
Modeling Complex Domains of Actions and Change

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Abstract

This paper studies the problem of modeling complex domains of actions and change within high-level action description languages. We investigate two main issues of concern: (a) can we represent complex domains that capture together different problems such as ramifications, non-determinism and concurrency of actions, at a high-level, close to the given natural ontology of the problem domain and (b) what features of such a representation can affect, and how, its computational behaviour. The paper describes the main problems faced in this representation task and presents the results of an empirical study, carried out through a series of controlled experiments, to analyze the computational performance of reasoning in these representations. The experiments compare different representations obtained, for example, by changing the basic ontology of the domain or by varying the degree of use of indirect effect laws through domain constraints. This study has helped to expose the main sources of computational difficulty in the reasoning and suggest some methodological guidelines for representing complex domains. Although our work has been carried out within one particular high-level description language, we believe that the results, especially those that relate to the problems of representation, are independent of the specific modeling language.

1 Introduction and Background

Over the last decade several new frameworks for reasoning about actions and change have been proposed. Together with the original frameworks of the situation and event calculi, we have seen a number of different action descrip-

tion languages emerging with recent implemented prototype systems [3, 1, 4, 7]. Many of these languages have been motivated by the desire to have simple representation frameworks, with semantics that relate more directly to the natural intended meaning of their statements. They, therefore, aspire to provide high-level representations of domains that are close to their natural specification.

This paper studies the problem of modeling complex domains of reasoning about actions and change within high-level action description languages. It aims to expose the main problems involved in this representation task and to study the computational behaviour of the ensuing representations. It considers the Zoo domain, proposed at the Logic Modeling Workshop of the ETAI electronic communication forum [2], as one representative complex domain that frameworks of reasoning about actions and change should aim to capture.

A complex domain brings together a number of different problems associated with reasoning about actions and change, such as ramifications, non-determinism and concurrency. Although all these aspects have been extensively studied and several solutions have been proposed these studies are largely done for one problem in isolation and with little attention to the computational behaviour of these solutions. In this work we study how we can use the knowhow generated over the years in these separate problems, in order to represent complex and realistic domains that encompass together all these different features. Despite the fact that we will use a particular representation framework, that of the Language \mathcal{E} , we believe that the results apply more generally. This language encompasses (partial) solutions to the main problems of reasoning about action and change that are based on the same principles used by most of the other approaches. Hence the findings of our work, especially those that refer to the representational task would apply to other formalisms as well.

In particular, we investigate two main issues of concern: (a) can we represent complex domains in a natural way

using directly the given natural ontology of the problem domain and (b) what features of such a representation can affect (and how) its computational behaviour. Our method of study uses an empirical investigation through a series of controlled experiments. In some of these experiments we compare different representations by varying, for example, the basic ontology of the domain or the degree of use of indirect effect laws through domain constraints. In other experiments, we investigate the performance of a fixed representation as we vary the type of problems we consider, e.g by varying the degree of incompleteness of information in a scenario or by varying the complexity of the narrative with irrelevant action occurrences.

These experiments help to analyze the computational difficulties of the reasoning by exposing their main sources. In turn, they suggest methodological guidelines on how to develop complete representations of complex domains with improved computational properties.

In the rest of this section we present briefly the specific action description language that we will use in our modeling study. Section 2 studies the main problems faced in the task of representing a complex domain (by analyzing these for the Zoo domain). Section 3 discusses some of the experiments carried out to study the computational behaviour of representations and presents their main conclusions. Section 4 discusses the overall conclusions drawn from our work.

1.1 The Action Description Language \mathcal{E}

Action description languages have been developed over the last years to provide high level representation frameworks for theories about actions and change. They generally do not have an explicit representation of the frame axioms and they have been extended to address the ramification and qualification problems. They have been motivated by the need to have simple representation frameworks with natural semantics that relate more directly to the natural interpretations of the domains.

