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An Alternative to Θ-Subsumption based on Terminological Reasoning

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An Alternative to Θ-Subsumption Based on Terminological Reasoning

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Abstract

Clause subsumption and rule ordering are long-standing research topics in machine learning (ML). Since logical implication can be reduced to rule-subsumption, the general subsumption problem for Horn clauses is undecidable [Plotkin, 1971b]. In this paper we suggest an alternative knowledge-representation formalism for ML that is based on a terminological logic. It provides a decidable rule-ordering which is at least as powerful as Θ-subsumption.

Contents

1 Introduction

There are two ways how to get a decidable rule ordering:

- One can restrict the expressiveness of the underlying knowledge representation language such that logical implication becomes decidable, e.g. Buntine's *generalized subsumption* [Buntine, 1988] with restriction to DATALOG.
- Alternatively, the rule ordering can be defined using only a weak approximation of logical implication. For example, the subset test used for Θ-*subsumption* [Plotkin, 1971a] is such a correct but incomplete operationalization of logical implication.

In the former case, as a side effect, the class of knowledge that can be learned will be very restricted, too. In the latter approach, the learning algorithms cannot be optimal, since they are always based on a suboptimal rule ordering. However, the class of knowledge that can be learned remains unconstrained in that case.

Θ-subsumption relies on the instantiation ordering of Herbrand terms which implies additional deficits: There are "too many" terms that are incomparable w.r.t. the instantiation ordering of Herbrand terms (e.g., $f(a,b)$, $f(a,a)$, $f(b,b)$, $f(b,a)$ are all incomparable). The weakness is also indicated by the fact that there are *linear* decision procedures for the instantiation problem of Herbrand terms.

These deficits are somehow inherent to the underlying Horn logic. As an alternative, we propose a rule-formalism based on a terminological logic (TL). This enables us to define a rule ordering much as Θ-subsumption, but which is based on terminological inferences instead of instantiation of Herbrand terms.

As terminological reasoning formalisms are tuned to be as much as expressive while remaining tractable or at least decidable, we gain a more fine grain ordering of an expressive and intuitive rule formalism (see [Boley *et al.*, 1991] for an application of a hybrid formalism including terminological logic, rules and constraints.

The rest of this paper is organized as follows: We start with an informal introduction to terminological logics (Section 2) before we construct in Section 3 the rule language from this formalism. In Section 4 we define the new rule ordering and illustrate it with an example. The paper then shows that our approach can be instantiated to Horn logic with Θ-subsumption.

2 Terminological Reasoning

In this Section we will introduce the *assertional* formalism (A-box) and the *terminological* formalism (T-box) of the concept language $\mathcal{ALCF}$ as a prototypical representant of the family of terminologic formalisms (e.g. [Borgida *et al.*, 1989]) that originated with KL-ONE [Brachman and Schmolze, 1985]. It is sufficiently rich to simulate Herbrand terms (see below) and to demonstrate our ideas. It is also possible to employ an even more expressive member of the family. As a new reasoning service we shall introduce *subsumption of A-boxes* which is crucial for our rule-ordering.

A *terminology* of the T-box consists of a set of *concept definitions* $C = t$ where C is the newly introduced concept name and t is a concept term constructed from concept names, roles, and attributes using the following concept forming operators:

conjunction	$(\sqcap)$
disjunction	$(\sqcup)$
negation	$(\neg)$
value-restriction	($\forall$*'role/attribute'.'concept term'*)
exists-in restriction	($\exists$*'role/attribute'.'concept term'*)

The following is a terminology on families.

$$
\begin{array}{lcl}
\mathsf{Female} & = & \neg\mathsf{Male} \\
\mathsf{Parent} & = & \mathsf{Human} \sqcap \exists \mathsf{child}.\mathsf{Human} \\
\mathsf{Woman} & = & \mathsf{Human} \sqcap \mathsf{Female} \\
\mathsf{Man} & = & \mathsf{Human} \sqcap \mathsf{Male} \\
\mathsf{Fos} & = & \mathsf{Parent} \sqcap \mathsf{Male} \sqcap \forall \mathsf{child}.\mathsf{Male} \\
\mathsf{Mod} & = & \mathsf{Parent} \sqcap \mathsf{Female} \sqcap \forall \mathsf{child}.\mathsf{Female}.
\end{array}
$$

In this toy terminology Male and Human are primitive concepts (i.e., they do not occur on the left-hand side of an equation), child is a role, and the other names are defined concepts.

It is possible to define a mapping from concept terms into first-order formulas providing a precise semantics. It is defined by a family of mappings ψ_x. Let C denote a concept name, R a role or attribute name, x a variable, and let s and t be concept terms. Then concept terms and the mappings can be defined according to the following scheme:

1. $\psi_x : \quad C \longmapsto C(x)$

2. $\psi_x : \quad s \sqcap t \longmapsto \psi_x s \wedge \psi_x t$
   $\psi_x : \quad s \sqcup t \longmapsto \psi_x s \vee \psi_x t$
   $\psi_x : \quad \neg t \longmapsto \neg \psi_x t$
   $\psi_x : \quad \exists R.s \longmapsto \exists y : (R(x,y) \wedge \psi_y s)$; with y a variable different from x
   $\psi_x : \quad \forall R.s \longmapsto \forall y : (R(x,y) \Rightarrow \psi_y s)$; with y a variable different from x

A concept definition $C = t$ is mapped to the formula $\forall x : (\psi_x C \Leftrightarrow \psi_x t)$.

