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Abstract

The range of applicability of the Full Event Calculus *is proven to be the* $\mathcal{K}$**sp-IA** *class in the* Features and Fluents *taxonomy. The proof is given with respect to the original definition of this preference logic, where no adjustments of the language or reasoning method were necessary. The result implies that the claims on the expressiveness and problem-solving power of this logic were indeed correct.*

1 Introduction

We consider two well established approaches to Nonmonotonic temporal Reasoning about Actions and Change: the *Event Calculus* approach by Shanahan [16] and the *Features and Fluents* approach by Sandewall [14, 15]. It turns out that, although the design of suitable preference logics is a common task to both approaches, Sandewall's approach emphasises the systematic classification of these logics, via formally proven assessments of their range of applicability, while Shanahan's approach does not use any similar methodology. The aim of this paper is to extend the benefit of Sandewall's systematic methodology to Shanahan's approach. As a case study, we show that the most useful among all definitions of the Event Calculus, the *Full Event Calculus* (FEC), is a preference logic to which Sandewall's systematic methodology applies. Shanahan originally proposed FEC as suitable, i.e. adequate in expressiveness and problem-solving power, for correctly solving a number of NRAC reasoning problems with the following characteristics. The information about actions is accurately and completely specified, actions succeed only if their preconditions are satisfied, successful actions may have a nondeterministic effect, state variables are truth-valued, the initial state of the world is accurately and completely specified, and there is no information at any later state than the initial one. The time structure consists in the set of natural numbers with their standard order relation. The reasoning implements temporal inertia. In this paper, the range of applicability of FEC is proven to be the $\mathcal{K}$**sp-IA** class in the *Features and Fluents* taxonomy. The proof is given with respect to the original definition of this preference logic, where no adjustments of the language or reasoning method were necessary. As $\mathcal{K}$**sp-IA** formally captures all of the above characteristics, this assessment result implies that the claims on the expressiveness and problem-solving power of FEC were indeed correct.

The general meaning of this assessment result is that the assessed logic is guaranteed, or *certified* to be correctly applicable to all reasoning problems in the class, i.e. the logic always gives the correct, intended set of conclusions when applied to any reasoning problem in that class. As the *Full Event Calculus* is the first of a family of other similar definitions, also involving important implementation issues, this assessment result discloses knowledge on how to certify the expressiveness and problem-solving power of these logics. Assuming the given implementation is correct, the final user would then be guaranteed on its fitness for a particular purpose [1], unlike all other products of similar nature.

Finally, a word on the Frame Problem. $\mathcal{K}$**sp-IA** admits an important sub-class, $\mathcal{K}$**sp-IAd**, obtained by restricting $\mathcal{K}$**sp-IA** to the case of purely deterministic actions. In 1986 [4, 5] Hanks and McDermott pointed out that none of the reasoning methods developed so far, including predicate circumscription, were correctly addressing the Frame Problem. They used the Yale Shooting Problem as a diagnostic example. In 1994 [14, page 168] Sandewall classified this problem, for which the $\mathcal{K}$**sp-IAd** class resulted to be the smallest class including a correct solution for it. As FEC is correctly applicable to $\mathcal{K}$**sp-IA**, and $\mathcal{K}\mathbf{sp\text{-}IAd} \subset \mathcal{K}\mathbf{sp\text{-}IA}$, then FEC implements a provably correct solution to the Hanks-McDermott problem.

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2 Preliminaries

We assume the reader familiar with the *Features and Fluents* systematic methodology. Readers with no preliminary knowledge in the topic are invited to consult [1, 15, 14]. Any concept not explicitly defined in this paper refers to [1].

The research task in this paper is precisely described as follows, with some preliminaries.

Definition 2.1 (Preference Logic) *[20, pages 73-77] Let $\mathcal{L}$ be a standard logic, i.e. a logic with the usual compositional model-theoretic semantics.*

- *Let $\ll$ be a strict partial order on interpretations for $\mathcal{L}$. Intuitively, $I_1 \ll I_2$ means that the interpretation I_2 is* preferred *over the interpretation I_1. $\mathcal{L}$ and $\ll$ define a new logic $\mathcal{L}_\ll$. We call such logics* preference logics.

