Efficient description logic reasoning in Prolog: The DLog system

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Abstract

Traditional algorithms for description logic (DL) instance retrieval are inefficient for large amounts of underlying data. As DL is becoming more and more popular in areas such as the Semantic Web and information integration, it is very important to have systems which can reason efficiently over large data sets. In this paper we present an approach to transform DL axioms, formalised in the $\mathcal{SHIQ}$ DL language, into a Prolog program under the unique name assumption. This transformation is performed with no knowledge about particular individuals: they are accessed dynamically during the normal Prolog execution of the generated program. This technique, together with the top-down Prolog execution, implies that only those pieces of data are accessed that are indeed important for answering the query. This makes it possible to store the individuals in a database instead of memory, which results in better scalability and helps in using DL ontologies directly on top of existing information sources. The transformation process consists of two steps: (1) the DL axioms are converted to first-order clauses of a restricted form, and (2) a Prolog program is generated from these clauses. Step (2), which is the focus of the present paper, actually works on more general clauses than those obtainable by applying step (1) to a $\mathcal{SHIQ}$ knowledge base. We first present a base transformation, the output of which can be either executed using a simple interpreter or further extended to executable Prolog code. We then discuss several optimisation techniques, applicable to the output of the base transformation. Some of these techniques are specific to our approach, while others are general enough to be interesting for DL reasoner implementors not using Prolog. We give an overview of *DLog*, a DL reasoner in Prolog, which is an implementation of the techniques outlined above. We evaluate the performance of DLog and compare it to some widely used DL reasoners, such as RacerPro, Pellet and KAON2.

KEYWORDS: description logic, logic programming, resolution, large data sets, open world

1 Introduction

Description Logics (DLs) are becoming widespread thanks to the recent trend of using semantics in various systems and applications. As an example, in the Semantic Web idea, semantics is captured in the form of expressive ontologies, described in the Web Ontology Language (OWL; Bechhofer 2004) which is intended to be the

standard knowledge representation format of the Web. The OWL DL fragment of this language is mostly based on the $\mathcal{SHIQ}$ DL language. Other application fields of DLs include natural language processing (Franconi 2003), medical systems (Stevens *et al.* 2002), information integration (Calvanese *et al.* 1998) and complex engineering and computer technology systems (Eisfeld 2002).

Similar to Motik (2006), the motivation for our work comes from the realisation that DLs are, or soon will be, used over large amounts of data. In an information integration system, for example, huge amounts of data are stored in external databases. On the Web, as another example, we already have tremendous amounts of meta-information which will significantly increase as the Semantic Web vision becomes more and more tangible. Obviously, these information sources cannot be stored directly in memory.

Thus, we are interested in querying DL concepts where the actual data set – the so-called ABox – is bigger than the available computer memory. We found that most existing DL reasoners are not suitable for this task, as these are not capable of handling ABoxes stored externally, e.g. in databases. This is not a technical problem: most existing algorithms for querying DL concepts need to examine the whole ABox to answer a query which results in scalability problems and undermines the point of using databases. Because of this, we started to investigate techniques which allow the separation of the inference algorithm from the data storage.

We have developed a solution, where the inference algorithm is divided into two phases. First we create a *query plan*, in the form of a Prolog program, from the actual DL knowledge base, without any knowledge of the content of the underlying data set. Subsequently, this query plan can be run on real data, to obtain the required results.

Naturally, the quality of the query plan greatly affects the performance of the execution. We have applied several optimisations to make the generated Prolog program more efficient. These ideas are incorporated in the reference implementation system called DLog, available at `http://dlog-reasoner.sourceforge.net`.

From the DL point of view, DLog is an ABox reasoning engine for the full $\mathcal{SHIQ}$ language. It deals with number restrictions as well as with all other modelling constructs present in $\mathcal{SHIQ}$. DLog maintains the unique name assumption and assumes that the ABox is consistent (see Section 3.1 for more details).

The paper is structured as follows: Section 2 discusses the background of the paper, introducing the field of DL and giving a summary of theorem-proving approaches for DLs. In Section 3 we start with two motivating examples to demonstrate the non-trivial nature of the translation of DL axioms to Prolog. We then present a complete, but inefficient, solution for generating Prolog programs from $\mathcal{SHIQ}$ knowledge bases. Section 4 discusses several optimisation schemes which significantly increase the efficiency of execution. Section 5 presents the architecture and the implementation details of the DLog system. In Section 6 we analyse the performance of DLog, comparing it with other reasoning systems. Finally, in Sections 7 and 8, we conclude with the discussion of future work and the summary of our results.

2 Background and related work

In this section we first provide a brief introduction to DLs, and then we give an overview of traditional, tableau-based DL reasoning approaches. Next, we discuss how resolution can be used for DL inference and summarise related work on using logic programming for DL reasoning, including our earlier contributions. Finally, we present the Prolog technology theorem-proving approach, the techniques of which are used extensively throughout the paper.

2.1 Description logics

DLs (Baader *et al.* 2004) constitute a family of simple logic languages used for knowledge representation. DLs are used for describing various kinds of knowledge of a specific field as well as of general nature. The DL approach uses *concepts* to represent sets of *objects* and *roles* to describe binary relations between concepts. Objects are the instances occurring in the modelled application field and thus are also called *instances* or *individuals*.

A DL knowledge base *KB* is a set of DL axioms consisting of two disjoint parts: the *TBox* and the *ABox*. These are sometimes referred to as $KB_{\mathcal{T}}$ and $KB_{\mathcal{A}}$. The TBox (terminology box), in its simplest form, contains terminology axioms of the form $C \sqsubseteq D$ (concept *C* is subsumed by concept *D*). The ABox (assertion box) stores knowledge about the individuals in the world: a concept assertion of the form $C(i)$ denotes that the *individual name i* is an instance of the concept *C*, while a role assertion $R(i, j)$ means that individual names *i* and *j* are related through role *R*. Usually one assumes that two different individual names denote two different individuals. This is the so-called unique name assumption (UNA).

Note the difference between 'individual names' and 'individuals'. The former are syntactic elements of the DL language, while the latter are the elements of the modelled domain. To make the paper easier to read we will sometimes use the phrase 'individual' instead of 'individual name', assuming that the context makes it clear that a syntactic element is being referred to.

Concepts and roles may be either *atomic* (referred to by a concept name or a role name) or *composite*. A composite concept is built from atomic concepts using *constructors*. The expressiveness of a DL language depends on the constructors allowed for building composite concepts or roles. Obviously there is a trade-off between expressiveness and the complexity of inference.

We use the DL language $\mathcal{SHIQ}$ in this paper. Here, concepts (denoted by *C* and *D*) are built from roles (denoted by *R* and *S*), atomic concepts and the top and bottom concepts ($\top$ and $\bot$) using the following constructors: intersection ($C \sqcap D$), union ($C \sqcup D$), negation ($\neg C$), value restriction ($\forall R.\, C$), existential restriction ($\exists R.\, C$) and qualified number restrictions ($\geqslant n\, R.\, C$ and $\leqslant n\, R.\, C$). The only role constructor in $\mathcal{SHIQ}$ is the inverse operator; thus roles can take the form R_A or R_A^-, where R_A is an atomic role.

The $\mathcal{SHIQ}$ language also allows the use of role subsumption ($R \sqsubseteq S$), role equivalence ($R \equiv S$) and transitivity axioms ($\mathsf{Trans}(R)$). Note that a role equivalence

$R \equiv S$ can be eliminated by replacing it with the two axioms $R \sqsubseteq S$ and $S \sqsubseteq R$. The set of role subsumption axioms is often called a *role hierarchy*. Each $\mathcal{SHIQ}$ axiom has a straightforward translation in first-order logic (FOL).

An important sub-language of $\mathcal{SHIQ}$ is $\mathcal{ALC}$, where number restrictions, role axioms and inverse roles are not allowed.

The basic inference tasks concerning the TBox can be reduced to determining if a given concept C is satisfiable with respect to a given TBox.

ABox inference tasks require both a TBox and an ABox. In this paper, we will deal with two ABox reasoning problems: instance check and instance retrieval. In an *instance check* problem, a *query concept* C and an individual i is given. The question is whether $C(i)$ is entailed by the TBox and the ABox. In an *instance retrieval* problem the task is to retrieve all individual names i, for which assertion $C(i)$ is entailed by the TBox and an ABox, for a given query concept C.

For more details on DLs we refer the reader to the first two chapters of Baader *et al.* (2004).

2.2 Reasoning on DLs

Several techniques have been developed for ABox reasoning. Traditional ABox reasoning is based on the *tableau inference* algorithm, which tries to build a model showing that a given concept assertion is satisfiable. To infer that an individual i is an instance of a concept C, an indirect assumption $\neg C(i)$ is added to the ABox, and the tableau algorithm is applied. If this reports inconsistency, i is proved to be an instance of C. The main drawback of this approach is that it cannot be directly used for high-volume instance retrieval because it would require checking all instances in the ABox, one by one.

To make tableau-based reasoning more efficient on large data sets, several techniques have been developed in recent years (see e.g. Haarslev and Möller 20004). These are used by the state-of-the-art DL reasoners, such as RacerPro (Haarslev *et al.* 2004) and Pellet (Sirin *et al.* 2007), the two tableau reasoners used in our performance evaluation in Section 6.

Some DL reasoners pose serious restrictions on the knowledge base to ensure efficient execution with large amounts of instances. For example, Horrocks *et al.* (2004) suggested a solution called the *instance store*, where the ABox is stored externally and is accessed in a very efficient way. The drawback is that the ABox may contain only axioms of the form $C(a)$; i.e. we cannot make role assertions.

2.3 Resolution theorem proving for DLs

Horrock and Voronkov (2006) discussed how a first-order theorem prover, such as Vampire, can be modified and optimised for reasoning over DL knowledge bases. This work, however, mostly focuses on TBox reasoning.

The paper by Hustadt *et al.* (2004) describes a resolution-based inference algorithm which is not as sensitive to the increase of the ABox size as the tableau-based methods. The system KAON2 (Motik 2006) is an implementation of this approach,

providing reasoning services over the DL language $\mathcal{SHIQ}$. In Section 6 we use KAON2 as one of the systems with which we compare the performance of DLog.

The basic idea of KAON2 is to first transform a $\mathcal{SHIQ}$ knowledge base into a skolemised first-order clausal form. However, instead of using direct clausification, first a structural transformation (Plaisted and Greenbaum 1986) is applied on the $KB_{\mathcal{T}}$ axioms. This transformation eliminates the nested concept descriptions by introducing new concepts; the resulting set of first-order clauses is denoted by $\Xi(KB)$. In the next step, basic superposition (Nieuwenhuis and Rubio 1995), a refinement of first-order resolution, is applied to saturate $\Xi(KB_{\mathcal{T}})$. The resulting set of clauses is denoted by $\Gamma(KB_{\mathcal{T}})$. Clauses $\Gamma(KB_{\mathcal{T}}) \cup \Xi(KB_{\mathcal{A}})$ are then transformed into a disjunctive datalog program (Eiter *et al.* 1997) entailing the same set of ground facts as the initial DL knowledge base. This program is executed using a disjunctive datalog engine written specifically for KAON2. In this approach, the saturated clauses may still contain (non-nested) function symbols which are eliminated by introducing a new constant f_i, standing for $f(i)$, for each individual i in the ABox. This effectively means that KAON2 has to read the *whole content* of the ABox before attempting to answer any queries.

Although the motivation and goals of KAON2 are similar to ours, unlike KAON2 (1) we use a pure two-phase reasoning approach (i.e. the ABox is not involved in the first phase), and (2) we translate into Prolog which has well-established, efficient and robust implementations. More details are provided in the upcoming sections.

2.4 DLs and logic programming

Grosof *et al.* (2003) introduced the term description logic programming (DLP), advocating a direct transformation of $\mathcal{ALC}$ description logic concepts into Horn clauses. It poses some restrictions on the form of the knowledge base, to disallow axioms requiring disjunctive reasoning. As an extension, Hustadt *et al.* (2005) introduced a fragment of the $\mathcal{SHIQ}$ language which can be transformed into Horn clauses. This work, however, still poses restrictions on the use of disjunctions. In Hogan *et al.* (2008) and Delbru *et al.* (2008) the authors presented a semantic search engine which works on web-scale and builds on the extension of the DLP idea. Further important work on DLP includes Samuel *et al.* (2008) and Motik and Rosati (2007).

Another approach of utilising logic programming in DL reasoning was proposed by the research group of the authors of the present paper. Earlier results of this work have been published in papers that appeared in conference proceedings. The first step of our research resulted in a resolution-based transformation of ABox reasoning problems into Prolog for the DL language $\mathcal{ALC}$ and an *empty TBox* (Nagy *et al.* 2006b). As the second step, we examined how ABox reasoning services can be provided with respect to a *non-empty* TBox: we extended our approach to allow ABox inference involving $\mathcal{ALC}$ TBox axioms of a restricted form (Nagy *et al.* 2006a). In Lukácsy *et al.* (2006) we presented a system doing almost full $\mathcal{ALC}$ reasoning, which uses an interpreter based on Prolog technology theorem prover (PTTP) techniques (see Section 2.5).

Zsolt Zombori has extended the saturation technique of Motik (2006) so that there are no function symbols in the resulting first-order clauses (Zombori 2008). The basic idea here is to use a slightly modified version of the basic superposition, where the order of certain resolution steps is changed. Zombori (2008) showed that these modifications do not affect satisfiability, and they require a finite number of additional inference steps, compared to the 'standard' basic superposition.

2.5 Prolog technology theorem proving

The PTTP approach was suggested by Mark E. Stickel in the late 1980s (Stickel 1992). PTTP is a sound and complete approach which builds a first-order theorem prover on top of Prolog. This means that an arbitrary set of general clauses is transformed into a set of Horn clauses, and Prolog execution is used to perform FOL reasoning. Note that PTTP does not support first-order equality reasoning, but there are extensions of PTTP, such as the Prolog technology term rewriting system, suitable for this task (Cheng *et al.* 1993).

In PTTP, each first-order clause gives rise to a number of Horn clauses, the so-called contrapositives. An FOL clause takes the form $\bigvee_{1 \leqslant i \leqslant n} L_i$, where L_i are literals (negated or non-negated atomic predicates). This clause has n contrapositives of the form $L_k \leftarrow \neg L_1, \ldots, \neg L_{k-1}, \neg L_{k+1}, \ldots, \neg L_n$, for each $1 \leqslant k \leqslant n$. Having removed double negations, the remaining negations are eliminated by introducing new predicate names for negated literals. For each predicate name P a new predicate name not_P is introduced, and all occurrences of $\neg P(X)$ are replaced by $not\_P(X)$, both in the head and in the body. The link between the separate predicates P and not_P is created by *ancestor resolution* (see below).

Note that the use of contrapositives has the effect that each literal of an FOL clause appears in the head of a Horn clause. This ensures that each literal can participate in a resolution step, in spite of the restricted selection rule of Prolog.

The PTTP approach uses ancestor resolution (Kowalski and Kuehner 1971) to support the *factoring* inference rule (the replacement of two unifiable literals by a single most general unifier of the two literals). Ancestor resolution is implemented in Prolog by building an *ancestor list* which contains *open* predicate calls – i.e. calls which were entered or re-entered but have not been exited yet, according to the procedure-box model of Prolog execution (Nilsson and Maluszynski 1990). Alternatively, an 'ancestor-of' relation between goals can be defined as the transitive closure of the 'parent-of' relationship, where goal PG is the *parent* of the goal G, if PG invokes a clause whose body contains G. The ancestor list contains all ancestors of a given goal, usually in the 'newest first' order.

Ancestor resolution is an inference step checking if the ancestor list contains a goal which can be unified with the negation of the current goal. If this is the case, then the current goal succeeds, and the unification with the ancestor element is performed. Note that in order to retain completeness, as an alternative to ancestor resolution, one has to try to prove the current goal using normal resolution, too.

There are two further features in the PTTP approach. First, to avoid infinite loops, iterative deepening is used instead of the standard depth-first Prolog search

strategy. Second, in contrast with most Prolog systems, PTTP uses occurs check during unification.

To sum up, PTTP uses five techniques to build a first-order theorem prover on the top of Prolog: contrapositives, renaming of negated literals, ancestor resolution, iterative deepening and occurs check.

3 DL reasoning in Prolog

We present a pure two-phase approach to $\mathcal{SHIQ}$ ABox inference. In the first phase, the $\mathcal{SHIQ}$ axioms are transformed into a Prolog program. The second phase is the execution of this program. Importantly, the ABox axioms are not modified by this transformation, and so the ABox can be stored externally, e.g. in a database.

The first phase, the transformation, is itself divided into two stages. First, the $\mathcal{SHIQ}$ axioms are converted into a set of first-order clauses of a specific form. The second stage deals with the transformation of FOL clauses into a Prolog program.

We first summarise some general assumptions and present two motivating examples. Next, we give an outline of the first stage of the transformation. Before proceeding to the second stage, we introduce the notion of *DL clause*, which is a first-order clause satisfying certain requirements. Each clause produced by the first stage of the transformation satisfies these requirements, but there are interesting DL clauses which cannot be derived from a $\mathcal{SHIQ}$ KB.

The second stage takes an arbitrary set of DL clauses and transforms these into a Prolog program. We first show how the PTTP approach can be specialised for DL clauses, resulting in a so-called DL program. We then present a simple interpreter for DL programs. Next, we describe how to extend DL programs so that they can be directly executed by Prolog, thus making it possible to compile a $\mathcal{SHIQ}$ KB to an executable Prolog program. Finally, we show some examples of this complete transformation process.

3.1 General considerations

Throughout this paper we assume (1) that different individual names denote different individuals (UNA) and (2) that the ABox is consistent.

Note that in the absence of the UNA one may have to perform complex deductions to determine whether two individuals are distinct. Namely the individuals i_1 and i_2 can be inferred to be different if one can find an *arbitrary* concept C, such that both $C(i_1)$ and $\neg C(i_2)$ hold. Thus deciding a simple inequality question potentially requires reading the whole ABox, which makes it impossible to perform ABox reasoning in a focused way.

Similarly, detecting the inconsistency of an ABox requires checking the whole content of the ABox.

As the main advantage of our approach – the focused nature of reasoning – is lost in both cases, we advocate using other approaches (e.g. tableau algorithms) for checking ABox consistency and answering ABox queries in the absence of the UNA.

```
1  ∃hasChild.(Patricide ⊓ ∃hasChild.¬Patricide) ⊑ Ans
2
3  hasChild(Iocaste,Oedipus).      hasChild(Iocaste,Polyneikes).
4  hasChild(Oedipus,Polyneikes).   hasChild(Polyneikes,Thersandros).
5  Patricide(Oedipus).             ¬Patricide(Thersandros).
```

Fig. 1. The Iocaste knowledge base.

We also assume that the ABox is extensionally reduced; i.e. beside roles, it contains only atomic concepts and their negations. An arbitrary knowledge base can be easily transformed to satisfy this constraint. First, one has to replace all composite concepts in the ABox (except for the negated atomic concepts) by new atomic concepts. Next, one has to extend the TBox with appropriate concept axioms, which define the newly introduced concept names to be equivalent to the composite concept they stand for.

In Sections 3 and 4 we assume that no predicate name contains the character _ (underline). This makes it possible to use prefixes containing an underline (such as not_) as names of various auxiliary predicates. This restriction does not apply in the DLog system, discussed in Section 5.

3.2 Translating by hand: Two motivating examples

Databases and the *negation as failure* feature of Prolog use the *closed world assumption* in which any object which is not known to be an instance of concept C is treated as an instance of $\neg C$. In contrast with this, the *open world assumption* is used in classical logic reasoning and thus in DL reasoning as well. When reasoning under the open world assumption, one is interested in obtaining statements which hold in all models of the knowledge base, i.e. those entailed by the knowledge base.

Figure 1 shows a famous DL example of the family of Oedipus and Iocaste, which is often used to demonstrate the difference between open and closed world reasoning (see e.g. Baader *et al.* 2004).

The only TBox axiom is shown in line 1, while the content of the ABox is given in lines 3–5. The TBox axiom expresses that somebody is considered to be an answer if she has a patricide child, who, in turn, has a non-patricide child. The ABox axioms describe the hasChild binary relation between certain individuals and also express the facts that Oedipus is known to be patricide, while Thersandros is known to be non-patricide. (Note that both patricide and non-patricide are unary relations.) Our task is to solve the instance-check problem Ans(Iocaste), i.e. to decide if the given knowledge base entails the fact that Iocaste belongs to the answer concept Ans.

Note that Iocaste can be shown to be an answer, in spite of the fact that one cannot *name* the child of Iocaste who has the desired property. That is solving this specific instance check problem requires *case analysis*: the child in question is either Polyneikes or Oedipus, depending on Polyneikes being a patricide or not.
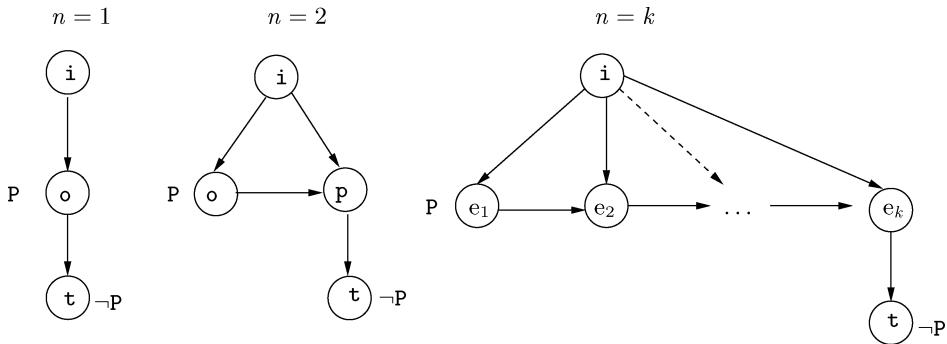
Fig. 2. Iocaste ABox patterns.

