AN ANALYSIS OF SYSTEMATIC APPROACHES TO REASONING ABOUT ACTIONS AND CHANGE

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ABSTRACT

Systematic approaches to reasoning about dynamical systems and causality provide a new view on how to proceed toward a general and uniform semantical framework which is independent from specific solutions to the frame problem, say. This direction of research enables to rigorously comparing known methodologies designed for reasoning about actions and change with respect to such a semantics.

Two actual systematic approaches, namely the Ego-World-Semantics[11,12] and the Action Description Language[5], are analyzed and compared in this paper. We present two equivalence results for ontological subclasses and elaborate the major differences. The ultimate aim of this analysis shall be a proposal about a combination of the two frameworks to obtain a powerful semantics which profits from the merits of both the Ego-World-Semantics as well as the Action Description Language.

1. Introduction

A key issue in Cognitive Science and Artificial Intelligence is to understand and model the ability of humans to reason about dynamical systems and causality. This kind of logical information processing is fundamental for prediction about effects of actions and events, for planning to achieve goals, for explaining observations, and many other intellectual capabilities. Automating this ability seems to be indispensable for creating autonomous robots and providing knowledge about everyday life for machines.

For more than 30 years research in this direction has focused on creating new or extending already existing specialized logical formalisms because classical logic, as it stands, seems to have difficulties — the technical *frame problem* — when used to express statements about non-static worlds. However, it has recently emerged that a more methodical and successful approach toward a general theory of actions and change consists in the development of an appropriate semantics first, instead of directly starting with a specific formalism.

Two independently developed, prominent systematic approaches to reasoning about actions and change are compared in this paper. Interpreting dynamical systems as a game between an active agent (the *ego*) and the reacting world is the basic notion underlying E. Sandewall's *Ego-World-Semantics* (EWS)[11,12]. The *Action Description Language* $\mathcal{A}$[5] is based on an elegant and natural way to describe the effects of actions. The main task of both approaches is to provide models given a complete description of actions and their effects along with a number of observations in certain situations.

Both systematic frameworks initiated a lot of further work, despite the fact that they were developed hardly two years ago, where several logics are assessed at their applicability to the semantics defined by the Ego-World-Semantics or the Action Description Language, respectively. The success of the two methodologies naturally raises the question whether they have a common ground. Nonetheless, this problem has not been investigated up to now.

The aim of this paper is to give a first answer to this question. Aside from the fact that the two approaches were developed with a similar intention, they share some fundamental assumptions:

- The approaches are systematic in the sense that they are based on a uniform semantics, and the key issue is to find a set of models given a number of action descriptions and a set of observations.
- The assumption of inertia is the overall principle stating that the value of a particular fact is static unless the fact is explicitly affected by an action.
- The concept of postdiction is supported, i.e. observations at some point of time can be used to derive additional information about situations before.
- Correct knowledge regarding the effects of actions is assumed, i.e. actions might have alternative, random effects but the set of possible effects is known.
- All actions which have been performed in a particular scenario are given.

In this paper, we fix the particular ontological subclass within the framework of the Ego-World-Semantics which is suitable for the Action Description Language and prove their equivalence. Furthermore, we use a recent extension of $\mathcal{A}$ regarding non-deterministic actions to obtain the analogous equivalence result for a more general ontological problem class. On the other hand, we elaborate an important feature supported by the Action Description Language but not by EWS.

The merits of our analysis are obvious: Firstly, once a logical system has been proved to be correct wrt some dialect of one of the two approaches, it is provably correct wrt the corresponding dialect of the other framework as well. Secondly, a clarification of the differences between both semantics yields a number of suggestions for improvements so that the two approaches can profit from the useful peculiarities of each other.

The paper is organized as follows. We give a brief introduction to the Action Description Language in Section 2 and the Ego-World-Semantics in Section 3, respectively. For more details, the reader should consult[5,13] and[11]. In addition, Section 2 includes a description of an extended version of the Action Description Language. Section 4 contains the main results of this paper: The respective ontological subclasses of EWS which are equivalent to $\mathcal{A}$ and its extension are fixed. Finally, a conclusion is given in Section 5.

