWL syntax and RDF
  - OWL DL restricted to FOL fragment ($\approx$DAML+OIL)
  - OWL Lite is “easier to implement” subset of OWL DL

Foundations

- Three species of OWL
  - OWL full is union of OWL syntax and RDF
  - OWL DL restricted to FOL fragment (≈DAML+OIL)
  - OWL Lite is “easier to implement” subset of OWL DL
- Semantic layering
  - OWL DL $\equiv$ OWL full **within DL fragment**
  - DL semantics officially **definitive**

Foundations

- Three species of OWL
  - OWL full is union of OWL syntax and RDF
  - OWL DL restricted to FOL fragment (≈DAML+OIL)
  - OWL Lite is “easier to implement” subset of OWL DL
- Semantic layering
  - OWL DL $\equiv$ OWL full **within DL fragment**
  - DL semantics officially **definitive**
- OWL DL based on $\mathcal{SHIQ}$ **Description Logic**

Foundations

☞ Three species of OWL

- OWL full is union of OWL syntax and RDF
- OWL DL restricted to FOL fragment ($\approx$DAML+OIL)
- OWL Lite is “easier to implement” subset of OWL DL

☞ Semantic layering

- OWL DL $\equiv$ OWL full **within DL fragment**
- DL semantics officially **definitive**

☞ OWL DL based on $\mathcal{SHIQ}$ **Description Logic**

☞ Benefits from many years of DL research

- Well defined **semantics**
- **Formal properties** well understood (complexity, decidability)
- Known **reasoning algorithms**
- **Implemented systems** (highly optimised)

OWL Class Constructors

Constructor	DL Syntax	Example	(Modal Syntax)
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	Human $\sqcap$ Male	$C_1 \wedge \ldots \wedge C_n$
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	Doctor $\sqcup$ Lawyer	$C_1 \vee \ldots \vee C_n$
complementOf	$\neg C$	$\neg$Male	$\neg C$
oneOf	$\{x_1 \ldots x_n\}$	{john, mary}	$x_1 \vee \ldots \vee x_n$
allValuesFrom	$\forall P.C$	$\forall$hasChild.Doctor	$[P]C$
someValuesFrom	$\exists P.C$	$\exists$hasChild.Lawyer	$\langle P \rangle C$
maxCardinality	$\leqslant n P$	$\leqslant$1hasChild	$[P]_{n+1}$
minCardinality	$\geqslant n P$	$\geqslant$2hasChild	$\langle P \rangle_n$

OWL Class Constructors

Constructor	DL Syntax	Example	(Modal Syntax)
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	Human $\sqcap$ Male	$C_1 \wedge \ldots \wedge C_n$
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	Doctor $\sqcup$ Lawyer	$C_1 \vee \ldots \vee C_n$
complementOf	$\neg C$	$\neg$Male	$\neg C$
oneOf	$\{x_1 \ldots x_n\}$	{john, mary}	$x_1 \vee \ldots \vee x_n$
allValuesFrom	$\forall P.C$	$\forall$hasChild.Doctor	$[P]C$
someValuesFrom	$\exists P.C$	$\exists$hasChild.Lawyer	$\langle P \rangle C$
maxCardinality	$\leqslant n P$	$\leqslant$1hasChild	$[P]_{n+1}$
minCardinality	$\geqslant n P$	$\geqslant$2hasChild	$\langle P \rangle_n$

☞ XMLS **datatypes** as well as classes in $\forall P.C$ and $\exists P.C$

- E.g., $\exists$hasAge.nonNegativeInteger

OWL Class Constructors

Constructor	DL Syntax	Example	(Modal Syntax)
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	Human $\sqcap$ Male	$C_1 \land \ldots \land C_n$
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	Doctor $\sqcup$ Lawyer	$C_1 \lor \ldots \lor C_n$
complementOf	$\neg C$	$\neg$Male	$\neg C$
oneOf	$\{x_1 \ldots x_n\}$	{john, mary}	$x_1 \lor \ldots \lor x_n$
allValuesFrom	$\forall P.C$	$\forall$hasChild.Doctor	$[P]C$
someValuesFrom	$\exists P.C$	$\exists$hasChild.Lawyer	$\langle P \rangle C$
maxCardinality	$\leqslant n P$	$\leqslant$1hasChild	$[P]_{n+1}$
minCardinality	$\geqslant n P$	$\geqslant$2hasChild	$\langle P \rangle_n$

