ESmodels: An Epistemic Specification Solver

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Abstract
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ESmodels is designed and implemented as an experiment platform to investigate the semantics, language, related reasoning algorithms, and possible applications of epistemic specifications. We first give the epistemic specification language of ESmodels and its semantics. The language employs only one modal operator K but we prove that it is able to represent luxuriant modal operators by presenting transformation rules. Then, we describe basic algorithms and optimization approaches used in ESmodels. After that, we discuss possible applications of ESmodels in conformant planning and constraint satisfaction. Finally, we conclude with perspectives.

KEYWORDS: logic programming, epistemic specification, knowledge representation

1 Introduction

The language of epistemic specification initially proposed in (Gelfond and Przymusinska 1991), (Gelfond and Przymusinska 1993), (Gelfond 1994), and (Gelfond 1991) is an extension of the language of answer set programs by modal operators K and M to represent beliefs of the agent capable of introspection in the presence of multiple belief sets. Intuitively, it use KF to denote an proposition F is believed to be true in each of the agent’s belief sets, and MF to denote an proposition F is believed to be true in some of the agent’s belief sets. This extension is believed to be useful by discussing its application to formalization of commonsense reasoning. Along its syntax and semantics in (Gelfond and Przymusinska 1991), a few efforts were made to establish reasoning algorithms in (Zhang 2006) and (Watson 1994), and theoretical foundation in (Zhang 2003), (Watson 2000), and (Wang and Zhang 2005). Recently, research on epistemic specifications increases again because introspective reasoning is becoming reality and foreseeable as showed in (Faber and Woltran 2011), (Faber and Woltran 2009), and (Truszczyński 2011). To eliminate some unintended interpretations which exist under the original definition, a new semantics is defined in (Gelfond 2011) to arguably close to the intuitive meaning of modalities. Currently, efforts are still desired to made to establish and validate properties of epistemic specifications and the corresponding reasoning algorithms, and to investigate the use of the language. The design and implementation of an epistemic specification solver is hoped to facilitate those efforts.

This article introduces an epistemic specification solver ESmodels that is recently being designed and implemented as a flexible platform for experiment with epistemic specifications. The language of ESmodels has two types of subjective literals Kl and ¬Kl. To express other types
of subjective literals, we propose a group of transformation rules rewriting epistemic specifications with arbitrary types of subjective literals in ESmodels’s language. In ESmodels, a generate-test algorithm for computing world views of the epistemic specification is employed. It is worth noting that efficient ASP solver Clasp is coupled into ESmodels to help to generate candidate world views efficiently. Optimization approaches are preliminarily used to promoting the efficiency of the basic algorithm. Presently, we are applying ESmodels in solving security conditions in conformant planning, and encoding constraint satisfaction problems.

2 Language

2.1 Syntax and Semantics

An ESmodels’s epistemic specification is a collection of finite rules in the following form

\[ l_0 \lor \ldots \lor l_k : - l_{k+1}, \ldots, l_j, S_1 \ldots, S_{l_m}, \text{not } l_{m+1}, \ldots, \text{not } l_n \]

where each \( l_i \) for \( 0 \leq i \leq n \) is an objective literal, i.e. either an atom \( A \) or the negation \( \neg A \) of \( A \), and \( S \) is either \( K \) or \( \neg K \), not is negation as failure. The set of all objective literals appears in an epistemic specification \( \Pi \) is denoted by \( \text{Lit}_\Pi \). Given a rule \( r \) in the above form, let head\((r)\) denote its head \( \{l_0, \ldots, l_k\} \), and body\((r)\) the body \( \{l_{k+1}, \ldots, l_j, S_1 \ldots, S_{l_m}, \text{not } l_{m+1}, \ldots, \text{not } l_n\} \).

Furthermore, let body\(^P\)(r) be the positive objective body \( \{l_{k+1}, \ldots, l_j\} \) and body\(^N\)(r) negative objective body \( \{l_{m+1}, \ldots, l_n\} \) of \( r \), and body\(^S\)(r) the subjective body \( \{l_{j+1}, \ldots, l_m\} \). In addition, we use body\(^K\)(r) to denote the set of objective literals in the body of \( r \) which appears in term \( K \), and body\(^K\)(r) to denote the set of objective literals in the body of \( r \) which appears in term \( \neg K \).

