Integrated Algorithms for HEX-Programs and Applications in Machine Learning

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Abstract. This paper summarizes my doctoral research on evaluation algorithms for HEX-programs, which extend Answer Set Programming with means for interfacing external computations. The focus is on integrating different subprocesses of HEX-evaluation, such as solving and external calls as well as grounding, and on applications of HEX-programs in the area of Machine Learning.

1 Motivation

Due to current trends in distributed systems and information integration, there is an increasing need for accessing external information sources from within knowledge representation formalisms such as Answer Set Programming (ASP) [17]. For instance, it might be necessary to integrate information derived from a (possibly remote) Description Logic (DL) ontology into the computation of an answer set. If the derivation in the ontology is relative to information in the ASP part, a bidirectional exchange between a DL reasoner and an ASP solver is required. This kind of interaction is not provided by ordinary ASP, and pre-computing all possible derivations from the ontology and adding them to the answer set program is often not feasible. Motivated by this, the HEX-formalism [4] has been developed, where external sources can be referenced in a program, and are evaluated during solving. The approach is related to SMT, but the focus is more on techniques for evaluating general external sources represented by arbitrary computations, i.e., it enables an API-like approach such that a user can define plugins without expert knowledge on solver construction.

By employing HEX, a user can, e.g., define a library function for concatenating strings, accessed via an external predicate \&concat. It could be used as illustrated by the following rule, where a first name and a last name are provided, and \&concat returns the full name: fullname(Full) ← \&concat\(F, L\)(Full), firstname(F), lastname(L).

HEX-programs are very expressive since they enable a bidirectional exchange of information between a logic program and external sources and thus, encompasses the formalization of nonmonotonic and recursive aggregates. Consequently, HEX is suited for a wide range of applications, but also requires sophisticated evaluation algorithms to deal with the complexity that goes along with the high expressiveness. For this reason, my thesis work aims at the design and implementation of novel integrated solving techniques for improving the efficiency of the formalism in general, as well as for specific classes of programs. Another focus of my work is on new applications that leverage the provided techniques, and in turn push the advancement of the formalism.
2 Goals of My PhD Thesis

Challenges regarding efficient evaluation of HEX-programs comprise the lack of a tight integration of the solving process with the evaluation of external sources and with the grounding procedure. Accordingly, the main goals of my doctoral research are:

1. to design advanced reasoning techniques that improve the evaluation of HEX-programs by tightly integrating processes which have so far been treated as mostly independent sub-problems.
2. to develop innovative applications of HEX-programs that utilize external atoms for integrating as well as realizing methods from the area of Machine Learning (ML).
3. to implement newly developed evaluation algorithms in the HEX-program solver DLVHEX \[7\], and to investigate their performance using benchmark problems.

3 Background

Here, I start by briefly summarizing the work most related to HEX and its applications, and I introduce the theoretical background which my thesis work is based on.

Related Work. As there are many scenarios where it is more natural, and often more efficient, to outsource some information or computation in ASP, several approaches exist for this purpose, realizing different degrees of integration. DLV-EX programs \[2\] represent an early approach, which enables bidirectional communication with an external source, and allows the introduction of new terms by value invention. The CLINGO system also provides a mechanism for importing the extension of user-defined predicates via function calls during grounding \[16\]. In both cases, the interaction is more restricted than in HEX such that, e.g., nonmonotonic aggregates cannot be expressed.

CLINGO 5 \[15\] provides generic interfaces for combining theory solving with ASP, but its semantics differs from HEX and the approach is targeted at system developers. Besides, there are extensions of ASP towards the integration of specific sources; e.g., the CLINGCON system \[23\] implements constraint ASP relying on a tailored integration of a constraint solver. The setting of HEX differs as its goal is to enable a broad range of users to implement custom external sources and to harness efficient solving techniques.

HEX has been applied to a wide range of use cases. Among them are a framework for executing scheduled actions in external environments (ActHEX \[14\]); a system for merging belief sets based on nested HEX programs (MELD system, \[24\]); and an artificial agent able of playing the computer game Angry Birds (AngryHEX, \[6\]).