Also note that the trivial Prolog translation of the DL knowledge base in Figure 1, shown below, is not appropriate, as the goal :- Ans(i) fails:

```
Ans(A) :-  hasChild(A, B), Patricide(B), hasChild(B, C), not_Patricide(C).

Patricide(o).    not_Patricide(t).
hasChild(i, o). hasChild(i, p). hasChild(o, p). hasChild(p, t).
```

Here, to follow the standard DL notation, predicate names corresponding to concepts start with capitals, while role names are written in lowercase. For the sake of conciseness we omit the apostrophes around Prolog predicate names starting with capitals, and we also use the abbreviations i, o, p and t for instance names.

Note that using negation as failure (the \+ operator) would not solve the problem: when the goal not_Patricide(C) in line 1 is replaced by \+ Patricide(C), every instance not known to be patricide is viewed as non-patricide, which is not correct. For example consider the ABox containing the axioms hasChild(i1, i2), hasChild(i2, i3) and Patricide(i2). This ABox does not entail Ans(i1), but the Prolog program using negation as failure does return success for this query.

There is an infinite number of ABox *patterns* which allow an individual to be proven to belong to concept Ans (Nagy *et al.* 2006b). These patterns are shown in Figure 2. Here the nodes of the pattern graph stand for individuals, while the edges represent the hasChild role instances. Furthermore, P and ¬P stand for Patricide and not_Patricide, respectively. Note that case $n = 2$ corresponds to the ABox given in Figure 1.

Consider the ABox corresponding to the general case (the rightmost pattern). We show that the individual i does belong to the concept Ans. Assume that there is a model of this ABox in which ¬Ans(i) holds. We show by induction that for each $j = 1, \ldots, k$, Patricide(e_j) holds in this model. This is true for $j = 1$. Assume that this is true for $j = m$. Because e_m is a patricide child of i, where the latter does not belong to Ans, all children of e_m have to be patricide. Thus e_{m+1} is a patricide, which completes the inductive proof. Hence e_k is a patricide child of i, who has a non-patricide child t, and thus i belongs to Ans. This contradicts our initial, indirect assumption, thus proving that i belongs to the concept Ans. See the paper by Nagy *et al.* (2006b) for the proof that the patterns of Figure 2 give an

```
1 Ans(X) :- hasChild(X,Y), hasChild(Y,Z), not_Patricide(Z), dPatricide(Y,X).
2
3 dPatricide(Z, _)    :- Patricide(Z).
4 dPatricide(Z, X)    :- hasChild(X, Y), hasChild(Y, Z), dPatricide(Y, X).
5
6 Patricide(o).    not_Patricide(t).
7 hasChild(i, o). hasChild(i, p). hasChild(o, p). hasChild(p, t).
```

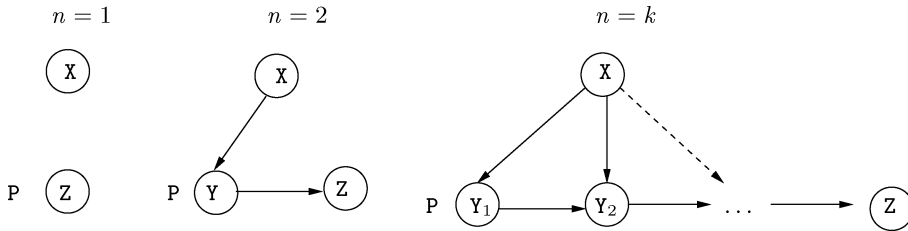Fig. 3. A Prolog translation of the Iocaste knowledge base.

Fig. 4. The pattern captured by `dPatricide/2`.

```
1 ∃hasChild.(∃hasChild.Clever ⊓ ∃hasChild.Pretty) ⊑ Happy
2
3 Clever(lisa). Pretty(lisa). hasChild(kate,bob). hasChild(bob,lisa).
```

Fig. 5. The Happy knowledge base.

exact characterisation of ABoxes entailing Ans(i), w.r.t. the TBox shown in line 1 of Figure 1.

A Prolog program, written by hand, solving the Iocaste problem is presented in Figure 3. We have shown in Nagy *et al.* (2006b) that this program is a sound and complete translation of the Iocaste problem, and it captures exactly the patterns shown in Figure 2. To see this, notice that `dPatricide(Z,X)` describes patterns of the form shown in Figure 4. The first clause of `dPatricide(Z,X)` (line 3) corresponds to the degenerate pattern for the case $n = 1$. The second clause (line 4) states that a new pattern corresponding to `dPatricide(Z,X)` can be obtained by extending a pattern corresponding to `dPatricide(Y,X)` by two new `hasChild` edges between `(X, Y)` and `(Y, Z)`.

Note that the program in Figure 3 may not terminate if the `hasChild` relations form a directed cycle in the ABox. If this cannot be excluded, then termination can be ensured, for example, by tabling (Warren 2007) or *loop elimination* (see Section 3.5).

Unlike in the Iocaste problem, we do not always need to use case analysis, and therefore we can generate simpler programs. For example, let us consider the DL knowledge base presented in Figure 5. Here we consider someone happy if she has a child who, in turn, has both a clever child and a pretty child (line 1).

The ABox given in line 3, together with the TBox axiom in line 1, implies that `kate` is happy. In this case, there is a straightforward Prolog translation for the TBox, as shown in Figure 6.

```
1  Happy(A) :- hasChild(A, B), hasChild(B, C), hasChild(B, D),
2             Clever(C), Pretty(D).
3
4  Clever(lisa). Pretty(lisa). hasChild(kate, bob). hasChild(bob, lisa).
```

Fig. 6. The straightforward Prolog translation of the Happy knowledge base.

One of the aims in the DLog project is to create a framework in which problems not requiring case analysis result in straightforward Prolog programs. As we show later in Section 4, we can actually generate programs for the Iocaste and Happy problems which are the same as, or very close to, the handmade programs presented here.

3.3 Building first-order clauses from a $\mathcal{SHIQ}$ knowledge base

In this section we deal with the first stage of the $\mathcal{SHIQ}$-to-Prolog transformation: converting a $\mathcal{SHIQ}$ KB to a set of first-order clauses of a specific form. The details of this transformation are presented in Zombori (2008); here we only give an outline and an illustrative example.

The basic idea of this conversion is to bring forward the inference steps that are independent of the ABox. In doing so, our aim is not to compute all consequences of the TBox – that would require too much time and is not needed anyway – but to perform those steps that complicate the ABox reasoning. Most notably, the translation of a DL TBox into first-order clauses involves introducing skolem functions which require special treatment. However, the fact that the ABox is function free suggests that all inference steps involving function symbols can be performed before accessing the ABox. Hence, instead of complicating the ABox reasoning, we break the reasoning into two parts: an ABox-independent TBox transformation is performed as the first phase, and this is followed by the actual data reasoning as the second phase.

In Zombori (2008) a new calculus is introduced, which extends the work described in Motik (2006). This calculus, similar to basic superposition, is shown to be sound, complete and terminating for any input derived from a $\mathcal{SHIQ}$ knowledge base. For any proof within the calculus, we can order the inference steps in such a way that all steps involving function symbols precede all steps involving clauses derived from the ABox. In the first stage of the reasoning we perform the steps that do not require the ABox. The clauses containing function symbols cannot play any role afterwards; thus we can simply remove them. The second stage – which is the focus of the present paper – makes use of the function-free nature of the clauses, when transforming these into a Prolog program.

Note that, as opposed to Motik (2006), all clauses containing function symbols are eliminated in the DL-to-Prolog transformation. This forms the basis of a pure two-phase reasoning framework, which allows us to store the content of the ABox in an external database.

For an arbitrary $\mathcal{SHIQ}$ knowledge base KB, let us denote by $DL(KB)$ the set of first-order clauses resulting from the first stage of the transformation. In the rest of

(1) $\neg R(x, y) \vee S(y, x)$

(2) $\neg R(x, y) \vee S(x, y)$

(3) $\mathbf{C}(x)$

(4) $\bigvee_{i,j,k} \neg R_k(x_i, x_j) \vee \bigvee_i \mathbf{C}(x_i) \vee \bigvee_{i,j} (x_i = x_j)$

(5) $R(a, b)$

(6) $C(a)$

Fig. 7. The structure of $DL(KB)$.

the paper we only make use of the fact that $DL(KB)$ contains clauses of a specific form, as listed in Figure 7.

Here clauses (1)–(4) are derived from $KB_{\mathcal{T}}$, the TBox part of the knowledge base, while clauses (5)–(6) are derived from the ABox. As for first-order clauses, all variable symbols appearing in (1)–(4) are universally quantified; R and S denote binary predicate names, which correspond to roles, and C is a possibly negated unary predicate name, corresponding to a concept. Symbols a and b are constants and $\mathbf{C}(x)$ denotes a non-empty disjunction of (positive or negative) unary literals, all having the variable x as their argument: $\mathbf{C}(x) = (\neg)C_1(x) \vee \ldots \vee (\neg)C_n(x)$, $n \geqslant 1$.

Clause (4) requires further explanation, as it is known to satisfy certain constraints. First, it contains at least one binary literal, at least one unary literal and a possibly empty set of variable equalities. Second, its binary literals contain all the variables of the clause. Third, if we build a graph from the binary literals by converting $\neg R(x, y)$ into an edge $x \rightarrow y$, then the graph obtained will always be a tree.

We illustrate the transformation of the TBox with a small example. Although the axioms are first translated to first-order clauses and the reasoning is performed on this form, we will give the DL equivalents of the transformed clauses, to make the example more compact. Let us consider the following TBox:

$$\top \quad \sqsubseteq \quad (\leqslant 1 \,\mathrm{hasChild}.\,\mathrm{Successful}) \tag{1}$$

$$\top \quad \sqsubseteq \quad (\geqslant 1 \,\mathrm{hasChild}.\,\mathrm{Clever}) \tag{2}$$

$$\mathrm{Clever} \quad \sqsubseteq \quad \mathrm{Successful} \tag{3}$$

$$(\geqslant 2 \,\mathrm{hasChild}.\,\top) \quad \sqsubseteq \quad \mathrm{Happy} \tag{4}$$

The transformation of (Zombori 2008) will effectuate the following three changes in the TBox:

- We know that everybody has a clever child (2), who is also successful (3). But since there can only be at most one successful child (1), it is impossible for a child to be successful and not clever. Accordingly, we will deduce the following axiom (more precisely, the first-order clause corresponding to this axiom):

$$\top \sqsubseteq (\forall \mathrm{hasChild}.\,(\mathrm{Clever} \sqcup \neg\mathrm{Successful})) \tag{5}$$

- How can a person turn out to be happy? If she has two children. But we already know that everyone has at least one clever child. So if she happens to have a non-clever child, then this child cannot be identical to the clever one; so they

are really two distinct children; hence the person is happy. Thus the following axiom is deduced:

$$(\exists \text{hasChild}. \neg \text{Clever}) \sqsubseteq \text{Happy} \tag{6}$$

- If we translate these six axioms to first-order clauses, (2) is the only one that will give rise to skolem functions. (Skolem functions are derived from $\geqslant$-concepts on the right side of $\sqsubseteq$ and from $\leqslant$-concepts on the left side of $\sqsubseteq$.) But we only need (2) to deduce (5) and (6). Once this is done, we can dispose of (2).

The following five axioms are thus produced as the output of the first stage:

$$\top \quad \sqsubseteq \quad (\leqslant 1 \,\text{hasChild}. \,\text{Successful})$$
$$\text{Clever} \quad \sqsubseteq \quad \text{Successful}$$
$$(\geqslant 2 \,\text{hasChild}. \top) \quad \sqsubseteq \quad \text{Happy}$$
$$\top \quad \sqsubseteq \quad (\forall \text{hasChild}. \,(\text{Clever} \sqcup \neg \text{Successful}))$$
$$(\exists \text{hasChild}. \neg \text{Clever}) \quad \sqsubseteq \quad \text{Happy}$$

The corresponding first-order clauses (where the variables are all universally quantified) are the following:

$\neg \text{hasChild}(x, y_1) \vee \neg \text{hasChild}(x, y_2) \vee \neg \text{Successful}(y_1) \vee \neg \text{Successful}(y_2) \vee y_1 = y_2$

$\neg \text{Clever}(x) \vee \text{Successful}(x)$

$\neg \text{hasChild}(x, y_1) \vee \neg \text{hasChild}(x, y_2) \vee \text{Happy}(x) \vee y_1 = y_2$

$\neg \text{hasChild}(x, y) \vee \text{Clever}(y) \vee \neg \text{Successful}(y)$

$\neg \text{hasChild}(x, y) \vee \text{Clever}(y) \vee \text{Happy}(x)$

Note that these clauses are indeed of the form listed in Figure 7. As the calculus used here is shown to be complete and sound in Zombori (2008), we know that no further TBox clauses need to be inferred and that the omission of clause (2) does not invalidate any ABox inference.

An important feature of the first stage is that it eliminates transitivity axioms by introducing auxiliary unary predicates, following the technique described in Motik (2006).

Finally, a minor technical remark: the clauses produced from a $\mathcal{SHIQ}$ knowledge base may contain binary literals corresponding to inverse roles. We avoid the need for constructing inverse role names by the following transformation: the predicate $R_A^-(X, Y)$ is replaced by $R_A(Y, X)$, where R_A is an atomic role.

3.4 DL clauses

In the remaining part of this paper we focus on how to transform clauses of the form shown in Figure 7 into efficient Prolog code. However, we note that for the general transformation, discussed in the present section, we use only certain properties of the clauses. These properties are satisfied by a subset of first-order clauses, which is, in fact, larger than the set of clauses that can be generated from a $\mathcal{SHIQ}$ KB. These properties are summarised in the following definition.

Definition 1 (*DL clauses*)

A first-order clause *C* is said to be a *DL clause* if it satisfies the following properties:

(p1) *C* consists of unary, binary and equality literals only. Moreover, *C* is function free; i.e. there is no literal in *C* which contains function symbols.

(p2) *C* either contains a binary literal, or it is ground, or it contains no constants, no (in)equalities and exactly one variable.

(p3) If there is a binary literal in *C*, then each variable in *C* occurs in at least one binary literal.

(p4) If *C* contains a positive binary literal *B*, then all the remaining literals, i.e. those in $C' = C \setminus \{B\}$, are negative binary literals, and the set of variables of C' and *B* is the same.

Note that the sub-condition 'contains ... no (in)equalities' of (p2) is practically unnecessary. More precisely, if we remove this sub-condition, we can show that any (in)equality occurring in *C* can be trivially deleted. Assume that there is a DL clause *C* which contains no binary literal and is not ground. Because of the weaker form of (p2), we still know that *C* contains no constants and exactly one variable. Thus, any equality literal contained in *C* has to be of the form $x = x$ or $x \neq x$. In the first case the literal is always true, making *C* useless, while the $x \neq x$ literal is always false, and so it can be removed from *C*.

Now we formulate the following proposition (proved by simply checking each of the clauses in Figure 7).

Proposition 1

For a given $\mathcal{SHIQ}$ knowledge base *KB*, every clause $C \in DL(KB)$ is a DL clause.

Note that the properties in Definition 1 are necessary but not sufficient conditions for being a clause of the form shown in Figure 7; i.e. these properties may also hold for a clause which cannot be derived from a $\mathcal{SHIQ}$ knowledge base. An example for such a clause is the following:

$$P(x) \vee \neg R(x, x). \tag{7}$$

In the rest of this section we discuss how to transform an *arbitrary* set of DL clauses, i.e. clauses satisfying Definition 1, into a Prolog program. However, in Section 4, which presents several optimisations of this transformation process, we will restrict the discussion to inputs produced from $\mathcal{SHIQ}$ KBs, i.e. sets of clauses of the form shown in Figure 7.

Let us now consider a certain type of unary predicates, namely those corresponding to the $\top$ (top) concept.

Definition 2 (*Top predicate*)

Let *S* be a set of DL clauses, and let *p* be a unary predicate name which appears somewhere in *S*. Predicate name *p* is said to be a *top predicate* if *S* entails $\forall x. p(x)$.

One can view top predicates as degenerate, as their negations correspond to unsatisfiable concepts. Recall that it is normally considered a modelling error if a DL knowledge base contains an unsatisfiable concept, i.e. a concept equivalent to $\bot$.

Technically, we have to deal with top predicates because of a subtle difference between the requirements of FOL and DL reasoning. When PTTP is asked to list all x instances satisfying $p(x)$, where p is a top predicate, it will normally return without instantiating x, which indicates that all domain elements satisfy p. In contrast with this, a DL reasoner is expected to enumerate all named individuals in the ABox as the answers to an instance retrieval query concerning a concept corresponding to a top predicate.

It can be shown that for DL clauses the top-predicate property does not depend on the ground clauses, i.e. on the ABox part of the knowledge base. Specifically, for $\mathcal{SHIQ}$ knowledge bases, one can determine if p is a top predicate by checking the satisfiability of the concept $\neg p$, using a suitable TBox reasoning engine.

In order to be able to formulate our results in a simpler form, we define a transformation removing all top predicates from a knowledge base.

Definition 3 (*Reduced form of a set of DL clauses*)
Let S be a set of DL clauses. We modify S in the following way: (1) we remove all literals in S which refer to a negated top predicate; (2) we remove every clause C from S, where C contains a positive literal with a top predicate. The remaining set of clauses is called the *reduced form* of S.

The following proposition shows that this reduction step preserves all information except for the top predicates.

Proposition 2
Let S be a set of DL clauses. Let us extend the *reduced form* of S with clauses of the form $p(x)$, for each top predicate p in S. This extended set of clauses is equivalent to S.

Proof
Easily follows form the fact that both transformation steps (1) and (2) in Definition 3 are sound. □

In the following, we will restrict our attention to sets of DL clauses which are in reduced form.

3.5 Specialising PTTP for DL clauses

In this section we discuss how to specialise various features of PTTP for the case of DL clauses.

Contrapositives. The first step in applying the PTTP approach to a set of DL clauses S is to generate the contrapositives of each clause in S. This, in turn, requires the introduction of new predicate names for negated literals.

We now reiterate the corresponding definitions from Section 2.5. On one hand, we extend these to handle equalities. On the other hand, we specialise these definitions for DL clauses. Recall that a DL clause is a non-empty disjunction of literals, each literal is a possibly negated atomic predicate, and an atomic predicate can take one

of the following three forms:

- a unary predicate $p(x)$;
- a binary predicate $p(x, y)$; and
- an equality $x = y$.

Definition 4 (*The canonical form of literals*)
Let L be a literal or a literal preceded by a negation symbol. The canonical form of L, denoted by $can(L)$, is defined as follows:

$$can(L) = \begin{cases} \texttt{not\_}p(x) & \text{if } L = \neg p(x), \\ \texttt{not\_}p(x, y) & \text{if } L = \neg p(x, y), \\ \texttt{dif}(x, y) & \text{if } L = \neg(x = y), \\ can(L') & \text{if } L = \neg\neg L', \\ L & \text{otherwise.} \end{cases}$$

In the above definition, the first two cases remove a negation from before atomic predicates and prefix the predicate name with 'not_'. The third case transforms an inequality to a call of the predicate `dif`. This is a predicate available in most Prolog systems, which ensures that its two arguments are not unifiable. For Prolog programs generated from DL clauses, where the variables are instantiated to constants sooner or later, this ensures that the arguments of `dif` are indeed different. The fourth case removes double negation, while the last one states that non-negated literals are left unchanged. This implies that an equality is handled by the standard Prolog predicate '='. We can implement inequality and equality using `dif` and '=' because of the UNA, which states that an inequality holds for any two distinct individual names, and thus an equality can hold only when its two sides are identical individual names.

Definition 5 (*DL-contrapositive of a DL clause*)
Let $DLC = \bigvee_{1 \leqslant i \leqslant n} L_i$ be an arbitrary DL clause. The Horn clause

$$can(L_k) \;\; :\text{-} \;\; can(\neg L_1), \ldots, can(\neg L_{k-1}), can(\neg L_{k+1}), \ldots, can(\neg L_n)$$

is called a DL-contrapositive of DLC, provided L_k is a (possibly negated) unary or binary predicate.

Note that we do not consider Horn clauses with an equality or inequality in the head. Such clauses could be used to infer that two individuals are equal or distinct. However, we work with the UNA, which decides the issue of equality, and so such deductions are unnecessary.

Definition 6 (*DL program*)
Let S be a set of DL clauses. The *DL program* corresponding to S is denoted by $PDL(S)$ and contains all DL-contrapositives of the clauses in S, i.e. $PDL(S) = \{C | C$ is a DL-contrapositive of C_0, and $C_0 \in S\}$.