2. The Action Description Language $\mathcal{A}$

Definition 1 A *domain* $\mathcal{D}$ is a tuple $(F, A, \mathcal{E}, \mathcal{V})$ where F and A are disjoint sets of symbols, called *fluent names* and *action names*, respectively, and $\mathcal{E}$ is a set of *effect propositions* of the form a `causes` f `if` $c_1, \ldots, c_m$ where $a \in A$ and $f, c_1, \ldots, c_m$ ($m \geq 0$) are *fluent literals*, i.e. elements of F possibly preceded by $\neg$. Furthermore, $\mathcal{V}$ is a set of *value propositions* of the form

$$f \ \texttt{after} \ [a_1, \ldots, a_n] \tag{1}$$

where f is a fluent literal and $a_1, \ldots, a_n \in A$ ($n \geq 0$). In case $n = 0$, For.1 is usually written as `initially` f. ■

Example 1. The *Yale Shooting scenario* describes a gun which might be loaded or not along with a turkey which is alive or dead. Three actions can be performed, viz. loading the gun, firing it which causes the turkey to drop dead provided the gun was loaded, and one action called waiting which is intended to have no effects at all. An instance of this scenario, called *Stanford Murder Mystery*, describes the reasoning process which has to be performed to conclude that the gun must have been loaded if the turkey was alive at the beginning and is observed to be dead after shooting and waiting. Let $\mathcal{D}_1$ denote the domain which consists of fluent names $F = \{loaded, alive\}$, action names $A = \{load, wait, shoot\}$, three effect propositions, namely

$$\begin{array}{lll} load \ \texttt{causes} \ loaded & \quad shoot \ \texttt{causes} \ \neg alive \ \texttt{if} \ loaded \\ & \quad shoot \ \texttt{causes} \ \neg loaded \end{array} \tag{2}$$

and two value propositions, namely

$$\texttt{initially} \ alive \quad \text{and} \quad \neg alive \ \texttt{after} \ [shoot, wait]. \tag{3}$$

Definition 2 Given a domain $\mathcal{D} = (F, A, \mathcal{E}, \mathcal{V})$, a *situation* σ is a subset of F. For any $f \in F$, if $f \in \sigma$ (resp. $f \notin \sigma$) then f (resp. $\neg f$) is said to *hold* in σ. The *transition function* Φ maps an action name a and a situation σ into a situation $\Phi(a, \sigma)$ such that the following conditions are satisfied: For all $f \in F$,

1. if a `causes` f `if` $c_1, \ldots, c_m$ in $\mathcal{E}$ and each c_i holds in σ then $f \in \Phi(a, \sigma)$,
2. if a `causes` $\neg f$ `if` $c_1, \ldots, c_m$ in $\mathcal{E}$ and each c_i holds in σ then $f \notin \Phi(a, \sigma)$,
3. if $\mathcal{E}$ does not contain such effect propositions then $f \in \Phi(a, \sigma)$ iff $f \in \sigma$.

A pair (σ_0, Φ) is a *model* of $\mathcal{D}$ iff $\sigma_0 \subseteq F$, called the *initial* situation, Φ is the transition function determined by $\mathcal{E}$, and each member of $\mathcal{V}$ is true in (σ_0, Φ): A value proposition like For.1 is *true* in (σ_0, Φ) iff f holds in $\Phi([a_1, \ldots, a_n], \sigma_0)$, where $\Phi([a_1, \ldots, a_n], \sigma) := \Phi(a_n, \Phi(a_{n-1}, \ldots, \Phi(a_1, \sigma) \ldots))$. $\mathcal{D}$ is *consistent* if it has a model, and an arbitrary value proposition is *entailed* by $\mathcal{D}$ iff it is true in every model. ■

Example 1 (continued). As regards $\mathcal{D}_1$, $\{alive\}$ is a situation where *alive* and $\neg loaded$ hold. The transition function Φ_1 determined by the propositions in For.2 is

$$\begin{array}{rcl} \Phi_1(load, \sigma) & = & \sigma \cup \{loaded\} \\ \Phi_1(shoot, \sigma) & = & \begin{cases} \sigma \setminus \{loaded, alive\}, & \text{if } loaded \in \sigma \\ \sigma, & \text{otherwise.} \end{cases} \\ \Phi_1(wait, \sigma) & = & \sigma \end{array} \tag{4}$$

Regarding the first value proposition in For.3, our domain $\mathcal{D}_1$ might have two models, viz. $(\{alive\}, \Phi_1)$ and $(\{alive, loaded\}, \Phi_1)$. However, following For.4 we find that $\Phi_1([shoot, wait], \{alive\}) = \Phi_1([wait], \{alive\}) = \{alive\}$, i.e. the former is not a model of the entire domain which requires $alive \notin \Phi_1([shoot, wait], \sigma_0)$ according to the second element in For.3. Hence, we conclude that `initially` *loaded* is entailed by $\mathcal{D}_1$.

