

Answer Set Programming in a Nutshell

Thomas Eiter

Institute of Information Systems
Vienna University of Technology (TU Wien)



eiter@kr.tuwien.ac.at

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Talk Outline

1. Introduction
2. Answer Set Semantics
3. Related Formalisms
4. Answer Set Solvers
5. ASP Extensions
6. ASP Applications
7. Conclusion

Introduction

- Answer Set Programming (ASP) is a recent problem solving approach
- The term was coined by Vladimir Lifschitz [1999,2002]
- Proposed by other people at about the same time, e.g. [Marek and Truszczyński, 1999],[Niemelä, 1999]
- It has roots in KR, logic programming, and nonmonotonic reasoning
- At an abstract level, relates to SAT solving and CSP.
- Book: [Baral, 2002]

Non-Monotonic Logic Programming

- “War of Semantics” in Logic Programming (1980/90ies):
Meaning of programs like $a \leftarrow \text{not } b$, $b \leftarrow \text{not } a$?
- Great Schism: Single model vs. multiple model semantics
- To date:
 - *Well-Founded Semantics* [van Gelder *et al.*, 1991]
 - *Stable Model Semantics (aka Answer Set Semantics)* by Gelfond & Lifschitz [1988,1991].
- Shift in LP: *Answer Sets (=models)*, not proofs, *represent solutions!*
- Need techniques *to compute models* (not proofs)
- Concerted European-level effort:

WASP

Working Group on Answer Set Programming,
IST-2001-37004, 2002-2005

ASP Paradigm

General idea: stable models are solutions!

Reduce solving a problem instance I to computing stable models of an LP



- 1 **Encode** I as a (non-monotonic) logic program P , such that solutions of I are represented by models of P
- 2 **Compute** some model M of P , using an ASP solver
- 3 **Extract** a solution for I from M .

Variant: Compute multiple models (for multiple / all solutions)

Nonmonotonic Logic Programs

- A *normal logic program* P is a (finite) set of rules of the form

$$a \leftarrow b_1, \dots, b_m, \text{not } c_1, \dots, \text{not } c_n$$

where all a, b_i, c_j are literals of the form p or $\neg p$, where p is a first-order atom from a (classical) FO signature.

In **standard ASP**, no function symbols are allowed;

- “ \neg ” is called strong negation (also written as “ $-$ ”)
 - a may be missing (*constraint*, see later)
- In *disjunctive programs*, the rule head may be a disjunction $a_1 \vee \dots \vee a_k$ of literals
- Notation: $HB_P =$ set of all ground (variable-free) literals p and $-p$ with predicates and ground terms constructible from P .

Answer Sets

- The Answer Set semantics is based on 3-valued Herbrand Models (=consistent sets of ground literals $M \subseteq HB_P$), with incomplete information of the world
- For programs without “–,” they are also called “stable models” and viewed 2-valued, with complete information of the world
- M satisfies a ground rule

$$a_1 \vee \dots \vee a_k \leftarrow b_1, \dots, b_m, \text{not } c_1, \dots, \text{not } c_n \quad (1)$$

if $\{b_1, \dots, b_m\} \subseteq M$ and $M \cap \{c_1, \dots, c_n\} = \emptyset$ implies $M \cap \{a_1, \dots, a_k\} \neq \emptyset$.

- M satisfies ground program P , if M satisfies each $r \in P$.

Answer Sets (ctd.)

- **Key:** elimination of negation

Gelfond-Lifschitz (GL) reduct P^M

Given program P , remove from the grounding of P , $ground(P)$,

- 1 every rule of form (1) where some c_i is in M , and
 - 2 all literals *not* c_j from the remaining rules.
- M is an *answer set* of P iff M is a minimal model of P^M (wrt. \subseteq).
 - Such M satisfies all rules, intuitively P justifies each atom in M .
 - Note for non-disjunctive P , “a minimal” = “the least”
 - Many equivalent definitions of answer set / stable model exist

Example

$$P = \{ \text{person}(\text{joey}); \\ \text{male}(X) \vee \text{female}(X) \leftarrow \text{person}(X); \\ \text{bachleor}(X) \leftarrow \text{male}(X), \text{not married}(X) \}$$

- $M_1 = \{\text{person}(\text{joey}), \text{male}(\text{joey}), \text{bachelor}(\text{joey})\}$ is stable
- $M_2 = \{\text{person}(\text{joey}), \text{male}(\text{joey}), \text{married}(\text{joey})\}$ is not stable

In general, no, one, or multiple stable models exist.

