Non-Atomic Actions in the Situation Calculus*

José Júlio Alferes, Renwei Li, and **Luís Moniz Pereira**

Centre for Artificial Intelligence, UNINOVA and
Department of Computer Science, U. Nova de Lisboa
2825 Monte da Caparica, Portugal

Abstract. In this paper we investigate non-atomic actions and changes in the framework of the situation calculus. We classify non-atomic actions into three types: simultaneous actions, inclusive selective actions, and exclusive selective actions. We show that the extended situation calculus with non-atomic actions has the same expressive power as the basic situation calculus. We identify a problem, called composition problem, which relates effects of non-atomic actions to those of their component actions. A defeasible solution to the composition problem is proposed. The believability of some choices of default rules for the composition problem are discussed. We also provide some simple examples to illustrate the usefulness of our default rules.

1 Introduction

The situation calculus [10] is a general framework for reasoning about actions and changes. Actually, it is a many-sorted first-order theory including three basic elements: actions, situations, and fluents. Its expressiveness and limitations had never been systematically studied until Gelfond, et al [5] argued that the attractive syntax of the situation calculus is not tied to the primitive ontology that was usually associated with its use. In line with [5], further efforts for formalizing concurrent actions were proposed in [9, 2, 1].

Inspired by [5, 9, 2, 1], in this paper we investigate three types of non-atomic actions: simultaneous actions, inclusive selective actions, and exclusive selective actions. We will show that the extended situation calculus with non-atomic actions has the same expressive power as the basic situation calculus. We will identify a problem, called composition problem, which relates effects of non-atomic actions to those of their component actions. A defeasible solution to the composition problem is proposed. The believability of some choices of default rules for the composition problem are discussed. We also provide some simple examples to illustrate the usefulness of our defeasible rules.

The rest of the paper is organized as follows. In Section 2 we briefly introduce the basic situation calculus. In Section 3 we extend the basic situation calculus [10] with non-atomic actions, and argue that the extended situation calculus has

* Published in: N. Mamede and C. Pinto-Ferreira (eds.), *Progress in Artificial Intelligence*, Lecture Notes in Artificial Intelligence 990, Springer-Verlag,1995, pp. 273-284

the same expressive power as the original situation calculus. In Section 4 we identify a problem, termed composition problem, concerning descriptions of effects of non-atomic actions. The composition problem is as follows: given descriptions of the effects of atomic actions how do we avoid *unnecessary* descriptions of effects of non-atomic actions? It will be indicated that the composition problem also exists in other formalisms for reasoning about non-atomic actions. In Section 5 and 6 we make use of defeasible rules of inference to solve the composition problem about simultaneous actions and selective actions, respectively. In Section 7 we discuss the believability of defaults for reasoning about simultaneous actions. In Section 8 we compare our work with others and make some discussions.

2 Basic situation calculus

In this paper a situation calculus without non-atomic actions is referred to as a basic situation calculus (BSC). In order to make a serious study of the situation calculus, it suffices to give a domain-specific alphabet Σ and then define the basic situation calculus as a first-order formalism on Σ.

The alphabet Σ of the situation calculus is defined to include: (i) A set of sorts including three special sorts: Act, Sit and $Bool$; (ii) A set $\mathcal{A}$ of sorted action symbols; (iii) A set of sorted predicate symbols including a special symbol $holds$ of the sort $Bool \times Sit$; (iv) A set of sorted function symbols including two special symbols: do of the sort $Act \times Sit \to Sit$, and S_0 of the sort Sit. There is a distinguished subset $\mathcal{F}$ of function symbols, called fluent symbols.

From the alphabet we can define terms and formulas as usual. In particular, we are interested in terms of sorts Act, Sit and $Bool$. All terms of the sort Act are actions. Terms of the sort $Bool$ used as first parameter of $holds$ are fluents. Situations are either S_0 or terms of form $do(a, s)$. We require that actions and fluents cannot have parameters of sorts Act and Sit.

