

Answer Set Programming for the Semantic Web

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23rd Int'l Conference on Logic Programming, Sept 8-13, 2007, Porto, Portugal

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(IST REWERSE, FWF Project P17212-N04)

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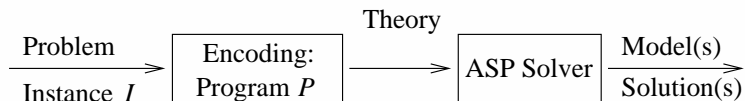
Answer Set Programming

- Term was coined by Vladimir Lifschitz (1999)
- Roots in KR, logic programming, nonmonotonic reasoning
- Proposed by other people (Marek & Truszczyński, Niemelä,...) at about the same time
- Makes fruitful use of the (often criticized) fact that non-monotonic logic programs (LPs) have multiple stable models (aka *answer sets*)
- At an abstract level, relates to SAT solving and CSP.

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 I / all solutions)

Answer Set Semantics

- 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 an atom.

- “ \neg ” is called strong negation (also written as “ \neg ”)
- a may be missing (constraint)
- HB_P is the set of all literals p and $\neg p$ with predicates and constants from P .
- In *disjunctive programs*, the rule head may be a disjunction $a_1 \mid \dots \mid a_k$ of literals

Answer Sets

- Consider a consistent set of ground literals $M \subseteq HB_P$
- Recall the Gelfond-Lifschitz (GL) reduct P^M :
remove from the grounding of P , $Ground(P)$,
 - 1 every rule $a \leftarrow b_1, \dots, b_m, not\ c_1, \dots, not\ c_n$,
where some c_i is in M , and
 - 2 all literals $not\ c_j$ from the remaining rules.
- Then, M is an answer set of P iff M is the least model of P^M
- Such an M satisfies all rules, and intuitively P justifies each atom in M
- Easily generalized to disjunctive P : “the least” \rightsquigarrow “a minimal”

Example

$$P = \{ \text{person}(\text{joey}); \\ \text{male}(X) \mid \text{female}(X) \leftarrow \text{person}(X) \}$$

- $M_1 = \{ \text{person}(\text{joey}), \text{male}(\text{joey}), \text{bachelor}(\text{joey}) \}$ 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:

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

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;

- **Nondeterminism in ASP:** Means to make guesses

- **Only limited support of function symbols in current ASP solvers**
(more is emerging)

Simple Horn LPs with function symbols are undecidable, while ASP strives for decidability

Some decidable fragments of ASP with function symbols:

- ω -restricted programs [Syrjänen, LPNMR01]
- finitary programs [Bonatti, 04],
finitely recursive programs [Baselice et al., ICLP07]
- FDNC programs [Simkus & E_, LPAR07]

ASP Applications

Problems in different domains (some with substantial amount of data), see

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

- information integration
- constraint satisfaction
- planning, routing
- biology
- diagnosis
- security analysis
- configuration
- computer-aided verification
- ...

ASP Showcase: <http://www.kr.tuwien.ac.at/projects/WASP/showcase.html>

ASP 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	distributed with XSB v2.6 http://xsb.sourceforge.net
aspps	http://www.cs.engr.uky.edu/ai/aspps/
ccalc	http://www.cs.utexas.edu/users/tag/cc/

- Some provide a number of extensions to the language described here.
- Answer Set Solver Implementation: see Niemelä's ICLP'04 tutorial.

ASP Extensions

- Many extensions have been proposed, partly motivated by applications
- Some are syntactic sugar, other strictly add expressiveness
- Incomplete list:
 - cardinality constraints (Smodels)
 - optimization: weight constraints, *minimize* (Smodels); weak constraints (DLV)
 - aggregates (Smodels, DLV)
 - templates (for macros)
 - preferences: e.g., PLP
 - KR frontends (diagnosis, planning,...) in DLV
- Comprehensive survey of extensions:

<http://www.tcs.hut.fi/Research/Logic/wasp/wp3/>

Semantic Web

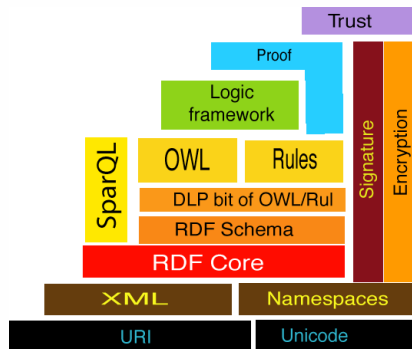
Why a “Semantic” Web?

