Systems, Engineering Environments, and Competitions

Yuliya Lierler, Marco Maratea, Francesco Ricca

The goal of this article is threefold. First, we trace the history of the development of answer set solvers, by accounting for more than a dozen of them. Second, we discuss development tools and environments that facilitate the use of answer set programming technology in practical applications. Last, we present the evolution of the answer set programming competitions, prime venues for tracking advances in answer set solving technology.

Answer set programming (ASP) is a prominent knowledge representation paradigm that found numerous successful industrial and scientific applications including product configuration, decision support systems for space shuttle flight controllers, large-scale biological network repairs, and team building and scheduling (see Erdem, Gelfond, and Leone [2016] for more details). The success story of ASP is largely due to its modeling language and the availability of efficient and effective answer set programming tools that encompass grounders, solvers, and engineering environments. Syntactically, simple answer set programs (or ASP programs) look like Prolog logic programs. Yet solutions to such programs are represented in ASP by sets of atoms called answer sets, and not by substitutions, as in Prolog. An answer set system typically consists of two tools, a grounder and a solver, and is used to compute answer sets. Since 2007, the series of ASP competitions has promoted the collection of challenging benchmarks as well as supplied researchers with a uniform platform for tracking the progress in the development of ASP solving technologies. More recent introduction of programming environments eased the development of ASP programs and the implementation of software systems based on ASP. In this article, we present a brief survey of (1) existing answer set grounders and solvers, (2) engineering tools and environments that support production of ASP-
based applications, and (3) ASP competitions. Our goal is to provide an interested reader with an outlook on existing ASP technologies together with sufficient literature pointers rather than in-depth explanation of research and engineering ideas behind these technologies.

ASP Grounders and Solvers

In ASP, solutions to logic programs are represented by sets of atoms called answer sets (stable models) (Gelfond and Lifschitz 1988). Answer set solvers, such as Smodels (Simons, Niemelä, and Soininen 2002), Smodelscc (Ward and Schlipf 2004), and DLV (Leone et al. 2006), to name some of the first implementations, compute answer sets of a given propositional logic program. Conceptually, most answer set solvers have a lot in common with satisfiability solvers (or SAT solvers), systems that compute satisfying assignments for propositional formulas in clausal normal form. Tools called grounders complement answer set solvers. A grounder is a software system that takes a logic program with variables as its input and produces a propositional program as its output so that the resulting propositional program has the same answer sets as the input program. Propositional programs are crucial in devising efficient solving procedures, yet it is the logic programming language with variables that facilitates modeling and effective problem solving in ASP.

There are three main grounders available for ASP practitioners: Lparse (Syrjänäen 2001), DLV-grounder (Leone et al. 2006), and GrinGo (Gebser, Schaub, and Thiele 2007). Grounders Lparse and GrinGo are stand-alone tools that are commonly used as front ends for distinct answer set solvers. System DLV encapsulates both a grounder and a solver. However, calling the system with an option –installate produces propositional (ground) program for the given input and exits the computation without accessing the solving procedure of the system.

“Native” answer set solvers such as Smodels, Smodelscc, and DLV are based on specialized search procedures in the spirit of the classic backtrack-search Davis-Putnam-Logemann-Loveland (DPLL) algorithm. The DPLL algorithm and its modifications are at the core of the majority of modern SAT solvers. This algorithm consists of performing three basic operations: decision, unit propagate, and backtrack. The unit propagate operation is based on a simple inference rule in propositional logic that given a formula \( F \) in clausal normal form allows utilization of knowledge about unit clauses occurring in \( F \) or being inferred so far by the DPLL procedure in order to conclude new inferences. Native answer set solvers replace the unit propagate operation of DPLL by specialized operations based on inference rules suitable in the context of logic programs. For example, Smodels implements five propagators called Unit Propaga-
ments conflict-driven backjumping and clause learning. The PC(ID)/answer set solvers MINISAT(ID) (Wittock, Mariën, and Denecker 2008) and WASP (Alviano et al. 2015; Alviano and Dodaro 2016) share a lot in common with the design of clasp. Lierler and Truszczynski (2011) present a study that draws parallels between several answer set solvers.