In an *A-box* (assertional box) concepts, roles, and attributes can be instantiated by individuals. Formally, an A-box is a *finite* set of role assertions $((i,j):r)$, membership assertions $(i:t)$, and equalities $(i=j)$, where i and j are individual names, r is a role or attribute name, and t is a concept term. Assertional axioms map as follows to first-order formulas:

$$\begin{aligned}(i,j):r &\longmapsto r(i,j)\\ i:t &\longmapsto \psi_i t\\ i=j &\longmapsto i=j\end{aligned}$$

In the images, individuals are considered as variables that are existentially quantified at A-box level. Note that we do not have a unique-name assumption.

Definition 2.1 (A-box subsumption) *Assume two A-boxes A and B such that $x_1,\cdots,x_n$, $n>0$, are exactly the individuals which occur both in A and B. Then A subsumes B w.r.t. $x_1,\cdots,x_n$ iff '$\forall x_1,\cdots,x_n:(\psi(B)\Rightarrow\psi(A))$' is a theorem in the theory generated by the current terminology.*

Two individuals i and j are *directly* linked in an A-box iff the A-box contains a role assertion of the form $(i,j):R$ or $(j,i):R$. *Linked* is the transitive reflexive closure of directly linked. An A-box is called *rooted* by (individuals) $x_1,\cdots,x_n$, $n>0$, iff every individual in the A-box is linked to at least one of the x_i and all x_i occur in the A-box. We have the following result:

Theorem 2.2 *For two A-boxes A and B which are both rooted by individuals $x_1,\cdots,x_n$, $n>0$, the A-box subsumption problem can be effectively decided.*

It turns out that this result holds also for various other concept languages, for example, [Baader and Hanschke, 1991].

3 The Rule Formalism

The rule language is based on the terminological formalism of the previous section. Its operational semantics can be based on a CLP scheme [Smolka, 1989; Jaffar and Lassez, 1987].

A *rule* takes the following form

$$p_0(\underline{x}^{(0)})\leftarrow p_1(\underline{x}^{(1)}),\cdots,p_n(\underline{x}^{(n)}),A(\underline{x}^{(0)},\cdots,\underline{x}^{(n)}).$$

where the p_i are predicate symbols with arities n_i, the $\underline{x}^{(i)}$ are tuples of individuals $(x_{i1},\cdots,x_{in_i})$, and $A(\underline{x}^{(0)},\cdots,\underline{x}^{(n)})$ is an A-box rooted by the individuals in the $\underline{x}^{(i)}$. It is interpreted as a logical formula in the obvious way.

In the next section we shall use a more compact notation for (a subclass of) rooted A-boxes, called ϕ-terms, which is inspired by Ait-Kaci's ψ-terms.

For example, the following fact in ϕ-term syntax

$$p(X : \mathsf{Woman}\{\mathsf{child} > Y : \mathsf{Man}\{\mathsf{child} > S : \mathsf{Human}\} \\ \mathsf{child} > S : \mathsf{Female}\}) \leftarrow \mathtt{true}.$$

translates to the following rule with an A-box that is rooted by X

$$\begin{aligned} p(X) \leftarrow\ & X : \mathsf{Woman}, \\ & Y : \mathsf{Man}, \\ & S : \mathsf{Female}, \\ & S : \mathsf{Human}, \\ & (X,Y) : \mathsf{child}, \\ & (X,S) : \mathsf{child}, \\ & (Y,S) : \mathsf{child}. \end{aligned}$$

Note, that Y could be instantiated with Ödipus.

4 Ordering the Rules

The idea behind the rule ordering is essential the same as for Θ-subsumption. The only difference is that instead of searching for a substitution Θ that acts as a witness for the instantiation relation, we employ the A-box subsumption of the terminological formalism. We call our ordering of rules *TL-subsumption.*

Assume that two rules

$$\begin{aligned} p_0(\underline{x}^{(0)}) &\leftarrow p_1(\underline{x}^{(1)}), \cdots, p_n(\underline{x}^{(n)}), A(\underline{x}^{(0)}, \cdots, \underline{x}^{(n)}). \\ q_0(\underline{y}^{(0)}) &\leftarrow q_1(\underline{y}^{(1)}), \cdots, q_m(\underline{y}^{(m)}), B(\underline{y}^{(0)}, \cdots, \underline{y}^{(m)}). \end{aligned}$$

over disjoint sets of variables are given. The p-rule is more general than the q-rule w.r.t. *TL-subsumption* ($<_{TL}$) iff there is a substitution σ such that the following holds:

1. $p_0(\underline{x}^{(0)})\sigma$ and $q_0(\underline{y}^{(0)})$ are equal,

2. $\{p_1(\underline{x}^{(1)})\sigma, .., p_n(\underline{x}^{(n)})\sigma\} \subseteq \{q_1(\underline{y}^{(1)}), .., q_m(\underline{y}^{(m)})\}$ and

3. the A-box

$$A(\underline{x}^{(0)}, .., \underline{x}^{(n)})\sigma$$

subsumes the A-box

$$B(\underline{y}^{(0)}, .., \underline{y}^{(m)})$$

w.r.t. $\underline{x}^{(1)}\sigma, .., \underline{x}^{(n)}\sigma$.

