This document describes the contributions of the 2016 Applications of Logic Programming Workshop (AppLP), which was held on October 17 and associated with the International Conference on Logic Programming (ICLP) in Flushing, New York City.

Focus and scope
The focus of the workshop was applications of logic programming, i.e., application problems, in whole or in part, that are solved by using logic programming languages and systems. A particular theme of interest was to explore the ease of development and maintenance, clarity, performance, and tradeoffs among these features, brought about by programming using a logic paradigm. The goal was to help provide directions for future research advances and application development.

Real-world problems increasingly involve complex data and logic, making the use of logic programming more and more beneficial for such complex applications. Despite the diverse areas of application, their common underlying requirements are centered around ease of development and maintenance, clarity, performance, integration with other tools, and tradeoffs among these properties. Better understanding of these important principles will help advance logic programming research and lead to benefits for logic programming applications.

The workshop was organized around four main areas of application: Enterprise Software, Control Systems, Intelligent Agents, and Deep Analysis. These general areas included topics such as business intelligence, ontology management, text processing, program analysis, model checking, access control, network programming, resource allocation, system optimization, decision making, and policy administration. The issues proposed for discussion included language features, implementation efficiency, tool support and integration, evaluation methods, as well as teaching and training.

Program and organization
The workshop program included four sessions, one for each area, and each session included an invited talk followed by contributed short talks. Participants were invited to submit a position paper, of one or two pages, explaining their application problems, solutions, rationales, and challenges. Besides an excellent submission for an invited talk, six others were chosen by the program committee to present their work in short talks. They were encouraged to make their talks accessible to non-specialists.

Others were invited to participate on panels. The workshop featured discussions in which the moderator directed a short question to a panelist, who presented their thoughts, after which the other panelists were given a brief time to respond and contribute their thoughts. At the end of the workshop, the floor was opened to the audience for a final open discussion.
The workshop brought together researchers and software engineers who are building applications using logic programming, and presented novel and challenging work and participated in lively discussions. Approximately 35 people participated in the morning session and about 55 in the afternoon. This document includes summaries of all presentations and discussions, followed by abstracts and position papers, following their order in the program:

- The morning consisted of two sessions and a panel discussion. Session 1 was titled “Enterprise Software and More”, with an invited talk by Molham Aref, and contributed talks by Jeffrey Rosenwald and by Paul Fodor for Iliano Cervesato and Edmund Lam. Session 2 was “Control Systems and More” with an invited talk by Marcello Balduccini and a contributed talk by Allesandra Russo. The panel discussion was on “Concurrent and Distributed Systems, Integration”, moderated by Warren, with panelists Manuel Hermenegildo, Boon Thau Loo, Theresa Swift and Jan Wielemaker.

- The afternoon included two sessions, another panel discussion, and an open discussion. Session 1 was titled “Intelligent Agents”, with an invited talk by Francesco Ricca and a contributed talk by Gopal Gupta. The panel was on “Knowledge and Constraint Systems, Integration”, moderated by Warren, with panelists Marc Denecker, Torsten Schaub, and Mirek Truszczynski. (Michael Gelfond was to be a panelist but unable to participate at the last minute.) Session 2 was on “Deep Analysis”, with an invited talk by C.R. Ramakrishnan, and contributed talks by Nikolaj Bjørner and by Paul Tarau. The open discussion was on “Directions for Research and Applications: Big Data Analysis in Depth and Scale”.

As chairs of AppLP, we were aided by a strong program committee who reviewed the submitted papers and provided helpful input on the program form. Each paper was reviewed by at least three committee members. The committee included:

- Manuel Hermenegildo IMDEA Software Institute, Spain
- Bob Kowalski Imperial College London, UK
- Nicola Leone University of Calabria, Italy
- Michael Leuschel Heinrich-Heine University in Dusseldorf, Germany
- Vladimir Lifschitz University of Texas at Austin, USA
- Enrico Pontelli New Mexico State University, USA
- Theresa Swift NOVA LINCS, Universidade Nova de Lisboa, Portugal
- Jan Wielemaker Vrije University Amsterdam, Netherlands

Local organization was aided by Bo Lin, Christopher Kane, and Saksham Chand of Stony Brook University. We would also like to thank Michael Kifer and Neng-Fa Zhou for their help as general chairs of ICLP. AppLP 2016 was greatly improved by the generous sponsorship of LogicBlox, Inc. for enabling additional discussions at organized lunch and dinner.
LogicBlox: Solver-Aided Declarative Programming — Invited talk by Molham Aref
This talk introduced the “smart database” system LogicBlox (developed by the company of the same name). It is organized as follows: (1) background information on enterprise systems and motivation for new systems like LogicBlox, (2) important features of their language LogiQL, (3) a brief explanation of their methods for efficiently computing queries, and (4) results comparing the performance of LogicBlox to other similar systems on standard benchmarks.

LogicBlox’s customers’ businesses are complex systems. Simplifying models of important domains in their businesses are required to manage this complexity and produce useful analysis. Current solutions, spreadsheets and enterprise systems, are too limited and coarse-grained to handle the complexity effectively. In addition, current enterprise systems are formed of many components that must be carefully coordinated, making them hard to use and maintain. LogicBlox strives to offer a unified system to avoid these issues.

The primary users of LogicBlox are domain experts who are best-suited to building models of their businesses, not application developers. The LogicBlox language, LogiQL, is an expressive, declarative language based on Datalog meant to be accessible to domain experts. The talk gives several examples illustrating how derivation rules can be built from relations using conjunction, disjunction, negation, as well as arithmetic operations, aggregation, recursion, and existential quantification. Also explained are integrity constraints, derivation rules with false in the conclusion, that are used to constrain the possible state.

The LogicBlox approach to efficient computation is “brains before brawn”, by using the best possible algorithms and data structures, rather than brute force and better hardware. Two examples demonstrate this approach. The first is the use of incremental computation to maintain materialized views and efficiently update the results of repeated queries as the database changes. The second is the use of the Leapfrog Triejoin, a worst-case optimal algorithm for computing multi-way joins. Simultaneous multi-way joins provide asymptotically better results for complex queries than sequences of pairwise joins. The algorithm has been further improved by the addition of worst-case optimal query planning and the results can be incrementally maintained.

LogicBlox is superior to similar systems at solving graph queries as shown by results for the clique benchmark. For a graph with one hundred thousand edges LogiBlox performed 33 times faster than Redshift and 57 times faster than HANA. For a graph with ten million edges, LogicBlox performed 227 times faster than Redshift, while HANA failed to achieve a result.

Logic Programming in the Materials Handling and Logistics Industries — Presentation by Jeffrey Rosenwald
This talks begins by comparing software engineering in two very different industries, materials handling—moving items around large warehouses—and telecommunications. The requirements for materials handling software are the same as the requirements for telecommunications. Each domain requires large, distributed software systems capable of handling large numbers of concurrent activities featuring complex functionalities. These systems must be in continuous operation for many
years with maintenance conducted while the system is in operation. The systems must meet strict 
quality and reliability guidelines, and display high-tolerance for both software and hardware fail-
ures. However, telecommunications systems have historically achieved greater success at meeting 
these requirements than materials handling systems.

This talk proposes that developers of materials handling systems take some lessons from the 
use of Erlang by telecommunications developers: making a process the locus of failure can prevent 
failure from spreading, processes communicate only by message passing, and processes can come 
and go. However, SWI-Prolog has several advantages over Erlang for writing materials handling 
software. The talk describes an agent-oriented system written in SWI-Prolog by building on a 
“holarchy of holons”. A holon is a small, stand-alone program that has a specific sphere of influence 
within the system. Among other virtues, the system at twenty thousand lines is an order of 
magnitude smaller than alternative systems written in Java.

Unfortunately, there is significant resistance to adopting a system written in Prolog. This is due 
to a suspicion of open source technologies in general, and, more specifically, an ignorance of Prolog 
in U.S. industry. Old businesses like materials handling are not willing to take a risk on a system 
built on such an unfamiliar basis. As a result, this system has been used for fast prototyping of 
continuous extensions and new installations but not as an adopted system in production.

Concurrent Logic Programming: Met and Unmet Promises — Presentation by Paul 
Fodor based on slides by Iliano Cervesato and Edmund Lam

This talk begins by describing the promise of logic programming. The declarative nature of logic 
programming promotes human-friendly descriptions of problems making them easier to understand 
and reason about. Some of this promise has been realized, but logic programming still struggles 
with very large programs and expected simplification of reasoning has not appeared consistently. 
The largest problem for logic programming is that it remains a fringe paradigm.

It is argued in this talk that this last problem can be addressed by applying logic program-
mimg to a high-profile problem: concurrent and distributed application development. This is a 
good choice because these applications are everywhere, they are difficult to get right, and no other 
programming paradigm contains a widely adopted solution. Logic programming is suited to spec-
ifying communication and synchronization in distributed applications, and reasoning about their 
correctness.