System LP2SAT (Janhunen 2006) represents a family of “translation-based” solvers. This family relies on a translation of propositional logic programs into logic formulas so that models of the resulting formula are in one-to-one correspondence with the answer sets of the input program. This translation may add auxiliary atoms in the process and may include the normalization of aggregates as well as the encoding of level mappings for nontight problem instances. The latter can be expressed in different terms including acyclicity checking. Pseudo-Boolean and SAT formulations resulted in a variety of systems, such as LP2ACY-CASP+CLASP, LP2ACYCPB+CLASP, LP2ACYCSAT+CLASP, and LP2ACYCSAT+GLUCOSE. Systems LP2DIFFZ3 and LP2DIFF+YICES utilize satisfiability modulo theory solvers (Nieuwenhuis, Oliveras, and Tinelli 2006) through a translation from logic programs to difference logic. Among other alternatives, solver LP2MIP relies on a translation into a mixed integer programming problem, and runs CPLEX as back-end, while LP2NORMAL+CLASP normalizes aggregates (of small to medium size) and uses clasp as a back-end ASP solver.

ASP systems have been also extended to exploit multicore and multiprocessor machines by introducing parallel evaluation methods. In particular, parallel techniques for the instantiation of programs were proposed as extensions of the Lparse (Pontelli, Baldacci, and Bermudez 2003) and DLV (Perri, Ricca, and Sirianni 2013) grounders. Recent approaches for extending the algorithm of clasp include that of Gebser, Kaufmann, and Schaub (2012b).

Automated algorithm selection techniques have been employed in ASP for obtaining solvers performing well across a wide heterogeneous set of inputs. The idea is to leverage a number of efficient implementations (or heuristically different variants of these) and apply machine-learning techniques for learning from a training set how to choose the “best” solver for an input program. System CLASPFOLIO (Gebser et al. 2011) combines variants of clasp, and is
Constraint answer set programming is a recent direction of research that attempts to combine advances in answer set programming with these in constraint processing. This new area has already demonstrated promising results, including the development of the solvers ACSOLVER, CLINGCON, EZC-SP, IDP, and MINGO. Lierler (2014) surveys the key features of constraint answer set programming languages and systems. This direction of research is inspired by the advances in the related field of satisfiability modulo theories.

Engineering Environments

The availability of efficient solvers makes ASP a valuable tool for many computationally intensive real-world applications. Effective large-scale software engineering requires infrastructure that includes advanced editors, debuggers, etc. These tools are usually collected in integrated development environments (IDE) that ease the accomplishment of various programming tasks by both novice and skilled software developers. The development of application programming interfaces (APIs) is also essential for allowing ASP-based solutions within large software frameworks common in the modern, highly technological world. The following subsections present an overview of both the IDEs for writing ASP programs and the available APIs for building full-fledged software systems based on ASP.

Development Environments for ASP

Several tools have been proposed in the last few years that aim at solving specific tasks arising during the development of ASP programs, including specialized editors, debuggers, testing tools, and visualization tools. The IDEs that collect several tools in the same framework are also now available. SealLion (Busoniu et al. 2013) is the first environment offering debugging for programs with variables. It also features unique tools for model-based engineering (using ER diagrams to model domains of answer set programs), testing through annotations, and bidirectional visualization of interpretations. The ASPIDE (Febbraro, Reale, and Ricca 2011) is a comprehensive framework that integrates several tools for advanced program composition and execution. To provide an overview of insides of ASP IDEs we briefly outline key features of ASPIDE.