- Undoubtedly, the World Wide Web is one of the most significant technical innovations of the last decades,
- The WWW will be (and already is) strongly impacting, and changing, our living, culture, and society.
- The WWW has been designed for human users, not for machines
- To process the data and information out on the Web, semantic annotation and description is needed.
- The Semantic Web is the vision of such an enriched, future generation Web
- Logic and logic-based formalisms (should/might) play an important role in this endeavor.

Topics in the Semantic Web

- Web services (description, discovery, invocation, composition, choreography, etc.)
- Knowledge management
- Trust, Privacy, Security
- Searching
- Data Annotation
- Ontology Management, Alignment
- Web Mining
- Reasoning on the Semantic Web
- ...

Building the Semantic Web (T. Berners-Lee, 04/2005)



- RDF is the data model of the Semantic Web
- RDF Schema semantically extends RDF by simple taxonomies and hierarchies
- OWL is a W3C standard, which builds on Description Logics
- Rule languages: *Rule Interchange Format (RIF)* WG of W3C

RDF/S (Resource Description Framework)

- **RDF data model:** labeled graph of resources (nodes) linked to other resources or literals by predicates.



- Usually represented in form of triples $\langle \textit{Subject}, \textit{Predicate}, \textit{Object} \rangle$ e.g.

```
http://www.polleres.net/index.html dc:creator
http://www.polleres.net/foaf.rdf#me.
http://www.polleres.net/foaf.rdf#me foaf:name "Axel Polleres"
```

```
<rdf:Description rdf:about="http://www.polleres.net/index.html">
  <dc:creator>
    <rdf:Description rdf:about="http://www.polleres.net/foaf.rdf#me">
      <foaf:name>Axel Polleres</foaf:name>
    </rdf:Description>
  </dc:creator>
</rdf:Description>
```

- Resources identified by URIs
- **RDF Schema (RDFS):** simple taxonomies on RDF vocabularies using `rdf:type`, `rdf:subClassOf`, `rdfs:subPropertyOf`
- RDF semantics has some subtleties (blank nodes, XML literals, RDF keywords treated as normal resources, reification, etc.)

Ontologies

- Knowledge about concepts, individuals, their properties and relationships
- W3C Standard (04/2004): *Web Ontology Language (OWL)*
- Three increasingly expressive sublanguages

OWL Hierarchy

- OWL Lite: Concept hierarchies, simple constraint features. ($\equiv SHIF(\mathbf{D})$)
 - OWL DL : Basically, DAML+OIL. ($\equiv SHOIN(\mathbf{D})$)
 - OWL Full: Allow e.g. to treat classes as individuals.
- OWL Syntax is based on RDF
 - Most widely considered: OWL DL
 - Currently, OWL 1.1 (an extension of OWL DL) is a submitted to W3C

Description Logics (DLs)

OWL / Description Logics offers more expressivity than RDF/S!

- The vocabulary of basic DLs comprises:
 - Concepts (e.g., *Wine*, *WhiteWine*)
 - Roles (e.g., *hasMaker*, *madeFromGrape*)
 - Individuals (e.g., *SelaksIceWine*, *TaylorPort*)
- Statements relate individuals and their properties using
 - logical connectives (\sqcap , \sqcup , \neg , \sqsubseteq , etc), and
 - quantifiers (\exists , \forall , $\leq k$, $\geq k$, etc)
- A DL knowledge base usually comprises
 - a T-Box (terminology, conceptualization), and
 - an A-Box (assertions, extensional knowledge)
- DLs are tailored for decidable reasoning (key task: satisfiability)

Example: The Wine Ontology

- Available at <http://www.w3.org/TR/owl-guide/wine.rdf>
- Some axioms from the T-Box

$Wine \sqsubseteq PotableLiquid \sqcap =1 hasMaker \sqcap \forall hasMaker. Winery;$
 $\exists hasColor. Wine \sqsubseteq \{ "White", "Rose", "Red" \};$
 $WhiteWine \equiv Wine \sqcap \forall hasColor. \{ "White" \}.$

- A wine is a potable liquid, having exactly one maker, who is a member of the class “*Winery*”.
- Wines have colors “*White*”, “*Rose*”, or “*Red*”.
- A *WhiteWine* is a wine with color “*White*”.
- The A-Box contains, e.g., $WhiteWine("StGenevieveTexasWhite")$, $hasMaker("TaylorPort", "Taylor")$

Formal OWL / DL Semantics

- The semantics is given by a mapping to First-Order Logic
Thus, DLs are (in essence) FO Logic in disguise