The language, Comingle (developed by Iliano Cervesato and Edmund Soon Lee Lam) supports 
the writing of mobile, distributed applications for Android and i386 in a system-centric way (rather 
than the error-prone node-centric fashion common to other programming paradigms). The lan-
guage implements a portion of first-order logic as horn clauses, evaluated with a forward-chaining 
semantics. Techniques for reasoning about Comingle applications are still being developed using 
“session types” and “coinductive methods” to determine that these applications behave the way 
they should. Initial results for application programming and reasoning are promising.

What Tweety-the-Penguin and Faulty Suitcases Tell Us about Productivity, Cyberse-
curity, and Data Sciences — Invited talk by Marcello Balduccini

This talk surveyed applications that use logic programming for knowledge representation, where 
knowledge representation has three components: (1) commonsense and non-monotonic reasoning 
(NMR), (2) non-monotonic logics and constraint satisfaction programming (CSP), and (3) reasoning 
about actions and change (RAC). NMR allows new knowledge to invalidate previous conclusions.
There are several formalisms for capturing NMR, including Prolog and ASP. Common sense and NMR can be used in ASP to capture RAC.

The first example application uses ASP to build an automated system, USA-Advisor, to provide decision-support for the Space Shuttle’s Reaction Control System (RCS). RCS is a complicated set of tanks, valves, jets, switches, circuits, plumbing, and computer commands that are used to maneuver the shuttle while it is in orbit. Given a maneuvering goal $G$, USA-Advisor determines whether a given set of RCS actions will achieve $G$, and if so, generates a plan to achieve $G$, in the presence of arbitrary multiple faults in RCS. Over many test instances the ASP-powered USA-Advisor was able to efficiently find a solution: 11 seconds on average, 1-2 minutes for hard cases.

The second example application is industrial-scale print shop scheduling. There are constraints on the scheduling, including resource consumption, device availability, job phases, new jobs, device failures, and heuristics. ASP does not scale well enough to handle a problem this complex. Prolog is efficient enough, but the implementation of the scheduler is not nearly as simple and clear as the abstract logic of the scheduler. The solution was a new language that combines ASP with CSP, called EZCSP. This provided the efficiency required for industrial problems, like print shop scheduling, but retains the clarity of an ASP implementation of the scheduler.

The third application is automated malware mitigation—the process of removing malware from an infected system effectively and safely. This requires substantial reasoning because of the complex interdependencies between components of an infected system. So a precise, formal definition of the mitigation task was required. This was done by modeling the infected system as an RAC problem. Doing so reduces the mitigation problem to a planning problem in which one looks for a sequence of actions that lead to a safe (i.e., malware-free) state. Testing on a 1000 simulated systems, each infected with 1 to 5 instances of malware and offering 1-40 essential services, yielded a success rate close to 90%, with the solution found in less than 2 seconds on average.

The fourth application is action-based information retrieval. Search engines excel at retrieving information about discrete facts, but do poorly at retrieving relevant information in response to complex queries about events. The response must contain information about the causes and outcomes of events. This can be done by representing this information as an instance of RAC. Reasoning about actions can be used to retrieve information about event outcomes. A representation framework has been built, natural language processing of source documents was used to build connections between documents that describe events, their causes, and their outcomes, and action-based retrieval has been demonstrated in case studies; but much of this problem remains open.

The talk concludes that many practical applications can, and are, being developed using the combination of the three components illustrated for knowledge representation.

**Distributed Systems Management: Logic Programming Solution and Challenges — Presentation by Alessandra Russo**

This talk presented an evaluation of efforts to apply logic programming to distributed systems management, focusing on two applications: policies for access control and distributed computing.

Access control policy languages must be expressive and provide a good framework for analysis. Logic programming languages are expressive enough to capture a range of existing policy languages and can provide clear formalizations of both policies and system states. Abductive constraint logic programming (ACLP) can be used for sound analysis of policy systems expressed as logic programs. However, the completeness of policy analysis through logic programming is only guaranteed under
certain conditions. Policy analysis also relies upon the closed world assumption, preventing the analysis from showing a property is satisfied for every finite domain.

There have been several proposals for applying logic programming to distributed computing. This talk advocated for a distributed state machine model of distributed computation. Datalog plus a notion of time can be used to clearly represent states and state transitions. The specification of the distributed computation is fully declarative on this model allowing direct application of logic-based analysis to the distributed program. Logic programming languages for distributed computations are expressive. Operational properties can be represented in the language. Both synchronous and asynchronous communication models can be represented. However, scalability remains an open problem.

Concurrent and Distributed Systems, Integration — Panel discussion with panelists
Manuel Hermenegildo, Boon Thau Loo, Teri Swift, and Jan Wielemaker, moderated by David Warren

Warren asks, “What is the biggest current stumbling block in your applications?” The question is addressed first to Swift.

Swift’s response is based on her work as a consultant for customs. She points out that Prolog requires many extensions to produce useful applications. In this case, it was extended for use as a server and for elastic search using Java, and use of Prolog is restricted to data standardization. She laments that she ended up with a Java program that included a little bit of Prolog.

Loo’s response concerns the use of Prolog for declarative networking. He points out that we face problems with usability, and with integration with legacy systems. In addition, he states that there is a problem getting people to adopt declarative networking using logic programming.

Wielemaker states that SWI-Prolog has been designed to work well with legacy systems and other systems and languages. He is currently working on a program in which Java components are being gradually replaced with Prolog components.

Hermenegildo points to the continuing scalability problems for logic programming applications. In addition, there is a significant adoption problem regarding newer, more advanced features that address these shortcomings.

Swift states that SWI-Prolog is the closest to a usably integrated logic programming language, but is still not quite there. She wants to integrate cluster computing as well.

Warren asks, “In a multi-language, multi-software ecosystem, what are the roles of logic programming languages?” The question is first addressed to Wielemaker

Wielemaker responds that there is no good general answer to this question. It is necessary to look at each language and compare it to the features offered by Prolog to determine how they can be effectively integrated.

Hermenegildo says that for some uses, for example provers, some LP software integration is automatic. But, there are still cases, such as networking, where careful deliberation is required to make a good choice about how to integrate LP.

Loo adds that, regarding network protocols and domain-specific languages, policy evaluation is the right use of LP. By contrast, data-level applications require a low-level approach.
Swift contends that we should reconsider the distinction between low-level and high-level problems/applications/programming. She says that Scala is an example of a language that does both low-level and high-level well.

Wielemaker proposes that Prolog is more flexible than it may seem. It can manage many different data models, but appropriate interfaces must be provided.

Warren asks, “What should the underlying LP technology you use do better to support your networking applications?” The question is first addressed to Loo.

Loo answers that there is a persistent problem with distribution in Datalog and Prolog. It is necessary to make the computations asynchronous. As a result, actual protocol implementations require extensions to Datalog and user-defined functions to work correctly. These extended programs become messy. It is no longer possible to prove their correctness without oversimplifying them.

Swift argues that there are already too many specialized features in XSB. They do not work together well, and it takes a lot of time to figure out which special features to use and how to integrate them together.

Wielemaker explains that the SWI-Prolog approach is to cover as many features of LP as possible, without doing any of them exceptionally well. He tries to do everything at a sufficient level of quality.

Hermenegildo agrees that special systems require specialized technologies. LP needs a good architecture for loading and unloading relevant, specialized features. He thinks we need standardization.

Loo concurs that standardization would be a good improvement. He thinks that LP should follow the software engineering model and offer an open API.

Warren asks, “Is there a practical role for parallelism in your existing applications?” The question is first addressed to Hermenegildo.

Hermenegildo answers, “Yes, all the time”. We have the hardware and we want to use it for LP applications. Funding for parallelism was solid in the 80’s and 90’s, but disappeared because the predicted bar to faster processors did not happen. But without that support, and now with the need for parallelism that can take advantage of the ubiquitous multi-core processors, the current technology for parallelism is not as good as the technology that was developed during that period of interest in parallelism.

Wielemaker also answers yes. He states that threading is good enough for many tasks, but for interdependent tasks or parallel computation of a single task, multi-threading is not good enough.

According to Loo, Parallel Datalog can be used for low-level networking tasks. One needs to pay special attention to the ordering. Ordering constraints make the problems more interesting.

Swift contends that shared-memory parallelism is not as important as distributed parallelism. There is no need to reinvent the wheel here. There are many teams working on parallel computation. We should integrate their results into our work on LP.

