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- Should the state play an active role and in what way?
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Technical Report

On Using The Situation Calculus Dynamically Rather Than Temporally

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Abstract

Yet another axiomatisation of the Yale shooting scenario is provided. The point illustrated by the axiomatisation is that, when using the situation calculus to represent knowledge about a dynamic system in which actions cause transitions between finitely many states, it is simpler to use the situation terms to model the states than to interpret situation terms as temporal indices.

Keywords: *circumscription, frame problem, minimal model, situation calculus, temporal projection problem, Yale shooting scenario*
Computing Review Categories: *F.4.1, I.2.3, I.2.4*

1 Introduction

In a classic paper [9], a formalism called the *situation calculus* was proposed, to be used for representing the knowledge needed to reason about dynamically changing systems. The situation calculus is a first-order language whose formulas contain a parameter that acts as a temporal index relative to which the properties of the changing system can be described. This parameter may be thought of as a variable of a particular *sort* (or type), namely of the sort whose values are situations (i.e. snapshots giving the complete state of the system at an instant of time). The situation calculus may therefore be viewed as a form of temporal logic, although not the kind of temporal logic that employs modal operators like $\Diamond$ and $\Box$. In this paper, we suggest that the situation parameter should be thought of non-temporally but nevertheless *dynamically*, as a variable ranging over states of the system. The distinction, while subtle, is profound. The temporal approach forces us to distinguish between a state of the system at one instant and the same state at another instant; the dynamic approach has the effect of simplifying matters by focusing directly on the states rather than on their positions along some time-line. We illustrate this simplification below by considering the Yale shooting scenario. This scenario affords instances of two general problems, the frame problem and the temporal projection problem, and was used in [2] to argue that the attempt to solve certain instances of the former problem by means of a specific technical device, namely circumscribing abnormality, would cause instances of the latter problem to arise. The next three sections explain what we understand by the frame problem, circumscribing abnormality, and the temporal projection problem.

2 The Frame Problem

Consider the dynamic system involving an individual named Fred and a gun. At some instant Fred is alive and the gun is unloaded. Actions that may have the effect of changing the state of the system are loading the gun, shooting the gun, and waiting. Intuitively we expect that loading an unloaded gun will succeed in changing the state to one in which the gun is loaded, shooting a loaded gun at Fred will kill Fred, and waiting will not change the state. This system is the *Yale shooting scenario* [2]. Our intuitive knowledge about the system can be represented by means of the following axioms: For the fact that at some known instant S_0 Fred is alive, we include axiom

$$A_1 = Holds(Alive, S_0).$$

Here *Holds* is a binary predicate constant representing a relation (the relation, whatever it may be, is called the extension of *Holds*), *Alive* is an individual constant of a particular sort, say **fact**, and S_0 is an individual constant of another sort, namely **situation**.

Since the gun becomes loaded at any time a load action takes place, we include axiom

$$A_2 = (\forall s)Holds(Loaded, Result(Load, s)).$$

(Here *Loaded* is a new individual constant of sort **fact**, while *Result(Load,s)* is a term of sort **situation** constructed by applying the binary function constant *Result* to a pair consisting of the individual constant *Load* of sort **action** and the variable *s* of sort **situation**).

For the fact that whenever Fred is shot with a loaded gun, he dies, we include axiom

$$\begin{aligned} A_3 = \quad & (\forall s)[Holds(Loaded, s) \\ & \rightarrow Holds(Dead, Result(Shoot, s))]. \end{aligned}$$