OWL property axioms as RDF Triples	DL syntax	FOL short representation
$\langle P \text{ rdfs:domain } C \rangle$	$\top \sqsubseteq \forall P^- . C$	$\forall x, y. P(x, y) \supset C(x)$
$\langle P \text{ rdfs:range } C \rangle$	$\top \sqsubseteq \forall P . C$	$\forall x, y. P(x, y) \supset C(y)$
$\langle P \text{ owl:inverseOf } P_0 \rangle$	$P \equiv P_0^-$	$\forall x, y. P(x, y) \equiv P_0(y, x)$
$\langle P \text{ rdf:type owl:SymmetricProperty} \rangle$	$P \equiv P^-$	$\forall x, y. P(x, y) \equiv P(y, x)$
$\langle P \text{ rdf:type owl:FunctionalProperty} \rangle$	$\top \sqsubseteq \leq 1P$	$\forall x, y_1, y_2. P(x, y_1) \wedge P(x, y_2) \supset y_1 = y_2$
$\langle P \text{ rdf:type owl:InverseFunctionalProperty} \rangle$	$\top \sqsubseteq \leq 1P^-$	$\forall x_1, x_2, y. P(x_1, y) \wedge P(x_2, y) \supset x_1 = x_2$
$\langle P \text{ rdf:type owl:TransitiveProperty} \rangle$	$P^+ \sqsubseteq P$	$\forall x, y, z. P(x, y) \wedge P(y, z) \supset P(x, z)$

OWL complex class descriptions	DL syntax	FOL short representation
owl:Thing	\top	$x = x$
owl:Nothing	\perp	$\neg x = x$
owl:intersectionOf ($C_1 \dots C_n$)	$C_1 \sqcap \dots \sqcap C_n$	$\bigwedge C_i(x)$
owl:unionOf ($C_1 \dots C_n$)	$C_1 \sqcup \dots \sqcup C_n$	$\bigvee C_i(x)$
owl:complementOf (C)	$\neg C$	$\neg C(x)$
owl:oneOf ($o_1 \dots o_n$)	$\{o_1 \dots o_n\}$	$\bigvee x = o_i$
owl:restriction (P owl:someValuesFrom (C))	$\exists P . C$	$\exists y. P(x, y) \wedge C(y)$
owl:restriction (P owl:allValuesFrom (C))	$\forall P . C$	$\forall y. P(x, y) \supset C(y)$
owl:restriction (P owl:value (o))	$\exists P . \{o\}$	$P(x, o)$
owl:restriction (P owl:minCardinality (n))	$\geq n P$	$\exists_{i=1}^n y_i . \bigwedge_{j=1}^n P(x, y_j) \wedge \bigwedge_{i \neq j} y_i \neq y_j$
owl:restriction (P owl:maxCardinality (n))	$\leq n P$	$\forall_{i=1}^{n+1} y_i . (\bigwedge_{j=1}^n P(x, y_i) \supset \bigvee_{i \neq j} y_i = y_j)$

Exploiting ASP for the Semantic Web

- Different ways to exploit ASP and ASP techniques have been considered
 - **As a host language for Web/Semantics Web formalisms**
 - Mapping / encoding of ontologies and DLs into ASP
 - Encoding of web query languages
E.g., SPARQL [Polleres, WWW07], [Polleres & Schindlauer, ALPSWS07]
 - **For ad hoc problem solving.** E.g.,
 - Web service composition, e.g., [Rainer, KI-WS05]
 - Web service repair, e.g, [Friedrich et al., in progress]
 - **For combining rules and ontologies**

Special Needs of Semantic Web

- Dealing with open worlds and domains
- Access to (semi-)structured data
cf. Frame-Syntax of HiLog, F-Logic
- Heterogeneity (integration)
- External sources, distributed computation
- Dynamics

Some Special ASP Extensions

- **Open logic programs** [Van Belleghem et al., 97], [Bonatti, ASP03]
Keep definition of some predicates open
- **Open Answer Set Programs** [Heymans & Vermeir, ASP03;DEXA03]
relax domain closure: add countably many anonymous elements
decidability via restrictions (e.g., conceptual LPs)
- **ASP-EX** [Calimeri & Ianni LPNMR05]
External sources of computation; impose safety
- **HEX-Programs** [E_ et al. IJCAI05]
HiLog ASP plus external sources
- **ONTODLV** [Dell'Armi et al., ASP07]
ASP + non-standard ontologies + OWL interface
- Several extensions to combine rules and ontologies

Expressing RDF/S in ASP

- Common: use a predicate `triple/3`:

```
triple("http://www.polleres.net/foaf.rdf#me",  
      "foaf:name", "Axel Polleres").
```

- RDFS semantics can be fully captured by DLV-EX, DLV-HEX [Ianni et al., ASP07]

E.g., subclass relation:

```
[...]  
triple(S,rdf:type,C2) :- triple(S,rdf:type,C1),  
                        triple(C1,rdfs:subClassOf,C2).
```

map triples to predicate notation (using higher-order features) and to frame constructs

```
P(S,O) :- triple(S,P,O).  
S : C   :- triple(S,rdf:type,C).  
S : C2 :- S : C1, rdfs:subClassOf(C1,C2).
```

- Technicalities for treating blank nodes and infinite axiomatic triples.