Horn clauses are usually grouped into predicates, according to the functor of the clause head. The functor of a term is a pair consisting of a name and arity (number of arguments). In Prolog, functors are normally denoted by the expression *Name/Arity*, for example `foo/2`. Thus a DL program can be also viewed as a set of *DL predicates*,

```
1  Ans(A)            :- hasChild(A, B), hasChild(B, C),
2                       Patricide(B), not_Patricide(C).
3  Patricide(o).
4  Patricide(A)      :- hasChild(B, A),  hasChild(C, B),
5                       Patricide(B), not_Ans(C).
6  not_Patricide(t).
7  not_Patricide(A) :- hasChild(A, B), hasChild(C, A),
8                       not_Ans(C), not_Patricide(B).
9
10 hasChild(i, o). hasChild(i, p). hasChild(o, p). hasChild(p, t).
```

Fig. 8. DL predicates of the Iocaste problem.

```
1  Happy(A)        :- hasChild(A, B), hasChild(B, C), hasChild(B, D),
2                     Clever(C), Pretty(D).
3
4  not_Clever(A) :- hasChild(B, C), hasChild(C, A), hasChild(C, D),
5                     Pretty(D), not_Happy(B).
6
7  not_Pretty(A) :- hasChild(B, C), hasChild(C, D), hasChild(C, A),
8                     Clever(D), not_Happy(B)
9
10 Clever(lisa). Pretty(lisa). hasChild(kate, bob). hasChild(bob, lisa).
```

Fig. 9. DL predicates of the Happy problem.

each of which consists of all clauses of the DL program, which have a given head functor. In the rest of the paper it is the context which determines whether we view the DL program as a set of Horn clauses or as a set of DL predicates. Accordingly, we use the term 'DL predicates' as a synonym of 'DL program'.

As an example, in Figure 8 we show the four DL predicates produced from the Iocaste knowledge base of Figure 1. Notice, for example, that the first clause of the Patricide/1 predicate comes from the ABox, while the second comes from the TBox. We also show the six DL predicates of the Happy KB in Figure 9. We have not included the DL predicate not_hasChild/2 in these examples because we will soon prove that clauses with a negated binary literal in the head are not needed (cf. Proposition 4).

Conjunctive queries. Given the notion of DL programs, we now discuss how such a program can be queried. Instance retrieval queries include possibly negated atomic concepts and unnegated (positive) binary roles, for example not_Patricide(A) and hasChild(A, B). The former is supposed to enumerate all possible individuals known to be non-patricide. The latter is expected to enumerate all pairs of individuals between whom the hasChild relation holds. In this paper we support *conjunctive queries* (Glimm *et al.* 2007), which are conjunctions of the above instance retrieval constructs. The execution of a conjunctive query with n distinct variables is expected to return a set of n-tuples, each being a variable assignment satisfying all the conjuncts. An example of a conjunctive query with three variables is (Patricide(X), hasChild(X, Y), not_Patricide(Y), hasChild(Y, Z)).

Basic simplifications. We now discuss three basic simplifications of PTTP for the special case of DL clauses. First, let us notice that the occurs check is not necessary, as DL clauses are function free. Next, for the case of conjunctive queries, we claim that (1) contrapositives with negated binary literals in the head can be removed from the DL program, and (2) ancestor resolution is not needed for roles. Before proving these claims let us observe the following proposition.

Proposition 3
In a DL program, a negated binary predicate can only be invoked within a negated binary predicate.

Proof
Let C be a clause in the DL program, such that the body of C contains a negated binary goal G. Accordingly, C is the contrapositive of a DL clause in which the binary literal corresponding to G is a positive literal. However, because of property (p4) in Definition 1, we know that this DL clause cannot contain any more positive binary literals, and moreover, it can only contain negative binary literals. Thus, the head of C must correspond to a negative binary literal. □

Proposition 4
Removing contrapositives with negated binary literals in the head from a DL program does not affect the execution of conjunctive queries.

Proof
This is a direct conclusion of Proposition 3 and the fact that a conjunctive query cannot contain negated binary goals. □

Note that when the clauses with a negated binary literal in the head are removed, no negative binary literals will remain in the bodies (as the latter only appear in clauses with negative binary heads; cf. Proposition 3). Thus, unless stated otherwise, the term *binary predicate* will refer to unnegated binary predicates, from now on.

Proposition 5
Ancestor resolution is not required for binary predicates to answer conjunctive queries w.r.t. a DL program S.

Proof
This trivially follows from the fact that negative binary predicates are never called and can never occur in the ancestor list. □

The binary-first rule. The next simplification of PTTP, the replacement of iterative deepening by *loop elimination*, requires that a specific restriction is imposed on the placement of the binary goals in clause bodies. We now present an important property of binary goals, introduce the *binary-first* body-ordering rule and discuss its implications.

Proposition 6

Let S be a set of DL predicates and B be a binary goal. If the Prolog execution of B w.r.t. S terminates with success, it instantiates both its arguments.

Proof

Let us indirectly assume that there is a binary goal $B(X, Y)$ which terminates, but one of its arguments, let us say X, remains uninstantiated. Since $B(X, Y)$ terminates, there is a finite Prolog proof tree T for it. Let us consider the nodes in T containing a binary goal with X as one of its arguments. As T is finite, there exists a 'lowest' of these, i.e. a node with no occurrences of X in binary goals below it. However, this contradicts property (p4) of DL clauses in Definition 1. $\square$

Definition 7 (*The binary-first rule*)

The body of a Prolog clause C is ordered according to the *binary-first rule* if (1) each binary goal B in the body of C precedes all unary and (in)equality goals containing any of the variables occurring in B, and (2) if the body of C contains a binary goal with the head variable as an argument, then at least one such goal precedes all unary goals.

For an arbitrary clause C containing a binary goal, condition (1) ensures that all unary and equality goals within C are called with a ground argument, while condition (2) guarantees that by the time the first unary goal in C is called, the head variable is ground.

Proposition 7

Let S be a set of DL predicates, and let us use the binary-first rule during the Prolog execution. (a) If a unary predicate is invoked with a variable argument V, then all its ancestors (including the outermost one, the concept query goal) are unary goals which have the given variable V as their argument. (b) Equality predicates (i.e. =/2 and dif/2) are always invoked with ground arguments.

Proof

(a) Let G be the unary goal which is invoked with the variable argument V in clause C. Because of condition (p4) in Definition 1 and Proposition 4, a unary goal can only be invoked from within a clause of a unary predicate. If there are binary goals within the body of C, then G is always preceded by a binary goal containing V according to (p3) in Definition 1 and the binary-first rule. Because of Proposition 6, however, we know that variable V is already instantiated by the time G is invoked. This means there can be no binary goals in the body of C, and so, according to (p2) in Definition 1, C contains a single variable. Consequently, V is the variable appearing in the head of C; i.e. the parent goal of G is a unary goal invoked with the same variable argument as G. By repeatedly applying this argumentation we can conclude that all ancestors of the given goal have the variable V as their argument. (b) Assume that an equality goal is invoked with an uninstantiated variable V within a Horn clause obtained from the DL clause C. Because of (p2) and (p3), there has to be a binary literal in clause C containing V. Because of (p4), this binary literal is negative. The binary-first rule means that the given binary literal is executed

before the equality predicate, and Proposition 6 ensures that V is instantiated, which contradicts our initial, indirect assumption.   □

Proposition 8
If the binary-first rule is applied, the `=/2` and `dif/2` predicate invocations can be replaced by `==/2` and `\==/2` (the standard Prolog term comparison predicates checking if their arguments are identical and non-identical respectively).

Proof
When invoked with ground arguments, the standard predicates `==/2` and `\==/2` have the exact same semantics as the predicates they replace.   □

Let us now examine which ancestor-descendant pairs are possible for unary predicates. In general, we have the following five cases, where variables X and Y are distinct, but predicate names q and p, as well as constants i and j can be the same:

(c1) within executing `p(i)` we encounter a goal `q(j)`;
(c2) within executing `p(i)` we encounter a goal `q(X)`;
(c3) within executing `p(X)` we encounter a goal `q(i)`;
(c4) within executing `p(X)` we encounter a goal `q(X)`; and
(c5) within executing `p(X)` we encounter a goal `q(Y)`.

The following proposition states that, in the case of DL predicates, some of these cases cannot occur.

Proposition 9
Let S be a set of DL predicates. When using the binary-first rule, cases (c2), (c3) and (c5) cannot occur during Prolog execution.

Proof
When the binary-first rule is used, cases (c2) and (c5) cannot occur, as a direct consequence of Proposition 7. Furthermore Proposition 6 and part (2) of Definition 7 (the binary first rule) ensure that the parent of a ground unary goal is ground, too. This implies that all ancestors of a ground unary goal are ground; hence case (c3) cannot occur.   □

Loop elimination. As the next simplification of the PTTP approach for DL programs, we replace iterative deepening by normal Prolog depth-first search, extended with a straightforward *loop elimination* technique. This feature, which involves pruning certain branches of the Prolog search tree, appeared already in PTTP, as an optimisation (Stickel 1992). However, in the context of DL programs, as opposed to arbitrary FOL clauses, loop elimination can itself ensure termination, as discussed below.

In the next two definitions we refer to an extension of Prolog execution in which the list of ancestor goals is maintained.

Definition 8 (Goals subject to loop elimination)
A Prolog goal G encountered in the context of an ancestor list L is *subject to loop elimination* if G occurs in L or, more precisely, if L contains an element G' for which $G == G'$ holds. Recall that `==` denotes the standard Prolog predicate which succeeds if its operands are identical.

Definition 9 (*Loop elimination*)

Let P be a Prolog program and G a Prolog goal. Executing G w.r.t. P using *loop elimination* means the Prolog execution of P extended in the following way: we stop the given execution branch with a failure whenever we encounter a goal G which is subject to loop elimination.

Using the notion of loop elimination we can formulate some termination results.

Proposition 10 (*Termination of DL execution*)

Let S be a set of DL predicates. Assuming loop elimination and that the binary-first rule is used, the execution of an arbitrary goal w.r.t. S always terminates.

Proof

Let us indirectly assume that there exists a goal G, the execution of which does not terminate. Because of loop elimination this can only happen if we can build an ancestor list with infinitely many distinct goals. Since the number of predicate and constant names is finite the ancestor list contains an infinite number of distinct variables.

According to part (a) of Proposition 7, unary goals on the ancestor list contain at most one variable. Property (p4) in Definition 1 implies that any variable appearing in a clause body within a binary DL predicate appears in the corresponding clause head, too. Thus a new variable can only be introduced when a binary goal is invoked in a unary predicate. However, property (p4) also implies that a binary predicate invokes binary goals only, with no new variables. Furthermore, Proposition 6 states that by the time a binary goal exits, both its arguments are instantiated. This means that the ancestor list can contain at most two uninstantiated variables at any time, contradicting our indirect assumption. □

Having proved that loop elimination and the binary-first rule guarantee termination, let us consider the issue whether loop elimination is complete, i.e. whether any solution that can be obtained by PTTP can also be obtained in the presence of loop elimination.

Note that for normal Prolog execution, loop elimination is obviously complete. That is given an arbitrary proof tree of a goal P in which goal G_1 appears in the subtree of an identical goal G_2 we can always create a new proof tree of P in which we replace the proof of G_1 by the proof of G_2. Continuing this process we can obtain a proof tree of P that does not contain any goals subject to loop elimination.

However, PTTP extends the normal Prolog execution by applying ancestor resolution for goals. This means that successful execution of a goal G may depend on the location of G within a proof tree (as this determines the ancestors of G). The completeness of loop elimination in the presence of ancestor resolution was first stated in Stickel (1992). We now give a reformulation of this statement.

Proposition 11 (*Completeness of loop elimination*)

Let T be a proof tree of a goal G corresponding to a PTTP execution, which contains a goal subject to loop elimination. It is possible to create another proof tree of goal G which contains no goals subject to loop elimination.

(a) DLog uses normal Prolog unification rather than unification with occurs check.
(b) DLog uses loop elimination instead of iterative deepening.
(c) DLog eliminates contrapositives with negated binary literals in the head.
(d) DLog does not apply ancestor resolution for roles.
(e) DLog uses deterministic ancestor resolution.

Fig. 10. A comparison of DLog with generic PTTP.

Deterministic ancestor resolution. We now present an important property of ancestor resolution for DL programs, which is the basis of our last simplification of the PTTP approach.

Proposition 12 (*Deterministic ancestor resolution*)
If loop elimination and the binary-first rule is applied for DL predicates, exactly one ancestor can be applicable in a successful ancestor resolution step, i.e. ancestor resolution is deterministic.

Proof
Let us examine cases (c1) and (c4), allowed by Proposition 9, for q = not_p, i.e. the case relevant for ancestor resolution. In case (c1), ancestor resolution succeeds if i and j are the same, and fails otherwise. Note that this ancestor resolution step can succeed only once. This is because loop elimination ensures that the ancestor list cannot contain p(i) more than once. Case (c4) succeeds with no substitution, and similar to (c1), it can succeed only once. This is because p(X) cannot occur in the ancestor list more than once, and if p(X) is there, then no goal of the form p(Y) can occur on the ancestor list, where Y is a variable different from X (cf. Proposition 7). □

Principles of DLog execution. To conclude this section, Figure 10 gives a summary of the principles we use in the execution of DL predicates and compare these to their counterparts in PTTP.
We also formulate the main result of this section as the following theorem.

Theorem 1 (*Soundness and completeness of the DLog execution*)
Let S be a set of DL clauses in reduced form and Q a conjunctive query. Let P be a set of Prolog clauses obtained from PDL(S) by removing clauses with negated binaries in the head, ordering clause bodies according to the binary-first rule and replacing =/2 and dif/2 by ==/2 and \==/2, respectively. Let us extend a standard Prolog engine with (1) loop elimination and (2) deterministic ancestor resolution for unary predicates only. If the extended Prolog engine is invoked with the program P and goal Q, it will terminate and enumerate those and only those ground instantiations of the variables of Q for which Q is entailed by S.

Proof
This is a direct consequence of the fact that PTTP is a sound and complete FOL theorem-proving technique and of Propositions 4, 10, 11 and 12. □

```
1  interp(true, _) :- !.
2  interp((Goal1, Goal2), AncList) :- !,
3      interp(Goal1, AncList),
4      interp(Goal2, AncList).
5  interp(Goal, AncList) :-
6      (   equality(Goal) -> call(Goal)                % (in)equalities
7      ;   member(Goal0, AncList), Goal0 == Goal -> fail    % loop elimination
8      ;   neg(Goal, NegGoal), memberchk(NegGoal, AncList) % ancestor resolut.
9      ;   NewAncList = [Goal|AncList],
10         clause(Goal, Body),
11         interp(Body, NewAncList)
12     ).
13
14 equality(_ == _).
15 equality(_ \== _).
```

Fig. 11. A full interpreter for DL clauses.

Corollary 1
Let KB be a $\mathcal{SHIQ}$ knowledge base and Q a conjunctive query in which no concept equivalent to $\top$ occurs. In this case the technique of Theorem 1, applied to $DL(KB)$ and Q provides finite, sound and complete execution for conjunctive queries.

3.6 Interpreting DL predicates

In Figure 11 we show a complete interpreter, which is able to execute DL predicates stored as normal dynamic predicates in Prolog.

The interpreter is invoked through the predicate `interp/2` with a conjunctive query in the first and an empty ancestor list in the second argument. The interpreter handles (in)equalities (line 6), ensures loop elimination (line 7) and provides deterministic ancestor resolution (cf. the use of `memberchk/2` in line 8). The new ancestor list is built in line 9. The auxiliary predicate `neg/2` in line 8 takes a goal `Goal` and returns its negated version `NegGoal`, as defined below.

Definition 10 (The negated version of a goal or a predicate)
The negated version of a Prolog goal G, denoted by *not_G*, is constructed by removing the `not_` prefix from the predicate name of G, if it has such a prefix, or otherwise adding this prefix to the predicate name.
We overload this notation and use it for predicate names and functors as well.

For example, if $G_1 = $ `p(X)` and $G_2 = $ `not_p(X)`, then their negated versions are *not_G_1* = `not_p(X)` and *not_G_2* = `p(i)`. Also, if P is the predicate `not_p/1`, then *not_P* denotes the predicate `p/1`.

We now show an example of invoking the interpreter. Assume that the DL predicates of the Iocaste problem, as shown in Figure 8, are loaded as dynamic Prolog predicates. One can then run the Iocaste query in the following way:

```
| ?- setof(X, interp('Ans'(X), []), Sols).
Sols = [i] ;
no
```

Note that the interpreter may return a solution several times, but the standard Prolog predicate `setof/3` forms a *set* of the solutions, i.e. an ordered list containing each solution only once. In Section 4.8 we discuss an optimisation which ensures that each solution of a unary predicate is returned exactly once.

According to Theorem 1, the interpreter is a sound and complete theorem prover for DL programs and composite queries.

3.7 Compiling DL predicates

The interpreted solution is pretty straightforward. However, for performance reasons, we also consider generating Prolog code which does not require a special interpreter. The idea is to include loop elimination and ancestor resolution in the DL predicates themselves and to extend the predicates with an additional argument for storing the ancestor list.

In contrast to the interpreter, the compiler treats TBox and ABox clauses separately. This is crucial to allow efficient execution of ABox queries, e.g. by using databases. Therefore, we now distinguish between the TBox and ABox part of a DL program.

Definition 11
Let P be a DL program. The ABox part of P, denoted by $P_{\mathcal{A}}$, is the set of all ground facts in P. The TBox part of P, denoted by $P_{\mathcal{T}}$, contains all remaining clauses, i.e. $P_{\mathcal{T}} = P \setminus P_{\mathcal{A}}$.

For example, in Figure 8, clauses in lines 3, 6 and 10 form the ABox DL predicates, while the remaining lines contain the TBox DL predicates.

We need the following notion for describing the transformation process.

Definition 12 (*Signature*)
Let P be a DL program. The *signature* of P is the set of functors of the form $C/1$ and $R/2$, where C is a unary predicate name and R is a binary predicate name which appears anywhere in P.

We will apply the notion of signature to the ABox and TBox part of a DL program (as these parts can be viewed as DL programs themselves). For example, if P is the Iocaste DL program shown in Figure 8, then the signature of P is {`Ans/1`, `not_Ans/1`, `Patricide/1`, `not_Patricide/1`, `hasChild/2`}. Note that predicate `not_Ans/1` has no clauses, but it still belongs to the signature. The signature of $P_{\mathcal{T}}$ is the same as that of P, while the signature of $P_{\mathcal{A}}$ excludes `Ans/1` and `not_Ans/1`.

We now define two auxiliary transformations which are used in the compilation of a DL predicate into Prolog code.

Definition 13 (*The expanded version of a term*)
Let T be a compound Prolog term with name N and arguments $A_1, \ldots, A_k$. Let Z be an arbitrary Prolog term. The *expanded version* of T w.r.t. Z, denoted by $Expd(T, Z)$, is defined as the term $N(A_1, \ldots, A_k, Z)$.

Definition 14 (*The ancestorised form of a clause*)
For an arbitrary Prolog clause C, whose head is H and body is $B_1, \ldots, B_n$, the *ancestorised* form of C, $\Omega(C)$, is a Prolog clause defined as follows: The head of $\Omega(C)$ is $Expd(H, \text{AL})$, where AL is a newly introduced variable. The body of $\Omega(C)$ is $E_0, E_1, \ldots, E_n$. Here, E_0 is the goal $\text{NewAL} = \text{[H|AL]}$, where NewAL is a new variable and $E_i = Expd(B_i, \text{NewAL})$, for $0 < i \leqslant n$.

As an example, the ancestorised form of the Iocaste clause shown in lines 1 and 2 in Figure 8 is the following:

```
1  Ans(A, AL) :- NewAL = [Ans(A)|AL], hasChild(A, B, NewAL),
2                 hasChild(B, C, NewAL), Patricide(B, NewAL),
3                 not_Patricide(C, NewAL).
```

Here AL denotes the old, while NewAL denotes the updated ancestor list.

Definition 15 (*The compiled form of a DL predicate*)
Let P be a DL predicate with the functor N/A and clauses $C_1, \ldots, C_n, n \geqslant 0$. Let H denote a most general goal with name N and arity A, i.e. a term whose each argument is a distinct variable. The *compiled version* of P, denoted by $\Delta(P)$, is the sequence of clauses $F_1, \ldots, F_{n+3}$, defined as follows, where not_H is the negation of goal H (see Definition 10):

F_1: $Expd(H, \text{AL})$:- member(G, AL), G==H, !, fail. (cf. Figure 11, line 7)
F_2: $Expd(H, \text{AL})$:- memberchk(not_H, AL). (cf. Figure 11, line 8)
F_3: $Expd(H, \text{AL})$:- abox:H.
F_{3+i}: $\Omega(C_i), 0 < i \leqslant n$.

This definition says that the compiled version of a predicate contains the ancestorised version of the clauses in the predicate, preceded with three new clauses. These new clauses are responsible for loop elimination, ancestor resolution and accessing the content of the ABox (stored in the Prolog module abox; cf. the prefix 'abox:').

Note that clause F_3 provides the link between a compiled predicate and its ABox part, where the predicate representing the ABox has one argument less than the compiled predicate. However, certain optimisations of Section 4 remove the additional argument of the compiled predicate. By placing the ABox predicates in the abox module we make sure that the ABox part is separated from the rest of the compiled predicate. However, for the sake of readability, we omit the abox: prefixes from the example programs presented in the paper.

Definition 16 (*The compiled form of a DL program*)
Let P be a DL program, and let $\{N_1/A_1, \ldots, N_k/A_k\}$ be the signature of $P_\mathcal{T}$. The compiled form of P is the set $\{C_1, \ldots, C_k\} \cup \{\text{abox:}C \mid C \in PDL(P_\mathcal{A})\}$, where $C_i = \Delta(Z_i)$ and $Z_i = \{C \in P_\mathcal{T} \mid N_i/A_i \text{ is the functor of the head of } C\}$.

Thus the compiled form of a DL program P is obtained by compiling the predicates belonging to each functor appearing in the TBox part of P and by adding the ABox DL predicates, stored in the `abox` Prolog module.