A snapshot of the user interface of ASPIDE is reported in figure 1. Logic programs are organized in projects collected in a workspace (displayed in the left panel in figure 1). The main editor for ASP programs (central frame in figure 1) offers code line numbering, find/replace, undo/redo, copy/paste, coloring of keywords, dynamic highlighting of predicate names, variables, strings, and comments. The editor is able to complete (on request) predicate names (learned while reading from the files belonging to the same project), as well as variable names (suggested by taking into account the rule one is currently writing). Programs can be modified in an assisted way, for instance, by considering bindings of variables, or by applying custom rewritings (that can be user defined). Syntax errors and some syntactic conditions (for instance, safety) are checked while writing and promptly outlined. ASPIDE suggests quick fixes that can be applied (on request) by automatically changing the affected part of code. Common programming patterns (such as guessing with disjunctive rules and specific constraints) are available as code templates that are expanded as rules (again on request). An outline view (left frame in figure 1) graphically represents program elements for quick access to the corresponding definition. Users accustomed to graphic programming environments can draw logic programs by exploiting a QBE-like tool for building logic rules (Febbraro, Reale, and Ricca 2010). The user can switch from the text editor to the visual one (and vice versa) thanks to a reverse-engineering mechanism from text to graphical format. The execution of ASP programs is fully customizable through a number of shortcuts, including toolbar buttons and drop-down menus, for a quick execution of files. The results are presented to the user in a view combining tabular representation of predicates and a treelike representation of answer sets. ASPIDE supports test-driven software development in the style of JUnit (see more details in Febbraro et al. [2011]).

Program development is enhanced in ASPIDE by additional tools such as the dependency graph visualizer, designed to inspect predicate dependencies and browsing the program; the debugger to find bugs (Dodaro et al. 2015); the DLV profiler; the ARVis comparator of answer sets; the answer set visualizer IDP-DRAW; and the data source plug-in that simplifies the connection to external DBMSs through JDBC. Notably, ASPIDE is an extensible environment that can be extended by users providing new plug-ins that support (1) new input formats, (2) new program rewritings, and even (3) customization of the visualization/output format of solver results. System ASPIDE is written in Java and is available for all the major operating systems, including Linux, Mac OS, and Windows.¹

Building Full-Fledged Applications with ASP

IDEs for ASP provide clear advantages for logic programmers, but are not enough to enable assisted development of full-fledged industry-level applica-
developed in imperative/object-oriented programming languages. Thus, ASP programs are eventually embedded in software components developed in imperative/object-oriented programming languages.

The development of APIs, which offer methods for interacting with an ASP system from an embedding program, is a necessary step in accommodating the use of ASP-based solutions within large software systems. Among the first proposals was the DLV Wrapper, a library that allows embedding ASP programs and controlling the execution of the DLV system from a Java program, and the ONTODLP API, a richer API that allows embedding ontologies and reasoning modules developed using the ONTODLP language (Ricca et al. 2009). More recently, the Potassco group from the University of Potsdam supported the embedding of ASP in Python and Lua programs using GrinGo and clasp. These interfaces provide a finer-grained access to grounder and solver functionality, and also allow incremental solving.

In APIs, however, the burden of the integration between ASP and Java is still in the hands of the programmer, who must take care of the (often repetitive and) time-consuming development of scaffolding code that executes the ASP system and gets data back and forth from logic-based to imperative representations.

These observations inspired the development of a hybrid language, called JASP (Febbraro et al. 2012), that transparently supports a bilateral interaction between ASP and Java. JASP introduces minimal syntax extensions both to Java and ASP. Its specifications are both easy to learn by programmers and easy to integrate with other existing Java technologies. The programmer can simply embed ASP code in a Java program without caring about the interaction with the underlying ASP system. An “ASP program” can access Java variables, and the answer sets that result from the execution of the ASP code are automatically stored in Java objects, possibly populating Java collections, in a transparent way. A distinctive feature of JASP is the clean separation between the two integrated programming paradigms interacting through a standard object-relational mapping (ORM) interface. JASP supports both (1) a default mapping strategy, which fits the most common programmers’ requirements, and (2) custom ORM strategies, which can be specified according to the Java Persistence API (JPA) to perfectly suit enterprise application development standards. The framework also encompasses an implementation of JASP as a plug-in for the Eclipse platform, called JDLV.

Another hybrid language combining Java and ASP was proposed by Oetsch, Pührer, and Tompits (2011), which employs a radically different strategy for the interaction with Java. For instance, Java methods including constructors can be called by exploiting special atoms in ASP rules.

