Rule-Based Agents in Temporalised Defeasible Logic

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Abstract. This paper provides a framework based on temporal defeasible logic to reason about deliberative rule-based cognitive agents. Compared to previous works in this area our framework has the advantage that it can reason about temporal rules. We show that for rule-based cognitive agents deliberation is more than just deriving conclusions in terms of their mental components. Our paper is an extension of [5,6] in the area of cognitive agent programming.

1 Introduction

There are two main trends in the agent literature for programming cognitive agents in a BDI (*belief, desire, intention*) framework. The first one is *system-based* wherein the main idea is to develop a formal specification language that provides an explicit representation of states and operations on states that underly any BDI implementation [14,13,1]. In this approach the main idea is to formalise the operational semantics of the implemented system. The second one can be termed *rule-based* where rules are used to represent or manipulate an agent's mental attitudes, i.e., an agent consists of a belief base, goal (desire) base, and intention base specified by logic formulas in the form of rules [7,3,4,8,15]. In addition to the three mental attitudes of beliefs, desires and intentions, the works above also include obligations, which are used to denote norms and commitments of social agents and social rationality. There are also works which club these two approaches like in [12]. Here we adopt the rule-based approach of [5,6] and extend it to accommodate temporal defeasible rules.

The main question we try to answer in this paper is: *What does it mean to deliberate for rule/policy-based agents?* (By policy we mean a set of rules.) Of particular concern to us is the reasoning process involved in the deliberation of a rule-based agent wherein the *agent can take a decision at t about what he/she has to do at t' based on her beliefs and policies at t*. In such a set up if no *relevant* event occurs then she can retain her deliberation at t'. Consider the following rule

$$p : t_p, \mathrm{OBL}\ q : t_q \Rightarrow (\mathrm{OBL}\ p : t_p \Rightarrow_{\mathrm{OBL}} s : t_s) : t_r \tag{1}$$

whose reading is if p is true at time t_p and q is obligatory at time t_q, then the deontic rule $\mathrm{OBL}\ p : t_p \Rightarrow_{\mathrm{OBL}} s : t_s$ is in force at time t_r. In this work we develop a formal machinery

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to reason about rules like (1). In general we want to accommodate in our framework rules of the type $(a : t \Rightarrow b : t' : t'')$ where t and t' indicate the time at which a and b hold, while t'' is the time of the rule being in force. To incorporate this simple temporal reasoning we have to express whether events and states are permanent or immanent. If we use non-monotonic rules as in some of the works above then deliberation means reasoning about how to derive conclusions in terms of intentions/goals/plans, i.e., just deriving conclusions from a theory. Though [4] proposes a deliberation language, it considers only snapshots of the deliberation process in the sense that the deliberation program is dependent on the agent's current state (one cycle). Put in Bratman's terms *to reason about intentions/goals/plans at t and decide for t*. A complete solution would require the addition of a temporal variable to allow reasoning about the deliberation process after each time round [9].

A formal framework like the one developed in this paper is useful in the domain of legal information systems to reason about normative conditionals [11,10]. Another domain wherein the framework could be useful is with regard to policy-based rationality as outlined by Bratman [2] in his pursuit for a *temporally extended rational agency*. The principle can be roughly stated as follows:

- At t_0 agent A deliberates about what policy to adopt concerning a certain range of activities. On the basis of this deliberation agent A forms a general intention to φ in circumstances of type ψ.
- From t_0 to t_1 A retains this general intention.
- At t_1 A notes that he/she will be (is) in circumstance ψ at t_2, where $t_2 \geq t_1$.
- Based on the previous steps A forms the intention at t_1 to φ at t_2.

Notice that Bratman is concerned only with policy-based intentions[3] and does not provide any formal framework to show the working aspect of his historical principle. In our model we have temporal rules for beliefs, desires, intentions and obligations as in (1) and a machinery based on defeasible logic (DL) to reason about such temporal rules.

Given the temporal nature of Bratman's historical principle, and the idea that some intentions can be retained from one moment to another, we must then account for two types of temporal deliberations: transient deliberations, which hold only for an instant of time, and persistent deliberations, in which an agent is going to retain them unless some intervening event that forces the agent to reconsider her deliberation occurs. This event can be just a brute fact or it can be a modification of the policy of the agent. Thus an agent must be able to cope with changes of the environment but also of her policies.

