Logic Programs with Compiled Preferences*

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Abstract

We describe an approach for compiling preferences into logic programs under the answer set semantics. An ordered logic program is an extended logic program in which rules are named by unique terms, and in which preferences among rules are given by a set of atoms of the form $s \prec t$ where $s$ and $t$ are names. An ordered logic program is transformed into a second, regular, extended logic program wherein the preferences are respected, in that the answer sets obtained in the transformed theory correspond with the preferred answer sets of the original theory. Our approach allows both the specification of static orderings (as found in most previous work), in which preferences are external to a logic program, as well as orderings on sets of rules. In large part then, we are interested in describing a general methodology for uniformly incorporating preference information in a logic program. Since the result of our translation is an extended logic program, we can make use of existing implementations, such as dlv and smodels. To this end, we have developed a compiler, available on the web, as a front-end for these programming systems.

Introduction

In commonsense reasoning one frequently prefers one outcome over another, or the application of one rule over another, or the drawing of one default conclusion over another. For example, in buying a car one may have various desiderata in mind (inexpensive, safe, fast, etc.) where these preferences come in varying degrees of importance. In legal reasoning, laws may apply by default but the laws themselves may conflict. So municipal laws will have a lower priority than state laws, and newer laws will take priority over old. Further, if these preferences conflict, there will need to be higher-order preferences to decide the conflict.

In this paper we explore the problem of preference orderings under the framework of extended logic programs under the answer set semantics (Gelfond & Lifschitz 1991). The general methodology was first proposed in (Delgrande & Schaub 1997), in addressing preferences in default logic. Previous work in dealing with preferences has for the most part treated preference information at the meta-level (see next to the last section for a discussion of previous approaches). In contrast, we remain within the framework of extended logic programs: We begin with an ordered logic program, which is an extended logic program in which rules are named by unique terms and in which preferences among rules are given by a new set of atoms of the form $s \prec t$, where $s$ and $t$ are names. Thus, preferences among rules are encoded at the object-level. An ordered logic program is transformed into a second, regular, extended logic program wherein the preferences are respected, in the sense that the answer sets obtained in the transformed theory correspond to the preferred answer sets of the original theory. The approach is sufficiently general to allow the specification of preferences among preferences, preferences holding in a particular context, and preferences holding by default.

Our approach can be seen as a general methodology for uniformly incorporating preference information within a logic program. This transformational approach has several advantages. First, it is flexible. So one can encode how a preference order interacts with other information, or how different types of preference orders (such as specificity, authority, recency, etc.) are to be integrated. Second, it is easier to compare differing approaches handling such orderings, since they can be represented uniformly in the same general setting. Thus, for instance, if someone doesn’t like the notion of preference developed here, they may encode their own within this framework. Lastly, it is straightforward implementing our approach: In the present case, we have developed a translator for ordered logic programs that serves as a front-end for the logic programming systems dlv (Eiter et al. 1997) and smodels (Niemelä & Simons 1997).

The next section gives background terminology and notation. Afterwards, our central approach is described, followed by an exploration of its formal properties. We then continue with an overview of further features and extensions, and provide a pointer to the implementation. Finally, a comparison with related work is given, and we conclude with a short discussion.

*This work was partially supported by the Austrian Science Fund Project N Z29-INF.
Definitions and Notation

We deal with extended logic programs, which allow for expressing both classical negation \[\neg\] as well as negation as failure \cite{Lifschitz1999}. We use “\(\lnot\)” for classical negation and “\(\neg\)” for negation as failure. Classical negation is also referred to as strong negation, whilst negation as failure is termed weak negation.

