On the construction of Dialectical Databases*

M. Capobianco, Carlos I. Chesñevar, Guillermo R. Simari

Laboratorio de Investigación y Desarrollo en Inteligencia Artificial
Departamento de Ciencias e Ingeniería de la Computación
Universidad Nacional del Sur
Bahía Blanca - Buenos Aires - ARGENTINA
{mc, cic, grs}@cs.uns.edu.ar

Abstract

Argumentation systems have substantially evolved in the past few years, resulting in adequate tools to model some forms of common sense reasoning. This has sprung a new set of argument-based applications in diverse areas.

In previous work, we defined how to use precompiled knowledge to obtain significant speed-ups in the inference process of an argument-based system. This development is based on a logic programming system with an argumentation-driven inference engine, called Observation Based Defeasible Logic Programming (ODeLP). In this setting was first presented the concept of *dialectical databases*, that is, data structures for storing precompiled knowledge. These structures provide precompiled information about inferences and can be used to speed up the inference process, as TMS do in general problem solvers.

In this work, we present detailed algorithms for the creation of dialectical databases in ODeLP and analyze these algorithms in terms of their computational complexity.

Keywords: Non-monotonic reasoning, Argumentation, Computational complexity.

1 Introduction

Argumentation systems have substantially evolved in the past few years, resulting in adequate tools to model some forms of common sense reasoning. This has sprung a new set of argument-based applications in diverse areas, where knowledge representation issues play a major role, such as clustering algorithms [17], intelligent web search [6] and critiquing systems [5].

In previous work [3], we defined how to use precompiled knowledge to obtain significant speed-ups in the inference process of an argument-based system. The development is based on a logic programming system that uses an argumentation driven inference engine, called Observation Based Defeasible Logic Programming (ODeLP). Logic programming approaches to argumentation [7, 21] have proved to be suitable formalization tools in different application domains as they combine the powerful features provided by logic programming for knowledge representation together with the ability to model complex, argument-based inference procedures in unified, integrated frameworks.

In these models, real time issues play a particu-

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larly important role when modeling most applications, specially those concerning interactive systems. In argument-based approaches a timely interaction is especially hard to achieve, as the inference process involved is complex and computationally expensive. To achieve this kind of interaction we proposed the use of precompiled knowledge for argumentation systems, in the same way *truth maintenance systems* (TMS) [12] use precompiled knowledge to improve the performance of problem solvers.

To implement this idea we defined in [3] the concept of *dialectical databases*. These are data structures that store precompiled knowledge, providing precompiled information about inferences that can be used to speed up the inference process, as TMS do in general problem solvers. We discussed the main issues of the integration of dialectical databases in ODeLP, such as defining the theoretical background and modifying the inference process to take advantage of the new component.

In this work, we present detailed algorithms for the creation of dialectical databases in ODeLP. Then, we analyze these algorithms in terms of their computational complexity. The remainder of this paper is organized as follows. First, we present a brief overview of the ODeLP system. Next, we detail the rol of dialectical databases as structures of precompiled knowledge to assist inference, and finally we formulate and analyze the algorithms for dialectical databases creation in ODeLP.

2 Related Work

Before addressing the contributions of our work, we present a brief overview of related work in the fields of precompiled knowledge. In *truth maintenance systems* (TMS) the use of precompiled knowledge helps improve the performance of problem solvers. A similar technique will be used in ODeLP to address real time constrains.

Truth Maintenance Systems (TMS) were defined by Doyle in [12] as support tools for problems solvers. The function of a TMS is to record and maintain the reasons for an agent's beliefs. Doyle describes a series of procedures that determine the current set of beliefs and update it in accord with new incoming reasons. Under this view, *rational thought* is deemed as the process of finding reasons for attitudes [12]. Some attitude (such as belief, desire, etc.) is rational if it is supported by some acceptable explanation.

TMS have two basic data structures: *nodes*, which represent beliefs, and *justifications* which model reasons for the nodes. The TMS believes in a node if it has a justification for the node and believes in the nodes involved in it. Although this may seem circular, there are assumptions (a special type of justifications) which involve no other nodes. Justifications for nodes may be added or retracted, and this accounts for a *truth maintenance procedure* [12], to make any necessary revisions in the set of beliefs. An interesting feature of TMS is the use of a particular type of justifications, called *non-monotonic*, to make tentative guesses. A non-monotonic justification bases an argument for a node not only on current beliefs in certain nodes, but also on lack of beliefs in other nodes. Any node supported by a non-monotonic justification is called an *assumption*.

TMS solve part of the belief revision problem in general problem solvers and provide a mechanism for making non-monotonic assumptions. As Doyle mentions in [12] performance is also significantly improved, even though the overhead required to record justifications for every program belief might seem excessive, we must consider the expense of not keeping these records. When information about derivations is discarded, the same information must be continually re-derived, even when only irrelevant assumptions have changed.

The fundamental actions of a TMS are:

- create a new node, to which the problem solving program using the TMS can attach the statement of a belief.
- add (or retract) a justification for a node, to represent a step of an argument for the belief represented by the node.
- mark a node as a contradiction, to represent the inconsistency of any set of beliefs which enters into an argument for the node.