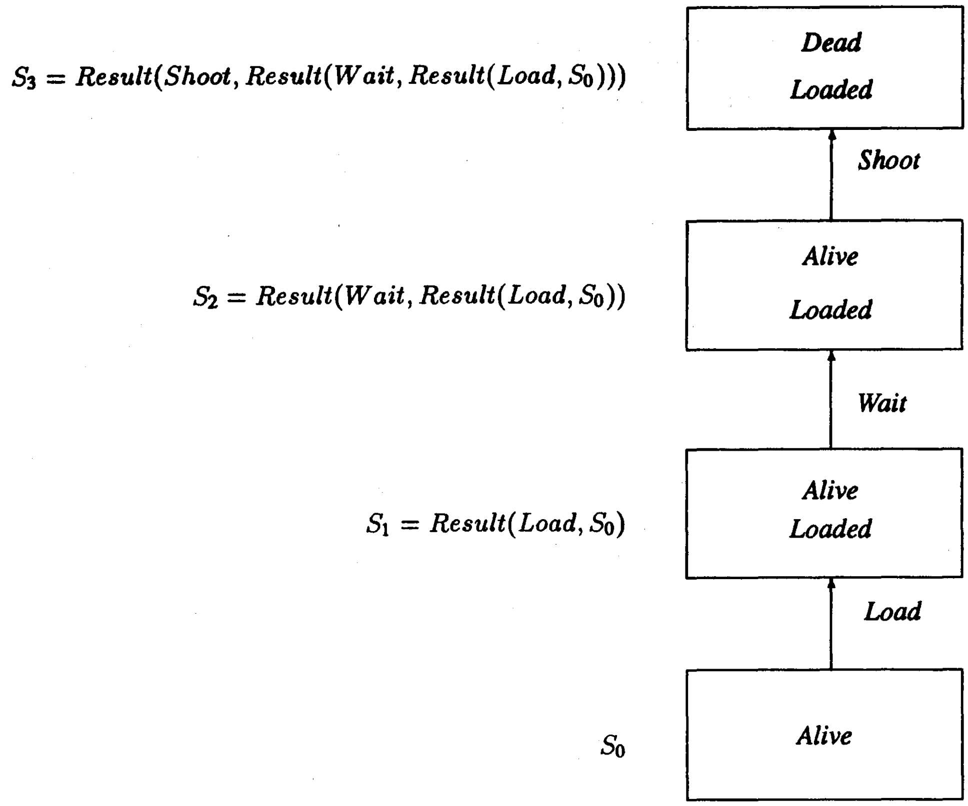

Figure 1. The intended Yale shooting scenario

(The only new terms in this axiom are the individual constant *Dead* of sort **fact** and *Shoot* of sort **action**).

To represent our conviction that Fred cannot be both *Alive* and *Dead* at the same time, we include the axiom

$$A_4 = (\forall s)[Holds(Alive, s) \leftrightarrow \neg Holds(Dead, s)].$$

In the standard axiomatisations of this scenario, we have no axiom constraining the effects of the action *Wait*. Of course, our intuition is that *Wait* should have no effects.

Figure 1 depicts the scenario as we would intuitively expect it to develop, namely that our individual is initially known to be alive, then the gun is loaded, then he waits for a while, then he is shot with the gun. As the figure illustrates, we expect Fred to be alive in the situation that results from loading the gun in the initial situation S_0, since the action of loading should not threaten Fred's life. However, the statement

$$Holds(Alive, Result(Load, S_0))$$

is not entailed by our very simple set of axioms. This suggests that we should augment our set of axioms by including

$$(\forall s)[Holds(Alive, s) \rightarrow Holds(Alive, Result(Load, s))].$$

This is an example of a frame axiom; such axioms differentiate the background unchanged by an action from the changing foreground. The *frame problem* is the problem of finding some alternative to the inclusion of such frame axioms.

One wishes to avoid resorting to frame axioms because

- humans don't seem to use frame axioms to make common sense inferences, so the inclusion of such axioms seems an untidy way to simulate human reasoning;
- in worlds of realistic complexity there are many actions and many facts that may hold in a given state of the system, and since the number of frame axioms is proportional to the product of the number of facts and the number of actions (because each action typically affects very few facts), using frame axioms in order to represent the aspects that remain unchanged would require an enormous number of such axioms;
- it may be very difficult to generate them, in view of the many exceptions that may complicate the task. As Ginsberg points out in [1]:

> 'Consider the example in which we remarked that moving an object never changes the location of another object. What if the objects are connected? A description suitable for monotonic reasoning will need to list the exceptions explicitly: If two objects are unconnected, then moving the first will never change the location of the second. The same problem occurs for the remark that moving an object never causes it to change color; imagine moving your car into the path of a spray paint gun. Cameras work because moving one object (the shutter) causes another object to change color (the film).'