Example 1 is based on just a single sequence of actions, namely $[shoot, wait]$, which can be interpreted as the real development in this scenario. But, in addition to this, it is conceivable to consider two or more such sequences during the very same reasoning process which then can be regarded as a kind of hypothetical reasoning. This shall be illustrated by the following example, motivated by a scene in a Pierre Richard movie[10]:

Example 2. An additional fluent name *broken* is introduced which describes the state of a vase. The action *shoot* is replaced by the actions *shoot-at-pierre* and *shoot-at-vase*, respectively, along with the effect propositions

$$\begin{array}{llll} \textit{shoot-at-pierre} & \texttt{causes} & \neg \textit{alive} & \texttt{if} \;\; \textit{loaded} \\ \textit{shoot-at-vase} & \texttt{causes} & \textit{broken} & \texttt{if} \;\; \textit{loaded} \end{array}$$

and, as in For.2, *shoot-at-pierre* `causes` $\neg$*loaded* and *shoot-at-vase* `causes` $\neg$*loaded*. Now, given the three value propositions

$$\texttt{initially}\ \textit{alive}, \quad \texttt{initially}\ \neg \textit{broken}, \quad \textit{broken}\ \texttt{after}\ [\textit{shoot-at-vase}] \tag{5}$$

each model (σ_0, Φ) requires that $loaded \in \sigma_0$ according to the second and third element of For.5. Hence, each model also supports $alive \notin \Phi([\textit{shoot-at-pierre}], \sigma_0)$.

This example demonstrates how different developments of the world can be considered within a single model. As this kind of reasoning is not provided by the Ego-World-Semantics, we define the following restriction on $\mathcal{A}$:

Definition 3 $\mathcal{A}^1$ is as $\mathcal{A}$ except that the value propositions describing a particular domain are based on a single sequence of actions $[a_1, \ldots, a_n]$ ($n \geq 0$), i.e. each value proposition is of the form `initially` f or f `after` $[a_1, \ldots, a_k]$, $1 \leq k \leq n$. Furthermore, the transition function Φ determined by this domain is only defined in case of $\Phi([a_1, \ldots, a_k], \sigma_0)$ ($0 \leq k \leq n$). ■

The Action Description Language $\mathcal{A}$ was recently extended by integrating non-deterministic actions, i.e. actions with alternative randomized effects[13]:

Definition 4 A domain description in $\mathcal{A}_{ND}$ is as in Definition 1 except that $\mathcal{E}$ might contain *extended effect propositions* of the form

$$a\ \texttt{alternatively causes}\ e_1, \ldots, e_k\ \texttt{if}\ c_1, \ldots, c_m \tag{6}$$

where $a \in A$ and $e_1, \ldots, e_k, c_1, \ldots, c_m$ are fluent literals ($k \geq 0$, $m \geq 0$). ■

Example 3. To formalize the *Russian Turkey* scenario, $\mathcal{D}_1$ is augmented by a third action called *spin* whose intended meaning is that its execution causes the gun to become randomly loaded or unloaded regardless of its state before. This can be expressed via the two extended effect propositions *spin* `alternatively causes` *loaded* and $spin$ $\texttt{alternatively causes}$ $\neg loaded$. Furthermore, let our modified domain $\mathcal{D}_3$ consist of a single value propositions, namely $alive$ $\texttt{after}$ $[load, spin, shoot]$. Due to the fact that the turkey is alive after shooting we intend to conclude that the gun became unloaded by spinning the gun.

To handle alternative effects, the notion of a transition function is replaced by a transition *relation* where two situations σ, σ' and an action name a are related iff σ' is a *possible* result of executing a in σ. In addition, a model includes an argument φ to determine, for this model, the choice of a particular alternative in any situation:

Definition 5 Given a domain $\mathcal{D} = (F, A, \mathcal{E}, \mathcal{V})$ in $\mathcal{A}_{ND}$, a *transition relation* Φ determined by $\mathcal{E}$ contains triples (σ, a, σ') such that the following conditions are satisfied: Let $\sigma, \sigma' \subseteq F$, and $a \in A$ then $(\sigma, a, \sigma') \in \Phi$ iff for all $f \in F$,

1. if a $\texttt{causes}$ f $\texttt{if}$ $c_1, \ldots, c_m$ in $\mathcal{E}$ and each c_i holds in σ then $f \in \sigma'$,
2. if a $\texttt{causes}$ $\neg f$ $\texttt{if}$ $c_1, \ldots, c_m$ in $\mathcal{E}$ and each c_i holds in σ then $f \notin \sigma'$,
3. let the set
$$\left\{ \begin{array}{c} a \ \ \texttt{alternatively causes} \ \ E_1 \ \ \texttt{if} \ \ C_1 \\ \vdots \\ a \ \ \texttt{alternatively causes} \ \ E_l \ \ \texttt{if} \ \ C_l \end{array} \right\}$$
contain all extended e-propositions such that $C_1, \ldots, C_l$ hold in σ [1] then we can choose a $\lambda \in \{1, \ldots, l\}$ such that all effects occurring in E_λ hold in σ', and
4. if neither f nor $\neg f$ is forced to hold in σ' by 1., 2., or 3. then $f \in \sigma'$ iff $f \in \sigma$.

