Description Logics with Transitive Roles

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Abstract

This paper describes the logic $\mathcal{ALCH}_{R^+}$, which extends $\mathcal{ALC}_{R^+}$ with a primitive role hierarchy, and presents an appropriate extension to the $\mathcal{ALC}_{R^+}$ satisfiability testing algorithm. $\mathcal{ALCH}_{R^+}$ is of interest because it provides useful additional expressive power and, although its satisfiability problem is Exptime-complete, the algorithm is relatively simple and is amenable to optimisation.

1 Introduction

The importance of transitively closed roles in Description Logics (DLs) has long been recognised [PL94], particularly in domains which are concerned with physically composed objects, for example in medicine [HRG96] and engineering [Sat95]. The logic $\mathcal{ALC}_+$ [Baa90] supports complete reasoning about roles and their transitive closures by extending $\mathcal{ALC}$ [SSS91] with union, composition and transitive closure role forming operators but, unfortunately, has a satisfiability problem which is Exptime-complete.

The $\mathcal{ALC}_{R^+}$ and $\mathcal{ALC}_\oplus$ DLs were investigated in the hope that a more restricted form of transitive role might lead to a satisfiability problem in a lower complexity class [Sat96]. $\mathcal{ALC}_{R^+}$ extends $\mathcal{ALC}$ by allowing the use of transitive roles in concept expressions. In [Sat96] an algorithm for deciding the satisfiability of $\mathcal{ALC}_{R^+}$ concept expressions is provided along with a proof of its soundness and completeness. It is also demonstrated that the complexity of the problem is Pspace-complete, the same as for $\mathcal{ALC}$ [DLNN95]. $\mathcal{ALC}_\oplus$ extends $\mathcal{ALC}_{R^+}$ to provide more expressive power by associating each non-transitive role R with a transitive super-role $R^\oplus$ s.t. $(R^\oplus)^\mathcal{I} \supseteq (R^+)^\mathcal{I}$. The extension to the $\mathcal{ALC}_{R^+}$ algorithm required for $\mathcal{ALC}_\oplus$ is relatively minor but, although [Sat96] does not present a soundness and completeness proof for the extension, it is shown that the problem is Exptime-complete, the same as for $\mathcal{ALC}_+$.

This paper describes $\mathcal{ALCH}_{R^+}$, a logic which generalises $\mathcal{ALC}_\oplus$ by allowing the definition of a role hierarchy, and presents an appropriate extension to the $\mathcal{ALC}_{R^+}$ algorithm. The $\mathcal{ALC}_{R^+}$ soundness and completeness proof has also been extended [Hor97b] but is not presented here due to space restrictions. For the same reason, a familiarity with the usual Tarski style model theoretic semantics for $\mathcal{ALC}$ is assumed [BHH+91].

As $\mathcal{ALCH}_{R^+}$ is more general than $\mathcal{ALC}_\oplus$, but still less expressive than $\mathcal{ALC}_+$, the complexity of its satisfiability problem is clearly also Exptime-complete. However it seems worthwhile to study this logic as it provides useful expressive power, allowing for example general inclusion axioms to be internalised in concept expressions, while having a satisfiability testing algorithm which is much simpler than that for $\mathcal{ALC}_+$, and thus more amenable to optimisation [Hor97a].

2 The $\mathcal{ALCH}_{R^+}$ Description Logic

The relationship between roles and their transitive orbits in $\mathcal{ALC}_\oplus$ is equivalent to introducing a limited form of role hierarchy—given a set of role names $\mathbf{R}$ and a set of transitive roles $\mathbf{R}_+ \subseteq \mathbf{R}$, the relationship between a role and its transitive orbit can be described by a role inclusion axiom of the form $R \sqsubseteq R^\oplus$ where $R \in \mathbf{R}$ and $R^\oplus \in \mathbf{R}_+$. $\mathcal{ALCH}_{R^+}$ generalises $\mathcal{ALC}_\oplus$ by allowing acyclic, but otherwise unrestricted, role inclusion axioms of the form $R \sqsubseteq S$, where $\{R, S\} \subseteq \mathbf{R}$. The semantics of the acyclic $\sqsubseteq$ relation mean that it is reflexive (for all $R \in \mathbf{R}$, $R \sqsubseteq R$), antisymmetric (for any two roles R and S, $R \sqsubseteq S \wedge S \sqsubseteq R \Rightarrow R = S$) and transitive ($R \sqsubseteq P \wedge P \sqsubseteq S \Rightarrow R \sqsubseteq S$). The $\sqsubseteq$ relation therefore defines a partial ordering in $\mathbf{R}$ which, like the concept subsumption relation, can be stored as a hierarchy, a directed acyclic graph in which each role is linked to its most specific super-roles and sub-roles.