Using terms and formulas we can describe domain-specific axioms. In particular, the initial conditions can be specified by formulas of the form $holds(F, S_0)$. The effect of actions can be specified by formulas of the form $holds(\phi, s) \to holds(\psi, do(a, s))$. In order to formally reason about changes, we may need *unique name axioms for actions* and *unique name axioms for states* [13]:

In order to correctly formalize dynamic world, in addition to which fluents are changed by which actions we need to indicate which fluents are *not* changed by which actions. This is the frame problem identified in [10]. One solution is simply to use the *frame axioms*. In order to avoid explicitly specifying frame axioms, many efforts have been made. One approach is to implicitly represent frame axioms as entailments of some uniform non-monotonic policy, as for example in [8, 7]. Another approach is Reiter [13], using *successor state axioms* and *precondition axioms for actions* in [13], which are from the combination of Pednault [11] and Haas-Schubert's explanation closure axioms [6, 15]. Although the solution of [13] is very elegant and parsimonious, it only applies in a class of domains satisfying the completeness assumption: For any action a and any fluent F, all the conditions under which a can lead to F becoming true or false in the successor state are known and characterized by some first-order formulas. When we admit non-atomic actions in the situation calculus, it is hardly possible to determine all the conditions under which a can lead to F becoming true or false in the successor state. In this paper we prefer to appeal to non-monotonic solutions to the frame problem. For example, we can also follow [4] to introduce four *inertia axioms* to represent the frame axioms. There are some subtleties here. For the purpose of this paper, we leave it open. For simplicity we will simply use Reiter's extension semantics [12] for the default rules proposed in this paper, although there are several other possibilities of choices.

3 Non-atomic actions

We consider two types of non-atomic actions: simultaneous actions and selective actions. Selective actions are further classified into exclusive selective actions and inclusive selective actions. By *simultaneous action* we mean that an agent performs several actions at the same time. For example, *to lift a bowl of soup* and *to open the door* at the same time can be regarded as a simultaneous action. By *selective action* we mean that an agent performs one or more of a set of actions at the same time. For example, *to go to Army* or *to perform an alternative service* can be regarded as an *exclusive* selective action. As another example, *to take an examination* or *to do an experimental work* or both can be regarded as an inclusive selective action.

Let a and b be two actions. We use $a \parallel b$ to represent a simultaneous action for performing a and b at the same time, $a+b$ to represent an (inclusive) selective action, $a\dot{+}b$ to represent an (exclusive) selective action. The situation calculus extended with non-atomic actions is generally called extended situation calculus (ESC). To be more specific, given an alphabet Σ, all actions ACT of the extended situation calculus for Σ is defined as follows: (i) All actions of the basic situation calculus for Σ are in ACT; (ii) If $a, b \in ACT$, then $a \parallel b, a+b, a\dot{+}b \in ACT$; (iii) No other actions are in ACT.

In general, the situation $do(a \parallel b, s)$ is different from $do(a, s)$ and $do(b, s)$, but the situation $do(a + b, s)$ is one of $do(a, s)$, $do(b, s)$, and $do(a \parallel b, s)$, and $do(a\dot{+}b, s)$ is one of $do(a, s)$ and $do(b, s)$. We will admit the commutative law for $\parallel$, $+$ and $\dot{+}$.

It can be seen that the extended situation calculus has *more* actions than the basic situation calculus. The *structure* of actions in the extended situation calculus is much richer than that in the basic situation calculus. In order to apply the extended situation calculus we need to describe effects of all non-atomic actions in the same way as for atomic actions.