A triple $(\sigma_0, \Phi, \varphi)$ is a *model* of $\mathcal{D}$ iff $\sigma_0 \subseteq F$, Φ is a transition relation determined by $\mathcal{E}$, and φ is a total mapping form pairs $([a_1, \ldots, a_n], \sigma)$ into a situation such that for any sequence of actions $[a_1, \ldots, a_n]$ ($n \geq 0$) and situation σ the following holds:

1. $\varphi([\,], \sigma) = \sigma$ and
2. $(\varphi([a_1, \ldots, a_{n-1}], \sigma), a, \varphi([a_1, \ldots, a_n], \sigma)) \in \Phi$.

Furthermore, the members of $\mathcal{V}$ must be true in $(\sigma_0, \Phi, \varphi)$, i.e. for each For.1 $\in \mathcal{V}$, f holds in $\varphi([a_1, \ldots, a_n], \sigma_0)$. $\mathcal{D}$ is said to be *consistent* iff it admits a model. ■

Example 3 (continued). The (extended) effect propositions of $\mathcal{D}_3$ determine a relation Φ_3 which is given by $(\sigma, a, \sigma') \in \Phi_3$ iff $\Phi_1(a, \sigma) = \sigma'$ if $a \in \{load, wait, shoot\}$ (c.f. For.4) and $(\sigma, spin, \sigma') \in \Phi$ iff $\sigma \setminus \{loaded\} = \sigma' \setminus \{loaded\}$, i.e. σ and σ' might differ on $loaded$ but not elsewhere. Now, there are two different kinds of possible models $(\sigma_0, \Phi_3, \varphi)$ of $\mathcal{D}_3$: While in any case $loaded \in \varphi([load], \sigma_0)$, both $loaded \in \varphi([load, spin], \sigma_0)$ and $loaded \notin \varphi([load, spin], \sigma_0)$ have to be considered. However, only in the latter case $alive \in \varphi([load, spin, shoot], \sigma_0)$ is possible — provided $alive \in \sigma_0$. Hence, $\mathcal{D}_3$ entails $\neg loaded$ $\texttt{after}$ $[load, spin]$.

Recently, a variety of logics designed for reasoning about actions have been proved to constitute a sound and complete encoding of $\mathcal{A}$, such as extended logic programs with two kinds of negation which use a special purpose semantics[4], an abductive logic programming approach[3], Reiter's approach[9], Baker's circumscription based approach[1] (both results established in[7]), and an approach based on equational logic programs[6,13]. The finally mentioned system has also been proved to be correct wrt $\mathcal{A}_{ND}$ [13].

[1] $C = c_1, \ldots, c_m$ is said to hold in a situation if all its fluent literals c_i's ($1 \leq i \leq m$) hold.

State r	$\texttt{Infl}(\mathit{shoot}, r)$	$\texttt{Trajs}(\mathit{shoot}, r)$
$\{\mathit{loaded}\hat{=}\texttt{false}, \mathit{alive}\hat{=}\texttt{false}\}$	$\{\}$	$\{\langle\rangle\}$
$\{\mathit{loaded}\hat{=}\texttt{false}, \mathit{alive}\hat{=}\texttt{true}\}$	$\{\}$	$\{\langle\rangle\}$
$\{\mathit{loaded}\hat{=}\texttt{true}, \mathit{alive}\hat{=}\texttt{false}\}$	$\{\mathit{loaded}\}$	$\{\langle \mathit{loaded} : \texttt{false}\rangle\}$
$\{\mathit{loaded}\hat{=}\texttt{true}, \mathit{alive}\hat{=}\texttt{true}\}$	$\{\mathit{loaded}, \mathit{alive}\}$	$\{\langle \mathit{loaded} : \texttt{false}, \mathit{alive} : \texttt{false}\rangle\}$

Figure 1: A trajectory description of *shoot* .