Our formal treatment is based on propositional languages. As usual, a literal, \(L\), is an expression of the form \(A \lor \lnot A\), where \(A\) is an atom. We assume a possibly infinite set of such atoms. The set of all literals is denoted by \(\text{Lit}\). A literal preceded by the negation as failure sign \(\lnot\) is said to be a weakly negated literal. A rule, \(r\), is an ordered pair of the form

\[
L_0 \leftarrow L_1, \ldots, L_m, \lnot L_{m+1}, \ldots, \lnot L_n, \quad (1)
\]

where \(n \geq m \geq 0\), and each \(L_i\) \((0 \leq i \leq n)\) is a literal. The literal \(L_0\) is called the head of \(r\), and the set \(\{L_1, \ldots, L_m, \lnot L_{m+1}, \ldots, \lnot L_n\}\) is the body of \(r\). If \(n = m\), then \(r\) is a basic rule; if \(n = 0\), then \(r\) is a fact. An (extended) logic program, or simply a program, is a finite set of rules. A program is basic if all rules in it are basic. We use \(\text{head}(r)\) to denote the head of rule \(r\), and \(\text{body}(r)\) to denote the body of \(r\). Furthermore, let \(\text{body}^+(r) = \{L_1, \ldots, L_m\}\) and \(\text{body}^-(r) = \{L_{m+1}, \ldots, L_n\}\). The elements of \(\text{body}^+(r)\) are referred to as the premisses of \(r\). We say that a rule \(r\) is defeated by a set of literals \(X\) iff \(\text{body}^-(r) \cap X \neq \emptyset\). As well, each literal in \(\text{body}^-(r) \cap X\) is said to defeat \(r\).

A set of literals \(X\) is consistent iff it does not contain a complementary pair \(A, \lnot A\) of literals. We say that \(X\) is logically closed iff it is either consistent or equals \(\text{Lit}\). Furthermore, \(X\) is closed under a basic program \(\Pi\) iff for any \(r \in \Pi\), \(\text{head}(r) \in X\) whenever \(\text{body}(r) \subseteq X\). The smallest set of literals which is both logically closed and closed under a basic program \(\Pi\) is denoted by \(\text{Cn}(\Pi)\).

Let \(\Pi\) be a basic program and \(X\) a set of literals. The operator \(T_{\Pi}^X\) is defined as follows:

\[
T_{\Pi}^X = \{\text{head}(r) \mid r \in \Pi, \text{body}(r) \subseteq X\}
\]

if \(X\) is consistent, and \(T_{\Pi}^X = \text{Lit}\) otherwise. Iterated applications of \(T_{\Pi}^X\) are written as \(T_{\Pi}^X(j \geq 0)\), where \(T_{\Pi}^X = X = T_{\Pi}^X T_{\Pi}^{X-1}X\) for \(i \geq 1\). It is well-known that \(\text{Cn}(\Pi) = \bigcup_{i \geq 0} T_{\Pi}^X\emptyset\), for any basic program \(\Pi\).

Let \(r\) be a rule. Then \(r^+\) denotes the basic program obtained from \(r\) by deleting all weakly negated literals in the body of \(r\), i.e., \(r^+ = \text{head}(r) \leftarrow \text{body}^+(r)\). The reduct, \(\Pi^X\), of a program \(\Pi\) relative to a set \(X\) of literals is defined by

\[
\Pi^X = \{r^+ \mid r \in \Pi \text{ and } r \text{ is not defeated by } X\}.
\]

In other words, \(\Pi^X\) is obtained from \(\Pi\) by (i) deleting any \(r \in \Pi\) which is defeated by \(X\) and (ii) deleting each weakly negated literal occurring in the bodies of the remaining rules. We say that a set \(X\) of literals is an answer set of a program \(\Pi\) if \(\text{Cn}(\Pi^X) = X\).

Clearly, for each answer set \(X\) of a program \(P\), it holds that \(X = \bigcup_{i \geq 0} T_{\Pi}^i \emptyset\). The answer set semantics for extended logic programs has been defined in \cite{GelfondLifschitz1991} as a generalization of the stable model semantics \cite{GelfondLifschitz1988} for general logic programs (i.e., programs not containing classical negation, \(\lnot\)). The reduct \(\Pi^X\) is often called the Gelfond-Lifschitz reduction.