Further stable model:

- $M_3 = \{\text{person}(\text{joey}), \text{female}(\text{joey})\}$

Inconsistent Programs

- Consider the program

$$\{ p \leftarrow \text{not } p. \}$$

- This program has NO answer sets
- Let P be a program and p be a new atom
- Adding

$$p \leftarrow \text{not } p.$$

to P “kills” all answer sets of P

Constraints

■ Adding

$p \leftarrow q_1, \dots, q_m, \text{not } r_1, \dots, \text{not } r_n, \text{not } p.$

to P “kills” all answer sets of P that:

- contain q_1, \dots, q_m , and
- do not contain r_1, \dots, r_n

■ Short:

Constraint

$\leftarrow q_1, \dots, q_m, \text{not } r_1, \dots, \text{not } r_n.$

Strong Negation

- Strong negation “ \neg ” is provided as possibility to express that something is provable false.
- This is different from negation as failure

Example

“At a railroad crossing, cross the rails if no train approaches.”

$walk \leftarrow at(L), crossing(L), not\ train_approaches(L).$

$walk \leftarrow at(L), crossing(L), \neg train_approaches(L).$

- As for expressiveness “ \neg ” is easily compiled away; for every predicate p ,
 - replace $\neg p$ by a fresh predicate p_{\neg} .
 - add the constraint $\leftarrow p(\vec{X}), p_{\neg}(\vec{X}).$

Exploiting Nondeterminism: Reviewer Selection

- (1) $paper(p_1); paper(p_2);$
- (2) $cand("Thomas", p_1); cand("Enrico", p_2); cand("Marco", p_2);$
- (3) $assign(X, P) \leftarrow cand(X, P), not \text{ } \neg assign(X, P);$
- (4) $\neg assign(X, P) \vee \neg assign(Y, P) \leftarrow cand(Y, P), cand(X, P), X \neq Y;$
- (5) $is_assigned(P) \leftarrow assign(X, P);$
- (6) $\leftarrow paper(P), not is_assigned(P).$

Use disjunction in choice (3)+(4)

Answer sets:

$$M_1 = \{ \dots, assign("Thomas", p_1), assign("Enrico", p_2), \neg assign("Marco", p_2) \};$$

$$M_2 = \{ \dots, assign("Thomas", p_1), assign("Marco", p_2), \neg assign("Enrico", p_2) \};$$

Reviewer Selection: Cyclic Negation

- (1) $paper(p_1); paper(p_2);$
- (2) $cand("Thomas", p_1); cand("Enrico", p_2); cand("Marco", p_2);$
- (3) $assign(X, P) \leftarrow cand(X, P), not \neg assign(X, P);$
- (4) $\neg assign(Y, P) \leftarrow cand(Y, P), assign(X, P), X \neq Y;$
- (5) $is_assigned(P) \leftarrow assign(X, P);$
- (6) $\leftarrow paper(P), not is_assigned(P).$

(3)+(4): Choice of one element using unstratified rules (cyclic negation)

Answer sets:

$$M_1 = \{ \dots, assign("Thomas", p_1), assign("Enrico", p_2), \neg assign("Marco", p_2) \};$$

$$M_2 = \{ \dots, assign("Thomas", p_1), assign("Marco", p_2), \neg assign("Enrico", p_2) \};$$

Some Properties of Answer Sets

Minimality, Non-monotonicity

Every answer set M of P is a minimal model of P (wrt. \subseteq).

E.g. $P = \{a \leftarrow \text{not } b\}$: $M = \{a\}$ $P \cup \{b \leftarrow\}$: $M = \{b\}$

Supportedness

Given an answer M of P , for every literal $a \in M$ there is some rule r from $\text{ground}(P)$ s.t. $M \models \text{Body}(r)$ and $M \cap \text{Head}(r) = \{a\}$.

But: stable \neq minimal + supported! E.g. $P = \{a \leftarrow b; b \leftarrow a; a \leftarrow \text{not } a\}$

Generalization of Stratified Semantics:

If a normal P is “-”-free and “not” is layered (“ P is stratified”), then P has a unique answer set, which coincides with the perfect model.

Failure of Cumulativity

From $a \in M$, for each answer set M of P , it does not follow that P and $P \cup \{a \leftarrow\}$ have the same answer sets (even if P has answer sets).