Hermenegildo says that we should try simple, intermediate approaches.
Applying ASP in Industrial Contexts: Lessons Learned and Current Directions — Invited talk by Francesco Ricca

This talk offered reflections on experiences using Answer Set Programming (ASP) for industrial applications. ASP is a declarative programming paradigm for logic programming and non-monotonic reasoning using stable-model semantics. There are several robust and efficient implementations, including DLV, Wasp, Clasp, CModels, and IDP. Areas of applications include artificial intelligence, knowledge representation and reasoning, information integration, data cleaning, bioinformatics, robotics, etc.

The talk describes the use of DLV and Wasp to build industrial applications in many of these areas and gives sustained attention to two of these applications. First was the use of DLV to build a system, ZLog, that classifies customers of a call center and routes the customer’s call to the most appropriate service. Categories are created by experts (call center operators) using a friendly GUI in ZLog, and then automatically translated into ASP rules. Category definitions and the customer database are fed to DLV, which computes the class of customers that fall into each category. Category classification then determines routing of call. ZLog runs in a production system at Telecom Italia where it handles 400 calls per second (over one million calls per day), and classifies each customer calling in in less than 100 ms.

The second application is a Team Builder for scheduling teams of employees at the Gioia Tauro seaport. Scheduling is subject to many constraints: number of workers of each role necessary for a shift, contractual constraints on employee assignments, fair distribution of workload and assignment to heavy or dangerous roles, etc. Manual team building took hours, and mistakes are costly in terms of team performance and penalties for contractual violations. The Team Builder application built using ASP offers a friendly GUI and guarantees that all constraints will be respected. For the seaport, Team Builder manages 130 employees and fills 36 meta-plans per week. Shift assignments for a day can be done in seconds and shift assignments for an entire month can be computed in less than ten minutes.

Several lessons emerged from the experience developing industrial applications using ASP. ASP can be effectively applied to real-world, industrial-scale problems. ASP applications can be rapidly developed, and are easy to understand, maintain, and extend because ASP is a purely declarative language. In order to realize these benefits, ASP programming requires the support of development tools, like IDEs, and integration with other programming languages and established development processes and platforms. These are necessary to indicate that ASP is not just for researchers. Such tools (ASPIDE and JASP) are being built, but more work is required. Also the ASP solver WASP has been extended to enable handling of problems, such as the Partner Units Problem and the Combined Constraints Problem that state-of-the-art ASP solvers cannot manage.

Building Large-Scale, Knowledge-Based Systems with ASP — Presentation by Gopal Gupta

This talk described several challenges that arise for building large-scale knowledge representation and reasoning systems using ASP, and then proposed a possible solution. Most ASP systems rely on SAT solvers, and this approach raises several issues for large-scale, knowledge-based systems. First, the program has to be finitely groundable, preventing the use of complex data structures to organize a large knowledge base. Second, grounding the program can result in exponential blowup, which is not feasible for a large knowledge base. SAT solvers will find the entire model of the program, which may contain a lot of unnecessary information, and hide the answer we are
looking for in the model. Finally, minor inconsistencies in the knowledge base will prevent the system from finding an answer set, but we cannot expect large knowledge bases to be entirely free of inconsistencies.

The proposed solution is a query-driven ASP system that supports the use of predicates. By making the system query-driven, the system searches only the part of the knowledge base relevant to the query and produces only a partial answer set. The query-driven approach addresses the concerns about unnecessary information in the answer set obscuring the answer we actually want. By supporting predicates, the system can execute programs without grounding them first, which addresses the issues regarding the use of data structures and the exponential blowup of the program. The final issue is addressed through incremental consistency checks as the relevant parts of the knowledge base are explored. If inconsistencies do not exist in the relevant part of the knowledge base, then they can be ignored.

This approach has been implemented in the s(ASP) language. s(ASP) is an extension of Prolog with stable-model semantics, allowance of general predicates, and goal-directed, query-driven execution. Several applications have been written using this language but challenges related to efficiency persist.

Knowledge and Constraint Systems, Integration — Panel discussion with panelists Marc Denecker, Michael Gelfond (could not attend), Torsten Schaub, Mirek Truszczynski, moderated by David Warren

Warren asks “In some of your applications, are there issues of scaling to very large data sizes?” Question was first addressed to Schaub.

Schaub responds Yes, and that data mining is the application where this problem is most apparent. We must treat problematic predicates specially by outsourcing them to a dedicated propagator. Logistics and robotics both require the generation of many new constants for discovered objects. The problem is not as bad for bioinformatics. Schaub is working on a new system that translates ASP into SAT and scales to 4000 objects per domain.

Denecker argues that some scale problems are not caused by the combinatorics of the search, but by the size of the knowledge that needs to be explicitly represented. I.e., the grounded programs are too large. This is a technical problem. A possible solution is lazy grounding.

Truszczynski contends that scalability problems are unavoidable for hard problems. The only genuine solutions are luck, in the form of patterns in the data, or excellent heuristics.

Warren asks “Do we have to compromise on pure declarative programming to get programs to run efficiently?”

Schaub responds that in Clingo, heuristics can be specified at the ASP level.

Denecker says that practical applications require whatever is necessary to make them work. Systems that use the same knowledge base to solve many different kinds of problems cannot be tainted with procedural tweaks.

Truszczynski states that it may not be realistic to expect actual systems to be that pure.

Warren asks “What are the limitations of the LP technology you use in your applications?”

Schaub responds that LP is no longer viewed as proof. People are using ASP for specifying constraints, but it is hard to model reactions in ASP as constraints. One needs linear equations for that.
Gopal Gupta: One needs goal-directed implementations.

Warren asks, “What are, and what should be, the roles of declarativity and procedurality in your applications?” Question was first addressed to Denecker.

Denecker responds that one example is interactive search applications. Heuristics do not matter in this context, because they are replaced by user choice. Such applications require sticking to a declarative approach.

In general we want systems in which interfaces are built or composed of procedural code that will interact with a declarative knowledge base and solver.

Truszczynski contends that it is critical that the knowledge base be represented declaratively. The role of procedural programming is for use in individual reasoning tasks performed on the knowledge base. A declarative approach should be used to describe knowledge.

Schaub expresses disagreement on this point. He argues that control must be exerted over the reasoning process. He thinks this can be solved by using procedural languages to build interfaces. This is necessary for number-crunching, but procedural language may not be necessary to control the process reasoning—this can be done declaratively.

Warren asks, “What are good new applications for logic-based technology?” Question was first addressed to Truszczynski.

Truszczynski replies that bioinformatics is one such application, where good work is being done by Schaub’s group. Something must be done for network security, such as anomalous behavior detection or policy specification. There are several other areas: declarative network management; decision theory, for modeling agent preferences and resolving conflicts, where research problems are in need of better support for optimization (Schaub’s Asprin system that incorporates preferences into the ASP solver may help); and program derivation, for generating a program from a natural language specification of the problem.

Schaub adds that the problem for bioinformatics is that we cannot model non-linear constraints. He also mentions logistics, as well as situations in which many different reasoning tasks are required to solve a problem, for example cognitive robotics.

Denecker says it is a problem of conquering infinite space. Some applications need to go from view to data.

Truszczynski adds that representation of, and reasoning about, uncertainty is critical.

Declarative Probabilistic Programming — Invited talk by C. R. Ramakrishnan

This talk presented an extension of logic programming to support probabilistic facts and probabilistic reasoning, and described the current state of probabilistic programming languages and their applications.

Logic programming is good for providing an executable specification of operational semantics. For example, a simple set of rules captures the semantics of the lambda calculus. Logic programming can do the same for abstract semantics. Context-insensitive pointer analysis can be specified with a small number of logic programming rules that look just like the formal inference rules used to define the pointer analysis.

Logic programming can also be used to build a model checker for logics with temporal properties, as exemplified with Computational Tree Logic (CTL). CTL contains formulas that describe states
of systems and the formulas that describe paths (sequences of states). Tabled resolution is required for the model checker to terminate, but query evaluation will be dynamically stratified. The time complexity for model checking is $O(|T| \cdot |\varphi|)$, where $|T|$ is the total number of states and transitions and $|\varphi|$ is the size of the formula $\varphi$. The space complexity is $O(|S| \cdot |\varphi|)$, where $|S|$ is the total number of states.

Probabilistic logic programming languages combine rules with probabilistic facts. The result of the query is a probability distribution. There are several systems for probabilistic logic programming, including ICL, PRISM, ProbLog, etc. Probabilistic logic programming can be applied to build model checkers for systems that have probabilistic temporal properties. Tabling is needed for probabilistic model checking, just as it was for non-probabilistic model checking. Inference for probabilistic temporal logics requires additional support to track and differentiate random variable valuations in different system runs and to ensure the computation terminates even though there may be infinitely many distinct system behaviors.

The performance of probabilistic LP-based model checking is comparable with other model checkers. It provides the first realistic model checkers for expressive languages, such as pi-calculus, mobile ad-hoc networks, multi-agent systems, etc. It supports the first implementation of a model checker for the GPL language. Ramakrishnan also introduced XPL, a logic for reasoning about systems that feature both probabilistic and non-deterministic choice.