The set of all generating rules of an answer set \(X\) from \(\Pi\) is defined as follows:

\[
\Gamma^X = \{r \in \Pi \mid r^+ \in \Pi^X \text{ and } \text{body}^+(r) \subseteq X\}.
\]

That is, each prerequisite of \(r\) is in \(X\) and \(r\) is not defeated by \(X\). Finally, a sequence \((r_i)_{i \in I}\) of rules is grounded iff, for all \(i \in I\), \(\{\text{head}(r_j) \mid j < i\}\) is inconsistent, or else \(\text{body}^+(r_i) \subseteq \{\text{head}(r_j) \mid j < i\}\).

Logic Programs with Preferences

A logic program over a propositional language \(\mathcal{L}\) is said to be ordered iff \(\mathcal{L}\) contains the following pairwise disjoint categories:

- a set \(\mathcal{N}\) of names serving as names for rules;
- a set \(\mathcal{A}\) of regular (propositional) atoms of a program; and
- a set \(\mathcal{A}_\prec\) of preference atoms \(s \prec t\), where \(s, t \in \mathcal{N}\) are names.

For each ordered program \(\Pi\), we assume furthermore a bijective function \(n(\cdot)\) assigning to each rule \(r \in \Pi\) a name \(n(r) \in \mathcal{N}\). To simplify our notation, we usually write \(n_r\) instead of \(n(r)\) (and we sometimes abbreviate \(n_r\) by \(n_i\)). Also, the relation \(i = n(r)\) is written as \(t : r\), leaving the naming function \(n(\cdot)\) implicit. The elements of \(\mathcal{A}_\prec\) express preference relations among rules.

Intuitively, \(s_r \prec s_{r'}\) asserts that \(r'\) has “higher” priority than \(r\). Thus, \(r'\) is viewed as having precedence over \(r\), i.e., \(r'\) should, in some sense, always be considered “before” \(r\).

Most importantly, we impose no restrictions on the occurrences of preference atoms. This allows for expressing preferences in a very flexible, dynamic way. For instance, we may specify

\[
n_r \prec n_{r'} \leftrightarrow p, \text{ not } q
\]

where \(p\) and \(q\) may themselves be (or rely on) preference atoms.

A special case is given by programs containing preference atoms only among their facts. We say that a logic program \(\Pi\) over \(\mathcal{L}\) is statically ordered if it is of the form \(\Pi = \Pi' \cup \Pi''\), where \(\Pi'\) is an ordered logic program over \(\mathcal{L} \setminus \mathcal{A}_\prec\) and \(\Pi'' \subseteq \{(s_r \prec s_{r'}) \mid r, r' \in \Pi'\}\). The static case can be regarded as being induced from an external

\footnote{In practice, function \(n\) is only required to be injective in order to allow for rules not participating in the resultant preference relation.}
Similarly, we introduce a special-purpose atom \( \text{ok}(n_r) \) given program \( \Pi \), a new, special-purpose atom \( \text{bl}(n_r) \) controlling application of rule \( r \) to detect the case where a rule has been applied. For rule \( r \) just if it is \( \prec \)-greater rule \( r' \), this will be the case just when \( r' \) is known to be blocked or applied.

More formally, given an ordered program \( \Pi \) over \( \mathcal{L} \), let \( \mathcal{L}^+ \) be the language obtained from \( \mathcal{L} \) by adding, for each \( r, r' \in \Pi \), new pairwise distinct propositional atoms \( \text{ap}(n_r), \text{bl}(n_r), \text{ok}(n_r) \), and \( \text{ok}'(n_r, n_{r'}) \). Then, our translation \( T \) maps an ordered program \( \Pi \) over \( \mathcal{L} \) into a regular program \( T(\Pi) \) over \( \mathcal{L}^+ \) in the following way.