- *Let α, β be in $\mathcal{L}$. α* preferentially entails *β, written $\alpha \models_\ll \beta$, if for any M, if $M \models_\ll \alpha$ then $M \models \beta$ or, equivalently, if the models (preferred and otherwise) for β are a superset of the preferred models for α.*

- *$\mathcal{L}_\ll$ is* monotonic *if for all $\alpha, \beta, \gamma \in \mathcal{L}$, if $\alpha \models_\ll \gamma$ then also $\alpha \wedge \beta \models_\ll \gamma$.* ∎

Definition 2.2 (Range of Applicability) *[1, definition 2.9] Let $\mathcal{L}_\ll$ be a preference logic, let Υ be a scenario description and let ζ be the mapping defined in terms of $\ll$ that selects those members of the classical model set $[\![\Upsilon]\!]$ which are minimal according to $\ll$, so that the maximally preferred models are the selected ones. We say that "$\mathcal{L}_\ll$ is correct for Υ" iff the preferred model set for Υ and the intended model set for Υ are identical, i.e. iff [2] $\zeta([\![\Upsilon]\!]) = \Sigma(\Upsilon)$. We call "range of applicability of $\mathcal{L}_\ll$" the class of all Υ such that $\mathcal{L}_\ll$ is correct for Υ. We call "classification of $\mathcal{L}_\ll$" the formally proven assessment of the range of applicability of $\mathcal{L}_\ll$.* ∎

Within model-theoretic AI, Shoham's 1986 [19] notion of model preference is a generalisation [20, pages 83-85] of McCarthy's 1980 [10] predicate circumscription, which in turn is a generalisation [12] of Clark's 1978 [2, 3] predicate completion. Shanahan's *Full Event Calculus* is a preference logic; in fact, as summarised in definition 3.1, it uses classical first-order logic as base logic and predicate circumscription as model-preference criterion.

As Shanahan's *Full Event Calculus* is a preference logic, the research task in this paper then consists in formally assessing its range of applicability. However, it is required by definition 2.2 that ζ and Σ use the same language for Υ. As meeting this requirement is not possible in the present case, we extend the notion of correctness by redefining it in terms of an immersion operator. We then say that "$\mathcal{L}_\ll$ is correct for Υ" iff $\zeta([\![T(\Upsilon)]\!]) = \Sigma(\Upsilon)$, where Υ is written in the underlying language and $T(\Upsilon)$ is the translation of Υ in the language of $\mathcal{L}_\ll$. If T is the identity operator, then $T(\Upsilon) \equiv \Upsilon$ and the previous definition of correctness applies. The following is the underlying language for Υ.

Definition 2.3 (Underlying Language) *[1, section 3.1.3] Let $\mathcal{T}$ be the time-point domain [1, section 3.1.1], $\mathcal{F}$ the set of all feature symbols, $\mathcal{V}$ the domain of all feature values, and $\mathcal{E}$ the set of all action symbols. Let $\langle \mathcal{H}, \sqsubseteq \rangle$ be the lattice whose elements, called* observations, *are members of $\mathcal{H} = \mathcal{T} \times \mathcal{F} \times 2^{\mathcal{O}} \times \mathcal{V}$ and the order relation $\sqsubseteq$ applies as follows: $\langle t_1, f_1, \{\ldots\}, v_1 \rangle \sqsubseteq \langle t_2, f_2, \{\ldots\}, v_2 \rangle$ iff $t_1 \sqsubseteq t_2$. The tuple $\langle t, f, \{\ldots\}, unknown \rangle$ is an abbreviation for $\bigvee_i \langle t, f, \{\ldots\}, v_i \rangle$, varying i over all possible tuples $\langle t, f, \{\ldots\}, v_i \rangle$ in $\mathcal{H}$. Let $\langle \mathcal{D}, \sqsubseteq \rangle$ be the lattice whose elements, called* rigid occurrences of actions, *are members of $\mathcal{D} = \mathcal{T} \times \mathcal{T} \times \mathcal{E}$ and the order relation $\sqsubseteq$ applies as follows: $\langle s_1, t_1, A_1 \rangle \sqsubseteq \langle s_2, t_2, A_2 \rangle$ iff $s_1 \sqsubseteq s_2$. The order relation $\sqsubset$ is an abbreviation for $\sqsubseteq \wedge \neq$. The relation $\langle s_1, t_1, A_1 \rangle = \langle s_2, t_2, A_2 \rangle$ simply means that A_1 and A_2 start at the same time-point, while $\langle s_1, t_1, A_1 \rangle \sqsubset \langle s_2, t_2, A_2 \rangle$ means that A_1 starts earlier than A_2. Let Υ be a scenario description.*