Epistemic specifications with variables are considered as shorthands for their ground instantiations. In the rest of this section, except special noted, we always consider the epistemic specification is grounded.

Let \( W \) be a non-empty collection of sets of objective literals, and \( l \) an objective literal.

- \( Kl \) is satisfied with regard to \( W \), denoted by \( W \models Kl \), iff \( \forall \omega \in W : l \in \omega \).
- \( \neg Kl \) is satisfied with regard to \( W \), denoted by \( W \models \neg Kl \), iff \( \exists \omega \in W : l \notin \omega \).

Definition 1

Let \( \Pi \) be an epistemic specification and \( W \) be a non-empty collection of sets of objective literals in \( \Pi \). \( W \) is a world view of \( \Pi \) iff \( W \) is the collection of all answer sets of \( \Pi^W \) denoted by \( AN(\Pi^W) \), where \( \Pi^W \) is an ASP program obtained from \( \Pi \) by the following reduct laws:

- RL1: removing all rules containing subjective literals not satisfied by \( W \);
- RL2: removing any remaining subjective literals of the form \( \neg Kl \);
- RL3: replacing any remaining subjective literals of the form \( Kl \) by \( l \).

Example 1

Let an epistemic specification \( \Pi_1 \) consist of the following three rules:

\[ p \lor q. \quad p : - \neg K q. \quad q : - \neg K p. \]

With regard to \( \{\{p\}\} \), \( \neg K q \) is satisfied while \( \neg K p \) is not satisfied. Hence, \( \Pi_1^{\{p\}} = \{p \lor q. \quad p : - \} \) and then \( AN(\Pi_1^{\{p\}}) = \{\{p\}\} \). So \( \{\{p\}\} \) is a world view of \( \Pi_1 \). Similarly, \( \{\{q\}\} \) is also a world view of \( \Pi_1 \).
2.2 Representation of Other Subjective Literals

To handle other subjective literals using ESmodels, namely \( \text{K} \not\text{not } l, \neg\text{K} \not\text{not } l, \text{M} l, \neg\text{M} l, \text{M} \not\text{not } l, \) and \( \neg\text{M} \not\text{not } l, \) we can convert an epistemic specification \( \Pi \) with arbitrary subjective literals in rules bodies into an epistemic specification \( \Pi^{ES} \) such that \( \Pi^{ES} \) has only subjective literals in the form \( \text{K} l \) or \( \neg\text{K} l \) by the following transformation procedure.

1. For each objective literal \( l \), add a rule \( l': \) \( \neg\text{not } l \) to \( \Pi^{ES} \) if there exist a subjective occurrence of \( \neg\text{K} \not\text{not } l \) or \( \text{M} l \) or \( \neg\text{M} l \) or \( \text{K} \not\text{not } l \) in \( \Pi \), where \( l' \) is a new created objective literal corresponding to \( l \).
2. Add each rule of \( \Pi \) to \( \Pi^{ES} \) after performing the following operations on it.
   - Replace \( \neg\text{K} \not\text{not } l \) by \( \neg\text{K} l' \);
   - Replace \( \text{M} l \) by \( \neg\text{K} l' \);
   - Replace \( \neg\text{M} l \) by \( \text{K} l' \);
   - Replace \( \text{K} \not\text{not } l \) by \( \text{K} l \);
   - Replace \( \neg\text{M} \not\text{not } l \) by \( \text{M} l \).

Then, we define its world view based semantics as follows.

**Definition 2**

For an epistemic specification \( \Pi \) with arbitrary subjective literals, let \( \text{Lit} \) be a set of objective literals appearing in \( \Pi \), and \( \Pi^{ES} \) its corresponding ESmodels epistemic specification, a collection of sets of objective literals \( W \) is a world view of \( \Pi \) iff there exists a world view \( W' \) of \( \Pi^{ES} \) such that \( W = \{ \omega \cap \text{Lit} | \omega \in W' \} \).

**Example 2**

Given an epistemic specification \( \Pi_2 : \{ p : \neg\text{M} q, \ q : \neg\text{K} p. \} \) then we have \( \text{Lit}_2 = \{ p, q \} \) and \( \Pi^{ES}_2 : \{ p : \neg\text{K} l. \ l : \neg\text{not } q. \ q : \neg\text{K} p. \} \). \( \Pi^{ES}_2 \) has two worlds \( \{ \{ q \} \} \) and \( \{ \{ p, l \} \} \), hence, \( \Pi_2 \) has two world views \( \{ \{ q \} \} \) and \( \{ \{ p \} \} \).