To summarise: The frame problem is the question: 'How can one formally represent information about which facts persist after the performance of which actions without explicitly including in the system description a potentially enormous, and conceivably difficult to formulate, set of frame axioms?'. And what makes the frame problem nontrivial is that there is no obvious alternative to the inclusion of frame axioms. Fortunately there turns out to be an exceedingly unobvious alternative.

3 Circumscribing Abnormality

In [8] a formal device called *circumscription* is proposed as a candidate for solving the frame problem. The method was elaborated in [6] and [7]. McCarthy intended circumscription to formalise the following aspect of human informal reasoning:

> '...common sense reasoning is ordinarily ready to jump to the conclusion that a tool can be used for its intended purpose unless something prevents its use.'

A human reasoning about the Yale shooting scenario will make the implicit assumption that a fact such as 'Fred is alive' will persist from one state to another unless the action that precipitates the transition is one that is known to affect that particular fact. If we think of the fact 'Fred is alive' as an object that may or may not have the attribute that it is affected by the action *Load*, say, then the implicit assumption is that as few objects have this attribute as possible. In other words, for certain predicate constants P, an object x does not belong to the extension of P unless it is required to by the axioms that explicitly record our knowledge. Of course, if we know precisely what the (finite) extension of P must contain, we can express this information explicitly by means of axioms. If, however, all we know is that the extension of P must be as small as possible, given the need to satisfy other axioms, then an indirect approach is necessary. Circumscription is intended as an indirect way to force the extension of P to be as small as possible when the exact content cannot be stipulated in the axioms representing our knowledge.

How does one express in a first-order language L the notion that a predicate constant P must have minimal extension? One often can't. Intuitively, a model of an axiom A has a minimal extension for P if no proper subset of P could have been chosen without losing the truth of A. So one needs a language that will permit quantification over subsets. In [3] it is shown that the minimality of P can be expressed very elegantly by means of a second-order formula, that is, a formula having a variable ranging over relations, not just over individual objects. Lifschitz's definition (somewhat simplified) expresses the following idea: Suppose we have an axiom A and wish to pick out those models of A in which the extension of some predicate constant P is minimal. Then the models we are interested in are precisely the models of the second-order formula

$$A \wedge \neg\exists p(A' \wedge p \prec P),$$

where A' is the wf obtained from A by replacing every occurrence of 'P' by 'p', and '$p \prec P$' is an abbreviation for the wf

$$(\forall x)(p(x) \rightarrow P(x)) \wedge \neg(\forall y)(P(y) \rightarrow p(y)).$$

The wf $A \wedge \neg\exists p(A' \wedge p \prec P)$ is *the circumscription of P in A*, or CIRC(A;P) for short. Informally CIRC(A;P) says 'A is the case, and there is no relation p such that

- p is a proper subset of the extension of P in some model M of A and
- a model N of A can be constructed by replacing the extension of P in M by p.'

McCarthy's approach to solving the frame problem involves the introduction of a predicate constant Ab, representing abnormality, which is minimised by circumscription. The idea is that such a predicate constant allows us to formulate a persistence axiom that says 'Normally, facts are unaffected by actions and continue to persist'. Such a persistence axiom replaces in one fell swoop the whole class of frame axioms we expected to have to include. Let us see how circumscription of abnormality ensures that Fred is alive in the situation that results from loading the gun in S_0. We shall modify the axioms given earlier with the help of the new predicate constant Ab. Intuitively, Ab represents a 3-ary relation whose triples comprise a fact, an action, and a situation, and the relation holds whenever execution of the action in the relevant situation may alter the fact.