- *The OBS part of Υ is a sub-lattice of $\langle \mathcal{H}_\Upsilon, \sqsubseteq \rangle$, whose elements are members of $\mathcal{H}_\Upsilon = \mathcal{T} \times \mathcal{F}_\Upsilon \times 2^{\mathcal{O}} \times \mathcal{V} \subseteq \mathcal{H}$, where F_Υ is the set of all features explicitly occurring in Υ.*

- *The SCD part of Υ is a sub-lattice of $\langle \mathcal{D}, \sqsubseteq \rangle$. Each tuple in SCD specifies the starting time, the ending time and the action symbol of an action scheduled for execution.*

- *The function $\Rrightarrow : \mathcal{D} \rightarrow 2^{\mathcal{H}_\Upsilon}$ maps each schedule's occurrence in a set of non-empty lattices of observations. The function $\Rrightarrow$ is parametric on the action type, and the LAW part of Υ consists in the definition of $\Rrightarrow$ as a set of action-laws in Full Trajectory Normal Form, one law for each action type. The Full Trajectory Normal Form for the action-laws is a mapping $\langle s, t, A \rangle \Rrightarrow \bigvee_{i=1}^{n} \bigwedge_{j=1}^{m} S_{ij}$ for which the action occurrence $\langle s, t, A \rangle$ is* expanded *into a formula in Full Disjunctive Normal Form, that is into a disjunction of conjunctions of trajectory formulas S_{ij}, each of which corresponds to the feature f_j in the alternative i. A trajectory formula for a given feature f_j in $\mathcal{F}$ is the first-order formula $\forall \tau \in [s, t] \subset \mathcal{T} . [\tau] f_j \hat{=} \varphi_j(\tau)$ where φ_j is a partial fluent defined over $D \subseteq [s, t] \subset \mathcal{T}$, and $s \neq t$.* ∎

The underlying language is very expressive. The assessment will reveal how much of that expressivity the specific logic is capable of using.

[2] Please note that ζ and Σ are defined in terms of Υ, hence they speak the same language.

3 Definition

The following definition first appeared in [17, section 3] then in [18, page 209]. The definition extends [16, chapter 16] and [17, section 1] to the case of actions with duration, and derives from Kowalski's 1992 [6] simplification of the 1986 [7] Kowalski and Sergot original Event Calculus.

Definition 3.1 (Full Event Calculus) *The calculus uses classical first-order logic as base logic, augmented with the formulas in table 1 and axioms in table 2 for representing the specific problem domain of interest and for controlling deduction, and uses McCarthy's 1986 [11] predicate circumscription* [3] *with forced separation as model-preference criterion. The language of the calculus is defined in table 1. Let* S_1 *be a conjunction of* $Initiates$, $Terminates$ *and* $Releases$ *formulae, let* S_2 *be a conjunction of* $Initially_P$, $Initially_N$, $Happens$ *and temporal ordering formulae, and let* S_3 *be a conjunction of Uniqueness of Names Axioms for actions and fluents. The set of logical consequences of the calculus are defined as being the set of logical consequences of* $\Delta \wedge \Gamma$*, according to the classical, Tarskian definition of logical consequence, written* $\{\alpha : \Delta \wedge \Gamma \vDash \alpha\}$*, where* Δ *is the conjunction of axioms* $A1 \ldots A7$ *in table 2,* Γ *is the conjunction* $CIRC[S_1; Initiates, Terminates, Releases] \wedge CIRC[S_2; Happens] \wedge S_3$ *where* $CIRC$ *is the circumscription of the given predicates, and* α *is either a positive or negative* $HoldsAt$ *formula. The minimisation of* $Happens$ *corresponds to the default assumption that there are no unexpected event occurrences. The minimisation of* $Initiates$, $Terminates$ *and* $Releases$ *corresponds to the default assumption that actions have no unexpected effects.* ■