HEX-Programs. HEX-programs \[4\] extend ASP by allowing the use of external atoms of the form \&g[p_1, ..., p_k]c_1, ..., c_l\) in rule bodies, where \&g\ is an external predicate name, \(p_1, ..., p_k\) are input predicate names or constants, and \(c_1, ..., c_l\) are output constants. The ground semantics of an external atom \&g[p_1, ..., p_k]c_1, ..., c_l\) is given by a Boolean \(1 + k + l\)-ary oracle function \(f_{\&g}\) s.t. an external atom evaluates to true for a given assignment \(A\) over ordinary atoms if the oracle function returns true, i.e. \(f_{\&g}(A, p_1, ..., p_k, c_1, ..., c_l) = t\), and to false otherwise. The notion of satisfaction is extended to HEX-rules and programs in the obvious way. Answer sets of a HEX-program \(\Pi\) are those assignments \(A\) to ordinary atoms which are minimal models of
the program consisting of all rules in $\Pi$ of which the body is satisfied under $A$ (the so-called FLP-reduct $[13]$, an alternative to the well-known GL-reduct).

The basic procedure for computing the answer sets of a HEX-program $\Pi$ consists in replacing each (ground) external atom $e_{&g[p_1, \ldots, p_k]}(c_1, \ldots, c_l)$ by an ordinary atom of the form $e_{&g[p_1, \ldots, p_k]}(c_1, \ldots, c_l)$ and adding a guess $e_{&g[p_1, \ldots, p_k]}(c_1, \ldots, c_l) \lor ne_{&g[p_1, \ldots, p_k]}(c_1, \ldots, c_l) \leftarrow$ for its evaluation $[8]$. The result of this translation is an ordinary answer set program; and ordinary ASP solvers such as CLASP can be used for computing model candidates. However, guesses for external atoms must be checked afterwards for compatibility with the external semantics. By integrating Conflict-Driven Nogood Learning (CDNL) search into the HEX-algorithm, the input-output relations can be learned from these checks in form of nogoods to avoid wrong guesses in the future search. Moreover, even if a model candidate complies with the answers of the corresponding oracle calls, it still needs to be checked for minimality wrt. the FLP-reduct.

4 Research Progress

In this section, I present the research results obtained since I started my PhD studies.

4.1 Integration of Solving and External Evaluations

In the beginning of my doctoral research, I worked on the tighter integration of the solving process and external calls $[11]$, which required an extension of the oracle semantics. Before, oracle functions were only defined for complete inputs to external atoms, such that they could only be evaluated after the whole input was decided. As a result, many wrong guesses could only be detected late during search and nogoods were large as they usually entailed the complete input assignment. However, this could not be improved when using two-valued assignments since external sources might be nonmonotonic, and they are black boxes such that theory specific techniques like in SMT cannot be applied.

We have overcome the mentioned challenges by extending the two-valued semantics to three-valued assignments that use the classical values true and false, and the new value unassigned. Based on partial assignments, we have introduced new evaluation techniques to increase the performance of HEX-evaluation, which can be utilized in the search for model candidates as well as the search applied during checking minimality wrt. the FLP-reduct. First, we have extended two-valued oracle functions to three-valued ones, which allows evaluation at any point during search under partial input. Second, nogoods now can also be learned under partial assignments, which are often significantly smaller. Moreover, given some input-output nogood, we obtain a set of minimal nogoods by applying a minimization procedure similar to the one in $[23]$. As an alternative, we also incorporated the QUICKXPLAIN algorithm $[19]$ for conflict minimization, which is more suited for nogoods that contain many irrelevant literals. The benefit of the new solving techniques has been verified by experiments using DLVHEX.

4.2 Integration of External Sources and Minimality Checking

In addition to the usual minimality check of ASP, a special minimality check wrt. the FLP-reduct is required during the evaluation of HEX-programs to avoid cyclic justifica-
tions via external sources. The check is a bottleneck in practice as it often accounts for most of the time required to evaluate HEX-programs. For this reason, syntactic information regarding atom dependencies has been used to detect situations where the external minimality check can be skipped \cite{5}. However, this approach overapproximates the real dependencies as a result of the black-box nature of external sources.

In our most recent work \cite{10}, we considered a tighter integration of minimality checking and external sources by showing how the real external dependencies can be approximated more closely by also taking semantic dependency information into account. The additional dependency information can be provided by a user or even generated automatically. This brings us closer to a clear-box view of external sources, and allows us to skip the external minimality check in more cases. Furthermore, we stated conditions under which the costs for checking and generating semantic dependency information can be reduced. Using an experimental evaluation, we could verify that having more fine-grained information about the actual dependencies among atoms is crucial for applications where otherwise the overestimation makes the minimality check infeasible.