Horn Clause Solvers for Network Verification — Presentation by Nikolaj Bjørner

This talk discussed the results of attempts to represent networks as Datalog programs, and then to use Horn clause solvers in Z3 to perform verification of properties of the network. Z3 has been used to find solutions to symbolic representations of problems from many domains. It has been applied to program analysis to determine whether an execution path is feasible (SAGE), whether policies satisfy a given contract (SecGuru), etc. In addition, Z3 contains several specialized engines when the formulas to which it is applied are constrained Horn clauses.

Horn clause solving is useful because networks can be expressed as Datalog programs using constrained Horn clauses, in which packets are represented as differences of cubes. For example, entries in a routing table can be expressed by rules where a predicate representing the current location of a packet and its source and destination is in the body of the rule, and the next hop location is in the head of the rule. The body will also contain constraints concerning the range of addresses that determine the next hop from the current location of the packet. Given this representation of the network, the problem of computing all the packets that will reach a given destination from a given source becomes a reachability problem that Horn clause solvers handle well.

The experience so far is that Z3 provides a general interface for network verification problems represented as Horn clauses, but that the Horn clause engines within Z3 each work on a very select set of problems.

Logic Programming from NLP to NLU? — Presentation by Paul Tarau

This talk describes the application of logic programming to Natural Language Understanding (NLU). One of the original motivations for logic programming was Natural Language Processing (NLP). There is an opportunity now for logic programming to help us achieve some of the objectives of NLU. Currently, statistical approaches to NLP are prevalent (through machine learning and “deep learning”), but for NLU we want observable behavior and human understandable output. We can
accomplish this by using some form of logical representation, which is the closest formal mechanism to natural language.

There is a rich assortment of both logical forms and logic programming tools available for building NLU systems. Graph-based NLP algorithms, such as TextRank, are effective, but do not feature NLU elements. They could be extended to NLU by using richer graphs built with logical representations of sentences. Another application, developed by the presenter and his colleagues, builds natural language-enabled agents using Prolog. Beyond Prolog, both constraint programming and ASP systems can provide LP-based support for the transition from NLP to NLU. Tarau mentions several applications for NLU that are all emerging now, such as interactive story telling, voice-enabled software agents (e.g., Siri, Cortana, etc.), home automation systems and IoT, and even search engines are moving toward becoming NLU-enabled question answering systems.

**Directions for Research and Applications: Big Data Analysis in Depth and Scale — Open discussion moderated by David Warren**

Warren asks the general audience, “What are the most important, real-world logic programming applications?”

Jeffrey Rosenwald: it is transforming unstructured logging data into something that a human can look at, or log analysis that can reveal anomalous data.

Paul Tarau: it is Prolog-based Natural Language Processing for interactive agents for games and story telling.

Gopal Gupta: it is the Internet of Things, processing states and observations for a huge numbers of sensors.

Torsten Schaub: it is assisted-living applications for smart homes. Careful research is being displaced by ad hoc solutions built into gadgets that are already being produced.

Warren asks, “What is the role of logic programming in Big Data?”

Jan Wielemaker answers that it is intrusion detection in networks. More generally, logic programming can be useful for preprocessing data from high-volume sources.

A participant says that he tried machine learning (supervised learning) for classification on Big Data, and explains that we can use logic programming rules to handle cases which machine learning classifies as “unknown”, which is a much smaller data set.

Rosenwald says that his system for materials handling and logistics collects gigabytes of data everyday, and logic programming can be used for filtering to reduce data size.

Tuncay Tekle states that LogicBlox is using Datalog to process Big Data for retail solutions. To prove the effectiveness of logic programming to the skeptical, we need to show that the additional revenue generated by LP solutions outweighs the cost of implementing and deploying the LP solution.

Annie Liu closed by suggesting that we should build a repository of logic programming applications.
Solver-Aided Declarative Programming (Abstract)

Molham Aref, LogicBlox, Inc.

I will summarize our work on a declarative programming language that offers native language support for expressing predictive (e.g. machine learning) and prescriptive (e.g. combinatorial optimization) analytics. The presentation gives an overview of the platform and the language. In particular, it focuses on the important role of integrity constraints, which are used not only for maintaining data integrity, but also, for example, for the specification of complex optimization problems and probabilistic programming.

Logic Programming in the Materials Handling and Logistics Industries

Jeffrey A. Rosenwald, Intelligrated, LLC

For quite some time, I have been using SWI Prolog to build systems that are used to control machinery that moves packages around 1 million sq. ft. warehouses. These kinds of systems are deployed in large retail distribution centers, airports, and parcel and postal sortation centers.

Characteristics of the application

- **Systems are big**—it is not unusual for a one sorter to have 20,000 alarm points.
- **High throughput**—range is typically $10^5$ to $10^6$ items sorted per day
- **High accuracy**—sortation mistakes are expensive. Error rate is about 1 in $10^4$ items sorted.
- **Heterogeneous**—different systems, platforms, and vendors may be involved,
- **Event-driven**—everyone reacts to events that occur on the machinery
- **Soft real-time**—end-to-end service times are measured in milliseconds. Some variability of service time is tolerable, within limits.
- **Fault-tolerant**—non-Byzantine failure, that is late or lost (infinitely late) messages, are recoverable.
- **High availability**—many sorters run 20 hours per day, 364 days a year. The execution epoch of the control system is measured in years. It is never taken down in the absence of failure.
- **Reliable and durable**—the machinery is built to last for 25 years (many are older than that)

Characteristics of the software design

- An agent-oriented design provides a collection of small stand-alone programs —a community of Holons organized in a Holarchy.
- Each Holon has a sphere of influence and a protocol.
- Holons communicate with one another anonymously by message passing using a publish and subscribe regime that spans the entire CPU cluster.
- The Holarchy can be deployed across a cluster of several CPUs, which provides for hot-standby redundancy, load sharing, and automatic fail-over.
Holons in the system play the following roles:
- two Holons interact with Siemens S7 Programmable Logic Controllers (PLCs) via TCP/IP byte streams to provide system control, alarm, and diagnostic surveillance,
- one Holon is responsible for Routing. That is, where an item ought to go when it’s seen (by a bar code scanner) at a particular place and time on the machinery,
- several Holons provide GUI elements for various control and status displays.

Characteristics of the implementation
- The system is fast, small, flexible, scalable, resilient, easy to understand and maintain, and darn-near bullet-proof.
- The amount of source code is about 20K lines of Prolog. This is nearly an order of magnitude smaller than it’s equivalent Java based counterpart.
- IPC messages are human-readable.
- The message pattern is loosely-coupled.
- Holons have almost no code dedicated to debugging.
- Debugging of dynamic behavior is done by lurking/logging on the broadcast channel.
- Unit testing of Holons is a highly effective method of eliminating defects.
- Badly formed messages cannot enter the system. They are detected early and discarded.
- Holons can be replaced on-the-fly, without taking the system down.
- The design is naturally parallel. Effective use of multi-core CPUs is free.
- Association, Parsing, and Pattern Matching are essential.
- Non-deterministic Content Addressable Memory that is afforded by the language provides an elegant solution to many problems.
- Base system does not have a relational database.
- Voluntarism is an important concept: Holons do things because it is in their nature to do so. They do things because they want to, not because they have to.

Barriers to adoption
- Materials Handling is an old business with many large entrenched players, with vested interests.
- Selection of technological platforms and systems at this scale is a business decision, not a technical one.
- Fear, Uncertainty, and Doubt
- Market penetration will likely be revolutionary, not evolutionary.
- Irrational fear of Open Source generally and of the GPL in particular.
- Incompatibility of the GPL with business models that espouse “ownership” of intellectual property.
- Prolog is almost unknown in the U.S., outside of academic circles.
- Angel Investors and Venture Capitalists are reluctant to invest in ideas that do not produce sustainable competitive advantage that can be sold. This usually means intellectual property: patents, copyrights, or trade secrets.

Here’s a video of a system deployed by Buemer/Crisplant (our European sister company). I would control the crossbelt sorter and induction conveyor (between 00:50—02:10). https://www.youtube.com/watch?v=14
Concurrent Logic Programming: Met and Unmet Promises

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Logic programming has been heralded as the quintessential declarative programming paradigm, although many instances provide extra-logical constructs that undermine this aspiration. The word “declarative” conjures two promises: the first is the ability to write code that reflects a natural, human-friendly, description of the problem at hands as opposed to a mechanistic, hardware-oriented, encoding of a solution. The second is the opportunity to reason logically about it, thereby automatically strengthening assurance, security and performance. While the first promise has been fairly successful in some domains, the second still has to live to its expectations. We explore both promises in the context of concurrent logic programming. We highlight them using CoMingle, a logic programming language designed to develop mobile Android applications.