Let us consider the following scenario. Our agent (Guido) has sent a paper to the PRICAI-06 conference, and he has the intention to attend the conference to present the paper if accepted. Guido's school policy for funding is that if somebody intends to travel then she has to submit the request for travel funds two weeks (15 days) before the actual travel. This scenario can be represented as follows:

$$r_1\ (\mathit{PRICAIpaperAccepted} : t_1 \Rightarrow_{\mathrm{INT}} \mathit{Travel} : t_2) : t_0 \tag{2}$$

$$r_2\ (\mathrm{INT}\ \mathit{Travel} : t_X \Rightarrow_{\mathrm{OBL}} \mathit{Request} : t_{X-15}) : t_0 \tag{3}$$

[3] In [2] historical principles for deliberative as well as non-deliberative intentions is outlined. Here we are concerned only with the policy-based aspect.

Rule r_1 states that Guido will form the intention to travel to PRICAI at a certain time in case the paper is accepted and that the rule is in force from t_0 (let us say that t_0 is the time when the paper is submitted to the conference), and r_2 encodes Guido's school travel policy (the policy is in force at time t_0). Suppose that Guido, at time t_1, receives the notification that the paper has been accepted, then at that time he forms the intention to travel to PRICAI at time t_2. This triggers his obligation to have the travel request submitted two weeks before the date of the conference. Accordingly, he plans to prepare the required paperwork in due time.

Time passes and two important events happen: the School updates the travel policy and Guido is appointed to a *research-only* position. The changes to the travel policy concerns research-only staff and the actual change is that, due to the new accounting software travel funds could be made available in less than one week. Thus the rule encoding the update to the policy is

$$r_3\ (\mathit{Research} : t_Y \Rightarrow (\mathrm{INT}\ \mathit{Travel} : t_X \Rightarrow_{\mathrm{OBL}} \mathit{Request} : t_{X-7}) : t_4) : t_3$$

Here t_3 is when the new policy has been issued and t_4 is the time the new policy will be effective. Based on the updated policy and the new event, Guido complies with the new obligation if he submit the application for funds one week before travelling. Accordingly, he can change his plans and can postpone to fill all forms to a later time.

2 Temporalised DL for Cognitive Agents

We focus on how mental attitudes and obligations jointly interplay in modelling agent's deliberation and behaviour. Such an interplay is modelled within a temporal setting. The logical framework is based on DL, which is a simple and flexible sceptical non-monotonic formalism that has proven able to represent various aspects of non-monotonic reasoning. We extend here the machinery developed in [11,6,5] to represent temporalised motivational attitudes of agents.

The basic language is based on a (numerable) set of atomic propositions $\mathit{Prop} = \{p, q, \dots\}$, a set of rule labels $\{r_1, r_2, \dots\}$, a discrete totally ordered set of instants of time $\mathscr{T} = \{t_1, t_2, \dots\}$, a set of modal operators $M = \{\mathrm{BEL}, \mathrm{DES}, \mathrm{INT}, \mathrm{OBL}\}$ (belief, desire, intention, and obligation, respectively), and the negation sign $\neg$. A plain literal is either an atomic proposition or the negation of it. If l is a plain literal then, for any $X \in M$, Xl and $\neg Xl$ are modal literals. A literal is either a plain literal or a modal literal. Given a literal l, $\sim l$ denotes the complement of l, that is, if l is a positive literal p then $\sim l = \neg p$, and if $l = \neg p$ then $\sim l = p$. A temporal literal is a pair $l : t$ where l is a literal and $t \in \mathscr{T}$. Intuitively, a temporal literal $l : t$ means that l holds at time t.

Knowledge in DL can be represented in two ways: facts and rules. *Facts* are indisputable statements, represented in the form of literal and modal literals. For example, "John is a minor". In the logic, this might be expressed as $\mathit{Minor}(\mathit{John})$. A *rule* is a relation (represented by an arrow) between a set of premises (conditions of applicability of the rule) and a conclusion. In this paper, conclusions usually correspond to literals, but for a special class of rules they can also be rules themselves; in addition all the conclusions and the premises will be qualified with the time when they hold. We consider four classes of rules: rules for belief, desire, intention and obligation. Each class of rules is qualified by labelling the arrow with any $X \in M$ (for belief, desire, intention, and obligation). If $X \in \{\text{DES}, \text{INT}, \text{OBL}\}$, applicability of the corresponding rules permits to derive only literals: more precisely, if the consequent of such rules is a literal $l : t$, then their applicability leads to obtain the modal literal $Xl : t$. For any consequent $l : t$ obtained through rules for $X \in \{\text{DES}, \text{INT}, \text{OBL}\}$, $l : t$ is called a temporal goal. Rules for belief play a special role. They constitute the basic inference mechanism of an agent, as they concern the knowledge an agent has about the world. For this reason, their conclusions, if obtained, are not modalised; on the other hand this is the only class of rules for which conclusions can be also rules (rules for $X \in M$).