The ASP Competition Series

ASP competitions are the events of the ASP community, where ASP solvers are evaluated for efficiency. Since 2007, they take place biennially and are affiliated with the International Conference on Logic Programming and Nonmonotonic Reasoning (LPNMR); the exception was the fifth event that took place in 2014, affiliated with the 30th International Conference on Logic Programming (ICLP). In this section we present the history and evolution, in terms of format, solvers participation, and winners, of the ASP competition series, by first summarizing the editions up to the fourth edition, and then focusing on the 2014 and 2015 events.

ASP Competitions up to 2013

In September 2002, participants of the Dagstuhl Seminar on Nonmonotonic Reasoning, Answer Set Programming, and Constraints (Brewka et al. 2002) agreed that standardization was one of the key issues for the development of ASP. This led to the initiative to establish an infrastructure for benchmarking ASP solvers, as already in use in related research fields of SAT and constraint programming. The first informal competition took place during that workshop in Dagstuhl, featuring five systems, namely DLV, Smodels, ASSAT, Cmodels, and ASPPS. The second informal edition took place in 2005, during another Dagstuhl meeting. Since then, the ASP competitions have been established as reference events for the community.

The First ASP Competition (Gebser et al. 2007) was organized in Potsdam with two main goals. The first goal was to collect benchmarks. It was achieved through a call for benchmarks to members of the community. The second goal was to set up a fair competition environment. In the competition, only decision problems were considered. There were three categories of benchmarks involved: (1) MGS (modeling, grounding, solving), where benchmarks were specified by a problem statement, a set of instances, and the names of the predicates and their arguments to be used by programmers to encode solutions; (2) SCORE (solver, core language), where benchmarks consisted of ground normal and disjunctive programs in the format common to DLV and Lparse; and (3) SLparse (solver, Lparse language), where benchmarks consisted of ground programs in Lparse format with aggregates.

Ten ASP solvers participated, with several new solvers compared to the first informal events, namely ASPER, clasp, NOMORE, GNT, LP2SAT, and PBMODELS, thus establishing the advent of CDCL solvers and solvers based on eager translation-based approaches to ASP solving. Solvers were ranked in terms of number of solved instances: DLV won the MGS and SCORE categories, while clasp was the best solver on the SLparse category.

The Second ASP Competition (Denecker et al.
The Fifth and Sixth ASP Competitions

The fifth and the sixth editions of the ASP competition series introduced significant modifications to the trend. We first outline the main changes, and then we speak of the two events separately.

The model and solve track was no longer an integral part of the events. Rather, it was organized as an (informal) on-site event. The reasons for this are that, first, organizing, and even more participating in, such a track requires a substantial amount of work. In addition, the participation from neighboring research communities was rather limited, probably due to the presence of competitions in the related research communities and the nonnegligible effort of participating. The first on-site event, called ASP Modeling Competition 2014, saw five participating teams. Each team was formed by three researchers and was allocated a fixed amount of time for solving a few problems.

The Fifth Answer Set Programming Competition (Calimeri et al. 2016) broke the usual timeline of the competition series in order to join the Olympic Games at the Vienna Summer of Logic, in affiliation with the 30th International Conference on Logic Programming (ICLP). It was jointly organized by the Aalto University, the University of Calabria, and the University of Genoa. This event did not feature a call for benchmarks and mostly relied on 2013 benchmarks. It was mainly conceived as a rerun of the system track of the previous event: participants to the 2013 event were invited to submit new versions of their solvers, but also new solvers were welcome. Several significant design changes and improvements in the competition settings were introduced, that is, (1) benchmark classes (called tracks in this edition) were defined based on the presence of language constructs (for example, aggregates, choice rules, presence of queries) in problem encoding rather than on a complexity basis, in order to both push the adoption of the new standard and allow participation also to solvers that may have not included all constructs, (2) novel encodings for almost all problems were proposed, to overcome some observed limitations of 2013 encodings, and (3) a simplified scoring schema for decision problems, based on solved instances only, and a scoring schema for optimization problems solely based on the solvers’ ranking on solution quality, were employed. Sixteen solvers entered the competition. Answer set solver clasp was the winner on the single-processor category, while its multithreaded version clasp-MT won the multithreaded category. Interestingly, the solver LP2NORMAL+CLASP, which normalizes aggregates and then resorts to clasp, was the best solver in an intermediate track, allowing for the full ASP-CORE-2 language, except optimization statements and no head cycle-free disjunction.