Logical specification of concurrent applications

Concurrent and distributed applications have traditionally been developed by writing a separate piece of code for each participating device (or class of devices). This node-centric approach puts the onus of handling messaging and synchronization on the programmer. This is no small burden: on the messaging side, the programmer needs to make sure that each sent message has a recipient and vice versa, and that sender and receiver agree on its format — simple tasks that quickly become a time sink as an application grows larger. The synchronization side is more tricky as the programmer is left alone battling the many pitfalls of concurrency (deadlocks, live locks and unwanted race conditions) — complex tasks even for small applications. Because the code running on each device is a separate control flow, little automation is available to alleviate these concerns as current program analysis techniques typically focus on individual control-flows and do not work well for reasoning about the executions of a concurrent program as a whole. These effects are compounded by the fact that, as mobile applications become commonplace, many of them are being developed by programmers with relatively little training or experience.

An alternative approach is to write a unified program that captures the behavior of a distributed application as a single entity. This system-centric approach gives the programmer a bird-eye’s view of the behavior he/she is trying to achieve. Being a single program, it is easier to automate basic checks such as message format consistency, for example as a form of type-checking. This unitary system-centric specification is automatically transformed into the node-centric code that runs on actual devices through a process called choreographic compilation. It is this transformation, rather than the programmer, that handles the tedium of managing communication and the intricacies of getting synchronization right.

While the system-centric approach to programming distributed application is not exclusive to the paradigm of logic programming (in fact, it underlies many of Google’s applications [4]), logic programming is proving particularly well-suited for this purpose [1, 5, 8, 10]. Logic programming provides a natural way to write specifications that represent how the distributed computation proceeds as a whole rather than forcing the point of view of any specific node. One language that embraces this philosophy is CoMingle [9]. CoMingle is a rule-based language for programming mobile distributed applications, originally Android apps. CoMingle implements a fragment of
first-order linear logic using a forward-chaining semantics, as found in languages based on multiset-rewriting such as CHR [3]. It enriches it with sorts (making it a strongly-typed polymorphic language), locations (which identify computing nodes), and multiset comprehensions (which provide a natural mechanism to manipulate arbitrarily many facts matching a given pattern). Specifically designated atomic facts allow CoMingle to trigger local computations and respond to them (used for example to process input from an Android device or to render output on the screen). We used an advanced prototype of CoMingle [7] to implement a number of mobile applications. We were able to write each of them in a few hours, which compares favorably with the standard node-centric approach. We built one such application both using CoMingle and by writing traditional code: the former was about one tenth of the size of the latter with no noticeable difference in performance [8]. This ease of development gave us time to experiment with application-level features, with new communication behaviors typically taking minutes to implement.

Reasoning about concurrent applications

Because in its purest form a program is a logical formula, logic programming has often been trumpeted as facilitating reasoning about one’s code, where reasoning is variedly understood as providing provable assurances of correctness, guaranteed performance, and more recently security. With a few exceptions (e.g., [11] about performance bounds), we argue that such expectations of correctness have not been met. For example, correctness presupposes a specification that can be compared with an implementation, but rarely does a programmer write two such formulas for the same problem, and in any case tools to verify the expected subsumption are rarely available.

Concurrent logic programs, for example the ones we wrote in CoMingle, similarly come short of availing themselves of the reasoning possibilities of the underlying logic. The consequences are somewhat more dire in this setting as writing concurrent programs is much harder than developing code that does not engage in synchronization. The proliferation and ease of deployment of mobile apps, again often developed by novices, means that there is a lot of buggy code out there, with much more to come.

Even in a large program, a fairly small part of the code of a distributed application is about concurrent interactions, often with recurring patterns (this is particularly evident in CoMingle programs, where inter-node communication and local computation are written in separate languages — CoMingle itself and Java, respectively). We postulate that this is an opportunity for logic-based methods, if not wholesale logical reasoning, to participate in the development of concurrent and distributed applications in the form of formal analysis tools. One promising idea is session types [6], which describe the communication pattern of a program, thereby allowing the implementation of a tool to statically catch messaging errors and deadlocks. Session types are currently limited to relatively simple interactions, but they are rapidly being developed to handle larger classes. Other techniques include logic-based modularity [2], which gives the programmer control over the scope of interactions (in contrast to the traditionally flat name-space of logic programming). One last class of techniques that holds substantial promises in the development of correct concurrent programs specifically is coinductive reasoning, for example in the form of bisimulation. While tools are still in their infancy, the growing realization that many program properties are coinductive in nature are sure to accelerate their development.

What logic programming does is to give the programmer a language that abstracts some idiosyncrasies of the underlying machine, ultimately letting him/her write less code: abstraction, not reasoning, makes small programs easier to get right. But as programs grow, coding complexity
creeps back up, with little available to the programmer to manage it in a typical logic programming language. We postulate that the largely untapped reasoning potential of logic programming in general, and concurrent logic programming in particular, holds the promise of providing assurances that is elusive in other paradigms.

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What Tweety-the-Penguin and Faulty Suitcases Tell Us about Productivity, Cybersecurity and Data Sciences (Abstract)

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The areas of research of commonsense, reasoning about actions and change, and constraint satisfaction have a long-standing tradition in the knowledge representation community. These areas have frequently developed independently of each other, but various forms of their combination have proven extremely useful for practical applications.

In this talk, we aim to convey some sense of the breadth of applications yielded by the research at the intersection of commonsense, reasoning about actions and change, and constraint satisfaction. We will start from our early, and somewhat unexpected, success in solving industrial-sized problems with a planning and diagnostic system for the Space Shuttle, and we will then expand to later work on hybrid reasoning, industrial scheduling, cybersecurity, and information retrieval.
Within the last decade, distributed systems have rapidly evolved from applications that run within local networks, using simple client/server architecture, to applications that run over complex large-scale networks and large-scale platforms across multiple administrative domains and geographical areas. This trend is set to continue with the increased deployment of embedded devices and Internet of Things technologies. Configuring and managing such systems is a significant challenge due to their openness and extensibility, their dynamic nature - new components appear, disconnect or migrate to new locations, and the many different functions for which management is required - failure, security, performance, accounting etc. To address these challenges rigorous and scalable solutions are required, which are able to adapt to the dynamic changes in the system and in the environment in which they operate.

For many years we have been using tools and techniques from AI for tackling management issues of distributed systems and networks working towards the aim of building autonomic management systems and we have seldom found ourselves proposing solutions in which logic programming plays a central role. Below we describe some of the technical challenges underpinning the development of solutions for configuration and management of distributed systems in the context of three different application domains – policy, security and distributed system management – and highlight the advantages that our LP approaches have provided to overcome them. We also briefly describe open issues and suggestions for future research that would lead these results to real industrial applications.

Policies in system management

Policy is a very generic term. In the context of system management, policies define how choices that affect the behaviour of systems should be governed. The aim of policy-based approaches to systems management is to provide a separation of the rules that govern the behaviour of a system from the actual functionality provided by that system [15]. Policy can describe how to handle failure, security, performance, accounting, etc. In our work we have developed dialects of LP for specifying and implementing policy (e.g. [11]), for automated policy analysis (e.g. [17], [3]), conflict resolution (e.g., [7]) and refinement (e.g., [2], [8]). The formalisation of action and change in LP has had tremendous impact in our work.

The earliest work is the event-condition-action PDL introduced in [11]. Its declarative semantics is founded on formal descriptions of action theories based on automata (e.g., [4]). The key challenges were the development of a language that can be (efficiently) implemented, that provides concise representation of policies, and that has a formal (declarative) semantics, a crucial aspect in order to enable automated analysis and conflict detection. In [3], an Event-Calculus language has been proposed to model management policies including authorization policies and uses early results in abductive LP for the analysis of event-based specifications [17] to automatically detect modality conflicts and application specific conflicts in the policies. With abduction not only policy conflicts are detected but also explanations are generated on how these conflicts may arise. The use of
LP and abductive-based solution has helped us formalising the policies in a rigorous manner and consequently reason about their correctness. On the other hand, the challenge presented by dynamic aspects of distributed systems managed by these policies could be hinder by the close world semantic or the notion of existing (fix) background knowledge of an abductive framework. We were able to overcome these limitation by developing a novel multi-threaded distributed abductive algorithm and system [14] that is open in that it can opportunistically make use of dynamic changes of the system configuration during the reasoning process.

One of the most difficult questions in policy management is how to do refinement. In system management, policies are related to high-level system goals (requirements), be these functional or not functional. The challenging task is how to support automated refinement (or generation) of operational policies (e.g., policies that the system is able to enforce) from high-level system requirements. In [2] we have defined policy refinement as a process of realisation of requirements expressed in terms of high-level abstract entities into policies expressed in terms of concrete objects/devices that when performed will achieve the high-level goal. This approach, however, assumes the existence of a complete LP representations of the domain (concrete objects/devices). Again in the context of dynamic systems, where components might “ad-hoc” join or leave the system (e.g. dynamic service composition), or high-level requirements might be changed at run-time, the refinement process would need also to be dynamic. So the key challenge for LP, in this case, would be how to support run-time refinement.