Besides the above classification, rules can be partitioned according to their strength into *strict rules* (denoted by $\rightarrow$), *defeasible rules* (denoted by $\Rightarrow$) and defeaters (denoted by $\rightsquigarrow$). Strict rules are rules in the classical sense: they are monotonic and whenever the premises are indisputable so is the conclusion. Defeasible rules, on the other hand, are non-monotonic: they can be defeated by contrary evidence. Defeaters are the weakest rules: they do not support directly conclusions, but can be used to block the derivation of opposite conclusions. Henceforth we use $\hookrightarrow$ as a metavariable for either $\rightarrow$ when the rule is a strict rule, $\Rightarrow$ when the rule is a defeasible rule, and $\rightsquigarrow$ when the rule is a defeater. Thus we define the set of rule, Rules, using the following recursive definition:

- a rule is either a rule for X, $X \in M$ or the empty rule $\perp$
- If r is a rule and $t \in \mathscr{T}$, then $r : t$ is a temporalised rule. (The meaning of a temporalised rule is that the rule is valid at time t.)
- Let A be a finite set of temporal literals, C be a temporal literal and r a temporalised rule, then $A \hookrightarrow_X C$, $A \hookrightarrow_X r$ are rules for $X = \text{BEL}$.
- Let A be a finite set of temporal literals and C be a temporal plain literal. Then $A \hookrightarrow_X C$ is a rule for $X \in \{\text{DES}, \text{INT}, \text{OBL}\}$.

For a rule r labelled with any $X \in M$ we will use $A(r)$ to indicate the body or antecedent of the rule and $C(r)$ for the head or consequent of the rule. It is also possible to have nested rules i.e., rules occurring inside rules for beliefs. However, it is not possible for a rule to occur inside itself. Thus for example, the following is a rule

$$p : t_p, \text{OBL}q : t_q \Rightarrow_{\text{BEL}} (\text{OBL}p : t_p \Rightarrow_{\text{INT}} s : t_s) : t_r \tag{4}$$

(4) means that if p is true at time t_p and q is obligatory at time t_q, then the intention rule $\text{OBL}p : t_p \Rightarrow_{\text{INT}} s : t_s$ is valid at time t_r. Every temporalised rule is identified by its rule label and its time. Formally we can express this relationship by establishing that every rule label r is a function $r : \mathscr{T} \mapsto \text{Rules}$. Thus a temporalised rule $r : t$ returns the value/content of the rule 'r' at time t. This construction allows us to uniquely identify rules by their labels, and to replace rules by their labels when rules occur inside other rules. In addition there is no risk that a rule includes its label in itself. For example if we associate the temporal rule $(\text{OBL}p : t_p \Rightarrow_{INT} s : t_s) : t_r$ to the pair $r_1 : t_r$, we can concisely rewrite (4) as

$$p : t_p, \text{OBL}q : t_q \Rightarrow_{\text{BEL}} r_1 : t_r \tag{5}$$

It should be noted that we have to consider two temporal dimensions for rules. The first regards the efficacy (effectiveness) of a rule i.e., the capacity of a rule to produce a desired effect at a certain time point, and the second shows when the rule is valid/comes into force. Consider the following two rules about a hypothetical tax regulation:

$$r_1 : (\mathit{Income} > 90K : 1\mathit{Mar} \Rightarrow_{\mathrm{OBL}} \mathit{Tax10} : 1\mathit{Jan}) : 1\mathit{Jan} : 15\mathit{Jan} \tag{6}$$

$$r_2 : (\mathit{Income} > 100K : 1\mathit{Mar} \Rightarrow_{\mathrm{OBL}} \mathit{Tax40} : 1\mathit{Jan}) : 1\mathit{Apr} : 1\mathit{Feb} \tag{7}$$

Rule r_1 states that if the income of a person is in excess of ninety thousand as of 1st March ($\mathit{Income} > 90K : 1\mathit{Mar}$) then he/she is obliged to pay the top marginal tax rate of 10 percent from 1st January ($\mathit{Tax10} : 1\mathit{Jan}$) with the policy being in force from 15 January, and effective from 1st January. This means that the norm becomes part of the tax regulation from 15 January, but it is effective from 1st January. Accordingly, the policy covers tax returns lodged after 15 January as well as all tax returns lodged before the validity of the policy itself. The second rule, valid (i.e., part of the tax regulation) from 1st February, establishes a top marginal tax rate of 40% for tax returns lodged after the effectiveness date of 1st April.