**Example 3**

Given an epistemic specification \( \Pi_3 : \{ p : \neg\text{not } q, \text{M} q, \ q : \neg\text{not } p, \text{M} q. \} \), then we have \( \Pi^{ES}_3 : \{ p : \neg\text{not } q, \neg\text{K} l. \ l : \neg\text{not } q. \ q : \neg\text{not } p, \neg\text{K} i. \ i : \neg\text{not } q. \} \). \( \Pi^{ES}_3 \) has two world views \( \{ \{ i, l \} \} \) and \( \{ \{ i, p, l \} , \{ q \} \} \), hence, \( \Pi_3 \) has two world views \( \{ \} \) and \( \{ \{ p \} , \{ q \} \} \).

2.3 Connection to Gelfond’s New Epistemic Specification

In the syntactic aspect of the epistemic specification defined in (Gelfond 2011), it allows two more subjective literals of forms, \( \text{K} \not\text{not } l \) and \( \neg\text{K} \not\text{not } l \), in the rule’s body. The modality \( \text{M} \) is defined to be expressed in terms of \( \text{K} \) by \( \text{M} l \overset{\text{def}}{=} \neg\text{K} \not\text{not } l \). Semantically, let \( W \) be a non-empty collection of sets of objective literals, and \( l \) an objective literal.

- \( \text{K} l \) is satisfied with regard to \( W \), denoted by \( W \models \text{K} l \), iff \( \forall S \in W : l \in S \).
- \( \neg\text{K} l \) is satisfied with regard to \( W \), denoted by \( W \models \neg\text{K} l \), iff \( \exists S \in W : l \notin S \).
- \( \text{K} \not\text{not } l \) is satisfied with regard to \( W \), denoted by \( W \models \text{K} \not\text{not } l \) iff for every \( S \in W, l \notin S \), otherwise \( S \models \neg\text{K} \not\text{not } l \).
The set $W$ is called a world view of $\Pi$ if $W$ is the collection of all answer sets of $\Pi^W$, where $\Pi^W$ is obtained by

- removing all rules containing subjective literals not satisfied by $W$;
- removing any remaining subjective literals of the form $\neg Kl$ or $\neg\text{Knot } l$;
- replacing any remaining subjective literals of the form $Kl$ by $l$ and any $\text{Knot } l$ by $\neg l$.

Theorem 1 shows that ESmodels can compute the world view of any Gelfond’s new epistemic specification.

**Theorem 1**

For any Gelfond’s new epistemic specification $\Pi$, let $\text{Lit}$ be a set of objective literals appearing in $\Pi$, a collection of sets of objective literals $W$ is a world view of $\Pi$ under Gelfond’s new definition iff there exists a world view $W'$ of $\Pi^{ES}$ such that $W = \{S \cap \text{Lit} | S \in W' \}$.

**Proof**

The main idea of this proof is as follows. Let $\text{Lit}^{ES}$ be objective literals appearing in $\Pi^{ES}$,

$\leftarrow$ direction: if there is a world view $W'$ of $\Pi^{ES}$, then for any $\omega \in W'$, $\omega$ is an answer set of $(\Pi^{ES})^{W'}$. Let $W = \{S \cap \text{Lit} | S \in W' \}$, then $\omega \cap \text{Lit}$ is an answer set of $\Pi^W$ under Gelfond’s new definition (because the Gelfond-Lifschitz reduction of $\Pi^W$ wrt. $\omega \cap \text{Lit}$ just possibly has less facts $\{l : \neg l \in \omega \cap \text{Lit} \text{ and } l \text{ does not appear in bodies of any rules}\}$ than the Gelfond-Lifschitz reduction of $(\Pi^{ES})^{W'}$ wrt. $\omega$).