- ☞ XMLS **datatypes** as well as classes in $\forall P.C$ and $\exists P.C$
  - E.g., $\exists$hasAge.nonNegativeInteger
- ☞ Arbitrarily complex **nesting** of constructors
  - E.g., Person $\sqcap$ $\forall$hasChild.(Doctor $\sqcup$ $\exists$hasChild.Doctor)

RDFS Syntax

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

OWL DL Semantics

OWL DL Semantics

☞ Semantics defined by **interpretations**: $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$

- concepts $\longrightarrow$ subsets of $\Delta^{\mathcal{I}}$
- roles $\longrightarrow$ binary relations over $\Delta^{\mathcal{I}}$ (subsets of $\Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$)
- individuals $\longrightarrow$ elements of $\Delta^{\mathcal{I}}$

OWL DL Semantics

☞ Semantics defined by **interpretations**: $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$

- concepts $\longrightarrow$ subsets of $\Delta^{\mathcal{I}}$
- roles $\longrightarrow$ binary relations over $\Delta^{\mathcal{I}}$ (subsets of $\Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$)
- individuals $\longrightarrow$ elements of $\Delta^{\mathcal{I}}$

☞ Interpretation function $\cdot^{\mathcal{I}}$ **extended** to concept expressions

- $(C \sqcap D)^{\mathcal{I}} = C^{\mathcal{I}} \cap D^{\mathcal{I}} \quad (C \sqcup D)^{\mathcal{I}} = C^{\mathcal{I}} \cup D^{\mathcal{I}} \quad (\neg C)^{\mathcal{I}} = \Delta^{\mathcal{I}} \setminus C^{\mathcal{I}}$
- $\{x_n, \ldots, x_n\}^{\mathcal{I}} = \{x_n^{\mathcal{I}}, \ldots, x_n^{\mathcal{I}}\}$
- $(\exists R.C)^{\mathcal{I}} = \{x \mid \exists y.\langle x, y\rangle \in R^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\}$
- $(\forall R.C)^{\mathcal{I}} = \{x \mid \forall y.(x, y) \in R^{\mathcal{I}} \Rightarrow y \in C^{\mathcal{I}}\}$
- $(\leqslant nR)^{\mathcal{I}} = \{x \mid \#\{y \mid \langle x, y\rangle \in R^{\mathcal{I}}\} \leqslant n\}$
- $(\geqslant nR)^{\mathcal{I}} = \{x \mid \#\{y \mid \langle x, y\rangle \in R^{\mathcal{I}}\} \geqslant n\}$

OWL Axioms

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

OWL Axioms

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

☞ $\mathcal{I}$ **satisfies** $C_1 \sqsubseteq C_2$ iff $C_1^{\mathcal{I}} \subseteq C_2^{\mathcal{I}}$; satisfies $P_1 \sqsubseteq P_2$ iff $P_1^{\mathcal{I}} \subseteq P_2^{\mathcal{I}}$

OWL Axioms

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

- $\mathcal{I}$ **satisfies** $C_1 \sqsubseteq C_2$ iff $C_1^{\mathcal{I}} \subseteq C_2^{\mathcal{I}}$; satisfies $P_1 \sqsubseteq P_2$ iff $P_1^{\mathcal{I}} \subseteq P_2^{\mathcal{I}}$
- $\mathcal{I}$ satisfies ontology $\mathcal{O}$ (is a **model** of $\mathcal{O}$) iff satisfies every axiom in $\mathcal{O}$

XML Datatypes in OWL

XML Datatypes in OWL

- OWL supports **XML Schema** primitive datatypes

XML Datatypes in OWL

- OWL supports **XML Schema** primitive datatypes
- Clean **separation** between “object” classes and datatypes
  - Disjoint interpretation domain: $d^{\mathcal{I}} \subseteq \Delta_{\mathbf{D}}$, and $\Delta_{\mathbf{D}} \cap \Delta^{\mathcal{I}} = \emptyset$
  - Disjoint datatype properties: $P_{\mathbf{D}}^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta_{\mathbf{D}}$

XML Datatypes in OWL

- OWL supports **XML Schema** primitive datatypes
- Clean **separation** between “object” classes and datatypes
  - Disjoint interpretation domain: $d^{\mathcal{I}} \subseteq \Delta_{\mathbf{D}}$, and $\Delta_{\mathbf{D}} \cap \Delta^{\mathcal{I}} = \emptyset$
  - Disjoint datatype properties: $P_{\mathbf{D}}^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta_{\mathbf{D}}$
- Philosophical reasons:
  - Datatypes structured by **built-in predicates**
  - Not appropriate to form new datatypes using ontology language