The above two rules illustrate the difference between the *effectiveness* and *validity* of a rule. In order to differentiate between the effectiveness and validity of a rule we introduce the notion of *temporalised rule with viewpoint* and 15 Jan in r_1 denotes exactly this. A conclusion or a temporalised rule with viewpoint is an expression $s@t$, where $t \in \mathscr{T}$, meaning that s "holds" when the agent reasons using the information available to her at t. Thus the expression $r_1 : t_1@t_2$ represents a rule r_1 valid at time t_2 and effective at time t_1. In the case of (6) this could be given as $s@16\mathit{Jan}$ where s is $(\mathit{Income} > 90K : 1\mathit{Mar} \Rightarrow_{\mathrm{OBL}} \mathit{Tax10} : 1\mathit{Jan}) : 1\mathit{Jan}$ and $t = 16\mathit{Jan}$. Thus for an agent intending to lodge a tax return on 16 Jan, there are no alternatives. She has to pay her taxes at the top marginal rate of 10%. However, should she postpone the decision after 1 February, then she has the option to evaluate when and how much tax she has to pay (10% if the tax return is lodged before 1 April and 40% if lodged afterward). Therefore she can plan her actions in order to achieve the most suitable result according to her goals. Hence, an agent equipped with such temporal rules should be able to figure out plans that are applicable at a particular time point. Temporal rules like (7) are more interesting, as they allow the agent to plan using rules having reference to past as well as future time points. We discuss more about *temporalised rule with viewpoint* in section 4. In addition the example shows that in general, unlike other approaches, there is no need to impose constraints on the time instants involved in a rule.

Another issue we need to consider here is that we have two different types of conditionals to derive beliefs and goals (i.e., rules labelled with $X \in M$): conditionals that initiate a state of affairs which persists until an interrupting event occurs, and conditionals where the conclusion is co-occurrent with the premises. To represent this distinction we introduce a further distinction of rules, orthogonal to the previous one, where rules are partitioned in persistent and transient rules. A persistent rule is a rule whose conclusion holds at all instants of time after the conclusion has been derived, unless interrupting events occur; transient rules, on the other hand, establish the conclusion only for a specific instant of time. We use the following notation to differentiate the various types of rules: with $\hookrightarrow^t_X$ we represent a transient rule for X, and with $\hookrightarrow^p_X$ a persistent rule.

Given a set R of rules, we denote the set of strict rules in R by R_s, the set of strict and defeasible rules in R by R_{sd}, the set of defeasible rules in R by R_d, and the set of defeaters in R by R_{dft}. $R[q:t]$ denotes the set of rules in R with consequent $q:t$. We use R^X for the set of rules for $X \in M$. The set of transient rules is denoted by R^{tr} and the set of persistent rules by R^{per}. Finally we assume a set of rule modifiers. A rule modifier is a function $m : \text{Rules} \times \mathscr{T} \mapsto \text{Rules} \times \mathscr{T}$.

The above constructions allow us to use rule modifiers on rule labels. Thus $m(r_1 : t_1) : t_2$ returns the rule obtained from r_1 as such at time t_1 after the application of the modification corresponding to the function m and the result refers to the content of the rule at time t_2. Given this basic notion of rule modifier, we can define some functional predicates, i.e. specific rule-modifications. For the sake of brevity, we omit the technical details on how to adapt the basic definition of rule modifier to cover these specific rule modifications: Delete, Update and Add. As we shall see, these functional predicates can only occur in the head of belief rules. For the moment let us see their intuitive reading. The functional predicate $\text{Delete}(r) : t'$ says that a given rule r is deleted at t'. More precisely, $\text{Delete}(r) : t'$ assigns the empty rule $r : (\perp) : t'$ to r as holding at t. The rule r is thus dropped at t' from the system and so, at t', r is no longer valid. If r is a rule for $X \in \{\text{DES}, \text{INT}, \text{OBL}\}$, let $\mathscr{A}$ and $\mathscr{C}$ be a set of temporal literals and a temporal plain literal respectively; if r is a rule for belief, let $\mathscr{A}$ be defined as before, while $\mathscr{C}$ is a temporal plain literal or a temporalised rule. Then