Some of the clauses in the compiled form of a predicate can be omitted under certain conditions. For example, we do not have to generate clauses of type F_2 for roles [cf. Figure 10(d)]. Furthermore, if N/A does not appear in the ABox signature, then we can omit the clause of type F_3 for the predicate N/A. Also, there are predicates which have no TBox clauses and thus consist of nothing but an F_3 clause. In case of such *atomic predicates* we can even get rid of the F_3 clause if we remove the additional argument (holding the ancestor list) from each invocation and precede it with the `abox:` module qualification. These optimisations will be covered in detail in Section 4.3.

Note that there can be predicates in a DL program that appear in clause bodies but not in clause heads. As an example, consider the predicate `not_Ans`, called in lines 5 and 8 of Figure 8. This predicate has no clauses, yet it can succeed using ancestor resolution.

Thus it is important that the operation Δ can be applied to empty predicates. In this case the compiled version consists solely of clauses F_2 and F_3 because clause F_1, serving for loop elimination, can be omitted, as an empty predicate cannot appear on the ancestor list. If, based on the ABox signature, we can omit F_3 as well, we get a special case: a compiled predicate which can succeed *only* through ancestor resolution, i.e. using clause F_2. Predicates of this type are called *orphan predicates*, while their invocations are called *orphan goals*. (For the exact definition of orphan predicates see Section 4.1.)

3.8 Compilation examples

As discussed above, the compilation of DL predicates relies on adding appropriate pieces of Prolog code to the DL clauses to handle ancestor resolution and loop elimination. We demonstrate this technique by presenting the complete Prolog translation of our two introductory examples.

The DL predicates of the Iocaste example were presented in Figure 8. The compiled form of this DL program is shown in Figure 12. All line number references in the following six paragraphs refer to this figure.

Most predicates in this program have an additional argument, used to pass the ancestor list from call to call. For example, in line 10, the goal `Patricide(D, C)` is invoked, where `C` contains the new ancestor list constructed in line 9.

In general, the content of the ABox can be either described as Prolog facts, as shown in lines 20 and 21, or stored externally in some database. In the latter case one has to provide 'stubs' to access the content of the ABox. Namely one should provide three predicates, for `Patricide/1`, `not_Patricide/1` and `hasChild/2`. These predicates should instantiate their head variables by querying the underlying database in an appropriate manner. In the following, for the sake of simplicity, we describe the content of the ABox as Prolog facts in the generated programs.

```
 1 Ans(A, B) :-  member(C, B), C == Ans(A), !, fail.
 2 Ans(A, B) :-  memberchk(not_Ans(A), B).
 3 Ans(A, B) :-  C = [Ans(A)|B], hasChild(D, E), hasChild(A, D),
 4               Patricide(D, C), not_Patricide(E, C).
 5
 6 Patricide(A, B) :- member(C, B), C == Patricide(A), !, fail.
 7 Patricide(A, B) :- memberchk(not_Patricide(A), B).
 8 Patricide(A, _) :- Patricide(A).
 9 Patricide(A, B) :- C = [Patricide(A)|B], hasChild(E, D),
10                    hasChild(D, A), Patricide(D, C), not_Ans(E, C).
11
12 not_Patricide(A, B) :- member(C, B), C == not_Patricide(A), !, fail.
13 not_Patricide(A, B) :- memberchk(Patricide(A), B).
14 not_Patricide(A, _) :- not_Patricide(A).
15 not_Patricide(A, B) :- C = [not_Patricide(A)|B], hasChild(E, A),
16                        hasChild(A, D), not_Patricide(D, C), not_Ans(E, C).
17
18 not_Ans(A, B) :- memberchk(Ans(A), B).
19
20 Patricide(o).    not_Patricide(t).
21 hasChild(i, o). hasChild(i, p). hasChild(o, p). hasChild(p, t).
```

Fig. 12. The complete Prolog translation of the Iocaste problem.

As the Iocaste example does not contain role axioms, the role predicate `hasChild` is an atomic predicate. Therefore the two-argument version is invoked directly, without ancestorisation (see e.g. `hasChild(D, E)` in line 3).

The first clauses of most predicates are responsible for loop elimination: the clauses in lines 1, 6 and 12 check whether the ancestor list contains the goal in question and cause the predicate to fail if this is the case.

Clauses in lines 2, 7, 13 and 18 are used to check whether the ancestor list contains the negation of the goal in question. If so, ancestor resolution takes place, which possibly substitutes the head variable A. As explained earlier, we leave a choice point here, so that the remaining clauses of the given predicate can be executed if, for example, the branch using the ancestor resolution fails.

Line 18 shows how an orphan predicate is translated, producing a single clause.

Having compiled the program of Figure 12, we can retrieve the instances of the concept `Ans` in the following way:

```
| ?- setof(X, 'Ans'(X, []), Sols).
Sols = [i] ?
```

Let us now compare the handmade translation of the Iocaste problem in Figure 3 with the machine translation shown in Figure 12. The goal `Ans(X)` in the former corresponds to `Ans(X, [])` in the latter. Furthermore, `dPatricide(Z, X)` corresponds to `Patricide(Z,[...Ans(X)...])`. The second argument of the `dPatricide/2` goal, variable X, stores the top individual of the Iocaste pattern (i.e. Iocaste herself), so that each member of the chain in Figure 2 can be checked to be a child of X.

```
1  Happy(A, B)       :- member(C, B), C == Happy(A), !, fail.
2  Happy(A, B)       :- memberchk(not_Happy(A), B).
3  Happy(A, _)       :- hasChild(A, B), hasChild(B, C), hasChild(B, D),
4                       Clever(C), Pretty(D).
5
6  not_Clever(A, B) :- member(C, B), C == not_Clever(A), !, fail.
7  not_Clever(A, B) :- memberchk(Clever(A), B).
8  not_Clever(A, B) :- F = [not_Clever(A)|B], hasChild(C, A), hasChild(D, C),
9                       hasChild(C, E), Pretty(E), not_Happy(D, F).
10
11 not_Pretty(A, B) :- member(C, B), C == not_Pretty(A), !, fail.
12 not_Pretty(A, B) :- memberchk(Pretty(A), B).
13 not_Pretty(A, B) :- F = [not_Pretty(A)|B], hasChild(C, A), hasChild(D, C),
14                       hasChild(C, E), Clever(E), not_Happy(D, F).
15
16 not_Happy(A, B)  :-  memberchk(Happy(A), B).
17
18 Clever(lisa). Pretty(lisa). hasChild(kate, bob). hasChild(bob, lisa).
```

Fig. 13. The complete Prolog translation of the Happy problem.

The same effect is achieved in the machine translation by placing `Ans(X)` on the ancestor list and retrieving it later using ancestor resolution.

A further difference is that the predicate `not_Patricide/2` does not appear in the handmade variant. This is because `not_Patricide/2` describes the same pattern as `Patricide/2` (see Figure 2) but builds it in the reverse order.

Also note that the predicates in the machine translation have more clauses than in the handmade version. Some of these are superfluous and will actually be removed by optimisations presented in Section 4. This includes the clause responsible for loop elimination in `Ans/2` and the one responsible for ancestor resolution in `Patricide/2`. However, the clause ensuring loop elimination in `Patricide/2` has to stay, as termination cannot be assured without it, in the presence of potentially cyclic `hasChild` relations.

To conclude the presentation of the generic compilation scheme we show the translation of the Happy knowledge base in Figure 13. Here a new ancestor list is built in lines 8 and 13. As a trivial simplification, we do not build a new ancestor list if it is not passed to any of the goals in the body. This happens when the clause invokes atomic predicates only, as in lines 3 and 4 of the `Happy` predicate.

Notice that the Prolog code in Figure 13 is much bigger than the handmade translation in Figure 6. However, the optimisations of Section 4 will simplify this code so that it becomes the same as that in Figure 6.

3.9 Summary

In this section we have shown how to transform a $\mathcal{SHIQ}$ DL knowledge base into a Prolog program performing instance retrieval tasks for the given knowledge base.

In the first stage of the transformation we convert the $\mathcal{SHIQ}$ axioms to an equivalent set of so-called DL clauses, using the techniques of Motik (2006) and

Zombori (2008). These clauses are then compiled to Prolog code, using specialised variants of PTTP techniques, such as ancestor resolution and loop elimination. We gave a formal description of the transformation process and proved that it is sound and complete and that it always terminates.

The transformation has an important property: it does not modify the ABox part of the $\mathcal{SHIQ}$ knowledge base in question. This allows for the ABox to be stored externally. Equally important is the fact that the transformation of the TBox part relies only on the signature of the ABox but not on the content.

4 Optimising DL compilation

The translation principles presented in the previous section are complete and result in programs which can already be executed in a standard Prolog environment, but they are not efficient enough. In this section we describe a series of optimisations which result in a much more efficient Prolog translation. We note that most of these optimisations could also be built into the interpreter itself, but here we deal with the compiled form only.

In Section 3 we introduced the general interpretation and compilation schemes for the so-called DL clauses, which are more general than the clauses obtained from $\mathcal{SHIQ}$ knowledge bases. However, in the present section, we do assume that the DL program to be optimised is obtained from a $\mathcal{SHIQ}$ knowledge base KB; i.e. it is of the form $PDL(DL(KB))$. In other words, we assume that the DL clauses, from which the given DL program originates, are of the form shown in Figure 7.

Regarding the issue of equality predicates, this implies that the body of a Horn clause can contain no equality goals, only inequalities. This is because the DL clauses in Figure 7 include equality literals but no inequalities, and in the process of building contrapositives the former become inequality goals. The binary-first body ordering ensures that these inequality goals are invoked only when ground, and thus – taking into account the UNA principle – they can be implemented using the \==/2 standard Prolog predicate.

4.1 Principles of optimisation

The process of optimisation is summarised in Figure 14. As the very first step we do filtering: we remove those clauses that need not to be included in the final program, as they are never used in the execution (see Section 4.2).

Next, we classify the remaining predicates (see Section 4.3). This information is used in subsequent optimisations to make the code generated from a specific class of predicates more efficient. The first two optimisations are global, in the sense that e.g. the removal a clause during filtering requires the examination of other parts of the knowledge base.

Classification is followed by a sequence of further optimisations. Most of these are *local* in the sense that they concern only a part of the program, e.g. a single predicate. The optimisations are independent of each other: any combination of these can be used when generating the final Prolog program (cf. the arrows in Figure 14). These optimisations are summarised below; note that some further,
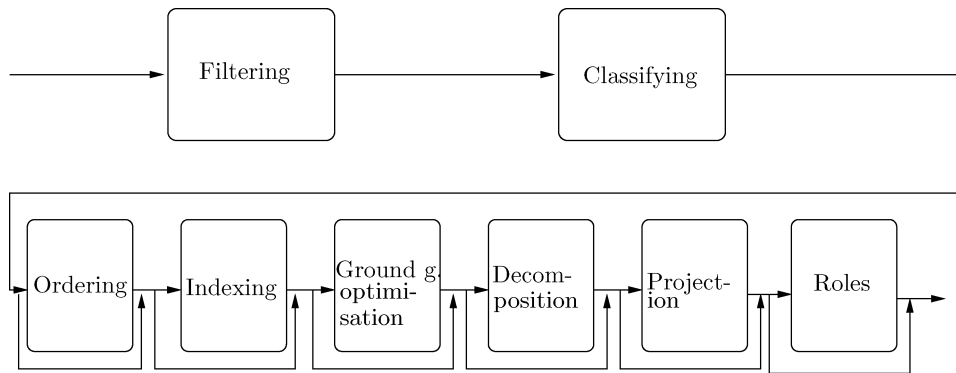
Fig. 14. The process of optimisation.

lower-level optimisations are described in Section 5.2:

(o1) Ordering of goals in clause bodies (Section 4.4).
(o2) Support for multiple argument indexing (Section 4.5).
(o3) Efficient ground goal execution (Section 4.6).
(o4) Decomposition of clause bodies (Section 4.7).
(o5) Projection for eliminating multiple answers (Section 4.8).
(o6) Efficient translation of roles and their inverses (Section 4.9).

All above optimisations except for (o2) and (o6) concern unary predicates. Therefore in the sections corresponding to (o1) and (o3)–(o5) we implicitly assume that all clauses discussed belong to unary predicates.

Before going into details we introduce some definitions regarding DL predicates, to be used in the upcoming sections. Note that a predicate is referred to by its functor or, if the arity is known from the context, by its name.

Definition 17 (*Predicate reachability*)
A predicate P_1 *directly calls* predicate P_2 if P_2 is invoked in any of the clauses of P_1. It is possible to *reach* P_2 from P_1 (1) if P_1 directly calls P_2 or (2) if there exists a predicate T from which it is possible to reach P_2 and P_1 directly calls T.

Thus, the relation *reach* is the transitive closure of the relation *directly calls* between predicates. As an example, let us consider the knowledge base in Figure 8. Here predicate not_Ans/1 is reachable from Ans/1, although it is not directly called. The definition of reachability can naturally be reformulated for clauses.

Definition 18 (*Reachability of clauses*)
A predicate P_2 is reachable from a clause C_1 if C_1 invokes a predicate T such that P_2 is reachable from, or identical to, predicate T. A clause C_2, belonging to a predicate P_2, is reachable from a clause C (predicate P) if the predicate P_2 is reachable from the clause C (predicate P).

Definition 19 (*Properties of DL predicates*)
A predicate P is recursive if it is reachable from itself. We speak about negative recursion if P is reachable from *not_P* or vice versa (Przymusinski 1994). We refine this

notion further by saying that P is an *ancestor negative recursion* (ANR) predicate if P can occur as an ancestor of *not_P* (i.e. the latter is reachable from the former). Furthermore, P is said to be a *descendant negative recursion* (DNR) predicate if P can become a descendant of *not_P* (i.e. the former is reachable from the latter).

Obviously P is ANR if, and only if, *not_P* is DNR (as *not_not_P* is P).

Using the above definitions, each DL predicate is classified into one of the following groups:

(1) A predicate P is *atomic* if all its clauses are ground and have empty bodies. Atomic predicates correspond to sets of ABox assertions. Examples for atomic predicates are `Clever/1`, `Pretty/1` and `hasChild/2` in the Happy and Iocaste DL programs.

(2) P is a *query predicate* if it is not atomic and it satisfies the following three conditions:

    (i) P is not recursive;

    (ii) P is not reachable from *not_P* (i.e. P is not DNR);

    (iii) all predicates invoked within the clauses of P are either atomic or query predicates.

Query predicates can be thought of as database queries. They can be defined in terms of atomic predicates using conjunction and disjunction only. Thus the execution of query predicates does not require any special features, such as keeping track of ancestors.

An example of a query predicate is `Happy/1` in Figure 9.

(3) A predicate is an *orphan* predicate if it has an invocation in a clause body (which is called *orphan goal* or *orphan call*), but it does not appear in the head of any of the clauses. Orphan goals can succeed only by ancestor resolution. Examples include predicates `not_Ans/1` and `not_Happy/1` in Figures 8 and 9.

(4) Finally, a predicate P is a *general* predicate if it is not atomic, query or orphan. A general predicate P can be further classified into subgroups based on whether P is recursive and of type ANR or DNR. The general predicates in the Iocaste knowledge base (Figure 8) are the following: `Ans/1` (not recursive, not DNR, ANR), `Patricide/1` (recursive, not DNR, not ANR) and `not_Patricide/1` (recursive, not DNR, not ANR).

4.2 Filtering

Filtering removes those clauses of the DL predicates that are not required in producing solutions.

Definition 20 (Eliminable clauses)
A clause C is called *eliminable* in a DL program DP if the body of C always fails in the execution of an arbitrary goal in DP.

Obviously, eliminable clauses can be removed from a DL program without changing its behaviour. The set of Prolog clauses obtained this way will still be called a DL program, but sometimes we will use the term *full DL program* to refer to the DL

program before any clauses have been removed. We now proceed to discuss special types of eliminable clauses.

Definition 21 (*False-orphan clauses*)
Let C be a clause of a predicate P in the DL program DP; C is said to have the *false-orphan* property w.r.t. DP if the body of C invokes an orphan predicate O, $P \neq not\_O$, and it is not possible to reach P (and thus C) from not_O in DP. In this case O is called a false-orphan goal in C.

Proposition 13
A clause C having the false-orphan property in DP is eliminable in DP.

Proof
Let C be a clause of a predicate P, which contains a false-orphan goal O. By definition, it is not possible to reach P from not_O, and $P \neq not\_O$. These two conditions imply that the ancestor list supplied to O contains no elements with the functor of not_O.

As an invocation of O can only succeed by ancestor resolution, the invocation of O fails, and so clause C can never succeed.   □

Consider a clause C, being the only clause of predicate P, which is removed because it has the false-orphan property defined above. At this point P becomes an orphan predicate, and some of the clauses invoking P may thus become eliminable, causing new orphan predicates to appear and so on.

Let us now define two new kinds of clauses, which later will be shown to be eliminable.

Definition 22 (*Two-orphan clauses*)
Let C be a clause in the DL program DP; C is said to have the *two-orphan* property w.r.t. DP if the body of C invokes predicates O_1 and O_2, which are orphans in DP and have different functors.

Definition 23 (*Contra-two-orphan clauses*)
Let C be a clause of a DL program DP. Let O_1, O_2 and O_3 be orphan predicates in DP, where $O_1 \neq O_2$. Clause C is said to have the *contra-two-orphan* property w.r.t. DP if the head of C is of the form $not\_O_1(X)$ and if the body of C contains the goals $O_2(Y)$ and $not\_O_3(Z)$, where X, Y and Z are not necessarily distinct variables or constants.

A clause having the contra-two-orphan property is a contrapositive of a specific two-orphan clause; hence the naming of the property.

For the next two propositions by a *clause of interest* we mean a clause having the two-orphan or the contra-two-orphan property. We will prove that a clause of interest cannot participate in a successful execution and hence can be eliminated. Furthermore, we show iteratively that clauses that become clauses of interest due to the elimination of other clauses of interest are eliminable, too. Therefore the next proposition speaks about a DL program in which we have already eliminated some clauses of interest (initially zero clauses).

Proposition 14

Let DP be a DL program obtained from a full DL program DP_0 by first removing zero or more clauses of interest and next repeatedly eliminating the clauses with the false-orphan property, as long as possible. If O is an orphan predicate in DP, and a clause C in DP invokes the predicate not_O, then C has either the two-orphan or the contra-two-orphan property.

Proof

We can assume that the clause $C \in DP$ is of the form '$H(Y)$:- $not\_O(X), G_1, \ldots, G_n$', $n \geqslant 0$. Consider clause C', '$O(X)$:- $not\_H(Y), G_1, \ldots G_n$', which is a contrapositive of the same DL clause as C is. Therefore C' had to be present in the full DL program DP_0. However, C' is not present in DP because it belongs to the predicate O, which is an orphan in DP. Thus clause C' was removed at some point. Let DP' be the last DL program in which C' is present, i.e. $DP' \supseteq DP \cup \{C'\}$ and C' has one of the three orphan-related properties introduced above, which justify its removal from DP'.

Let us first discuss if there can be any false-orphan goals in C' w.r.t. the program DP'. Because O is an orphan predicate in DP, there is a clause D in DP which calls O, and because there are no false-orphans in DP, this clause is reachable from not_O. Thus in DP', which contains the clause C' belonging to the predicate O, all goals in the body of C' are reachable from not_O through clause D. Consequently, all these goals are also reachable from the clause C of predicate H, as C contains the goal $not\_O(X)$. This means that the first goal in the body of C', $not\_H(Y)$, cannot be a false-orphan in DP' because it is reachable from its negation H. Consider now a goal G_i, $0 < i \leqslant n$, and assume that it is an orphan goal in DP'. Because $DP' \supseteq DP$, G_i is an orphan goal in DP, too. As G_i is present in the body of C, and there are no false-orphans in DP, C is reachable from not_G_i in DP. But then, in DP', G_i in C' is also reachable from not_G_i, as C' is reachable from C, which, in turn, is reachable from not_G_i. Thus G_i in C' is not a false orphan in the DL program DP'. We have thus shown that the clause C' does not have the false-orphan property w.r.t. DP'.

Next, assume that C' has the contra-two-orphan property in DP'. This implies that the head of C' is the negation of an orphan; i.e. not_O is an orphan in DP'. Again because $DP' \supseteq DP$, not_O is an orphan predicate in DP and thus has no clauses. This is a contradiction to the fact stated above that a goal with the functor O occurs in a clause D *reachable* from not_O.

This means that C' has the two-orphan property in DP'. We now consider two cases. If the set $\{G_i | 0 < i \leqslant n\}$ contains two orphan goals with different functors, then clause C has the two-orphan property, as well. Otherwise, $not\_H(Y)$ has to be an orphan goal, and there has to be another orphan goal, with a different functor, amongst the G_i's, say G_k. Let $O_1 = not\_H$, and let O_2 and Z denote the name and argument of the goal G_k (i.e. $G_k = O_2(Z)$). Using this notation the head of C is of the form $not\_O_1(Y)$, while its body contains the goals $O_2(Z)$ and $not\_O(X)$, where $O_1 \neq O_2$ holds. Thus C satisfies the contra-two-orphan property. $\square$

Proposition 15
Let DP be a DL program obtained from a full DL program by removing some clauses of interest and/or some clauses having the false-orphan property. Any clause having the two-orphan property or the contra-two-orphan property in DP is eliminable.

Proof
Let DP' be the DL program obtained from DP by repeatedly eliminating the clauses with the false-orphan property as long as possible.