For the fact that at some known instant S_0 Fred is alive, we include axiom

$$A_1 = Holds(Alive, S_0).$$

Since the gun becomes loaded at any time a load action takes place, we include axiom

$$A_2 = (\forall s)Holds(Loaded, Result(Load, s)).$$

For the fact that whenever Fred is shot with a loaded gun, he dies, we include axiom

$$\begin{aligned} A_3 = \quad & (\forall s)[Holds(Loaded, s) \\ & \rightarrow Holds(Dead, Result(Shoot, s)) \wedge \\ & Ab(Alive, Shoot, s)]. \end{aligned}$$

To represent our conviction that Fred cannot be both *Alive* and *Dead* at the same time, we insert the axiom

$$A_4 = (\forall s)[Holds(Alive, s) \leftrightarrow \neg Holds(Dead, s)].$$

To reflect our belief that 'normal' facts persist across the occurrence of 'normal' actions, we include the persistence axiom

$$\begin{aligned} A_5 = \quad & (\forall fas)[Holds(f, s) \wedge \neg Ab(f, a, s) \\ & \rightarrow Holds(f, Result(a, s))]. \end{aligned}$$

Axiom A_5 is our substitute for the frame axioms and will, with the help of circumscription, ensure that, unless a fact is known to be abnormal with respect to an action, that fact will be unaffected by the action. (Hence we must explicitly include in axiom A_3 the stipulation that aliveness is abnormal with respect to shooting in any situation in which the gun is loaded.)

If we circumscribe the predicate constant *Ab* in the axioms A_1 through A_5, in other words consider only models of these axioms in which the extension of *Ab* is minimal, then in each of these models

$$Holds(Alive, Result(Load, S_0))$$

is true. To see this it is sufficient to note that Fred is alive in situation S_0 by axiom A_1 and that by axiom A_5 Fred's aliveness must persist into situation $Result(Load, S_0)$ – unless aliveness is abnormal with respect to loading (which, in a model with a minimal extension for *Ab*, cannot be the case). Thus the circumscription of *Ab* solved at least the instance of the frame problem that we were considering.

4 The Temporal Projection Problem

The argument that shows Fred to be alive in situation $Result(Load, S_0)$ depends upon the claim that, in a model with minimal extension for *Ab*, aliveness cannot be abnormal with respect to loading. As pointed out in [2], the question as to what is abnormal in a minimal model is not as simple as one might have hoped. The 'intended' minimal model for the Yale shooting scenario, depicted in Figure 1, has an extension for the predicate constant *Ab* containing only one abnormality. To see this, we reason as follows. We know *Alive* must be true in situation S_0. Since nothing in our axioms compels us to believe that being *Alive* is abnormal with regard to the action *Load* in situation S_0, the extension of *Ab* need not contain a member asserting the abnormality of *Alive* relative to *Load* and S_0. Hence, by A_5, Fred is still *Alive* in situation $Result(Load, S_0)$. Reasoning along the same lines, the gun must be loaded in $Result(Load, S_0)$, while *Alive* should not be abnormal with respect to *Wait* and situation $Result(Load, S_0)$. Nor should *Loaded* be abnormal with respect to *Wait* and situation $Result(Load, S_0)$, which in turn means that, in situation $Result(Wait, Result(Load, S_0))$, Fred must be *Alive* and the gun *Loaded*. By A_3, aliveness must be abnormal with respect to shooting in $Result(Wait, Result(Load, S_0))$. Nothing forces us to assume that being *Loaded* is abnormal with respect to shooting in situation $Result(Wait, Result(Load, S_0))$, so the extension of *Ab* needs contain only a single member, namely that asserting the abnormality of aliveness with respect to shooting referred to above.