$$\text{Update}(r, \mathscr{A}) : t' \qquad \text{Update}(r, \mathscr{C}) : t'$$

say that we operate, at t' an update of r which replaces a subset or all components in the antecedent of r with other appropriate components and the consequent with a new appropriate element of the language. The new version of r will hold at t'. Similarly

$$\text{Add}(r', A(r'), C(r')) : t'$$

indicates that a new rule r' is added at t' to the system, and that r' has the antecedent and consequent specified by $A(r')$ and $C(r')$.

3 Conflicts between Rule Modifications

Table 1 summarises the basic conflicts between rule modifications. Notice that conflicts

Modifications		Conditions
$\text{Delete}(r) : t'$	$\text{Update}(r, \mathscr{A}) : t''$	$t' = t''$
$\text{Delete}(r) : t'$	$\text{Update}(r, \mathscr{C}) : t''$	$t' = t''$
$\text{Delete}(r) : t'$	$\text{Add}(r, A(r), C(r)) : t''$	$t' = t''$

Table 1. Conflicts

obtain only if the conflicting modifications apply to the same time instant. Deleting a rule r is incompatible with any update of r (first and second rows from the top). This is the only case of real conflict. In fact, the third row from the top considers a "residual" but in theory possible conflict between modifications, namely, between those of deleting and adding at the same time a rule r. This case is marginal essentially because adding a rule r usually means that r is not valid in the theory. However, nothing prevents to add a rule r which is already valid in the system. In this case, the operation is redundant, but, if performed together with deleting r, we have indeed a conflict between modifications.

4 Temporalised Rule with View Point

In [11] we showed how to derive temporal literals in a DL framework. But this is of limited use and what we need is a way to derive temporal rules. In this section we extend the framework developed in [11,6,5] with *temporal rules with a view point*. What this means is that we can reason about temporal rules that are valid at a particular instant of time. Suppose that we have a defeasible theory $D = (\mathscr{T}, F, R, \prec)$ where $\mathscr{T}$ is discrete totally ordered set of instants of time, F is a finite set of temporalised literals, R a finite set of rules (comprising strict, defeasible and defeater rules) and $\prec$ a ternary relation (superiority relation) over $R \times R \times \mathscr{T}$, meaning that one rule is stronger than another rule at a particualr time; for example $r_1 \prec_t r_2$ means that rule r_2 is stronger than rule r_1 at time t. Conclusions in DL can have one of the following four forms (where X ranges over M):

$+\Delta_X @t\ q : t'$ meaning that q is definitely provable with mode X, at time t' with viewpoint t, in D (i.e., using only facts and strict rules).

$-\Delta_X @t\ q : t'$ meaning that we have proved that q is not definitely provable with mode X, at time t' with viewpoint t, in D.

$+\partial_X @t\ q : t'$ meaning that q is defeasibly provable with mode X, at time t' with viewpoint t, in D

$-\partial_X @t\ q : t'$ meaning that we have proved that q is not defeasibly provable with mode X, at time t' with viewpoint t, in D.

For example, $+\partial_{\mathrm{OBL}} @t_1\ q : t_0$ means that we have a defeasible proof for OBLq at t_0, or, in other words, that OBLq holds at time t_0 when we use the rules in force in the system at time t_1. However, these tags do not take care whether a conclusion $q : t$ is obtained via transient rules (that is, q holds only at time t_0) or via persistent rules, in such a case for every t' such that $t_0 < t'$, the property q persists at time t', unless we have other evidence on the contrary, i.e., a piece of evidence that terminates the property q. To reflect these issues, we introduce auxiliary proof tags for persistent and transient conclusions. Formally, $+\Delta_X @t\ p$ means that either $+\Delta_X^{tr} @t\ p$ or $+\Delta_X^{pr} @t\ p$, i.e., either p is transient at t or it is persistent at t; $-\Delta_X @t\ p$ means both $-\Delta_X^{tr} @t\ p$ or $-\Delta_X^{pr} @t\ p$, i.e., it is not true that p is transient at t and that p is not persistent at t.

