It depends on the context!
A decidable logic of actions and plans based on a ternary dependence relation

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Abstract

In this paper we argue for a weak form of causality in terms of a dependence relation involving actions, atoms and formulae in order to deal with the frame and ramification problems. This relation allows the atoms to change their value without forcing or causing it. Once integrated in the framework of the Logic of Actions and Plans $\mathcal{LAP}$, it gives us a simple and powerful formalism to reasoning about actions and a decision procedure in terms of tableau methods. We also show how to deal with scenarios involving indeterminate and indirect effects of actions which no other causal framework can handle.

Keywords: Reasoning about actions, causality, dependence relation, context.

1 Introduction

The reasoning about actions field has gained a very powerful framework to deal with the frame and ramification problems with the logic of actions and plans $\mathcal{LAP}$ [1].

$\mathcal{LAP}$ is a simple multimodal logic where formulae are constructed in the following way: We use an $S4$ operator $\Box$ to represent laws (static or dynamic ones) and a collection of K operators $[\alpha]$, one for each action α, in order to state the behavior of actions.

Given α an action and A, A' classical propositional formulae, the formula $\Box\langle\alpha\rangle\top$ is read as "α is executable". $\Box(A' \to [\alpha]A)$ as "if A', then after α A". $\Box[\alpha]A$ is an abbreviation for $\Box(\top \to [\alpha]A)$. For example, in the Yale shooting scenario (YSS) [6], the formula $\Box(\mathit{Loaded} \to [\mathit{shoot}]\neg \mathit{Alive})$ states that, in every Kripke world, shooting will kill the victim if the gun is loaded. In the same scenario, the formula $\Box(\mathit{Walking} \to \mathit{Alive})$ is a static law saying that it is always true that someone who is walking must be alive.

In $\mathcal{LAP}$, every action α has the modal logic K, and the modal operator $\Box$ has logic $S4$. Actions and the $\Box$ operator are linked by an axiom $I(\Box, [\alpha])$ stating that $\Box A \to [\alpha]A$.

In order to solve the frame problem, in [1] $\mathcal{LAP}$ was augmented with a weak causal connection denoted by a dependence relation $\leadsto$ between *actions* and *literals*, giving the base logic $\mathcal{LAP}_{\leadsto}$. In that work, it was also proposed a sound and complete inference engine based on semantic tableau systems [5], constituting a complete solution to representation and inference tasks. With $\mathcal{LAP}_{\leadsto}$, we can reason about actions without having to write down all the frame axioms and in a way not subjected to the same counter-examples that have invalidated most of the approaches in the literature along the history.

Nevertheless, even though with that formalism we do not have to write all the domain specific frame axioms, we are obliged to write down *conditional frame axioms* [1]. As an example, the formula below is needed for correctly dealing with the YSS:

$$\Box((\neg \mathit{Loaded} \wedge \mathit{Alive}) \to [\mathit{shoot}]\mathit{Alive}) \tag{1}$$

Formulae of the type of (1) establish that if a given condition is true, then some literal persists along the execution of a given action. Without considering such conditional frame axioms, it is not possible to derive the intended conclusions in $\mathcal{LAP}_{\leadsto}$.

This point has constituted a criticism from the community, since a satisfactory solution to the frame problem is presumed not to have any kind of such axioms. Instead, it is desired to leave such information about persistence implicit in the domain description, although this is generally done by hiding this information in very complex semantics, whose indirect effect are the lack of real theorem provers for them.

Other causal approaches have been proposed in the literature in the last decade, in particular Thielscher's influence relation [15], Lin's *Caused* predicate [10] and McCain and Turner's causal laws [12]. However, as pointed out in [2], there are some subtleties that cannot be captured by these approaches without stating non-change information in the domain description.

More recently, Zhang and Foo [16] have proposed a base logic similar to ours and have defined causality in terms of modal operators. But they fail to derive implicit qualifications.