We will consider the problem of modeling complex domains within the particular action description Language \mathcal{E} [7, 8]. The vocabulary of the Language \mathcal{E} consists of a set Φ of *fluent constants*, a set of *action constants*, and a partially ordered set $\langle \Pi, \preceq \rangle$ of *time-points*. This vocabulary depends each time on the domain being modeled. A *fluent literal* is either a fluent constant F or its negation $\neg F$. In the current implementation of the language, the only time structure that is supported is that of the natural numbers, so we restrict our attention here mainly to domains of this type.

Domain descriptions in the Language \mathcal{E} are collections of the following types of statements (where A is an action

constant, T is a time-point, F is a fluent constant, L is a fluent literal and C is a set of fluent literals):

- *t-propositions* of the form: L **holds-at** T
- *h-propositions* of the form: A **happens-at** T
- *c-propositions* of the form: A **initiates** F **when** C or, A **terminates** F **when** C
- *r-propositions* of the form: L **whenever** C
- *p-propositions* of the form: A **needs** C .

For the purposes of this paper it is sufficient to describe the semantics of the language in an informal way, giving the intended meaning of each type of sentence and describing the basic tenets of the reasoning supported. T-propositions record observations that particular fluents hold or do not hold at particular time-points. H-propositions state that particular actions occur at particular time-points. C-propositions state general “action laws” – the intended meaning of “ A **initiates** F **when** C ” is that “ C is a minimally sufficient set of conditions for an occurrence of A to initiate F ”. R-propositions, also called **ramifications or domain constraints**, serve a dual role in that they describe both static constraints between fluents and ways in which fluents may be indirectly affected by action occurrences. As a constraint this must be satisfied as a classical implication at any time point. The intended meaning of “ L **whenever** C ” is that “at every time-point that C holds, L holds, and hence every action occurrence that brings about C also brings about L ”. P-propositions state necessary conditions for an action to occur.

The semantics of \mathcal{E} are based on a notion of a *model* of a domain D that assigns a truth value to each fluent at each time point. A model encompasses two basic requirements:

Persistence Direct and indirect action laws, stated by c-propositions and through r-propositions respectively, are the only way to bring about a change (over time) in the truth value of a fluent, when an appropriate action occurs. This new value persists in time from then onwards, until another such point of change.

Consistency The model must satisfy as classical implications the r-propositions at each time point and as facts the t-propositions together with all the preconditions C at times T that follow from each p-proposition A **needs** C and associated h-proposition A **happens-at** T .

Given a consistent domain D and a query or goal G comprising a set of t-propositions, we say that G is a **credulous or possible** conclusion of D iff there is a model of D in

which G is true and that G is a **skeptical or necessary** conclusion of D iff G is true in all models of D .

As an example, consider the following simple “bulb domain” with action constants *SwitchOn*, *SwitchOff* and *Break* and fluents *Light* and *Normal*:

SwitchOn **initiates** *Light* **when** {*Normal*}
SwitchOff **terminates** *Light*
Break **terminates** *Normal*
 \neg *Light* **whenever** { \neg *Normal*}
SwitchOn **needs** { \neg *Light*}
SwitchOn **happens-at** 2
Normal **holds-at** 0

This domain has as a skeptical conclusion *Light* holds-at 4, but the conclusion is only credulous when we remove the last sentence.

The Language \mathcal{E} has been implemented [9] via an argumentation-based translation of the language. This system, called \mathcal{E} -RES, can support directly a variety of modes of common sense reasoning such as: default persistence in credulous or skeptical form, assimilation of observations and their diagnosis possibly under incomplete information, as well as combinations of these. The computational model on which this is based integrates argumentation goal-oriented proofs for default persistence, together with classical theorem proving techniques for the satisfaction of the constraints expressed in a domain. It also employs a (weak) notion of syntactic relevance in order to help focus the computation to the relevant part of the theory.

This argumentation-based reformulation also extends the Language \mathcal{E} allowing its action laws to be treated as default laws.