The Sixth ASP Competition (Gebser, Maratea, and Ricca 2015) was jointly organized by the same institutions as the previous event. Its design maintained
some choices of the last event, for example, tracks based on language features, the scoring schemes, and the adherence to the ASP-CORE-2 standard language. It also presented some novelities, for instance (1) a call for benchmarks stage focused on obtaining new benchmarks arising from applications of practical impact, and/or being ASP focused, that is, whose encodings are nontight, and (2) a benchmarks selection stage was introduced to classify instances according to their expected hardness. Moreover, a “marathon” track was added, where the best performing systems are given more time for solving hard instances. Thirteen solvers entered the competition. The winner of the regular track was the multiengine solver ME-ASP, while the winner of the marathon track was WASP.

Conclusion

Answer set programming is a thriving research field that features dozens of solvers and applications. Engineering environments for ASP facilitate the adoption of the technology by a broad spectrum of users. Quest for the ideal settings of the ASP competitions attests to the ever-changing, fast-paced life of the field, which strives to advance answer set programming.

Acknowledgments

This work was partially supported by MIUR under PON project SI-LAB BA2KNOW Business Analytics to Know, and by Regione Calabria, programma POR Calabria FESR 2007-2013, projects ITravel PLUS and KnowRex: Un sistema per il riconoscimento e l’estrazione di conoscenza.

Notes

1. Available from www.mat.unical.it/ric-

References


Alviano, M.; Calimeri, F.; Charwat, G.; Dao-

Tran, M.; Dodaro, C.; Ianni, G.; Krennwall-

ner, T.; Kronegger, M.; Oetsch, J.; Pfandl, A.; Pührer, J.; Redl, C.; Ricca, F.; Schneider, P.; Schwengwerer, M.; Spender, L. K.; Wal-


Alviano, M.; Dodaro, C.; Faber, W.; Leone, N.; and Ricca, F. 2015. Advances in WASP. In Logic Programming and Nonmonotonic Reasoning — 13th International Conference, LPNMR 2015, Lecture Notes in Computer Science volume 9345, 40–54. Berlin: Springer. dx.doi.org/10.1007/978-3-319-23264-5_5


za, Italy. www.mat.unical.it/aspcomp2013/files/ASP-CORE-2.01c.pdf


Denecker, M.; Vennekens, J.; Bond, S.; Geb-


Yuliya Liierler is an assistant professor of computer science at the University of Nebraska at Omaha. Her research interests are in the area of knowledge representation, automated reasoning, declarative problem solving, and natural language understanding. Her work spans theoretical foundations as well as practical implementations of methods for automated reasoning based on model generation, and applications of these methods. She completed her Ph.D. in computer science at the University of Texas at Austin in 2010.

Marco Maratex (www.star.dist.unige.it/~marco) is an associate professor in computer engineering at the University of Genoa, Italy. He obtained his Ph.D. at the Faculty of Engineering at University of Genoa in 2005. From 2010 to 2014 he was an assistant professor at the University of Genova. In fall 2015 he was a university lecturer at the Institute for Information Systems of the Faculty of Informatics at the Vienna University of Technology, in the DBAI group. His research interests include artificial intelligence, logic programming, and knowledge representation and reasoning, in particular answer set programming.

Francesco Ricca is an associate professor in the Department of Mathematics of the University of Calabria, Italy. He received his Laurea Degree in computer science engineering in 2002 and a Ph.D. in computer science and mathematics in 2006 from the University of Calabria, Italy. He is interested in declarative logic-based languages, consistent query answering and data integration, ontologies and, in particular, on the issues concerning their practical applications: system design and implementation, and development tools. Ricca is coauthor of more than 70 refereed articles published in international journals, collections, and conference proceedings.