Computation / Complexity Issues

- For model computation, the following questions are of primary interest:

- 1 Computing some stable model of a given program P .
- 2 Computing all stable models of a given program P .
- 3 Given M and P , is M a stable model of P ?
- 4 What search problems can be expressed by ASP?

- Following “classical” complexity theory, 1 and 2 have been reshaped as decision problems (does there exist some / yet another stable model)
- Problem 4 requires to resort to “nontraditional” complexity theory cf. [Marek and Remmel, 2003].
- Survey: [Dantsin *et al.*, 2001]

Basic Results

Theorem

Deciding whether a normal logic program P has some stable model is

- NP-complete in the propositional case;
 - NEXPTIME-complete in the datalog (function-free) case;
 - Σ_1^1 -complete in the general first-order case.
-
- Similar results hold for deciding,
 - given P and a collection \mathcal{C} of its stable models, whether P has some stable model $M \notin \mathcal{C}$;
 - given P and a ground atom a , whether $a \in M$ for some stable model M of P (brave reasoning)
 - Cautious reasoning ($a \in M$ for *all* stable models of P) has complementary complexity.

Complexity: FO Logic Programs

Theorem

Deciding whether a normal logic program P with function-symbols has some stable model is Σ_1^1 -complete.

Rough Sketch (for more, see [Schlipf, 1995]):

- Stable model existence of program P can be expressed by an existential second-order sentence Φ of form

$$\exists \mathbf{T} \forall \mathbf{x} \exists \mathbf{y} \phi(\mathbf{T}, \mathbf{x}, \mathbf{y}),$$

where $\phi(\mathbf{T}, \mathbf{x}, \mathbf{y})$ is quantifier-free first order.

- Conversely, every Σ_1^1 sentence is equivalent to a sentence Φ of this form (by second-order Skolemization)
 Φ can be expressed (over the Herbrand universe) by stable model existence.

Complexity: FO Logic Programs /2

- Suppose wlog $\phi_i(\mathbf{T}\mathbf{x}, \mathbf{y}) = \bigvee_{i=1}^n \phi_i(\mathbf{T}, \mathbf{x}, \mathbf{y})$ is in DNF.
- Then, the program

$$\begin{aligned}
 T(\mathbf{x}) &\leftarrow \textit{not } T'(\mathbf{x}) && \text{for each } T \in \mathbf{T} \\
 T'(\mathbf{x}) &\leftarrow \textit{not } T(\mathbf{x}) \\
 \textit{sat}(\mathbf{x}) &\leftarrow \phi_i^*(\mathbf{T}, \mathbf{x}, \mathbf{y}) && \text{for each } i = 1, \dots, n \\
 \textit{sat}(\mathbf{x}) &\leftarrow \textit{not } \textit{sat}(\mathbf{x}) \\
 \textit{eq}(x, x) &\leftarrow
 \end{aligned}$$

where $\phi^*(\mathbf{T}, \mathbf{x}, \mathbf{y})$ is $\phi(\mathbf{T}, \mathbf{x}, \mathbf{y})$ but

- “ \neg ” is replaced by “*not*”, and
- “ $=$ ” is replaced by “*eq*” (if present),

has some stable model iff Φ is true on its Herbrand universe.

Complexity of Disjunctive Stable Models

Theorem

Deciding whether a disjunctive logic program P has some stable model is

- Σ_2^P -complete in the propositional case;
 - $\text{NEXPTIME}^{\text{NP}}$ -complete in the datalog case;
 - Σ_1^1 -complete in the general first-order case.
-
- Note: no complexity increase in the full FO case (!)
 - Disjunction can be compiled away:
 - Express stable model existence as $\exists \mathbf{M} \forall \mathbf{M}' \psi(\mathbf{M}, \mathbf{M}')$, where ψ is a Boolean combination of existential sentences.
 - rewrite to $\exists \mathbf{M} \forall \mathbf{x} \forall \mathbf{M}' \exists \mathbf{y} \psi'(\mathbf{M}, \mathbf{x}, \mathbf{M}', \mathbf{y})$, where ψ' is quantifier-free.
 - Emulate Arithmetic to express $\forall \mathbf{M}' \exists \mathbf{y} \psi'$ in FOL.