As Hanks and McDermott show, this 'intended' model is not the only minimal model. An unintended minimal model, depicted in Figure 2, can be constructed by reasoning as follows. For brevity, use the names S_1, S_2, and S_3 for the situations that result from S_0 by successively performing the actions *Load*, *Wait*, and *Shoot*. Assume that Fred is still alive in S_2. Is this possible? Well, if we do not want Fred to die when shot, *Alive* should not be abnormal with respect to *Shoot* in S_2. But then A_3 can be satisfied only if the gun is not loaded in S_2. Since S_1 is the situation resulting from S_0 by virtue of the action *Load*, axiom A_2 forces the gun to be loaded in S_1. Hence by A_5, the gun would be loaded in S_2 unless *Loaded* is abnormal with respect to *Wait* in S_1. Including a corresponding element in the extension of *Ab* (and nothing else) delivers a minimal model, but this minimal model possesses the counter-intuitive property that Fred is alive in S_2, which means that we cannot infer from our axioms, even after circumscribing *Ab*, that the sequence of loading, waiting and shooting will kill Fred. The existence of an unintended minimal model in which waiting mysteriously unloads the gun makes the Yale shooting scenario host to an instance of the general temporal projection problem. The temporal projection problem is distinct from the frame problem; circumscribing *Ab* and including a persistence axiom solved the frame problem for the Yale shooting scenario, but did not solve the problem of predicting whether Fred would be alive or not at the conclusion of a sequence of actions.

Various fixes have been proposed, such as the use of a more complicated form of circumscription called pointwise circumscription in [5], but, as Hanks and McDermott remark, these lose along the way 'the original idea behind circumscription, [namely] that a simple, problem-independent extension to a first-order theory would 'minimize' predicates in just the right way'.

In the section that follows, we show that the unintended minimal models may be avoided without sacrificing the simple idea of circumscribing abnormality. All that is needed is to view situations as states rather than temporal instants.

5 The Non-temporal Approach

In the discussion of the Yale shooting scenario, it was assumed that each situation was 'the complete state of the universe at an instant of time', in accordance with the original intuition expressed in [9]. The complete set of situations constituted an infinite branching time-tree:

$$\begin{array}{ll}
S_0, & \\
Result(Load, S_0), & Result(Load, Result(Load, S_0)), \ldots \\
 & Result(Wait, Result(Load, S_0)), \ldots \\
 & Result(Shoot, Result(Load, S_0)), \ldots \\
Result(Wait, S_0), & Result(Load, Result(Wait, S_0)), \ldots \\
 & Result(Wait, Result(Wait, S_0)), \ldots \\
 & Result(Shoot, Result(Wait, S_0)), \ldots \\
Result(Shoot, S_0), & Result(Load, Result(Shoot, S_0)), \ldots \\
 & Result(Wait, Result(Shoot, S_0)), \ldots \\
 & Result(Shoot, Result(Shoot, S_0)), \ldots
\end{array}$$

However, many dynamic systems undergo transitions from one state to another without there being any obvious temporal direction involved. Just think of the blocks world, for instance: each state of the blocks world consists of a configuration of blocks some of which may be on others, and actions such as moving one block from the top of a second to the top of a third result in a change of state – but there is no point in labelling some states as earlier in time than other states, since the appropriate sequence of

