The Semantic Web: (Ontology) Languages and Reasoning

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Semantic Web Ontology Languages

US **DAML** programme (in cooperation with W3C and a cast of thousands) aim to develop so-called **Semantic Web**

- Most existing Web resources only human understandable
  - Markup (HTML) provides rendering information
  - Textual/graphical information for human consumption
- Semantic Web aims at machine understandability
  - **Semantic** markup will be added to web resources
  - Markup will use **Ontologies** for shared understanding
- Requirement for a suitable ontology language
  - Compatible with existing Web standards (XML, RDF, RDFS)
  - Captures common KR idioms
  - Formally specified and of adequate expressive power
  - Can provide reasoning support
- DAML-ONT language developed to meet these requirements

OIL and DAML+OIL

Meanwhile, somewhere in darkest Europe…

- **OIL** language already developed to meet similar requirements
  - Extends existing Web standards (XML, RDF, RDFS)
  - Intuitive (frame) syntax plus high expressive power
  - Well defined semantics via mapping to $\mathcal{SHIQ}$ DL
  - Can use DL systems to reason with OIL ontologies
- Two efforts merged to produce single language, **DAML+OIL**
- Detailed specification agreed by **Joint EU/US Committee on Agent Markup Languages**
- Proposed W3C Ontology Language WG will take DAML+OIL as starting point (?)

DAML+OIL Language Overview

DAML+OIL is an **ontology** language

- Describes **structure** of the domain (i.e., a Tbox)
  - RDF used to describe specific **instances** (i.e., an Abox)
- Structure described in terms of **classes** (concepts) and **properties** (roles)
- Ontology consists of set of **axioms**
  - E.g., asserting class subsumption/equivalence
- Classes can be names or **expressions**
  - Various **constructors** provided for building class expressions
- **Expressive power** determined by
  - Kinds of axiom supported
  - Kinds of class (and property) constructor supported

DAML+OIL Overview: Class Constructors

Constructor	DL Syntax	Example
intersectionOf	$C_1 \sqcap ... \sqcap C_n$	Human $\sqcap$ Male
unionOf	$C_1 \sqcup ... \sqcup C_n$	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., $\forall$hasChild.$($Doctor $\sqcup$ $\exists$hasChild.Doctor$)$

DAML+OIL Overview: Axioms

Axiom	DL Syntax	Example
subClassOf	$C_1 \sqsubseteq C_2$	Human $\sqsubseteq$ Animal $\sqcap$ Biped
sameClassAs	$C_1 \doteq C_2$	Man $\doteq$ Human $\sqcap$ Male
subPropertyOf	$P_1 \sqsubseteq P_2$	hasDaughter $\sqsubseteq$ hasChild
samePropertyAs	$P_1 \doteq P_2$	cost $\doteq$ price
sameIndividualAs	$\{x_1\} \doteq \{x_2\}$	$\{$President_Bush$\} \doteq \{$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	$P_1 \doteq P_2^-$	hasChild $\doteq$ 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**

DAML+OIL

- Is a **Description Logic** (but don't tell anyone)
- More precisely, DAML+OIL is $\mathcal{SHIQ}$
  - Plus **nominals**
  - Plus **datatypes** (simple concrete domains)
  - With RDFS based syntax
- $\mathcal{SHIQ}$/DAML+OIL was not built in a day (or even a year)
  - $\mathcal{SHIQ}$ is based on 15+ years of DL research
- Can use DL reasoning with DAML+OIL
  - Existing $\mathcal{SHIQ}$ implementations support (most of) DAML+OIL

Why Reasoning Services?

Reasoning is important for:

- Ontology **design**
  - 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

"**The Semantic Web needs a logic on top**" (Henry Thompson)

Why Decidable Reasoning?