Example 1. Let $Switchon$ and $Shoot$ denote two actions: switching on the light and shooting, respectively. Then $Switchon \parallel Shoot$ is a simultaneous action to denote *switching on the light and shooting at the same time.* The effects of actions can be described as follows:

$$holds(Lighton, do(Switchon, s))$$
$$holds(Loaded, s) \rightarrow holds(Dead, do(Shoot, s))$$
$$holds(Lighton, do(Switchon \parallel Shoot, s))$$
$$holds(Loaded, s) \rightarrow holds(Dead, do(Switchon \parallel Shoot, s))$$

Note that, however, the situation $do(Switchon \parallel Shoot, s)$ is not the same as $do(Switchon, s)$, nor as $do(Shoot, s)$.

Example 2. Let $Air, Train, Bus$ denote three actions: go to Paris by air, by train, and by bus, respectively. Then $Air \dot{+} Train \dot{+} Bus$ is a selective action to denote *going to Paris by air or by train or by bus*. We can use the following formulas as its effect descriptions:

$$holds(Paris, do(Air \dot{+} Train \dot{+} Bus, s))$$

Note that we also have the following three formulas as effect descriptions of the constituent component actions of $Air \dot{+} Train \dot{+} Bus$:

$$holds(Paris, do(Air, s))$$
$$holds(Paris, do(Train, s))$$
$$holds(Paris, do(Bus, s))$$

The situation $do(Air \dot{+} Train \dot{+} Bus, s)$ is the same as one of $do(Train, s))$, $do(Air,\ s)$, and $do(Bus,\ s))$, but different from the other two, although the fluent $Paris$ is true in all of them.

It can be seen that any basic situation calculus (BSC) of [10] is a subset of an extended situation calculus (ESC). That is to say, ESC is as expressive as BSC. But is BSC as expressive as ESC? Our conclusion is that ESC does not increase the expressive power of BSC. Note that if we ignore the internal structure of the expressions $Switchon \parallel Shoot$ and $Air \dot{+} Train \dot{+} Bus$ and consider them as atomic ones, say $\overline{Switchon \parallel Shoot}$ and $\overline{Air \dot{+} Train \dot{+} Bus}$, then the extended situation calculus becomes the same as the non-extended one. This observation can be used to prove the equivalence between ESC and BSC. The following claim is formalized and proved in the extended version of this paper as a proposition.

Claim 1. The extended situation calculus (ESC) has the same expressive power as the basic situation calculus (BSC) in the sense that for any ESC we can construct an equivalent BSC.

4 The composition problem

When the extended situation calculus is applied to a practical universe of discourse, each non-atomic action α should be considered as being uninterrupted and look like an atomic action, and its effect should be given in the form of $holds(\phi, s) \rightarrow holds(\psi, do(\alpha, s))$. It is, however, often difficult or unnecessary to do so, since there are too many non-atomic actions. On the other hand, given the description of effects of atomic actions, we may be able to derive the effects of non-atomic actions.

Example 3. Suppose there is a banking account for donations. Let the atomic action set be $\{ \; donate(n) \mid n \in \aleph \; \}$. The effects of atomic actions may be described as follows:

$$holds(balance(x), s) \to holds(balance(x+d), do(donate(d), s))$$

Assume two donators donate their money d_1 and d_2 at the same time. Then, we can use $donate(d_1) \parallel donate(d_2)$ to represent the simultaneous donations. The effect of $donate(d_1) \parallel donate(d_2)$ may be described by the following formula:

$$\begin{array}{l} holds(balance(x), s) \to \\ holds(balance(x+d_1+d_2), do(donate(d_1) \parallel donate(d_2), s)) \end{array}$$

In the above example it seems that the description of effects of the simultaneous action $donate(d_1) \parallel donate(d_2)$ is *unnecessary and redundant*, and thus can be omitted, since it can be derived from effects of atomic actions by using the so-called interleaving model.