Every node in the TMS has an associated set of justifications. Each justification represents a different reason for asserting it. The node is believed if and only if at least one of the justifications is *valid*.[1] In this case it is say to be *in* the set of beliefs. Otherwise, the node is *out* of this set. It is important to mark that the distinction between *in* and *out* is not that between *true* and *false*. The former classification refers to current possession of valid reason for belief; while *true* and

[1] see [12] for a precise definition.

```
lion(simba).
lion(mufasa).
puppy(simba).
feline(X) -< lion(X).
climbs_tree(X) -< feline(X).
~climbs_tree(X) -< lion(X).
climbs_tree(X) -< lion(X), puppy(X).
~climbs_tree(X) -< sick(X).
```

Figure 1: An ODeLP program modeling the behavior of a group of lions

false evaluate inferences according to its truth value, independently of any reason.

In the TMS, each potential belief to be used as a hypothesis or a conclusion of an argument must be given its own distinct node. When uncertainty about some inference P exists, nodes for both P and its negation must be provided. Either of these nodes can have or lack well-founded arguments, leading to a four-element belief set (neither P nor $\sim P$ are believed, exactly one is believed, or both are believed). The author details the procedures needed to establish the state of every node, and to update these states in case new justifications or facts are added to the TMS.

Since the appearance of TMS a large body of literature and applications have been developed [10, 11, 13, 19, 14, 2]. The original idea appears not to have been any particular technical mechanism, but the general concept of an independent module for belief maintenance [19].

3 Observation-based DeLP

Defeasible Logic Programming (DeLP) [15] provides a language for knowledge representation and reasoning that uses *defeasible argumentation* to decide between contradictory conclusions through a *dialectical analysis*. Codifying the knowledge base of the agent by means of a DeLP program provides a good trade-off between expressivity and implementability. Extensions of DeLP that integrate possibilistic logic and vague knowledge along with an argument-based framework have also been proposed [8]. Recent research has shown that DeLP provides a suitable framework for building real-world applications (e.g. clustering algorithms [17], intelligent web search [6] and critiquing systems [5]) that deal with incomplete and potentially contradictory information.

In such applications, DeLP is intended to model the behavior of a single intelligent agent in a *static* scenario. DeLP lacks the appropriate mechanisms to represent knowledge in dynamic environments, where agents must be able to perceive the changes in the world and integrate them into its existing beliefs [20]. The ODeLP framework aims at solving this problem by modeling perception as new facts to be added to the agent's knowledge base. Since adding such new facts may result in inconsistencies, an associated updating process is used to solve them.

In what follows, we present a brief reference of the ODeLP language. The interested reader can consult [3] for a more detailed version.

The language of ODeLP is based on the language of logic programming. Standard logic programming concepts (such as signature, variables, functions, etc) are defined in the usual way. Literals are atoms that may be preceded by the symbol "$\sim$" denoting *strict* negation, as in extended logic programming.

ODeLP programs are formed by *observations* and *defeasible rules*. Observations correspond to facts in the context of logic programming, and represent the knowledge an agent has about the world. *Defeasible rules* provide a way of performing tentative reasoning as in other argumentation formalisms [7].

Definition 3.1. An *observation* is a ground literal L representing some fact about the world, obtained through the perception mechanism, that the agent believes to be correct. A *defeasible rule* has the form $L_0 \prec L_1, L_2, \ldots, L_k$, where L_0 is a literal and $L_1, L_2, \ldots, L_k$ is a non-empty finite set of literals.

Definition 3.2. An *ODeLP program* is a pair $\langle \Psi, \Delta \rangle$, where Ψ is a finite set of observations and Δ is a finite set of defeasible rules. In a program $\mathcal{P}$, the set Ψ must be *non-contradictory* ($i.e.$, it is not the case that $Q \in \Psi$ and $\sim Q \in \Psi$, for any literal Q).

Example 3.1. Fig. 1 shows an ODeLP program for modeling the behavior of a group of lions. Observations describe that Mufasa is a lion, and Simba is a puppy lion. The rules establish that felines usually climb trees, lions usually don't. Exceptionally, puppy lions can climb trees. The remaining rule states that seriously sick animals cannot climb trees.

Given an ODeLP program $\mathcal{P}$, a query posed to $\mathcal{P}$ corresponds to a ground literal Q which must be supported by an *argument* [16]. Arguments are built on the basis of a *defeasible derivation* computed by backward chaining applying the usual SLD inference procedure used in logic programming. Observations play the role of facts and defeasible rules function as inference rules. In addition to provide a proof supporting a ground literal, such a proof must be non-contradictory and minimal for being considered as an argument in ODeLP. Formally:

Definition 3.3. *[Defeasible Derivation]*Let $\mathcal{P} = \langle \Psi, \Delta \rangle$ be an ODeLP program and let Q be a ground literal. A finite sequence of ground literals,

$$s = Q_1, Q_2, \ldots, Q_{n-1}, Q$$

is said to be a *defeasible derivation* for Q from $\mathcal{P}$ (abbreviated $\mathcal{P} \mathrel{|\!\sim} Q$) if for every Q_i, $1 \leq i \leq n$, there exists a defeasible rule $r \in \Delta$ and an ground instance t of r, $t = Q_i \prec L_1, \ldots, L_m$, where $L_1, \ldots, L_m$ are ground literals previously occurring in the sequence s.