The proof tags are labelled with the mode used to derive the rule, according to their appropriate proof conditions. It is not possible to give the complete set of proof conditions in this paper. Here we concentrate only on the proof conditions to derive defeasible persistence of both rules with belief mode, and literals. The proof conditions given here are extensions of those given in [11] for the temporal aspects and can be used for goals and planning as in [6,5]. The proof conditions missing in this paper can be obtained from the corresponding conditions of [11,6,5] using the same intuition on which the proof conditions we are going to show illustrate.

Provability is based on the concept of a *derivation* (or proof) in D. A derivation is a finite sequence $P = (P(1), \dots, P(n))$ of tagged literals satisfying the proof conditions (which correspond to inference rules for each of the kinds of conclusion). $P(1..n)$ denotes the initial part of the sequence P of length n. A strict derivation (i.e., a conclusion tagged with Δ) is a monotonic derivation using forward chaining of rules, i.e., modus ponens. In DL a defeasible derivation, on the other hand, has three phases. In the first phase we propose an argument in favour of the concussion we want to prove. In the simplest case this consists of an applicable rule for the conclusion (a rule is applicable if the antecedent of it has already been proved). Then in the second phase we examine all possible counter-arguments (rules for the opposite conclusion). Finally we have to rebut the counter-arguments. Thus we have to provide evidence against the counter-argument. Accordingly, we can demonstrate that the argument is not as such (i.e., some of its premises are not provable), or we can show that the counter-argument is weaker than an argument for the conclusion.

For persistent conclusions we have another method. We can use a derivation of the conclusion at a previous time provided that no terminating event occurred in between. In [11] the rules are given, but here rules are can also be derived. Thus in the proof conditions we have to cater for this option. Accordingly, we have to give conditions that allows us to derive rules instead of literals. For the sake of simplicity we will assume that all rules in R can be overruled/modified. Then we have to extend the notation $R[x:t]$ to the case where x is a rule label (and rule-modifiers). Given a set of belief rules R and a set of rule modifiers $M = \{m_1, \ldots, m_n\}$, then

$$R[r:t_r] = \{s \in R : A(s) = m_i(v:t_v) \text{ and } m_i(v:t_v) = r:t_r\}$$

$R[r:t_r]$ gives the set of nested rules whose head results in the rule $r:t_r$ after the application of the rule modifier; and

$$R[\sim r:t_r] = \{s \in R : A(s) = m_i(r:t_r) \text{ and } m_i(r:t_r) \text{ is in conflict with } r:t_r\}$$

The set $R[\sim r:t_r]$ gives the set of rules that modify $r:t_r$ and the modification is in conflict with the $r:t_r$, see Table 1 for such conflicts.

We can now give the proof conditions for $+\partial^{pr}$ to derive a rule.

If $P(n+1) = +\partial^{pr}_{\mathrm{BEL}}@t\ r:t_r$ then
1a) $r:t_r@t \in R^{\mathrm{BEL}}$ or
1b) $\exists s:t_s \in R^{\mathrm{BEL}}[r:t_r]$ such that $+\partial_{\mathrm{BEL}}@t\ s:t_s \in P(1..n)$ and
$\forall Y_a a:t' \in A(s), +\partial_{Y_a}@t\ a:t' \in P(1..n)$; and
2) $\forall v:t_v \in R^{\mathrm{BEL}}[\sim r:t_r]$ if $+\partial_{\mathrm{BEL}}@t\ v:t_v \in P(1..n)$, then either
2.1) $\exists Y_b b:t'' \in A(v)$ such that $-\partial_{Y_b}@t\ b:t'' \in P(1..n)$ or
2.2 a) $v:t_v \prec_t r:t_r$ if 1a obtain or b) $v:t_v \prec_t s:t_s$ if 1b obtain; or
3) $+\partial^{pr}_{\mathrm{BEL}}@t'\ r:t_r \in P(1..n)$, $t' < t$ and
3.1) $\forall t'', t' \leq t'' < t, \forall s:t_s \in R[\sim r:t_r]$ if $+\partial_{\mathrm{BEL}}@t''\ s:t_s \in P(1..n)$, then
3.1.1) $\exists Y_a a:t_a \in A(s), -\partial_{Y_a}@t''\ a:t_a \in P(1..n)$ or $t_s < t_r$; and
4) $+\partial^{pr}_{\mathrm{BEL}}@t\ r:t'_r \in P(1..n)$, $t'_r < t_r$ and
4.1) $\forall t', t'_r \leq t'' < t_r, \forall s:t_s \in R[\sim r:t_r]$ if $+\partial_{\mathrm{BEL}}@t'\ s:t_s \in P(1..n)$, then
4.1.1) $\exists Y_a a:t_a \in A(s), -\partial_{Y_a}@t'\ a:t_a \in P(1..n)$ or $t_s < t'_r$.