As the essence of the Frame Problem is how do we use logic to represent the effects of actions without having to explicitly represent all their non-effects, the above method is a solution to the Frame Problem.

The conceptual basis of the above model-preference criterion is the partitioning of the set of premises and the application of different selection functions to the classical model set of the resulting and distinct sets of premises. The set of selected models is then chosen by filter preferential entailment, using predicate circumscription as selection function. The filtering technique was first described by Sandewall in 1989 [13], and occurs within the Event Calculus literature as the principle of forced separation [16, chapter 16 and page 81].

[3] The generalisation of the 1980 [10] definition, allowing predicates, functions and constants to vary, and allowing many predicates to be minimised in parallel.

4 Classification

We shall now proceed to the assessment of the range of applicability of this logic. Are the underlying semantics and the logic's semantics equivalent? Is the intended model set for Υ equal to the set of logical consequences $EC(T(\Upsilon))$?

Let the relation $\langle t, f, v\rangle \in \Sigma\,(\Upsilon)$ be a shorthand for "exists an interpretation $\langle M, H\rangle$ such that $\langle \mathcal{B}, M, H, \mathcal{P}, \mathcal{C}\rangle \in Mod(\Upsilon)$ and $H(t, f) = v$", according to the known definition of intended model set. Let the relation $\langle t, f, true\rangle \in EC(T(\Upsilon))$ be a shorthand for $\Delta \wedge \Gamma \vDash HoldsAt(f, t)$, and the relation $\langle t, f, false\rangle \in EC(T(\Upsilon))$ be a shorthand for $\Delta \wedge \Gamma \vDash \neg HoldsAt(f, t)$, where (1) Δ is the conjunction of axioms $A1 \ldots A7$ (def. 3.1), (2) Γ is the conjunction $CIRC[S_1; Initiates, Terminates, Releases] \wedge CIRC[S_2; Happens] \wedge S_3$ (def. 3.1), and (3) all formulae in S_1 and S_2 are in $T(\Upsilon)$ (definition 4.1).

Definition 4.1 (Immersion Operator) *Let* $\mathcal{L}_1$ *be the underlying language (definition 2.3), and let* $\mathcal{L}_2$ *be the language of the logic (definition 3.1). The immersion operator* $T : \mathcal{L}_1 \to \mathcal{L}_2$ *is defined as follows:*

- $T(\langle 0, f, true\rangle) = Initially_P(f)$ *and* $T(\langle 0, f, false\rangle) = Initially_N(f)$*;*
- $T(\langle s, t, A\rangle) = Happens(A, s, t)$*;*
- $T(\langle s, t, A\rangle \Rrightarrow \bigvee_{i=1}^{n} \bigwedge_{j=1}^{m} S_{ij})$ *is translated into a set of formulas, one* $Initiates(A, f, s)$ *formula for any fluent* f *becoming true as the effect of a deterministic action* A*, one* $Terminates(A, f, s)$ *formula for any fluent* f *becoming false as the effect of a deterministic action* A*, one* $Releases(A, f, s)$ *formula for any fluent* f *becoming randomised (true or false) as the effect of a non-deterministic action* A*, one* $HoldsAt(f, s)$ *formula for any positive precondition (*$\langle s, f, true\rangle$*) to the successful execution of the action* A*, and one* $\neg HoldsAt(f, s)$ *formula for any negative precondition (*$\langle s, f, false\rangle$*) to the successful execution of the action* A*. Preconditions are explicit conditions for the truth of* $Initiates$, $Terminates$ *and* $Releases$ *formulae.* ■

The following two propositions by Lifschitz [8] are needed for the assessment. We reproduce them as in Shanahan [16, page 280].