**Definition 1** Let \( \Pi = \{r_1, \ldots, r_k\} \) be an ordered logic program over \( \mathcal{L} \). For each \( r \in \Pi \), let \( \tau(r) \) be the collection of rules depicted in Figure 1, where \( \mathcal{L}^+ \) is the language obtained from \( \mathcal{L} \) by adding, for each \( r, r' \in \Pi \), new pairwise distinct propositional atoms \( \text{ap}(n_r), \text{bl}(n_r), \text{ok}(n_r) \), and \( \text{ok}'(n_r, n_{r'}) \). Then, our translation \( T \) maps an ordered program \( \Pi \) over \( \mathcal{L} \) into a regular program \( T(\Pi) \) over \( \mathcal{L}^+ \) in the following way.

**Definition 2** Let \( \Pi \) be an ordered logic program over language \( \mathcal{L} \) and \( X \) a set of literals. We say that \( X \) is a preferred answer set of \( \Pi \) iff \( X = Y \cap \mathcal{L} \) for some answer set \( Y \) of \( T(\Pi) \).

In what follows, answer sets of standard (i.e., unordered) logic programs are also referred to as regular logic programs.
answer sets.

As an illustration of our approach, consider the following program II:

\[
\begin{align*}
    r_1 & = \neg a \leftarrow \neg a, \not c \\
    r_2 & = b \leftarrow \neg a, not c \\
    r_3 & = c \leftarrow not b \\
    r_4 & = n_3 < n_2 \leftarrow not d
\end{align*}
\]

where \( n_i \) denotes the name of rule \( r_i \) (\( i = 1, \ldots, 4 \)). This program has two regular answer sets, one containing \( b \) and the other containing \( c \); both contain \( \neg a \) and \( n_3 < n_2 \). However, only the first is a preferred answer set. To see this, observe that for any \( X \subseteq \{\text{head}(r) \mid r \in T(\Pi)\} \), we have \( n_1 < n_3 \notin X \) for each \( (i, j) \neq (3, 2) \). We thus get for such \( X \) and \( i, j \) that \( \text{ok}'(n_i, n_j) \in T_{\Pi}^1 \emptyset \) by (reduced) rules \( c_2(r_i, r_j) \), and so \( \text{ok}(n_i) \in T_{\Pi}^2 \emptyset \) via rule \( c_1(r_i) = c_1(r_i) \).

Analogously, we get \( \text{ap}(n_i), \text{ap}(n_i), \neg a, n_3 < n_2 \). Now consider the following rules from \( T(\Pi) \):

\[
\begin{align*}
    a_2(r_2) & : \text{ap}(n_2) \leftarrow \text{ok}(n_2), \neg a, not c \\
    b_1(r_2, \neg a) & : \text{bl}(n_2) \leftarrow \text{ok}(n_2), not a \\
    b_2(r_2, c) & : \text{bl}(n_2) \leftarrow \text{ok}(n_2), c \\
    a_2(r_3) & : \text{ap}(n_3) \leftarrow \text{ok}(n_3), not b \\
    b_2(r_3, c) & : \text{bl}(n_3) \leftarrow \text{ok}(n_3), b \\
    c_3(r_3, r_2) & : \text{ok}(n_3, n_2) \leftarrow (n_3 < n_2), \text{ap}(n_2) \\
    c_4(r_3, r_2) & : \text{ok}(n_3, n_2) \leftarrow (n_3 < n_2), \text{bl}(n_2)
\end{align*}
\]

Given \( \text{ok}(n_2) \) and \( \neg a \), rule \( a_2(r_2) \) leaves us with the choice between \( c \notin X \) or \( c \in X \). First, assume \( c \notin X \). We get \( \text{ap}(n_2) \) from \( a_2(r_2) \), \( T(\Pi)^X \). Hence, we get \( b, \text{ok}(n_3, n_2) \), and finally \( \text{ok}(n_3) \), which results in \( \text{bl}(n_3) \) via \( b_2(r_3, c) \). Omitting further details, this yields an answer set containing \( b \) while excluding \( c \). Second, assume \( c \in X \). This eliminates \( a_2(r_2) \) when turning \( T(\Pi) \) into \( T(\Pi)^X \).