Security

Security (and privacy) is perhaps the area of system management most easily identified with policy-based models and in which LP as modeling tool has had the most impact (e.g. [5],[10]). [3] already touches on issues related to access control in the context of general policies but the work in [8] addresses the challenge of specification and analysis of policy in which the enforcement requires monitoring the system over time. A typical example of these types of policy are obligation that an entity must fulfill in the future in order to obey policy. An LP dialect is used to described policy and an abductive procedure tailored for the analysis is introduced.

In order to avoid conflicts and non determinism, many management systems use ordered sets of rules in their configuration. In such scenarios, the first ”matching” rule is executed whilst the others are ignored; firewall rules being a classical example. Generating configurations that can be directly deployed into existing systems, i.e, without adding additional interpreters requires therefore to synthesise not only the rules but also their ordering, whilst preserving desired properties. We have successfully used argumentation in LP for this purpose to synthesise complete firewall configurations on real examples [1].

Trust Management Systems (TMS) are concerned with distributed access control in which policies defining under what conditions a subject is able to access resources expect to get credentials from the subject prior to evaluation. Reciprocally, the subject may have policies that condition the server providers (of the resources) that the subject will accept. These policies may also need credentials from the server provider before evaluation. Little has been known about system independent formalizations of TM. Recently, a general axiomatization for logic-based trust management with a Kripke model theoretic semantics and a Hilbert-style proof system was introduced in [6]. Our contribution in [16] was to link [6] to results from Miller’s scoping and modules for LP and provide an alternative axiomatization that allowed us to define and implement an ASP-based theorem prover, but most importantly, to establish the computational complexity of doing proofs in this logic.

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Declarative distributed computing

More recently, we have directed our attention to a much broader class of problems in distributed systems and network management, with the aim of developing a general but rigorous framework for formalising distributed algorithms, analysing and reasoning about their correctness in situations where networks are dynamic (e.g. nodes can join and/or leave the network during the execution). These are hard and open problems that are not only relevant in network management but to any application domain that requires distributed computations. Again, building upon theoretical results on reasoning about actions [9], and their translations to causal logics, we have been able to propose a declarative approach to distributed computing called D2C (see [13]). In D2C distributed algorithms can not only be specified as action theories of fluents and actions, but also executed as collections of (input/output) automata, and analysed using the results on connecting causal theories and Answer Set Programming (ASP). The declarative semantics has enabled us to provide automated translation of a distributed algorithm expressed in D2C and the underlying communication model (e.g. synchronous or asynchronous) from the causal logic-based specification into ASP programs, providing a framework for implementation and analysis. We have demonstrated the generality of our declarative approach by showing how it can be used to analyse different classes of network routing protocols, as well as execute distributed algorithms for pattern formation in multi-robot systems [12].

Directions of research

Much can be said about future research but we would like to conclude with just three questions that can be used as discussion points to think about future work:

- Is policy learning an alternative to policy refinement? A better integration of numerical methods and logic programs will be helpful.
- Is the perception that LP/Datalog is not efficient enough for high-throughput applications in security real?
- What does it mean to do distributed logic programming? Is declarative networking the appropriate abstraction - implementations of distributed logic programs.

Key problems common to the above three aspects of future research are the scalability of LP and the close world assumption of the domain. For example, in declarative distributed computing, the analysis of routing protocol, which is known to be an NP-hard problem, if based only on ASP computation can handle only toy networks composed of no more than four nodes. In our experience, it has sometime been the case that the time and space used for grounding a problem are too much to start considering real industrial application problems. The question is how can we improve the scalability and also how can we represent generic domains.

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Applying ASP in Industrial Contexts: Lessons Learned and Current Directions

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Answer Set Programming (ASP) is a declarative programming paradigm that has been proposed in the area of logic programming and nonmonotonic reasoning. ASP has become a popular choice for solving complex problems, as witnessed by the numerous scientific applications that are based on ASP, and it is nowadays attracting increasing interest also beyond the scientific community. We report on the development of some applications of ASP in industrial contexts. We focus on the lessons we have learned and on current developments. We outline the advantages of ASP from the software engineering point of view, and we stress the importance of extending tools and development environments to speed-up and simplify the implementation of real-world applications.

Applying ASP in industrial contexts

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scientific applications in the areas of Artificial Intelligence [2, 18, 3, 14], Bioinformatics [13, 21, 8], and Databases [25, 24, 4, 5, 22], to mention a few. Nowadays, ASP is attracting increasing interest also beyond the scientific community [20, 17], and counts already some successful application in industrial products. In particular, we report on our on-the-field experience in the development of some industrial applications of ASP, namely:

- A platform employed by the call-centers of Italia Telecom, which classifies in real-time the incoming calls for optimal routing.
- A tool for the automatic generation of the teams of employees [26] that has been employed in the sea port of Gioia Tauro for intelligent resource allocation.
- A tool for travel agents for the intelligent allotment of touristic packages [11].
- An ASP-based platform for data cleaning [27] developed for analyzing and cleaning-up the archives of the Italian Healthcare System storing data on tumor diseases.

These applications were implemented by using DLV [23], which is the first ASP system that is undergoing an industrial exploitation by a company, called DLVSYSTEM.

Lessons learned and current directions

A lesson learned by developing real world applications is that ASP allows one to develop complex features at a lower (implementation) price than in traditional imperative languages. Indeed, the possibility of modifying complex reasoning task by editing text files, and testing it “on-site” together with the customer has been often a great advantage of the ASP-based development. ASP can bring several advantages from a Software Engineering viewpoint, and the main qualities are flexibility, readability, extensibility, and ease of maintenance of ASP-based solutions. Nonetheless, in order to boost the adoption of ASP in the scientific community and especially in industry, it is important to provide programming tools that make easier the development of applications. For this reason, we endowed DLV with development tools conceived to ease the usage and the integration of ASP-based technologies in the existing programming environments tailored for imperative/object-oriented languages. In particular, we have developed two tools for developers: ASPIDE [16] and JDLV [15].

ASPIDE is an extensible integrated development environment for ASP, which integrates powerful editing tools with a collection of development tools for program testing and rewriting, database access, solver execution configuration and output-handling. JDLV is a plug-in for Eclipse, supporting a hybrid language that transparently enables the interaction between ASP and Java.

Currently we are working on application-driven improvements of ASP tools. In particular, we are studying means for simplifying the extension of ASP systems with problem-specific heuristics so to speedup the evaluation of very hard real-world problem instances [10]. Our experience in the development of systems and applications of ASP suggests that modifying an ASP implementation is very complex, and can be carried out effectively only by a few expert researchers. On the other hand, the implementation of a good heuristic requires a knowledge about the domain, which is likely to be found on people from industry. Thus, we are working on the extension of the ASP system WASP [1] that allows one to easily plug-in, test and evaluate new domain-heuristics also by software developers working in the industry [10].

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Building Large-scale Knowledge-based Systems with ASP

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Answer Set Programming (ASP) [1] has emerged as a successful paradigm for developing intelligent applications. ASP is based on adding negation as failure to logic programming under the stable model semantics regime [2]. ASP allows for sophisticated reasoning mechanisms that are employed by humans (common sense reasoning, default reasoning, counterfactual reasoning, abductive reasoning, etc.) to be modeled elegantly. Numerous systems have been built to execute answer set programs that are extremely sophisticated and efficient. CLASP is the best representative of these systems [8]. These systems restrict programs to predicates that only have variables and constants as arguments (general structures are not allowed). Answer sets (or stable models) of such programs are computed by grounding the program rules with the (finite) Herbrand universe, suitably transforming it, and then using a SAT solver to compute models of the transformed program. These models of the transformed program are the stable models of the original Answer Set Program. There are many problems with this model-finding approach that rely on a SAT solver:

1. Since SAT solvers can only handle propositional programs, these approaches only work for finitely-groundable programs. That is, programs with structures and lists occurring in arguments of predicates cannot be executed, as grounding of such programs will result in an infinite-sized program (due to the Herbrand universe being infinite). In many instances, lists and structures are essential for representing information.

2. Grounding of the program can lead to an exponential blowup in program size. For programs to be executable in such a system, a programmer has to be aware of how the grounding process works and how the ASP solver works and then they have to write their code in such a way that this blowup is minimized. This places undue burden on the programmer, as the programmer has to have knowledge of the grounding procedure as well as the model-finding process.

3. If the number of constants in the program is large, then a SAT-based approach is infeasible due to the size of the grounded program that will be created. It is next to impossible to build a general-purpose knowledge-based system using such an approach, as such a knowledge-based system will potentially have tens of thousands of constants.