Definition 3.4. Given a ODeLP program $\mathcal{P}$, an *argument* $\mathcal{A}$ for a ground literal Q, also denoted $\langle \mathcal{A}, Q \rangle$, is a subset of ground instances of the defeasible rules in $\mathcal{P}$ such that: (1) there exists a defeasible derivation for Q from $\Psi \cup \mathcal{A}$, (2) $\Psi \cup \mathcal{A}$ is non-contradictory, and (3) $\mathcal{A}$ is minimal with respect to set inclusion in satisfying (1) and (2).

Given two arguments $\langle \mathcal{A}_1, Q_1 \rangle$ and $\langle \mathcal{A}_2, Q_2 \rangle$, we will say that $\langle \mathcal{A}_1, Q_1 \rangle$ is a *sub-argument* of $\langle \mathcal{A}_2, Q_2 \rangle$ iff $\mathcal{A}_1 \subseteq \mathcal{A}_2$.

To use defeasible rules in arguments we must first obtain their *ground instances*, changing variables for ground terms, so that variables with the same name are replaced for the same term.

As in most argumentation frameworks, arguments in ODeLP can attack each other. This situation is captured by the notion of *counterargument*.

Definition 3.5. An argument $\langle \mathcal{A}_1, Q_1 \rangle$ *counterargues* an argument $\langle \mathcal{A}_2, Q_2 \rangle$ at a literal Q if and only if there is a sub-argument $\langle \mathcal{A}, Q \rangle$ of $\langle \mathcal{A}_2, Q_2 \rangle$ such that Q_1 and Q are complementary literals.

Defeat among arguments is defined combining the counterargument relation and a preference criterion "$\preceq$". An argument $\langle \mathcal{A}_1, Q_1 \rangle$ *defeats* $\langle \mathcal{A}_2, Q_2 \rangle$ if $\langle \mathcal{A}_1, Q_1 \rangle$ is a counterargument of $\langle \mathcal{A}_2, Q_2 \rangle$ at a literal Q and $\langle \mathcal{A}_1, Q_1 \rangle \preceq \langle \mathcal{A}, Q \rangle$ (proper defeater) or $\langle \mathcal{A}_1, Q_1 \rangle$ is unrelated to $\langle \mathcal{A}, Q \rangle$ (*blocking defeater*).

Defeaters are arguments and may in turn be defeated. Thus, a complete dialectical analysis is required to determine which arguments are ultimately accepted. Such analysis results in a tree structure called *dialectical tree*, in which arguments are nodes labeled as undefeated (`U-nodes`) or defeated (`D-nodes`) according to a marking procedure. Formally:

Definition 3.6. The *dialectical tree* for an argument $\langle \mathcal{A}, Q \rangle$, denoted $\mathcal{T}_{\langle \mathcal{A}, Q \rangle}$, is recursively defined as follows:

1. A single node labeled with an argument $\langle \mathcal{A}, Q \rangle$ with no defeaters (proper or blocking) is by itself the dialectical tree for $\langle \mathcal{A}, Q \rangle$.

2. Let $\langle \mathcal{A}_1, Q_1 \rangle, \langle \mathcal{A}_2, Q_2 \rangle, \ldots, \langle \mathcal{A}_n, Q_n \rangle$ be all the defeaters (proper or blocking) for $\langle \mathcal{A}, Q \rangle$. The dialectical tree for $\langle \mathcal{A}, Q \rangle$, $\mathcal{T}_{\langle \mathcal{A}, Q \rangle}$, is obtained by labeling the root node with $\langle \mathcal{A}, Q \rangle$, and making this node the parent of the root nodes for the dialectical trees of $\langle \mathcal{A}_1, Q_1 \rangle, \langle \mathcal{A}_2, Q_2 \rangle, \ldots, \langle \mathcal{A}_n, Q_n \rangle$.

For the marking procedure we start labeling the leaves as `U-nodes`. Then, for any inner node $\langle \mathcal{A}_2, Q_2 \rangle$, it will be marked as `U-node` iff every child of $\langle \mathcal{A}_2, Q_2 \rangle$ is marked as a `D-node`. If $\langle \mathcal{A}_2, Q_2 \rangle$ has at least one child marked as `U-node` then it is marked as a `D-node`.

Dialectical analysis may in some situations give rise to *fallacious argumentation* [16]. In ODeLP, dialectical trees avoid fallacies applying additional constraints when building *argumentation lines* (the different possible paths in a dialectical tree). These constrains also avoid circular argumentation. The resulting kind of trees is called *Acceptable dialectical trees*. The notions that follow have been developed to address these issues.