Also, \( b_1(r_2, \neg a) \) is defeated since \( \neg a \) is derivable. \( b_2(r_2, c) \) is inapplicable, since \( c \) is only derivable (from \( \text{ap}(n_3) \) via \( a_1(r_3) \)) in the presence of \( \text{ok}(n_3) \). But \( \text{ok}(n_2) \) is not derivable since neither \( \text{ap}(n_2) \) nor \( \text{bl}(n_2) \) is derivable. Since this circular situation is unresolved, there is no preferred answer set containing \( c \).

Properties of the Approach

Our first result ensures that the dynamically generated preference information enjoys the usual properties of strict orderings. To this end, we define the following relation: for each set \( X \) of literals and every \( r, r' \in \Pi \), the relation \( r \prec_X r' \) holds iff \( n_r < n_{r'} \in X \).

Theorem 1 Let \( \Pi \) be an ordered logic program and \( X \) a consistent answer set of \( T(\Pi) \). Then \( \prec_X \) is a strict partial order. Moreover, if \( \Pi \) has only static preferences, then \( \prec_X = \prec_Y \) for any answer set \( Y \) of \( T(\Pi) \).

The following results shed light on the functioning induced by translation \( T \); they elaborate upon the logic programming operator \( T_{\Pi}(\Pi) \):

Theorem 2 Let \( X \) be a consistent answer set of \( T(\Pi) \) for an ordered program \( \Pi \), and let \( \Omega = T(\Pi)^X \). Then, for any \( r \in \Pi \):

1. \( \text{ok}(n_r) \in X \);
2. \( \text{ap}(n_r) \in X \iff \text{bl}(n_r) \notin X \);
3. if \( r \) is not defeated by \( X \), \( \text{ok}(n_r) \in T_{\Omega}^0 \), and \( \text{body}^+(r) \subseteq T_{\Omega}^0 \), then \( \text{ap}(n_r) \in T_{\Omega}^{\max(i,j)+1} \);
4. \( \text{ok}(n_r) \in T_{\Omega}^0 \) and \( \text{body}^+(r) \notin X \) implies \( \text{bl}(n_r) \in T_{\Omega}^{i+1} \emptyset \);
5. if \( r \) is defeated by \( X \) and \( \text{ok}(n_r) \in T_{\Omega}^0 \), then \( \text{bl}(n_r) \in T_{\Omega}^0 \) for some \( j > i \);
6. \( \text{ok}(n_r) \notin T_{\Omega}^0 \) implies \( \text{ap}(n_r) \notin T_{\Omega}^0 \) and \( \text{bl}(n_r) \notin T_{\Omega}^0 \) for all \( j, k < i + 2 \).

The next result shows that the translated rules are considered in accord to the partial order induced by the given preference relation:

Theorem 3 Let \( \Pi \) be an ordered logic program, \( X \) a consistent answer set of \( T(\Pi) \), and \( (r_i)_{i \in I} \) a grounded enumeration of the set \( \Gamma_X^\pi(\Pi) \) of generating rules of \( X \) from \( T(\Pi) \). Then, for all \( r, r' \in \Pi \):

\[
\text{If } r \prec_X r', \text{ then } j < i,
\]

for all \( r_i \) equaling \( a_k(r) \) or \( b_k(r, L) \), and some \( r_j \) equaling \( a_k(r') \) or \( b_k(r', L') \), with \( k, k' = 1, 2, L \in \text{body}(r) \), and \( L' \in \text{body}(r') \).

For static preferences, our translation \( T \) amounts to selecting the answer sets of the underlying unordered program that comply with the ordering, \( < \).