XML Datatypes in OWL

- OWL supports **XML Schema** primitive datatypes
- Clean **separation** between "object" classes and datatypes
  - Disjoint interpretation domain: $d^{\mathcal{I}} \subseteq \Delta_{\mathbf{D}}$, and $\Delta_{\mathbf{D}} \cap \Delta^{\mathcal{I}} = \emptyset$
  - Disjoint datatype properties: $P_{\mathbf{D}}^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta_{\mathbf{D}}$
- 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
    - Only need sound and complete decision procedure for $d_1^{\mathcal{I}} \cap \ldots \cap d_n^{\mathcal{I}}$, where d_i is a (possibly negated) datatype

Reasoning with OWL DL

Reasoning

Reasoning

- ☞ Why do we want it?

Reasoning

- Why do we want it?
  - Semantic Web aims at “machine understanding”
  - **Understanding** closely related to **reasoning**

Reasoning

- ☞ Why do we want it?
  - Semantic Web aims at “machine understanding”
  - **Understanding** closely related to **reasoning**
- ☞ What can we do with it?

Reasoning

- Why do we want it?
  - Semantic Web aims at “machine understanding”
  - **Understanding** closely related to **reasoning**
- What can we do with it?
  - **Design and maintenance** of ontologies
    - Check class consistency and compute class hierarchy
    - Particularly important with large ontologies/multiple authors

Reasoning

- ☞ Why do we want it?
  - Semantic Web aims at "machine understanding"
  - **Understanding** closely related to **reasoning**
- ☞ What can we do with it?
  - **Design and maintenance** of ontologies
    - Check class consistency and compute class hierarchy
    - Particularly important with large ontologies/multiple authors
  - **Integration** of ontologies
    - Assert inter-ontology relationships
    - Reasoner computes integrated class hierarchy/consistency

Reasoning

- Why do we want it?
  - Semantic Web aims at “machine understanding”
  - **Understanding** closely related to **reasoning**
- What can we do with it?
  - **Design and maintenance** of ontologies
    - Check class consistency and compute class hierarchy
    - Particularly important with large ontologies/multiple authors
  - **Integration** of ontologies
    - Assert inter-ontology relationships
    - Reasoner computes integrated class hierarchy/consistency
  - **Querying** class and instance data w.r.t. ontologies
    - Determine if set of facts are consistent w.r.t. ontologies
    - Determine if individuals are instances of ontology classes
    - Retrieve individuals/tuples satisfying a query expression
    - Check if one class subsumes (is more general than) another w.r.t. ontology
    - . . .

Why Decidable Reasoning?

Why Decidable Reasoning?

☞ OWL DL constructors/axioms restricted so reasoning is **decidable**

Why Decidable Reasoning?

- OWL DL 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
  - OWL DL provides powerful but still decidable **ontology language**
  - Further layers may (will) extend OWL
    - Will almost certainly be undecidable

Why Decidable Reasoning?

- OWL DL 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
  - OWL DL provides powerful but still decidable **ontology language**
  - Further layers may (will) extend OWL
    - Will almost certainly be undecidable
- Facilitates provision of **reasoning services**
  - Known “practical” **algorithms**
  - Several implemented **systems**
  - Evidence of **empirical tractability**

Why Decidable Reasoning?

- OWL DL 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
  - OWL DL provides powerful but still decidable **ontology language**
  - Further layers may (will) extend OWL
    - 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 $\mathcal{O}$