$\to$ direction: if $W$ is a world view of $\Pi$, then we create $W'$ as follows: for each $\omega \in W$, we have $\omega' = \omega \cup \{l \in \text{Lit}^{ES} - \text{Lit} | l : \neg \text{not } l' \in \Pi^{ES}, l' \notin \omega\}$ in $W'$. Then, $\omega'$ is an answer set of $(\Pi^{ES})^{W'}$ (because the Gelfond-Lifschitz reduction of $(\Pi^{ES})^{W'}$ wrt. $\omega'$ just possibly has more facts $\{l : \neg l \in \omega \cap \text{Lit} \text{ and } l \text{ does not appear in bodies of any rules}\}$ than the Gelfond-Lifschitz reduction of $\Pi^W$ wrt. $\omega$).

**Example 4**

Given an epistemic specification $\Pi_4 : \{p : \neg M p\}$, under Gelfond’s definition $\Pi_4$ has two world views $\{\{\}\}$ and $\{\{p\}\}$. By the transformation defined in last subsection, we have $\Pi_4^{ES} : \{p : \neg Kl \colon \neg \text{not } p\}$, and ESmodels can find $\Pi_4^{ES}$’s two world views: $\{\{l\}\}$ and $\{\{p\}\}$, that is, $\Pi_4$ also has two world views $\{\{\}\}$ and $\{\{p\}\}$ by ESmodels.

### 3 Computing World Views in ESmodels

A generate-test algorithm forms a basis of computing world views in ESmodels. Now, we are taking two preliminary steps to optimize the algorithm.

#### 3.1 Basic Algorithm

Let $\Pi$ be an epistemic specification, $EL(\Pi)$ be a set of objective literals such that $l \in EL(\Pi)$ iff $Kl$ or $\neg Kl$ occurring in $\Pi$. Then, we call a pair $(S, S')$ an assignment of $EL(\Pi)$ iff

$$S \cup S' = EL(\Pi) \text{ and } S \cap S' = \emptyset$$

Then, we define an answer set program $\Pi^{(S, S')}$ obtained by:

- removing from $\Pi$ all rules containing subjective literals $Kl$ such that $l \in S'$, or subjective literal $\neg Kl$ such that $l \in S$, 

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- removing from the rest rules in $\Pi$ all other occurrences of subjective literals of the form $\neg K_l$,
- replacing remaining occurrences of literals of the form $K_l$ by $l$.

**Theorem 2**

Given an epistemic specification $\Pi$ and a collection $W$ of sets of objective literals. $W$ is a world view of $\Pi$ if an assignment $(S, S')$ of $EL(\Pi)$ exists such that

- $W$ is the collection of all answer sets of $\Pi^{(S, S')}$,
- $W$ satisfies the assignment, that is, $S \cap (\bigcap_{A \in W} A) == S$ and $S' \cap (\bigcap_{A \in W} A) == \emptyset$.

**Proof**

If both $S \cap (\bigcap_{A \in W} A) == S$ and $S' \cap (\bigcap_{A \in W} A) == \emptyset$ are satisfied, we have $\Pi^{(S, S')} == \Pi^W$. Hence, if $W$ is the collection of all answer sets of $\Pi^{(S, S')}$ then $W$ is the collection of all answer sets of $\Pi^W$, that is, $W$ is a world view of $\Pi$.

By Theorem 2, an immediate method of computing the world views of an epistemic specification includes three main stages: generating a possible assignment, reducing the epistemic specification into an answer set program, and testing if the collection of the answer sets of the answer set program satisfies the assignment. At a high level of abstraction, the method can be implemented as showed in the following algorithm.

**Algorithm 1 ESMODELS.**

**Input:**
- $\Pi$: An epistemic specification;

**Output:**
- All world views of $\Pi$;

1: for every possible assignment of $EL(\Pi)$ $(S, S')$ of $\Pi$ do
2: $\Pi' = \Pi^{(S, S')}$ \{reduces $\Pi$ to an answer set program $\Pi'$ by $(S, S')$\}
3: $W = \text{computeASs}(\Pi')$ \{computes all answer sets of $\Pi'$\}
4: if $S \cap (\bigcap_{A \in W} A) == S$ and $S' \cap (\bigcap_{A \in W} A) == \emptyset$ then
5: output $W$
6: end if
7: end for

ESMODELS firstly gets all subjective literals $EL(\Pi)$ and generates all possible assignments of $EL(\Pi)$. For each assignment $(S, S')$, the algorithm reduces $\Pi$ to an answer set program $\Pi'$, i.e., $\Pi' = \Pi^{(S, S')}$. Next, it calls exiting ASP solver like Smodels, Clasp to compute all answer sets $W$ of $\Pi'$. Finally, it verifies the $W$. $W$ is a world view of $\Pi$, if $W$ satisfies $S \cap (\bigcap_{A \in W} A) == S$ and $S' \cap (\bigcap_{A \in W} A) == \emptyset$. ESMODELS stops, when all possible assignments are tested.