Expressing Ontologies in ASP/2

- ASP techniques for encoding OWL / DLs have been considered e.g. by
 - Alsac and Baral [2002]
 - Swift [LPNMR04]
 - Hustadt, Motik, and Sattler [KR04]
 - Heymans et al. [2003+]
- Works only under limitations
- Noticable: Hustadt et al.'s mapping of *SHIQ* to disjunctive datalog; basis for the KAON2 DL solver
- **Main problem:** important differences between ASP and OWL/DLs

LP vs. Classical Logic

- ASP and OWL/DLs have related yet different underlying settings
- At the heart, the difference is between LP and Classical logic
- **Main Differences:**
 - Closed vs. Open World Assumption
 - Negation as failure vs. classical negation
 - Strong negation vs. classical negation
 - Unique names, equality

LP / Classical Logic: CWA vs. Open World Assumption (OWA)

- LP aims at building a single model, by closing the world

Reiter's CWA:

If $T \not\models A$, then conclude $\neg A$, for ground atom A

- FO logic / description logics keep the world open
- In the Semantic Web, this is often reasonable
- However, taking the agnostic stance of OWA may be not helpful for drawing rational conclusions under incomplete information
- A mix of CWA and OWA may be appropriate [Damasio et al., PPSWR06], [Polleres et al., EWSC06]

LP / Classical Logic: NAF vs. Classical Negation

P : $wine(X) \leftarrow whiteWine(X).$
 $nonWhite(X) \leftarrow not\ whiteWine(X).$
 $wine(myDrink).$

T : $\forall X. (WhiteWine(X) \supset Wine(X)) \wedge$
 $\forall X. (\neg WhiteWine(X) \supset NonWhite(X)) \wedge$
 $Wine(myDrink).$

- Query $nonWhite(myDrink)$?
 - Conclude $nonWhite(myDrink)$ from P .
 - Do not conclude $nonWhite(myDrink)$ from T .

LP / Classical Logic: Strong vs. Classical Negation

P : $wine(X) \leftarrow whiteWine(X).$
 $\quad \neg wine(myDrink).$

T : $\forall X. (WhiteWine(X) \supset Wine(X)) \wedge$
 $\quad \neg Wine(myDrink).$

- Conclude $\neg WhiteWine(myDrink)$ from T ;
- Do not conclude $\neg whiteWine(myDrink)$ from P
- Note: no contraposition in LP!

$\neg whiteWine(X) \leftarrow \neg wine(X).$

is not equivalent to

$wine(X) \leftarrow whiteWine(X).$

LP / Classical Logic: Unique Names, Equality

- In LP, usually we have *Unique Names Assumption (UNA)*:
Syntactically different ground terms are different objects.
- Thus, usually only Herbrand interpretations are considered in LP
- Ontology languages like OWL don't make UNA, and allow to link objects (owl:sameAs)
- OWL considers also non-Herbrand interpretations
- Further, related problems with existential quantifiers:

$$\mathcal{T} : \forall X \exists Y. (Wine(X) \supset hasColor(X, Y))$$

(in DL Syntax, $Wine \sqsubseteq \exists hasColor$)

Simple skolemization does not work in general

Generic Settings for KB Combination

A hybrid knowledge base $\mathcal{KB} = \langle \mathcal{T}, P \rangle$ has

- a FO theory \mathcal{T} (the *classical component*)
- an LP P (the *rules component*)

- Predicates are either “*classical*” or “*rules*” predicates
- Occurrence of rules-predicates in a FO theory is usually restricted, function symbols are disallowed.

Main reason: Combinations of Horn logic and very simple DLs are undecidable [Levy & Rousset, AIJ98].

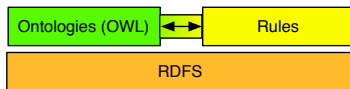
- Problems with recursion and *unsafety* of rules
- L&R used *role-safety*: at least one of X, Y in a role atom $R(X, Y)$ in a rule r occurs in rules-predicate in r not occurring in any rule head.

Generic Settings for KB Combination

- Safety (in several versions) is a key tool to decidability for several combination approaches.
- Different approaches to a semantics for $\mathcal{KB} = \langle \mathcal{T}, \mathcal{P} \rangle$
 - Strict semantic separation (loose coupling)
 - Tight integration
 - Full integration
- Surveys and Discussion
 - KNOWLEDGEWEB [Pan et al., 2004]
 - REVERSE [Antoniou et al., 2005]
 - Rosati, E_ et al. [ReasoningWeb2006]

KB Combination: Loose Coupling

- **Strict semantic separation between rules / ontology**



- View rule base and FO theory as separate components
- They are connected through a minimal interface for exchanging knowledge (formulas).

