Embracing Causality in Specifying the Indeterminate Effects of Actions

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Abstract
This paper makes the following two contributions to formal theories of actions: showing that a causal minimization framework can be used effectively to specify the effects of indeterminate actions; and showing that for certain classes of such actions, regression, an effective computational mechanism, can be used to reason about them.

Introduction
Much recent work on theories of actions has concentrated on primitive, determinate actions. In this paper, we pose ourselves the problem of specifying directly the effects of indeterminate actions, like we do for the primitive, determinate ones.

There are several reasons why we think this is an important problem. First of all, there are actions whose effects, when described at a natural level, are indeterminate. Second, one can argue that there is no absolute defining line between determinate and indeterminate actions. The differences have a lot to do with the levels of descriptions. The effects of an action may be determinate at one level of description, but indeterminate at another. So a theory that treats determinate and indeterminate actions in fundamentally different ways will have difficulties coping with language changes. Finally, even if all the primitive actions have determinate effects, there are still needs for specifying directly the effects of complex actions that are often indeterminate. For instance, these specifications may be part of the inputs to a program synthesizer.

Our contributions in this paper are two folds. We first show that the causal minimization framework of (Lin [5]) can be used effectively to specify the effects of indeterminate actions. We then show that for certain classes of such actions, regression, an effective computational mechanism, can be used to reason about them.

Logical Preliminaries
We shall investigate the problem in the framework of the situation calculus [8]. Our version of it employs a many sorted second-order language. We assume the following sorts: situation for situations, action for actions, fluent for propositional fluents, truth-value for truth values true and false, and object for everything else.

We use the following domain independent predicates and functions:
- The binary function $do$ - for any action $a$ and any situation $s$, $do(a, s)$ is the situation resulting from performing $a$ in $s$.
- The binary predicate $H$ - for any propositional fluent $p$ and any situation $s$, $H(p, s)$ is true if $p$ holds in $s$.
- The binary predicate $Poss$ - for any action $a$ and any situation $s$, $Poss(a, s)$ is true if $a$ is possible (executable) in $s$.
- The ternary predicate $Caused$ - for any fluent $p$, any truth value $v$, and any situation $s$, $Caused(p, v, s)$ is true if the fluent $p$ is caused to have the truth value $v$ in the situation $s$. For instance, $Caused(loade, true, do(loade, s))$ means that the action load causes loaded to be true in the resulting situation.

We shall make use some additional special predicates and functions, and will introduce them when they are needed.

We assume that all theories in this paper will include the following basic axioms:
- For the predicate $Caused$, the following two basic axioms:
  \[ Caused(p, true, s) \supset H(p, s). \] 
  \[ Caused(p, false, s) \supset \neg H(p, s). \]
- For the truth values, the following unique names and domain closure axiom:
  \[ true \neq false \land (\forall v)(v = true \lor v = false). \]
• The unique names assumptions for fluent and action names (we assume there are only finitely many of them). Specifically, if \( \{F_1, \ldots, F_n\} \) is the set of the fluent names, then we have:
\[
F_i(\bar{x}) \neq F_j(\bar{y}), \quad \text{if} \quad i \neq j \text{ are different},
\]
\[
F_i(\bar{x}) = F_i(\bar{y}) \implies \bar{x} = \bar{y}.
\]

Similarly for action names. In the following, we shall denote this set of unique names axioms by \( D_{una} \).

• The set \( \Sigma \) of foundational axioms in [6] for the discrete situation calculus. These axioms characterize the structure of the space of situations. For the purpose of this paper, it is enough to mention that they include the following unique names axioms for situations:
\[
s \neq do(a, s),
\]
\[
do(a, s) = do(a', s') \implies (a \neq a' \land s = s').
\]

In the rest of this paper, we shall frequently make use of the following shorthand notation: If \( F \) is a fluent name of arity \( \text{object}^n \rightarrow \text{fluent} \), then we define the expression \( F(t_1, \ldots, t_n, t_s) \) to be a shorthand for the formula \( H(F(t_1, \ldots, t_n, t_s)) \), where \( t_1, \ldots, t_n \) are terms of sort \( \text{object} \), and \( t_s \) a term of sort \( \text{situation} \). So if \( \text{white} \) is a fluent, then \( \text{white}(s) \) is a shorthand for \( H(\text{white}, s) \).

### Minimizing Causation

The approach of (Lin [5]) to specifying the effects of actions can be summarized as follows:

1. Formalize the causal laws and constraints of the domain by a set \( T \) of axioms.
2. Circumscribe (minimize) \( \text{Caused} \) in \( T \cup \Sigma \cup D_{una} \cup \{1, 2, 3\} \) with all other predicates fixed.
3. The resulting theory, \( T' \), together with the following generic frame axiom: Unless caused otherwise, a fluent’s truth value will persist:
\[
\text{Poss}(a, s) \supset \neg (\exists v) \text{Caused}(p, v, do(a, s)) \supset [H(p, do(a, s)) \equiv H(p, s)],
\]
will generate the appropriate frame axioms.

Lin [5] also discusses how the action preconditions can be generated. However, in this paper we shall not concern us with this problem, but assume, following (Reiter [10]), that for each action \( A(\bar{x}) \), we are given an action precondition axiom of the form:
\[
\text{Poss}(A(\bar{x}), s) \equiv \Psi_A(\bar{x}, s),
\]
where \( \Psi_A \) is a formula that does not quantify over situation variables, and does not mention any situation dependent atomic formulas except those of the form \( H(t, s) \), where \( t \) is a propositional fluent term.