Example 4. Consider the *Going To Paris* example. We have the following four formulas to describe the effects of three atomic actions and a selective action.

$$\begin{array}{ll} holds(Paris, do(Air, s)) & holds(Paris, do(Train, s)) \\ holds(Paris, do(Bus, s)) & holds(Paris, do(Air \dot{+} Train \dot{+} Bus, s)) \end{array}$$

The description of the effect of $Air \dot{+} Train \dot{+} Bus$ does not seem to be necessary; it is actually redundant, since $Paris$ is true in all the situations $do(Air, s)$, $do(Train, s))$, $do(Bus, s))$, $do(Air \dot{+} Train \dot{+} Bus, s)$.

We can find many other examples in which effects of non-atomic actions *may* be derived from effects of their component actions. It is certainly favoured to avoid describing unnecessary descriptions of effects of non-atomic actions, if the effects of the non-atomic actions can be derived from the effects of their component actions. Now the problem is: how do we avoid unnecessary descriptions of effects of non-atomic actions, given descriptions of effects of atomic actions? If a description of effects of non-atomic actions has been omitted, how do we derive it later? This problem is referred to as the composition problem for non-atomic actions in this paper.

The composition problem concerns the relationship between effects of non-atomic actions and their component actions. In reality, when some atomic action is performed, it has some certain effect; when it is performed simultaneously with other actions, either it may have the same effect as if it were performed atomically, or it may have additional side-effects, or it may have different effects from those when it is performed atomically. The following example is about side-effects of simultaneous actions.

Example 5. For the sake of business a shop has a special policy: If a client buys toothpaste and toothbrush, then the shop gives a soap to the client free of charge. Let the atomic actions be $\{buy(x) \mid x \in \{paste, brush, soap\}\}$. Then, the effects of atomic actions may be described as follows: $holds(has(x), do(buy(x), s))$. The effects of the simultaneous action $buy(paste) \parallel buy(brush)$ are as follows:

$$holds(has(paste), do(buy(paste) \parallel buy(brush), s)) \tag{1}$$

$$holds(has(brush), do(buy(paste) \parallel buy(brush), s)) \tag{2}$$

$$holds(has(soap), do(buy(paste) \parallel buy(brush), s)) \tag{3}$$

The formula (3) above may be regarded as a side-effect of the simultaneous action $buy(paste) \parallel buy(brush)$. The formulas (1) and (2) can be omitted, but it does not seem to be possible to omit (3), since we don't have general knowledge about how to derive it from effects of atomic actions.

5 Effects of simultaneous actions

Defeasible reasoning allows for "jumping to conclusions" or reaching conclusions which rely in part on the "absence of evidence to the contrary". In this paper we make use of normal default rules of the form $\frac{\phi:\varphi}{\varphi}$, where ϕ and φ are first-order sentences. Recall that there is always an extension for a normal default theory [12].

By using default rules of the above form, now we can solve the composition problem for simultaneous actions. For simultaneous actions composed of two atomic actions we propose to use the following default:

$$\frac{\begin{array}{l} holds(p, do(a; b, s)) \\ holds(p, do(b; a, s)) \end{array} : holds(p, do(a \parallel b, s))}{holds(p, do(a \parallel b, s))} \tag{4}$$

where we use $holds(p, do(x; y, s))$ denote $holds(p, do(y, do(a, s)))$. It can be seen that the above default rule characterizes a class of so-called interleaving traces of the simultaneous actions. Now let's consider some examples to see whether the above default works in practice.

If we apply the above default to the donation example we can achieve the correct answer. For a very large class of domains, the above default really works. We should emphasize that by use of the above rule of inference we can only omit *unnecessary* descriptions of effects of simultaneous actions. Sometimes we still need to give the *necessary* descriptions of effects. In the brush-paste-soap scenario, for example, we still need to give the formula (3) to describe the *side-effect* of the simultaneous action, while formulas (1) and (2) for the simultaneous action $buy(paste) \parallel buy(brush)$ can be omitted.