4. SAT-based ASP solvers do not allow reasoning with real numbers.

5. SAT-based model-finding approaches compute the entire model. That is obviously an overkill. Most of the time users are interested in a specific piece of information. Thus, if we have a general purpose knowledge-based system, then the current ASP systems will compute the entire model, i.e., everything that can be inferred from the knowledge-base will be computed.

6. Often, it is hard to isolate the solution that is embedded in the model that is produced by the SAT solver. For example, if one solves the Tower of Hanoi problem using a SAT-based ASP solver, then the answer set will contain a large set of moves that are in the model. One cannot easily isolate the sequence of moves that represent the solution to the problem.
7. Since ASP systems compute the entire model, even a minor inconsistency in a narrow part of the knowledgebase will result in the system concluding that no answer set exists. A practical, large, real-world knowledgebase is very likely going to contain inconsistencies.

We have been working on designing query-driven answer set programming systems [3]. A query-driven system computes the partial answer set that contains the query (thus, it does not compute the entire answer set). Having a query-driven system addresses problems 5, 6 and 7 mentioned above [4], however, issues mentioned in points 1, 2, 3, and 4 above still remain as problems. To alleviate problems 1, 2, 3 and 4 above, we have extended our system to allow general-purpose predicates. Thus, our extended system, called s(ASP), admits answer set programs containing predicates that are allowed to have variables, constants and structures as arguments [5, 6].

Our s(ASP) system does not ground the program. It can be thought of as full Prolog extended with negation-as-failure under the stable model semantics regime [6]. Problem 1, 2, 3, and 4 above are eliminated by s(ASP), since programs do not have to be grounded prior to execution. The s(ASP) system is publicly available [5], and has been used to develop a number of non-trivial applications based on ASP. Some of these applications cannot be executed on traditional ASP systems such as CLASP, as these applications make use of lists and structure to represent information. They have been developed by people who are not experts in ASP. These applications include:

• A system for automatically performing degree audit of a student’s undergraduate transcript at a US University, i.e., automatically determining if a student can graduate with a degree or not. The system represents the graduation requirements laid out in the course catalog as ASP clauses. Use of negation is important for representing these requirements. The system has to make use of lists, and has hundreds of courses that appear as constants in the program (hence its grounding will produce an inordinately large program).

• A system for disease management, particularly, for chronic heart failure. This system automates the 80-page guidelines (that the American College of Cardiology has developed) by representing them in ASP. While the current system can be run under systems such as CLASP due to the number of constants not being too large, the final system that models a doctor’s full knowledge will have quite a few constants, and advanced data-structures may be needed.

• A system that represents high-school level knowledge about cells (in the discipline of biology) as answer set programs. It can answer high-school level questions posed as s(ASP) queries. The goal is to represent the knowledge in the entire introductory biology textbook as an answer set program, and then be able to automatically answer questions that would be asked of a student (the questions have to be translated into ASP queries that are then executed to find the answer).

• A recommendation system for birthday gifts: This system codes a human’s knowledge about friends, level of friendship, a person’s wealth level, generosity level, and hobbies as answer set programs. When queried, the system can recommend a birthday present for a particular friend.

We believe that the ASP paradigm is a very powerful paradigm that allows for complex human thought processes to be elegantly emulated. Complex reasoning patterns that humans use can be elegantly modeled using ASP [7]. However, as argued above, the current model-finding, SAT-solver based approaches are not able to realize the full-power of ASP. We argue that query-driven implementations of predicate ASP are crucial to the paradigm’s success. An additional advantage
of a query-driven approach over model-finding approaches is that in the latter case, everything has
to be modeled in the ASP paradigm, while in the former case both the standard logic programming
paradigm and the ASP paradigm can be made to work together.

Significant progress has been made with the realization of the s(ASP) system, however, consid-
erable amount of research remains to be done. We urge the community to invest effort in developing
query-driven predicate ASP systems.

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Declarative Probabilistic Programming for Program Analysis (Abstract)

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Logic Programming has been successfully used for deriving efficient program analyzers and
model checkers from succinct, high-level specifications. In this talk, we will examine what made logic
programming especially suited for this task. We will survey some of the key technical developments
that helped in these applications. We will also consider extensions to traditional logic programming
semantics and inference techniques to treat probabilistic systems, and describe current work in the
analysis of programs and models that use these extensions.

Horn Clause Solvers for Network Verification

Nikolaj Bjørner, Nuno P. Lopes, and Andrey Rybalchenko, Microsoft Research

We describe our experiences using solvers for Horn clauses with special emphasis on Network
Verification. Z3 is a general purpose theorem prover with a plethora of special purpose engines.
Some of these engines are dedicated to solving Horn clauses. One use Horn clause solving is Symbolic
Model Checking of software. Other uses are for checking reachability properties in packet switched
networks. Stratified Datalog can conveniently encode such properties, where the relations range
over packet headers. Packet headers are in turn bit-vectors. We developed Network Optimized
Datalog (NoD) to solve Horn clauses originating from Network Verification.
Table 1: Summary of Horn clause engines in Z3.

| Application Area                     | Solver       | To handle CHCs with                        |
|--------------------------------------|--------------|-------------------------------------------|
| Software Model Checking              | SeaHorn [5]  | Linear arithmetic, bit-vectors, arrays    |
| Software Model Checking              | Duality [11] | Linear arithmetic and arrays              |
| Software Model Checking              | PDR [6]      | Linear arithmetic                         |
| Network Verification                 | NoD [10]     | Bit-wise operations over bit-vectors      |
| Points-to analysis                   | Finite Domains [7] | Bottom-up Datalog with hash-tables        |
| Cyclic Induction proofs              | Tabulation search | Algebraic data-types and arithmetic      |
| Symbolic execution                   | DFS SLD resolution | Quantifier free SMT constraints       |
| Bounded Model checking               | Bounded BFS unfolding | Quantifier free SMT constraints       |

Horn Clause Engines in Z3

This position paper highlights specialized support for logic program analysis in the context of Z3 [2]. Our main applications of Horn clause solving with Z3 are currently around software model checking and network verification. Z3 solves satisfiability of first-order logical formulas modulo a set of built-in theories, such as linear real and integer arithmetic, machine arithmetic (bit-vectors) and algebraic data-types. For the special case where formulas are Constrained Horn Clauses (CHCs), Z3 admits dedicated engines for solving satisfiability of these formulas. The available use cases are summarized in Table 1.

By a CHC, we understand a formula of the form ∀⃗x : head(⃗x) ← body(⃗x), where head is either a predicate \( p(⃗x) \), or the logical constant \( \text{false} \), and body is \( q_1(⃗x_1) \land ... \land q_n(⃗x_n) \land \varphi(⃗x) \) \((n \geq 0)\), where \( q_i \) are predicate symbols taking different subsets of \( ⃗x \) as arguments and all functions and predicates in \( \varphi \) are interpreted in a background theory. For example, \( \varphi \) could be of the form \( x + 2 \cdot y > 4 \), where the meaning of \( +, \cdot, > \) are defined by the standard model for arithmetic.

The engines summarized in Table 1 apply to different classes of Horn formulas. They also use widely different engines. These engines range from using interpolations to encode classes of failed SLD resolution proofs, bottom-up Datalog for finite domains using explicit hash-tables or using tables that are encoded symbolically, to SLD resolution with tabulation. For finite domains, the Z3 Datalog engine supports stratified negation. As a default table representation it uses hash-tables with column indexes, which is suitable for domains where tables remain relatively small (up to a few million entries). For networking, it encodes tables symbolically. The idea with tabulation search is to establish that there are no derivations of \( \text{false} ← \text{body} \), but creating goals from the predicates in \( \text{body} \), and carrying along the side constraints from the interpreted formulas. Sub-goals that are found to be subsumed by previous sub-goals are discarded.