### 3.2 Optimization Approaches

#### 3.2.1 Reducing Subjective Literals

However, ESMODELS has a high computational cost, especially with a large number of subjective literals. Therefore, we introduce a new preprocessing function to reduce $EL(\Pi)$ before generating all possible assignments of $EL(\Pi)$. We first give several propositions.
Let $\Pi$ be an epistemic specification and a pair $(S, S')$ of objective literals of $\Pi$, $T_{\Pi}$ be an lower bound operator on $(S, S')$ defined as follows:

$$T_{\Pi}(S, S') = \{ \text{head}(r) \mid \text{head}(r) = 1, \text{body}^+(r) \subseteq S, \text{body}^-(r) \subseteq S' \},$$

where $\text{body}^+(r) = \text{body}^P(r) \cup \text{body}^K(r)$, $\text{body}^-(r) = \text{body}^N(r) \cup \text{body}^{-K}(r)$. Intuitively, $T_{\Pi}(S, S')$ computes the objective literals that must be true and that not true with regard to $S$ and $S'$ which are sets of literals known true and known not true respectively. Clearly, we can use this operation to reduce the searching space of subjective literals. This idea is guaranteed by the following definitions and propositions.

**Definition 3**

A pair $(S, S')$ of sets of objective literals is a partial model of an epistemic specification $\Pi$ if, for any world view $W$ of $\Pi$, $S \cap (\bigcap_{A \in W} = S$ and $S' \cap (\bigcap_{A \in W} = \emptyset$.

**Theorem 3**

$T_{\Pi}(S, S')$ is a partial model if $(S, S')$ is a partial model of an epistemic specification $\Pi$.

**Proof**

Let $(A, B)|_1$ to denote $A$ of a pair $(A, B)$, and $(A, B)|_2$ to denote $B$. The main idea of this proof is as follows. For any world view $W$ of $\Pi$, $S \cap (\bigcap_{A \in W} = S$ and $S' \cap (\bigcap_{A \in W} = \emptyset$, by the definition of $T_{\Pi}$, the Gelfond-Lifschitz reduction of $\Pi^W$ wrt. any $\omega \in W$ must have $l = |l \in T_{\Pi}(S, S')|_1$ and must not have any rule with head in $T_{\Pi}(S, S')|_2$, hence, we have $T_{\Pi}(S, S')|_1 \cap (\bigcap_{A \in W} = T_{\Pi}(S, S')|_1$ and $T_{\Pi}(S, S')|_2 \cap (\bigcap_{A \in W} = \emptyset$. □

**Corollary 1**

Let, $T_{\Pi}(S, S') = T_{\Pi}(T_{\Pi}^{-1}(S, S'))$, then $T_{\Pi}^h(\emptyset, \emptyset)$ is a partial model of $\Pi$.

**Proof**

Because $(\emptyset, \emptyset)$ is a partial model, $T_{\Pi}(\emptyset, \emptyset)$ is a partial model, and so on, $T_{\Pi}^2(\emptyset, \emptyset)$ ... $T_{\Pi}^h(\emptyset, \emptyset)$ are partial models of $\Pi$ □

An epistemic specification rule $r$ is defeated by $(S, S')$ if $\text{body}^+(r) \cap S' \neq \emptyset$ or $\text{body}^-(r) \cap S' \neq \emptyset$. Let $(S, S')$ be a partial model of an epistemic specification $\Pi$, $\Pi|_{(S, S')}$ is obtained by

- removing from $\Pi$ all rules defeated by $(S, S')$,
- removing from the rest rules in $\Pi$ all other occurrences of literals of the form not $l$ or $\neg K l$ such that $l \in S'$,
- removing remaining occurrences of literals of the form $l$ or $K l$ such that $l \in S$.
- adding $l$ if $l \in S$
- adding $l$ if $l \in S$