2 Complex Domain Representations

In this section we study how the Zoo domain, defined at the Logic Modeling Workshop (LMW) [2], can be represented in the Language \mathcal{E} . We will follow closely the presentation of the domain and guidelines given at LMW trying to address all the issues raised there. This section is therefore best read in conjunction with the documentation available at LMW. We will present the different aspects of representing such a complex domain, while trying to expose the main problems faced and choices made.

The LMW describes the Zoo domain as “...a world containing the main ingredients of a classical zoo: cages, animals in the cages, gates between two cages, as well as gates between a cage and the exterior. In the Zoo world there are animals of several species, including humans. Actions in the world may include movement within and between cages,

opening and closing gates, ..., riding animals, etc.”

2.1 Background Landscape and Active Structure

Our first task is to represent the **landscape and active structure** of the domain i.e. describe the background information of the Zoo environment and the objects that populate it. This information is generally taken to be static, not changing over time. For this type of information the Language \mathcal{E} has a simple facility of using **constant** fluents and declaring the static state of affairs for these at some initial time point (time 0). For example, we declare the known animals in the domain by a set of statements of the following form:

animal($-$) **is_constant**
animal(*john*) **holds-at** 0
animal(*jane*) **holds-at** 0
animal(*elly*) **holds-at** 0
 ...

In addition, we can use ramification statements to represent static information that is derived from other such information e.g. that “an animal is large when it is an adult and belongs to a large species”:

animal_is_large(A) **whenever** {*animal_is_adult*(A),
animal_species(A, S), *species_is_large*(S)}.

In the same way, we represent the zoo terrain by declaring all its positions and the neighbor relation via a constant fluent *neighbor_pos*($-, -$) and ramification statements to express its properties e.g. *neighbor_pos*(P_1, P_2) **whenever** {*neighbor_pos*(P_2, P_1)} for the symmetry of this relation.

We then reason with the Closed World Assumption on these static fluent predicates at time 0 and project their truth value unchanged to any other time point. If complete information for a background fluent predicate is not known at 0, then this predicate would not be declared as constant and thus would be interpreted under the Open World Assumption with the possibility to assume its truth value.

We note that the inherent propositional nature of the Language \mathcal{E} does pose some representational restrictions. We need for example to define the primary typing constants, which enumerate entities of the landscape and hence only domains with known predefined entities can be represented. In general, the underlying ontology of the language can be extended with a notion of sorted variables over a set of finite sorts. The details of this are not important for this work. In this paper, we will assume that we have in the Zoo domain the basic types of animals, species, gates, locations and positions, defined as constant fluents, and that any variable ($i=1,2,3,\dots$) denoted by A_i, S_i, G_i, L_i , or P_i has the respective type.

2.2 Action Effect Laws

Till now we have only been concerned with the static aspects of the representation of the domain i.e. representing information at one time slice. The central part of any domain of reasoning about actions and change is that of its **Action laws specifying the effects of actions**. In the Language \mathcal{E} action laws are represented directly via c-propositions. For example, the effect of the $move_to_position(A, P)$ action in the Zoo domain, that the animal “A” takes the position “P” is represented by:

$$move_to_position(A, P) \text{ initiates } animal_pos(A, P) \\ \text{when } \{reachable(A, P)\}^1.$$

Here this effect law depends on the condition that at the time of the action the position “P” is reachable by “A”, namely that “P” is an adjacent position to the position of the animal “A” at the time of the action. This means that an instance of the action $move_to_position(A, P)$ could occur without successfully reaching “P”. Alternatively, we can remove this condition from the effect law and set it as a pre-condition for the action to occur via the statement:

$$move_to_position(A, P) \text{ needs } \{reachable(A, P)\}.$$

This choice depends on how we wish to interpret the occurrence of events in a given narrative. If when given an event we mean that this event has successfully occurred, then this alternative is more appropriate and allows for more conclusions to be drawn, given an action occurrence. For example, we would include the statement

$$move_to_position(A, P) \text{ needs } \{\neg rides(A, A_1)\}$$

to capture the requirement that a rider cannot perform the $move_to_position$ action at the time that s/he is riding. Under this interpretation of event occurrences this way of representing these preconditions allows us to draw more conclusions from knowledge that an action has occurred. If then, we are given that $move_to_position(john, p_1)$ happened at time T then we would conclude that *john* is not riding any (known) animal at T. Depending on other information in the domain we maybe able to project this backward or forward in time.