Expressiveness over Finite Structures

- Recall:

Fagin's Theorem

Over finite relational structures, $\Sigma_1^1 = \text{NP}$

- Stable models have balanced expressiveness

Theorem

Over finite relational structures, stable model existence for

- normal logic programs = NP [Schlipf, 1995]
- disjunctive logic programs = Σ_2^P [Eiter *et al.*, 1997a]

- Note: similar results hold for brave reasoning;
- For disjunctive logic programs, negation can be even restricted to equality and input relations!

ASP vs. Prolog

■ ASP features “pure” declarative programming

Under answer set semantics,

- the order of program rules does not matter;
- the order of subgoals in a rule does not matter;
- termination is not an issue.

■ Nondeterminism in ASP: Possibility to make guesses

■ But: function symbols are banned from standard ASP solvers

- Simple Horn LPs with function symbols are undecidable
- Some decidable fragments: ω -restricted programs, finitary programs, finitely recursive programs, FDNC programs ...

see e.g. [Baselice *et al.*, 2007], [Bonatti and Baselice, 2008], [Calimeri *et al.*, 2008] (DLV-complex), [Šimkus and Eiter, 2007]

Relationship to SAT

- Answer sets of a LP P are particular classical models of P
- Clarke aimed at characterizing the model of a (monotonic) normal program P by syntactic “completion” $Comp(P)$ [Clark, 1978]

Example

$$P = \{p \leftarrow q\}; \quad Comp(P) = \{p \leftrightarrow q, q \leftrightarrow \perp\}$$

- $Comp(P)$ captures the stable models of a normal LP P , if P is *tight* (= acyclic positive recursion in M).
- Does not hold in general

Example

$$P = \{p \leftarrow q, q \leftarrow p\}; \quad Comp(P) = \{p \leftrightarrow q, q \leftrightarrow p\}$$

$Comp(P)$ doesn't capture the single stable model $M = \{p, q\}$;

Note: P is not tight in M .

Relationship to SAT (ctd.)

- With additional *loop formulas* $LF(P)$, it is possible to capture the stable models [Lin and Zhao, 2002].

Stable models = completion + loop formulas

Intuitively, $LF(P)$ contains clauses enforcing that truth of atoms in a cycle must be supported from an atom outside.

Example (ctd.)

$$\begin{array}{l}
 P_1 = \{ p \leftarrow q \}: \quad LF(P_1) = \top \qquad \text{Comp}(P_1) \cup LF(P_1) \equiv p \leftrightarrow q \\
 P_2 = \{ p \leftarrow q, \quad LF(P_2) = p \wedge q \supset \perp \quad \text{Comp}(P_2) \cup LF(P_2) \equiv \neg p \wedge \neg q \\
 \qquad \qquad q \leftarrow p \}:
 \end{array}$$

- Also feasible for disjunctive programs + non-propositional program [Lee and Lifschitz, 2003], [Chen *et al.*, 2006].
- Based on this, some ASP solvers employ SAT solvers.
- Downside: exponentially many loop formulas in general

Relationship to SAT (ctd.)

- Benefits of ASP over SAT:
 - Transitive closure expressible
 - Express, to some extent. reasoning about multiple models
 - “high level”,
 - predicates, rules, negation as failure, many constructs
- Comparisons of ASP/SAT Efficiency
e.g., [Cadoli *et al.*, 2006], [Arieli *et al.*, 2004]
- Also relationship to / coupling with CSP has been explored
e.g., [Baselice *et al.*, 2005]
- Some ASP systems (e.g. aspps) are strongly constraint driven.
- Constraints play an important role in model search

Relationship to Non-Classical/Non-monotonic Logics

■ **Nonmonotonic Logics:**

Close relationship to other standard logics/formalisms in Nonmonotonic Reasoning (Autoepistemic Logic, Circumscription, Default Logic)

Normal Logic Programs under Answer Set Semantics can be considered as a Fragment of Reiter's Default Logic [Gelfond and Lifschitz, 1991]

■ **McDermott-style Nonmonotonic Modal Logics**

Close relationship to nonmonotonic Logic K45 [Marek and Truszczyński, 1993]

■ **Equilibrium Logic** [Pearce, 2006],[Pearce and Valverde, 2006]

Reconstruction of Answer Set Semantics in terms of the *Logic of Here and There*

Answer Set Solvers

- NP-/ Σ_2^p -completeness: Efficient computation of answer sets is not easy!
- Need to handle, for applications
 - 1 complex data (large data volumes)
 - 2 search
- Efforts to realize tractable fragments
- Many ASP solvers are available (function-free programs)

Approach:

- Logic programming and deductive database techniques (for 1.)
- SAT/Constraint Programming techniques for 2.