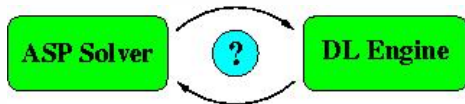
“safe interface”

Examples: TRIPLE [Sintek & Decker, 02]; non-monotonic dl-programs [E_ et al., 04]; defeasible logic+DLs [Antoniou et al., 04]

Loose Coupling: Non-monotonic dl-Programs

- An extension of answer set programs with **queries to DL knowledge bases** (through **dl-atoms**)
- dl-atoms allow to query a DL knowledge base differently

bidirectional flow of information, with clean technical separation of DL engine and ASP solver



- Use dl-programs as “glue” for combining inferences on a DL base.

DL-atoms

Basic Idea:

- Query the DL base \mathcal{T} using the query interface of the DL engine
Query Q may be concept/role instance $C(X)/R(X, Y)$, subsumption $C \sqsubseteq D$ etc (recent extension: conjunctive queries)
- Allow to **modify** the extensional part (ABox) of \mathcal{T} , by adding positive (\uplus) or negative (\uplus) assertions
- Q evaluates to true iff the modified \mathcal{T} proves Q .

Examples: wine ontology

- $DL[Wine](\text{"ChiantiClassico"})$
- $DL[Wine](X)$
- $DL[RedWine \uplus my_red; Wine](X)$
add all assertions $RedWine(c)$ to \mathcal{T} , such that $my_red(c)$ holds.
- $DL[RedWine \uplus my_white; hasColor](X, \text{"Red"},)$
add all assertions $\neg RedWine(c)$ to \mathcal{T} , such that $my_white(c)$ holds.

dl-Programs: Answer Sets

Answer Sets:

- As usual, via grounding of the rules
- Consider a consistent set of ground literals $M \subseteq HB_{P^*}$ ($P^* = P$ with additional constants from \mathcal{T})
- A ground dl-atom $DL[\langle Add \rangle; Q](\mathbf{c})$ **is true in M** , iff $\mathcal{T} \cup \langle Add \rangle^M \models Q(\mathbf{c})$ for the modification $\langle Add \rangle^M$
- Use a reduct P^M akin to the Gelfond-Lifschitz reduct
- In building P^M , treat dl-atoms like ordinary atoms
- M is an answer set iff M is the least (resp. a minimal) model of P^M

Variants by different treatment of the dl-atoms.

Example: Wine Selection

is_redWine(" Chianti_21").
person(" axel"). *my_Wine*(" axel", " whiteWine").
person(" gibbi"). *my_Wine*(" gibbi", " redWine").
wineBottle(*X*) \leftarrow *DL*[\langle Add \rangle; " Wine"](*X*).

ok_Bottle(*X*, *Z*) \leftarrow *my_Wine*(*X*, " RedWine"), *wineBottle*(*Z*), *DL*[\langle Add \rangle; " RedWine"](*Z*).
ok_Bottle(*X*, *Z*) \leftarrow *my_Wine*(*X*, " WhiteWine"), *wineBottle*(*Z*), *DL*[\langle Add \rangle; " WhiteWine"](*Z*).
takeBottle(*X*) | \neg *takeBottle*(*X*) \leftarrow *wineBottle*(*X*).
hasBottle(*X*) \leftarrow *takeBottle*(*X*), *ok_Bottle*(*X*, *Z*).
 \leftarrow *person*(*X*), *not hasBottle*(*X*).

- Answer sets depend on the instances of *Wine*, *RedWine*, *WhiteWine*

E.g., { *wineBottle*(" SelaksIceWine"), *wineBottle*(" TaylorPort"), ...,
ok_Bottle(" axel", " SelaksIceWine"), *ok_Bottle*(" gibbi", " TaylorPort"), ...,
takeBottle(" SelaksIceWine"), *takeBottle*(" TaylorPort"), ... }

- Add knowledge *is_redWine*(" Chianti_21") to \mathcal{T} : $\langle Add \rangle = RedWine \uplus is_redWine$
wineBottle(" Chianti_21") is in all answer sets

Example: Mutual Flow

- Existing network, encoded in OWL KB
- New nodes to be added

Condition: don't connect to nodes with high traffic (traffic depends on number of connections)

- Specify models for possibilities

connect(*X*, *Y*) \leftarrow *newNode*(*X*), *DL*[*Node*](*Y*), *not overloaded*(*Y*).
overloaded(*X*) \leftarrow *DL*[*wired* \uplus *connect*; *HighTrafficNode*](*X*).