The above law of change for the action $move_to_position(A, P)$ expresses a **direct** effect. This action can also have other effects, for example that a rider A_1 of the animal A will also acquire the new position P , when A moves to P . In comparison, this is not a direct effect but nevertheless, as argued in the

¹Note that the current version of the \mathcal{E} -RES system, that implements the Language \mathcal{E} , requires that the typing of each variable of a fluent or action to be stated explicitly each time the fluent or action is used in a statement. Hence in \mathcal{E} -RES this will written as:

$$move_to_position(A, P) \text{ initiates } animal_pos(A, P) \\ \text{when } \{animal(A), position(P), reachable(A, P)\}.$$

recent literature (e.g. [11]), actions should be allowed to have such **indirect** effects. This poses a dilemma in the representation. Indirect effects could be represented either by explicit direct effect laws or via the domain constraints (or ramification statements) of the theory. In the above example we could have the additional direct laws:

$$move_to_position(A, P) \text{ initiates } animal_pos(A_1, P) \\ \text{when } \{rides(A_1, A)\}, \\ move_to_position(A, P) \text{ terminates } animal_pos(A, P_1) \\ \text{when } \{animal_pos(A, P_1)\}$$

for moving an animal’s rider along with the animal and terminating the animal’s current position, respectively. On the other hand, we could omit these, since the following domain constraints (stating that an animal’s rider always has the same position with the ridden animal and that an animal cannot be at two positions at the same time) would generate the required effects indirectly:

$$animal_pos(A_1, P) \text{ whenever } \{animal_pos(A, P), \\ rides(A_1, A)\}, \\ \neg animal_pos(A, P_1) \text{ whenever } \{animal_pos(A, P), \\ P_1 \neq P\}.$$

However, such domain constraints are also needed in the representation to suitably restrict the assumptions that we might make while reasoning, when we have incomplete information in the theory.

Hence a dilemma emerges, either (1) to use direct laws to explicitly enumerate all possible effects of an action together with domain constraints which do not generate indirect effects, but simply act as integrity constraints for assumptions relating to incomplete fluents or (2) to use direct laws for the basic effects of an action and let the domain ramification constraints generate the other effects indirectly. We will see below that these two choices can be semantically different and that they differ in their computational performance.

2.3 Domain Constraints

To represent the whole Zoo domain we need to define all direct action laws for each of the type of actions together with their pre-conditions (as we have done above for $move_to_position$) and state the various **domain constraints** that the specification of the problem requires. In addition, to the domain constraints given above, we also have several other statements. For example, we have:

$$false \text{ whenever } \{animal_species(A, human), \\ rides(A_1, A)\}, \\ \neg rides(A, A_1) \text{ whenever } \{rides(A, A_2), A_1 \neq A_2\}$$

to capture the fact that a human cannot be ridden and to

represent the fact that an animal cannot ride two animals at the same time. Here the first domain is written in this particular way as a denial to indicate that it is not necessary to produce indirect effects through it.

The domain constraints are also used to define various auxiliary dynamic predicates that we need, such as *reachable* used above:

$$\begin{aligned} & \textit{reachable}(A, P) \textbf{ whenever } \{ \textit{animal_pos}(A, P_1), \\ & \quad \textit{neighbor}(P_1, P) \}, \\ & \neg \textit{reachable}(A, P) \textbf{ whenever } \{ \textit{animal_pos}(A, P_1), \\ & \quad \neg \textit{neighbor}(P_1, P) \} \end{aligned}$$

Note that here we do have the option (or dilemma) to define such dynamic predicates via direct effect laws of the actions, but this would be more complex and non-modular requiring the full enumeration of all cases where the fluent *reachable* could be affected. Its definition through the above domain constraints and their indirect effects that they embody, provides a compact and modular way of representing such a dynamic predicate.