The default (4) can be extended for simultaneous actions composed of more than two atomic actions. Let $A = \{a_1, \cdots, a_n\}$ for any $n \geq 1$. We use $Per(A)$ to stand for the set of all ordered permutations of A. For example, $Per(\{a, b, c\}) =$

$\{a;b;c, a;c;b, b;a;c, b;c;a, c;a;b, c;b;a\}$. For simultaneous actions $a_1 \parallel \cdots \parallel a_n$, we propose to use the following default:

$$\frac{\Pi(p, A, s) \ : \ holds(p, do(a_1 \parallel \cdots \parallel a_n, s))}{holds(p, do(a_1 \parallel \cdots \parallel a_n, s))} \tag{5}$$

where $\Pi(p, A, s)$ denotes $\bigwedge_{e \in Per(A)} holds(p, do(e, s))$. And thus reasoning about change caused by simultaneous actions amounts to computing extensions for a default theory. Hence we can use properties of default logic to study properties of changes caused by simultaneous actions.

6 Effects of selective actions

Intuitively, the situation $do(a + b, s)$ is one of $do(a, s)$, $do(b, s)$, and $do(a \parallel b, s)$. Thus we immediately have the following non-default rule of inference for effects of selective actions:

$$\frac{holds(p, do(a, s)), holds(p, do(b, s)), holds(p, do(a \parallel b, s))}{holds(p, do(a + b, s))} \tag{6}$$

Combining it with (4), we then have the following default rule:

$$\frac{\begin{array}{c} holds(p, do(a, s)) \\ holds(p, do(b, s)) \\ holds(p, do(a;b, s)) \\ holds(p, do(b;a, s)) \end{array} \ : \ holds(p, do(a \parallel b, s))}{holds(p, do(a + b, s))} \tag{7}$$

Later we will see that there are also a few other alternatives to (4), thus there are a few other alternatives to (7). On the other hand, the default (7) is not a normal one. In addition, the effect of $a \parallel b$ may be just directly given. Taking all these factors into account, we propose the following default to replace (6) and (7).

$$\frac{\begin{array}{c} holds(p, do(a, s)) \\ holds(p, do(b, s)) \\ holds(p, do(a \parallel b, s)) \end{array} \ : \ holds(p, do(a + b, s))}{holds(p, do(a + b, s))} \tag{8}$$

Note that although (6) is not a default, conclusions from it may still be defeasible, since reasoning about $a \parallel b$ may involve the default (4), not additionally mentioning that the action a and b may also denote simultaneous actions. There are some subtle discussions and arguments here on (6), (7) and (8). For the space limitation we will not go into deeper discussions.

In practice we often use the exclusive selective action. Intuitively, the situation $do(a \dot{+} b, s)$ is one of $do(a, s)$ and $do(b, s)$. In this case, we simply modify (6) into the following rule of inference:

$$\frac{holds(p, do(a, s)), holds(p, do(b, s))}{holds(p, do(a \dot{+} b, s))} \tag{9}$$

Note that the action a and b may be also simultaneous actions. Thus, conclusions from (9) may also be defeasible. For conservative reasoning we propose the following default for effects of exclusive selective action:

$$\frac{\begin{array}{l} holds(p, do(a, s)) \\ holds(p, do(b, s)) \end{array} \; : \; holds(p, do(a \dot{+} b, s))}{holds(p, do(a \dot{+} b, s))} \tag{10}$$

The above discussions can be extended for selective actions composed of more than two actions.

7 Believability

Since defaults are used to solve the composition problem, conclusions from default rules should be understood as beliefs, which can be defeated by new facts. On the other hand, we can use other defaults instead of the previous defaults. That is to say, some defaults will lead our reasoning more non-monotonic than others. In this section, we discuss believability of defaults for simultaneous actions.