We propose a new dependence relation that does not oblige us to write down any kind of non-change statement. We do this by adding a parameter to each tuple of the dependence relation with the aim of denoting the *context* (a particular condition) in which an action may influence a given atom. This makes the dependence relation more informative, eliminating the need for stating conditional frame axioms in the description of the domain. Once having done this, we augment the base logic $\mathcal{LAP}$ with the new dependence relation, giving a new approach to the frame and ramification problems.

The resulting logic $\mathcal{LAPD}$ can treat the same class of scenarios for which $\mathcal{LAP}_{\leadsto}$ does, but it is simpler than the latter in the elaboration of domain descriptions. The advantage of using modal logic appears in the proof procedure, for it is straightforward to adapt the tableau system of $\mathcal{LAP}$ to $\mathcal{LAPD}$.

This paper is organized as follows: in Section 2, we introduce our new contextual dependence relation. In Section 3, we incorporate this new causal notion into the base logic $\mathcal{LAP}$, obtaining a new dependence-based formalism, and give its semantics. In Section 4, we show why conditional frame axioms are useless within our approach. In Section 5 we define its axiomatics, discuss its computational properties and also sketch our proof procedure. In

Section 6, we apply our framework to some scenarios in reasoning about actions. In the final section, we give some conclusions and future work.

2 Contextual dependence

We present here a new dependence relation capable of capturing the *contexts* in which actions are executed. We define a ternary dependence relation involving *actions*, *atomic formulae* and *formulae*[1]. The role of the latter formulae is to characterize the particular circumstance in which the actions may influence the truth values of the atomic formulae.

Saying that an atom P *depends* on a certain action α in a given *context* C means that if C is true, then, after the execution of α, P *may* have its truth value changed. We shall say that α may change P in the context C and this concept will be represented by the expression α $\mathsf{influences}$ P if C.

In order to better illustrate these ideas, consider the action *shoot*, the atom *Alive* and the formula $\mathit{Loaded} \wedge \mathit{Alive}$. As the action *shoot* may change the truth value of *Alive* if *Loaded* and *Alive* are both true, then the expression shoot $\mathsf{influences}$ Alive if $\mathit{Loaded} \wedge \mathit{Alive}$ must be in our contextual dependence relation.

An important point to be highlighted here is the fact that the notion of dependence only *permits* change, and does not necessarily *cause* it. This can be better seen in non-deterministic domains, like the Russian turkey scenario [13], where, after shooting, the victim might die, and might as well keep on being alive.

We define $ACT = \{\alpha, \beta, \ldots\}$ as the set of *actions*, like *shoot*, *load*, etc. $ATM = \{P, Q, \ldots\}$ is the set of *atomic formulae*, or *atoms*, for short. Examples of atoms are *Loaded* and *Alive*. $LIT = ATM \cup \{\neg P : P \in ATM\}$ is the set of *literals*. If L is a literal, then $|L|$ will be used to denote its associated atom. The set of all formulae of Classical Propositional Logic will be denoted by $PFOR$.

Definition 2.1 A *contextual dependence relation* is a ternary relation $\mathcal{D} \subseteq ACT \times ATM \times PFOR$. ■

[1] Formulae of Classical Propositional Logic, without modal operators.

The triples (α, P, C) will be written α $\textsf{influences}$ P $\textsf{if}$ C and represent the fact that "α *may* change P in the context C". In other words, this means that "the execution of action α *may* change the truth value of the atom P, as long as the formula C is true".

Remark 2.1 Disjunctive contexts seem to be rare. We conjecture that, in practice, the formula denoting the context C will in general be a *conjunction* of literals. The expression α $\textsf{influences}$ P $\textsf{if}$ $C_1 \vee C_2$ could be substituted by α $\textsf{influences}$ P $\textsf{if}$ C_1 and α $\textsf{influences}$ P $\textsf{if}$ C_2. Therefore we can suppose w.l.o.g. that contexts are conjunctions of literals.