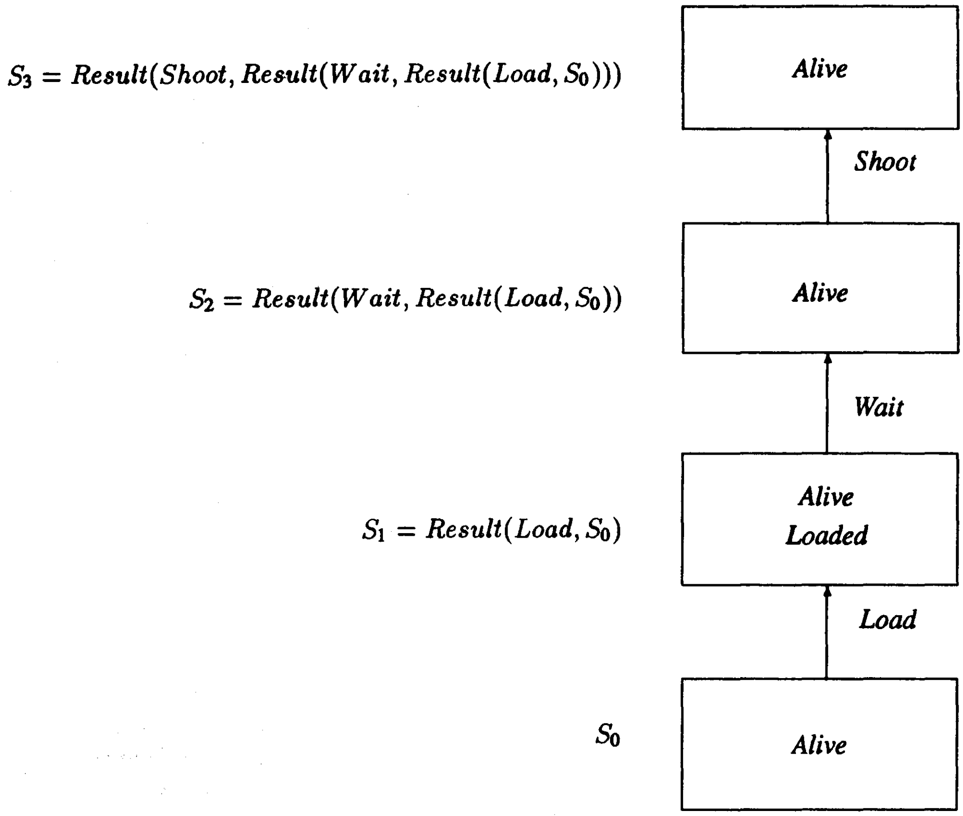

Figure 2. Scenario of our unintended model

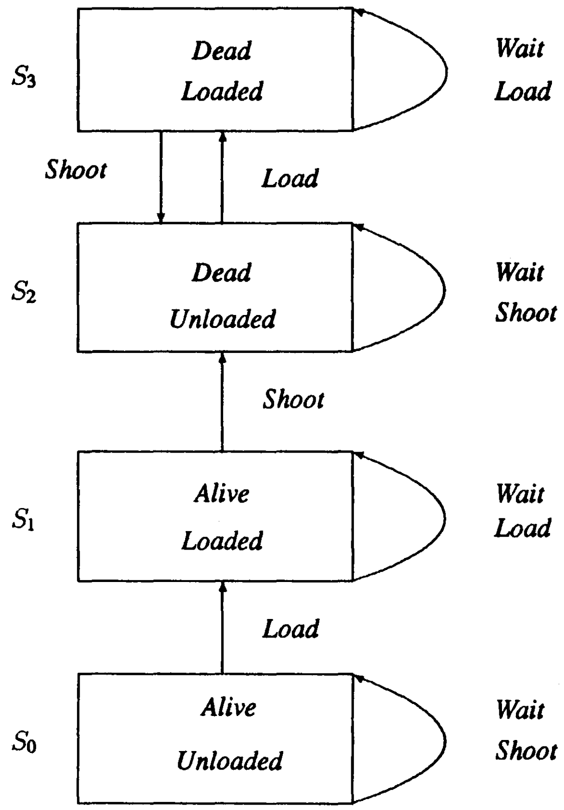

Figure 3. The sequence of events in the Yale shooting scenario

actions can transform any state into any other state. The situation calculus can clearly be used to represent information about such systems in a non-temporal but dynamic fashion in which situations represent states of the system (unassociated with temporal instants) and actions trigger transitions from one state to another. Intuitively, each state is characterised by the set of facts that hold in that state. This re-interpretation of situations was suggested by the following remark in [4]:

> 'Equations (3)–(5) can be interpreted as the description of a deterministic finite automaton *A* with 4 internal states, corresponding to all possible combinations of values of the fluents *loaded* and *alive*. The input symbols of *A* are *load, wait, shoot.*'

What follows is a simple axiomatisation of the Yale shooting scenario that avoids both the frame problem and the temporal projection problem, and whose simplicity is largely due to the fact that only four situations need be considered, rather than infinitely many as is the case in the temporal approach. The system is depicted in Figure 3. Situations S_0, S_1, S_2, and S_3 represent the four possible states of the system, namely Fred alive and gun unloaded, Fred alive and gun loaded, Fred dead and gun unloaded and lastly Fred dead and gun loaded.

Consider the following set of axioms. For the facts that at some known situation S_0 Fred is alive and the gun is unloaded and that loading and shooting change the situations as pictured in Figure 3, we include axiom

$$\begin{aligned} A_1 = \quad & Holds(Alive, S_0) \wedge Holds(Unloaded, S_0) \wedge \\ & S_1 = Result(Load, S_0) \wedge \\ & S_2 = Result(Shoot, S_1) \wedge \\ & S_3 = Result(Load, S_2). \end{aligned}$$

For the fact that the gun becomes loaded at any time a load action takes place and furthermore that a gun being loaded is abnormal with respect to staying unloaded, we include axiom

$$\begin{aligned} A_2 = \quad & (\forall s)[Holds(Unloaded, s) \\ & \rightarrow Holds(Loaded, Result(Load, s)) \wedge \\ & Ab(Unloaded, Load, s)]. \end{aligned}$$

For the facts that shooting a loaded gun unloads it, that whenever Fred is shot with a loaded gun, he dies, and furthermore that being shot with a loaded gun is abnormal with respect to staying alive, we include axiom

$$\begin{aligned} A_3 = \quad & (\forall s)[Holds(Loaded, s) \\ & \rightarrow Holds(Unloaded, Result(Shoot, s)) \wedge \\ & Ab(Loaded, Shoot, s) \wedge \\ & Holds(Dead, Result(Shoot, s)) \wedge \\ & Ab(Alive, Shoot, s)]. \end{aligned}$$

For the assertion that Fred is not dead and alive at the same time and that the gun is not loaded and unloaded at the same time we include

$$\begin{aligned} A_4 = \quad & (\forall s)[(Holds(Alive, s) \leftrightarrow \neg Holds(Dead, s)) \wedge \\ & (Holds(Loaded, s) \leftrightarrow \neg Holds(Unloaded, s))]. \end{aligned}$$

For the assertion that 'normal' facts persist across the occurrence of 'normal' actions, we include the persistence axiom

$$\begin{aligned} A_5 = \quad & (\forall fas)[Holds(f, s) \wedge \neg Ab(f, a, s) \\ & \rightarrow Holds(f, Result(a, s))]. \end{aligned}$$

We have no axiom containing *Wait*, but since according to the existing axioms no fact is known to be abnormal with respect to the occurrence of action *Wait*, we intend that every fact true before the *Wait* action occurs should also be true after it occurs.

Since the scenario we have in mind involves four states, one for each legal combination of facts, we introduce the domain closure axiom

$$A_6 = (\forall s)(s = S_0 \vee s = S_1 \vee s = S_2 \vee s = S_3).$$

Now circumscribing *Ab* with respect to axioms A_1 to A_6 solves both the frame problem and, because this is achieved without permitting the existence of minimal models in which waiting mysteriously unloads the gun, the temporal projection problem. It is easy to see that the inclusion of the persistence axiom, A_5, solves the frame problem. To see that in all minimal models the sequence *Load, Wait,* and *Shoot* results in Fred's death we argue as follows.