Let us indirectly assume that there is a successful execution path in DP, which uses a clause of interest, and of these consider the one used earliest, say C. As a clause having the false-orphan property cannot be part of a successful execution, the path in question is a valid path in DP'.

Let us first assume that C is a two-orphan clause. For this clause to succeed, the two orphans with different functors require two different ancestor goals, which are their negations, i.e. negations of orphans. One of the ancestors can come from the query goal, but the other has to be present in an earlier clause. Because of Proposition 14, this is a clause of interest, which contradicts the fact that C is the earliest such clause in the execution.

Next, assume that C has the contra-two-orphan property. In this case C has to be the very first clause used because if there were a preceding clause C_0, then C_0 would have to contain a negated orphan goal (as the head of C is a negated orphan), and so, again due to Proposition 14, C_0 would be a clause of interest. As C is the first clause called, the ancestor list supplied to the goals in its body contains only the head of C. However, a contra-two-orphan clause contains an orphan goal whose functor is different from that of the negated clause head, and so this orphan goal fails, contradicting our initial assumption. $\square$

We note that a clause containing several orphan goals, all with the same functor, cannot be eliminated, as all these goals can succeed by resolving against a single ancestor in the ancestor list.

Proposition 15 makes it possible to iteratively remove all three kinds of eliminable clauses introduced. This process terminates when there are no clauses with the above properties:

Definition 24 (*Filtered DL programs*)
A DL program is *filtered* if there are no clauses in the program which have the false-orphan property, the two-orphan property or the contra-two-orphan property.

Proposition 16
Let DP be a filtered DL program. If O is an orphan predicate in DP, then no clause in DP can contain a goal which invokes the predicate *not_O*.

Proof
This is a simple consequence of Proposition 14. $\square$

This means that in a filtered program an orphan goal can succeed only if the initial query predicate is its negation (cf. the `not_Ans/1` orphan goal in Figure 12).

Another consequence of Proposition 16 is that ancestor resolution for orphan predicates is deterministic. We have proved earlier that ancestor resolution in general is deterministic (cf. Proposition 12), but for this we had to assume that the binary-first rule was applied. Note that this assumption is not needed now.

Implementation. Our first optimisation is to transform the DL program into an equivalent filtered form. To obtain a filtered program we use an iterative process. Here we start from the initial DL program, and we eliminate as many clauses as we can. However, if we successfully eliminate the last remaining clause of at least one predicate, then we will start the whole process again. We do as many iterations as needed to reach a fixpoint, i.e. to have a set of clauses from which we cannot eliminate any more clauses.

Example. As an example for filtering, let us consider the DL program of the Happy problem presented in Figure 9. In the first iteration, we can eliminate clauses in lines 4, 5, 7 and 8, as they invoke the orphan goal `not_Happy(B)`, and there is no way to reach these clauses from predicate `Happy/1`.

As these were the last clauses of their corresponding predicates, `not_Clever/1` and `not_Pretty/1` have actually become orphans. Therefore, we apply one more iteration. Now we cannot eliminate anything else: we have reached a fixpoint, containing a single TBox clause in lines 1 and 2 (and the ABox facts in line 10).

4.3 Classification

Within the filtered DL program we distinguish between different groups of predicates based on their properties. This classification is useful when generating the Prolog programs, as it provides guidelines for what to generate, and it also serves as a basis for further optimisations. As discussed in Section 4.1, we distinguish between atomic, orphan, query and general predicates.

A predicate P is classified as atomic or orphan simply by checking whether the specified condition holds for P.

However, to determine the set of query predicates, we use an iterative process similar to the one used in filtering (cf. Section 4.2). The idea is that we iterate as long as we find at least one new query predicate. We note that we actually use a single iterative process which encapsulates filtering as well as query predicate classification.

All the remaining predicates are classified as general predicates.

Use of classification information. Having classified the predicates of a DL program we can apply specific compilation schemes for certain classes. We now examine each of the predicate classes:

- *Atomic predicates.* Atomic predicates directly correspond to tables in a database, and thus their translation does not require an extra argument for the ancestor list.
- *Query predicates.* The conditions in the definition guarantee that in the case of a query predicate P, we (i) do not need to check for loops, (ii) do not need to apply ancestor resolution and (iii) do not need to pass the ancestor list to any of the goals in the body of P.

```
1  Happy(A) :- hasChild(A, B), hasChild(B, C), hasChild(B, D),
2              Clever(C), Pretty(D).
3
4  Clever(lisa). Pretty(lisa). hasChild(kate, bob). hasChild(bob, lisa).
```

Fig. 15. The Happy program after filtering and classification.

    Consequently, the code for query predicates does not require the additional argument for the ancestor list, similarly to atomic predicates.

- *Orphan predicates.* The translation of an orphan predicate is a predicate consisting of a single clause of type F_2 (cf. Definition 15). When an orphan predicate is invoked, a small optimisation can be applied regarding the ancestor list argument. The body of an orphan predicate contains nothing but an ancestor check: if the ancestor list contains the negation of the orphan predicate, then it succeeds. Now, unless the orphan predicate is invoked from within its negation, the ancestor list passed to it need not include the parent goal, i.e. the predicate from which it is invoked. This means that the ancestor list argument can be the same as the one in the parent goal. This is the case, for example, in lines 10 and 16 in Figure 12. Thus, in these two lines, the second argument of the orphan goal not_Ans, namely variable C, can be replaced by the variable B.
- *General predicates.* We need to generate loop tests only for recursive and ancestor tests only for DNR predicates. Updating the ancestor list is only required for ANR predicates.

Examples. We now discuss some examples of how the Prolog code can be simplified due to classification. The DL predicate Happy/1 in Figure 9 is classified as a query predicate. Having removed DL predicates not_Clever/1 and not_Pretty/1 in the filtering step, we can further simplify the Happy program by removing the ancestor list arguments. This results in the code shown in Figure 15. Note that we have actually obtained the handmade translation for the Happy problem (see Figure 6).

    When the classification optimisation is applied to the Iocaste program of Figure 12, lines 1, 2, 7 and 13 are disposed of. Lines 1 and 2 can be removed because predicate Ans/1 is classified as a non-recursive non-DNR general predicate. Ancestor tests in lines 7 and 13 can be omitted, as Patricide/1 and not_Patricide/1 are non-DNR predicates.

4.4 Body ordering

An important optimisation is to order the goals in the body of the generated clauses so as to minimise the execution time. This is a generic idea used in some form or other by many systems. For example, in the case of databases, query optimisation is an essential task, as without it one would not be able to answer complex queries (Freytag 1989). Query optimisation is similarly important when querying non-relational information sources, such as XML (Fernández *et al.* 2004).

    Query optimisation often relies on statistical information, such as the size of database tables and the number of distinct values in a given column. In the present

work we do not take into account such information, and so we restrict our attention to optimisations which consider only the TBox part of the DL programs.

Prolog systems also use body reordering. For example, the Mercury compiler reorders the conjunctions in clauses for more efficient execution (Somogyi *et al.* 1996). Body reordering, instantiation analysis and related techniques are used by many parallel systems as well. For example, in the Andorra system (Costa *et al.* 1991) the deterministic goals in a clause are moved to the front.

In our case we have very special clauses to work with, as described in Section 3.4. This allows us to use a simple, specialised ordering technique.

Below we first propose a possible ranking between the different kinds of goals in a body. This ranking uses heuristics applicable for DL programs. Next, we introduce the simple algorithm we use for body ordering. Note that this algorithm is actually only the first step, as it forms the basis of a more complex body restructuring technique described in Section 4.7.

4.4.1 Ranking of goals

Let us start with considering some principles for ranking:

- Atomic and query predicates can be answered by using ABox facts only; i.e. they correspond to (maybe complex) database queries.
- General predicates, such as `Patricide/2`, may require complex, possibly recursive, execution on the Prolog side.

These considerations lead to some heuristics which are summarised below:

- We invoke atomic and query predicates before general predicates.
- We prefer to invoke a ground role predicate at a given point, instead of a role predicate with one or two uninstantiated variables. The former simply checks whether a relation holds between two individuals. The latter enumerates all possible pairs of individuals for which the given relation holds, leaving a possibly huge choice point behind.
- Given two role predicates with potentially uninstantiated variables we prefer to invoke first the one having the *head variable*, i.e. the variable in the head of a clause, as its argument. The main justification for this is that the head variable may actually be instantiated, which is not the case for any other variable.

A further issue to discuss is the place of the orphan goals within a body. Recall that orphan goals can only succeed by ancestor resolution and if their negation is the query goal. For example, the orphan goal `not_Ans(E, C)` in line 10 in Figure 12 can only succeed if invoked within an `Ans(X)` query goal. However, when an orphan goal succeeds, its first argument (variable `E` above) may stay uninstantiated.

These properties of orphan goals suggest that they should be put in the first available place in which they are ground. However, it also seems to be a good idea to move an orphan goal to the very front of the body. This is because orphan goals

```
 1  Orphan goal
 2  Ground inequality
 3  Ground role
 4  Ground atomic or query concept
 5  Role with one unbound variable
 6  Role with two unbound variables, at least one of which is a head variable
 7  Role with two unbound variables
 8  Non-ground atomic or query concept
 9  Ground general concept
10  Non-ground general concept
```

Fig. 16. The base ranking of the different types of goals within a body.

```
1  Input parameters: $B$, $R$, $V$, $i := 1$
2  If $B = \emptyset$, exit with $G_1, \ldots, G_{i-1}$
3  $G_i :=$ highest priority goal in $B$ according to ranking $R$ w.r.t. variables $V$
4  $B := B \setminus \{G_i\}$
5  If $G_i$ is non-orphan $V := V \cup$ variables of goal $G_i$
6  $i := i + 1$
7  Go to step 2
```

Fig. 17. The ordering algorithm used to optimise the execution of a body.

tend to fail very often: if they are placed at the front, in the case of failure, we do not need to execute the rest of the clause.

Note, however, that placing orphan goals at the front invalidates the proof of Proposition 12 on page 364, as now case (c2) can also happen. Fortunately, Proposition 16 ensures that ancestor resolution remains deterministic for DL programs, even if the invocations of the orphan goals are moved to the front of a body.

Based on the above discussion, we have designed an appropriate ranking order, called *base ranking*, which is summarised in Figure 16. Here we define 10 categories of goals and give orphan goals the highest priority. Higher priority means earlier placement in the body. If there are more goals within the same category, the selection between them is unspecified; i.e. any of them can be chosen. For example, if we have two non-ground atomic concepts, either of these can come first.

Note that the base ranking ensures the binary-first rule introduced in Definition 7, except for orphan goals. Furthermore, part (b) of Proposition 7 ensures that the variables occurring in inequalities will get instantiated; so we do not have to deal with non-ground inequalities.

4.4.2 The ordering algorithm

In Figure 17 we present a simple algorithm which orders the body of a clause of a DL program. This algorithm has three inputs: the body to be ordered (B), a

```
1 Patricide(A, B) :- C = [Patricide(A)|B], not_Ans(E, C), hasChild(D, A),
2                    hasChild(E, D), Patricide(D, C).
```

Fig. 18. The reordered version of the main clause of `Patricide/2`.

```
1 Happy(A) :- hasChild(A, B),
2             hasChild(B, C), Clever(C),
3             hasChild(B, D), Pretty(D).
```

Fig. 19. The reordered version of the `Happy/1` clause.

predefined ranking of the different kinds of goals (R) and an initial variable list (V) containing those variables that are known to be instantiated at the beginning.

The idea is to repeatedly select the highest priority goal from the remaining goals and place it in the ordered goal sequence forming the final body [see step (3) of Figure 17]. To be able to assess the groundness of arguments we keep track of the set V of variables instantiated so far; V is initialised from the input parameter [Figure 17, step (1)] and is updated to include the variables of the goal selected [Figure 17, step (5)]. Having selected a goal, we continue by iteratively ordering the rest of the body [Figure 17, step (7)].

As an example, reordering the body of the main clause of `Patricide/2` (cf. lines 9 and 10 in Figure 12) yields the clause presented in Figure 18. Here the orphan call `not_Ans/2` is moved to the front. It is followed by a role predicate containing a head variable. The next goal is also a role predicate with at least one variable instantiated: the instantiation state of variable E is not known at compile time. Finally, the last goal is a ground general concept call. To make the comparison of the original and the reordered clauses easier, in Figure 18 we keep the variable naming of the original clause.

As another example, the reordered version of the clause `Happy/1` from Figure 15 is presented in Figure 19. Note that the goal `Clever(C)` is now moved forward into the place in which it first becomes ground.

4.5 Multiple argument indexing

In this section we discuss a transformation of role predicates which makes their Prolog execution more efficient.

Notice that goal `has_child(E, D)` in line 2 in Figure 18 is always called with the second argument instantiated. If we use a database system to store the content of the ABox, this call is executed efficiently. This is because databases can do indexing on every column of a table. In most Prolog systems, however, indexing is done only on the first head argument. This may raise performance issues if we use Prolog for storing large amounts of ABox facts.

To achieve multiple argument indexing in the generated programs we do the following: for each role P we generate a new role idx_P. This new set of Prolog facts (called *index predicate*) captures the inverse relation between the arguments of P, i.e. $idx\_P(X, Y)$ holds if, and only if, $P(Y, X)$ holds. In the case of the Iocaste

problem this effectively means that we add the following index predicate to the generated program:

```
1 idx_hasChild(o, i).
2 idx_hasChild(p, i).
3 idx_hasChild(p, o).
4 idx_hasChild(t, p).
```

Consider an invocation of a role P in which the second argument is instantiated, but the first is (possibly) not. We replace each such invocation by a call of idx_P with the two arguments switched. For example, the ordered clause for Patricide/2 in Figure 18 takes the following form (note that the variable E cannot be assumed to be instantiated by the orphan call not_Ans(E, B)):

```
1 Patricide(A, B) :- C = [Patricide(A)|B], not_Ans(E, B), hasChild(D, A),
2                    idx_hasChild(D, E), Patricide(D, C).
```

Note that we do not actually have to generate index predicates for every role in the ABox because using compile-time analysis we can identify those role predicates $P_1, \ldots, P_i$ that need indexing at all (i.e. those which are called at least once in such a way that their second argument is ground, but the first is possibly not).

Also note that most Prolog implementations create a choice point when both arguments of a role predicate P are instantiated, although it is obvious that such invocations can only succeed once (as an ABox cannot contain a given $P(i, j)$ axiom twice). For example, consider the goals hasChild(i, o) or idx_hasChild (p, i).

To avoid these choice points we apply the commonly known technique of using auxiliary predicates. Namely, given a role predicate $R/2$ (including the index predicates introduced above) with facts F we do the following: for every maximal set $D \subseteq F$ of facts, which share their first argument, we introduce a single *grouping clause* $R(A, Y)$:- $T(Y)$. Here, Y is a variable and A is the constant shared by all of the facts in the first argument position in D; T is the name of a newly introduced predicate containing facts $T(Z_1), \ldots, T(Z_k)$ which correspond to the constants in the second arguments of the facts in D, i.e. $\{Z_1, \ldots, Z_k\} = \{B | R(A, B) \in D\}$.

As an example, we show the optimised version of the four clauses of the predicate idx_hasChild/2 introduced above. Here, line 2 contains a grouping clause invoking the auxiliary predicate idx_hasChild_p/1. This makes it possible for Prolog not to create any choice points when invoking the goal idx_hasChild(p, i) or idx_hasChild(p, o):

```
1 idx_hasChild(o, i).
2 idx_hasChild(p, Y) :- idx_hasChild_p(Y).
3 idx_hasChild(t, p).
4
5 idx_hasChild_p(i).
6 idx_hasChild_p(o).
```

```
1  choice_Patricide(A, B) :-
2          (   nonvar(A) -> det_Patricide(A, B)
3          ;   nondet_Patricide(A, B)
4          ).
5
6  nondet_Patricide(A, B) :- member(C, B), C == Patricide(A), !, fail.
7  nondet_Patricide(A, _) :- Patricide(A).
8  nondet_Patricide(A, B) :- C=[Patricide(A)|B], not_Ans(D,B), hasChild(E,A),
9                            idx_hasChild(E, D), det_Patricide(E, C).
10
11 det_Patricide(A, B) :- member(C, B), C == Patricide(A), !, fail.
12 det_Patricide(A, _) :- Patricide(A), !.
13 det_Patricide(A, B) :- C=[Patricide(A)|B],not_Ans(D,B), idx_hasChild(A,E),
14                        idx_hasChild(E, D), det_Patricide(E, C), !.
```

Fig. 20. The two variants of predicate `Patricide/2`.

4.6 Ground goal optimisation

An important optimisation step is to make sure that the truth value of ground goals, i.e. goals with all arguments instantiated, is calculated only once. Note that by default this behaviour is not provided by the Prolog execution but is supported, for example, by Mercury (Somogyi *et al.* 1996).

To achieve this, we duplicate a general or query predicate P; i.e. we create two versions of P depending on whether we assume that the head variable is instantiated or not. These variants of P are called non-deterministic (*nondet*) and deterministic (*det*) variants, respectively.

We also create a *choice* predicate for the general case that checks if the head variable is ground at runtime. This predicate then calls either the *nondet* or the *det* variant of predicate P.

The differences between the two variants of a predicate P are the following:

(1) We place a Prolog cut (denoted by !) at the end of each clause in the *det* variant. This results in pruning the rest of the search space after a successful execution of the *det* variant.

(2) We order the body of the clauses in the *det* variant based on the assumption that the head variable H is instantiated (i.e. the ordering algorithm in Figure 16 is executed with the initial variable list $V = \{H\}$).

Finally, we transform every goal in the program calling a general or query predicate P into another goal which calls `choice_P` instead. This technique is illustrated in Figure 20.

In lines 9 and 14 of Figure 20, instead of `choice_Patricide/2`, we directly invoke predicate `det_Patricide/2`. This is a further optimisation step. Namely we can directly call the *det* variant of a predicate P if we know already at compile time that the first argument of the specific invocation of P is ground. In our case we can be sure that variable E is instantiated at the time of calling `det_Patricide/2`, because the predicate call `idx_hasChild(E, D)` instantiates it.

Note the difference between the body goals in the *nondet* and *det* variants in Figure 20 (lines 8–9 and 13–14, respectively). In the *det* variant we assume that variable A is instantiated at call time; therefore we use the idx variant of the goal hasChild(E, A).

Proposition 9 ensures that all unary goals within a *det* variant of a predicate are ground at the time of their invocation. Thus all these goals will directly invoke the *det* variant of their predicate.

4.7 Decomposition

The goal of decomposition is to split a body into independent components. This is achieved by uncovering the dependencies between the goals of the body. This process introduces a higher-level body ordering, where the independent goal groups are ordered first, and then the individual groups are split and ordered recursively. More importantly, the discovery of independent components makes it possible to use a generalisation of the ground goal optimisation, by applying this technique to a whole independent goal group. For DL programs generated from a $\mathcal{SHIQ}$ KB this practically means recovering certain useful structural properties of the initial TBox axioms. Before we go into details we show an example to demonstrate a problem which can be solved using decomposition.

4.7.1 An introductory example

Let us recall the single clause of the predicate Happy/1 shown in Figure 19, stating that someone is happy if she has a child having both a clever and a pretty child. Although the body of this clause is ordered according to our base ranking, in certain cases the execution of it is far from optimal. For example, consider the ABox specified below:

```
hasChild(kate, bob).
hasChild(bob, lisa_i).        for i = 1... n
Clever(lisa_i).               for i = 1... n
```

Thus we know that bob is the child of kate, and he has n clever children, but nobody is known to be pretty. This ABox does not entail that kate is happy; i.e. the goal Happy(kate) fails. However, obtaining this negative answer involves lots of useless computation. Namely we enumerate all children of bob and check whether they are clever. We do this in spite of the fact that bob has no pretty children at all, even though having a pretty grandchild is a necessary condition for kate being happy. What happens is that we explore the choice point created in line 2 in Figure 19, although goals in line 3 are bound to fail.

Note that this behaviour would not change if we applied ground goal optimisation here, i.e. if we used the *det* variant of the clause (cf. Section 4.6) in Figure 19. The order of the goals in the body would be the same. The cut at the end of the clause would not matter either, as the goal Happy(kate) fails.

What we need here is the realisation that the hasChild(B, C), Clever(C) group of subgoals, used for checking that bob has a clever child, is independent of the

```
1  Happy(A) :-
2      hasChild(A, B),
3      (   hasChild(B, C),
4          Clever(C) -> true
5      ),
6      (   hasChild(B, D),
7          Pretty(D) -> true
8      ).
```

Fig. 21. The decomposed version of the `Happy/1` clause.

remaining subgoals of the body. Thus, once we have proved that `bob` has a clever child, there is no point in proving this property in other ways.

4.7.2 *The solution*

In the above example, the real reason behind the inefficient execution is that during the Prolog translation we do not utilise the structural properties of the TBox axiom in Figure 5. This axiom actually describes that somebody is happy if she has a child satisfying a certain condition, namely having a clever child as well as a pretty child. This condition can be split into two independent parts: `hasChild(B, C)`, `Clever(C)` and `hasChild(B, D)`, `Pretty(D)`. The two parts share only a single variable B. If B is ground, we can stop enumerating her children once a clever one is found, as a new value for variable C cannot affect the remaining goals.

The solution is to use this knowledge by *decomposing* the body of clause `Happy/1`, as shown in Figure 21.

The clause for `Happy/1` starts with a single goal representing the condition that somebody should have at least one child in order to be happy (line 2). The required properties of this child are captured by the two consecutive *components* in the clause (lines 3–5 and 6–8). The idea here is that we only look for the first solution of these components; i.e. we place an implicit Prolog cut at the end of the component (by using the conditional expression operator `->`). This ensures that once a component succeeds, it prunes the rest of its search space. This is, in fact, the ground goal optimisation, applied to a whole component rather than to a single goal.