3 A new logic of actions and plans

As done with the binary dependence relation $\rightsquigarrow$, we can combine the logic of actions and plans $\mathcal{LAP}$ with the new dependence relation $\mathcal{D}$ defined so far, obtaining the new logic $\mathcal{LAPD}$. In this sense, the $\mathcal{LAP}$-models must satisfy that whenever all the contexts in which an action may influence a given atom P are false, then the truth value of P must be preserved along the execution of that action.

As an example, consider the action *shoot* and the atom *Alive* in the YSS. We have that the only way of *shoot* affecting *Alive* is when $\mathit{Loaded} \wedge \mathit{Alive}$ is true. Thus, in a circumstance in which we have $\neg \mathit{Loaded}$, the persistence of *Alive* will be guaranteed by the falsehood of the context $\mathit{Loaded} \wedge \mathit{Alive}$.

For the same scenario, considering the action *wait* and the literal *Loaded*, as *wait* does not affect *Loaded*, it does not matter the circumstance, there will not be in $\mathcal{D}$ any expression of the form *wait* $\textsf{influences}$ *Loaded* $\textsf{if}$ C, whatever the context C is. In this case, we guarantee the persistence of *Loaded* through the execution of *wait*.

With this dependence-based condition, one eliminates the $\mathcal{LAP}$-models in which non-intuitive changes occur in the following way: suppose that we are in a particular situation (a possible world in our Kripke semantics) w in which the atom P is false. First, imagine that the only element of $\mathcal{D}$ involving both α and P is α $\textsf{influences}$ P $\textsf{if}$ C. Thus, as long as C is true, the execution of α may change, or not, the truth value of P, since our causal notion only allows change, not forcing it. But surely α will not change the value of P if C

is false. Suppose now that there is no $C \in PFOR$ such that α $\mathsf{influences}$ P if $C \in \mathcal{D}$. Then, the execution of α may never make P true, and hence P will still be false after α.

Definition 3.1 Let $\mathcal{D}$ be a ternary dependence relation. A model of $\mathcal{LAPD}$ is a $\mathcal{LAP}$-model $\mu = \langle W, \{R_\alpha : \alpha \in ACT\}, R_\Box, \tau\rangle$, such that whenever $wR_\alpha w'$ then for every α and for every $P \in ATM$, if, for all $C \in PFOR$ such that α $\mathsf{influences}$ P if C, $w \not\models C$, then $w \in \tau(P)$ if and only if $w' \in \tau(P)$. ■

Given a dependence relation $\mathcal{D}$, we say that a formula A is true in a $\mathcal{LAPD}$-model $\mu = \langle W, \{R_\alpha : \alpha \in ACT\}, R_\Box, \tau\rangle$ if $w \models A$ for every $w \in W$. A is $\mathcal{LAPD}$-valid (noted $\models_{\mathcal{LAPD}} A$) if A is true in all $\mathcal{LAPD}$-models.

4 Inferring conditional frame axioms

Once defined our dependence relation in terms of contexts, we immediately have an alternative to the conditional frame axioms. This will be shown along this section.

Definition 4.1 Let $\alpha \in ACT$, $P \in ATM$ and $\mathcal{D}$ a dependence relation. We define

$$Pre_{\mathcal{D}}(\alpha, P) = \bigvee_{(\alpha \ \mathsf{influences}\ P\ \mathsf{if}\ C) \in \mathcal{D}} C$$

■

In other words, $Pre_{\mathcal{D}}(\alpha, P)$ is the disjunction of all contexts in which α may affect the truth value of atom P, given a dependence relation $\mathcal{D}$.

Theorem 4.1 $\models_{\mathcal{LAPD}} \Box((\neg Pre_{\mathcal{D}}(\alpha, |L|) \wedge L) \rightarrow [\alpha]L)$. ■

With this result, we can see that in a domain description using a dependence relation $\mathcal{D}$ there is no need for a set of conditional frame axioms, since all the conclusions that are obtained with the aid of the latter can also be inferred with the former.