Let us briefly examine the above proof conditions. To prove a rule at time t, the rule must be in force at time t, i.e., the rule must be one of the given rules (condition 1a). There is a second possibility that the rule is derived from another rule. The second rule must be provable and applicable at t (condition 1b). However, this is not enough since there could have been modifications to the rule effective at t. Thus we have to show that either all eventual modifications were not applicable (2.1) or the modifications were not successful since they were defeated (2.2a and 2.2b). Finally the rule could be provable because it was persistent, i.e., it was persistently in force before (3), and no modification occurred in between. The possible modifications in force after the rule was in force were not applicable to the rule. Or (4) the rule was persistently effective before, and its effectiveness was not revoked.

The conditions for positive persistent defeasible proofs are as follows:

If $P(n+1) = +\partial_X^{pr}@t\ q : t'$ then
1) $+\Delta_X^{pr}@t\ q : t' \in P(1..n)$, or
2) $-\Delta_X@t \sim q : t' \in P(1..n)$, and
  2.1) $\exists r : t_r \in R_{sd}^{X,pr}[q : t']$: $+\partial_{\mathrm{BEL}}@t\ r : t_r \in P(1..n)$, and
    $\forall Y_a a : t_a \in A(r : t_r), +\partial_{Y_a}@t\ a : t_a \in P(1..n)$ and
  2.2) $\forall s : t_s \in R^X[\sim q : t]$: if $+\partial_{\mathrm{BEL}}@t\ s : t_s$, then either
    2.2.1) $\exists Y_a a : t_a \in A(s : t_s), -\partial_{Y_a}@t\ a : t_a \in P(1..n)$; or
    2.2.2) $\exists w : t_w \in R^X[q : t]$: $+\partial_{\mathrm{BEL}}@t\ w : t_w \in P(1,,n)$ and
      $\forall Y_a a \in A(w : t_w), +\partial_{Y_a}@t\ a : t_w \in P(1..n)$ and $w \succ s$; or
3) $\exists t'' \in \mathscr{T}$: $t'' < t$ and $+\partial_X^{pr}@t''\ q : t' \in P(1..m)$ and
  3.1) $\forall t'''\ t'' < t''' \leq t\ \forall s : t_s \in R^X[\sim q : t']$: if $+\partial_{\mathrm{BEL}}@t'''\ s : t_s \in P(1..n)$, then
    3.1.1) $\exists Y_a a : t_a \in A(s : t_s), -\partial_{Y_a}@t'''\ a : t_a \in P(1..n)$ or
    3.1.2) $\exists v : t_v \in R^X[q : t'], +\partial_{\mathrm{BEL}}@t'''\ v : t_v \in P(1..n)$ and
      $\forall Y_b b : t_b \in A(v : t_v) + \partial_{Y_b}@t'''\ b : t_b \in P(1..n)$ and $s : t_s \prec_{t'''} v : t_v$; or
4) $\exists t'' \in \mathscr{T}$: $t'' < t'$ and $+\partial_X^{pr}@t\ q : t'' \in P(1..m)$ and
  4.1) $\forall t'''\ t'' < t''' \leq t'\ \forall s : t_s \in R^X[\sim q : t''']$: if $+\partial_{\mathrm{BEL}}^{pr}@t\ s : t_s \in P(1..n)$, then
    4.1.1) $\exists Y_a a : t_a \in A(s : t_s), -\partial_{Y_a}@t\ a : t_a \in P(1..n)$ or
    4.1.2) $\exists v : t_v \in R^X[q : t'''] + \partial_{\mathrm{BEL}}@t\ v : t_v \in P(1..n)$ and
      $\forall Y_b b : t_b \in A(v : t_v) + \partial_{Y_b}@t\ b : t_b \in P(1..n)$ and $s : t_s \prec_{t'''} v : t_v$.