Definition 3.7. *[Argumentation line]* [9]
Let $\mathcal{P} = \langle \Psi, \Delta \rangle$ be a DLP and let $\langle \mathcal{A}, q \rangle$ be an argument in $\mathcal{P}$. An *argumentation line* starting from $\langle \mathcal{A}, q \rangle$, denoted $\lambda^{\langle \mathcal{A},q \rangle}$ (or simply λ), is a possibly infinite sequence of arguments

$$\lambda^{\langle \mathcal{A},q \rangle} = [\langle \mathcal{A}_0, q_0 \rangle, \langle \mathcal{A}_1, q_1 \rangle, \ldots, \langle \mathcal{A}_n, q_n \rangle, \ldots]$$

satisfying the following conditions:

1. If $\langle \mathcal{A}, q \rangle$ has no defeaters, then $\lambda^{\langle \mathcal{A},q \rangle} = [\langle \mathcal{A}, q \rangle]$.
2. If $\langle \mathcal{A}, q \rangle$ has a defeater $\langle \mathcal{B}, s \rangle$ in $\mathcal{P}$, then $\lambda^{\langle \mathcal{A},q \rangle} = \langle \mathcal{A}, q \rangle \circ \lambda^{\langle \mathcal{B},s \rangle}$.

where the '$\circ$' operator stands for adding $\langle \mathcal{A}, q \rangle$ as the first element of $\lambda^{\langle \mathcal{B},s \rangle}$.

In each argumentation line

$$\lambda^{\langle \mathcal{A},q \rangle} = [\langle \mathcal{A}_0, q_0 \rangle, \langle \mathcal{A}_1, q_1 \rangle, \ldots, \langle \mathcal{A}_n, q_n \rangle, \ldots]$$

the argument $\langle \mathcal{A}_0, q_0 \rangle$ is supporting the main query q_0, and every argument $\langle \mathcal{A}_i, q_i \rangle$ defeats its predecessor $\langle \mathcal{A}_{i-1}, q_{i-1} \rangle$. Thus, for $k \geq 0$, $\langle \mathcal{A}_{2k}, q_{2k} \rangle$ is a supporting argument for q_0 and $\langle \mathcal{A}_{2k+1}, q_{2k+1} \rangle$ is an interfering argument for q_0. In other words, every argument in the line supports q_0 or interferes with it. As a result, an argumentation line can be split in two disjoint sets: λ_S of supporting arguments, and λ_I of interfering arguments.

Using the terms introduced above, the fallacies that arise in ODeLP programs can be classified as follows:

1. An argument $\mathcal{A}_1$ may be introduced in an argumentation line both as an interfering and supporting argument, producing a *contradictory* argumentation line *e.g.*, $\lambda_1 = [\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3, \mathcal{A}_1, \ldots]$.
2. An argument $\mathcal{A}_1$ may appear as a supporting argument for itself. Hence, a *circular* argumentation line is obtained, *e.g.*, $\lambda_2 = [\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3, \mathcal{A}_4, \mathcal{A}_1, \ldots]$.

Argumentation lines as λ_1 and λ_2 should not justify $\mathcal{A}_1$, since they represent flawed reasoning processes. In the first one, the problem arises from accepting $\mathcal{A}_3$ as a defeater of $\mathcal{A}_2$ because $\mathcal{A}_3$ is contradictory with $\mathcal{A}_1$. Since the internal coherence is essential to the dialectical process, an agreement should exists between the supporting (resp. interfering) arguments in an argumentation line. The fact that $\mathcal{A}_3$ and $\mathcal{A}_1$ contradict each other violates this condition. In the second case, the argument $\mathcal{A}_1$ is supporting itself, which is clearly superfluous and repetitive.

These fallacious situations can be generalized to cycles of any length. An even cycle evidences contradictory argumentation, while an odd cycle indicates circular argumentation. To solve these problems, we define the following concepts:

Definition 3.8. Contradictory set of arguments
A set of arguments $S = \bigcup_{i=1}^{n} \{\langle \mathcal{A}_i, q_i \rangle\}$ is *contradictory* with respect to a DLP program $\mathcal{P} = \langle \Psi, \Delta \rangle$ if and only if the set $\Psi \cup \bigcup_{i=1}^{n} \mathcal{A}_i$ allows the derivation of complementary literals.

Definition 3.9. Acceptable argumentation line [9]
Let $\mathcal{P} = \langle \Psi, \Delta \rangle$ be a DLP, and let

$$\lambda = [\langle \mathcal{A}_0, q_0 \rangle, \langle \mathcal{A}_1, q_1 \rangle, \ldots, \langle \mathcal{A}_n, q_n \rangle, \ldots]$$

be an argumentation line in $\mathcal{P}$, such that

$$\lambda' = [\langle \mathcal{A}_0, q_0 \rangle, \langle \mathcal{A}_1, q_1 \rangle, \ldots, \langle \mathcal{A}_k, q_k \rangle, \ldots]$$

is an initial segment of λ. The sequence λ' is an *acceptable argumentation line* in $\mathcal{P}$ if and only if it is the longest initial segment in λ satisfying the following conditions:

1. The sets λ'_S and λ'_I are each non-contradictory sets of arguments with respect to $\mathcal{P}$.
2. No argument $\langle \mathcal{A}_j, q_j \rangle$ in λ' is a sub-argument of an earlier argument $\langle \mathcal{A}_i, q_i \rangle$ of λ' $(i < j)$.
3. There is no subsequence of arguments
$$[\langle \mathcal{A}_{i-1}, q_{i-1} \rangle, \langle \mathcal{A}_i, q_i \rangle, \langle \mathcal{A}_{i+1}, q_{i+1} \rangle]$$
in λ', such that $\langle \mathcal{A}_i, q_i \rangle$, is a blocking defeater for $\langle \mathcal{A}_{i-1}, q_{i-1} \rangle$ and $\langle \mathcal{A}_{i+1}, q_{i+1} \rangle$ and is a blocking defeater for $\langle \mathcal{A}_i, q_i \rangle$.