2.4 Issues in the choice of Representation

We return now to study in more detail the above dilemma and in particular how this is related to non-determinism in the domain and its representation. One of the actions of the Zoo domain, that of *throwoff*(A_1, A_2), is specified to be non-deterministic. Animal A_1 throws off its back A_2 and the latter can land at any position reachable from their common position at the time of the throw. As there could be many such reachable positions and we do not know at which one the animal would fall this is a non-deterministic action. The argumentation semantics of the Language \mathcal{E} allows us to represent such a non-deterministic action law in the same way as any other law:

$$\begin{aligned} & \textit{throwoff}(A_1, A_2) \textbf{ initiates } \textit{animal_pos}(A_2, P) \\ & \quad \textbf{ when } \{ \textit{reachable}(A_2, P) \}. \end{aligned}$$

This effect law does not contain any explicit qualifications to state that the animal would fall in one position only provided that it does not fall on anyone of the other (reachable) positions. This qualification is implicitly produced by the domain constraint that an animal cannot have two different positions at the same time. The combination of these two statements captures the non-determinism of the action. An inconsistency is not produced (although apparently it would be), because for each direct initiation of a particular position P that the action law produces, the domain constraint then produces the indirect effect that all other positions are terminated. In this way each position can be chosen. Note that it is important that the blockage of the other positions is not captured simply by the static application of the constraint, but that at the same time the position

of an animal changes to P we also have a change with regards to all the other positions, namely they “begin to be false”.

We therefore see a useful need for the production of indirect effects, i.e. of change through the domain constraints. This provides a natural mechanism of implicit qualification of the several direct laws for a non-deterministic action. Alternatively, we would need to qualify explicitly the direct law with the condition that the animal can not be at any other position. This would be complex and difficult to express because the qualifications to the action law need to refer to the state of the world after the action has occurred.

The same behaviour can also be observed in the case of concurrent actions whose effects are contradictory. Consider for example the simultaneous occurrence of a *getoff*(A, A_1, P) and a *move_to_position*(A_1, P_1) action, at a time when the animal A is riding another animal A_1 . The first action requires that A has the position P as its direct effect, while the second action would give that A has the different position P_1 since A is riding A_1 . Again, the above constraint that an animal can have only one position at a time, acts as a qualifier and splits this scenario in a non-deterministic way into two possibilities. In effect, in the first case A manages to get off before A_1 moves, whereas in the second case A_1 moves first and then A gets off. The domain constraint gives an implicit qualification to the two effect laws involved, in a way that would be very difficult (and unnatural) to represent explicitly.

Concurrent action scenaria also show the main difference between direct and indirect effect laws. Let us return to the indirect effect law that a rider acquires the same position of the animal that s/he is riding and compare it with its direct effect law counterpart as given above. A difference between the two laws shows up when we consider, for example, the concurrent *getoff* and *move_to_position* scenario, above. The direct law would allow the rider to move to the new position with the animal, whereas the indirect law would not generate this effect. This is because the condition of *rides* in the direct law case needs to hold at the exact time of the action, while in the indirect law case this needs to hold at an infinitesimal time (or next time point) after this, so that both conditions in the ramification can hold together to produce its conclusion. Indeed, due to the simultaneous *getoff* action, *rides* holds at the time of these actions, but not later as it is terminated by this action unconditionally. Hence, in this concurrent scenario we would not get the second possibility of the indirect generation of the rider moving with the animal.

In this way we see that direct laws can be stronger than a corresponding indirect effect law and in fact could be used to break non-determinism when we do not want this. To see this better and show its significance for the task of modeling

a domain, let us consider a case where the non-determinism could exist as a result of the occurrence of one action alone. Consider the domain constraint that two animals at different positions cannot ride each other:

$$\neg \text{rides}(A, A_1) \text{ whenever } \{ \text{animal_pos}(A, P), \\ \text{animal_pos}(A_1, P_1), P_1 \neq P \}.$$

This would then give indirect effects of the termination of riding when we perform actions that change the position of the rider alone (such as *getoff* or *throwoff*). But it would also give the indirect effect that riding is terminated when the animal moves and hence it changes its position relative to its rider. In fact, adding the above ramification to the representation and performing an action $\text{move_to_position}(A_1, P_1)$, at a time point where the animal A_1 is ridden by another animal, results in two possibilities: either the rider comes off and is at the original position of A_1 , or the rider stays on and is at the new position P_1 where the animal has moved to. With regards to the effect of the action $\text{move_to_position}(A_1, P_1)$ on the position of the rider the action is non-deterministic.