We shall be using the following lemma for computing the circumscription of \( \text{Caused} \):

**Lemma 1** Let \( W = T \cup \Sigma \cup D_{una} \cup \{1, 2, 3\} \). Then \( \text{Circum}(W, \text{Caused}) \), the result of circumscribing \( \text{Caused} \) in \( W \) with all other predicates fixed, is equivalent to
\[
\{\text{Poss}(T, \text{Caused}) \} \cup \Sigma \cup D_{una} \cup \{1, 2, 3\}.
\]

**Proof:** This is because the predicate \( \text{Caused} \) occurs only negatively in \( \Sigma \cup D_{una} \cup \{1, 2, 3\} \).

To illustrate how to use this approach to specify the effects of indeterminate actions, consider Reiter’s example of dropping a pin on a checkerboard: The pin may land inside a white square, inside a black square, or touching both.

We introduce three fluents: \( \text{white} \) (all or part of the pin is in a white square), \( \text{black} \) (all or part of the pin is in a black square), and \( \text{holding} \) (the agent is holding the pin); and two actions: \( \text{drop} \) (the agent drops the pin on the checkerboard), and \( \text{pickup} \) (the agent picks up the pin). We have the following action precondition axioms:\(^{3}\)
\[
\text{Poss}(\text{drop}, s) \equiv \text{holding}(s) \land \neg \text{white}(s) \land \neg \text{black}(s),
\]
\[
\text{Poss}(\text{pickup}, s) \equiv \neg \text{holding}(s) \land (\text{white}(s) \lor \text{black}(s)).
\]

We have the following effect axioms:
\[
\begin{align*}
\text{Poss}(\text{pickup}, s) & \supset \quad \text{Caus}(\text{holding}, \text{true}, \text{do}(\text{pickup}, s)), \quad (5) \\
\text{Poss}(\text{pickup}, s) & \supset \quad \text{Caus}(\text{white}, \text{false}, \text{do}(\text{pickup}, s)), \quad (6) \\
\text{Poss}(\text{pickup}, s) & \supset \quad \text{Caus}(\text{black}, \text{false}, \text{do}(\text{pickup}, s)), \quad (7) \\
\text{Poss}(\text{drop}, s) & \supset \quad \text{Caus}(\text{holding}, \text{false}, \text{do}(\text{drop}, s)), \quad (8) \\
\text{Poss}(\text{drop}, s) & \supset \quad \text{Caus}(\text{white}, \text{true}, \text{do}(\text{drop}, s)) \land \\
& \quad \text{Caus}(\text{black}, \text{false}, \text{do}(\text{drop}, s)) \lor \\
& \quad \text{Caus}(\text{white}, \text{false}, \text{do}(\text{drop}, s)) \land \\
& \quad \text{Caus}(\text{black}, \text{true}, \text{do}(\text{drop}, s)) \lor \\
& \quad \text{Caus}(\text{black}, \text{true}, \text{do}(\text{drop}, s)). \quad (9)
\end{align*}
\]
Suppose these are the only effect axioms, and there are no causal rules and state constraints.\(^{4}\) By Lemma 1, it is easy to see that circumscribing \( \text{Caused} \) in
\[
\{(5) - (9)\} \cup \Sigma \cup D_{una} \cup \{1, 2, 3\}
\]
yields:
\[
\text{Poss}(a, s) \land \text{Caused}(p, v, do(a, s)) \supset
\]
\(^{3}\)Recall that as we have defined in Section 4, \( \text{holding}(s) \), for instance, is a shorthand for \( H(\text{holding}, s) \).

\(^{4}\)Notice that the state constraint \( (\forall s) \neg \text{holding}(s) \land (\text{white}(s) \lor \text{black}(s)) \) has been built into the action effect and precondition axioms.
a = pickup ∧ [(p = holding ∧ v = true) ∨ (p = white ∧ v = false) ∨ (p = black ∧ v = false)] ∨ a = drop ∧ [(p = holding ∧ v = false) ∨ p = white ∨ p = black].

From this and the generic frame axiom (4), we can deduce the following successor state axiom (Reiter [10]) for holding:

\[ \text{Poss}(s, a) ∨ \text{holding}(d(o(a), s)) \equiv (a = pickup ∨ (\text{holding}(s) ∧ a ≠ drop)). \]

We don’t get successor state axioms for white and black. But we have the following explanation closure axioms:
\[ \text{Poss}(a, s) ∧ ¬[\text{white}(s) \equiv \text{white}(d(o(a), s))] \supset (a = pickup ∨ a = drop), \]
\[ \text{Poss}(a, s) ∧ ¬[\text{black}(s) \equiv \text{black}(d(o(a), s))] \supset (a = pickup ∨ a = drop). \]

These axioms, together with the effect axioms, yield the following disjunction of successor state axioms:
\[ \text{Poss}(a, s) \supset \]
\[ \{(\text{white}(d(o(a), s)) \equiv (a = drop ∨ (\text{white}(s) ∧ a ≠ pickup)) ∧ \}
\[ \text{black}(d(o(a), s)) \equiv (a = drop ∨ (\text{black}(s) ∧ a ≠ pickup)) \} \]
\[ \{(\text{white}(d(o(a), s)) \equiv (a = drop ∨ (\text{white}(s) ∧ a ≠ pickup)) \} \]
\[ \{\text{black}(d(o(a), s)) \equiv (a = drop ∨ (\text{black}(s) ∧ a ≠ pickup)) \}. \]

Notice the correspondences between the three cases and those in drop’s effect axiom for white and black.