3. The Ego-World-Semantics

Due to the aim of this paper, when stating the formal definitions regarding EWS we concentrate on a restricted version of an ontological subclass called $\mathcal{K}$-*IbsA* .[2]

Definition 6 Let $\mathcal{F}$ be a set of symbols called *binary features* and A be a set of action names. A *state* r is a mapping from $\mathcal{F}$ into $\{\texttt{true}, \texttt{false}\}$. The effects of actions on states are described by means of a *trajectory table* which consists in a pair $(\texttt{Infl}, \texttt{Trajs})$ such that, for each action name $a \in A$ and state r , $\texttt{Infl}(a, r) \subseteq \mathcal{F}$ contains the features which are affected when executing a in r , and $\texttt{Trajs}(a, r)$ is a non-empty set of *trajectories* of the form $\langle f_1 : \nu_1, \ldots, f_m : \nu_m \rangle$ where $f_1, \ldots, f_m \in \texttt{Infl}(a, r)$ and $\nu_1, \ldots, \nu_m \in \{\texttt{true}, \texttt{false}\}$. A *possible result* of executing action a in state r is obtained by choosing a member of $\texttt{Trajs}(a, r)$ and executing its assignments in r . A *chronicle* is a triple $(\texttt{A}, \textsc{scd}, \textsc{obs})$ where $\texttt{A}$ is a formula representing a trajectory table,[3] the *schedule* $\textsc{scd}$ is a set $\{[0,1]a_1, \ldots, [n-1, n]a_n\}$ where $a_1, \ldots, a_n \in A$ ($n \geq 0$), and $\textsc{obs}$ is a set of *observations* of the form $[\tau]f \hat{=} \nu$ where $0 \leq \tau \leq n$, $f \in \mathcal{F}$, and $\nu \in \{\texttt{true}, \texttt{false}\}$. ■

If each set $\texttt{Trajs}(a, r)$ contains a single element then the chronicle belongs to a subclass called $\mathcal{K}$-*IbsAd* where only deterministic actions (d) are considered.

Example 1 (reformulated). Given the features $\mathcal{F}_1 = \{\mathit{loaded}, \mathit{alive}\}$, each set depicted in the leftmost column of Figure 1 represents a state. The entire table defines the effects of *shoot* : $\texttt{Infl}(\mathit{shoot}, r)$ contains the features which are affected when executing *shoot* in r . The trajectories in $\texttt{Trajs}(\mathit{shoot}, r)$ determine the resulting states by assuming that each assignment in the trajectory is performed while no other feature changes its value, e.g. executing *shoot* in $\{\mathit{loaded}\hat{=}\texttt{true}, \mathit{alive}\hat{=}\texttt{false}\}$ yields $\{\mathit{loaded}\hat{=}\texttt{false}, \mathit{alive}\hat{=}\texttt{false}\}$. To encode the Stanford Murder Mystery we use $\textsc{scd}_1 = \{[0,1]\mathit{shoot}, [1,2]\mathit{wait}\}$ and $\textsc{obs}_1 = \{[0]\mathit{alive} \hat{=} \texttt{true}, [2]\mathit{alive} \hat{=} \texttt{false}\}$. Let $\mathcal{J}_1$ denote this chronicle. Note that in any case $\texttt{Trajs}(\mathit{shoot}, r)$ contains only a single element as *shoot* is deterministic. In contrast, each $\texttt{Trajs}(\mathit{spin}, r)$ contains two

[2] I.e. we assume complete and accurate knowledge ($\mathcal{K}$), the world acts completely inertial (I), we consider alternative effects, depending on the situation where an action is executed (A), and we only consider binary features (b) and single-step actions (s) — see[11].

[3] For the purpose of our analysis it is not necessary to know how $\texttt{A}$ is constructed given a trajectory table. The interested reader should consult[11].

State r	$\mathtt{Infl}(spin, r)$	$\mathtt{Trajs}(Spin, r)$
$\{loaded \hat{=} \mathtt{false}, alive \hat{=} \mathtt{false}\}$	$\{loaded\}$	$\{\langle loaded : \mathtt{true}\rangle, \langle\rangle\}$
$\{loaded \hat{=} \mathtt{false}, alive \hat{=} \mathtt{true}\}$	$\{loaded\}$	$\{\langle loaded : \mathtt{true}\rangle, \langle\rangle\}$
$\{loaded \hat{=} \mathtt{true}, alive \hat{=} \mathtt{false}\}$	$\{loaded\}$	$\{\langle\rangle, \langle loaded : \mathtt{false}\rangle\}$
$\{loaded \hat{=} \mathtt{true}, alive \hat{=} \mathtt{true}\}$	$\{loaded\}$	$\{\langle\rangle, \langle loaded : \mathtt{false}\rangle\}$

Figure 2: A trajectory description of the non-deterministic action *spin* .

trajectories — one where the gun becomes loaded and one where it becomes unloaded. Hence, *spin* is non-deterministic (see Figure 2).