Definition 3 Let \( (\Pi, <) \) be a statically ordered program. An answer set \( X \) of \( \Pi \) is called \( < \)-preserving if \( X \) is either inconsistent, or else there exists a grounded enumeration \( (r_i)_{i \in I} \) of \( \Gamma_X^\pi(\Pi) \) such that, for every \( i, j \in I \), we have:

1. if \( r_i < r_j \), then \( j < i \); and
2. if \( r_i < r' \) and \( r' \in \Pi \setminus \Gamma_X^\pi(\Pi) \), then \( \text{body}^+(r') \notin X \) or \( r' \) is defeated by the set \( \{\text{head}(r_j) \mid j < i\} \).

The next result furnishes semantical underpinnings for statically ordered programs; it provides a correspondence between preferred answer sets and regular answer sets of the original program:

Theorem 4 Let \( (\Pi, <) \) be a statically ordered logic program and \( X \) a set of literals. Then, \( X \) is a preferred answer set of \( (\Pi, <) \) iff \( X \) is a \( < \)-preserving answer set of \( \Pi \).

This gives rise to the following corollary:

Corollary 1 Let \( (\Pi, <) \) and \( X \) as in Theorem 4. If \( X \) is a preferred answer set of \( (\Pi, <) \), then \( X \) is an answer set of \( \Pi \).

Note that the last two results have no counterparts in the general (dynamic) case, due to the lack of a regular answer set of the original program. The preference information is only fully available in the answer sets of the translated program (hence the restriction of the notion of \( < \)-preservation to the static case).

Also, if no preference information is present, our approach is equivalent to standard answer set semantics.
Moreover, the notions of statically ordered and (dynamically) ordered programs coincide in this case.

**Theorem 5** Let \( \Pi \) be a logic program over \( \mathcal{L} \) and \( X \) a set of literals. If \( \Pi \) contains no preference information, i.e. if \( \mathcal{L} \cap \mathbf{A}_x = \emptyset \), then the following statements are equivalent:

1. \( X \) is a preferred answer set of statically ordered logic program \( (\Pi, \emptyset) \);
2. \( X \) is a preferred answer set of ordered logic program \( \Pi \);
3. \( X \) is a regular answer set of logic program \( \Pi \).

Recently, Brewka and Eiter (Brewka & Eiter 1999) suggested two principles, simply termed **Principle I** and **Principle II**, which, they argue, any defeasible rule system handling preferences should satisfy. The next result shows that our approach obeys these principles. However, since the original formulation of Principle I and II is rather generic—motivated by the aim to cover as many different approaches as possible—we must instantiate them in terms of our formalism. It turns out that Principle I is only suitable for statically ordered programs, whilst Principle II admits two guises, one for statically ordered programs, and another one for (dynamically) ordered programs.

Principles I and II, formulated for our approach, are as follows:

**Principle I.** Let \((\Pi, \prec)\) be a statically ordered logic program, and let \( X_1 \) and \( X_2 \) be two (regular) answer sets of \( \Pi \) generated by \( R \cup \{r_1\} \) and \( R \cup \{r_2\} \), respectively, where \( r_1, r_2 \notin R \). If \( r_1 \lessdot r_2 \), then \( X_1 \) is not a preferred answer set of \((\Pi, \prec)\).

**Principle II-S (Static Case).** Let \( X \) be a preferred answer set of statically ordered logic program \((\Pi, \prec)\), let \( r \) be a rule wherein \( body^+(r) \not\subseteq X \), and let \( \prec' \) be a strict partial order which agrees with \( \prec \) on rules from \( \Pi \). Then, \( X \cup A \) is an answer set of \((\Pi \cup \{r\}, \prec')\), where

\[
A = \{ n_r \lessdot n_s \mid r \prec' s \} \cup \{ \neg (n_s \lessdot n_r) \mid r \prec' s \}
\]

**Principle II-D (Dynamic Case).** Let \( X \) be a preferred answer set of a (dynamically) ordered logic program \( \Pi \), and let \( r \) be a rule such that \( body^+(r) \not\subseteq X \). Then, \( X \) is an answer set of \( \Pi \cup \{r\} \).

