Answer Set Programming for the Semantic Web

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Contents

- Recall Answer Set Programming
- Semantic Web
- ASP for Semantic Web
- Focus: Combining Rules and Ontologies
- Research Issues

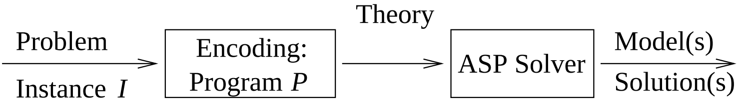
Answer Set Programming

- 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 / all solutions)

Answer Set Semantics

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

$$a \leftarrow \; b_1, \ldots, b_m, not \;\; c_1, \ldots, not \;\; c_n$$

  where all a, b_i, c_j are literals of the form p or $-p$, where p is an atom.

  - "$-$" is called strong negation (also written as "$\neg$")
  - a may be missing (constraint)

- HB_P is the set of all literals p and $-p$ with predicates and constants from P.
- In *disjunctive programs*, the rule head may be a disjunction $a_1 \mid \cdots \mid a_k$ 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 $a \leftarrow b_1, \ldots, b_m, not\ \ c_1, \ldots, not\ \ c_n$, 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

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

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

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

Further stable model:

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

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

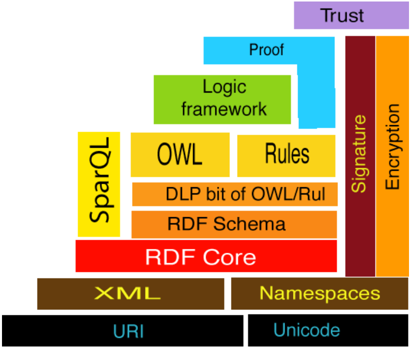
Why a "Semantic" Web?

- 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 ⟨*Subject*, *Predicate*, *Object*⟩ 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. $(\risingdotseq \mathcal{SHIF}(\mathbf{D}))$
- OWL DL : Basically, DAML+OIL. $(\risingdotseq \mathcal{SHOIN}(\mathbf{D}))$
- 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
$\langle P$ rdfs:domain $C\rangle$	$\top \sqsubseteq \forall P^{-}.C$	$\forall x, y.P(x, y) \supset C(x)$
$\langle P$ rdfs:range $C\rangle$	$\top \sqsubseteq \forall P.C$	$\forall x, y.P(x, y) \supset C(y)$
$\langle P$ owl:inverseOf $P_0\rangle$	$P \equiv P_0^{-}$	$\forall x, y.P(x, y) \equiv P_0(y, x)$
$\langle P$ rdf:type owl:SymmetricProperty $\rangle$	$P \equiv P^{-}$	$\forall x, y.P(x, y) \equiv P(y, x)$
$\langle P$ rdf:type owl:FunctionalProperty $\rangle$	$\top \sqsubseteq \leqslant 1P$	$\forall x, y_1, y_2.P(x, y_1) \wedge P(x, y_2) \supset y_1 = y_2$
$\langle P$ rdf:type owl:InverseFunctionalProperty $\rangle$	$\top \sqsubseteq \leqslant 1P^{-}$	$\forall x_1, x_2, y.P(x_1, y) \wedge P(x_2, y) \supset x_1 = x_2$
$\langle P$ 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	$\bot$	$\neg x = x$
owl:intersectionOf ($C_1 \ldots C_n$)	$C_1 \sqcap \ldots \sqcap C_n$	$\bigwedge C_i(x)$
owl:unionOf ($C_1 \ldots C_n$)	$C_1 \sqcup \ldots \sqcup C_n$	$\bigvee C_i(x)$
owl:complementOf (C)	$\neg C$	$\neg C(x)$
owl:oneOf ($o_1 \ldots o_n$)	$\{o_1 \ldots o_n\}$	$\bigvee x = o_i$
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))	$\geqslant n\,P$	$\exists_{i=1}^{n} y_i.\ \bigwedge_{j=1}^{n} P(x, y_j) \wedge \bigwedge_{i \neq j} y_i \neq y_j$
owl:restriction (P owl:maxCardinality (n))	$\leqslant n\,P$	$\forall_{i=1}^{n+1} y_i.(\bigwedge_{j=1}^{n} P(x, y_i) \supset \bigvee_{i \neq j} y_i = y_j)$

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 $\mathcal{SHIQ}$ 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

$$
\begin{array}{ll}
P: & wine(X) \leftarrow whiteWine(X). \\
& nonWhite(X) \leftarrow not \;\; whiteWine(X). \\
& wine(myDrink).
\end{array}
$$

$$
\begin{array}{ll}
\mathcal{T}: & \forall X.\,(WhiteWine(X) \supset Wine(X)) \wedge \\
& \forall X.\,(\neg WhiteWine(X) \supset NonWhite(X)) \wedge \\
& Wine(myDrink).
\end{array}
$$

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

LP / Classical Logic: Strong vs. Classical Negation

$$\begin{array}{ll} P: & wine(X) \leftarrow whiteWine(X). \\ & -wine(myDrink). \\ \mathcal{T}: & \forall X.\,(WhiteWine(X) \supset Wine(X)) \land \\ & \neg Wine(myDrink). \end{array}$$

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

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

is not equivalent to

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

LP / Classical Logic: Unique Names, Equality

- In LP, usally 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:

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

(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].