Models of a chronicle are obtained by interpreting a dynamically changing world as a game between an ego who initiates actions and the world which reacts according to the descriptions of effects:

Definition 7 A *timepoint* is a natural number or 0 . Given a timepoint n , referred to as *now*, a *history* R is a mapping from timepoints $\{0, \ldots, n\}$ into the set of states. A *finite development* is a tuple $(\mathcal{B}, R, \mathcal{A}, \mathcal{C})$ where $\mathcal{B}$ is a set of timepoints with largest member n , R is a history, $\mathcal{A}$ is a set of actions which have been completed at time n , and $\mathcal{C}$ is a set of actions which have been started but are not completed at time n . Hence, elements in $\mathcal{A}$ are of the form (s, a, t) while elements in $\mathcal{C}$ are pairs (s, a) , where $s < t \leq n$ are timepoints and a is an action name. If $\mathcal{J} = (\mathtt{A}, \mathrm{SCD}, \mathrm{OBS})$ is a chronicle then the set of intended models of $\mathcal{J}$, written $\mathcal{M}od(\mathcal{J})$, is a set of finite developments which are obtained as follows: Starting with the development $(\{0\}, R_0, \{\}, \{\})$ where R_0 maps timepoint 0 to an arbitrary initial state, the ego selects the first action according to SCD and adds it to the set of non-completed actions, i.e. the development changes to $(\{0\}, R_0, \{\}, \{(0, a_1)\})$. Afterwards, the world adds the next timepoint 1 to $\mathcal{B} = \{0\}$, executes a_1 in $R_0(0)$ by choosing one possible resulting state r_1 according to the trajectory table described by $\mathtt{A}$, and moves the action from $\mathcal{C}$ to $\mathcal{A}$. This yields the finite development $(\{0,1\}, R_1, \{(0, a_1, 1)\}, \{\})$ where $R_1(0) = R_0(0)$ and $R_1(1) = r_1$. Then the ego selects the next element according to SCD , the world reacts and so forth. The game ends after the ego has selected the final element of the schedule and the world has executed it. The final development $(\{0, \ldots, n\}, R_n, \mathcal{A}, \{\})$ is a member of $\mathcal{M}od(\mathcal{J})$ iff each observation $[\tau] f \hat{=} \nu$ in OBS is true in R_n , i.e. $R_n(\tau)(f) = \nu$. $\mathcal{J}$ is *consistent* iff $\mathcal{M}od(\mathcal{J})$ is non-empty. ■

Example 1 (continued). On the analogy of $\mathcal{D}_1$, we can find a single model of $\mathcal{J}_1$,[4] namely $(\{0,1,2\}, R_2, \{(0, shoot, 1), (1, wait, 2)\}, \{\})$ where $R_2(0)$ is the state $\{loaded \hat{=} \mathtt{true}, alive \hat{=} \mathtt{true}\}$ and $R_2(1) = R_2(2) = \{loaded \hat{=} \mathtt{false}, alive \hat{=} \mathtt{false}\}$.

This result obviously resembles the solution obtained by $\mathcal{A}$ and the value propositions in For.3. An analogous observation can be made by comparing Example 3 and

[4] Provided the effects of *wait* are appropriately defined: For any state r , $\mathtt{Infl}(wait, r) = \{\}$ and $\mathtt{Trajs}(wait, r) = \{\langle\rangle\}$.

its encoding as a chronicle in the Ego-World-Semantics. In the following section, we formally compare the set of models of a domain description given in $\mathcal{A}$ or $\mathcal{A}_{ND}$, and the set of intended models of a corresponding chronicle.

4. Equivalence Results

Let σ be a situation based on a set of fluent names F and r a state based on a set of binary features $\mathcal{F}$ such that $F = \mathcal{F}$ then σ and r *coincide* iff for each $f \in F$ we find that $f \in \sigma$ iff $f \hat{=} \texttt{true}$ holds in r. For instance, $\{alive\}$ and $\{loaded \hat{=} \texttt{false}, alive \hat{=} \texttt{true}\}$ coincide. Given a situation σ, by r_σ we denote a state such that both coincide and vice versa, i.e. r and σ_r shall coincide as well.

Definition 8 Let $\mathcal{D} = (F, A, \mathcal{E}, \mathcal{V})$ be a consistent domain in $\mathcal{A}^1$. The *corresponding chronicle* $\mathcal{J}_\mathcal{D} = (\texttt{A}, \text{SCD}, \text{OBS})$ contains the features $\mathcal{F} = F$ and the action names A, and is constructed as follows: Let $\mathcal{D}$ be based on $[a_1, \ldots, a_n]$ ($n \geq 0$, see Definition 3) then $\text{SCD} = \{[0,1]a_1, \ldots, [n-1,n]a_n\}$. Furthermore, OBS is obtained by translating each value proposition f `after` $[a_1, \ldots, a_k]$ in $\mathcal{V}$ into $[k]f \hat{=} \texttt{true}$ if f is a positive fluent literal and $[k]f \hat{=} \texttt{false}$ if f is negative ($0 \leq k \leq n$). Finally, `A` describes a trajectory table $(\texttt{Infl}, \texttt{Trajs})$ which is generated as follows: Let Φ be the transition function determined by $\mathcal{E}$ then $\texttt{Infl}(a, r) = \{ f \in F \mid f \in \sigma_r \not\Leftrightarrow f \in \Phi(a, \sigma_r) \}$ and