Different sophisticated algorithms have been developed
(like for SAT solving)

Answer Set Solvers

| | |
|------------|---|
| DLV | http://www.dbai.tuwien.ac.at/proj/dlv/ * |
| Smodels | http://www.tcs.hut.fi/Software/smodels/ ** |
| GnT | http://www.tcs.hut.fi/Software/gnt/ |
| Cmodels | http://www.cs.utexas.edu/users/tag/cmodels/ |
| ASSAT | http://assat.cs.ust.hk/ |
| NoMore(++) | http://www.cs.uni-potsdam.de/~linke/nomore/ |
| Platypus | http://www.cs.uni-potsdam.de/platypus/ |
| clasp | http://www.cs.uni-potsdam.de/clasp/ |
| XASP | http://xsb.sourceforge.net , distributed with XSB v2.6 |
| aspps | http://www.cs.engr.uky.edu/ai/aspps/ |
| ccalc | http://www.cs.utexas.edu/users/tag/cc/ |

* + extensions, e.g. DLVEX, DLVHEX, DLV^{DB}, DLT, DLV-complex ** + Smodels_cc

- Several provide a number of extensions to the language described here.
- Answer Set Solver Implementation: see Niemelä's ICLP'04 tutorial.
- ASP Solver competition: see LPNMR 2007 conference;
- ASPARAGUS Benchmark platform <http://asparagus.cs.uni-potsdam.de/>

Architecture of ASP Solvers

Typically, a two level architecture

1 Grounding Step:

Given a program P with variables, generate a (subset) of its grounding which has the same models

2 Model Search:

More complicated than in SAT/CSP Solving:

- Candidate generation (classical model)
- model checking (stability!)
 - for SAT, model checking is in ALOGTIME
 - for normal programs, model checking is P-complete
 - for disjunctive programs, model checking is coNP-complete

Grounding Step

- Efficient grounding is at the heart of current systems
- Sophisticated techniques
 - DLV's grounder (built-in);
 - lparse (Smodels), gringo (clasp)
 - XASP, aspps
- Special techniques used:
 - “*Safe rules*” (DLV); every variable in a rule must occur on a unnegated atom in the body, whose predicate is not = or any another built-in predicate
 - *domain-restriction* (Smodels)
- Problem: Grounding bottleneck [Eiter *et al.*, 2007]
Research on nonground evaluation (e.g., You *et al.*, Schaub *et al.*);
XASP (XSB Extensions)

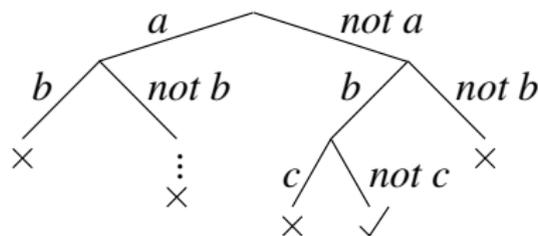
Model search

- Applied for ground programs.
- Different Techniques:
 - Translations to SAT (e.g. Cmodels, ASSAT)
 - tailored search procedures (Smodels, DLV, NoMore, aspps, clasp)

$a:- \text{not } b.$

$b:- \text{not } a.$

$c:- \text{not } c, a.$



- Backtracking procedures for assigning truth value to atoms
- Similar to DPPL algorithm for SAT
- Important: Heuristics (which atom/rule to consider next); involved
- Stability check: unfounded sets, reductions to UNSAT

ASP Extensions

- Many extensions have been proposed, partly motivated by applications
- Some are syntactic sugar, other strictly add expressiveness
- Incomplete list:
 - nested expressions
 - cardinality constraints (Smodels)
 - optimization: weight constraints, *minimize* (Smodels); weak constraints (DLV)
 - aggregates (Smodels, DLV)
 - templates (for macros, DLT), external functions (DLVEX, DLVHEX)
 - Frame Logic syntax (for Semantic Web)
 - preferences: e.g., PLP, ordered programs
 - KR frontends (diagnosis, abduction, planning,...) in DLV
- Comprehensive survey of extensions (2005):
<http://www.tcs.hut.fi/Research/Logic/wasp/wp3/>

Weak Constraints

- Allow the formalization of optimization problems in an easy and natural way.
- Constraints vs. weak constraints:
 - Constraints “kill” unwanted models;
 - Weak constraints express desiderata which should be satisfied, if possible.
- The answer sets of a program P with a set W of weak constraints are those answer sets of P which minimize the number of violated constraints.
- Such answer sets are called *optimal or best models of (P, W)* .
- Other solvers feature similar constructs.