If $\mathbf{R}$ is the set of all role names, $\mathbf{R}_+ \subseteq \mathbf{R}$ is the set of transitive roles names and $\sqsubseteq$ is the inclusion relation which defines a partial ordering in $\mathbf{R}$, then as well as being correct for $\mathcal{ALC}$ concept expressions, an $\mathcal{ALCH}_{R^+}$ interpretation $\mathcal{I} = (\Delta^\mathcal{I}, \cdot^\mathcal{I})$ must satisfy the additional conditions:

1. if $\langle d,e\rangle \in R^{\mathcal{I}}$ and $\langle e,f\rangle \in R^{\mathcal{I}}$ and $R \in \mathbf{R}_+$, then $\langle d,f\rangle \in R^{\mathcal{I}}$
2. if $R \sqsubseteq S$, then $R^{\mathcal{I}} \subseteq S^{\mathcal{I}}$

3 The Expressiveness of $\mathcal{ALCH}_{R^+}$

$\mathcal{ALCH}_{R^+}$ allows complex role hierarchies to be established. Consider Figure 1, for example, which shows a fraction of the role hierarchy from a medical terminology model developed as part of the GALEN project [RH97], with the notation R_+ being used to denote that R is a transitive role. $\mathcal{ALCH}_{R^+}$ is able to capture the knowledge that part-whole relations in the GALEN model are subdivided into structural roles and process roles, and that the structural roles are further subdivided into *HasDivision*, *isMadeOf* and *hasLayer*.

This is still strictly less expressive than $\mathcal{ALC}_+$. $\mathcal{ALC}_+$ can simulate a primitive role hierarchy by using role disjunction: the role *StructuralPartitiveAttribute* can be represented in $\mathcal{ALC}_+$ by the role expression $(\mathit{StructuralPartitiveAttribute} \sqcup \mathit{HasDivision} \sqcup \mathit{isMadeOf} \sqcup \mathit{hasLayer})^+$, capturing the knowledge that *StructuralPartitiveAttribute* is a transitive super-role of *HasDivision*, *isMadeOf* and *hasLayer*. Unlike $\mathcal{ALCH}_{R^+}$, however, $\mathcal{ALC}_+$ can also simulate a non-primitive role hierarchy. It can, for example, represent a role such as *ancestor* with the expression parent^+, capturing the knowledge that *ancestor* is exactly equal to the transitive closure of *parent*.

Unlike $\mathcal{ALC}_\oplus$, $\mathcal{ALCH}_{R^+}$'s role hierarchy also enables internalisation [Baa90] to be used to test satisfiability w.r.t. a terminology $\mathcal{T}$ which contains a set of general concept inclusion axioms (GCIs). If $\mathcal{T}$ contains the axioms $C_1 \sqsubseteq D_1, \ldots, C_n \sqsubseteq D_n$, where $C_1, \ldots, C_n, D_1, \ldots, D_n$ are arbitrary concept expressions, the satisfiability of a concept expression A w.r.t. $\mathcal{T}$ can be tested by:

1. Forming the GCIs into a single concept expression $G \doteq (D_1 \sqcup \neg C_1) \sqcap \ldots \sqcap (D_n \sqcup \neg C_n)$;
2. Defining a role $\mathit{T} \in \mathbf{R}_+$ s.t. $\forall R \in \mathbf{R}. R \sqsubseteq \mathit{T}$;
3. Testing the satisfiability of $A \sqcap G \sqcap \forall \mathit{T}.G$.