Lets analyze the rationale for the conditions in definition 3.9. Condition 1 prohibits the use of contradictory information on either side (proponent or opponent). Condition 2 eliminates circular reasoning. Finally, condition 3 enforces the use of an stronger argument to defeat an argument which acts as a blocking defeater. The reason for this policy is a simple one: ODeLP does not use accrual of reasons. Suppose that argumentation lines with two consecutive blocking are allowed and consider the following scenario. An argument $\langle \mathcal{A}, h \rangle$ is blocked by $\langle \mathcal{B}, \sim h \rangle$ who is in turn blocked by $\langle \mathcal{C}, h \rangle$. If there is no more arguments to take into account, $\langle \mathcal{A}, h \rangle$ would be warranted. Nevertheless, the arguments for h are no better than the arguments for $\sim h$, h is warranted because there is more

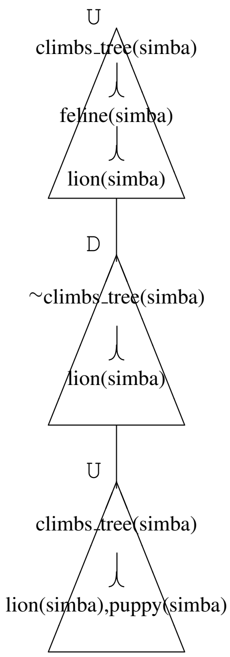

Figure 2: Dialectical tree from Example 3.2

arguments supporting this conclusions. This is clearly accrual of reasons.

Finally, the notion of warrant is grounded on acceptable dialectical trees. Given a query Q and an ODeLP program $\mathcal{P}$, we will say that Q is *warranted* wrt $\mathcal{P}$ iff there exists an argument $\mathcal{T}_{\langle\mathcal{A},Q\rangle}$ such that the root of its associated dialectical tree $\mathcal{T}_{\langle\mathcal{A},Q\rangle}$ is marked as a U-node.

Solving a query Q in ODeLP accounts for trying to find a warrant for Q, as shown in the following example.

Example 3.2. Consider the program shown in Example 3.1, and let `climbs_tree(simba)` be a query wrt that program. The search for a warrant for `climbs_tree(simba)` will result in an argument $\langle\mathcal{A},$ `climbs_tree(simba)`$\rangle$ with one defeater, $\langle\mathcal{B},$ `~climbs_tree(simba)`$\rangle$ that is in turn defeated by $\langle\mathcal{C},$ `climbs_tree(simba)`$\rangle$. The structure of these arguments is detailed in Fig. 2.

Using specificity as the preference criterion, $\langle\mathcal{B},$ `~climbs_tree(simba)`$\rangle$ is proper defeater for $\langle\mathcal{A},$ `climbs_tree(simba)`$\rangle$, but $\mathcal{B}$ is in turn properly defeated by $\langle\mathcal{C},$ `climbs_tree(simba)`$\rangle$. In this case `climbs_tree(simba)` is a warranted fact.

Suppose now we learn that Simba is sick. In ODeLP we can add this fact to the knowledge base using an updating function [3, 18]. Then, a new argument will arise that could not have been built before, $\langle\mathcal{D},$ `~climbs_tree(simba)`$\rangle$ detailed Fig. 3.

Using specificity as the preference criterion, $\langle\mathcal{D},$ `~climbs_tree(simba)`$\rangle$ is a blocking defeater for both $\langle\mathcal{A},$ `climbs_tree(simba)`$\rangle$ and $\langle\mathcal{C},$ `climbs_tree(simba)`$\rangle$. The resulting dialectical tree is shown Fig.3. Now, the marking procedure determines that the root node is a `D-node` and therefore `climbs_tree(simba)` is no longer warranted.

4 Precompiling Knowledge in ODeLP: dialectical databases

The ODeLP language was specifically designed to be integrated in practical applications. Therefore, the inference engine should be able to address real-time constrains that arise in these scenarios. To do this, we use precompiled knowledge to avoid recomputing arguments which were already computed before, in a TMS fashion.