Classes of Indeterminate Actions

The indeterminate effects of drop are inclusive in that the pin may land on a white square, a black square, or both. To see how such inclusive indeterminate effects can be represented succinctly, notice first that under the two general axioms (1) and (2) about Caused, the effect axiom (9) is equivalent to the following three axioms:
\[ \text{Poss}(\text{drop}, s) \supset \{\text{Caused}(\text{white}, \text{true}, d(o(\text{drop}, s))) \lor \]
\[ \text{Caused}(\text{black}, \text{true}, d(o(\text{drop}, s))) \} \]
\[ \text{Poss}(\text{drop}, s) \supset \{\text{Caused}(\text{white}, \text{true}, d(o(\text{drop}, s))) \lor \]
\[ \text{Caused}(\text{white}, \text{false}, d(o(\text{drop}, s))) \} \]
\[ \text{Poss}(\text{drop}, s) \supset \{\text{Caused}(\text{black}, \text{true}, d(o(\text{drop}, s))) \lor \]
\[ \text{Caused}(\text{black}, \text{false}, d(o(\text{drop}, s))) \}. \]

Notice that under the domain closure and unique names axiom (3) for truth values, the last axiom is equivalent to
\[ \text{Poss}(\text{drop}, s) \supset (\exists v) \text{Caused}(\text{black}, v, d(o(\text{drop}, s))). \]

This axiom is like the releases propositions in the action description language of [3]. Notice here the necessity of something like the predicate Caused. The corresponding sentence in terms of H:
\[ \text{Poss}(\text{drop}, s) \supset \{H(\text{black}, d(o(\text{drop}, s))) \lor \]
\[ \neg H(\text{black}, d(o(\text{drop}, s))) \}

is just a tautology.

In general, if the action α has inclusive indeterminate effects on the fluent terms P₁, ..., Pₙ, i.e. causes at least one of them to be true and the rest of them to be false, under the context γ, then we have the following causal laws:
\[ \text{Poss}(\alpha, s) ∧ γ \supset \{\text{Caused}(P_{i}, \text{true}, d(o(\alpha, s))) \lor \]
\[ \text{Caused}(P_{i}, \text{true}, d(o(\alpha, s))) \} \]
\[ \text{Poss}(\alpha, s) ∧ γ \supset \{\text{Caused}(P_{i}, \text{true}, d(o(\alpha, s))) \lor \]
\[ \text{Caused}(P_{i}, \text{false}, d(o(\alpha, s))) \} \]

where 1 ≤ i ≤ n.

The number of indeterminate effects need not be finite. If, under the context γ, the action α has the inclusive indeterminate effects on F(x) for those x that satisfies φ, then we have the following causal laws:
\[ \text{Poss}(\alpha, s) ∧ γ ∧ (\exists x) \phi(x) \supset \]
\[ (\exists x)[\phi(x) ∧ \text{caused}(F(x), \text{true}, d(o(\alpha, s)))], \]
\[ \text{Poss}(\alpha, s) ∧ γ ∨ (\forall x)[\phi(x) \supset \]
\[ \text{Caused}(F(x), \text{true}, d(o(\alpha, s))) \lor \]
\[ \text{Caused}(F(x), \text{false}, d(o(\alpha, s))) \} \].

For instance, playing loud rock and roll music will make some of the nearby people (including the person who plays it) happy, and the rest of them unhappy: let γ be true, φ(x) be nearby(x, s), and F(x) be happy(x).

Contrast to the inclusive indeterminate effects, we have the exclusive ones. For instance, flipping a coin causes exactly one of {head, tail} to be true. Generally, if the action α has exclusive indeterminate effects on the fluent terms P₁, ..., Pₙ, i.e. causes exactly one of them to be true and the rest of them to be false, under the context γ, then we have the following causal laws:
\[ \text{Poss}(\alpha, s) ∧ γ ∨ \{\text{Caused}(P_{i}, \text{true}, d(o(\alpha, s))) \lor \]
\[ \text{Caused}(P_{i}, \text{true}, d(o(\alpha, s))) \} \]
\[ \text{Poss}(\alpha, s) ∧ γ ∨ \{\text{Caused}(P_{i}, \text{true}, d(o(\alpha, s))) \lor \]
\[ \text{Caused}(P, \text{false}, d(o(\alpha, s))) \} \]
\[ \text{Poss}(\alpha, s) ∧ γ ∨ \{\text{Caused}(P_{i}, \text{true}, d(o(\alpha, s))) \lor \]
\[ \text{Caused}(P, \text{false}, d(o(\alpha, s))) \} \]
\[ \text{Poss}(\alpha, s) ∧ γ ∨ \{\text{Caused}(P_{i}, \text{true}, d(o(\alpha, s))) \lor \]
\[ \text{Caused}(P, \text{false}, d(o(\alpha, s))) \} \].