Note that the goal `hasChild(A, B)` in line 2 generates a choice point, which we cannot eliminate here, as we cannot be sure that B has the required properties. On the other hand, if the ground goal optimisation (cf. Section 4.6) is also applied, then the cut (`!`) at the end of the *det* variant clause prunes this choice point.

4.7.3 *The process of decomposition*

Decomposition relies on identifying independent components in clause bodies, i.e. subgoal sequences which do not share uninstantiated variables. Such techniques have been extensively studied, mostly in the context of parallel execution of logic programs, for example in Muthukumar and Hermenegildo (1992).

Because of the special properties of DL predicates we can apply here a very simple algorithm. The decomposition process is actually a modification of the

(2a)	Split B into a partition $\{B_1, \ldots, B_n\}$ w.r.t. V;
(2b)	If $n = 1$ continue at 3;
(2c)	Apply the ordering algorithm recursively (starting from step 1) for (B_j, R, V), producing a (possibly composite) goal C_j, for each $j = 1, \ldots, n$, and return $G_1, \ldots, G_{i-1}, c(C_1), \ldots, c(C_n)$.

Fig. 22. The process of decomposition (extension of the algorithm in Figure 17).

```
nondet_Ans(A, B) :-
        C=[Ans(A)|B],
        hasChild(A, D),
        (   hasChild(D, E),
            det_not_Patricide(E, C) ->
            true
        ),
        det_Patricide(D, C).
```

Fig. 23. The `Ans/1` clause after decomposition.

ordering algorithm introduced in Figure 17: the steps (2a)–(2c) shown in Figure 22 are added after step 2 of the ordering algorithm.

Decomposition starts with step (2a), which partitions the set of body goals into one or more subsets in such a way that goals in different partitions share only variables in V (the set of variables considered to be instantiated) and the maximal number of partitions is obtained. If the decomposition results in a single partition [see step (2b)], then we continue with the normal goal-ordering algorithm.

If multiple partitions have been obtained, then each of these is ordered and recursively decomposed [step (2c)]. In this case the output of the modified ordering algorithm contains the goals collected so far, followed by the components. The latter are distinguished from ordinary goals by being encapsulated in a $c(\ldots)$ structure. This marks the independent units in which pruning can be applied.

Note that the components themselves also undergo an ordering phase, but this is not detailed here.

We illustrate the idea of recursive decomposition on the *nondet* variant of clause `Ans/1` from the Iocaste problem. The result is shown in Figure 23. The first evaluation of the step (2a) yields a single component. Therefore step (3) of the ordering algorithm (Figure 17) is performed; the highest priority goal is selected and placed at the beginning of the body (see line 3 of Figure 23). Next, the process of decomposition is repeated for the remaining goals, where the evaluation of step (2a) yields two components, shown in lines 4–7 and 8, respectively. As the second component contains a single goal, there is no need for explicit pruning (as the call of a `det_...` predicate leaves no choice points behind).

Also note that variables used for ancestor resolution in the generated program are not considered during the decomposition process, as this is performed on the DL program directly. This is the reason why goals in line 5 and line 8 can be placed into separate components, although both of them contain variable `C`.

4.8 Projection and supersets

As discussed in the previous section, decomposition helps in reducing the number of unnecessary choice points in a clause body by using conditional structures. However, the choice point in the first component of the *nondet* variant of a clause has to remain, and this can cause serious performance problems.

As an example, let us consider the behaviour of the clause `nondet_Ans/2`, shown in Figure 23, when run on a large Iocaste pattern. Here, the first component is the goal `hasChild(A, D)` in line 3, which enumerates all objects in the parent–child relationship. Let us assume that the first few facts in the `hasChild/2` predicate are `hasChild(i, `e_i`)`, for $i = 1, \ldots, k$ (cf. the rightmost pattern in Figure 2). Thus the goal `hasChild(A, D)` first succeeds with the substitution `A = i, D = `e_1. As explained in Section 3.2, the remaining two components of `nondet_Ans/2` (lines 4–8 of Figure 23) will complete successfully, without leaving a choice point, and thus the solution `A = i` is obtained. We now backtrack to the choice point in line 3, to look for other individuals satisfying `nondet_Ans/2`. However, the next few substitutions returned by the `hasChild` goal in line 3 will be `A = i, D = `e_i, $i = 2, \ldots, k$. In all these substitutions `A` obtains the value `i`, which is already known to be a solution. Thus the exploration of this part of the search space is absolutely useless. Having obtained a solution `A = i`, one should ignore all further ABox facts of the form `hasChild(i, _)`. However, one cannot cut away the choice point in line 3 because there could be other `hasChild(x, _)` facts, which lead to further solutions. Contrastingly, no such problem appears in the *det* version of the same predicate, as a cut is placed at the very end of the clause (cf. the ground goal optimisation, Section 4.6).

We eliminate the need for the *nondet* variant of a predicates by the optimisation presented in this section. This works by first calculating a so-called superset of the predicate, which is a set of individuals containing all the solutions of the predicate. Next, the elements of the superset are enumerated, and the *det* variant of the predicate is called for each individual in the superset.

We now proceed with the definition of the notion of superset. Next, we show how it can be used to eliminate the non-deterministic predicates from the generated programs.

4.8.1 The notion of superset

Let $I(P)$ denote the set of solutions of a predicate (clause) P w.r.t. a Prolog program. By a solution of a clause C we mean a solution of the predicate which C belongs to, obtained through the successful execution of clause C.

Definition 25 (*The superset of a predicate or a clause*)
A set of instances S for which $I(P) \subseteq S$ holds is called a *superset* of predicate (clause) P.

According to the definition, the superset of a predicate is a set of instances which contains all the solutions of the predicate (and possibly some other individuals as

well). For example, the set of individuals $\{\texttt{i},\texttt{o},\texttt{p}\}$ forms a superset of predicate `Ans/1`, as it contains the individual `i`.

Now, given a predicate P and one of its supersets S, we can eliminate the *nondet* variant of P as follows: we create a new predicate which invokes the *det* variant of P for each individual $i \in S$. Technically, this logic can be built into the *choice* predicate, as exemplified below:

```
1 choice_Ans(A, B) :-
2         (   nonvar(A) -> det_Ans(A, B)
3         ;   member_of_superset_Ans(A),
4             det_Ans(A, B)
5         ).
6 ...
```

Here we call the *det* variant directly if `A` is instantiated (line 2). However, we also call the *det* variant if `A` is uninstantiated (line 4), following a goal (in line 3) which enumerates the elements of the superset in the variable `A`.

This technique has an important property: it ensures that each solution is returned only once. For example, invoking `choice_Ans(A, [])` enumerates instance `i` only once w.r.t. the usual Iocaste ABox. The above scheme can be used for supersets which *do not fit into memory*: the Prolog goal `member_of_superset_Ans(A)` can be implemented as a database invocation which enumerates the individuals in the superset.

We noted at the end of Section 4.6 that all goals within a *det* variant themselves invoke the *det* variant of their predicate. Thus, if the projection optimisation is applied to all predicates of a program, then the *choice* predicates can only be called from the conjunctive query. Such predicates are called *entry predicates* and are known to have an empty ancestor list argument.

We now describe an algorithm which assigns a set of instances to a predicate P, and then we show that this set is actually a superset of P.

4.8.2 Calculating supersets

Our goal is to find a method for building supersets for predicates such that the supersets (1) do not contain too many non-solutions and (2) are easy to calculate.

Definition 26 (*Projection of predicates*)
The *projection* of a role predicate P with respect to its nth ($n = 1, 2$) argument is $Pr_n(P) = \{v_n | (v_1, v_2) \in I(P)\}$. The projection of a concept predicate C with respect to its only argument is $Pr_1(C) = I(C)$. If G is a goal, $Pr_n(G)$ means the projection of the predicate invoked by the goal G w.r.t. its nth argument.

For example, $Pr_1(\texttt{hasChild(A,B)})$ w.r.t. the usual Iocaste knowledge base is the set $\{\texttt{i},\texttt{o},\texttt{p}\}$, excluding `t`, as `t` has no children. Note that this projection can be calculated by the Prolog call `setof(A, B^hasChild(A, B), R)`.

We now introduce the notion of *projected label* for clauses. This is either a superset of the clause or the functor of a predicate whose solution set contains all solutions

of the given clause. Within this definition we use a refinement of the notion of DNR predicate: a call of a predicate Q in the body of predicate P is said to be a DNR invocation if P is reachable from not_Q.

Definition 27 (*Projected label*)

Let C be a unary clause in a DL program DP. Let W be the set of all atomic and query goals in C which contain the head variable. We define the *projected label* of C, denoted by $Pl(C)$, as follows.

If C is a fact of the form $C(a)$, then $Pl(C)$ is the set $\{a\}$. Otherwise, if $W \neq \emptyset$, then $Pl(C)$ is calculated as the intersection of the projections of the goals in W w.r.t. the head variable, i.e. $Pl(C) = \cap_{G_i \in W} Pr_{p_i}(G_i)$, where p_i is the position of the head variable in the goal G_i.

If $W = \emptyset$ and C contains a goal which is not a DNR invocation, then $Pl(C)$ is the functor of an arbitrary such goal (e.g. the one which comes first w.r.t. the standard Prolog term ordering). If all goals in C are DNR invocations, then $Pl(C)$ is the set of all individual names in DP.

The notion of projected label has an interesting invariant: $I'(Pl(C)) \supseteq I(C)$, where the function I' takes either a functor of a predicate P and maps it to $I(P)$ or an arbitrary set S and maps it to itself. The invariant states that the 'solution set' of the projected label of a clause C contains all the solutions of C. This invariant can be easily checked by going through the four cases of the definition.

As an example, let us consider the Iocaste program presented in Figure 8. The projected label of the clause in lines 1 and 2 is the set $Pr_1(\text{hasChild(A, B)})$, while the projected label of the clause `not_Patricide/1` in lines 7 and 8 is the intersection $Pr_1(\text{hasChild(A, B)}) \cap Pr_2(\text{hasChild(C, A)})$. As a second example, let us consider a case in which the projected label is a functor: if C is `p(X) :- q(X), r(X)`, then $Pl(C) = \text{q/1}$, assuming that `q/1` and `r/1` are general, non-DNR predicates.

Using the definition of the projected label, we introduce the notion of miniset graphs, which we will use to define the notion of the miniset of a predicate.

Definition 28 (*The miniset graph of a DL program*)

Let S be a DL program containing the predicates $\{P_1, \ldots, P_n\}$, where a predicate P_i consists of clauses $\{C_{i1}, \ldots, C_{ik_i}\}$. The *miniset graph* of S is a labelled directed graph $(V, E, \mathcal{L})$, where $\mathcal{L}$ is a function assigning labels to vertices. To each predicate P_i and each clause C_{ij} there corresponds a node in the graph: p_i and c_{ij}, respectively. Thus $V = \cup_{P_i \in S} \{p_i, c_{i1}, \ldots, c_{ik_i}\}$.

Each node p_i is labelled with the functor of P_i, i.e. $\mathcal{L}(p_i) =$ the functor of P_i. A node corresponding to a clause C_{ij} is labelled with the projected label of the clause, i.e. $\mathcal{L}(c_{ij}) = Pl(C_{ij})$.

There are directed edges from each predicate node P_i to the nodes representing its clauses, i.e. $(p_i, c_{ij}) \in E, 1 \leqslant i \leqslant n, 1 \leqslant j \leqslant k_i$. Furthermore, for each clause C_{ij} whose projected label is a predicate functor F, there is an edge from the corresponding node c_{ij} to the node of the predicate with the functor F.

As an example, the miniset graph of the Iocaste program of Figure 8 is shown in Figure 24.
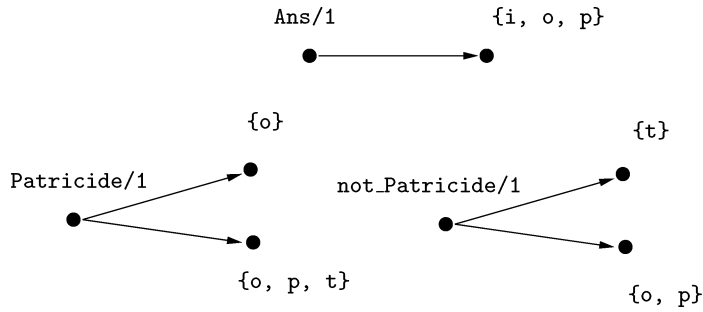
Fig. 24. The miniset graph of the Iocaste DL program in Figure 8.

Now we are ready to formulate the definition of the miniset of a predicate.

Definition 29 (*The miniset of a predicate*)
Let G be a miniset graph of a DL program. The *miniset $M(P)$* of a predicate P in this program is calculated as the union of the labels of the nodes which (1) are reachable from the node corresponding to P in the graph G and (2) are labelled with a set.

For example, the miniset of predicate `Patricide/1` in the Iocaste knowledge base is $\{o\} \cup \{o, p, t\} = \{o, p, t\}$. Note that for an ABox stored in a database the calculation of minisets can be done using database queries, as the projected labels in the miniset graph refer only to atomic and query predicates.

Proposition 17
For an arbitrary predicate P in a DL program DP, $M(P)$ is a superset of P.

Proof
If predicate Q has clauses $C_1, \ldots, C_n$, then $I(Q) = \cup_{C_i \in Q} I(C_i)$, assuming Q cannot succeed using ancestor resolution. When solving P, ancestor resolution cannot be used at the very first entry to P, because the ancestor list is then empty. Furthermore, if there is an edge from a clause C to a predicate Q in the miniset graph of DP, then the invocation of Q is known to be non-DNR, as specified in the definition of the projected label. This means that ancestor resolution is not applicable when Q is invoked from C. Also note that the invariant $I(C) \subseteq I(Q)$, similar to that mentioned after the definition of projected label, holds for the edge $C \to Q$.

   Each execution of the goal $P(X)$ has a corresponding finite path in the miniset graph of DP. The end point of this path has a set as a label, which contains the value assigned to X. Thus the answer to the query $P(X)$ is contained in a set label reachable from P and thus in $M(P)$, too. □

4.8.3 Implementation

In our implementation we calculate the miniset of a predicate P in the following way: First, for each clause reachable from P in the miniset graph, we collect the conjunction of the goals participating in the construction of the projected label for the given clause. Next, we build an auxiliary predicate whose body is the disjunction

```
 1 choice_Ans(A, B) :-
 2         (   nonvar(A) -> det_Ans(A, B)
 3         ;   setof(A, C^hasChild(A,C), D), member(A, D), det_Ans(A, B)
 4         ).
 5
 6 det_Ans(A, B) :- C = [Ans(A)|B],
 7                  hasChild(A, D),
 8                  (   hasChild(D, E),
 9                      det_not_Patricide(E, C) ->
10                      true
11                  ),
12                  det_Patricide(D, C), !.
13
14 choice_Patricide(A, _) :-
15         Patricide(A).
16
17 ...
```

Fig. 25. The final Prolog translation of the Iocaste problem.

of these conjunctions. Finally, we calculate the set of solutions of this auxiliary predicate using the standard predicate `setof` and enumerate the members of the superset using the list membership predicate `member`.

Below we show an example of superset calculation for a fictitious predicate, assuming it gives rise to three conjunctions shown in lines 4–6, where X is the head variable:

```
 1 member_of_superset_goal(A) :- setof(X, goal(X), S), member(A, S).
 2
 3 goal(X) :-
 4         (   hasChild(Y, X), hasChild(X, Z), hasFriend(X, W)
 5         ;   hasChild(X, Y)
 6         ;   Rich(X)
 7         ).
```

Note that we simplify the `goal/1` above: we omit the first branch of this disjunction (line 4), as it is subsumed by the more general goal in the second branch (line 5).

There are cases when the projection optimisation is not applied. For very simple predicates, e.g. those invoking atomic goals only, calculating the projection is simply a duplication of work, and so this optimisation is not used. Another case is when all goals in the body of a clause are DNR invocations (i.e. can succeed via ancestor resolution). The superset of such a clause (and of its predicate, too) is defined to contain all the individuals in the ABox. Obviously, in such cases the superset optimisation is not applied either. The definition of superset could be refined to decrease the number of such cases. As an alternative, source-to-source transformation techniques can be used to eliminate the need for ancestor resolution in the very early phase of execution, as discussed in Lukácsy *et al.* (2008).

To conclude this section, in Figure 25 we show the most interesting parts of the compiled Iocaste problem. To save space we have omitted the definition of the

predicate `det_Patricide/2` (already shown in lines 11–14 of Figure 20), as well as the *choice* and *det* variants of the predicate `not_Patricide/2`, which are very similar to corresponding variants of `Patricide/2`. All optimisations discussed so far have been applied here, including the superset optimisation. Notice how simple is the entry predicate for `Patricide` (lines 14 and 15): it only invokes the atomic ABox predicate. This is because the last clause of `Patricide/2` (cf. lines 9 and 10 in Figure 12) contains an orphan goal which cannot succeed when `Patricide` is used as an entry predicate (as it has an empty ancestor list argument). For the same reason the clauses for loop elimination and ancestor resolution (cf. lines 6 and 7 in Figure 12) can be removed. This leaves us with a single clause with a single atomic goal, for which there is no point in generating the superset. Because of this, we do not even generate the conditional structure usually present in *choice* predicates.

4.9 Transforming role axioms

We present here a compilation scheme for $\mathcal{SHIQ}$ role axioms which is more efficient than the one introduced in Section 3.7. We consider role subsumption axioms only, as an equivalence axiom $R \equiv S$ can be replaced by two subsumptions, and the transitivity axioms are removed by the first stage of the transformation (see Section 3.3).

The general scheme of Section 3.7 applies loop elimination for role axioms. This is required because, for example, the subsumption axioms $R \sqsupseteq S$ and $S \sqsupseteq R$ are transformed into the following two DL clauses, whose Prolog execution obviously leads to an infinite loop:

```
1  R(A, B) :- S(A, B).
2  S(A, B) :- R(A, B).
```

In general, looping of role predicates is related to role equivalence (roles R and S above are obviously equivalent). The main idea is to avoid the need for loop elimination by designating one of the equivalent roles as the representative of the others. All invocations of these predicates are replaced by appropriate calls of the representative predicate. Furthermore, of the two subsumption axioms stating role equivalence, we keep only the one in which the non-representative role is defined in terms of the representative one. In the above example, if R is the representative, we replace all occurrences of S by R throughout the TBox and retain only the second of the above clauses, the one corresponding to the axiom $S \sqsupseteq R$.

Note that the above scheme does not work when a role subsumption axiom states that a role R is a *symmetric*: $R^- \sqsubseteq R$. The Prolog translation of this axiom, `R(X, Y) :- R(Y, X)`, is an obvious loop. We break this loop by introducing an auxiliary predicate name `base_R`, replacing all occurrences of R in clause heads by `base_R` and defining the predicate R in terms of `base_R` by the two clauses `R(X, Y) :- base_R(X, Y)` and `R(X, Y) :- base_R(Y, X)`.

We start the formal discussion with some auxiliary definitions.

Definition 30 (*Reduced graph*)
Let G be an arbitrary directed graph. The *reduced graph* of G, denoted by G_r, is defined as follows: The vertices of G_r are the strongly connected components (SCC) of G. There is an edge in G_r from A to B if, and only if, there is an edge in G from one of the vertices in the SCC corresponding to A to one of the vertices in the SCC corresponding to B.

Definition 31 (*Canonical inverse of role*)
Let R be an atomic role or its inverse. The canonical inverse of R, denoted by $Inv(R)$, is defined as follows:

$$Inv(R) = \begin{cases} S & \text{if } R = S^-, \\ R^- & \text{otherwise.} \end{cases}$$

Definition 32 (*The role dependency graph*)
For a given knowledge base KB the role dependency graph $G = (V, E)$ is defined as follows: The set of vertices V of G is the set of atomic roles occurring in KB and of their inverses. There is a directed edge from P_i to P_j *and* from $Inv(P_i)$ to $Inv(P_j)$ if, and only if, $P_i \sqsubseteq P_j \in KB$.

Let G be a role dependency graph w.r.t. a knowledge base KB, and let us consider its reduced graph G_r. Notice that each node of G_r is a component of the original graph whose elements are equivalent roles. Also notice that if roles $R_1, \ldots, R_n$ all belong to a single component E, then roles $Inv(R_1), \ldots, Inv(R_n)$ belong to a single component as well, which we call the inverse of the first component and denote by E^-. A role is symmetric if, and only if, its component is the inverse of itself.

Consider the set $E \cup E^-$, where E is a component of a role dependency graph. Predicate invocations of two roles in this set return the same pairs of individuals (possibly in a different order). Therefore we designate a single atomic role name, say the one which comes first in the lexicographic order, as the *representative* of all roles in this set. Thus for any role $R \in E \cup E^-$, let $Repr(R)$ denote the first of the atomic role names in this set, according to the lexicographic order.

We now discuss how to transform role predicate invocations and role predicate heads, so that they use representative roles only. The transformation schemes for invocations and heads are the same, except for symmetric roles R, where the auxiliary predicate `base_R` is used in the heads to break the loops.