Proposition 4.1 $CIRC[\Sigma \wedge \forall\,\overline{x}.\rho(\overline{x}) \leftarrow \phi(\overline{x}); \rho]$ *is equivalent to* $\Sigma \wedge \forall\,\overline{x}.\rho(\overline{x}) \leftrightarrow \phi(\overline{x})$ *if* Σ *and* $\phi(\overline{x})$ *do not mention the predicate* ρ.

Proposition 4.2 *[8, page 341, proposition 7.1.1] Let* $\overline{\rho}$ *be the tuple of predicate symbols* $\rho_1, \ldots, \rho_n$*. If all occurrences* *in Σ of the predicate symbols in $\overline{\rho}$ are positive* [4]*, then*

$$CIRC[\Sigma;\overline{\rho}] = CIRC[\Sigma;\rho_1] \wedge \ldots \wedge CIRC[\Sigma;\rho_n]$$

Theorem 4.1 (assessment) *For all $\Upsilon \in \mathcal{K}$**sp-IA** and $\langle t,f,v\rangle \in \mathcal{H}_\Upsilon$, the following relation holds: $\langle t,f,v\rangle \in EC(T(\Upsilon)) \Leftrightarrow \langle t,f,v\rangle \in \Sigma_{\mathcal{K}\textbf{sp-IA}}(\Upsilon)$.*

PROOF. The following standard reduction applies. By proposition 4.2, the second-order formula $CIRC[S_1; Initiates, Terminates, Releases]$ reduces to the second-order formula $CIRC[S_1; Initiates] \wedge CIRC[S_1; Terminates] \wedge CIRC[S_1; Releases]$. By proposition 4.1 each $CIRC$ minimisation, including $CIRC[S_2; Happens]$, reduces to first-order predicate completion. In what follows, this reduction is used at each EC-evaluation, and the reference to an EC-axiom involves the application of the Uniqueness of Names Axioms in $\mathcal{S}_3$. The proof is by induction.

1. The ego-world game starts at time $\tau = 0$. The initial state of the world is represented by means of tuples $\langle 0,f,true\rangle$ or $\langle 0,f,false\rangle$ in the OBS part of Υ. This results either in $HoldsAt(f,t) \in EC(T(\Upsilon))$ by axiom $A1$, or in $\neg HoldsAt(f,t) \in EC(T(\Upsilon))$ by axiom $A4$.

2. The world player persists until the ego player communicates its intention to perform an action, so that no tuples occur in SCD whose starting time is the present time τ. This trivially results in temporal inertia, by either axiom $A1$ or $A4$ depending on how f was initialised, or by axiom $A2$ or $A5$ depending on how was it last modified.

3. The ego player, suddenly, adds the tuple $\langle \tau, E\rangle$ to the current-action set $\mathcal{C}$, where τ is the point in time where this update occurs. Then the world player executes the action and terminates it at τ' by removing the tuple $\langle \tau, E\rangle$ from $\mathcal{C}$ and adding the tuple $\langle \tau,\tau',E\rangle$ to the past-action set $\mathcal{P}$. The ego may also decide to terminate E earlier, let say at $\tau'' \in (\tau,\tau')$, so that it may autonomously remove the tuple $\langle \tau, E\rangle$ from $\mathcal{C}$ and add $\langle \tau,\tau'',E\rangle$ to $\mathcal{P}$. Let show what are the corresponding logical consequences of EC, pointwise. By definition 4.1, we know it exists a single formula $Happens(E,\tau,\tau')$ (or $Happens(E,\tau,\tau'')$) to refer to. <u>If</u> the feature f does not belong to the set of those features which would be modified by a successful execution of E (i.e. $f \notin Infl(E,\sigma_t)$), <u>then</u> the feature is neither $Clipped$ nor $Declipped$, and the situation described at point 2 then occurs up to τ' (or τ''). Otherwise,