Guess-Check-Optimize Methodology

- Complements a natural “Guess & Check” Methodology
- Use weak constraints to filter out best (optimal) solutions
- Divide P into three main parts:

Guessing Part

$G \subseteq P$: The answer sets of $G \cup F_I$ represent “solution candidates” for instance I .

Checking Part (optional)

$C \subseteq P$: The answer sets of $G \cup C \cup F_I$ represent the admissible solutions of I .

Optimization Part (optional)

The optimization part $O \subseteq P$ consists of weak constraints, and defines an objective function $f : \text{Answer_Sets}(G \cup C \cup F_I) \rightarrow \mathbb{N}$.
The answer sets minimizing f are selected.

Employee Assignment

- Goal: Divide employees in two project groups p_1 and p_2 .
 - 1 Skills of group members should be different.
 - 2 Persons in the same group should not be married to each other.
 - 3 Members of a group should possibly know each other.
- Requirement 1) is more important than 2) and 3), which are equally important
- Layers $[:x]$ express the relative importance of the requirements.
- ASP Solution (DLV) [Leone *et al.*, 2006]

```
assign(X,p1) v assign(X,p2) :- employee(X).  
:~ assign(X,P), assign(Y,P), same_skill(X,Y).      [:2]  
:~ assign(X,P), assign(Y,P), married(X,Y).         [:1]  
:~ assign(X,P), assign(Y,P), X!=Y, not know(X,Y). [:1]
```

ASP Applications

Problems in different domains, see

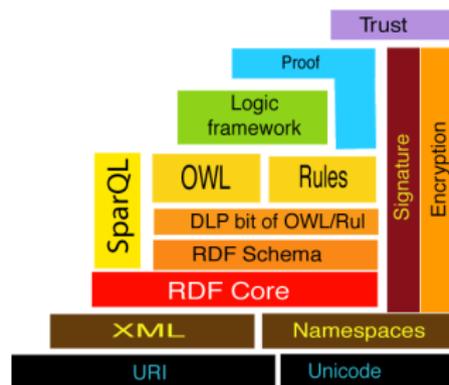
<http://www.kr.tuwien.ac.at/projects/WASP/report.html>

- information integration
- constraint satisfaction
- planning, routing
- diagnosis (e.g., Space shuttle reaction control [Nogueira *et al.*, 2001])
- security analysis
- configuration
- computer-aided verification
- biology / biomedicine
- knowledge management
- ...

ASP Front-Ends

- Some systems/groups offer *front-ends* for specific applications
- These frontends might be built-in or on top of an underlying ASP system
- DLV, e.g., offers a range of frontends
 - diagnosis
 - planning
 - inheritance reasoning
 - SQL3
 - ...
- Development of frontends for applications is a major research stream in ASP

ASP for the Semantic Web



- *RDF (Resource Description Framework)* is the SW data model
- RDF Schema enriches RDF by simple taxonomies and hierarchies
- More expressive: *OWL (Web Ontology Language)* which builds on Description Logics
- Rule languages: *Rule Interchange Format (RIF)* WG of W3C
- ASP in this context: see [Eiter, 2007]

ASP around Ontologies

- Different ways to exploit ASP and ASP techniques for ontologies:
 - **as a host language for ontology reasoning tasks**
 - Mapping / encoding of ontologies and DLs into ASP
 - Encoding of web query languages
 - **for (ad hoc) ontology management:** alignment, integration, merging, etc
 - **as a component for adding / integration rules with ontologies**
- Several extensions of ASP are geared towards this, e.g.,
 - Open Answer Set Programs [Heymans *et al.*, 2007]
 - Stable model theory for Rules on RDF/S: [Analyti *et al.*, 2005]
 - Nonmonotonic dl-programs / NLP-DL [Eiter *et al.*, 2008]
 - HEX programs /DLVHEX [Eiter *et al.*, 2005]
 - ONTODLP / ONTODLV [Calimeri *et al.*, 2003], [Ricca *et al.*, 2008]