As an example, consider the action *shoot*, the atom *Alive* and the literal $\neg$*Loaded*, and suppose $\mathcal{D} = \{shoot\ \mathsf{influences}\ Alive\ \mathsf{if}\ Loaded \wedge Alive\}$. Then the conditional frame axiom (1) is $\mathcal{LAPD}$-valid. In other words, the persistence of *Alive* follows from the dependence information in $\mathcal{D}$, making completely unnecessary, thus, the statement of the conditional frame axiom (1).

In the sequel, we define an axiomatics for $\mathcal{LAPD}$ and briefly sketch its inference method.

5 Proof theory

5.1 Axiomatics and complexity

Given a ternary dependence relation $\mathcal{D}$, we axiomatize the class of $\mathcal{LAPD}$-models in the same way as done for $\mathcal{LAP}$ in [1, Section 4.2], adding an axiom scheme founded on the dependence relation:

- $Persist([\alpha]) : \neg Pre_{\mathcal{D}}(\alpha, |L|) \wedge L \rightarrow [\alpha]L$, if α $\mathsf{influences}$ $|L|$ if C is in $\mathcal{D}$, $C \in PFOR$.

In order to show the soundness and completeness of $\mathcal{LAPD}$ with respect to its semantics, we have the following result:

Theorem 5.1 For all dependence relation $\mathcal{D}$ over $ACT \times ATM \times PFOR$, the axiomatics of $\mathcal{LAPD}$ is sound and complete with respect to the class of $\mathcal{LAPD}$-models. ■

The theorem below shows that the complexity of $\mathcal{LAPD}$ is the same as that of $\mathcal{LAP}$.

Theorem 5.2 $\mathcal{LAPD}$ is decidable, and the satisfiability problem in $\mathcal{LAPD}$ is EXPTIME-complete. ■

This theorem guarantees that the inclusion of the ternary dependence relation $\mathcal{D}$ in $\mathcal{LAP}$ does not increase the computational complexity of the basic logic.

5.2 Proof procedure

In this section, we briefly sketch the tableau-based proof method for $\mathcal{LAPD}$. Here, we can assume w.l.o.g. that the context C is a set of literals. In essence, we replace the rules (SF) and (SB), which have to do with the binary dependence, in the method proposed in [1] by the following tableau rules in order to capture the semantical aspect of the dependence-based condition stated in Section 3 ($w :: L$ means "the literal L is true at world w", and $w \stackrel{\alpha}{\rightarrow} w'$ reads "w' is accessible from w by an execution of α"):

$$(RP)\frac{w :: L; w \stackrel{\alpha}{\rightarrow} w' \text{ and } C \not\subseteq w \text{ for all } \alpha \ \mathsf{influences}\ |L| \ \mathsf{if}\ C \in \mathcal{D}}{w' :: L}$$

$$(RB)\frac{w' :: L; w \overset{\alpha}{\rightarrow} w' \text{ and } C \not\subseteq w \text{ for all } \alpha \ \mathsf{influences}\ |L| \ \mathsf{if}\ C \in \mathcal{D}}{w :: L}$$

We call (RP) the *rule of persistence* and it captures the intuitive meaning of the semantics of dependence: all literals in a node of a tableau that depend on the execution of a given action α in a context that does not verify must be propagated to the node following the execution of that action.

Rule (RB) is the *rule of back-propagation* and expresses that if a given literal L is true in a node but it was not caused to change its truth value, then L must also be true in the antecedent node. This kind of rule is needed only to guarantee the completeness of the method, as shown in [1].

In order to get soundness, we have to define a particular strategy where rules (RP) and (RB) are applied at the end. Thus, the tableau can be proved sound and complete. Following the work in [9], we can also show that it is a decision procedure. Moreover, its implementation is straightforward in Lotrec System [3].

6 Some scenarios in $\mathcal{LAPD}$

In this section, we use $\mathcal{LAPD}$ as the base formalism for modeling and inferring in some typical scenarios. It is worthy noting that in none of the scenario descriptions that follow there is the need for stating conditional frame axioms, since their semantical aspects have already been implicitly captured by means of the contextual dependence relation $\mathcal{D}$.