Set of operators/axioms restricted so that reasoning is **decidable**

- Consistent with Semantic Web's **layered architecture**
  - XML provides syntax transport layer
  - RDF provides basic relational language
  - RDFS provides basic ontological primitives
  - DAML+OIL provides (decidable) logical layer
  - Further layers (e.g., **rules**) will extend DAML+OIL
    - → Extensions will almost certainly be **undecidable**
- Facilitates provision of **reasoning services**
  - Known algorithms
  - Implemented systems
  - Evidence of **empirical tractability**

Challenges

- **Increased expressive power**
  - Datatypes
  - Nominals
  - Extensions to DAML+OIL
- **Performance (even of existing $\mathcal{SHIQ}$ implementations)**
  - Inverse roles and qualified number restrictions
  - Very large KBs
  - Reasoning with individuals
- **Tools and Infrastructure**
  - Support for large scale ontological engineering and deployment
- **New reasoning tasks**
  - Querying
  - Lcs/matching
  - Sanctioning
  - . . .

Increased Expressive Power: Datatypes

DAML+OIL extends $\mathcal{SHIQ}$ with datatypes and nominals

Datatypes

- DAML+OIL has simple form of datatypes
  - Unary predicates plus disjoint abstract/datatype domains
- Theoretically not particularly challenging
  - Existing work on concrete domains [Baader & Hanschke, Lutz]
  - Algorithm already known for $\mathcal{SHOQ}(\mathbf{D})$ [Horrocks & Sattler]
- May be practically challenging
  - All XMLS datatypes supported
- Already seeing some (limited) implementations
  - Cerebra system (Network Inference)
  - RACER system (Hamburg)

Increased Expressive Power: Nominals

Nominals

- DAML+OIL has **oneOf** constructor
  - Extensionally defined concepts, e.g., $\{Mary\}^{\mathcal{I}} = \{Mary\}$
  - Equivalent to nominals in modal logic
- Theoretically **very** challenging
  - Resulting logic has known high complexity (NExpTime)
  - No known "practical" algorithm
  - Not obvious how to extend tableax techniques in this direction
    - Loss of tree model property
    - Spy-points: $\top \sqsubseteq \exists R.\{Spy\}$
    - Finite domains: $\{Spy\} \leqslant n R^{-}$
- Relatively straightforward (in theory) without **inverse roles**
  - Algorithm for $\mathcal{SHOQ}(\mathbf{D})$ deals with nominals
  - Practical implementation still to be demonstrated

Increased Expressive Power: Extensions

- DAML+OIL not expressive enough for all applications
- Extensions wish list includes:
  - Feature chain (path) agreement, e.g., output of component of composite process equals input of subsequent process
  - Complex roles/role inclusions, e.g., a city located in part of a country is located in that country
  - Rules—proposal(s) already exist for “datalog/LP style rules”
  - Temporal and spatial reasoning
  - . . .
- May be impossible/undesirable to resist such extensions
- Extended language sure to be undecidable
- How can extensions best be integrated with DAML+OIL?
- How can reasoners be developed/adapted for extended languages
  - Some existing work on language **fusions** and **hybrid** reasoners