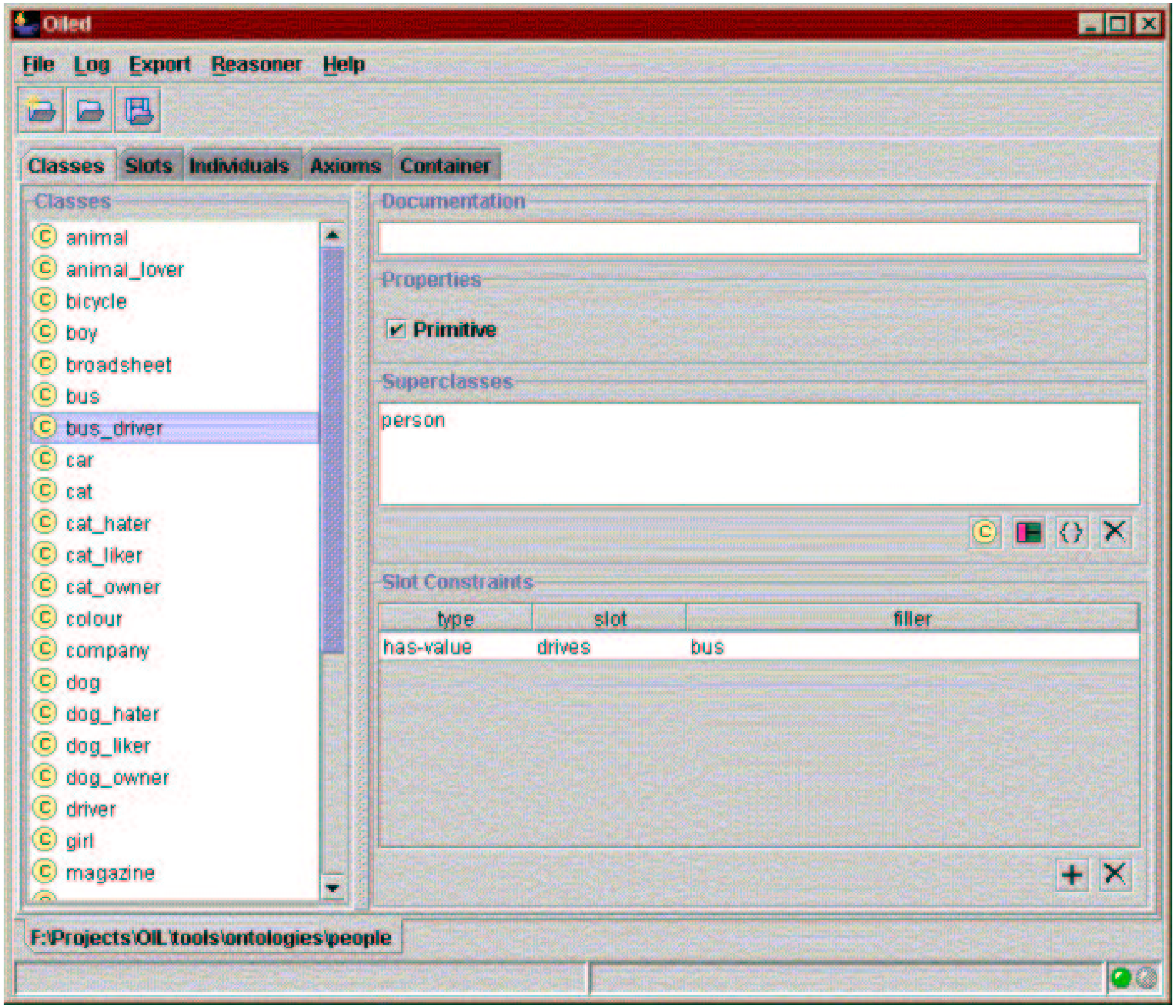
☞ **Retrieval** — retrieve set of individuals that instantiate C

- set of i s.t. $i \in C^{\mathcal{I}}$ in all models $\mathcal{I}$ of $\mathcal{O}$

☞ Problems all **reducible** to consistency (satisfiability):

- $C \sqsubseteq_{\mathcal{O}} D$ iff $C \sqcap \neg D$ 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

☞ DL reasoning based on tableaux algorithms

Highly Optimised Implementation

- ☞ DL reasoning based on tableaux algorithms
- ☞ Naive implementation $\longrightarrow$ effective non-termination

Highly Optimised Implementation

- ☞ DL reasoning based on tableaux algorithms
- ☞ Naive implementation $\longrightarrow$ effective non-termination
- ☞ Modern systems include **MANY** optimisations

Highly Optimised Implementation

- DL reasoning based on tableaux algorithms
- 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

- DL reasoning based on tableaux algorithms
- 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 and Implementation Challenges

Challenges

Challenges

☞ **Increased expressive power**

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

Challenges

- **Increased expressive power**
  - Existing DL systems implement (at most) $\mathcal{SHIQ}$
  - OWL extends $\mathcal{SHIQ}$ with datatypes and nominals
- **Scalability**
  - Very large KBs
  - Reasoning with (very large numbers of) individuals

Challenges

- **Increased expressive power**
  - Existing DL systems implement (at most) $\mathcal{SHIQ}$
  - OWL 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
  - ...