In all scenario descriptions below, KB represents the set of observations and LAW that of static, effect and executability laws in $\mathcal{LAPD}$.

Example 6.1 (Forcing a door [1]) Consider a door that can be closed or barricaded (by a cupboard, for example), and two actions: *open*, that opens a door if it is not barricaded, and *force*, that is stronger and unconditionally opens it. In $\mathcal{LAPD}$ it is as follows:

$$LAW = \left\{ \begin{array}{l} \Box(Barricaded \rightarrow Closed), \\ \Box[open]\neg Closed, \\ \Box[force]\neg Closed \end{array} \right\}$$

$$\mathcal{D} = \left\{ \begin{array}{c} open \text{ influences } Closed \text{ if } Closed, \\ force \text{ influences } Closed \text{ if } Closed, \\ force \text{ influences } Barricaded \text{ if } Barricaded \end{array} \right\}$$

$$KB = \{Closed, Barricaded\}$$

From the above modeling, we can conclude

$$\models_{\mathcal{LAPD}} (KB \wedge LAW) \rightarrow [force](\neg Closed \wedge \neg Barricaded),$$

which means that in $\mathcal{LAPD}$, like in $\mathcal{LAP}_{\leadsto}$, it is possible to derive the indirect effect of action *force*. Notice, however, that as with $\mathcal{LAP}_{\leadsto}$, we also have to write down the indirect dependence between *force* and *Barricaded*. Nevertheless, as argued in [1], all the approaches that do not do things this way fail in solving this example.

Another important conclusion one can obtain with our approach is the implicit qualification [4] for action *open*, that is, such action cannot be executed if the door is barricaded:

$$\models_{\mathcal{LAPD}} (KB \wedge LAW) \rightarrow [open]\bot$$

■

Remark 6.1 We consider that for a given effect law $\Box(A \rightarrow [\alpha]L)$ it is reasonable to have α influences $|L|$ if $A \wedge \neg L$ in the dependence relation $\mathcal{D}$, otherwise it would seem a bit strange. So, we assume that every effect law has a corresponding element in $\mathcal{D}$.

Example 6.2 (Toulouse suitcase [1]) Consider an extension of Lin's suitcase [10] where we want to express that if both locks of the suitcase are linked (by a rigid metal bar, for example), then they are always in the same position. The representation of this situation in $\mathcal{LAPD}$ is given below ($i = 1, 2$):

$$LAW = \left\{ \begin{array}{l} \Box\langle toggle_1\rangle\top, \\ \Box(Linked \rightarrow (Up_1 \leftrightarrow Up_2)), \\ \Box((Up_1 \wedge Up_2) \rightarrow Opened), \\ \Box(\neg Up_i \rightarrow [toggle_i]Up_i, \\ \Box(Up_i \rightarrow [toggle_i]\neg Up_i \end{array} \right\}$$

$$\mathcal{D} = \left\{ \begin{array}{c} toggle_i \text{ influences } Up_i \text{ if } \top, \\ toggle_1 \text{ influences } Up_2 \text{ if } Linked, \\ toggle_2 \text{ influences } Up_1 \text{ if } Linked, \\ toggle_1 \text{ influences } Opened \text{ if } Up_2 \wedge \neg Opened, \\ toggle_2 \text{ influences } Opened \text{ if } Up_1 \wedge \neg Opened \end{array} \right\}$$

This example is problematic for causal approaches that are not action indexed. ■

More generally, we claim that all the existing approaches fail to handle scenarios having actions with both indeterminate and indirect effects, as examplified in the following scenario:

Example 6.3 (The Mailboxes scenario) Suppose $Mbox_1$ means "the message is in mailbox 1", and $Mbox_2$ "the message is in mailbox 2", and consider the actions $save_1$ and $save_2$, that always save an email message in $Mbox_1$ and in $Mbox_2$, respectively. Suppose too we have a non-deterministic *save* action that saves the email in one of the two mailboxes or in both. We represent the fact that the email is saved in $Mbox_1$ or in $Mbox_2$ or in both by the atom *Saved*. The representation of this scenario in $\mathcal{LAPD}$ is as follows ($i = 1, 2$):

$$LAW = \left\{ \begin{array}{l} \Box\langle save\rangle\top, \Box\langle save_i\rangle\top, \\ \Box(Saved \leftrightarrow Mbox_1 \vee Mbox_2), \\ \Box[save]Saved, \\ \Box[save_i]Mbox_i \end{array} \right\}$$

$$\mathcal{D} = \left\{ \begin{array}{c} save \text{ influences } Saved \text{ if } \neg Saved, \\ save \text{ influences } Mbox_i \text{ if } \neg Mbox_i, \\ save_i \text{ influences } Mbox_i \text{ if } \neg Mbox_i, \\ save_i \text{ influences } Saved \text{ if } \neg Saved \end{array} \right\}$$

$$KB = \{\neg Saved, \neg Mbox_1, \neg Mbox_2\}$$

From the above representation, we can conclude

$$\models_{\mathcal{LAPD}} (KB \wedge LAW) \rightarrow [save](Mbox_1 \vee Mbox_2)$$

It seems to us that this example is problematic for all the existing proposals (i.e. approaches allowing the representation of actions with indirect and indeterminate effects). We think that the problem is the following: if we have indirect nondeterministic effects, then

1. we must exempt these effects from minimization of change (in order to avoid exclusive interpretation of inclusive disjunctions, cf. Reiter's "dropping a coin on a chessboard" example);

2. as the effect is indirect, this exemption must be specified indirectly: mentioning the context where it applies, but without mentioning the action.

Then it is difficult to exclude that another action applies in exactly the same context, but without the indirection. As an example, in Lin's approach [11], in order to obtain the intended conclusions, we are obliged to state $Poss(save_1, s) \rightarrow Caused(Mbox_2, false, do(save_1, s))$, which is unintuitive. ■

7 Conclusions and further work

In this work, we have presented a new causal dependence that combined with the logic of actions and plans $\mathcal{LAP}$ results in a powerful framework to reasoning about actions.

In essence, our method is a modification of that in [1], which defines a binary relation between actions and literals as a way of expressing causal information. In our approach, however, we consider a ternary one, since we argue that with it we can get a more intuitive domain description. In this sense, we have seen that our definition of a contextual dependence allows a more economic representation of the domain under consideration, for the presence of contexts establishes a more informative causal notion, eliminating the need for stating conditional frame axioms in the set of action laws.

We have also briefly sketched our tableau method, that constitutes a decision procedure. This gives to our formalism a higher degree of practical applicability and makes it a more complete solution compared to other approaches in the literature.

We have made an analysis of typical scenarios constituting good instances of the frame and ramification problems. In our approach we can treat them in a more economic way than using $\mathcal{LAP}_{\leadsto}$, without increasing the complexity of the solution. In fact, at the price of writing conditional frame axioms, $\mathcal{LAP}_{\leadsto}$ deals with the same class of problems than $\mathcal{LAPD}$.

We have also investigated the behavior of a ternary dependence in scenarios involving actions with indirect effects and our solution permits us to obtain the desired conclusions. In this sense, we believe our approach unifies a more robust solution to the frame and ramification problems with a higher degree of representational parsimony [14].

In the forcing a door scenario, we were able to capture implicit qualifications. However, in the same way as [1], we have to state indirect dependences in $\mathcal{D}$. An argument in response to possible criticisms is the fact that there is no approach capable of solving the forcing a door scenario without explicitly stating in one way or another the relation between the action and the indirect effects — which is what these approaches would like to avoid.

With respect to situations involving non-determinism, our method applies too, as shown in the mailboxes scenario. In this case, it suffices to state in $\mathcal{D}$ the correct dependences relating an action and each atom it can affect. In the same way, as long as we concern, there is no approach in the literature capable of solving this example in a better way.

We plan to pursue our work by extending our solution by an account of sensing and communication actions. This will be done by integrating the approach in [7, 8], the long-term aim being a unified logic of actions and beliefs.

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