- Mutual effects between the LP and the ontology!

dl-Programs: Applications

- dl-programs facilitate some advanced reasoning tasks
 - **Closed World Reasoning**

Emulate *CWA* and *Extended CWA (ECWA)* on top of a DL knowledge base.
 - **Default Reasoning**

Poole's-style and Reiter's Default Logic over DL bases (for restricted fragments)

E.g., network example: connect new node X by default to node Y .
 - **Minimal Model Reasoning**

Single out “minimal” models of a DL base

dl-Programs: Minimal Models

- A DL base with disjunctive information:

$$\mathcal{T} = \{ \textit{Artist}(\textit{"Jody"}), \textit{Artist} \equiv \textit{Painter} \sqcup \textit{Singer} \}$$

- Single out “minimal” models (in the setting of Extended CWA):

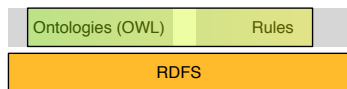
$$\begin{aligned} \bar{p}(X) &\leftarrow \textit{not } p(X). \\ \bar{s}(X) &\leftarrow \textit{not } s(X). \\ p(X) &\leftarrow \textit{DL}[\textit{Painter} \sqcup \bar{p}, \textit{Singer} \sqcup \bar{s}; \textit{Painter}](X). \\ s(X) &\leftarrow \textit{DL}[\textit{Painter} \sqcup \bar{p}, \textit{Singer} \sqcup \bar{s}; \textit{Singer}](X). \end{aligned}$$

Answer sets (corresponding to minimal models):

$$M_1 = \{p(\textit{"Jody"}), \bar{s}(\textit{"Jody"})\}, \quad M_2 = \{s(\textit{"Jody"}), \bar{p}(\textit{"Jody"})\}$$

- Extendible to keep concepts “fixed” \rightsquigarrow ECWA($\phi; P; Q; Z$)

KB Combination: Tight semantic integration



- Integrate FOL statements and the logic program to a large extent, but keep predicates separate.
- Build an integrated model as the union of two models, one for the FO theory and one for the rules, which share the same domain.

“safe interaction”

Examples: CARIN [Levy & Rousset, 98]; DLP [Grosz et al., 03]; SWRL [Horrocks et al., 04]; DL-safe rules [Motik et al., 05]; R-hybrid KBs, R⁺-hybrid KBs, $\mathcal{DL}+log$ [Rosati, DL99;05] [Rosati, PPSWR05;KR06]

Tight integration: $\mathcal{DL}+log$

[Rosati, KR06] Latest in chain of extensions of the DL \mathcal{ALC} with rules
[$\mathcal{AL-Log}$; R-, R⁺-hybrid KBs]

- Fixed countably infinite domain, *standard names* for the elements.
- Models of $\mathcal{KB} = \langle \mathcal{T}, P \rangle$ are of form $\mathcal{I} \cup M$, where \mathcal{I} is a model of the classical predicates, M of the rules-predicates
- No strong negation, weak negation limited to rules-predicates
- Uses **weak (DL-)safety**: each variable X occurs in some positive body atom, which is a rules atom if X occurs in the head.
- Weak safety allows to **access unnamed individuals** in classical atoms (not possible in dl-programs)

$girl(X) \leftarrow kid(X), father(Y, X), not\ likes(X, cars);$

- Decidable, if certain union of conjunctive queries containment (CQ/UCQ) in \mathcal{T} is decidable

$\mathcal{DL}+log$: Semantics

- $\mathcal{DL}+log$ has a stable model (answer set) semantics
- Roughly, a 2-step reduction
- **Step 1:** Take some interpretation \mathcal{I} of the classical predicates.
 - Ground P and “reduce” it wrt. \mathcal{I} , by “evaluating” classical atoms in rules wrt. \mathcal{I} .
 - The resulting ground program $P_{\mathcal{I}}$ contains no classical predicates.
- **Step 2:** Build a stable model M of $P_{\mathcal{I}}$ as usual

$\mathcal{DL}+\log$: Example

$$\mathcal{T} = \{ \text{Female} \sqsubseteq \neg \text{Male}; \text{Female} \sqcup \text{Male} \sqsubseteq \text{Person} \\ \text{Person} \sqsubseteq \exists \text{father}^- . \text{Male}; \text{Person}(\text{joey}) \quad \}$$
$$P = \{ \text{boy}(X) \mid \text{girl}(X) \leftarrow \text{kid}(X); \\ \text{Male}(X) \leftarrow \text{boy}(X); \\ \text{Female}(X) \leftarrow \text{girl}(X); \\ \text{girl}(X) \leftarrow \text{kid}(X), \text{father}(Y, X), \text{not likes}(X, \text{cars}); \\ \text{kid}(\text{joey}) \quad \}$$