Although the satisfiability problems for both logics are EXPTIME-complete, the additional expressive power of $\mathcal{ALC}_+$ is manifested in a more complex satisfiability testing algorithm which requires both reasoning about role expressions[1] and a more sophisticated cycle detection (blocking) mechanism in order to differentiate between cycles which lead to a valid model and those which do not. The algorithm for $\mathcal{ALCH}_{R^+}$ on the other hand does not need to consider role expressions, and cycle detection is straightforward as all cycles lead to valid models. This simplicity makes the algorithm amenable to a range of optimisation techniques which greatly enhance its performance in realistic applications: the optimised algorithm has been used in the FaCT system [FaC] and its effectiveness has been demonstrated by classifying a large medical terminology knowledge base which includes both a complex role hierarchy and numerous transitive roles [Hor97a].

4 A Tableau Algorithm for $\mathcal{ALCH}_{R^+}$

Like other tableau algorithms, the $\mathcal{ALCH}_{R^+}$ algorithm tries to prove the satisfiability of a concept expression D by demonstrating a model of D—an interpretation $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$ s.t. $D^{\mathcal{I}} \neq \emptyset$. The model is represented by a tree whose nodes correspond to individuals, each node being labelled with a set of $\mathcal{ALCH}_{R^+}$-concepts. When testing the satisfiability of an $\mathcal{ALCH}_{R^+}$-concept D these sets are restricted to subsets of $\mathit{sub}(D)$, where $\mathit{sub}(D)$ is the closure of the subconcepts of D. The soundness and completeness of the algorithm can proved by showing that the tree it creates corresponds to a tableau for D and that D is satisfiable if and only if there exists a tableau for D but, due to space restrictions, the proof is not presented here. As usual, it is assumed that D is in negation normal form, i.e., that negations are applied only to primitive concepts. This can easily be achieved using a combination of DeMorgan's laws and the identities $\neg\exists R.C = \forall R.\neg C$ and $\neg\forall R.C = \exists R.\neg C$.

The algorithm builds a tree where each node x of the tree is labelled with a set $\mathcal{L}(x) \subseteq \mathit{sub}(D)$ and may, in addition, be marked *satisfiable*. The tree is initialised with a single node x_0, where $\mathcal{L}(x_0) = \{D\}$, and expanded either by extending $\mathcal{L}(x)$ for some leaf node x or by adding new leaf nodes. For a node x, $\mathcal{L}(x)$ is said to contain a *clash* if, for some concept C, $\{C, \neg C\} \subseteq \mathcal{L}(x)$ or $\perp \subseteq \mathcal{L}(x)$. $\mathcal{L}(x)$ is called a *pre-tableau* if it is clash-free and contains no unexpanded conjunction or disjunction concepts. Note that $\emptyset$ is a pre-tableau.

Edges of the tree are either unlabelled or labelled R for some role name R occuring in $\mathit{sub}(D)$. Unlabelled edges are added when expanding $A \sqcup B$ concepts in $\mathcal{L}(x)$ and are the mechanism whereby the algorithm explores the alternative expansions offered by disjunctions. Labelled edges are added when expanding $\exists R.A$ terms in $\mathcal{L}(x)$ and correspond to relationships between pairs of individuals.

A node y is called an *R-successor* of a node x if there is an edge from x to y labelled R; y is called a *$\sqcup$-successor* of x if there is a path, consisting of unlabelled edges, from x to y. A node x is an *ancestor* of a node y if there is a path from x to y regardless of the labelling of the edges. Note that both the $\sqcup$-successor and ancestor relations are reflexive: nodes are connected to themselves by the empty path.

The algorithm initialises a tree $\mathbf{T}$ to contain a single

[1] A relatively efficient mechanism for dealing with this problem using finite state automata is suggested in [Baa90].