**Theorem 6** Statically ordered logic programs obey Principles I and II-S. Furthermore, ordered logic programs enjoy Principle II-D.

Observe that, since transformation \( T \) is clearly polynomial in the size of ordered logic programs, and because of Theorem 3, the complexity of our approach is inherited from the complexity of standard answer set semantics in a straightforward way. We just note the following result:

\[
\text{The inclusion of } A \text{ is necessary because we encode the preference information at the object level.}
\]

**Theorem 7** Given an ordered program \( \Pi \), checking whether \( \Pi \) has a preferred answer set is NP-complete.

**Further Issues and Refinements**

In this section, we sketch the range of applicability and point out distinguishing features of our approach. We briefly mention two points concerning expressiveness, and then sketch how we can deal with preferences over sets of rules. Lastly, we refer to the implementation of our approach.

First, we draw the reader’s attention to the expressive power offered by dynamic preferences in connection with variables in the input language, such as

\[
n_1(x) \lessdot n_2(y) \leftarrow p(y), \text{ not } (x = c), \quad (2)
\]

where \( n_1(x), n_2(y) \) are names of rules containing the variables \( x \) and \( y \), respectively. Although such a rule represents only its set of ground instances, it is actually a much more concise specification. Also, since most other approaches employ static preferences of the form \( n_1(x) \lessdot n_2(y) \), such approaches would necessarily have to express \( \emptyset \) as an enumeration of static ground preferences rather than a single rule.

Second, we note that transformation \( T \) is also applicable to disjunctive logic programs (where rule heads are disjunctions of literals). To see this, observe that the transformed rules unfold the conditions expressed in the body of the rules, while the rules’ head remain untouched, as manifested by rule \( a_1(r) \).

Third, we have extended the approach to allow for preferences between sets of rules. Although we do not include a full discussion here, we remark that this extension has also been implemented (see below). In order to refer to sets of rules, the language is adjoined by a set \( \mathcal{M} \) of terms serving as names for sets of rules, and, in addition, the set \( \mathbf{A}_x \) may now include atoms of the form \( m \lessdot m' \) with \( m,m' \in \mathcal{M} \). Accordingly, set-ordered programs contain preference information between names of sets. Informally, set \( \mathcal{M} \) of rules is applicable iff all its members are applicable. Consequently, if \( \mathcal{M}' \) is preferred over \( \mathcal{M} \), then \( \mathcal{M} \) is considered after all rules in \( \mathcal{M}' \) are found to be applicable, or some rule in \( \mathcal{M}' \) is found to be inapplicable.

As before, set-ordered programs are translated into standard logic programs, where suitable control elements \( \text{ok}(\cdot), \text{bl}(\cdot), \text{ap}(\cdot) \), ranging over names of sets, take care of the intended ordering information.

As an example, consider where in buying a car one ranks the price \((c)\) over safety features \((s)\) over power \((p)\), but safety features together with power is ranked over price. Taking \( r_x = x \leftarrow \text{not } \neg x \), for \( x \in \{e, s, p\} \), we can write this (informally) as:

\[
m_1 : \{r_p\} < m_2 : \{r_s\} < m_3 : \{r_e\} < m_4 : \{r_p, r_s\}
\]

The terms \( m_1, m_2, m_3, \) and \( m_4 \) are names of sets of rules. If we were given only that not all desiderata can be satisfied (i.e. \( \leftarrow p, e, s \) then we could apply the rules in the set (named) \( m_4 \) and conclude that \( p \)
and $s$ can be met. Furthermore, sets of rules are described extensionally by means of atoms in(·). Thus, the set $m_4 : \{ r_p, r_s \}$ is captured by in$(n_p, m_4) \leftarrow$ and in$(n_s, m_4) \leftarrow$. Accordingly, we have in$(n_p, m_1) \leftarrow$, in$(n_s, m_2) \leftarrow$, and in$(n_p, m_3) \leftarrow$. Given rules $r_{m_1} r_{m_2} r_{m_3}$, the previous facts about in, the specification of our example is completed by the preferences $m_i < m_{i+1}$ for $i = 1, 2, 3$.