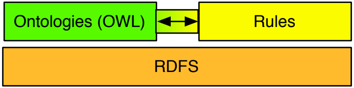
  - Problems with recursion and *unsafety* of rules
  - L&R used *role-safety*: at least one of X, Y in a role atom $R(X, Y)$ in a rule r occurs in rules-predicate in r not occurring in any rule head.

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 $\mathcal{KB} = \langle \mathcal{T}, P \rangle$
  - Strict semantic separation (loose coupling)
  - Tight integration
  - Full integration
- Surveys and Discussion
  - KNOWLEDGEWEB [Pan et al., 2004]
  - REWERSE [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).

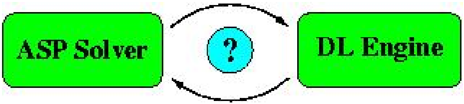
"safe interface"

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 ($\cup\!\!\!\!-$) assertions
- Q evaluates to true iff the modified $\mathcal{T}$ proves Q.

Examples: wine ontology

- $DL[Wine](\text{"}ChiantiClassico\text{"})$
- $DL[Wine](X)$
- $DL[RedWine \uplus my\_red; Wine](X)$

  add all assertions $RedWine(c)$ to $\mathcal{T}$, such that $my\_red(c)$ holds.

- $DL[RedWine \cup\!\!\!\!- my\_white; hasColor](X, \text{"}Red\text{"})$

  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

$is\_redWine(\text{"}Chianti\_21\text{"}).$

$person(\text{"}axel\text{"}).\quad my\_Wine(\text{"}axel\text{"}, \text{"}whiteWine\text{"}).$

$person(\text{"}gibbi\text{"}).\quad my\_Wine(\text{"}gibbi\text{"}, \text{"}redWine\text{"}).$

$wineBottle(X) \leftarrow DL[\langle Add\rangle; \text{"}Wine\text{"}](X).$

$$ok\_Bottle(X,Z) \leftarrow my\_Wine(X, \text{"}RedWine\text{"}), wineBottle(Z), DL[\langle Add\rangle; \text{"}RedWine\text{"}](Z).$$

$$ok\_Bottle(X,Z) \leftarrow my\_Wine(X, \text{"}WhiteWine\text{"}), wineBottle(Z), DL[\langle Add\rangle; \text{"}WhiteWine\text{"}](Z).$$

$$takeBottle(X) \mid -takeBottle(X) \leftarrow wineBottle(X).$$

$$hasBottle(X) \leftarrow takeBottle(X), ok\_Bottle(X,Z).$$

$$\leftarrow person(X), not\ \ hasBottle(X).$$

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

  E.g., { $wineBottle(\text{"}SelaksIceWine\text{"}), wineBottle(\text{"}TaylorPort\text{"}), \ldots,$
  $ok\_Bottle(\text{"}axel\text{"}, \text{"}SelaksIceWine\text{"}), ok\_Bottle(\text{"}gibbi\text{"}, \text{"}TaylorPort\text{"}), \ldots,$
  $takeBottle(\text{"}SelaksIceWine\text{"}), takeBottle(\text{"}TaylorPort\text{"}), \ldots$ }

- Add knowledge $is\_redWine(\text{"}Chianti\_21\text{"})$ to $\mathcal{T}$: $\langle Add\rangle = RedWine \uplus is\_redWine$

  $wineBottle(\text{"}Chianti\_21\text{"})$ 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:

$$\mathcal{T} \quad = \quad \{\; \mathit{Artist}(\text{“}\mathit{Jody}\text{”}), \quad \mathit{Artist} \equiv \mathit{Painter} \sqcup \mathit{Singer} \;\}$$

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

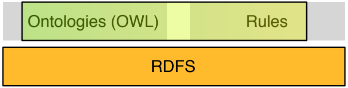
$$\begin{aligned} \overline{p}(X) &\leftarrow \mathit{not}\;\; p(X). \\ \overline{s}(X) &\leftarrow \mathit{not}\;\; s(X). \\ p(X) &\leftarrow \mathit{DL}[\mathit{Painter} \uplus \overline{p}, \mathit{Singer} \uplus \overline{s}; \mathit{Painter}](X). \\ s(X) &\leftarrow \mathit{DL}[\mathit{Painter} \uplus \overline{p}, \mathit{Singer} \uplus \overline{s}; \mathit{Singer}](X). \end{aligned}$$