Let DP be a DL program generated from a knowledge base KB, and let G be the role dependency graph of KB. Let $RR = Repr(R)$ denote the representative of a role R. Let us consider the compiled version of the program DP, as defined in Section 3.7. We first remove the ancestor list arguments and the loop elimination clauses (denoted by F_2 in Definition 15) from all role predicates. We then perform the following transformations on all role predicate invocations and heads, except for those prefixed with the module name `abox` (occurring in the bodies of clauses of type F_3):

(a) If R and RR belong to the same component of G, then the role predicate invocation $R(X, Y)$ is replaced by $RR(X, Y)$; otherwise it is replaced by $RR(Y, X)$.

(b) If R is not a symmetric role, then the role predicate head is transformed as described in point (a) above.

(c) If R is a symmetric role, then the role predicate head $R(X, Y)$ is replaced by `base_RR(X, Y)`.

Here we view the compiled program as a set of clauses rather than a set of predicates. This is important for two reasons. First, when replacing role names with their representatives, several instances of the same clause may be produced, of which only one should be kept. Second, changing clause heads means that clauses are moved from one predicate to another.

Finally the compiled DL program is extended with the following predicates:

- For each symmetric atomic role name R, which is a representative of a set of roles, we add the following definition: $R(X, Y)$:- `base_R(X, Y)` and $R(X, Y)$:- `base_R(Y, X)`. This way R becomes the symmetric closure of `base_R`, which is populated using the ABox and/or role subsumption axioms.
- For each atomic role name R, which is not a representative of a role set, we build the (tautological) clause $R(X, Y)$:- $R(X, Y)$ and transform its body according to point (a) above. Such clauses will only be used when the role R occurs in a composite query. [An alternative is not to include these clauses, and to apply the transformation of point (a) above to the composite query.]

The above transformation can be easily combined with the role-indexing technique introduced in Section 4.5. This is incorporated in the DLog system, but the details are not discussed here.

The transformation scheme has several advantages. First and foremost, it ensures that the evaluation of a role predicate cannot loop, and so there is no need for the ancestor list argument and the loop-elimination clause in the role predicates. Furthermore, it avoids those duplicate solutions that are due to interchangeability of equivalent roles. However, a role predicate can still produce duplicate solutions (e.g. when the role subsumes two other roles sharing a solution), and the transformation scheme could be refined further to improve the efficiency of execution.

4.10 Summary

We presented several optimisations which result in a much more efficient Prolog translation, in comparison with the generic compilation scheme described in Section 3. These optimisations preserve the most important property of the generic compilation scheme, e.g. the separation of the TBox from the ABox. In the following we give a brief summary of the optimisations presented.

In *filtering*, we remove those clauses that do not need to be included in the final program, as they are not used in the execution. We proved that the certain clauses (those having the *false-orphan*, the *two-orphan* or the *contra-two-orphan* property) can be removed.

Classification puts each predicate into one of the four categories: *atomic*, *query*, *orphan* and *generic*. For each class, we presented an optimised translation scheme.

The *ordering* optimisation arranges the body goals so as to minimise the execution time. We defined a heuristic and specified an ordering algorithm which uses this heuristic.

The *indexing* optimisation is introduced to get around the problem that in most Prolog systems indexing is done only on the first head argument, and this may raise performance issues if we use Prolog for storing large amounts of ABox facts.

The *ground goal optimisation* makes sure that if a ground goal succeeds, then all choice points within it are pruned. To achieve this, we create two versions of each unary predicate, which handle the cases of the head variable being instantiated or uninstantiated.

The goal of *decomposition* is to split a body into independent components: this recursive process introduces a more refined notion of body ordering and a generalisation of the ground goal optimisation. We described the decomposition process and specified its relation to the body-ordering algorithms.

The idea of the *superset* optimisation is to determine, for each predicate P, a set of instances S for which $I(P) \subseteq S$ holds, where $I(P)$ is the set of solutions of P. If the size of S is not significantly larger than that of $I(P)$, then we can use S to efficiently reduce the initial instance retrieval problem to a finite number of instance checks. We defined the notions of miniset graphs and minisets and showed that the so-called miniset of a predicate fulfils the above criteria.

Finally, we defined an efficient translation scheme for the $\mathcal{SHIQ}$ role axioms $(R \sqsubseteq S)$.

5 The DLog system

In this section we first introduce the software architecture of the DLog system. Next, we discuss the implementation specific optimisations we have developed. Finally, we present the various parameters one can use to tune the behaviour of the DLog system.

5.1 Architecture

DLog is a resolution-based DL ABox reasoner for the $\mathcal{SHIQ}$ DL language, which implements the techniques described in the paper. DLog has been developed in Prolog, involving a total of approximately 180 KB of Prolog source code. Our main implementation is in SICStus Prolog; a port to SWI Prolog has been completed recently.

The general architecture of the DLog implementation is shown in Figure 26. The system can be used as a server or as a stand-alone application. In either case, the input of the reasoning process is provided by a DIG file. The DIG format (Bechhofer 2006) is a standardised XML-based interface for DL Reasoners.

The input file has three parts: the (potentially) large ABox, the smaller TBox and the Ask part describing the queries. The content of the ABox is asserted into module abox, either with no modifications or (if the indexing optimisation is applied) together with the index predicates. Note that the ABox can also be supplied as a database. This is essential for really large data sets.
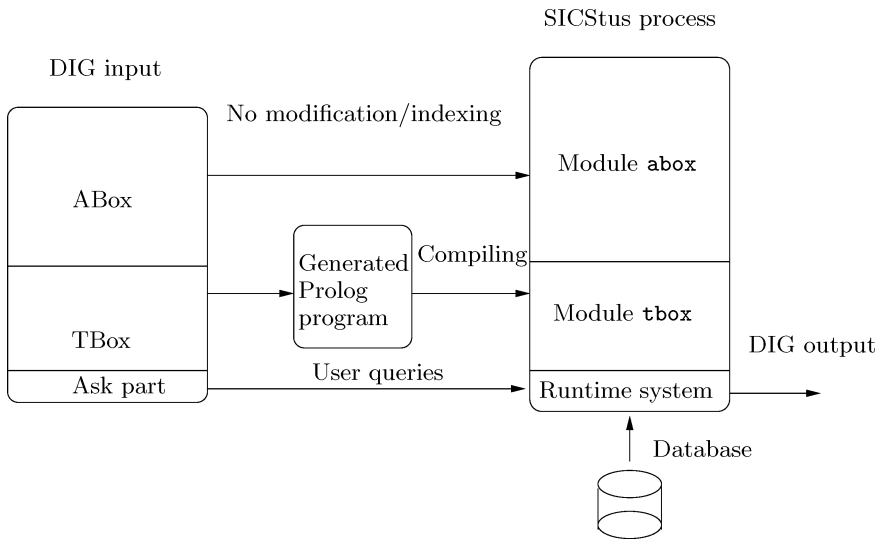
Fig. 26. The architecture of the DLog system.

The content of the TBox is transformed into a Prolog program following the techniques described in previous sections. This program is then compiled into module `tbox`.

The content of the Ask part in the DIG input contains the user queries. In the simplest case, the user poses an instance retrieval query which directly corresponds to a concept in the TBox. Such cases are answered by directly invoking the appropriate choice predicate. In the more complex case we have a *conjunctive query* as introduced in Section 3.5.

We handle conjunctive queries by reducing the problem of query answering to a normal DL reasoning task (Horrocks *et al.* 2000). We simply apply body reordering (Section 4.4) and decomposition (Section 4.7) on a conjunctive query and use normal Prolog execution for the resulting goal. We are aware that much more sophisticated techniques are available (Motik 2006), but at the moment our simple approach seems to be efficient enough.

5.2 Low-level optimisations

During the implementation we have applied several optimisations which can be considered implementation specific or low level. Below we give a brief summary of these optimisations.

Loop and ancestor separation. It is worth separating the data structures used for loop elimination and ancestor resolution. This way we can update them separately, which results in more efficient execution.

Hashing. Rather than using lists, we introduced a more efficient data structure to store the goals used for loop elimination and ancestor resolution. For this purpose we developed a special hashing library written in Prolog and C, relying on the foreign language interface of the Prolog system used.

As an example for the benefits of hashing consider the following DL knowledge base:

```
1  ∃hasFriend.Alcoholic  ⊑  ¬Alcoholic
2  ∃hasParent.¬Alcoholic  ⊑  ¬Alcoholic
3
4  hasParent(i1, i2). hasParent(i1, i3). hasFriend(i2, i3).
```

This TBox states that if someone has a friend who is alcoholic, then she is not alcoholic (she sees a bad example). Furthermore, if someone has a non-alcoholic parent, then she is not alcoholic either (she sees a good example). The ABox contains two `hasParent` and one `hasFriend` role assertions but nothing about someone being alcoholic or non-alcoholic. Interestingly, it is possible to conclude that `i1` is non-alcoholic, as one of her parents is bound to be non-alcoholic (as at least one of two people who are friends has to be non-alcoholic).

For certain ABoxes, the Prolog translation of this knowledge base has a runtime which is quadratic in the number of `hasParent` relations if the ancestors are stored in a list. An example of such an ABox is the following:

$$\texttt{hasParent(i}_k\texttt{, i}_{k+1}\texttt{)}, \ k \ = \ 1,\ldots,n$$
$$\texttt{hasFriend(i}_{n+1}\texttt{, i}_{n+2}\texttt{)}$$
$$\texttt{hasParent(i}_{n+2+t}\texttt{,i}_{n+1+t}\texttt{)}, \ t \ = \ 1,\ldots,n$$

Here, for each individual $\texttt{i}_{n+1+t}$, $t > 0$, the Prolog code checks if the ancestor list contains the term $\texttt{not\_Alcoholic(i}_{n+1+t}\texttt{)}$. This has a linear cost w.r.t. the size of the ancestor list, assuming that the check for a given ancestor is performed by a linear scan of the ancestor list. The quadratic time complexity can be reduced to (nearly) linear when a hash table is used for storing the ancestors (with a nearly constant time ancestor check).

Placing the update operations. In the translation scheme presented in Section 4 the extension of the ancestor list takes place at the very beginning of each clause (see e.g. line 6 of Figure 25). However, updating a hash structure is more expensive than adding a new element to a list. Therefore we perform the hash update operation as late as possible, i.e. before the first goal which uses the updated hash value. This, for example, corresponds to moving the ancestor update operator in line 6 of Figure 25 to before line 9.

Clause-level categorisation. The predicate categorisation (see Section 4.3) can be refined so that the characteristics of individual clauses of the predicate are taken into account. For example, even if a predicate is recursive, some of its clauses will never lead to recursive calls of this predicate. For these clauses, there is no point in updating the loop data structure. Similarly, if *not_P* cannot be reached from a clause of *P*, then there is no need for updating the ancestor data structure in the given clause.

5.3 Execution parameters

Most of the optimisations discussed in Section 4 can be enabled/or disabled in DLog, resulting in different generated Prolog programs. The possible parameter settings are summarised below (the parameter values allowed are shown in parentheses; the first value is the default):

- decompose (yes/no): whether to decompose the bodies (Section 4.7)
- indexing (yes/no): whether to generate index predicates for roles (Section 4.5);
- projection (yes/no): whether to calculate supersets (Section 4.8);
- filtering (yes/no): whether to do filtering (Section 4.2);
- ground_optim (yes/no): whether to use ground goal optimisation (Section 4.6);
- orphan (first/general): whether orphan calls are brought to the beginning of the clause or handled in the same way as general concept calls;
- hashing (yes/no): whether to apply hash tables instead of lists for storing ancestors.

6 Performance evaluation

This section presents a comparison of the performance of DLog with that of existing DL reasoning systems. The aim here is to obtain an insight into the practical applicability of the methods described in Sections 3 and 4.

During the tests we have found several anomalies which resulted in significant performance drops in the case of certain DL reasoners. We believe that most of these will be fixed by the respective authors in the near future. Here, however, we took each system 'as it is', which means that we examined how their most up-to-date version performs on various inputs.

Our tests suggest that resolution-based techniques are very promising in practical applications, where the TBox is relatively small, but the ABox is huge.

6.1 Test environment

We have compared our system with three state-of-the-art DL reasoners: RacerPro 1.9.0, Pellet 1.5.0 and the latest version of KAON2 (August 2007). RacerPro (Haarslev *et al.* 2004) is a commercial system, and Pellet (Sirin *et al.* 2007) is open source, while KAON2 (Motik 2006) is free of charge for universities for non-commercial academic usage. We did not consider other available reasoning systems mainly because they either are outdated or do not support ABox reasoning at all (e.g. this is the case for the widely used FaCT system).

We contacted the authors of each reasoning system in order to obtain the preferred sequence of API calls for running our tests. From one of them we did not receive any response; so we used the API according to the documentation. The benchmarks were executed by a test framework we have specifically developed for testing DLog and other systems. For each query, we started a clean instance of the reasoner and loaded the test knowledge base. Next, we measured the time required to execute the given query. Each query was executed five times. The best and the worst results were

excluded, and the remaining three were used for calculating an average. In case the execution was very fast (less than 10 milliseconds) we have repeated the test 1,000 times and calculated the average. We made sure that all systems return the same answers for the given queries.

The tests were performed on a Fujitsu-Siemens S7020 laptop with a Pentium-M 1.7 GHz processor, 1.25 GB memory, Ubuntu Linux 7.04 with Linux kernel 2.6.20-16 and SICStus Prolog 3.12.8. The version of the Java virtual machine, used for KAON2 and Pellet, is 1.5.0.

6.2 Test ontologies

For the benchmark we have used three families of ontologies. The first one corresponds to the Iocaste problem introduced in Figure 1. For performing this test we have created a program which generates random Iocaste knowledge bases using certain initial parameters (number of nodes, branching factor and the like).

First we used this program to generate 'clean' Iocaste ontologies, i.e. DL knowledge bases with the ABox containing nothing else but Iocaste patterns of a given size (cf. Figure 2). These knowledge bases are named `cN`, where `N` is the size of the pattern. For example, `c100` denotes the DL knowledge base with a single TBox axiom and an ABox containing 102 individuals according to Figure 2 with $n = 100$.

We have also generated 'noisy' Iocaste knowledge bases. By 'noise' we mean irrelevant individuals, role and concept assertions which we added to the ABoxes (for example pairs in `hasChild` relation which are not relevant to the Iocaste problem). We did this in order to be able to measure how sensitive the inference engines are to this kind of ABox modification. By using irrelevant nodes we actually simulate real-life search situations, where the task is to find some specific instances within huge amounts of data. The noisy Iocaste knowledge bases are named `n1`, `n2`, `n3` and `n4`. Table 1 shows the properties of the clean and noisy Iocaste ontologies, together with their DLog compilation times, under various parameter settings.

The top four rows of the table contain information on the knowledge bases. The first row gives the size of the corresponding DIG files (in megabytes); the second and third show the number of TBox and ABox axioms, while the fourth row shows the time (in seconds) it took for the DLog system to parse the DIG files and convert them to Prolog terms (load time). We can see that the largest clean ontology contains a bit more than 20,000 ABox axioms, while the largest noisy ontology has more than 30,000 axioms. Each ontology contains only a single TBox axiom (cf. Figure 1).

Subsequent sections in Table 1 correspond to the various parameter settings we have tried the DLog system with. For each setting, we give the translation time (the time it took to generate the Prolog program as described in Sections 3 and 4) and the time it took the SICStus Prolog system to actually compile the generated program. The total time is the sum of three values: the load time, the translation time and the compile time.

In our tests, out of the possible 2^8 option variations (cf. Section 5.3), we have only used the following ones:

Table 1. *Properties of the Iocaste test ontologies (times in seconds)*

Test file	c10	c20	c100	c1000	c10000	n1	n2	n3	n4
Size (MB)	0	0	0.02	0.19	1.88	0.01	0.06	0.35	2.82
TBox	1	1	1	1	1	1	1	1	1
ABox	22	42	202	2,002	20,002	100	646	3,897	30,797
Load (s)	0.04	0.06	0.13	0.23	0.78	0.12	0.21	0.23	0.88
base									
Translate	0	0.01	0.01	0.08	0.67	0.01	0.02	0.13	1.10
Compile	0.03	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.01
Total	**0.07**	**0.08**	**0.15**	**0.33**	**1.47**	**0.14**	**0.24**	**0.38**	**1.99**
g(n)									
Translate	0.01	0	0.01	0.08	0.69	0	0.04	0.18	1.04
Compile	0	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02
Total	**0.05**	**0.08**	**0.16**	**0.32**	**1.48**	**0.14**	**0.27**	**0.43**	**1.94**
p(n)									
Translate	0.01	0.01	0.02	0.08	0.71	0.01	0.02	0.15	1.29
Compile	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.02
Total	**0.06**	**0.08**	**0.16**	**0.33**	**1.50**	**0.14**	**0.25**	**0.39**	**2.19**
f(n)									
Translate	0.01	0.01	0.01	0.07	0.72	0.01	0.02	0.16	1.05
Compile	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.03
Total	**0.06**	**0.08**	**0.15**	**0.31**	**1.52**	**0.14**	**0.25**	**0.40**	**1.96**
i(n)									
Translate	0	0.01	0.01	0.02	0.30	0.01	0.04	0.06	0.52
Compile	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0	0.01
Total	**0.05**	**0.08**	**0.15**	**0.27**	**1.10**	**0.14**	**0.26**	**0.29**	**1.41**
o(n)									
Translate	0	0	0.01	0.08	0.70	0.01	0.04	0.11	1.10
Compile	0.01	0.01	0.01	0	0.03	0.01	0.01	0.02	0.01
Total	**0.05**	**0.07**	**0.15**	**0.31**	**1.51**	**0.14**	**0.26**	**0.36**	**1.99**
d(n)									
Translate	0	0	0.01	0.08	0.71	0.01	0.02	0.15	1.05
Compile	0	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02
Total	**0.04**	**0.07**	**0.15**	**0.32**	**1.50**	**0.14**	**0.25**	**0.39**	**1.95**
pd(n)									
translate	0.01	0.02	0.02	0.07	0.71	0.01	0.02	0.12	1.06
compile	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.01
total	**0.06**	**0.09**	**0.17**	**0.32**	**1.51**	**0.14**	**0.24**	**0.37**	**1.95**
od(n)									
translate	0.01	0.01	0.01	0.08	0.73	0.02	0.03	0.12	1.04
compile	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.04
total	**0.06**	**0.08**	**0.15**	**0.33**	**1.53**	**0.16**	**0.25**	**0.36**	**1.96**

- `base`: everything is left as default;

- [g(n)]: do not use ground goal optimisation;

- [p(n)]: do not use projection;

Table 2. *Properties of the LUBM test ontologies*

Test file	lubm1	lubm2	lubm3	lubm4
OWL file size (MB)	6.90	15.84	23.24	32.97
DIG file size (MB)	16.57	37.99	58.80	81.74
Concept assertions	18,128	40,508	58,897	83,200
Role assertions	49,336	113,463	166,682	236,514

- `[f(n)]`: do not use filtering;
- `[i(n)]`: do not use indexing;
- `[o(n)]`: handle orphan goals as general concept goals;
- `[d(n)]`: do not use decomposition;
- `[pd(n)]`: do not use projection and decomposition; and
- `[od(n)]`: do not use decomposition and handle orphan goals as general concept goals.

Table 1 shows that most settings have very similar compile-time properties. However, the setting `[i(n)]` disables the generation of index predicates, which results in a more compact code. This means shorter translation and compilation times.

Note that the Iocaste ontologies, both the clean and the noisy ones, use the $\mathcal{ALC}$ DL language.

The second ontology we used for testing is VICODI (Nagypál and Motik 2003), an ontology about European history, created manually. It is the result of an European Union Information Society Technologies programme project. Technically VICODI is an $\mathcal{ALH}$ ontology with a fairly simple TBox and a huge ABox. We have obtained VICODI from the VICODI homepage in the form of a Protege project. We have converted this project into OWL and DIG formats using Protege 3.3.1 and used these as inputs for the various reasoners. The sizes of these converted files are 9.5 and 23 megabytes, respectively.

The VICODI TBox consists of 182 concept and 9 role subsumption axioms. The ABox contains 84,550 role axioms and 29,614 concept axioms.

Finally, we have also tested our system on the Leigh University Benchmark (LUBM; Guo *et al.* 2004). The LUBM was developed specifically as a benchmark for the performance analysis of DL reasoners. The ontology describes the organisational structure of universities, and it uses the $\mathcal{ALCHI}$ language. The ABox part can be automatically generated by specifying a size parameter (the number of universities).

We have used four variants of the ontology, denoted by `lubm1`, `lubm2`, `lubm3` and `lubm4`. All contain 36 concept inclusion, 6 concept equivalence, 5 role inclusion and 4 role equivalence axioms. They also contain a transitive role and 21 domain and 18 range restrictions. The number of ABox axioms in the various LUBM ontologies and their sizes in megabytes are shown in Table 2.

6.3 Results

We now present the performance results for the Iocaste, VICODI and LUBM ontologies. For each case we give a detailed explanation of the results.

6.3.1 The Iocaste ontologies

The performance results of the DLog system on the Iocaste ontologies are presented in Table 3. Here, we show four values for each parameter setting. Three values (loop, ancres, orphancres) give statistical information, describing the number of loop eliminations, ancestor resolutions and orphan ancestor resolutions (ancestor resolutions in orphan goals). Finally, we show the most important value, the runtime in seconds.

With the best settings (`base`) DLog solved each task within a fraction of a second, including the biggest clean and the biggest noisy cases as well. Actually, using projection (cf. Section 4.8) seems to be a key factor, as without it the performance drops dramatically. We can also notice that the lack of multiple argument indexing (cf. Section 4.5) has very negative effect on the execution time. With the last parameter setting DLog was unable to solve all tasks (this is denoted by —). In this setting we do not use decomposition, and we treat orphans as normal predicates. The reason why this setting has the worst performance is that it causes the orphan goal `not_Ans(D, B)` to be placed at the very end of the corresponding `det_Patricide/2` clause (cf. Figure 20).