Note that the prerequisites of the default rule (5) are conjunctions of some formulas of the form $holds(p, do(e, s))$. More credulous people may think that the prerequisites might be too strong, and thus the conclusions would be too conservative. A simple modification of the prerequisites in the default (5) is just to change conjunction into disjunction. That is to say, for simultaneous action $a_1 \parallel \cdots \parallel a_n$, we may use the following default rule:

$$\frac{\Sigma(p, A, s) \; : \; holds(p, do(a_1 \parallel \cdots \parallel a_n, s))}{holds(p, do(a_1 \parallel \cdots \parallel a_n, s))} \tag{11}$$

where $A = \{a_1, \cdots, a_n\}$ and $\Sigma(p, A, s)$ denotes $\bigvee_{e \in Per(A)} holds(p, do(e, s))$. Obviously, the beliefs from (11) are less believable than those from (5), but (11) can also be justified by practical examples. For example, in the donation scenario if we use (11) instead of (5), we still achieve the same result.

In what follows, we will define a partial ordering relation among default theories to indicate some beliefs are more believable than others. We start with the general definition of believability, then present some defaults alternative to (4), and then discuss their believability.

Definition 2. Let $D = \{D_i \mid D_i$ is a set of defaults for any $i \geq 1\}$. We define a partial ordering relation $\preceq$ on D as follows: $D_i \preceq D_j$ iff $M_i \subseteq M_j$, where M_i and M_j are the extensions for $\langle W, D_i \rangle$ and $\langle W, D_j \rangle$, respectively, for any set of first-order sentences W. When $D_i \preceq D_j$, we say that beliefs in M_i for D_i are more believable than those in M_j for D_j. The partial ordering relation $\preceq$ is simply called believability relation.

In particular, $\{\} \preceq D_i$ for any D_i. The extension for $\langle W, \{\}\rangle$ is just $Th(W)$, which cannot be defeated by any new facts. Hence, $\{\}$ is the most believable. Now consider two sets of normal defaults D_1 and D_2. Suppose $D_1 \subseteq D_2$. Then, $D_1 \preceq D_2$. That is to say, the more normal defaults are used, the less believable the conclusions from them. Thus, the empty set of normal defaults are the most believable. The following proposition is particularly useful for the following discussion.

Proposition 3. *Let D_1 and D_2 be two sets of closed normal defaults. Suppose for any normal default $\{\frac{\phi\,:\,\psi}{\psi}\} \in D_1$ there is a normal default $\{\frac{\varphi\,:\,\psi}{\psi}\} \in D_2$ such that $\vdash \phi \rightarrow \varphi$. Then, $D_1 \preceq D_2$.*

For non-atomic actions, by admitting different set of default rules we have different default theories. Some of them are more believable than others. For example, for $a \parallel b$ we can have four possible default rules :

$$(\delta_1) \quad \frac{\begin{array}{c} holds(p, do(a; b, s)) \\ holds(p, do(b; a, s)) \end{array} : holds(p, do(a \parallel b, s))}{holds(p, do(a \parallel b, s))}$$

$$(\delta_2) \quad \frac{holds(p, do(a; b, s)) \ : \ holds(p, do(a \parallel b, s))}{holds(p, do(a \parallel b, s))}$$

$$(\delta_3) \quad \frac{holds(p, do(b; a, s)) \ : \ holds(p, do(a \parallel b, s))}{holds(p, do(a \parallel b, s))}$$

$$(\delta_4) \quad \frac{\begin{array}{c} holds(p, do(a; b, s)) \\ \vee \\ holds(p, do(b; a, s)) \end{array} : holds(p, do(a \parallel b, s))}{holds(p, do(a \parallel b, s))}$$

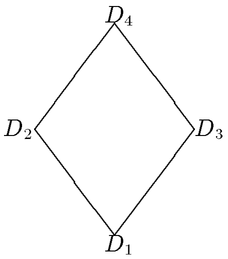

Fig. 1. Lattice of default rules.