To illustrate TL-subsumption consider the following example in the domain of *"soap-opera story generation"*. We want to order rules which state under which conditions a man and a woman should marry.

A very general rule is as follows:

$$\begin{array}{l} \mathsf{marry}(X,Y) \ \leftarrow \\ \quad \mathsf{visits}(\mathrm{X}{:}\mathsf{Man},\mathrm{L}{:}\mathsf{Location}), \\ \quad \mathsf{visits}(\mathrm{Y}{:}\mathsf{Woman},\mathrm{L}). \end{array} \tag{1}$$

Here Location is a primitive concept, and the rule says that two people should marry if they meet at some location. This rule can, for example, be made more restrictive by further restricting the variables by additional literals or (more special) concepts:

$$\begin{array}{l} \mathsf{marry}(X,Y) \ \leftarrow \\ \quad \mathsf{visits}(\mathrm{X}{:}\mathsf{Father},\mathrm{L}{:}\mathsf{Location}), \\ \quad \mathsf{visits}(\mathrm{Y}{:}\mathsf{Mother},\mathrm{L}). \end{array} \tag{2}$$

$$\begin{array}{l} \mathsf{marry}(X,Y) \ \leftarrow \\ \quad \mathsf{visits}(\mathrm{X}{:}\mathsf{Father},\mathrm{L}{:}\mathsf{Location}), \\ \quad \mathsf{visits}(\mathrm{Y}{:}\mathsf{Mother},\mathrm{L}{:}\mathsf{Pleasant}). \end{array} \tag{3}$$

$$\begin{array}{l} \mathsf{marry}(X,Y) \ \leftarrow \\ \quad \mathsf{visits}(\mathrm{X}{:}\mathsf{Man}\{\mathsf{child}{>}\mathrm{Son}{:}\mathsf{Man}\},\mathrm{L}{:}\mathsf{Location}), \\ \quad \mathsf{visits}(\mathrm{Y}{:}\mathsf{Woman}\{\mathsf{child}{>}\mathrm{Daughter}{:}\mathsf{Woman}\},\mathrm{L}). \end{array} \tag{4}$$

$$\begin{array}{l} \mathsf{marry}(X,Y) \ \leftarrow \\ \quad \mathsf{visits}(\mathrm{X}{:}\mathsf{Fos}\{\mathsf{child}{>}\mathrm{Son}{:}\mathsf{Man}\},\mathrm{L}{:}\mathsf{Location}), \\ \quad \mathsf{visits}(\mathrm{Y}{:}\mathsf{Mod}\{\mathsf{child}{>}\mathrm{Daughter}{:}\mathsf{Woman}\},\mathrm{L}), \\ \quad \mathsf{married}(\mathrm{Son},\ \mathrm{Daughter}). \end{array} \tag{5}$$

Here Pleasant is again a primitive concept, and we get the following ordering of the rules:

$$\begin{array}{l} (1) <_{TL} \ (2) <_{TL} (3) \\ \qquad\quad\ \ (2) <_{TL} (4) <_{TL} (5) \end{array}$$

The rules (3) and (4) as well as (3) and (5) are not comparable w.r.t. $<_{TL}$.

As our terminological formalism provides attributes and a complement operator it is possible to map Herbrand terms into the set of A-boxes that are rooted by one individual such that two Herbrand terms s and t are unifiable iff $\tilde{s}(X), \tilde{t}(Y), X = Y$ is satisfiable. Here $\tilde{s}$ and $\tilde{t}$ are the images under the mapping mentioned before. This embedding naturally extends to a mapping from Horn rules to our rule formalism.

We have the following result that shows that TL-subsumption is at least as powerful as Θ-subsumption.

Theorem 4.1 *Let two Horn rules r_1 and r_2 be given. Then r_1 is more general than r_2 w.r.t. Θ-subsumption iff $\tilde{r}_1 <_{TL} \tilde{r}_2$.*

5 Conclusions

In this paper we have presented an alternative knowledge-representation formalism for ML based on a terminological logic. It allows a decidable rule-ordering which is at least as powerful as Θ-subsumption. Future research should explore the benefit one could get by adapting existing ML algorithms for Horn logic to our rule formalism. In particular, it should be explored to which extent the reasoning services of terminological systems such as individual/concept classification and consistency tests [Nebel, 1990] could be employed in future enhanced ML algorithms.

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