Lastly, the approach has been implemented in Prolog and serves as a front-end to the logic programming systems dlv and smodels. The current prototype is available at

http://www.cs.uni-potsdam.de/~torsten/plp/.

This URL contains also diverse examples taken from the literature. Both the dynamic approach to (single) preferences and the set-based approach have been implemented. We note also that the implementation differs from the approach described here in two respects: first, the translation applies to named rules only, i.e., it leaves unnamed rules unaffected; and second, it provides a module which specifies the rules containing variables, whereby rules of this form are processed by applying an additional grounding step. A more detailed account regarding the implemented front-end can be found in (Delgrande, Schaub, & Tómpos 2000).

**Comparison with Related Work**

Dealing with preferences on rules seems to necessitate a two-level approach. This in fact is a characteristic of many approaches found in the literature. The majority of these approaches treat preference at the meta-level by defining alternative semantics. (Brewka 1996) proposes a modification of well-founded semantics in which dynamic preferences may be given for rules employing not. (Zhang & Foo 1997) and (Brewka & Eiter 1999) propose different prioritized versions of answer set semantics. In (Zhang & Foo 1997), static preferences are addressed first, by defining the reduct of a logic program $\Pi$, which is a subset of $\Pi$ that is most preferred. For the following example, their approach gives two answer sets (one with $p$ and one with $\neg p$) which seems to be counter-intuitive; ours in contrast has a single answer set containing $\neg p$.

$$
\begin{align*}
q_1 & : p \leftarrow \text{not} \ q_1 \\
r_2 & : \neg p \leftarrow \text{not} \ q_2 \\
r_1 & < r_2
\end{align*}
$$

Moreover, the dynamic case is addressed by specifying a transformation of a dynamic program to a set of static programs.

Brewka and Eiter (Brewka & Eiter 1999) address static preferences on rules in extended logic programs. They begin with a strict partial order on a set of rules, but define preference with respect to total orders that conform to the original partial order. Preferred answer sets are then selected from among the collection of answer sets of the (unprioritised) program. In contrast, we deal only with the original partial order, which is translated into the object theory. As well, only preferred extensions are produced in our approach; there is no need for meta-level filtering of extensions.

A two-level approach is also found in (Gelfond & Son 1997), where a methodology for directly encoding preferences in logic programs is proposed. The “second-order flavour” of this approach stems from the reification of rules and preferences. For example, a rule $p \leftarrow r, \neg s$, not $q$ is expressed by the formula $\text{default}(n, p, [r, \neg s], [q])$ where $n$ is the name of the rule. The Prolog-like list notation $[r, \neg s]$ and $[q]$ raises the possibility of an infinite Herbrand universe; this is problematic for systems like smodels and dlv that rely on finite Herbrand universes.

**Conclusion**

We have described an approach for compiling preferences into logic programs under the answer set semantics. An ordered logic program, in which preferences appear in the program rules, is transformed into a second, extended logic program wherein the preferences are respected, in that the answer sets obtained in the transformed theory correspond with the preferred answer sets of the original theory. In a certain sense, our transformation can be regarded as an axiomatisation of (our interpretation of) preference. Arguably then, we describe a general methodology for uniformly incorporating preference information in a logic program. In this approach, we avoid the two-level structure of previous work. While the previous “meta-level” approaches must commit themselves to a semantics and a fixed strategy, our approach (as well as that of (Gelfond & Son 1997)) is very flexible with respect to changing strategies, and is open for adaptation to different semantics and different concepts of preference handling.

The approach is easily restricted to reflect a static ordering in which preferences are external to a logic program. We also indicated how the approach can be extended to deal with preferences among sets of rules. Finally, this paper demonstrates that our approach is easily implementable; indeed, we have developed a compiler, as a front-end for dlv and smodels.

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