where 1 ≤ i ≤ n, and ∨ is the exclusive or operator:
\[ \varphi_{1} ∨ \cdots ∨ \varphi_{k} ≡ (\varphi_{1} ∨ \cdots ∨ \varphi_{k}) ∧ \bigwedge_{1 ≤ i ≠ j ≤ k} ¬(\varphi_{i} ∧ \varphi_{j}). \]
Again, the number of indeterminate effects need not be finite. If, under the context \( \gamma \), the action \( \alpha \) has the exclusive indeterminate effects on \( F(x) \), for those \( x \) that satisfies \( \varphi \), then we have the following causal laws:

\[
Poss(\alpha, s) \land \gamma \land (\exists x) \varphi(x) \supset (\exists x)[\varphi(x) \land caused(F(x), true, do(\alpha, s))],
\]

\[
Poss(\alpha, s) \land \gamma \supset (\forall x)\{\varphi(x) \supset [caused(F(x), \text{true}, do(\alpha, s)) \lor Caused(F(x), \text{false}, do(\alpha, s)))]\},
\]

where \( (\exists! x) \) means there is a unique \( x \). For instance, picking a ball from a bag causes one to hold one and only one of the balls in the bag; let \( \gamma \) be true, \( \varphi(x) \) be in-bag \((x, s)\), and \( F(x) \) be holding \((x)\).

There are, of course, actions with indeterminate effects that are neither inclusive or exclusive. In general, if the number of the indeterminate effects of an action \( A(\xi) \) is finite, then its effect axioms can be written of the following forms:

\[
Poss(A(\xi), s) \supset (\forall p, s)[\varphi(\xi, p, v, s) \supset Caused(p, v, do(A(\xi), s))],
\]

\[
Poss(A(\xi), s) \supset (\forall p, v)[\varphi(\xi, p, v, s) \supset Caused(p, v, do(A(\xi), s))]
\]

\[
\vdots
\]

\[
(\forall p, v)[\varphi(\xi, p, v, s) \supset Caused(p, v, do(A(\xi), s))],
\]

where \( \varphi \) and \( \varphi_i \)s are formulas that do not quantify over situation variables, and do not mention any other situation dependent atomic formulas except those of the form \( H(t, s) \).

For instance, the two effect axioms about drop can be rewritten as:

\[
Poss(\text{drop}, s) \supset (\forall p, s)[p = \text{holding} \land v = \text{false} \supset Caused(p, v, do(\text{drop}, s))],
\]

\[
Poss(\text{drop}, s) \supset (\forall p, v)[(p = \text{white} \land v = \text{true} \lor p = \text{black} \land v = \text{false}) \supset Caused(p, v, do(\text{drop}, s))]
\]

\[
(\forall p, v)[(p = \text{white} \land v = \text{false} \lor p = \text{black} \land v = \text{true}) \supset Caused(p, v, do(\text{drop}, s))]
\]

\[
(\forall p, v)[(p = \text{white} \land v = \text{true} \lor p = \text{black} \land v = \text{true}) \supset Caused(p, v, do(\text{drop}, s))]
\]

Notice that (10) and (11) can be combined into a single axiom of the latter form. But as we shall see later, it is beneficial to have a separate axiom for determinate effects.

**Computing Successor State Axioms**

We now consider how to reason with the theories of the actions whose effects are specified by axioms of the forms (10) and (11).

Let \( T_{\text{s}a} \) be a given set of the effect axioms of the forms (10) and (11). Then the conjunction of the sentences in \( T_{\text{s}a} \) is separable (Lifschitz [4]) w.r.t. Caused. Therefore, according to a result in [4], Circum(T_{\text{s}a}.Caused), the circumscription of Caused in \( T_{\text{s}a} \), is computable by a first-order sentence. In general, this sentence, together with \( D_{\text{una}} \), will yield a disjunction of successor state axioms, which is often large and cumbersome to reason with. In particular, it is not clear how to compute regression, a computationally effective mechanism for tasks such as planning and temporal projection [11, 9, 10], w.r.t. such disjunctions.

**A Transformation**

To overcome this, we introduce a new ternary predicate \( \text{Case} \) of the arity object \( \times \) action \( \times \) situation, and a distinguished constant \( 0 \) and a unary function \( \text{succ} \) over sort object. We use the convention that if a natural number \( n \) occurs as an object term in a formula, then it is considered to be a shorthand for the term obtained from \( 0 \) by applying \( n \) times the function \( \text{succ} \).

For instance, in \( \text{Case}(2, a, s) \), the number 2 is a shorthand for \( \text{succ}(\text{succ}(0)) \).

Now we shall consider \( \text{Case} \) to be an auxiliary predicate introduced for computational purposes. Later, we shall consider some possible interpretations of this predicate.