**Theorem 4**

If $(S, S')$ is a partial model of an epistemic specification $\Pi$, $\Pi|_{(S, S')}$ and $\Pi$ have the same world views.
Proof
The main idea in this proof is as follows. For any world view $W$ of $\Pi$, if $S \cap (\bigcap_{A \in W} A) = S$ and $S' \cap (\bigcap_{A \in W} A) = \emptyset$, then $\Pi^W$ and $((\Pi, S, S'))^W$ have the same answer sets. And, for any world view $W$ of $((\Pi, S, S'))$, we have that $W$ is a world view of $\Pi$. □

By theorem 3 and 4, we can design PreProcess showed in algorithm 2. Firstly, it sets the pair $(S, S')$ as $(\emptyset, \emptyset)$. Then it expands the partial model of $\Pi$ and reducts the $\Pi'$ according to $(S, S')$. Next, we updates the partial model by the new program. Finally, it compares the new partial model with the previous one. If the partial model is stable, it stops and returns $\Pi'$; Otherwise, it repeats this procedure.

**Algorithm 2 PreProcess.**

| Input: | $\Pi$: An epistemic specification; |
| Output: | $\Pi'$: A reduction of $\Pi$; |
| 1: | $(S, S') = (\emptyset, \emptyset)$, |
| 2: | repeat |
| 3: | $(S, S') = T_{\Pi'}(S, S')$ |
| 4: | $\Pi' = \Pi'_{(S, S')}$ |
| 5: | until $S, S'$ are fixed |
| 6: | return $\Pi'$ |

Obviously, PreProcess and partial model are very helpful for reducing search space. We thus provide an EFFICIENT ESMODELS as follows:

**Algorithm 3 EFFICIENT ESMODELS.**

| Input: | $\Pi$: An epistemic specification; |
| Output: | All world views of $\Pi$; |
| 1: | $\Pi'$=PreProcess($\Pi$) |
| 2: | for every possible assignment of $EL(\Pi')$ do |
| 3: | $\Pi'$ = $\Pi'_{(S, S')}$ |
| 4: | $\Pi'$=PreProcess($\Pi'$) |
| 5: | $W$ = computerASs($\Pi'$) |
| 6: | if $S \cap (\bigcap_{A \in W} A) = S$ and $S' \cap (\bigcap_{A \in W} A) = \emptyset$ then |
| 7: | output $W$ |
| 8: | end if |
| 9: | end for |

3.2.2 Using Multicore Technology

In $ESmodels$, another way of improving efficiency is the use of multicore technology. Based on Algorithm 3, by parallel generation of possible assignments and parallel calling of ASP solver, the efficiency of $ESmodels$ can be improved greatly.
4 Applications

4.1 Conformant Planning

Consider the planning problem with multiple possible initial states, what makes it become much harder is to find a so called secure plan that enforces the goal from any initial state. \cite{Eiter et al. 2003} gives three security conditions to check whether a plan is secure:

1. the actions of the plan are executable in the respective stages of the execution;
2. at any stage, executing the respective actions of the plan always leads to some legal successor state; and
3. the goal is true in every possible state reached if all steps of the plan are successfully executed.

Here, we consider a track of effects of executing an action sequence as a belief set, thus can intuitively encode those security conditions in epistemic specification constraints. We use \texttt{nonexecutable} to denote the actions are not executable, \texttt{inconsistent} to denote that a state is illegal, \texttt{success} to sign a state satisfies the goal, and \texttt{goal(m)} to denote the state reached after a given steps number \texttt{m} satisfies the goal, and \texttt{o(A,T)} to denote an action \texttt{A} happens in the step \texttt{T}:

\begin{itemize}
  \item for security condition 1: \texttt{\neg M nonexecutable}.
  \item for security condition 2: \texttt{\neg M inconsistent}.
  \item for security condition 3: \texttt{success \leftarrow goal(m)} and \texttt{\neg K success}.
\end{itemize}

Moreover, to guarantee the above security testing is put on tracks caused by the same action sequence, we write a new constraint:

\[ \leftarrow \neg K o(A,T), o(A,T). \]  

Intuitively, rule (1) says that \textit{if one action A happened in stage T of one track, it happened in stage T of all tracks}. Thus, we can easily get a \textbf{Conformant Planning Module} consisting of the above five constraints and the following action generation rules:

- Set a planning horizon \texttt{m}: \#\texttt{const x = m, step(0..x)}.
- Generating one action for each step: \{\texttt{o(A,T) : action(A)}\} \texttt{1 \leftarrow step(T), T < m}.

