Logical Foundations for the Semantic Web

Reasoning with Expressive Description Logics: Theory and Practice

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Talk Outline

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Introduction to Description Logics

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The Semantic Web: Killer App for (DL) Reasoning?

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Web Ontology Languages

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Reasoning with DAML+OIL

  OilEd Demo

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- Reasoning with DAML+OIL
    - OilEd Demo
- Research Challenges

Introduction to Description Logics

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- ☞ 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**

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- ☞ A family of logic based Knowledge Representation formalisms
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  - 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

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Phase 1:

- ☞ Incomplete systems (Back, Classic, Loom, . . .)
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- Tableau-based systems (Kris, Crack)
- Investigation of optimisation techniques

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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

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- ☞ Mature **implementations**

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- ☞ 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

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    - Service description and discovery
- ☞ **Commercial** implementations
  - Cerebra system from Network Inference Ltd

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- ☞ Web made possible through established **standards**
  - **TCP/IP** for transporting bits down a wire
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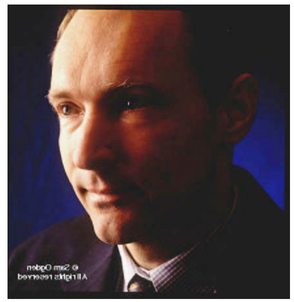

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- Ontologies can be used, e.g.:
  - To facilitate buyer–seller communication in **e-commerce**
  - In semantic based **search**
  - To provide richer **service descriptions** that can be more flexibly interpreted by intelligent agents

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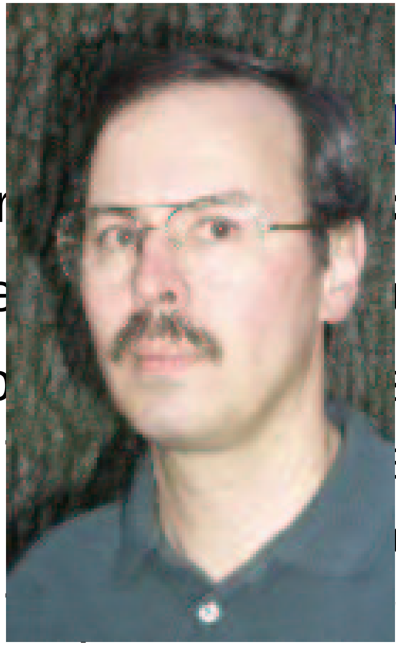

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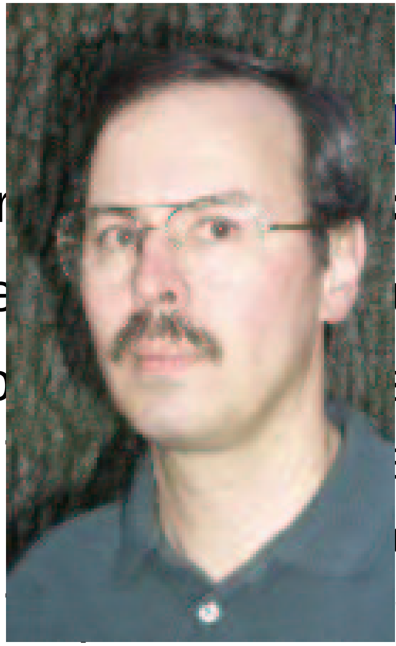

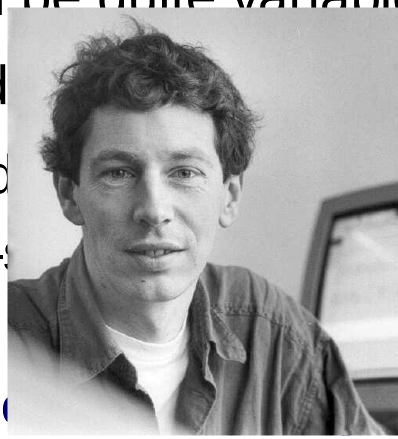

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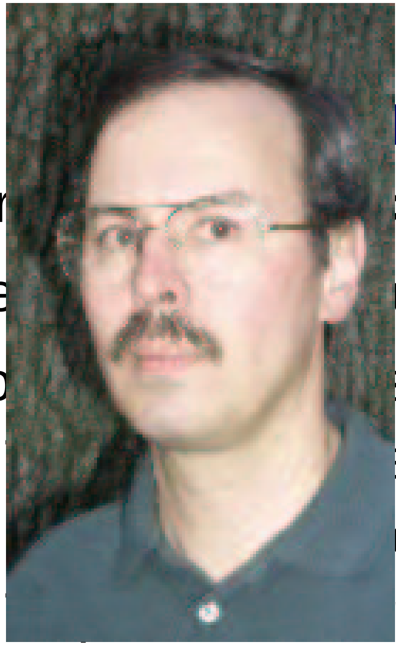
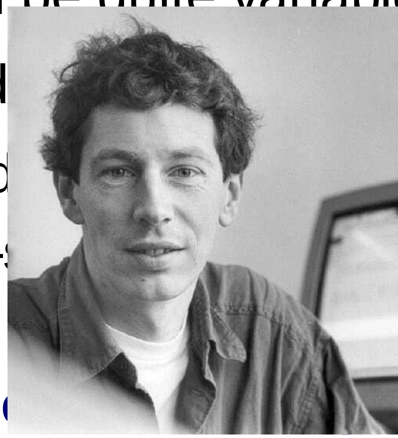