In this case we do not want this and we have a preference for the rider to move along with the animal that it rides. We can achieve this preference in a natural way by explicitly stating the preferred effect through a direct effect law. Despite the fact that we have a domain constraint that gives, as an indirect effect, that the rider moves along with the animal, we **also** represent this explicitly by a direct initiation law for the action $\text{move_to_position}(A, P)$, i.e. we keep both sentences in the dilemma presented above in this section. This then blocks the indirect effect of terminating the riding by the movement of the animal as the required condition for this, namely that the rider is at a different position immediately after the action, cannot now be supported due to the strong argument of changing its position to that of the animal's new position through the new direct law and the constraint that the rider can only have one position at a time. The explicit statement of the direct law has given preference to it.

In summary, we see that the ramifications and their indirect effects provide an implicit form of qualification through the general constraint properties of the domain. This means that the theory treats its effect laws as default laws where one can qualify another through these constraints. The direct effect laws set out preferences amongst conflicting possibilities. The redundancy of repeating an indirect law as a direct law as well, forms a natural way of setting a preference. We give emphasis to effects by articulating them explicitly.

2.5 An example Scenario

Closing this section, we show how a particular scenario can be represented. A scenario is given by stating events, i.e. specific instances of actions that occurred (through h-propositions) and observations, that is values of fluents at specific time points (through t-propositions). For example,

throwoff(*elly*, *john*) **happens-at** 1
move_to_position(*john*, *p1*) **happens-at** 2
mount_animal(*john*, *dumpo*) **happens-at** 3
reachable(*john*, *p1*) **holds-at** 2

represents the scenario that *elly* threw off *john*, who then observed that position *p1* was reachable, moved to position *p1*, and then mounted *dumpo*. In this scenario we would reason to $\text{rides}(\text{john}, \text{elly})$ at time 1 or 0 as a necessary (or skeptical) conclusion, but that $\text{animal_pos}(\text{john}, \text{p2})$ at time 2, where *p2* is any neighbor of *p1*, is a possible (or credulous) conclusion. At time 4 onwards we can conclude that $\text{rides}(\text{john}, \text{dumpo})$ is necessarily true. But if we are given also that $\text{move_to_position}(\text{dumpo}, \text{p3})$ **happens-at** 3, then $\text{rides}(\text{john}, \text{dumpo})$ at 4 will only be a possible conclusion. Observing that $\text{animal_pos}(\text{john}, \text{p3})$ **holds-at** 5 i.e. that *john* and *dumpo* have the same position then $\text{rides}(\text{john}, \text{dumpo})$ at 4 would be a necessary conclusion.

3 Computational Behaviour of Representations

In this section we study empirically, via suitable controlled experiments, the computational behaviour of a representation and try to ascertain what factors of the representation might or might not affect this behaviour. We have conducted two major types of experiments: (a) given a fixed representation of the Zoo domain, we have examined various scenarios that differ in the amount of given information, its relevancy to the queries and the type of queries performed, and (b) given some fixed scenarios and queries, we have examined various representations that differ on the extend the action effects are represented directly/indirectly and on the richness of the vocabulary used. The basic scale of the domains on which we have carried these experiments is of the order of 3 thousand ground clauses per time point. A scenario typically spans over 3-6 time points.

As the representative results² presented in figure 1 suggest, increasing the information in a scenario can affect positively the computational performance, even if the extra

²All numbers shown in the tables of this paper are in seconds measured on a Pentium II, 266 MHz, PC. The absolute value of these times are not important as the purpose of the experiments is to compare different cases.

information given explicitly in the scenario is a necessary conclusion of this.