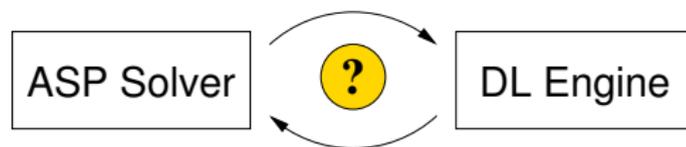
Combining Rules and Ontologies

- Major Issue: Combining rules and ontologies (logic framework)
- ASP and ontology formalisms like RDF/s, OWL resp. Description Logics have related yet different underlying settings
- This makes combination non-trivial
- At the heart, the difference is between LP and Classical logic
- **Main Differences:**
 - Closed vs. Open World Assumption (CWA vs. OWA)
 - Negation as failure, strong negation vs. classical negation
 - Unique names assumption (UNA), treatment of equality

| supplier | branch | address |
|----------|--------|-----------------|
| Barrilla | Roma | Piazza Spagna 1 |
| Barilla | Milano | Via Cadorno 2 |
| DeCecco | Roma | Via Salaria 10 |

Non-monotonic dl-Programs

- An extension of answer set programs with *queries to DL knowledge bases* (through *dl-atoms*) [Eiter *et al.*, 2008]
- dl-atoms allow to query a DL knowledge base differently
bidirectional flow of information, with clean technical separation of DL engine and ASP solver (“loose coupling”)



- Use dl-programs as “glue” for combining inferences on a DL base.
- System Prototype: NLP-DL
<http://www.kr.tuwien.ac.at/research/systems/semweblp/>;
- ONTODLP/ONTODLV [Ricca *et al.*, 2008]: ASP + native ontologies + OWL interface

Data Integration

- Integrate data from local sources into global database, obeying local/global schema constraints [Lenzerini, 2002]
- Inconsistencies \Rightarrow global database “Repairs” [Arenas *et al.*, 1999]:
- But: multiple repairs, query answering on them is quickly intractable
- Use ASP as an expressive formalism for *em repair specification and query answering* [Arenas *et al.*, 2000] etc.
- **Infomix** (IST-2002-33570; TU WIEN, U “La Sapienza”, U Calabria, Rodan Systems): prototype system with ASP at the core [Leone *et al.*, 2005]
- Powerful information integration thanks ASP which similar systems (Hippo, ConQuer) could not host
 - can handle only limited schema constraints
 - have restrictions on queries (syntactic conditions)
- More discussion see [Eiter, 2005]

Workflow Management

- Execution management of orchestrated Web Services [Friedrich et al., 2008], in context of WS-DIAMOND (EU IST)

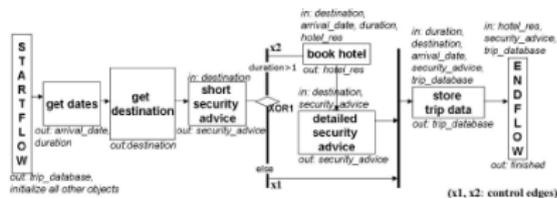


Figure 1. The trip planning example

- Problem: faulty action executions discovered; repair the workflow instance
 - Input:** Work flow spec in WS-BPEL, exec log, faulty activities
 - Output:** repair plan, taking contingencies into account
- Complex problem:
 - contingencies \Rightarrow conditional planning
 - concurrency
 - transient errors, indeterministic actions

Workflow Management(ctd.)

- Friedrich et al. use ASP to compute repair plans
- different types of repair actions: re-execution (undo/redo), action substitution, compensation (undo)
- E.g., rules whether an activity is ok at a time point (=node in a tree):

```
-ok(A, T)   if failure(A, T).  
-ok(A, T2) if activity(A), -ok(A, T1), next(T1, T2),  
              not substituted(A, T2), not isTransFaulty(A, T1).  
ok(A, T2)  if activity(A), node(T2), not -ok(A, T2).
```

- Benefits of ASP:
 - readable specification
 - reasoning about time / time points
 - reason about dependencies (paths) in the control graph
 - inertia, default assumptions (exception handling)
- Prototype implementation in DLV: can handle medium sized orchestrated web services

Conclusion

- ASP is a recent problem solving paradigm
- A body of theoretical work
- KR features, transitivity
- Many extensions & solvers
- Serves as a host formalism (good for prototyping)
- Assessment concerning applications:
 - N. Leone's LPNMR'07 talk