$$\texttt{Trajs}(a, r) \;=\; \langle\, f_1 : \nu_1 \,, \;\ldots\;, \; f_k : \nu_k \,\rangle \tag{7}$$

where $a \in A$, r is a state, $\{f_1, \ldots, f_k\} = \texttt{Infl}(a, r)$ and $\nu_i = \texttt{true}$ if $f_i \in \Phi(a, \sigma_r)$ and $\nu_i \hat{=} \texttt{false}$ otherwise ($1 \leq i \leq k$).

Let $\mathcal{J} = (\texttt{A}, \text{SCD}, \text{OBS})$ be a consistent chronicle in $\mathcal{K}$-IbsAd based on features $\mathcal{F}$ and action names A. The corresponding domain $\mathcal{D}_\mathcal{J} = (F, A, \mathcal{E}, \mathcal{V})$, where $F = \mathcal{F}$, is constructed as follows: Let $\text{SCD} = \{[0,1]a_1, \ldots, [n-1,n]a_n\}$ then $\mathcal{V}$ is obtained by translating each observation $[k]f \hat{=} \texttt{true}$ in OBS into f `after` $[a_1, \ldots, a_k]$ and each observation $[k]f \hat{=} \texttt{false}$ into $\neg f$ `after` $[a_1, \ldots, a_k]$ ($0 \leq k \leq n$). Finally, let $(\texttt{Infl}, \texttt{Trajs})$ be the trajectory table described by `A`. For each a, r and each assignment $f : \nu$ which is contained in $\texttt{Trajs}(a, r)$, $\mathcal{E}$ includes the effect proposition

$$a \;\texttt{causes}\; e \;\texttt{if}\; c_1, \ldots, c_m \tag{8}$$

where $e = f$ (resp. $e = \neg f$) if $\nu = \texttt{true}$ (resp. $\nu = \texttt{false}$) and $c_1, \ldots, c_m$ is an exact definition of the situation σ_r, i.e. $\{c_1, \ldots, c_m\} = \sigma_r \cup \{\neg f \mid f \in F \setminus \sigma_r\}$. ■

Example 1 (continued). According to this definition, the value propositions in For.3 determine the two sets SCD_1 and OBS_1, respectively, and vice versa. Furthermore, the transition function For.4, applied to *shoot*, is translated into the table depicted in Figure 1. On the other hand, applying the second part of Definition 8 to this trajectory table yields a slightly different set of effect propositions, viz.

$$\begin{array}{llll}
\textit{shoot} & \texttt{causes} & \neg \textit{loaded} & \texttt{if} \;\; \textit{loaded}, \neg \textit{alive} \\
\textit{shoot} & \texttt{causes} & \neg \textit{loaded} & \texttt{if} \;\; \textit{loaded}, \textit{alive} \\
\textit{shoot} & \texttt{causes} & \neg \textit{alive} & \texttt{if} \;\; \textit{loaded}, \textit{alive}
\end{array}$$

but this is irrelevant for the equivalence result.

Lemma 9 *Let $\mathcal{D}$ be a consistent domain in $\mathcal{A}^1$ and $\mathcal{J}$ be a consistent chronicle in $\mathcal{K}$-IbsAd. If $\mathcal{J} = \mathcal{J}_\mathcal{D}$ or $\mathcal{D} = \mathcal{D}_\mathcal{J}$ then transition in $\mathcal{D}$ and $\mathcal{J}$ coincides.*

Proof (sketch): Let Φ be the transition function determined by the effect propositions of $\mathcal{D}$ then we have to show that for each action name a, situation σ, and state r', $\Phi(a,\sigma)$ and r' coincide iff r' is the result of executing a in state r_σ. In case $\mathcal{J} = \mathcal{J}_\mathcal{D}$ this follows from the fact that constructing the trajectory table of $\mathcal{J}$ via Definition 8 is based on Φ. In case $\mathcal{D} = \mathcal{D}_\mathcal{J}$ the claim follows from the fact that each assignment in the (single) trajectory of $\texttt{Trajs}(a, r_\sigma)$ is translated into an effect proposition which is applicable in σ but not elsewhere (c.f. For. 8). ■

Let (σ_0, Φ) be a model of a domain in $\mathcal{A}^1$ which is based on the action sequence $[a_1, \ldots, a_n]$ and let $(\mathcal{B}, R, \mathcal{A}, \{\})$ be a finite development then they are said to *correspond* iff $\mathcal{B} = \{0, \ldots, n\}$, $\mathcal{A} = \{(0, a_1, 1), \ldots, (n-1, a_n, n)\}$, and $\Phi([a_1, \ldots, a_k], \sigma_0)$ and $R(k)$ coincide for each $k = 0, \ldots, n$.