We have compared the performance of DLog, using the `base` parameter setting, with that of the other three reasoning systems. These aggregate results are shown in Table 4. In this table, as in the rest of the paper, whenever we compare various systems/options, the best total time is given in bold.

Here, for each Iocaste ontology and each reasoning system we give the following values: the load time, the runtime and their sum, the total time. The load time in the case of the DLog system includes parsing, translating and SICStus compilation (cf. Table 1). For the other systems, load time is the time it takes to reach the point at which a query can be posed. (We do not have detailed information what the systems are actually doing here other than parsing the input.) Note that the size of the input given to DLog is bigger than that for the other systems, as the DIG format is more verbose than the OWL one.

KAON2 showed a very poor performance on the clean Iocaste ontologies: `c10` was the only test case it was able to solve within the time limit. To understand better what is going on we have tested KAON2 with clean Iocaste patterns of length $n = 11, \ldots, 15$. The results of this experiment are summarised in Table 5. Here we can see that KAON2 scales very badly when increasing the size of the pattern. Note that the increase between the consecutive test cases is minimal: the ontology c_{i+1} has one more instance and two more role assertions than the ontology c_i.

Another interesting thing is that KAON2 actually ran *faster* on ontology `c11` than on `c10`. It also seems to scale reasonably well (at least compared to the other cases) from `c13` to `c14`.

Table 3. *Dlog results for the Iocaste ontologies (times in seconds)*

Test file	c10	c20	c100	c1000	c10000	n1	n2	n3	n4
base									
Loop	0	0	0	0	0	0	2	6	0
Ancres	0	0	0	0	0	0	0	0	0
Orphanc	18	38	198	1,998	19,998	81	130	448	3,197
Runtime	**0**	**0**	**0**	**0.01**	**0.11**	**0**	**0**	**0**	**0.02**
g(n)									
Loop	0	0	0	0	0	0	2	6	0
Ancres	0	0	0	0	0	0	0	0	0
Orphanc	18	38	198	1,998	19,998	81	130	448	3,197
Runtime	**0**	**0**	**0**	**0.01**	**0.12**	**0**	**0**	**0**	**0.02**
p(n)									
Loop	0	0	0	0	0	0	2	6	0
Ancres	0	0	0	0	0	0	0	0	0
Orphanc	99	399	9,999	10^6	10^8	81	130	448	3,197
Runtime	**0**	**0**	**0.04**	**4.14**	**500.42**	**0**	**0**	**0**	**0.01**
f(n)									
Loop	0	0	0	0	0	0	2	6	0
Ancres	0	0	0	0	0	0	0	0	0
Orphanc	18	38	198	1,998	19,998	81	130	448	3,197
Runtime	**0**	**0**	**0**	**0.01**	**0.11**	**0**	**0**	**0**	**0.02**
i(n)									
Loop	0	0	0	0	0	0	2	6	0
Ancres	0	0	0	0	0	0	0	0	0
Orphanc	18	38	198	1,998	19,998	81	130	448	3,197
Runtime	**0**	**0**	**0**	**0.10**	**9.58**	**0**	**0**	**0**	**0.02**
o(n)									
Loop	0	0	0	0	0	0	2	6	0
Ancres	0	0	0	0	0	0	0	0	0
Orphanc	9	19	99	999	9,999	45	47	53	46
Runtime	**0**	**0**	**0**	**0.01**	**0.12**	**0**	**0**	**0**	**0.02**
d(n)									
Loop	0	0	0	0	0	0	2	9	0
Ancres	0	0	0	0	0	0	0	0	0
Orphanc	18	38	198	1,998	19,998	81	130	445	3,197
Runtime	**0**	**0**	**0**	**0.01**	**0.13**	**0**	**0**	**0**	**0.02**
pd(n)									
Loop	0	0	0	0	0	0	2	9	0
Ancres	0	0	0	0	0	0	0	0	0
Orphanc	99	399	9,999	10^6	10^8	81	130	445	3,197
Runtime	**0**	**0**	**0.04**	**4.15**	**502.98**	**0**	**0**	**0**	**0.02**
od(n)									
Loop	0	0	—	—	—	0	2	43	0
Ancres	0	0	—	—	—	0	0	0	0
Orphanc	256	2,302	—	—	—	0	0	0	0
Runtime	**0**	**3.56**	**—**	**—**	**—**	**0.01**	**0.03**	**0.18**	**4.11**

Table 4. *Aggregate results for the Iocaste ontologies (times in seconds)*

Test file	c10	c20	c100	c1000	c10000	n1	n2	n3	n4
DLog									
Load	0.07	0.08	0.15	0.33	1.47	0.14	0.24	0.38	1.99
Runtime	0	0	0	0.01	0.11	0	0	0	0.02
Total	**0.07**	**0.08**	**0.15**	**0.34**	**1.58**	**0.14**	**0.24**	**0.38**	**2.01**
KAON2									
Load	0.45	—	—	—	—	0.46	0.60	0.97	2.36
Runtime	0.72	—	—	—	—	0.67	4.72	63.60	425.17
Total	1.17	—	—	—	—	1.13	5.32	64.57	427.53
RacerPro									
Load	0.01	0.01	0.03	0.51	4.68	0.03	0.10	0.68	6.04
Runtime	0.07	0.09	0.15	1.68	79.91	0.10	0.47	1.76	23.25
Total	0.08	0.10	0.18	2.19	84.59	0.13	0.57	2.44	29.29
Pellet									
Load	1.27	1.35	1.44	2.19	—	1.32	1.53	2.36	5.92
Runtime	0.19	0.32	1.31	456.40	—	0.33	0.80	2.48	23.95
Total	1.46	1.68	2.76	458.58	—	1.65	2.33	4.84	29.87

Table 5. *Performance of KAON2 on the Iocaste ontologies (times in seconds)*

Test file	c10	c11	c12	c13	c14	c15
Runtime	0.72	0.68	3.51	16.18	17.03	309.91

In the case of the noisy ontologies KAON2 also behaved strangely. Although it was able to solve all the tests within 10 minutes, we definitely expected KAON2 to solve these cases much faster. This is because KAON2 uses resolution, similar to DLog, which theoretically means that it should be resistant to noise to a large extent.

We have actually learnt (Motik 2007, personal communication) that in KAON2 many things depend on the order of rule applications, something which is a very difficult task to set properly. Choosing a bad order may result in a big performance drop. This may be a reason for the anomalies we have seen in the case of the Iocaste ontologies.

RacerPro was able to solve each test case within the time limit. It showed a very consistent behaviour in the case of both the clean and the noisy variants. From the test results it seems that RacerPro scales linearly but with a much worse constant than DLog. As a tableau-based reasoner, RacerPro showed a surprisingly good performance in the case of the largest noisy variant n4 as well (23.25 seconds).

Pellet was nearly as fast as RacerPro in the case of the noisy variants. On the clean Iocaste ontologies, however, it was clearly outclassed by RacerPro, as Pellet was not able to solve c10000 within 10 minutes, and in all the other cases it was fairly slow as well. We have also found that in several cases Pellet threw certain

Table 6. *The in-memory and database variants of* n4 *(times in seconds)*

DLog	Load time	Translation time	Compilation time	Runtime	Total
In-memory	0.88	0.52	0.01	0.02	1.43
Database	0.05	0.01	0.01	0.36	0.43

Java exceptions on the very same input it successfully processed earlier or later. We guess that this can be due to the use of Java hash codes.

As a conclusion, we state that DLog is several orders of magnitude faster on the Iocaste benchmark than the other ABox reasoning system examined, considering both the reasoning time (runtime) and the total execution time.

Using databases. Instead of creating large internal Prolog databases for storing the ABox, we can actually put the content of the ABox into a real database and use DLog to generate a program from only the TBox. We used this technique for the largest noisy variant n4 with the option setting [i(n)]. Here, according to Tables 1 and 3, we use 1.41 seconds for the compilation and 0.02 seconds for runtime. By using a database for storing the content of the ABox, we expected drastic decrease in the total compilation time, with a slight increase in the execution time.

The actual (MySQL) database contains 15 tables, of which 10 correspond to concepts (i.e. they have only one column), while the rest corresponds to roles (i.e. they have two columns). Note that because of the top-down execution, the Prolog program generated from the TBox actually accesses only tables Patricide, not_Patricide and hasChild. We have 5,058 pairs in hasChild relation; 855 instances are known to be patricide, and 314 are known to be non-patricide.

The performance results are summarised in Table 6. The database variant of n4 enumerated all the instances of concept Ans in 0.36 seconds. This, compared to the original 0.02 seconds, is much slower. However, the time we spent at compile time was altogether 0.07 seconds, resulting in a total execution time of 0.43 seconds.

From the figures of Table 6, one may think that the main benefit of using a database for storing the ABox lies in reducing the compilation time. However, we believe that by using further optimisations, such as transforming query predicates to database queries, the version using a database can also produce better execution times than the in-memory variant.

We have thus shown that it is feasible to use a database for storing the content of an ABox, and in the case of the Iocaste ontologies, the database approach provides better overall performance than the variant which stores the ABox as Prolog facts.

Hashing. We have also measured how much the execution time is affected by the data structures used for storing ancestor goals. For this, we have picked the best parameter setting, base, and run the tests by replacing the hash tables with simple lists as assumed throughout Section 4. The results are summarised in Table 7 together with the hash-based results from Table 3.

We can see that in the case of the large Iocaste patterns (c1000 and c10000) the hashing implementation outperforms the solution using lists significantly.

Table 7. *The effect of hashing on the Iocaste ontologies (times in seconds)*

Test file	c10	c20	c100	c1000	c10000	n1	n2	n3	n4
Hash	0	0	0	**0.01**	**0.11**	0	0	0	**0.02**
List	0	0	0	0.11	10.52	0	0	0	0.03

Table 8. *Aggregate results for the VICODI ontology (times in seconds)*

	DLog	KAON2	RacerPro	Pellet
Load time	8.61	**5.88**	34.96	—
VQ_1				
Runtime	**0.05**	0.36	76.48	—
Total	8.66	**6.24**	111.44	—
VQ_2				
Runtime	**0.09**	0.35	76.61	—
Total	8.70	**6.23**	111.57	—

6.3.2 VICODI

To test the performance of the DL reasoners on the VICODI ontology, we used the following two queries, borrowed from Motik (2006):

```
VQ₁(X)     ≡ Individual(X)
VQ₂(X,Y,Z) ≡ Military-Person(X), hasRole(Y, X), related(X, Z)
```

The results are summarised in Table 8. The DLog system used 8.61 seconds to load the VICODI ontology. From this, 4.91 seconds were actually spent on parsing the input and transforming the DL knowledge base into DL predicates. DLog used 3.38 seconds to generate the Prolog code. The rest (0.36 seconds) was used by SICStus Prolog to compile the generated Prolog program. Having loaded the knowledge base, the execution was nearly instantaneous: 0.05 seconds for VQ_1 and 0.09 seconds for VQ_2.

RacerPro spent nearly 35 seconds for loading the ontology. The execution of VQ_1 was fairly slow: it took 76.48 seconds to enumerate all the instances of class Individual. We also measured the execution time by first checking the consistency of the ABox and then preparing the query-answering engine before posing the query itself. The consistency check took 65.86 seconds, the query engine preparation 1.29 seconds and the query itself 8.25 seconds. This results in a total time of 75.40, which (as expected) is comparable to the total time of simply loading and querying.

In the case of VQ_2, RacerPro produced nearly the same results. We believe this is because RacerPro spends most of its time in checking ABox consistency, which requires the same amount of time in both queries.

Pellet was unable to answer any of the queries within the 10-minute time limit. We believe that Pellet properly read the input, as we could formulate VICODI queries which Pellet was able to answer, but this was not the case for queries VQ_1 and VQ_2. We have also tried the Windows version of Pellet, but we have experienced the same

behaviour. Actually, in Motik (2006) Pellet 1.3 beta was tested against the VICODI ontology with acceptable results. Thus it seems that recent changes in the Pellet reasoner are responsible for the performance drop we have found.

KAON2 could not read the VICODI OWL input we generated with Protege: we got an exception. To be able to run the tests, we used a version of the ontology specifically made for KAON2 (available on the VICODI website). This version of the ontology is physically twice as large as the normal OWL dialect (i.e. it is 18 MB). On this, KAON2 was very convincing. It took 5.88 seconds to load the ontology and 0.36 seconds to answer query VQ_1. Answering query VQ_2 was even a bit faster; it required 0.35 seconds. We note that neither RacerPro nor Pellet supports this format of the VICODI ontology, and so the comparison is not fully fair.

To conclude we can say that KAON2 had the best overall performance when dealing with the VICODI ontology. DLog answered the queries even faster than KAON2, but for the compile-time tasks we needed a few seconds more. We note, however, that the DIG input is larger by 5 MB than the KAON2 version of the VICODI ontology, which naturally results in more load time work for us.

6.3.3 LUBM

We have tested the LUBM ontologies with the following two queries:

```
LQ₁(X)      ≡ Person(X), hasAlumnus(http://www.University0.edu, X)
LQ₂(X,Y)    ≡ Chair(X), Department(Y), worksFor(X, Y),
              subOrganizationOf(Y, http://www.University0.edu)
```

These queries were selected from the 14 test queries available on the LUBM homepage. Answering LQ_1 requires proper handling of role subsumptions and inverses; LQ_2 is interesting, as it is a complex conjunctive query. The performance results are summarised in Table 9. For DLog we used the `base` parameter setting; i.e. we apply all optimisations.

Loading `lubm1` took DLog 6.96 seconds. From this it took 5.29 seconds to read the DIG file and create the DL predicates. We needed 1.47 seconds to generate the Prolog code. Finally, it took 0.18 seconds for SICStus Prolog to compile the generated code. Answering LQ_1 required only 0.26 seconds, while LQ_2 was answered instantaneously.

Loading the larger `lubm` ontologies required much more time, and the time needed for answering LQ_1 increased roughly in proportion with the load time. However, the second query, LQ_2, was executed instantaneously on all of the LUBM ontologies.

Note that a significant part of the compile-time work for DLog is the generation of the index predicates (cf. Section 4.5). This effectively doubles the number of the role assertions. The use of this optimisation becomes unnecessary if we use a Prolog system with multiple argument indexing or if we store the ABox externally in a database – which is the preferred use of the DLog system. Also note that the DIG input given to DLog is significantly larger (cf. Table 2) than the OWL input the other reasoning systems use.

Table 9. *Aggregate results for the LUBM ontologies (times in seconds)*

Query	LQ$_1$				LQ$_2$			
Test file	lubm1	lubm2	lubm3	lubm4	lubm1	lubm2	lubm3	lubm4
DLog								
Load	6.96	11.83	15.79	21.34	6.96	11.83	15.79	21.34
Runtime	**0.26**	**0.63**	**0.92**	**1.32**	**0**	**0**	**0**	**0**
Total	**7.22**	**12.46**	**16.71**	**22.66**	**6.96**	**11.83**	**15.79**	**21.34**
KAON2								
Load	6.56	13.56	20.66	28.73	6.56	13.56	20.66	28.73
Runtime	0.70	0.99	1.33	1.69	0.66	0.93	1.27	1.62
Total	7.26	14.55	21.99	30.42	7.12	14.49	21.93	30.35
RacerPro								
Load	24.84	91.57	X	X	24.84	91.57	X	X
Set-up	29.41	112.29	X	X	29.41	112.29	X	X
Runtime	2.69	5.89	X	X	4.07	7.49	X	X
Total	56.94	209.75	X	X	58.32	211.35	X	X
Pellet								
Load	16.76	—	—	—	16.76	—	—	—
Set-up	4.84	—	—	—	4.84	—	—	—
Runtime	27.09	—	—	—	27.19	—	—	—
total	48.69	—	—	—	48.79	—	—	—

KAON2 behaved very nicely on the LUBM ontologies: it was able to answer both queries LQ$_1$ and LQ$_2$ on all ontologies very quickly. We note that the official version of KAON2 was actually unable to solve the LUBM tests due to certain technical problems. After contacting the author, the bugs causing this failure were quickly fixed.

RacerPro managed to solve both queries on the ontologies lubm1 and lubm2 with total times between 56.94 and 211.35 seconds. Here we can see the usual pattern: there is no real difference between the execution times of LQ$_1$ and LQ$_2$. Unfortunately, on the bigger ontologies, RacerPro had memory problems (denoted by X in Table 9).

Pellet solved the queries only on the smallest LUBM ontology. This required 48.69 and 48.79 seconds. On the larger ontologies Pellet did not signal memory problems but simply ran out of the 10 minutes of allotted time.

Note that in the case of RacerPro and Pellet we also show the set-up time which is the time of the ABox consistency tests these systems always perform at start-up. We can see that RacerPro really spends most of its time in this phase. On the other hand, Pellet spends fairly little on consistency checking.

To sum up the results of the LUBM tests we can say that DLog and KAON2 were the only systems able to solve both queries on all LUBM ontologies. Of these two systems DLog emerges as the winner by a small margin. (Although in terms of runtime DLog is much faster.) It is again worth noticing that, as in other cases, the execution times of DLog and KAON2 are very good compared to those of the tableau-based reasoners.

7 Future work

In this section we give a brief overview of future work on the DLog system, for improving its performance as well as extending its capabilities.

Partial evaluation. Recall property (p2) in Definition 1, which states that each DL clause either contains a binary literal or is ground, or it contains no constants and exactly one variable. Note that the body of the latter type of clauses is actually a conjunction of concept goals. It is because of such clauses that the ancestor list can be non-ground.

One can apply partial evaluation techniques, such as in Venken (1984), to unfold clauses containing no binary literals. Such unfolding should be continued until each clause contains either a binary literal or a unary literal corresponding to an ABox predicate. Both these types of literals ensure that all their arguments are ground upon exit. This means that we no longer need to cater to the execution of unary predicates with uninstantiated arguments (except for the outermost query predicate). Also, the ancestor list becomes ground, which simplifies hashing. The absence of logic variables in the data structures opens up the possibility of compiling into Mercury code, rather than Prolog, which is expected to execute much faster than standard Prolog. Some initial results on work in this direction are reported in Lukácsy *et al.* (2008).

Tabling in the presence of ancestors. It is often the case that the same goal is invoked several times during query execution. Tabling (Warren 2007) can be used to prevent unnecessary execution of such goals. Note, however, that unary goals in DLog have an additional ancestor list argument. In most cases this additional argument differs from call to call, making traditional tabling techniques useless. Therefore it looks worthwhile to develop special tabling methods for DLog execution, which keep track of those ancestors that are actually required for the successful completion of a given goal invocation. This is expected to improve the execution of queries on knowledge bases heavily relying on ancestor resolution, such as the `Alcoholic` example of Section 5.2.

Relaxing the UNA. Allowing different individual names to denote the same individual is very important, as web-based reasoning requires exactly this. However, dismissing the UNA has serious implications on the transformation process.

First, the definition of the DL program (Section 3.5) has to be modified: we can no longer omit the contrapositives with an equality or an inequality in the head. Such clauses will become parts of the two Prolog predicates for inferring the equality and inequality of individuals. The inequality predicate has to be further extended with some generic code, as explained in Section 3.1, which has to read the whole ABox. This, however, goes against the main idea of the work presented here: focusing on a small part of the ABox during query execution.

A possible compromise is to support a user-defined equality relation. This would mean that the user can specify an equality relation for individual names. The transitive–symmetric–reflexive closure of this relation is then used as the equality, while the complement of the latter becomes the inequality relation. In this case

we can retain the transformation process, changing only the code generated for the invocations of equality and inequality relations. However, a user-defined equality can be inconsistent with the rest of the knowledge base: e.g. while the user specifies that $i_1 = i_2$, the ABox can contain assertions $C(i_1)$ and $\neg C(i_2)$. Therefore this approach needs further investigation.

Other improvements. As explained in Section 5.1, presently we apply a simple query-ordering technique for execution of conjunctive queries. This can be improved using the techniques of Motik (2006). Furthermore, we presently do not use statistical information in query ordering. Techniques relying on statistical data are well researched in the context of databases. The use of such techniques in DLog should be investigated, as these can result in significant increase of execution performance.

The transformation scheme for role predicates, discussed in Section 4.9, can be made more efficient by e.g. removing redundant role axioms.

We also plan the extension of the external interfaces of DLog to support new input formats, in addition to the DIG standard. We presently have an experimental interface to support database queries. Further work is needed to implement general interfaces to database systems, including optimisations such as passing appropriate conjunctive queries to database management systems, instead of single queries.

8 Summary and conclusions

In this paper we have presented the DL reasoning system DLog. Unlike the traditional tableau-based approach, DLog determines the instances of a given $\mathcal{SHIQ}$ concept by transforming the knowledge base into a Prolog program. This technique allows us to use top-down query execution and to store the content of the ABox externally in a database, something which is essential when large amounts of data are involved.

We have compared DLog with the best available ABox reasoning systems. The test results show that DLog is significantly faster than traditional tableau-based reasoning systems in all our benchmarks. In most of the cases DLog also outperforms KAON2, which uses a resolution-based approach similar to DLog.

We note that trends and behaviours of the various algorithms on certain inputs can be more interesting than the actual runtimes (as the latter can be very much affected by specific implementation details). Considering also this, we argue that DLog and KAON2 are much better suited for large data sets than tableau-based reasoners.

As an overall conclusion, we believe that our results are very promising and clearly show that DL reasoning is an interesting application field for Prolog and logic programming.

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