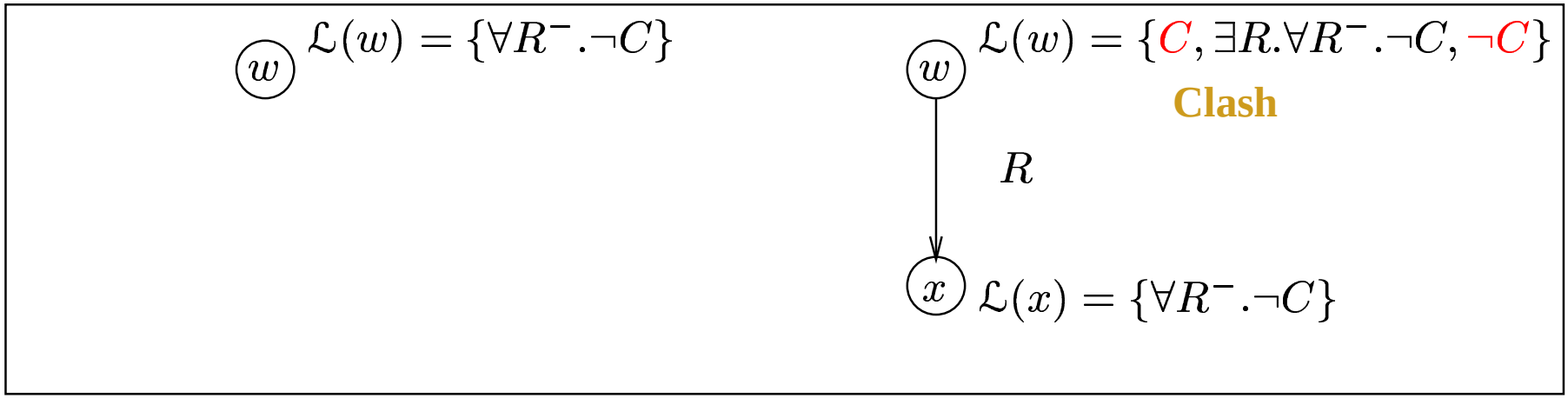
Performance Problems I

Evidence of empirical tractability mostly w.r.t. $\mathcal{SHF}$— problems can arise when systems extended to $\mathcal{SHIQ}$

- ☞ Trace technique no longer works
  - Whole model must be kept in memory
  - More costly state saving/restoring when searching non-deterministic expansions
  - More complex flow of control during expansion/search
- ☞ E.g., $\exists S.\neg C \sqcap \exists R.A$ w.r.t. $\mathcal{T} = \{A \sqsubseteq (\forall R^{-}.\forall S.C) \sqcup (\forall R^{-}.\forall S.D)\}$

Performance Problems II

- Important optimisations no longer (fully) work
  - Problems with caching as cached models can affect parent
  - E.g., consider $\forall R^{-}.\neg C$ and $C \sqcap \exists R.\forall R^{-}.\neg C$



  - Interactions with blocking even more problematical
  - Similar problems with model merging

Performance Problems III

- Qualified number restrictions can also cause problems
  - Even relatively small numbers can mean significant non-determinism
- Reasoning with very large KBs
  - Web ontologies can be expected to grow very large
- Reasoning with individuals (Abox)
  - Deployment of web ontologies will mean reasoning with (possibly very large numbers of) individuals
  - Unlikely that standard Abox techniques will be able to cope

Performance Solutions (Maybe)

- Excessive memory usage
  - Problem exacerbated by over-cautious double blocking condition (e.g., root node can never block)
  - Promising results from more precise blocking condition [Sattler & Horrocks]
- Qualified number restrictions
  - Problem exacerbated by naive expansion rules
  - Promising results from optimised expansion using Algebraic Methods [Haarslev & Möller]
- Caching and merging
  - Can still work in some situations (work in progress)
- Reasoning with very large KBs
  - RACER system shown to work with ≈100k concept KB [Haarslev & Möller]
  - But KB only exploited small part of DL language

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

- Ontology design and maintenance
  - Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
  - Need integrated **environments** including 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
- . . .

New Reasoning Tasks

- Querying
  - Retrieval (instances of a concept) and realisation (most specific class of instance) wont be sufficient
  - Minimum requirement will be conjunctive query style language [Tessaris & Horrocks]
  - May also need to answer "what can I say about x?" style of query [Bechhofer & Horrocks]
- Explanation (e.g., to support ontology design) [McGuinness, Borgida et al]
- Least common subsumer and/or matching (e.g., to support ontology integration and "bottom up" design) [Baader, Küsters & Molitor]
- ...

Summary

Semantic Web may be **killer app** for KRR (and many other areas)

The good news:

- We made a big sale
- Huge opportunity for everyone working in the area

The bad news (maybe):

- Now we need to deliver
- Major challenges for everyone working in the area
- Must **exploit, adapt** and **extend** existing work

Customers not noted for their patience!