Answer sets (corresponding to minimal models):

$$M_1 \;=\; \{p(\text{“}\mathit{Jody}\text{”}), \overline{s}(\text{“}\mathit{Jody}\text{”})\}, \qquad M_2 \;=\; \{s(\text{“}\mathit{Jody}\text{”}), \overline{p}(\text{“}\mathit{Jody}\text{”})\}$$

- Extendible to keep concepts “fixed” $\leadsto$ ECWA(ϕ; 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 [Grosof et al., 03]; SWRL [Horrocks et al., 04]; DL-safe rules [Motik etal., 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

$$\mathcal{T} = \{\ \mathit{Female} \sqsubseteq \neg \mathit{Male};\quad \mathit{Female} \sqcup \mathit{Male} \sqsubseteq \mathit{Person}$$
$$\mathit{Person} \sqsubseteq \exists \mathit{father}^{-}.\mathit{Male};\quad \mathit{Person}(\mathit{joey})\ \}$$

$$P = \{\ \mathit{boy}(X) \mid \mathit{girl}(X) \leftarrow \mathit{kid}(X);$$
$$\mathit{Male}(X) \leftarrow \mathit{boy}(X);$$
$$\mathit{Female}(X) \leftarrow \mathit{girl}(X);$$
$$\mathit{girl}(X) \leftarrow \mathit{kid}(X), \mathit{father}(Y, X), \mathit{not}\ \mathit{likes}(X, \mathit{cars});$$
$$\mathit{kid}(\mathit{joey})\ \}$$

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

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

  $M = \{\mathit{kid}(\mathit{joey}), \mathit{boy}(\mathit{joey})\}$ is not a stable model
- Take $\mathcal{I}$ where *joey* belongs to *Male*, *Person*:

  No stable model (in any such M, $\mathit{likes}(\mathit{joey}, \mathit{cars})$ 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	$\exists x(F(x) \rightarrow \forall x F(x))$
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 /2

- 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

$$\mathbf{K}h_1 \vee \cdots \vee \mathbf{K}h_l \leftarrow \mathbf{K}b_1, \ldots \mathbf{K}b_m, \mathit{not}\ \ b_{m+1}, \ldots, \mathit{not}\ \ b_n$$

  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. **K**)
- Faithfully extends LP and DL; generalizes CARIN, $\mathcal{AL}$-*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

$$\mathcal{T} = \{\ \mathit{Female} \sqsubseteq \neg \mathit{Male};\quad \mathit{Female} \sqcup \mathit{Male} \sqsubseteq \mathit{Person}$$
$$\mathit{Person} \sqsubseteq \exists \mathit{father}^{-}.\mathit{Male};\quad \mathit{Person}(\mathit{joey});\quad \mathit{Diabetic} \sqsubseteq \mathit{Person}\ \}$$

$$P = \{\ \mathbf{K}\mathit{boy}(X) \vee \mathbf{K}\mathit{girl}(X) \leftarrow \mathbf{K}\mathit{kid}(X);$$
$$\mathbf{K}\mathit{Male}(X) \leftarrow \mathbf{K}\mathit{boy}(X);$$
$$\mathbf{K}\mathit{Female}(X) \leftarrow \mathbf{K}\mathit{girl}(X);$$
$$\mathbf{K}\mathit{girl}(X) \leftarrow \mathbf{K}\mathit{kid}(X), \mathbf{K}\mathit{father}(Y, X), \mathit{not}\ \mathit{likes}(X, \mathit{cars});$$
$$\mathbf{K}\mathit{kid}(\mathit{joey});$$
$$\mathbf{K}\mathit{offer}(X, \mathit{cake}) \leftarrow \mathbf{K}\mathit{Person}(X), \mathit{not}\ \mathit{Diabetic}(X)\qquad \}$$

- 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	$\mathcal{DL}$+*log*	QEL	hybrid MKNF
Distinguish classical and rule predicates	+	+	–	–
Domain of Discourse for *P*				
Herbrand Universe of *P*	–	+/–	–	+
Combined Signature	+	+/–	–	+
Arbitrary domains	–	–	+	–
Uniqueness of Names				
unique names in HU of *P*	+	+/–[1]	–	+/–[1]
Special equality predicate	–[2]	–[2]	–	≈
No uniqueness	–	+/–	+	+/–
Interaction from FO Theories to Rules				
Single models	–	+	+	+
Multiple models / Entailment	+	–	–	–
Interaction from Rules to FO Theories				
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

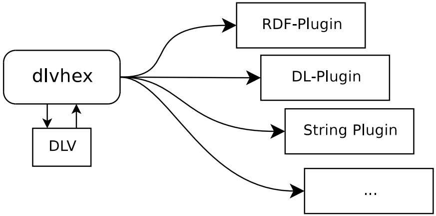
- NLP-DL implements dl-programs (prototype)

  `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, . . .)

- ...

Further Aspects

- **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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