- Classical predicates *Male*, *Female*, *father* occur in rules.
- Take \mathcal{I} where *joey* belongs to *Female*, *Person*:

$M = \{ \text{kid}(\text{joey}), \text{girl}(\text{joey}) \}$ is a stable model

$M = \{ \text{kid}(\text{joey}), \text{boy}(\text{joey}) \}$ is not a stable model

- Take \mathcal{I} where *joey* belongs to *Male*, *Person*:
No stable model (in any such M , *likes(joey, cars)* must be false)

KB Combination: Full integration

- No separation between vocabularies

Examples:

- Hybrid MKNF knowledge bases [Motik & Rosati, IJCAI07];
 - G-hybrid knowledge bases [Heymans et al., ALPSWS06]
 - Quantified Equilibrium Logic [Pearce et al., RR07]
 - Autoepistemic Logic [de Bruijn et al., IJCAI07]
 - Open Answer Set Programs [Heymans et al., 03+]
-
- Related:
 - Terminological Default Logic [Baader and Hollunder, 1995]
 - Description Logics of Minimal Knowledge [Donini et al., 2002]

Full Integration: Quantified Equilibrium Logic (QEL)

- Builds on FOL version of Equilibrium Logic (EL) [Pearce, 96;06]
- Reconstructs Answer Sets in terms of the standard, nonclassical Logic of here & there (resp. 3-valued Gödel Logic).
- Models $\mathcal{M} = \langle (D, \sigma), I_h, I_t \rangle$ of the func.-free FO Logic **QHT**^s correspond to intuitionistic Kripke models for two worlds, $h \leq t$, with domain D .
- Axiomatization by first-order intuitionistic logic plus further axioms

equality axioms	$x = x, x = y \rightarrow (F(x) \rightarrow F(y))$ (y substitutable for x in formula $F(X)$)
Hosoi's axiom	$\alpha \vee (\neg\beta \vee (\alpha \rightarrow \beta))$
SQHT	$\exists x(F(x) \rightarrow \forall xF(x))$
DE	$x = y \vee x \neq y$

- A model \mathcal{M} of \mathcal{T} is *in equilibrium*, if $I_h = I_t$ and I_h is minimal, i.e., can not be decreased.

- QEL provides a useful logical foundation for different combination approaches:
 - The equilibrium models of a logic program P correspond to Heymans et al.'s [ALPSWS2006] generalised open answer sets of P .
 - Models of $\mathcal{KB} = \langle \mathcal{T}, P \rangle$ in several other combination approaches (G-hybrid, R-hybrid, R^+ -hybrid KBs) can be elegantly captured
 - For that, take $\mathcal{T} \cup P \cup st(\mathcal{T})$, where

$$st(\mathcal{T}) = \{\forall x p(x) \vee \neg p(x) \mid p \in \Sigma_{\mathcal{T}}\}.$$

Note: $st(\mathcal{T}) \models \neg\neg\phi \rightarrow \phi$, for each $\phi \in \mathcal{T}$.

- QEL has further usages (e.g., *strong equivalence* of hybrid KBs)

Full Integration: Hybrid MKNF

- Builds on a FO-version of Lifschitz's modal logic MKNF [IJCAI91]
- Rules of form

$$\mathbf{K}h_1 \vee \dots \vee \mathbf{K}h_l \leftarrow \mathbf{K}b_1, \dots, \mathbf{K}b_m, \text{not } b_{m+1}, \dots, \text{not } b_n$$

where the h_i, b_j are function-free FO atoms

- $\mathbf{K}\phi \approx \phi$ is known to hold under the values of the *not*-atoms, Kripke-based semantics (“maximal” S5-models wrt. \mathbf{K})
- Faithfully extends LP and DL; generalizes GARIN, \mathcal{AL} -Log
- Allows “closed world glasses” on classical predicates, stating exceptions
- Extensions with both modal and non-modal atoms in rules allow to generalize $\mathcal{DL}+log$ (equi-satisfiable)
- Decidable under DL-safety: each variable occurs in some positive rule atom in the body.