The notion of *dialectical databases* is fundamental for precompiled knowledge in ODeLP. A dialectical database for a given program $\mathcal{P}$ collects a set of schematic arguments, called *potential arguments*, and

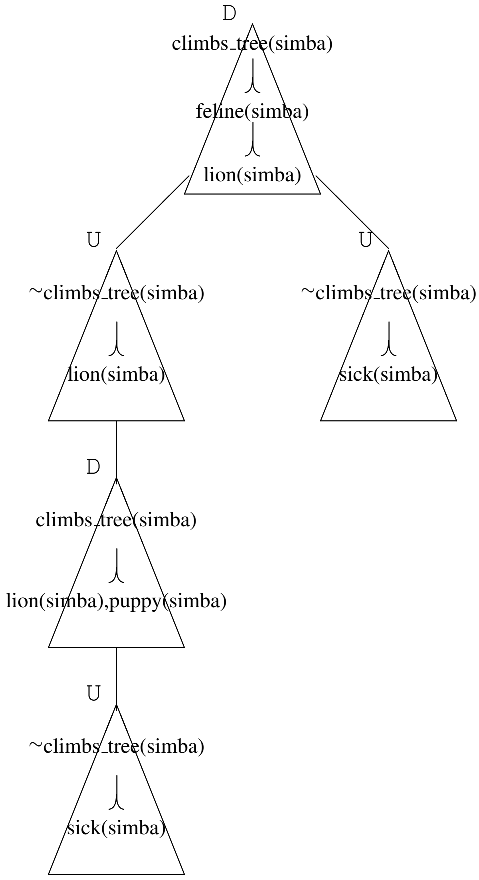

Figure 3: Final dialectical tree from Example 3.2

the defeat relation among them. Every potential argument represents a set of arguments that are obtained using *different* instances of the *same* defeasible rules. This avoids generating and storing many arguments which are structurally identical, only differing in the constant names being used to build the corresponding derivations. The dialectical database is also defined independently from the observation set Ψ, so it does not have to be changed if the set of observations is updated with new perceptions. Next we introduce a set of auxiliary notions that will be used to formally define dialectical databases.

Definition 4.1. Let A be a set of defeasible rules. A set $\mathcal{B}$ formed by ground instances of the defeasible rules in A is an *instance of A* iff every instance of a defeasible rule in $\mathcal{B}$ is an instance of a defeasible rule in A.

Example 4.1. If A ={ `s(X) -≺ ~r(X);` `~r(X) -≺ p(X)`} then $\mathcal{B}$ = { `s(t) -≺ ~r(t);` `~r(a) -≺ p(a)`} is an instance of A.

Definition 4.2. Let Δ be a set of defeasible rules. A subset A of Δ is a *potential argument* for a literal Q, noted as $\langle\langle \mathsf{A}, \mathsf{Q} \rangle\rangle$, if there exists a non-contradictory set of literals Φ and an instance $\mathcal{B}$ of the rules in A such that $\langle \mathcal{B}, Q \rangle$ is an argument wrt $\langle \Phi, \Delta \rangle$.

In the definition above the set Φ stands for a state of the world (set of observations) in which we can obtain the instance $\mathcal{B}$ from the set A of defeasible rules such that $\langle \mathcal{B}, Q \rangle$ is an argument (as stated in Def.3.4). Note that the set Φ must necessarily be non-contradictory to model a coherent scenario.

Precompiled knowledge associated with an ODeLP program $\mathcal{P} = \langle \Psi, \Delta \rangle$ will involve the set of all potential arguments that can be built from $\mathcal{P}$ as well as the defeat relation among them. Then, instead of computing a query for a given ground literal Q, the ODeLP interpreter will search for a potential argument A for Q such that a particular instance $\mathcal{B}$ of A is an argument for Q wrt $\mathcal{P}$.

To speed-up inference, the defeat relations among potential arguments must also be recorded, as we will see later on. To do this, we extend the concepts of counterargument and defeat for potential arguments. A potential argument $\langle\langle \mathsf{A}_1, \mathsf{Q}_1 \rangle\rangle$ *counter-*

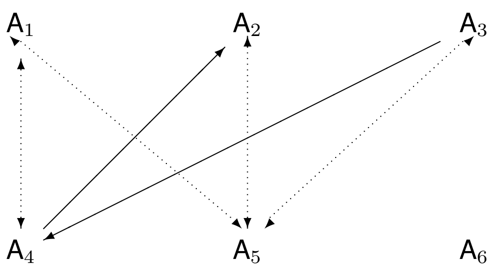

Figure 4: Dialectical database corresponding to Example 4.2.

argues $\langle\langle A_2, Q_2\rangle\rangle$ at a literal Q if and only if there is a potential sub-argument $\langle\langle A, Q\rangle\rangle$ of $\langle\langle A_2, Q_2\rangle\rangle$ such that Q_1 and Q are contradictory literals.[2] Note that potential counter-arguments may or may not result in a real conflict between the instances (arguments) associated with the corresponding potential arguments. In some cases instances of these arguments cannot co-exist in any scenario (*e.g.*, consider two potential arguments based on contradictory observations). The notion of defeat is also extended to potential arguments, redefining the preference criterion accordingly.

Finally, using potential arguments and their associated defeat relation, we can formally define the notion of *dialectical databases* associated with a given ODeLP program $\mathcal{P}$.