Challenges

- **Increased expressive power**
  - Existing DL systems implement (at most) $\mathcal{SHIQ}$
  - OWL 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**
  - Support for large scale ontological engineering and deployment

Increased Expressive Power: Datatypes

Increased Expressive Power: Datatypes

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

Increased Expressive Power: Datatypes

- **OWL** 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

- **OWL** 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
  - Large number of XMLS datatypes may be supported

Increased Expressive Power: Datatypes

- **OWL** 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
  - Large number of XMLS datatypes may be supported
- Already seeing some (partial) **implementations**
  - Cerebra system (Network Inference), Racer system (Hamburg)

Increased Expressive Power: Nominals

Increased Expressive Power: Nominals

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

Increased Expressive Power: Nominals

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

- OWL **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: $\{Spy\} \sqsubseteq \leqslant nR^{-}$
  - ?? **automata** based algorithms ??

Increased Expressive Power: Nominals

- OWL **oneOf** constructor equivalent to hybrid logic **nominals**
  - Extensionally defined concepts, e.g., EU $\equiv \{\text{France}, \text{Italy}, \ldots\}$
- 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: $\{Spy\} \sqsubseteq \leqslant n R^{-}$
  - ?? **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

Other Reasoning Tasks

Other Reasoning Tasks

☞ **Querying**

- Retrieval and instantiation wont be sufficient
- Minimum requirement will be **DB style query language**
- May also need “what can I say about x?” style of query

Other Reasoning Tasks

- **Querying**
  - Retrieval and instantiation wont be sufficient
  - Minimum requirement will be **DB style query language**
  - May also need “what can I say about x?” style of query
- **Explanation**
  - To support ontology design
  - Justifications and proofs (e.g., of query results)

Other Reasoning Tasks

- **Querying**
  - Retrieval and instantiation wont be sufficient
  - Minimum requirement will be **DB style query language**
  - May also need “what can I say about x?” style of query
- **Explanation**
  - To support ontology design
  - Justifications and proofs (e.g., of query results)
- “**Non-Standard Inferences**”, e.g., LCS, matching
  - To support ontology integration
  - To support “bottom up” design of ontologies

Summary

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
- ☞ **OWL** is an ontology language designed for the web
  - Exploits existing standards: XML, RDF(S)
  - Adds KR idioms from object oriented and frame systems
  - Formal rigor of a **logic**
  - Facilitates provision of **reasoning support**

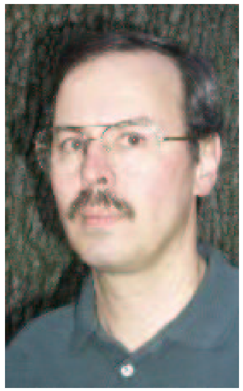
Summary

- **Semantic Web** aims to make web resources accessible to automated processes
- **Ontologies** will play key role by providing vocabulary for semantic markup
- **OWL** is an ontology language designed for the web
  - Exploits existing standards: XML, RDF(S)
  - Adds KR idioms from object oriented and frame systems
  - Formal rigor of a **logic**
  - Facilitates provision of **reasoning support**
- **Challenges** remain
  - Reasoning with nominals
  - (Convincing) demonstration(s) of scalability
  - New reasoning tasks

Acknowledgements

Acknowledgements

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

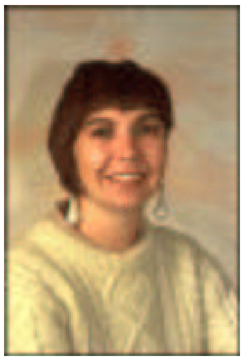


Acknowledgements

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

Acknowledgements

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



Resources

Slides from this talk

`http://www.cs.man.ac.uk/~horrocks/Slides/glasgow03.pdf`

FaCT system (open source)

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

OilEd (open source)

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

DAML+OIL

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

W3C Web-Ontology (WebOnt) working group (OWL)

`http://www.w3.org/2001/sw/WebOnt/`

Description Logic Handbook

Cambridge University Press

Select Bibliography

I. Horrocks. DAML+OIL: a reason-able web ontology language. In *Proc. of EDBT 2002*, number 2287 in Lecture Notes in Computer Science, pages 2–13. Springer-Verlag, Mar. 2002.

I. Horrocks, P. F. Patel-Schneider, and F. van Harmelen. Reviewing the design of DAML+OIL: An ontology language for the semantic web. In *Proc. of AAAI 2002*, 2002. To appear.

I. Horrocks and S. Tessaris. Querying the semantic web: a formal approach. In I. Horrocks and J. Hendler, editors, *Proc. of the 2002 International Semantic Web Conference (ISWC 2002)*, number 2342 in Lecture Notes in Computer Science. Springer-Verlag, 2002.

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

Select Bibliography

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.

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.

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.