In any model *M* of the axioms, there is a situation denoted by S_0 in which Fred is alive and the gun is unloaded, this is so by A_1. *M* also has a second situation, denoted by S_1, in which the gun is loaded – this is so by A_2 – and the extension of *Ab* contains a member stating that unloadedness is abnormal with respect to S_0 and the action of loading. In S_1, Fred may or may not be alive, depending on the extension of *Ab*. If the extension of *Ab* fails to contain a member asserting that Fred's aliveness is abnormal with respect to S_0 and the action of loading, then Fred is alive in S_1, by A_4. We will argue that in no minimal model of the axioms can the extension of *Ab* contain such a member. *M* also has a third situation, denoted by S_2, in which the gun is unloaded and Fred is dead, by A_3. Moreover, also by A_3, the extension of *Ab* contains two members asserting that the loadedness of the gun is abnormal with respect to shooting in S_1 and that the aliveness of Fred is abnormal with respect to shooting in S_1. Finally, *M* has a fourth situation denoted by S_3, in which the gun is loaded, by A_2, which also ensures that *Ab* contains an appropriate member describing the abnormality of unloadedness in S_2 w.r.t. loading, and Fred is dead or alive, depending on the extension of *Ab*. If the extension of *Ab* fails to contain a member asserting that Fred's deadness is abnormal with respect to S_2 and the action of loading, then Fred will still be dead in S_3, by A_4. We will argue that in no minimal model of the axioms can the extension of *Ab* contain such a member. By A_3, the extension of *Ab* must contain members asserting that loadedness is abnormal with respect to shooting in S_3 and aliveness is abnormal with respect to shooting in S_3.

To summarise, the extension of *Ab* in any model of the axioms must contain members asserting that

in S_0 unloadedness is abnormal with respect to loading;

in S_1 aliveness is abnormal with respect to shooting and loadedness is abnormal with respect to shooting;

in S_2 unloadedness is abnormal with respect to loading;

in S_3 aliveness is abnormal with respect to shooting and loadedness is abnormal with respect to shooting.

No minimal model can contain more than these elements in the extension of *Ab*, nor can any of these be omitted without falsifying an axiom. Hence, in particular, a member asserting that loadedness is abnormal in S_1 with respect to waiting cannot be made to belong to the extension of *Ab* in a minimal model; nor can a member asserting that deadness is abnormal in S_2 with respect to loading. Hence in all minimal models of the axioms Fred is dead in the situations denoted by S_2 and S_3.

This shows that, provided we are willing to interpret situations non-temporally as states, the Yale shooting scenario does not afford an instance of either the frame problem or the temporal projection problem that we are unable to handle by circumscribing *Ab*-predicates. McCarthy's approach to solving the frame problem by circumscribing abnormality therefore remains an effective resource. The significance of the Yale shooting scenario suggests, therefore, that the situation calculus is better viewed as a form of dynamic logic than as a form of temporal logic.

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Notes for Contributors

The prime purpose of the journal is to publish original research papers in the fields of Computer Science and Information Systems, as well as shorter technical research papers. However, non-refereed review and exploratory articles of interest to the journal's readers will be considered for publication under sections marked as Communications or Viewpoints. While English is the preferred language of the journal, papers in Afrikaans will also be accepted. Typed manuscripts for review should be submitted in triplicate to the editor.

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Manuscripts for *review* should be prepared according to the following guidelines.

- Use wide margins and $1\frac{1}{2}$ or double spacing.
- The first page should include:
  - title (as brief as possible);
  - author's initials and surname;
  - author's affiliation and address;
  - an abstract of less than 200 words;
  - an appropriate keyword list;
  - a list of relevant Computing Review Categories.
- Tables and figures should be numbered and titled. Figures should be submitted as original line drawings/printouts, and not photocopies.
- References should be listed at the end of the text in alphabetic order of the (first) author's surname, and should be cited in the text in square brackets [1–3]. References should take the form shown at the end of these notes.

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1. As (a) LaTeX file(s), either on a diskette, or via e-mail/ftp – a LaTeX style file is available from the production editor;
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