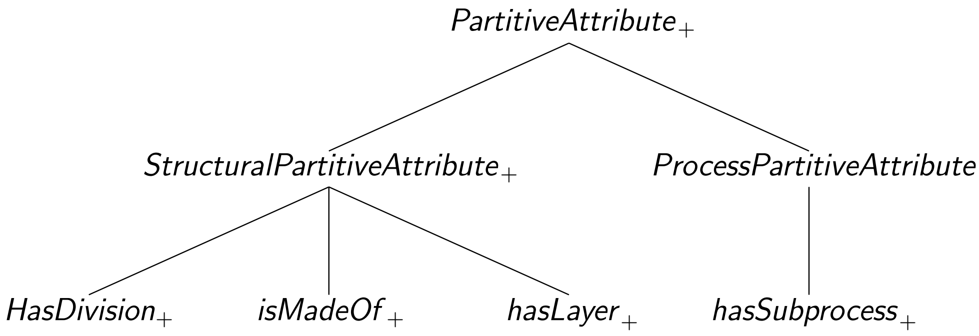

Figure 1: A fraction of the GALEN role hierarchy

node x_0, called the *root* node, with $\mathcal{L}(x_0) = \{D\}$. **T** is then expanded by repeatedly applying the rules from Table 1 until either the root node is marked *satisfiable* or none of the rules is applicable. If the root node is marked *satisfiable* then the algorithm returns *satisfiable*; otherwise it returns *unsatisfiable*.

5 Conclusion

$\mathcal{ALCH}_{R^+}$ usefully extends the expressive power of $\mathcal{ALC}_{R^+}$ and $\mathcal{ALC}_\oplus$ by supporting both a primitive role hierarchy and the internalisation of GCIs.

The complexity of subsumption reasoning in $\mathcal{ALCH}_{R^+}$ is EXPTIME-complete, the same as for $\mathcal{ALC}_+$, but the algorithm is much simpler and is amenable to a range of optimisation techniques. Although the underlying complexity means that intractabile problems may still arise, in practice the algorithm has demonstrated acceptable performance in realistic applications.

The complexity class of a problem is a relatively coarse grained measure and, while not underestimating the importance of theoretical complexity results, experience with $\mathcal{ALCH}_{R^+}$ suggests that consideration may also need to be given to the 'practical' complexity of subsumption testing algorithms.

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$\sqcap$-rule:	If	x is a leaf of $\mathbf{T}$, $\mathcal{L}(x)$ is clash-free, $A \sqcap B \in \mathcal{L}(x)$ and $\{A, B\} \not\subseteq \mathcal{L}(x)$
	then	$\mathcal{L}(x) \longrightarrow \mathcal{L}(x) \cup \{A, B\}$
$\sqcup$-rule:	If	x is a leaf of $\mathbf{T}$, $\mathcal{L}(x)$ is clash-free, $A \sqcup B \in \mathcal{L}(x)$, $A \notin \mathcal{L}(x)$ and $B \notin \mathcal{L}(x)$
	then	create two $\sqcup$-successors y, z of x with: $\mathcal{L}(y) = \mathcal{L}(x) \cup \{A\}$ $\mathcal{L}(z) = \mathcal{L}(x) \cup \{B\}$
$\exists$-rule:	If	x is a leaf of $\mathbf{T}$ and $\mathcal{L}(x)$ is a pre-tableau
	then	for each $\exists R.A \in \mathcal{L}(x)$ do: 1. $\ell_{Rx} := \{A\} \cup \{C \mid \forall S.C \in \mathcal{L}(x)$ and $R \sqsubseteq S\}$ $\cup \{\forall S.C \mid \forall S.C \in \mathcal{L}(x),\ S \in \mathbf{R}_+$ and $R \sqsubseteq S\}$ 2. If for some ancestor w of x, $\ell_{Rx} \subseteq \mathcal{L}(w)$ then create an R-successor y of x with $\mathcal{L}(y) = \emptyset$ 3. Otherwise create an R-successor y of x with $\mathcal{L}(y) = \ell_{Rx}$
SAT-rule:	If	a node x is not marked *satisfiable*, and one of the following is true of x: 1. $\mathcal{L}(x)$ is a pre-tableau containing no concepts of the form $\exists R.A$ 2. $\mathcal{L}(x)$ is a pre-tableau and all R-successors of x are marked *satisfiable* 3. $\mathcal{L}(x)$ is not a pre-tableau and some $\sqcup$-successor of x is marked *satisfiable*
	then	mark x *satisfiable*

Table 1: Tableau expansion rules for $\mathcal{ALCH}_{R^+}$

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