Research Topics

- Function symbols
- Program equivalence, optimization:
E.g., *strong equivalence* [Lifschitz *et al.*, 2001] (many further notions [Woltran, 2008])
$$P \equiv_s Q \text{ iff for all } R, P \cup R \text{ and } Q \cup R \text{ have the same answer sets}$$
- Proof systems (e.g., tableaux-based systems, [Gebser and Schaub, 2007], resolution [Bonatti, 2001])
- Modularity (e.g., [Janhunen *et al.*, 2007], [Eiter *et al.*, 1997b])
- Incremental model building (e.g., [Gebser *et al.*, 2008], [Calimeri *et al.*, 2007])
- Nonground ASP processing (e.g., top down, You *et al.*; cf. XASP)
Also magic sets [Faber *et al.*, 2008]), lazy grounding (e.g. Pontelli *et al.*)
- Debugging, software tools, methodology (e.g., [Brain *et al.*, 2007])

Expressing Disjunctive Stable Models in Σ_1^1

Rough Outline:

- Existence of a stable model is expressible by a second-order sentence

$$\exists \mathbf{M} \forall \mathbf{M}' \psi(\mathbf{M}, \mathbf{M}'), \quad (2)$$

where \mathbf{M}, \mathbf{M}' are lists of predicate variables and ψ is a first-order formula (in fact, a Boolean combination of existential sentences).

- This sentence can be rewritten to

$$\exists \mathbf{M} \forall \mathbf{x} \forall \mathbf{M}' \exists \mathbf{y} \psi'(\mathbf{M}, \mathbf{x}, \mathbf{M}', \mathbf{y}), \quad (3)$$

where $\psi'(\mathbf{M}, \mathbf{x}, \mathbf{M}', \mathbf{y})$ is quantifier-free.

Lemma

Over arithmetic on the natural numbers \mathcal{N} in a relational setting ($+$, $*$, exp are given by their graphs), formulas $\forall \mathbf{P} \exists \mathbf{z} \alpha(\mathbf{P}, \mathbf{z}, \dots)$, where $\alpha(\mathbf{P}, \mathbf{z}, \dots)$ is quantifier-free, are equivalent to first-order formulas.

Expressing Disjunctive Stable Models in Σ_1^1 (ctd.)

- We can emulate the natural numbers by a subset of the Herbrand universe, and conversely code the Herbrand universe (by Gödel numbering) to the natural numbers.
- Employing this, the formula

$$\forall \mathbf{M}' \exists \mathbf{y} \psi'(\mathbf{M}, \mathbf{x}, \mathbf{M}', \mathbf{y}) \quad (4)$$

is (under this encoding) equivalent to a first-order formula $\alpha(\mathbf{M}, \mathbf{x})$.

- Plugging this into (3), we obtain a Σ_1^1 sentence

$$\exists \mathbf{M} \forall \mathbf{x} \alpha(\mathbf{M}, \mathbf{x}). \quad (5)$$

- The relations $+$, $*$, *exp* and the Gödel encoding can be provided with “guessed” predicates and first-order formulas.
- Hence, (2) is equivalent to a Σ_1^1 sentence

ASP vs Prolog: Greatest Common Divisor

Problem:

Compute the greatest common divisor of two integers $n, m > 0$

- Classical Method: Euclid's algorithm (DLV code):

$$\begin{aligned}gcd(X, X, X) &\leftarrow \#int(X), X > 1. \\gcd(T, X, Y) &\leftarrow X < Y, gcd(T, X, Y1), Y = Y1 + X. \\gcd(T, X, Y) &\leftarrow X > Y, gcd(T, X1, Y), X = X1 + Y.\end{aligned}$$

- Similar code in Prolog
- But: A genius like Euclid is *not* the average user

Question:

Natural encoding ?

Natural Greatest Common Divisor Encoding

ASP (DLV code):

```
% Declare when T divides a number N.  
divisor(T, N) ← #int(T), #int(N), #int(M), N = T * M.  
% Declare common divisors  
  
cd(T, N1, N2) ← divisor(T, N1), divisor(T, N2).  
% Single out non-maximal common divisors T  
  
larger_cd(T, N1, N2) ← cd(T, N1, N2), cd(T1, N1, N2), T < T1.  
% Apply double negation: take non non-maximal divisor  
  
gcd(T, N1, N2) ← cd(T, N1, N2), not larger_cd(T, N1, N2).
```

- Note: a stratified program, use of “double negation”.
- A corresponding “natural” encoding in Prolog has to be more thoughtful!

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