Using \( \text{Case} \), we transform the indeterminate effect axiom (11) into the following sentences that have the form of a deterministic effect axiom:

\[
Poss(A(\xi), s) \land \text{Case}(1, A(\xi), s) \supset (\forall p, v)[\varphi(\xi, p, v, s) \supset \text{Caused}(p, v, do(A(\xi), s))],
\]

\[
\vdots
\]

\[
Poss(A(\xi), s) \land \text{Case}(n, A(\xi), s) \supset (\forall p, v)[\varphi_n(\xi, p, v, s) \supset \text{Caused}(p, v, do(A(\xi), s))] \]

\[
\text{Circum}(T_{\text{s}a}.\text{Caused}),
\]

\[
(\forall p, v)[\varphi(\xi, p, v, s) \supset \text{Caused}(p, v, do(A(\xi), s))],
\]

\[
(\forall p, v)[(p = \text{white} \land v = \text{true} \lor p = \text{black} \land v = \text{false}) \supset \text{Caused}(p, v, do(\text{drop}, s))]
\]

\[
(\forall p, v)[(p = \text{white} \land v = \text{false} \lor p = \text{black} \land v = \text{true}) \supset \text{Caused}(p, v, do(\text{drop}, s))]\)

Notice that (10) and (11) can be combined into a single axiom of the latter form. But as we shall see later, it is beneficial to have a separate axiom for determinate effects.

\[
(\forall p, v)[(p = \text{white} \land v = \text{true} \lor p = \text{black} \land v = \text{true}) \supset \text{Caused}(p, v, do(\text{drop}, s)),
\]

(13)

Notice that (10) and (11) can be combined into a single axiom of the latter form. But as we shall see later, it is beneficial to have a separate axiom for determinate effects.

\[
(\forall p, v)[(p = \text{white} \land v = \text{false} \lor p = \text{black} \land v = \text{false}) \supset \text{Caused}(p, v, do(\text{drop}, s))]
\]

\[
(\forall p, v)[(p = \text{white} \land v = \text{true} \lor p = \text{black} \land v = \text{true}) \supset \text{Caused}(p, v, do(\text{drop}, s))]
\]

\[
(\forall p, v)[(p = \text{white} \land v = \text{true} \lor p = \text{black} \land v = \text{true}) \supset \text{Caused}(p, v, do(\text{drop}, s))]
\]

(13)

Notice that (10) and (11) can be combined into a single axiom of the latter form. But as we shall see later, it is beneficial to have a separate axiom for determinate effects.

\[
(\forall p, v)[(p = \text{white} \land v = \text{false} \lor p = \text{black} \land v = \text{false}) \supset \text{Caused}(p, v, do(\text{drop}, s))]
\]

(13)

Notice that (10) and (11) can be combined into a single axiom of the latter form. But as we shall see later, it is beneficial to have a separate axiom for determinate effects.
in lights of the following Theorem 1 which will establish the correctness of the above transformation.

Notice also that this transformation applies only to the indeterminate effect axiom (11). This is why it is beneficial to put as much information as possible into (10).

In the following, we shall denote by $T'_{ea}$ the set of axioms obtained from $T_{ea}$ by replacing every indeterminate effect axiom in it of the form (11) by the axioms (14) - (15). We shall denote by $D_{case}$ the set of constraints (16) and (17). Notice that this set is also depended on $T_{ea}$.

Given two theories $T_1$ and $T_2$ such that $T_1$'s language is $T_2$'s augmented by a new predicate $P$, we say that these two theories are equivalent with respect to $T_2$'s language if $T_1$ is a conservative extension of $T_2$: a structure is a model of $T_2$ iff it can be extended into a model of $T_1$. As it turns out, this is the same as saying that $T_2$ is the result of forgetting $P$ in $T_1$ according to (Lin and Reiter [7]), and according to a result there, when $T_1$ is finite, this is the same as saying that $T_2$ is logically equivalent to the sentence $(\exists P). \bigwedge T_1$, where $\bigwedge T_1$ is the conjunction of the sentences in $T_1$.

We have:

**Theorem 1** Under the unique names axioms $D_{una}$, the result of circumscribing Caused in $T'_{ea} \cup D_{case}$ is a conservative extension of the result of circumscribing Caused in $T_{ea}$:

$$D_{una} \models \text{Circum}(T'_{ea}, \text{Caused}) \equiv (\exists \text{Case}) \text{Circum}(T'_{ea} \cup D_{case}, \text{Caused}).$$

**Corollary 1.1** Under the unique names assumptions, for any formula $\varphi$ that does not mention Case, $\text{Circum}(T_{ea}, \text{Caused}) \models \varphi$ iff $\text{Circum}(T'_{ea} \cup D_{case}, \text{Caused}) \models \varphi$.

### Computing Successor State Axioms

Having established the correctness of the above transformation, we now proceed to show how to generate successor state axioms from the resulting axioms.

Notice first that the sentence (10) can be rewritten into an axiom of the following form:

$$\text{Poss}(\hat{A}z, s) \land \varphi(x, p, v, s) \supset \text{Caused}(p, v, \text{do}(A(x), s)).$$

Similarly, we can do the same for axioms of the form (14) - (15). Now from these axioms in $T'_{ea}$, we can generate, for each fluent $F$, two new axioms of the following forms:

$$\text{Poss}(a, s) \land \gamma^a_P(\vec{x}, a, s) \supset \text{Caused}(F(\vec{x}), \text{true}, \text{do}(a, s)), \quad (18)$$

$$\text{Poss}(a, s) \land \gamma^a_P(\vec{x}, a, s) \supset \text{Caused}(F(\vec{x}), \text{false}, \text{do}(a, s)), \quad (19)$$

where $\gamma^a_P$ and $\gamma^a_P$ do not quantify over situation variables, and the only situation dependent atomic formulas in them are either of the form $H(t, s)$ or of the form $\text{Case}(t_1, t_2, s)$.