Methods that are suitable for software model checking are described in depth in [1]. Program analysis by reduction to logic program analysis has received steady attention from the program analysis [13] and program verification communities [4]. A common trait of these methods is that they look for symbolic solutions to Horn clauses. In a nutshell, a symbolic solution is a definition of the free predicates using interpreted formulas. For example, if a CHC is of the form \( \forall ⃗x, ⃗y : p(⃗x) ← q(⃗y) \land \varphi(⃗x, ⃗y) \), then a symbolic solution are formulas \( \psi_p(⃗x) \) and \( \psi_q(⃗y) \), such that the formula \( \forall ⃗x, ⃗y : \psi_p(⃗x) ← \psi_q(⃗y) \land \varphi(⃗x, ⃗y) \) is valid modulo a background theory. Symbolic solutions correspond to inductive invariants from Hoare Logic. As a general takeaway, we show that all stan-

\[1\] The last three cases are un-tuned and are rarely used.
standard transformations on Horn clauses, such as Magic transformations, in-lining for K-indutiveness, partial assertion in-lining, and fold-unfold transformations preserve inductive invariants modulo interpolation. That is, each transformation also comes with a (cheap) method for translating symbolic solutions of the original Horn clauses to solutions of the transformed ones. Conversely, solutions to the transformed systems can be translated to solutions to the original clauses when the background theory admits Craig interpolation. Some transformation methods were invented in the context of symbolic model checking. For example, K-induction is a widely used method where the invariant is shown to hold in the first $K$ steps, and then it is shown inductive by assuming it holds in the previous $K$ steps. Property Directed Reachability (PDR), was invented for finite state machine (hardware) model checking, we imported it to Horn clauses with theories. This allows going beyond finite state machines and model programs with procedure calls. A clear appeal of using Horn clauses is that they offer a well defined interchange format between tool layers that handle details specific to a programming language in one end, and symbolic solving engines in the other end.

Network Verification and Logic Programming

Networking and logic programming are no strangers [9, 8]. In the context of Z3, we developed a special purpose engine for verifying packet based forwarding. Our engine is called NoD (Network optimized Datalog). NoD is currently used as part of the Batfish tool [3] that checks reachability properties in wide area networks that are configured using BGP and OSPF. One of the inherent challenges with using distributed routing protocols, such as BGP and OSPF, is that the routes are computed without reference to network access control lists (ACLs). NoD checks that the ACLs are placed in a consistent way.

The table representation in NoD represents sets of bit-vectors using don’t care bits. For example, the two bit-vectors 101 and 111 can be represented using just one ternary bit-vector $1 \star 1$. The representation also includes set-difference operations, such that $10, 00, 11$ is represented by $11 \{\star \star \}$. The use of ternary bit-vectors for packet-switched network analysis was chosen because the main operations performed on packets are bit-masking and updates to ranges of bits. These operations easily map to set operations on ternary bit-vectors.

Technological Barriers and Aspirations

There are many possible extensions and improvements of Z3’s Horn clause engines. For symbolic model checking we found that a notion of model-based projection to be useful. It amounts to partial quantifier elimination that use ground models as a starting point. When coupled with proof-based half-interpolation it offers a powerful combination that applies to several theories, such as integer, real arithmetic, arrays, polynomial real arithmetic, and algebraic data-types. There are many unexplored extensions to using model-based projection with proof-based interpolation. Our engines for finite domains currently do not mix well with engines that are suitable for infinite domains. Abstract interpretation offers hints of one approach, using reduced products, but our current use of reduced products have not been successful in meshing SMT with abstract interpretation approaches.

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Logic Programming: from NLP to NLU?

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Natural Language Processing (NLP) was one of the original motivations leading to programming in logic [9] back in the seventies, with Colmerauer’s Metamorphosis Grammars [2] and with Pereira and D.H.D Warren’s Definite Clause Grammars [17], enhanced later with mechanisms for hypothetical reasoning [5]. Montague Grammars (implemented in Prolog by D.S. Warren [19]) and work by Veronica Dahl on defining logic representations for more realistic fragments of natural languages (including long distance dependencies and anaphora resolution) [4] have all shown a penchant of Logic Programming towards the higher objectives of Natural Language Understanding (NLU).

After being long delayed (and partly frozen by the AI winter) recent progress in NLU promises to bring disruptive paradigm shifts in human-computer interaction and several directly and indirectly related industries. In fact, hopes for more logic-based NLU are high again, partly due to the possibility of sharing successful technologies and tools with successful fields like deep-learning neural-networks, machine learning, statistical parsers and graph-based NLP.

This brings us to the obvious question: what new role can logic programming play in this new context?

When trying to sketch an answer, after more than a decade spent on other research topics, we became aware that one can benefit today from the extended logic programming ecosystem, consisting of classic tools like Prolog, constraint solvers, Answer-Set Programming and SAT/SMT systems, as well as machine learning techniques implemented on top of inductive and probabilistic logic programming [6].

One of the research directions we have worked on in the past, that turned out to be remarkably successful, is graph-based NLP. It has originated in a Prolog program that was using WordNet’s semantic links to improve word-sense disambiguation (WSD) [14], by building a graph connecting words, sentences with their semantic equivalence classes (synsets) and then guessing the most likely sense associated to a word, by running the PageRank algorithm [16] on the graph. A few months later, an unsupervised version of the algorithm [13] based on graphs connecting sentences to word occurrences has been shown to extract high quality summaries and keywords. It later became one of the most popular techniques for the task [15], implemented in virtually all widely used programming languages and several NLP libraries.

While recently revisiting the topic, it became clear that involving logic programming tools is likely to enhance graph based NLP. The use of logic-based implementations of Combinatorial Categorial Grammars (CCGs) looks especially appealing as it provides lexicalized representations easier to correlate with words and word phrases. The NLU-component coming from extracting logic representations is likely to make the links in the graph structure more meaningful.

A simple reducer for a subset of CCG rules looks as follows:

```prolog
:-op(400, xfx, (/)).
:-op(400, xfx, (\)).
red(Xs):-red(Xs,s). % reduce a sentence to root symbol s.
```
Interestingly, Prolog’s DCGs can be used to build the CCGs representation of a sentence as in:

```
the -->[np/n].
cat -->[n].
chased -->[(s/np)\np].
dog -->[n].
playful --> [n/n].
quiet -->[n/n].
quick -->[n/n].
and --> [X/X].
```

```
sent-->the,quick,and,playful,dog,chased,the,quiet,cat.
```

When executed it accepts a sentence as follows:

```
?- sent(S,[I]),red(S).
S = [np/n, n/n, n/n, n/n, n, (s/np)\np, np/n, n/n, n] .
```

More elaborate parsers can be built using CYK or \textit{A*} parsers and tools like tabling in Prolog provide the means to do that efficiently. Interestingly, the CCG parsing problem can also be nicely expressed and executed directly with Answer Set Programming tools as shown in [12].

Tools like the \textit{boxer} program [1] can, in combination with a statistically trained CCG parser like [3], build Prolog clauses describing semantically labeled first-order formulas representing input sentences, ready to be further explored with standard and probabilistic logic programming algorithms as well as graph based algorithms exploiting the richer link structure between their underlying concepts.

An emerging field in NLP these days is sentiment analysis, as knowing what the opinion of an author is about a topic is as important and knowing what a document is about. Modalities and negation detection provided by a logic component combining syntactic and semantic parsing can improve sentiment analysis. Figuring out the implicit entailment links important for understanding a story line or the rhetorical structures involved in an argument is also likely to benefit from logic representations.

Another NLU-minded application we have worked more than a decade or ago is the use of Prolog-based natural language-enabled agents [18]. They interacted with the Prolog version of WordNet and Google’s metasearch API to bring in knowledge distributed over the internet. The integration of logic inferences and a Prolog representation (as dynamic clauses or backtrackable assumptions [5]) of the agents’ short-term memory, have significantly enhanced the quality of the dialog, with shared virtual worlds and interactive story telling systems developed on top of them [8, 7]. These days, fields like interactive story telling have become an integral part of computer games (e.g., Minecraft Story Mode) and voice-enabled software agents are part of major mobile phone (e.g., Siri, Cortana, Google Ok) and platforms are making their way in home automation systems (e.g., Alexa) and more generally in the upcoming Internet-of-Things (IOT) platforms.

Revisiting some of the logic programming-based NLP tools we have used in the past, can today benefit from access to improved metasearch as well as massive online knowledge repositories.
like Wikipedia. Involving constraint programming libraries, now part of most widely used Prolog systems is likely to improve the speed and the accuracy of WSD, an important NLU component. Involving SAT-solvers and ASP-based systems can help narrowing down some of the heavily combinatorial aspects related to the inherent ambiguity of natural language, as well as in dealing with incomplete or noisy information streams one faces in voice and image recognition tasks.

Finally this brings us to the possible synergies between logic programming and deep-learning neural network technologies \cite{11}, credited for the new “AI-Spring”, brought by successful applications to popular fields like vehicle automation, vision and internet search. Tools like Google’s TensorFlow and word2vec \cite{10} are specifically focused on enabling extensions transforming quantitatively represented meaning fragments into more human-friendly logic representations, ready for inference steps that reveal implicit connections between facts and events. Integrating logic programming components with this family of tools, possibly involving the quantitative means provided by probabilistic logic programming opens the door for being part of this the re-emergence of AI-based techniques in new application domains.

Of special practical interest are logical formalisms based on lexicalized natural language representations (e.g., CCGs) that are likely to enable interaction at word level between symbolic and connectionist representations. As the same lexicalized representations can also enable synergies with graph-based methods in natural language processing \cite{15}, we expect a significant practical impact from logic programming tools bringing together these NLP fields.

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