QUERY / RESULT	1/Y	2/Y	3/N	4/Y	5/N	6/Y	7/Y	8/Y	9/N	10/N
COMPLETE	9	12	2	13	12	7	8	11	3	2
INCOMPLETE	14	33	19	19	17	9	11	28	4	17

Figure 1: Complete vs Incomplete Scenario Knowledge

These experiments have also shown that it is possible to use simple syntactic relevancy checks to focus the computation to the relevant (w.r.t. the query at hand) part of the domain. In fact, the experiments have helped us develop further a semantically enhanced notion of relevancy that neutralizes to some extent the effect of additional irrelevant information in the scenario. Figure 2 shows that the addition of irrelevant actions in a scenario does not have a significant impact on the computation. The stability under irrelevant information also depends strongly on the type of representation used and the choice of vocabulary, as we will see below in the second class of experiments. Finally, as expected in some cases, particularly in scenarios with a lot of missing information, skeptical queries can be significantly slower than the corresponding credulous queries.

QUERY / RESULT	1/Y	2/Y	3/N	4/N	5/Y	6/Y	7/Y	8/Y	9/Y	10/N
RELEVANT	35	48	17	54	49	31	42	38	261	266
IRRELEVANT	43	70	24	81	67	48	93	112	290	440

Figure 2: Relevant vs Additional Irrelevant Actions

As mentioned above, the second class of experiments considers changes in the representation. Figure 3 compares the computational behaviour between representations which use direct effect laws to a different degree. In general, using only direct laws gives a significantly better computational performance than a representation that uses to a maximum indirect effect laws. We should note though, as we have seen in section 2, that the first representation cannot always fully capture the domain e.g. the non-determinism of conflicting concurrent actions. In such cases, this becomes inconsistent and is unable to return an answer. It is also noteworthy, that when effect laws are duplicated in the representation both directly and indirectly, the behaviour varies from being as good as a representation that primarily uses direct effects, to being worse than a representation that primarily uses indirect effects. This depends mostly on whether the specific laws that are duplicated as direct laws can generate a large number of additional indirect effects.

Another series of experiments has examined the effects on the computational behaviour of using an enriched, more specific vocabulary of the domain in the representation. Starting from a minimally sufficient vocabulary, we have

QUERY / RESULT	1/Y	2/N	3/N	4/Y	5/N	6/N	7/Y	8/Y	9/N	10/Y
DIRECT (D)	17	22	7	19	8	33	15	22	9	8
INDIRECT (I)	42	26	3	14	362	18	9	43	328	37

Figure 3: Direct vs Indirect Effect Laws

developed a number of other equivalent representations using more specialized vocabularies that separate explicitly different specific cases for an action, e.g. the single action fluent *move_to_position* is replaced by *move_in_cage*, *enter_cage* and *exit_cage*. Similarly, we can distinguish explicitly in the vocabulary some of the fluent properties e.g. those that refer to the (2 dimensional) position on the floor from the properties that refer to the third dimension off the floor. We have found that a representation that uses, in this way, a carefully selected ontology and proper typing can significantly improve its computational efficiency. This occurs mainly by reducing the number of assumptions (sometimes impossible ones) from being considered in the reasoning.

With regards to the issue of scaling of the computational behaviour of the representations, our experiments suggest that the representation that maximizes the use of direct effect laws scales up relatively well. These are preliminary results, tested only on small sized domains that contain up to a maximum of 15 positions in the terrain, corresponding to around 25,000 ground clauses. Representations with non-minimal use of indirect effect laws scale up poorly.