Given these two effect axioms, we generate the following successor state axiom for $F$:

$$\text{Poss}(a, s) \supset F(\vec{x}, \text{do}(a, s)) \equiv \gamma^a_P(\vec{x}, a, s) \vee (F(x, s) \land \neg \gamma^a_P(\vec{x}, a, s)). \quad (20)$$

Now let $D_{ss}$ be the set of successor state axioms, one for each fluent, so generated. Our claim is that, under some reasonable conditions, $D_{ss}$ captures all the information about the truth values of the fluents in $\text{Circum}(T_{ea}, \text{Caused}) \cup \{1, 2, 4\}$. More precisely, we have:

**Theorem 2** Under the assumption that the following consistency condition [10] is satisfied for each fluent $F$:

$$D_{una} \cup D_{ap} \cup D_{case} \models (\forall \vec{x}, a, s). \text{Poss}(a, s) \supset \neg (\gamma^a_P(\vec{x}, a, s) \land \gamma^a_P(\vec{x}, a, s)),$$

the theory

$$\Sigma \cup D_{una} \cup D_{ap} \cup \{\text{Circum}(T'_{ea}, \text{Caused})\} \cup D_{case} \cup \{1, 2, 3, 4\} \models \varphi$$

is a conservative extension of the theory

$$\Sigma \cup D_{una} \cup D_{ap} \cup D_{ss} \cup D_{case} \cup \{3\} \models \varphi.$$

**Corollary 2.1** Under the assumptions in the theorem, for any formula $\varphi$ that does not mention Caused,

$$\Sigma \cup D_{una} \cup D_{ap} \cup \{\text{Circum}(T'_{ea}, \text{Caused})\} \cup D_{case} \cup \{1, 2, 3, 4\} \models \varphi$$

iff

$$\Sigma \cup D_{una} \cup D_{ap} \cup D_{ss} \cup D_{case} \cup \{3\} \models \varphi.$$

**Corollary 2.2** Under the assumptions in the theorem, for any formula $\varphi$ that does not mention Caused and Case,

$$\Sigma \cup D_{una} \cup D_{ap} \cup \{\text{Circum}(T_{ea}, \text{Caused})\} \cup \{1, 2, 3, 4\} \models \varphi$$

iff

$$\Sigma \cup D_{una} \cup D_{ap} \cup D_{ss} \cup D_{case} \cup \{3\} \models \varphi.$$

**Proof:** Apply Theorem 1 and Theorem 2. □

Theorem 2 informs us that if we are only concerned with the truth values of fluents, then the original effect axioms as well as the basic axioms about Caused can all be discarded. In particular, this is the case with the projection problem.

Technically, the consistency conditions are needed because without these conditions, the successor state axiom (20) may not entail the formula

$$\text{Poss}(a, s) \supset F(\vec{x}, \text{do}(a, s)) \supset \neg F(\vec{x}, \text{do}(a, s)),$$

which is a consequence of the effect axiom (19) and the two basic axioms (1) and (2) about causality.
Example 1 Consider again our checkerboard example. We shall consider only the successor state axioms for white and black. The indeterminate effect axiom (13) of drop is translated into:

\[
Poss(\text{drop}, s) \land \text{Cas}(1, \text{drop}, s) \supset \]
\[
[\text{Caused(white, true, do(drop, s))] \land \]
\[
\text{Caused(black, false, do(drop, s))}],
\]
\[
Poss(\text{drop}, s) \land \text{Cas}(2, \text{drop}, s) \supset \]
\[
[\text{Caused(white, false, do(drop, s))] \land \]
\[
\text{Caused(black, true, do(drop, s))}],
\]
\[
Poss(\text{drop}, s) \land \text{Cas}(3, \text{drop}, s) \supset \]
\[
[\text{Caused(white, true, do(drop, s))] \land \]
\[
\text{Caused(black, true, do(drop, s))}].
\]
Together with the original determinate effect axioms, we have:

\[
Poss(a, s) \supset \]
\[
[a = \text{drop} \land (\text{Cas}(1, \text{drop}, s) \lor \text{Cas}(3, \text{drop}, s))] \supset \]
\[
\text{Caused(white, true, do(a, s))},
\]
\[
Poss(a, s) \supset \]
\[
[a = \text{pickup} \lor (a = \text{drop} \land \text{Cas}(2, \text{drop}, s))] \supset \]
\[
\text{Caused(white, false, do(a, s))}.
\]
Thus we have the following successor state axiom for white:

\[
Poss(a, s) \supset \{\text{white}(\text{do(a, s)}) \equiv \]
\[
[a = \text{drop} \land (\text{Cas}(1, \text{drop}, s) \lor \text{Cas}(3, \text{drop}, s))] \lor \]
\[
\text{white}(s) \land \]
\[
\neg[a = \text{pickup} \lor (a = \text{drop} \land \text{Cas}(2, \text{drop}, s))].
\]
A similar successor axion can be obtained for black. It can be seen that the consistency conditions are satisfied for both white and black.

We shall not get into details regarding the accompanied constraints about Case, but note that for this example, all constraints of the form (17) are logical consequence of the unique names assumptions. So the following is the only nontrivial constraint about Case:

\[
\text{Cas}(1, \text{drop}, s) \lor \text{Cas}(2, \text{drop}, 2) \lor \text{Cas}(3, \text{drop}, 3).
\]

Regression and Some of Its Properties
Once we have a successor state axiom for each fluent, regression becomes syntactic substitutions [10]: for any formula \(\varphi(s)\) that does not quantify over situation, and action \(a\), the regression of a formula \(\varphi(s)\) over \(a\), written \(R(\varphi(s), a)\), is the result of replacing in \(\varphi(s)\) every atomic formula of the form \(H(F(\tilde{t}), s)\) by \(\Phi_F(F(a), s)\), where

\[
Poss(a, s) \supset [F(\tilde{a}, \text{do}(a, s))] \equiv \Phi_F(F(a), s)
\]
is the successor state axiom for \(F\).