Combine the conformant planning module with a planning domain (including action axioms e.g., inertial law) encoded in an answer set program, the result epistemic specification represents a conformant planning problem, and its world view(s) corresponds to the secure plan(s) of the problem. Here, we use a case provided in \cite{Palacios and Geffner 2006} to demonstrate the conformant planning approach using epistemic specification. Given a conformant planning problem \texttt{P} with an initial state \texttt{I = p \lor q} (i.e., nothing else is known; there is no CWA), and action \texttt{a} and \texttt{b} with effects \texttt{a} causes \texttt{q} if \texttt{r}, \texttt{a} causes \texttt{\neg s} if \texttt{r}, and \texttt{b} causes \texttt{s} if \texttt{q}, the planning goal is \texttt{q, s}. Then, we describe the planning domain as follows.

\begin{itemize}
  \item Signature: \texttt{action(a), action(b)}.
  \item Fluent: \texttt{fluent(in, p), fluent(in, q), fluent(in, r), fluent(in, s)}.
  \item Causal Laws: \texttt{h(pos(q), T + 1) \leftarrow \neg o(a,T), h(pos(p), T), step(T)}.
  \item Inertial Laws:
    \begin{itemize}
      \item \texttt{h(pos(X), T + 1) \leftarrow \neg fluent(in, X), h(pos(X), T), step(T), not h(neg(X), T + 1)}.
      \item \texttt{h(neg(X), T + 1) \leftarrow fluent(in, X), h(neg(X), T), step(T), not h(pos(X), T + 1)}.
    \end{itemize}
\end{itemize}
Initial: $1\{h(pos(p), 0), h(pos(q), 0)\}2$
$1\{h(pos(F), 0), h(neg(F), 0)\}1 - fluent(in, F)$.

Goal: $goal(T) : -h(pos(q), T), h(pos(s), T), step(T)$.

When we set $m = 2$, ESmodels can find the unique world view including twelve literal sets, and each of them includes $o(a, 0)$ and $o(b, 1)$ that means the program has a conformant plan $a \ b$.

### 4.2 Constraints Satisfaction

In some situations, constraints on the variable are with epistemic features, that is, a variable’s value is not only affected by the values of other variables, but also determined by all possible values of other variables. Here, we demonstrate the use of ESmodels in solving such constraint satisfaction problems using a dinner problem: Jim, Bones, Checkov, Mike, Jack, Uhura, and Scotty, and Tommy received a dinner invitation, and the constraints on their decisions and the constraints description in epistemic specification rules are as follows:

- if Checkov may not participate, then Jim will participate: $jim : - not checkove$.
- if Jim may not participate, then bones will participate: $bones : - not jim$.
- if only one of Jack and Mike will participate: $jack : - not mike, mike : - not jack$.
- if Jack must participate, then Uhura will participate: $uhura : -Kjack$.
- if Uhura may not participate, then Scotty will participate: $scotty : - not uhura$.
- if Scotty must participate, then Tommy will participate: $tommy : -Kscotty$.
- Checkov will participate. $checkov$.

ESmodels can find the unique world view $\{\{checkov, tommy, scotty, jim, mike\}\{checkov, tommy, scotty, jim, jack\}\}$ that means Jim, Checkov, Scotty, and tommy must participate, Bones and Uhura must not participate, Jack and Mike may or may not participate.

### 5 Conclusion

ESmodels is an epistemic specification solver designed and implemented as an experiment platform to investigate the semantics, language, related reasoning algorithms, and possible applications of epistemic specifications. A significant feature of this solver is that its language is more compact than that defined in literatures, but capable of representing many subjective literals via a group of transformation rules. Besides, this solver can compute world views under Gelfond’s new definition, while that presented by Zhang in (Zhang 2007) and Watson in (Watson 1994) are based on the early definition of epistemic specifications. In addition, we find the compact encoding of conformant planning problems and constraint satisfaction problems in the epistemic specification language, which primarily shows Esmodels’s potential in applications.

The work presented here is primary. Now, we are designing and exploring more efficient algorithm for ESmodels and evaluate it using those benchmarks in the conformant planning field.

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1 In the early related work, Gelfond investigated the value of epistemic specifications in formalizing commonsense reasoning.
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