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- Requirements for web ontology language:
  - **Compatible** with existing Web standards (XML, RDF, RDFS)
  - **Easy to understand** and use (based on familiar KR idioms)
  - **Formally specified** and of “adequate” expressive power
  - Possible to provide **automated reasoning** support

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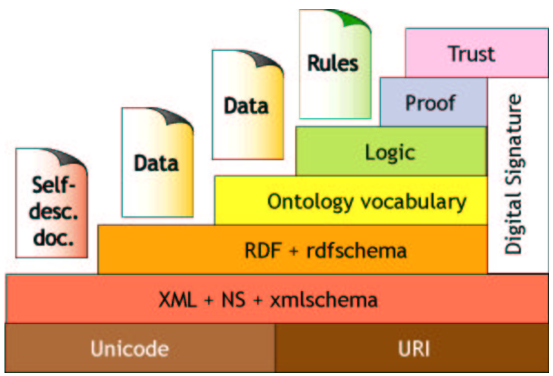

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  - E.g., Person **subclass of** Animal whose parents are all Persons
- Uses RDF for class/property membership assertions (ground facts)
  - E.g., john **instance of** Person; $\langle \text{john}, \text{mary} \rangle$ instance of parent

DAML+OIL Language

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  - Well defined **semantics**
  - **Formal properties** well understood (complexity, decidability)
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  - Various **constructors** provided for building class expressions
- **Expressive power** determined by
  - Kinds of constructor provided
  - Kinds of axiom allowed