The following result is immediate:

Lemma 2 Let \(D_{sa}\) be a set of successor state axioms, one for each fluent. We have:

\[
\mathcal{D}_{sa} = (\forall s).Poss(\alpha, s) \supset [\varphi(s) \equiv R(\varphi, \alpha)].
\]
In the rest of this section, we assume that we’ve given an action theory of the form:

\[
\mathcal{D} = \Sigma \cup D_{ana} \cup D_{ap} \cup D_{sa} \cup D_{case} \cup D_{S_0},
\]
where \(D_{case}\) is a set of Case constraints of the form (16) or of the form (17), and \(D_{S_0}\) is a set of sentences that do not mention any other situation term except \(S_0\), and do not mention \(Poss, \text{Caused}, \text{and Case}\). The other components of \(\mathcal{D}\) have the usual meaning.

Our main concern is the soundness and completeness of regression for doing temporal projection with respect to the initial database. Our first positive result is about Case independent temporal projections:

Theorem 3 Let \(\varphi(s)\) be a formula that does not quantify over situation variable, does not mention any other situation term except \(s\), and does not mention \(Poss, \text{Caused}, \text{and Case}\). Let \(\alpha\) be an action term. If, under \(\mathcal{D}_{ana}\), \(R(\varphi, \alpha)\) is equivalent to a formula that does not mention Case, then

\[
\mathcal{D} \models \varphi(\text{do}(\alpha, S_0))
\]
iff

\[
D_{S_0} \cup D_{ana} \models \Psi(S_0) \land R(\varphi, \alpha)(S_0),
\]
where \(D_{ap} \models \text{Poss}(\alpha, S_0) \equiv \Psi(S_0)\), \(R(\varphi, \alpha)(S_0)\) is obtained from \(R(\varphi, \alpha)\) by replacing \(s\) by \(S_0\), and \(\varphi(\text{do}(\alpha, S_0))\) is obtained from \(\varphi(s)\) by replacing \(s\) by \(\text{do}(\alpha, S_0)\).

Notice that this theorem depends on the particular form the constraints in \(D_{case}\) have: they are about Case only, that is, the result of forgetting it will yield a tautology: \((\exists \text{Case})D_{case} \equiv true\). Under the unique names assumptions, \(R(\varphi, \alpha)\) is equivalent to a formula that does not mention Case. This condition holds if the action \(\alpha\)'s effects on the fluents in \(\varphi\) are definite. Thus Theorem 3 informs us for reasoning about the determinate effects of actions, the auxiliary predicate \(\text{Case}\) can be rightly ignored.

When either \(\varphi(s)\) or its regression mentions \(\text{Case}\), we need to include constraints on \(\text{Case}\):

Theorem 4 Let \(\varphi(s)\) be a formula that does not quantify over situation variables, and does not mention Poss and Caused. Let \(\alpha\) be an action term. If \(D_{case}\) does not mention \(H\), then

\[
\mathcal{D} \models \varphi(\text{do}(\alpha, S_0))
\]
iff

\[
D_{S_0} \cup D_{ana} \cup D_{case} \models \Psi(S_0) \land R(\varphi, \alpha)(S_0).
\]

Given the forms (16) and (17) the constraints in \(\mathcal{D}_{case}\) must take, \(\mathcal{D}_{case}\) does not mention \(H\) if all the indeterminate effects of actions are context free. This
condition is needed because although $D_{case}$ itself contains no information about $H$, it can when used together with some assumptions about $Case$ that can be easily incorporated into the query $\varphi(s)$.

Finally, notice that Theorem 3 and Theorem 4 can be generalized to temporal projections with sequences of actions.

The Ramification Problem

Although the framework of [3] was introduced for handling the ramification problem, we have so far ignored this problem in this paper. We now show how the indirect effects of actions can be represented.

Consider again our checkerboard example. Suppose that for whatever reasons, whenever the pin is touching both a white and a black square, our friend Fred will be happy. This constraint can be represented as:

$$white(s) \land black(s) \supset Caused(happy, true, s). \quad (21)$$

Notice that this causal law is different from the effect axioms in that the situation in both the antecedent and the consequent is the same. Thus it plays the role of a traditional domain constraint. With this causal rule, under the unique names assumptions about fluents, circumscribing $Caused$ will yield:

$Caused(happy, v, s) \equiv (v = true \land white(s) \land black(s))$.

And we have:

$$Poss(a, s) \supset \begin{cases} \{[white(do(a, s))] \equiv \\
(a = drop \lor (white(s) \land a \neq pickup)) \land \\
[black(do(a, s))] \equiv \\
(a = drop \lor (black(s) \land a \neq pickup)) \land \\
happy(do(a, s)) \equiv (a = drop \lor happy(s))] \land \\
{[white(do(a, s))] \equiv \\
(a = drop \lor (white(s) \land a \neq pickup)) \land \\
[black(do(a, s))] \equiv \\
(black(s) \land a \neq pickup \land a \neq drop)) \land \\
happy(do(a, s)) \equiv happy(s)\} \lor \\
{[white(do(a, s))] \equiv \\
(white(s) \land a \neq pickup \land a \neq drop)) \land \\
[black(do(a, s))] \equiv \\
(a = drop \lor (black(s) \land a \neq pickup)) \land \\
happy(do(a, s)) \equiv happy(s)\}. \end{cases}$$

Notice that two of the three cases include the frame axiom $happy(do(a, s)) \equiv happy(s)$. This can be avoided if we use the predicate $Case$.