Definition 4.3. Let $\mathcal{P} = \langle \Psi, \Delta \rangle$ be an ODeLP program. The *dialectical database* of $\mathcal{P}$, denoted as $\mathcal{DB}_\Delta$, is a 3-tuple $(PotArg(\Delta), D_p, D_b)$ such that:

1. $PotArg(\Delta)$ is the set $\{\langle\langle A_1, Q_1\rangle\rangle, \ldots, \langle\langle A_k, Q_k\rangle\rangle\}$ of all the potential arguments that can be built from Δ.
2. D_p and D_b are relations over the elements of $PotArg(\Delta)$ such that for every $(\langle\langle A_1, Q_1\rangle\rangle, \langle\langle A_2, Q_2\rangle\rangle)$ in D_p (respectively D_b) it holds that $\langle\langle A_2, Q_2\rangle\rangle$ is a proper (respectively blocking) defeater of $\langle\langle A_1, Q_1\rangle\rangle$.

Example 4.2. Consider the program in example 3.1. The dialectical database of $\mathcal{P}$ is composed by the following potential arguments:

- $\langle\langle A_1$, climbs_tree(X) $\rangle\rangle$,
  $A_1 = \{$climbs_tree(X) $\prec$ feline(X)$\}$.
- $\langle\langle A_2$, climbs_tree(X) $\rangle\rangle$,
  $A_2 = \{$climbs_tree(X) $\prec$ feline(X), feline(X) $\prec$ lion(X)$\}$.
- $\langle\langle A_3$, climbs_tree(X) $\rangle\rangle$,
  $A_3 = \{$climbs_tree(X) $\prec$ lion(X), puppy(X)$\}$.
- $\langle\langle A_4$,~climbs_tree(X) $\rangle\rangle$,
  $A_4 = \{$~climbs_tree(X) $\prec$ lion(X)$\}$.
- $\langle\langle A_5$,~climbs_tree(X) $\rangle\rangle$,
  $A_5 = \{$~climbs_tree(X) $\prec$ sick(X)$\}$.
- $\langle\langle A_6$, feline(X) $\rangle\rangle$,
  $A_6 = \{$feline(X) $\prec$ lion(X)$\}$.

and the defeat relations:

- $D_p = \{(A_2, A_4), (A_4, A_3)\}$
- $D_b = \{(A_1, A_4), (A_4, A_1), (A_1, A_5), (A_5, A_1), (A_2, A_5), (A_5, A_2), (A_3, A_5), (A_5, A_3)\}$.

The relations are also depicted in figure , where proper defeat is indicated with a normal arrow and blocking defeat is distinguished with a dotted arrow.

5 Algorithms for building dialectical databases

Given an ODeLP program $\mathcal{P}$, its dialectical database $\mathcal{DB}_\Delta$ can be understood as a graph from which *all* possible dialectical trees computable from $\mathcal{P}$ can be obtained. In previous work [3], it was already addressed how to use precompiled knowledge for computing warrants with respect to a given program. In this section we address how to build this graph for a given set of defeasible rules Δ.

[2]Note that $P(X)$ and $\sim P(X)$ are contradictory literals although they are non-grounded. The same idea is applied to identify contradiction in potential arguments.

To build the dialectical database for a given program we need to obtain every potential argument and record the defeat relation among them. This is done by algorithm BuildDialecticalDatabase. Briefly speaking, it first uses the algorithm ObtainPotentialArgs to select a of candidates that may be potential arguments for the set Δ in the set Candidates. Every member of this set is later analyzed to verify if it complies with the conditions present in definition 4.2. To do that, CreateInstance consistently replaces variables in a given potential argument for a set of literals. Then the argument obtained in $\langle \mathcal{A}, Q_1 \rangle$ must be consistent and minimal (requirements present in definition 4.2) to be finally added in the set of PotArgs.

If the answer is positive, then it is selected as a potential arguments and its defeaters are found using the algorithm FindDefeaters that compares the potential argument to be added into the set with the potential arguments already considered to update the defeat relations D_b and D_p.

Algorithm 1. BuildDialecticalDatabase

input: Δ
output: PArgs, D_p, D_b
//(a dialectical database)

```
PArgs := ∅
ObtainPotentialArgs(Δ, Candidates)
   For every ⟪A,Q⟫ in Candidates
      CreateInstance(⟪A,Q⟫, 𝒜, Q₁)
      Ψ := G(⟨𝒜,Q₁⟩)
      //Calculates the ground for 𝒜, that
      // is the literals in 𝒜 that do not
      // appear in the head of a rule
      If Literals(𝒜) is not contradictory
      and G(𝒜) ∪ 𝒜 |~ Q₁ and
      no 𝒜' ⊂ 𝒜 is such that G(𝒜') ∪ 𝒜' |~ Q₁
      then
         FindDefeaters(PArgs,⟪A,Q⟫,D_p,D_b)
         PArgs := PArgs ∪{⟪A,Q⟫}
```

Next, we analyze the auxiliary algorithms used by BuildDialecticalDatabase. The algorithm ObtainPotentialArgs finds the set of potential arguments using backward chaining from every rule in Δ. This is an smart way to build this set, that results in computational gains with respect to finding all the set of rules that can be obtained from Δ. First, it chooses a rule to guide the backward chaining. Then, it uses the algorithm FindCandidates that recursively considers every potential argument that can be found starting with that rule. This algorithm also marks rules that have been already used to avoid re-computing potential arguments that have been already added into the set of candidates.