In general, our empirical study has revealed two main computational bottlenecks: (a) the number of additional consequences drawn from the conclusions of a query that need to be considered to ensure that the query can be consistently satisfied in the whole domain and (b) the number of counter-proofs (counter-arguments) that are generated via persistence on an assumption needed to prove the query. Our experiments have helped us address (at least partly) these difficulties. The enhanced notion of relevancy, which helps us avoid unnecessary re-computation of known consequences and a (non-minimal) choice of vocabulary that distinguishes explicitly different scenarios, can result in significant improvement of computational behaviour. Another potential source of improvement can come from the way we use direct and indirect effect laws. Generally, the more use of direct laws the better the performance, but there is a trade off here with the reduction in modularity and readability of a representation that uses direct laws extensively. In some cases the computational gain is relatively small to justify this and a representation that combines the use of these two types of effect laws is overall better.

We have also begun to examine the same problems using a different computational model in place of the argumentation based model used so far. We have translated the Lan-

guage \mathcal{E} to a SAT theory so that we can then employ a SAT solver for query answering. This translation is not complete and supports only a restricted class of domains. In particular, it does not support domains with non-deterministic actions, or concurrent actions that generate conflicting effects nor domains in which the ramifications form cycles. Initial results indicate that the SAT-based approach has a more stable behaviour. They also indicate that it scales up better as we increase the number of actions in a scenario, but not so as we increase the number of positions in the terrain of the Zoo domain. An interesting difference of the SAT-based approach is the fact that it is difficult to employ relevancy notions in it. Some simple forms of relevancy can be used, but this requires that for each query we need to translate the relevant part of the domain theory afresh and this can have an adverse effect on its performance.

4 Related Work and Conclusions

We have studied how to model complex domains of action and change based on the theoretical foundations that the community at large has developed over the last decade. In particular, we have addressed the challenge set by the Logic Modeling Workshop [2], to apply this theory in modeling complex domains that encompass together many different aspects of the problem. As in the related work of [5, 6, 12] our work shows that the existing frameworks of action description languages are sufficiently expressive to meet this representational challenge.

Moreover, applying this otherwise well understood theory of reasoning about actions and change to capture complex domains has helped to expose more clearly some problems. For example, it has shown a link between non-determinism and an implicit qualification of effect laws via the domain constraints where the explicit representation of an indirect effect law as a direct law can give this higher priority. As mentioned in the introduction, we believe that these considerations are independent of the particular framework that we have used to carry out our study and that they would apply also to other approaches that are based on the same underlying principles for developing a theory for reasoning about actions and change. Differences may arise in the computational aspects of the different frameworks. For this reason we have concentrated more on comparison experiments and have tried to exposed inherent computational problems. Also the propositional nature of the particular framework that we have used could be limiting in the static aspects of the representation, i.e. in the ability to represent knowledge at any single time or situation. But this does not affect the ability to represent the dynamic aspects of a problem domain. At this initial stage of the study we believe that it is methodologically correct to de-couple these two aspects and examine at a later stage how they would

affect each other.

Our study of the computational behaviour of representations has suggested some methodological guidelines for modeling complex domains that can help us control their computational performance. These include the balanced use of direct and indirect effect laws and the adoption of an appropriate vocabulary as presented in the previous section. To cross check these comparison results it would be useful to study similar experiments using other languages, e.g. using the Causal Calculator [10] with its SAT based computation. We also need to study how other mechanisms, external to the reasoning, can help focus more the computation to the relevant part of the theory.

More work is needed to understand better what factors can influence the computational performance of a representation and how this would scale up. We also need to develop a stricter methodology on how to choose a vocabulary for a complex domain that would give it good computational properties. In our work so far this choice was mostly motivated by the natural common sense reasoning that we as humans apply to the domain and our use of a specific vocabulary for it. In fact, a distinction between “natural” and “formal” (or compact) representations emerges, where the first type of representation uses a non-minimal enriched vocabulary which helps it encode directly in the domain qualitative solutions to computational problems (e.g. the geometry of a terrain) and thus results to a better computational behaviour. This and its possible link to qualitative reasoning in AI is an interesting problem for future study.

Our work has been mainly motivated with trying to understand a natural computational model of human common-sense reasoning and how this is affected both by issues of representation and methods of computation. In the future we plan to investigate, through a series of cognitive experiments, how natural are these representations and how well they capture the human common sense reasoning in the domain of action and change.

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