The constraint (21) and the original effect axioms of $drop$ yields the following new effect axioms:

$$Poss(drop, s) \supset (\forall p, v)\{ [p = holding \land v = false] \supset Caused(p, v, do(drop, s))] \lor$$

$$Poss(drop, s) \supset \begin{cases} \{[p = white \land v = true] \lor \\
p = black \land v = false\} \supset Caused(p, v, do(drop, s))] \lor \\
(\forall p, v)\{ [p = white \land v = black] \lor \\
p = black \land v = true\} \supset Caused(p, v, do(drop, s))] \lor \\
(\forall p, v)\{ [p = white \land v = true] \lor \\
p = black \land v = true\} \lor$$

$Caused(p, v, do(drop, s)].$}

Apply the transformation of Section to this set of effect axioms will yield the same successor state axioms in Example 1 for $white$ and $black$, and the following one for $happy$:

$$Poss(a, s) \supset happy(do(a, s)) \equiv (a = drop \land Case(drop, 3, s)) \lor happy(s).$$

This example shows the flexibility of the $Case$ predicate when there are state constraints.

Constraints can also yield implicit indeterminate effects. For instance, if there are $k$ black squares, then we'll have:

$$Caused(black, true, s) \equiv$$

$$Caused(black_1, true, s) \lor \cdots \lor$$

$$Caused(black_k, true, s),$$

$$Caused(black, false, s) \equiv$$

$$Caused(black_1, false, s) \land \cdots \land$$

$$Caused(black_k, false, s),$$

$$(\exists v)Caused(black, s, v) \equiv (\exists v)Caused(black_1, s, v),$$

for any $1 \leq i \leq k$. Notice that the last axiom schema postulates that whenever an action affects the truth values of $black_i$, then it also affects the truth values of $black_j$, for any $1 \leq i, j \leq k$.

Related Work and Discussions

Epistemologically, we have shown how the causal minimization framework of [5] can be used to specify the indeterminate effects of actions. Computationally, we have shown how goal regression can be used to reason about them.

There have been other proposals in the literature (e.g., [1, 2, 3, 12]) for specifying the effects of indeterminate actions. To the best of our knowledge, the computational contribution of this work is novel.

Among the extant approaches, the ones in [3] and [1] seem closest to ours. As we mentioned in Section , the $releases$ propositions of [3]: A $releases$ $F$ corresponds to the following axiom in our language:

$$Poss(A, s) \supset Caused(F, true, do(A, s)) \lor$$

$$Caused(F, false, do(A, s)).$$
Regarding the work of [1], the \( \text{In}(F) \) and \( \text{Out}(F) \) predicates there correspond to \( \text{Caused}(F, \text{true, do}(a, s)) \) and \( \text{Caused}(F, \text{false, do}(a, s)) \), respectively, in our language. However, the formalism of [3] is limited because no complex \textit{releases} propositions are allowed. For instance, one cannot write expressions like

\[(\forall a). a \text{ releases } F \leftrightarrow a \text{ releases } F'.\]

The formalism of [1] is also limited because the action parameters of its \( \text{In} \) and \( \text{Out} \) predicates are not made explicit, thus cannot be quantified over.

Finally, we want to remark on the auxiliary predicate \( \text{Case} \). In this paper, we have used it entirely for computational purposes. However, there are some interesting possible interpretations of this predicate.

There is a sense that \( \text{Case} \) can be interpreted in probabilistic terms. For instance, if

\[
\text{Poss}(\text{drop}, s) \land \text{Case}(1, \text{drop}, s) \supset \\
\text{Caused(white, true, do(\text{drop}, s))} \land \\
\text{Caused(black, false, do(\text{drop}, s))},
\]

then \( \text{Case}(1, \text{drop}, s) \) may stand for the probability of the pin lying entirely within a white square after it has been dropped. Under this interpretation, the first constraint (16) on \( \text{Case} \), in this example the following one:

\[
\text{Case}(1, \text{drop}, s) \lor \text{Case}(2, \text{drop}, s) \lor \text{Case}(3, \text{drop}, s),
\]

says that the explicitly enumerated possible outcomes are both exclusive and exhaustive, and the constraints (17) simply eliminate redundant outcomes. In this regard, it would be interesting to formally connect our approach to probabilistic ones. This is a future research that we’re pursuing.

Another possible interpretation of \( \text{Case} \) is based on the view that in principle, it is always possible to reduce indeterminate actions to determinate ones, and one way of doing this is to introduce new fluents to name those low level contexts under which the effects of actions will be determinate. According to this view, \( \text{Case} \) can be seen as playing the role of such new fluents. For instance, \( \text{Case}(1, \text{drop}, s) \) may name the context under which \( \text{drop} \) has the effect of causing the pin lying entirely within a white square. We are currently exploring the possible impact of this interpretation as well.

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