Let $D_i = \{\delta_i\}$ for $i = 1, 2, 3, 4$. Then, by use of the above proposition it is easy to verify $D_1 \preceq D_2$, $D_1 \preceq D_3$, $D_2 \preceq D_4$, and $D_3 \preceq D_4$, as shown in figure 1.

The above discussion can be generalized for simultaneous actions of the form $a_1 \parallel \cdots \parallel a_n$. Generally, there are $n! + 2$ particularly interesting defaults for the simultaneous action $a_1 \parallel \cdots \parallel a_n$. For the sake of space limitation we will not delve into deeper discussions.

8 Comparison and discussion

The situation calculus was proposed as a general framework for reasoning about changes [10]. It was long believed that the expressiveness was rather restricted and limited, but no serious study on its expressive power had been made until Gelfond, et al [5] presented a pioneering effort and made a clarification. The main purpose of [5] is to clarify some misbeliefs on the situation calculus. The recent popularity enjoyed by the situation calculus is due to [5]. With respect to concurrent actions, a few interesting examples are given about independence, cancellation, conflict, etc. Although the ideas of [5] are profound, the specific details need to be elaborated. Recent approaches to dealing with concurrent actions in the framework of the situation calculus include [1, 2, 9], all of them are in line with the pioneering work [5]. Although there are some similarities between this paper and [1, 2, 9], some technical differences still exist, summarized as follows.

The focus of [1] is only on the concurrent actions. In particular, it discusses the concurrent actions where a constituent action may be composed of a sequence of actions. In [1] the exact meaning of "concurrent actions" is not clearly defined, and selective actions are totally ignored. In this paper we indicated that simultaneous actions are those composed of some actions which are performed at the same time. Thus we are dealing with common-sense actions in our reality, but not those concurrent actions introduced in software engineering. In addition, in this paper we have proposed some default rules to deal with (exclusive and inclusive) selective actions.

In [2], a language denoted by $\mathcal{A}_C$ and a translation methodology of theories from $\mathcal{A}_C$ to extended logic programs ELPs of [3] are proposed. In the translation, the following axioms, which are among major contributions of [2], play a vital rôle:

$$
\begin{array}{ll}
(a)\ holds(f, do(a, s)) & \leftarrow subsetof(b, a), holds(f, do(b, s)), \\
& \quad not\ noninherit(f, a, b, s) \\[2ex]
(b)\ \neg holds(f, do(a, s)) & \leftarrow subsetof(b, a), \neg holds(f, do(b, s)), \\
& \quad not\ noninherit(\overline{f}, a, b, s) \\[2ex]
(c)\ noninherit(\overline{F}, x, y, s) & \leftarrow subsetof(y, x), subsetof(A, x), \\
& \quad \neg subsetof(A, y), not\ \overline{holds(P_1, s)}, \\
& \quad \cdots, not\ \overline{holds(P_n, s)}
\end{array}
$$

where $noninherit(e, a, b, s)$ means "action a does not inherit fluent literal e from subaction b in situation s." According to these axioms, concurrent actions normally inherit their component actions' effects. This is the case when subactions are independent of each other. For example, the effect of $Switchon||Opendoor$ is the *net aggregation* of effects of *Switchon* and *Opendoor*. When subactions are independent of each other, both [2] and our default rules can achieve the same conclusions. When subactions are dependent on each other, some effect descriptions of concurrent actions can be omitted by use of our default rules and some cannot, as shown before. In the donation example, however, it is not clear whether and how to use the above ELP rules (a), (b) and (c) to derive effects of $donate(d_1)||donate(d_2)$ from effects of $donate(d)$. It seems that the default rules (5) are more expressive than the above axioms.