Hybrid MKNF: Example

$$\begin{aligned} T = & \{ \textit{Female} \sqsubseteq \neg \textit{Male}; \textit{Female} \sqcup \textit{Male} \sqsubseteq \textit{Person} \\ & \textit{Person} \sqsubseteq \exists \textit{father} \neg .\textit{Male}; \textit{Person}(\textit{joey}); \textit{Diabetic} \sqsubseteq \textit{Person} \} \\ P = & \{ \mathbf{K} \textit{boy}(X) \vee \mathbf{K} \textit{girl}(X) \leftarrow \mathbf{K} \textit{kid}(X); \\ & \mathbf{K} \textit{Male}(X) \leftarrow \mathbf{K} \textit{boy}(X); \\ & \mathbf{K} \textit{Female}(X) \leftarrow \mathbf{K} \textit{girl}(X); \\ & \mathbf{K} \textit{girl}(X) \leftarrow \mathbf{K} \textit{kid}(X), \mathbf{K} \textit{father}(Y, X), \textit{not likes}(X, \textit{cars}); \\ & \mathbf{K} \textit{kid}(\textit{joey}); \\ & \textit{Koffer}(X, \textit{cake}) \leftarrow \mathbf{K} \textit{Person}(X), \textit{not Diabetic}(X) \} \end{aligned}$$

- Offer cake to persons, with exception of diabetics
- Assume that, by default, a person is not suffering from diabetes
- Not expressible in $\mathcal{DL}+log$ in this way

Assessment

	dl-programs	<i>DL+log</i>	QEL	hybrid MKNF
Distinguish classical and rule predicates	+	+	-	-
<i>Domain of Discourse for P</i>				
Herbrand Universe of <i>P</i>	-	+/-	-	+
Combined Signature	+	+/-	-	+
Arbitrary domains	-	-	+	-
<i>Uniqueness of Names</i>				
unique names in HU of <i>P</i>	+	+/- ¹	-	+/- ¹
Special equality predicate	- ²	- ²	-	\approx
No uniqueness	-	+/-	+	+/-
<i>Interaction from FO Theories to Rules</i>				
Single models	-	+	+	+
Multiple models / Entailment	+	-	-	-
<i>Interaction from Rules to FO Theories</i>				
Single models	-	+	+	-
Multiple models / Entailment	+	-	-	+
Decidability	+ ³	+ ⁴	-	+ ³

- 1 The setting (standard names, Herbrand interpretations) implies the UNA.
- 2 Extendible with axioms for a congruence relation.
- 3 Essentially, satisfiability for the underlying DL must be decidable.

Systems / Implementations of Combinations

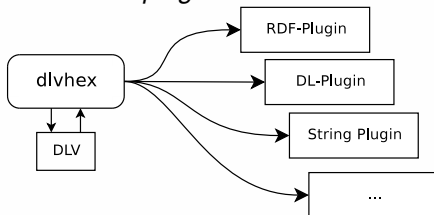
- NLP-DL implements dl-programs (prototype)

<http://con.fusion.at/nlpdl/>

- DLVHEX implements fragments of HEX-programs (prototype)

<http://con.fusion.at/dlvhex/>

Feature: external software *plugins*



Used for various applications (ontology merging, bio-ontologies, e-government, web querying, policy management, ...)

- ...

- **Probabilistic ASP for SW** [Lukasiewicz, ESQUARU05;07]
- **Fuzzy ASP for SW** [Lukasiewicz, RuleML06],
[Lukasiewicz & Straccia, RR07]
- **Rules plus RDF/S:**
Stable model theory for extended RDF/S [Analyti et al., ISWC05]
- **Well-founded semantics**
[E_ et al., RuleML04], [Drabent & Maluszynski; RR07] [Knorr et al., DL07]

Conclusion

- ASP has potential for Semantic Web, for different uses
- Promising applications and usages (e.g., SPARQL, TRIPLESTORES)
- **Pro's and Con's**
 - + Declarativity
 - + Expressiveness
 - + Rich suite of constructs and extensions
 - Mismatch to standard ontologies
 - Scalability (for some tasks)
 - Less commercialized

Research Issues

- **Semantics for rules plus ontologies?**

Only small scale KBs; larger examples / use cases are missing

- **Computational and semantic properties**

- expressiveness

- **Efficient implementations, algorithms**

- scalable complexity

- **Knowledge combination/integration beyond ontologies**

E.g., with rule bases under different semantics, cf. [Baral et al., RuleML06]

- **Language extensions of ASP**

E.g. need for function symbols, value invention (increasing domains)

- **Further applications**

Further Material

More in depth tutorials on “Answer Set Programming for the Semantic Web,” covering different aspects and providing hand-on examples:

- Tutorial at ESWC 2006, available at
<http://rease.semanticweb.org/>,
<http://asptut.gibbi.com/>,
<http://con.fusion.at/asptut>
- Tutorial at ESTC 2007
- Tutorial at “Giornata GULP: Applications of LP and related CL paradigms” March 9th, 2007 (slides are available on the Web)

Background: https://www.mat.unical.it/ianni/wiki/Answer_Set_Programming_for_the_Semantic_Web

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