4.3 Integration of Grounding and Solving

During the second year of my PhD studies, I worked on integrating the lazy-grounding ASP solver Alpha \cite{26} into the DLVHEX system, with the goal to achieve a tighter integration of HEX-solving and grounding. Lazy grounding avoids an exponential blowup of the grounding by interleaving grounding and solving, whereby rules are grounded on-the-fly depending on the satisfaction of their bodies. The resulting approach exhibits promising results for classes of programs where the grounding bottleneck of ASP is an issue \cite{12}. This issue is even more challenging to tackle within the framework of HEX due to the need for grounding external atoms; and nonmonotonic dependencies and value invention (i.e., import of new constants) from external sources make the integration nontrivial. As a result, we needed to introduce a novel external source interface to incrementally extend a HEX-program grounding, where new output terms may appear during solving. This resulted in a novel evaluation algorithm for HEX-programs that can incorporate lazy-grounding solvers as backend solvers.

4.4 Applications of HEX-Programs in Machine Learning

As HEX allows to integrate different formalisms, it is well-suited for combining diverse forms of reasoning. In this branch of my research, my goal was to exploit this strength for two new applications in the area of ML. The first one integrates an external statistical classifier, while the second encodes an existing approach for logic-based ML.

**Hybrid Classification of Visual Objects** A basic task in Statistical Relational Learning \cite{18} is Collective Classification \cite{25}, which is simultaneously finding correct labels for a number of interrelated objects, e.g., predicting the classes of objects in a complex visual scene. Even if advanced algorithms for object recognition have been developed, they may fail unavoidably and yield ambiguous results due to few training data, noisy
inputs, or inherent ambiguity of visual appearance. It is then still possible to draw on further information from the context in which an object occurs to disambiguate its label.

We approached the Collective Classification problem in ASP by defining Hybrid Classifiers (HC) that combine a local classifier, which predicts the probability of each local label based on object features, with context constraints (weighted ASP constraints) using object relations [9]. At this, external atoms of HEX can be used to interface an ontology reasoner, a spatial reasoning calculus as well as the local classifier directly from within the encoding. This has not been realized in the first version of the approach, where the integration was created ad-hoc using a pre-processing step. However, the usage of external atoms for this purpose will be described in my dissertation.

To obtain a probabilistic semantics, we embedded our encoding into the formalism $LP^{MLN}$ [21], such that an HC corresponds to an $LP^{MLN}$ program. We showed that solutions of the resulting HC encoding can be obtained efficiently via a backtranslation from $LP^{MLN}$ into classical ASP with weak constraints [1], and by leveraging combinatorial optimization capabilities of ASP solvers. Experiments wrt. object classification in indoor and outdoor scenes exhibit significant accuracy improvements compared to using only a local classifier.

Meta-Interpretive Learning In the area of Inductive Logic Programming (ILP), Meta-Interpretive Learning (MIL) is a recent approach, introduced by Muggleton et al. [22], that learns logic programs from examples and background knowledge by instantiating meta-rules. The Metagol system [3] efficiently solves MIL-problems by relying on the query-driven search of Prolog. Its focus on positive examples, however, effects that Metagol can detect the derivability of negative examples only at a later check, which can severely hit performance. Viewing MIL-problems as combinatorial search problems, they can alternatively be solved by employing ASP, which may result in performance gains as a result of efficient conflict propagation. By employing modern ASP solvers, violations of negative examples can potentially be propagated earlier.

However, a straightforward ASP-encoding of MIL results in a huge search space due to a lack of procedural bias and the need for grounding. To address this challenge, we have encoded MIL in the HEX-formalism [20]. Our encoding utilizes external atoms to outsource background knowledge that defines manipulations of complex terms such as lists and strings, which is easy to realize in Prolog but less supported by ASP. Moreover, we identified a class of MIL-problems which can be solved efficiently by using our HEX-encodings, and showed empirically that the performance can be increased compared to Metagol by employing HEX. In addition, by abstracting from term manipulations in the encoding and by exploiting the HEX-interface mechanism, the import of constants can be entirely avoided in order to mitigate the grounding bottleneck.

5 Future Work

The overarching theme of my thesis is to tightly integrate different mechanisms employed during HEX-solving, and a number of new evaluation techniques has been developed for this purpose. However, there are several further ways in which these tech-
niques can be combined, extended and exploited for different parts of solving in the future.

First, while we have only employed simple heuristics for deciding the frequency of external evaluations during HEX-solving, dynamic heuristics could also be used, where the frequency is adjusted according to the amount of information gained from previous calls. Second, our HEX-algorithm that exploits lazy-grounding could be combined with a pre-grounding algorithm, where the respective grounding mechanisms are applied for different modules of a HEX-program based on their properties. Moreover, additional semantic dependency information, which we used for deciding the necessity of the external minimality check, is also valuable for reducing the number of external evaluations during the model search and grounding, and could be utilized there as well.

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