The focus of [9] is on the epistemological completeness proposed in [8]. Intuitively, a theory of an action is epistemologically complete if, given a complete description of the initial situation, the theory enables us to predict a complete description of the resulting situation when the action is performed. Lin and Shoham use some circumscriptive minimization techniques to deal with their generalized frame problem, which looks similar to our composition problem (a study of the precise relationship is still needed). Lin and Shoham's formalism enjoys the epistemological completeness. It seems that all of our formalism, and formalisms in [2, 1] do not have precisely this property. Actually it is questionable that epistemological completeness is always required. For example, $Holds(Open, do(Opendoor||Closedoor, s))$ could be derivable in [9] as indicated in [2], but it cannot be derived in either our formalism or [2, 1]: the effect of $Opendoor||Closedoor$ is unknown. In this case, we think that the epistemological completeness should not be required.

Acknowledgements
This work was partially supported by ESPRIT Project COMPULOG II (No. 6810) and and a post-doctoral fellowship under PRAXIS XXI/BPD/4165/94 of JNICT. We would also like to thank Gerd Wagner and Carlos Damásio for helpful discussions.

References

1. Alferes, J.J., R. Li, and Pereira, L.M., Concurrent Actions and Changes in the Situation Calculus, *Proc. of IBERAMIA 94*, Hector Geffner (ed.), McGraw-Hill, 1994, 93–104
2. Baral, C. and Gelfond, M., Representing concurrent actions in extended logic programming, *IJCAI*, 1993, pp. 866–871
3. M. Gelfond and V. Lifschitz, Logic programs with classical negation, In. *Logic Programming: proc. of the 7th Int'l Conf.*, D. Warren and P. Szeredi, eds., 1990, pp. 579–597
4. M. Gelfond and V. Lifschitz, Representing actions in extended logic programs, *Joint International Conference and Symposium on Logic Programming*, K. Apt (ed.), 1992, 559–573
5. Gelfond, M., Lifschitz, V., and Rabinov, A., What are the limitaions of the situation calculus?, Automated Reasoning: Essays in Honor of Woody Bledsoe, R. Moore (ed.), 1991, 167–179

6. Haas, A., The case for domain-specific frame axioms, *Proc. of the Workshop on the Frame Problem in Artificial Intelligence*, Morgan Kaufmann Publishers, Inc., 1987, 343–348
7. V. Lifschitz, Toward a metatheory of action, *Proc. of KR'91*, J. Allen, R. Fikes and E. Sandewall (eds.), Morgan Kaufmann Publishers, Inc., 376–386
8. F. Lin and Y. Shoham, Provably correct theories of actions: preliminary report, *Proc. of AAAI-91*, 1991
9. F. Lin and Y. Shoham, Concurrent actions in the situation calculus, *Proc. of AAAI-92*, 1992, 590–595
10. McCarthy, J. and Hayes, P.J., Some philosophical problems from the standpoint of artificial intelligence, in: B. Meltzer and D. Michie, (eds.), *Machine Intelligence*, 4, Edinburgh, 1969, 463–502
11. Pednault, E. P. D., ADL: Exploring the middle ground between STRIPS and the situation calculus, *Proc. of KR'89*, R. J. Brachman, H. Levesque, R. Reiter (eds.), Morgan Kaufmann Publishers, Inc., 324–332
12. Reiter, R., A logic for Default Reasoning, *Artificial Intelligence*, 13, 1980, 81–132
13. Reiter, R., The frame problem in the situation calculus: A simple solution (sometimes) and a completeness result for goal regression, *Artificial Intelligence and Mathematical Theory of Computation: Papers in Honor of John McCarthy*, V. Lifschitz (ed.), Academic Press, San Diego, CA, 1991, 359–380
14. Reiter, R., Proving properties of states in the situation calculus, *Artificial Intelligence*, 64:2, 1993, 337–351
15. Schubert, L., Monotonic solution of the frame problem in the situation calculus: An efficient method for worlds with fully specified actions, *Knowledge Representation and Defeasible Reasoning*, H. E. Kyberg, R. P. Loui, and G. N. Carlson (eds.), Kluwer Academic Press, Boston, 1990, 23–67

This article was processed using the LaTeX macro package with LLNCS style