Clause 1 of the above proof condition allows us to infer a defeasible persistent conclusion from a strict persistent conclusion with the same mode. Clause 2 requires that the complement of the literal we want to prove is not definitely provable (or definitely provable for $-\partial$), but it does not specify whether it is persistent or transient: remember that what we want to achieve is to see whether the literal or its complement are provable at t but not both; in the same way, and for the same reason, q can be attacked by any rule for the complement of q (clauses 2.2.1). An important issue in all clauses of this proof condition is that each time we have to use a rule (either to support the conclusion (2.1), to attack it (2.2) or to rebut the attack (2.2.2)) we must have that the rule is provable at time t of the derivation ($@t$). Clauses 3 and 4 are the clauses implementing persistence (i.e., the conclusion has been derived at a previous time and carries over to the current time). Essentially clause 3 ensures that the conclusion has been derived at a previous time t'' and no interrupting event occurred between t'' and t; while clause 4 takes care of the case where q is derived persistently for a time before t', and that no interrupting event will occur between the effectiveness of q and the time q is expected to hold according to the current derivation.

5 Summary

In this paper we combined and extended the approaches presented in [11] and [6,5]. In particular we have extended the programming cognitive agents approach with temporalised literals. This makes the resulting logic more expressive and more suitable for the task at hand. In addition we have introduced the notion of view-point. The deliberation of an agent based on a policy depends not only on the environment but also on the rules in force in the policy at the time of deliberation and at the time when the plan resulting from the deliberation will be executed. These two aspects are neglected in the literature on agent planning. In addition the framework we propose can handle revision of theories in the same way the framework is inspired to handle complex modification of normative codes [10]. An aspect we did not consider here is how to extend the temporal framework to reason with actions and their duration. This matter is left for future work.

References

1. R.H. Bordini, A.L. C. Bazzan, R. de O. Jannone, D.M. Basso, R.M. Vicari, and V.R. Lesser. Agentspeak(xl): efficient intention selection in BDI agents via decision-theoretic task scheduling. In *AAMAS'02*, pp. 1294–1302, 2002.
2. M.E. Bratman. *Intentions, Plans and Practical Reason*. Harvard University Press, 1987.
3. J. Broersen, M. Dastani, J. Hulstijn, and L. van der Torre. Goal generation in the BOID architecture. *Cog. Sc. Quart.*, 2:428–447, 2002.
4. M. Dastani, F. de Boer, F. Dignum, and J.-J. Meyer. Programming agent deliberation. In *AAMAS'03*, pp. 91–104, ACM Press, 2003.
5. M. Dastani, G. Governatori, A. Rotolo, and L. van der Torre. Preferences of agents in defeasible logic. In *Australian AI05*, pp. 695–704. Springer, 2005.
6. M. Dastani, G. Governatori, A. Rotolo, and L. van der Torre. Programming cognitive agents in defeasible logic. In *LPAR 2005*, pp. 621–636. Springer, 2005.
7. M. Dastani and L.W.N. van der Torre. Programming BOID-plan agents: Deliberating about conflicts among defeasible mental attitudes and plans. In *AAMAS 2004*, pp. 706–713, 2004.
8. M. Dastani, B. van Riemsdijk, F. Dignum, and J.-J. Meyer. A programming language for cognitive agents: Goal directed 3APL. In *ProMAS'03*, pp. 111–130. Springer, 2003.
9. A.S. d'Avila Garcez and L.C. Lamb. Reasoning about time and knowledge in neural symbolic learning systems. In Sebastian Thrun, Lawrence saul, and Bernhard Schö lkopf, editors, *Advances in Neural Information Processing Systems 16*. MIT Press, 2004.
10. G. Governatori, M. Palmirani, R. Riveret, A. Rotolo, and G. Sartor. Norm modifications in defeasible logic. In *JURIX05*, pp. 13-22. IOS Press, 2005.
11. G. Governatori, A. Rotolo, and G. Sartor. Temporalised normative positions in defeasible logic. In *ICAIL*, pp. 25–34. ACM Press 2005.
12. K.V. Hindriks, F.S. De Boer, Hoek W. van der, and J.-J. Meyer. Agent programming in 3(apl). *Autonomous Agents and Multi-Agent Systems*, 2(4):357–401, 1999.
13. M.D. Inverno and M. Luck. Engineering agentspeak(l): A formal computational model. *Journal of Logic and Computation*, 8:1–27, 1998.
14. A.S. Rao. Agentspeak(L): BDI agents speak out in a logical computable language. Technical report, Australian Artificial Intelligence Institute, 1996.
15. M. Birna van Riemsdijk, M. Dastani, and J.-J. Meyer. Semantics of declarative goals in agent programming. In *AAMAS 2005*, pp. 133-140. ACM Press, 2005.