   (a) <u>If</u> all preconditions for the action E are successfully met (i.e. all $HoldsAt$ and $\neg HoldsAt$ test conditions for $Initiates$, $Terminates$ and $Releases$ clauses are met by axioms $A3$ and $A6$), or no precondition exists at all (in which case the above tests are trivially met), <u>then</u> action E is successfully executed. Only one of the following three situations may then occur.

   - $t = \tau$: then is either $Initially_P(f)$ by $T(\Upsilon)$, $\neg Clipped(0,f,t)$ by axiom $A3$ and $HoldsAt(f,t) \in EC(T(\Upsilon))$ by axiom $A1$, or $Initially_N(f)$ by $T(\Upsilon)$, $\neg Declipped(0,f,t)$ by axiom $A6$ and $\neg HoldsAt(f,t) \in EC(T(\Upsilon))$ by axiom $A4$.
   - $\tau < t < \tau'$: then is either $Declipped(\tau,f,\tau')$ (if $Initiates(a,f,\tau) \vee Releases(E,f,\tau)$), or $Clipped(\tau,f,\tau')$ (if $Terminates(a,f,\tau) \vee Releases(E,f,\tau)$), so that it is neither $HoldsAt(f,t) \in EC(T(\Upsilon))$ by axiom $A2$, nor is $\neg HoldsAt(f,t) \in EC(T(\Upsilon))$ by axiom $A5$ respectively, i.e. inertia is not assumed in (τ,τ') (occlusion).
   - $t = \tau'$: then is either (1) $Initiates(a,f,\tau)$ by $T(\Upsilon)$, then is $HoldsAt(f,\tau')$ by axiom $A2$, (2) $Terminates(a,f,\tau)$ by $T(\Upsilon)$, then is $\neg HoldsAt(f,\tau')$ by axiom $A5$, or (3) $Releases(a,f,\tau)$ by $T(\Upsilon)$, then is both $Declipped(\tau,f,\tau')$ and $Clipped(\tau,f,\tau')$, so that it is neither $HoldsAt(f,t) \in EC(T(\Upsilon))$ by axiom $A2$, nor is $\neg HoldsAt(f,t) \in EC(T(\Upsilon))$ by axiom $A5$, i.e. inertia is not assumed after τ' (nondeterminism).

   The case for τ'' in place of τ' is identical.

   (b) If there is at least one precondition which is not met, then the action is executed without any effect, and the situation described at point 2 occurs up to τ' (or τ'').

4. The ego-world game ranges to infinity, where the intended-model set is defined. Due to the choice of assumptions, the situations described at point 2 and 3 repeat themselves to the infinity, for both semantics, the semantics mirroring the underlying semantics. ■

Corollary 4.1 *For all $\Upsilon \in \mathcal{K}$**sp-IA**, is $EC(T(\Upsilon)) \subseteq [\![\Upsilon]\!]$.*

PROOF. $EC(T(\Upsilon)) = \Sigma_{\mathcal{K}\textbf{sp-IA}}(\Upsilon) \subseteq \Sigma_{\mathcal{K}\textbf{-IA}}(\Upsilon) \subseteq [\![\Upsilon]\!]$. ■

[4] An occurrence of a predicate symbol in a formula ϕ is *positive* if it is in the scope of an even number of negations in the equivalent formula ψ that is obtained by eliminating the connectives $\rightarrow$ and $\leftrightarrow$ from ϕ.

The use of this preference logic for solving the Hanks-McDermott [4, 5] problem and the Russian Shooting Problem is explained in [17, 16]. Theorem 4.1 gives a more general insight into how this is done, and guarantees that the reasoning method indeed gives the correct answers for these specific reasoning problems, as well as for all other problems in the $\mathcal{K}$**sp**-**IA** class.