DAML+OIL Class Constructors

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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}	$x_1 \vee \ldots \vee x_n$
toClass	$\forall P.C$	$\forall$hasChild.Doctor	$[P]C$
hasClass	$\exists P.C$	$\exists$hasChild.Lawyer	$\langle P \rangle C$
maxCardinalityQ	$\leqslant n P.C$	$\leqslant 1$hasChild.Male	$[P]_{n+1} C$
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- 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

```
<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">
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- ☞ Interpretation function $\cdot^{\mathcal{I}}$ **extended** to concept expressions
  - $(C \sqcap D)^{\mathcal{I}} = C^{\mathcal{I}} \cap D^{\mathcal{I}} \quad (C \sqcup D)^{\mathcal{I}} = C^{\mathcal{I}} \cup D^{\mathcal{I}} \quad (\neg C)^{\mathcal{I}} = \Delta^{\mathcal{I}} \setminus C^{\mathcal{I}}$
  - $\{x_n, \ldots, x_n\}^{\mathcal{I}} = \{x_n^{\mathcal{I}}, \ldots, x_n^{\mathcal{I}}\}$
  - $(\exists R.C)^{\mathcal{I}} = \{x \mid \exists y. \langle x, y \rangle \in R^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\}$
  - $(\forall R.C)^{\mathcal{I}} = \{x \mid \forall y. (x, y) \in R^{\mathcal{I}} \Rightarrow y \in C^{\mathcal{I}}\}$
  - $(\leqslant n R.C)^{\mathcal{I}} = \{x \mid \#\{y \mid \langle x, y \rangle \in R^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\} \leqslant n\}$
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Axiom	DL Syntax	Example
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sameClassAs	$C_1 \equiv C_2$	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}
differentIndividualFrom	$\{x_1\} \sqsubseteq \neg\{x_2\}$	{john} $\sqsubseteq$ $\neg${peter}
subPropertyOf	$P_1 \sqsubseteq P_2$	hasDaughter $\sqsubseteq$ hasChild
samePropertyAs	$P_1 \equiv P_2$	cost $\equiv$ price
inverseOf	$P_1 \equiv P_2^-$	hasChild $\equiv$ hasParent$^-$
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- $\mathcal{I}$ satisfies ontology $\mathcal{O}$ (is a **model** of $\mathcal{O}$) iff satisfies every axiom in $\mathcal{O}$

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- 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 DAML+OIL

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  - **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
    - ...

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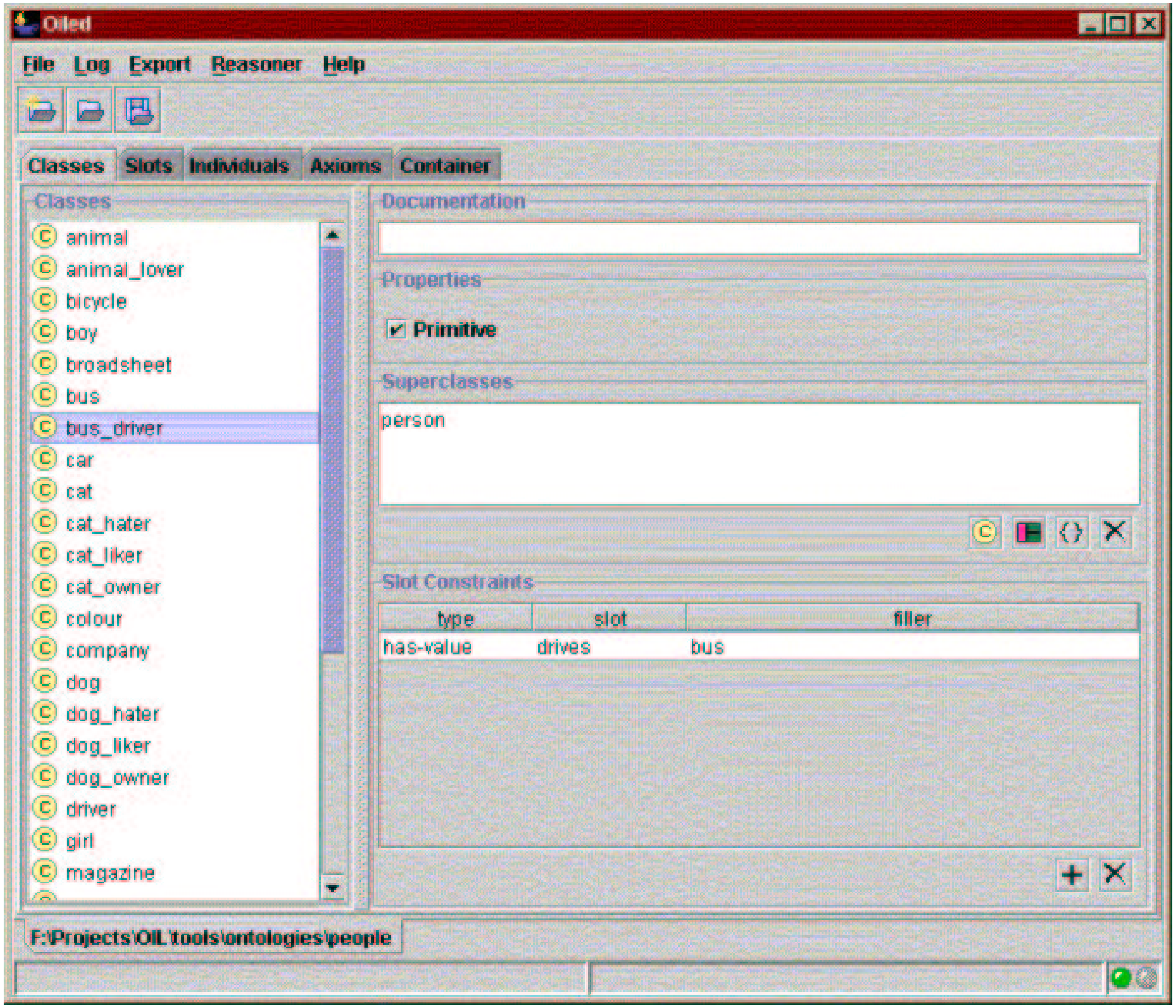
☞ Problems all **reducible** to consistency (satisfiability):

- $C \sqsubseteq_{\mathcal{O}} D$ 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

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- ☞ 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

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  - Support for large scale ontological engineering and deployment

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  - Cerebra system (Network Inference), Racer system (Hamburg)

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- **Standard solution** is weaker semantics for nominals
  - Treat nominals as (disjoint) primitive classes
  - Loose some inferential power, e.g., w.r.t. max cardinality

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- 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

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- "**Non-Standard Inferences**", e.g., LCS, matching
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  - To support "bottom up" design of ontologies

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- ☞ **Challenges** remain
  - Reasoning with full language
  - (Convincing) demonstration(s) of scalability
  - New reasoning tasks

Acknowledgements

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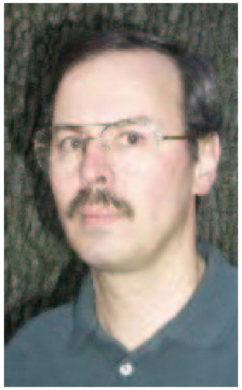

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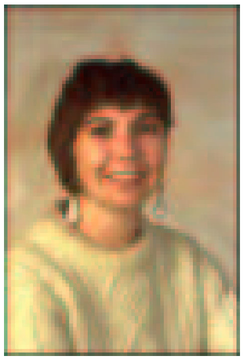

Resources

Slides from this talk

`http://www.cs.man.ac.uk/~horrocks/Slides/cade02.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/`

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

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

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.