Algorithm 2. Obtain Potential Arguments

input: Δ
output: Candidates

```
Candidates := ∅
Marked := ∅
For every rule such that r ∈ Δ and
r ∉ Marked
   FindCandidates(r, NewCand)
   Candidates := Candidates ∪ NewCand
```

Algorithm 3. FindCandidates

input: $r = \alpha \prec \beta$ //uninstanciated rule
output: Cand //candidates found from r

```
Cand := {⟪{α ⤙ β}, α⟫}
For every literal p ∈ β such that
there is a rule with p in the head, p ⤙ γ
      FindCandidates(p ⤙ γ, C)
      For every Cᵢ ⊂ C, Cᵢ <> ∅
         Cand := Cand ∪{⟪{α ⤙ β} ∪ Cᵢ, α⟫}
      Marked := Marked ∪{α ⤙ β}
```

Finally, CreateInstance consistently replaces variables in a given potential argument for a set of literals. It uses backward chaining and composes substitutions to build the instance, if any exists. This algorithm requires defeasible rules in the set A to be standarized apart so that they do not contain common variables. That is, for any pair of rules r_1, r_2 in A it must hold that the intersection between the set of variables in r_1 and the set of variables in r_2 is empty.

Algorithm 4. CreateInstance

input: ⟨⟨A, Q⟩⟩
//a candidate potential argument
output: $\mathcal{A}$, Q_1

```
CreateStack(S)
Instanciate(Q, Q1)
//Sets as goal an instance of Q
push(Q1,S)
θ:= {}
While S is not empty
   goal := pop(S)
   If there exists a rule r in A and
   a substitution σ
   such that head(r)σ = goal
   then
      new_body := apply σ body(r)
      θ := compose θ and σ
      push(new_body,S)
   else
      r := pop(S)
      If there exists a substitution σ
      and an observation α
      such that rσ = α
      then θ := compose θ and σ
      else fail
      //It is not possible to find
      //an instance
𝒜 := apply θ to every rule in A
```

5.1 Complexity results

In this section we analyze the complexity of algorithm BuildDialecticalDatabase since this algorithm resumes the construction process of ODeLP's precompiled knowledge.

To do this, we first consider the complexity of auxiliary algorithms. Note that the analysis presented here holds for ODeLP programs with a finite Herbrand base. We plan to extend this analysis in future work to full ODeLP programs.

CreateInstance consistently replaces variables in a given potential argument for a set of literals. This task is analogous to the following decision problem: *is a given subset of defeasible rules an argument for a literal from a given program P?*. In [4] this is shown to be a **P**-complete problem for the DeLP system. This result is an upper bound for ODeLP, where there is no strict knowledge and thus complexity is clearly reduced.

ObtainPotentialArguments returns every set of rules that may be a potential argument for Δ. A rough upper bound for the number of potential arguments is $2^{|\Delta|}$. Therefore, Obtain potential arguments is in $O(2^{|\Delta|})$.

Algorithm FindDefeaters must compare the potential argument to be added with every potential argument that is already in the set `PArgs`. This is also in $O(2^{|\Delta|})$.

Finally, we analyze algorithm BuildDialecticalDatabase. It first calls ObtainPotentialArguments. Then, for every argument in the set `Candidates`, it does following four tasks:

1. Calls algorithm CreateInstance.
2. Checks consistency: this check depends on the number of literals in the argument, that can be bounded by the number of literals in the signature of the program, noted by $|Lit|$. Thus, this task is in P.
3. Checks minimality: a simple algorithm for verifying whether a set of defeasible rules is minimal with respect to set inclusion (for entailing a given literal l) would delete every rule at a time and verify if the remaining set of rules can entail l. Worst case of the minimality condition is considered when we assume that the argument has $|\Delta|$ defeasible rules. In this case computing minimality condition takes $|\Delta|$ to verify that l cannot be entailed for a subset of the rules in the potential argument. Then every loop is in P and the problem of checking minimality is solvable in polynomial time.
4. Calls algorithm FindDefeaters.

Therefore the cost of the loop is in $O(2^{|\Delta|})$ and the number of times it is executed is bounded by $2^{|\Delta|}$. Then algorithm BuildDialecticalDatabase is in Σ_p^2, that is, the second level of the polynomial hierarchy.[3]

6 Conclusions and future work

The notion of dialectical databases was proposed in [3] to comply with real time requirements needed to model agent reasoning in dynamic environments. In

[3] The interested reader may consult [1] for more information on the polynomial hierarchy.

this paper we have devised a set of algorithms for the construction of the precompiled knowledge component in ODeLP.

We have also analyzed the complexity of these algorithms from a theoretical standpoint. Even though the algorithms are computationally expensive we must recall that the task of building precompiled knowledge is performed only once, after codifying the program. Moreover, the dialectical database is not affected by changes in the program's observations and the set of rules is not expected to change in applications using ODeLP.

As future work, we will analyze how the use of precompiled knowledge in the inference process reduces complexity in ODeLP. We also plan to extend the complexity analysis, currently valid for programs with a finite Herbrand base, to full ODeLP programs.

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