5 Conclusion

In this paper, the range of applicability of Shanahan's Circumscriptive *Full Event Calculus* is proven to be the $\mathcal{K}$**sp**-**IA** class in the *Features and Fluents* taxonomy. The assessment is proven by referring to the original definition of this preference logic, where no adjustments of the language or reasoning method were necessary. The result implies that the claims on the expressiveness and problem-solving power of this logic were indeed correct.

The $\mathcal{K}$**sp**-**IA** class is that subclass of $\mathcal{K}$-**IA** where accurate and complete information about actions ($\mathcal{K}$), complete knowledge about the initial state of the world (**s**) and no information at any later state than the initial one (**p**), together with strict inertia in integer time (**I**) of possibly non-deterministic actions (**A**), are the assumed characteristics. Time-points are natural numbers, and features are truth-valued (**I**). The extension of the *Full Event Calculus* so to encompass the full $\mathcal{K}$-**IA** class, which is the broadest class defined in [14], involves allowing backward (abductive) reasoning. This extension is already available, it is called *Abductive Event Calculus* [18] [16, chapter 17], and its range of applicability is currently being investigated.

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Table 1. The Language of the Event Calculus

Formula	Meaning
	What is true when (OBS):
$Initially_P(f)$	Fluent f holds from time 0
$Initially_N(f)$	Fluent f does not hold from time 0
	What happens when (SCD):
$Happens(a, t1, t2)$	Action a starts at time $t1$ and ends at time $t2$
	What actions do (LAW):
$Initiates(a, f, t)$	Fluent f starts to hold after action a at time t
$Terminates(a, f, t)$	Fluent f ceases to hold after action a at time t
$Releases(a, f, t)$	Fluent f is not subject to inertia after action a at time t
	Temporal Constraints:
$t1 < t2, t1 \leq t2$	standard order relations between natural numbers
	Logical Machinery:
$HoldsAt(f, t)$	Fluent f holds at time t
$Clipped(t1, f, t2)$	Fluent f is terminated between times $t1$ and $t2$
$Declipped(t1, f, t2)$	Fluent f is initiated between times $t1$ and $t2$

Note. The intuition behind $Initiates(A, f, s)$, $Terminates(A, f, s)$ and $Releases(A, f, s)$ formulae is that the effect of the action A, starting at time s and ending at time t, is exerted on the fluent f at time t only.

Table 2. The Axioms of the Event Calculus

$$HoldsAt(f, t) \longleftarrow Initially_P(f) \wedge \neg Clipped(0, f, t) \quad \text{(A1)}$$

$$HoldsAt(f, t) \longleftarrow t2 < t \wedge Happens(a, t1, t2) \wedge Initiates(a, f, t1) \wedge \neg Clipped(t1, f, t) \quad \text{(A2)}$$

$$Clipped(t1, f, t4) \longleftrightarrow \exists\, a, t2, t3\, [\, t1 < t3 \;\wedge\; t2 < t4 \wedge Happens(a, t2, t3) \wedge [Terminates(a, f, t2) \vee Releases(a, f, t2)]] \quad \text{(A3)}$$

$$\neg HoldsAt(f, t) \longleftarrow Initially_N(f) \wedge \neg Declipped(0, f, t) \quad \text{(A4)}$$

$$\neg HoldsAt(f, t) \longleftarrow t2 < t \wedge Happens(a, t1, t2) \wedge Terminates(a, f, t1) \wedge \neg Declipped(t1, f, t) \quad \text{(A5)}$$

$$Declipped(t1, f, t4) \longleftrightarrow \exists\, a, t2, t3\, [\, t1 < t3 \;\wedge\; t2 < t4 \wedge Happens(a, t2, t3) \wedge [Initiates(a, f, t2) \vee Releases(a, f, t2)]] \quad \text{(A6)}$$

$$Happens(a, t1, t2) \longrightarrow t1 \leq t2 \quad \text{(A7)}$$