Theorem 10 *Let $\mathcal{D}$ be a domain in $\mathcal{A}^1$ and $\mathcal{J}_\mathcal{D}$ be given via Definition 8. For each model of $\mathcal{D}$ there exists a corresponding member of $\mathcal{M}od(\mathcal{J}_\mathcal{D})$ and vice versa.*

Let $\mathcal{J}$ be a chronicle in $\mathcal{K}$-IbsAd and $\mathcal{D}_\mathcal{J}$ be given via Definition 8. For each member of $\mathcal{M}od(\mathcal{J})$ there exists a corresponding model of $\mathcal{D}_\mathcal{J}$ and vice versa.

Proof (sketch): Without value propositions the claim follows from Lemma 9, and a value proposition $f\ \texttt{after}\ [a_1, \ldots, a_k]$ is true in (σ_0, Φ) if and only if the corresponding observation $[k]f \mathrel{\hat{=}} \nu$ is true in the history of a corresponding finite development. ■

On the analogy of Definition 8, domains in $\mathcal{A}^1_{ND}$, which forms a restriction on $\mathcal{A}_{ND}$ in the spirit of Definition 3, can be translated into chronicles in $\mathcal{K}$-IbsA and vice versa:

Definition 11 Let $\mathcal{D} = (F, A, \mathcal{E}, \mathcal{V})$ be a consistent domain in $\mathcal{A}^1_{ND}$. The corresponding chronicle $\mathcal{J}_\mathcal{D} = (\texttt{A}, \text{SCD}, \text{OBS})$ is constructed as in Definition 8 but the trajectory table is determined by the transition relation Φ of $\mathcal{D}$ as follows: If a is an action name and r a state then $f \in \texttt{Infl}(a, r)$ iff there is at least one σ' such that $(\sigma_r, a, \sigma') \in \Phi$ and the truth values of f regarding σ_r and σ' are different. Furthermore, each such σ' determines a trajectory in $\texttt{Trajs}(a, r)$ analogously to For.7.

Let $\mathcal{J} = (\texttt{A}, \text{SCD}, \text{OBS})$ be a consistent chronicle in $\mathcal{K}$-IbsA. The corresponding domain $\mathcal{D}_\mathcal{J}$ is constructed as in Definition 8 but the trajectory table determines a set of extended effect propositions as follows: If a is an action name and r a state then for each trajectory $\langle f_1 : \nu_1, \ldots, f_k : \nu_k \rangle \in \texttt{Trajs}(a, r)$, the extended effect proposition

$$a\ \texttt{alternatively causes}\ e_1, \ldots, e_k\ \texttt{if}\ c_1, \ldots, c_m$$

is generated, where $e_i = f_i$ (resp. $e_i = \neg f_i$) if $\nu_i = \texttt{true}$ (resp. $\nu_i = \texttt{false}$) and $c_1, \ldots, c_m$ is an exact definition of σ_r. ■

Analogously to Lemma 9 we can prove that transition coincides in so far as if $(\sigma, a, \sigma') \in \Phi$ then $r_{\sigma'}$ is a possible result of executing a in r_σ and vice versa. Furthermore, let the correspondence relation between models be as before but it is required that $\varphi(k)$ and $R(k)$ coincide for any k, then Theorem 10 can be generalized to $\mathcal{A}^1_{ND}$ and $\mathcal{K}$-IbsA.

5. Conclusion

We have given a first answer to the question of how two prominent systematic approaches to reasoning about actions and change are related. We have fixed the respective ontological subclasses in the Ego-World-Semantics which are equivalent to the Action Description Language and an extension handling non-deterministic actions. On the other hand, we have elaborated a fundamental difference between the two frameworks.

An important consequence of this analysis should be a proposal about a combination of the two systems to profit from the merits of both. For example, the concept of hypothetical developments could be integrated into EWS. To this end, the notions of schedules and observations have to be generalized such that several schedules are considered and each observation is bound to a particular schedule. On the other hand, the expressive power of the language underlying E. Sandewall's framework as well as the complex methods to reasoning about time form valuable suggestions for extending $\mathcal{A}$.

Furthermore, future research effort should concentrate on continuation of our analysis concerning new developments in the two investigated frameworks like the recent extensions of $\mathcal{A}$ regarding concurrent actions[2] or actions with indirect effects[8].

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