Unit 4 – Combining Rules with Ontologies

Thomas Eiter

KBS Group, Institute of Information Systems, TU Vienna

Reasoning Web Summer School 2008

Introduction

- In the previous units, we were looking at combining rules and ontologies more from a practical angle
- Several systems/approaches presented provide means to perform "low level" or "ad hoc" integration
- Now we look at this issue from a more principled, theoretical perspective

Unit Outline

1. Introduction
2. LP vs. Classical Logic
3. Sample Combination Approaches
4. Further Aspects

The Issue

- Description Logics have been carefully crafted as fragments of FO Logic (in essence) that are decidable.
- While powerful, the standard DLs have limits with respect to expressing relationships.

Example: defining uncle from brother and parent

- easy in LP:

$$uncleOf(X, Y) \leftarrow parentOf(Z, Y), brotherOf(X, Z).$$

- in many DLs, the role $uncleOf$ is not definable from roles $brotherOf$ and $parentOf$!

- Note: the DL $\mathcal{SROIQ}$ (in forthcoming OWL2) allows role composition

Remedy

- relations as the one above are naturally expressed as *rules*, which are at the core of *Logic Programming*:
- a rule

$$a_1 \vee \cdots \vee a_l \leftarrow b_1, \ldots, b_k, not\, b_{k+1}, \ldots, not\, b_m,$$

where $l = 1$ and $k = m$ can be naively read as a first-order sentence

$$(\forall)\, b_1 \wedge \ldots \wedge b_k \supset a_1$$

where $(\forall)$ denotes the universal quantification of all variables.

- SWRL adds such Horn clauses to OWL
- However, while semantically smooth, this leads to undecidability in general

Remedy (ctd.)

- This calls for decidable fragments. E.g.,
  - DL-safe Horn rules, or
  - Description Logic Programs (DLPs) which restrict OWL ontologies to Horn rules in disguise
- Furthermore, such uniform approaches are *monotonic* and rules have more a *constraints* flavor than real rules semantics.
- They lack, e.g.,
  - minimality aspects
  - negation as failure
- We consider here *hybrid knowledge bases*, in which (full-fledged) non-monotonic Logic Programming, based on the expressive Answer Set Semantics [Gelfond and Lifschitz, 1991] (aka *Answer Set Programming*), is combined with ontologies in (monotonic) classical logic.

Hybrid Knowledge Bases

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

- a FO theory $\mathcal{T}$ (the *classical component*) in a FO language with signature (vocabulary) $\Sigma_\mathcal{T}$.
- an LP P (the *rules component*) with signature Σ_P.

The combined signature of $\mathcal{KB}$ is $\Sigma_{\mathcal{KB}} = \Sigma_\mathcal{T} \cup \Sigma_P$.

- 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 and Rousset, 1998].

LP vs. Classical Logic

- Nonmonotonic Logic Programs 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
  - Treatment of equality
  - Existential quantification
  - Decidability enforcement
- See e.g. [de Bruijn *et al.*, 2006], [Eiter *et al.*, 2006], [Rosati, 2006a], [Motik *et al.*, 2006];
  impact for SW architecture [Horrocks *et al.*, 2005], [Kifer *et al.*, 2005]

CWA vs. Open World Assumption

- LP aims at building a *single model*, by "closing" the world/senario

Reiter's CWA:

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

- FO logic / DL knowledge bases describe *(multiple) possible worlds/scenarios*

  they 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 [Bruijn *et al.*, 2005], [Damásio *et al.*, 2006], [Polleres *et al.*, 2006], [Williamson *et al.*, 2007]

Negation as Failure vs. Classical Negation

$$
\begin{array}{rrcl}
P: & person(X) & \leftarrow & author(X). \\
& nonAuthor(X) & \leftarrow & not\ author(X). \\
& person(joe\_doe). & &
\end{array}
\qquad
\begin{array}{rl}
\mathcal{T}: & \forall X.\,(Author(X) \supset Person(X)) \wedge \\
& \forall X.\,(\neg Author(X) \supset NonAuthor(X)) \wedge \\
& Person(joe\_doe).
\end{array}
$$

- Query: Is joe_doe not an author?
  - Conclude $nonAuthor(joe\_doe)$ from P:

    $Author(joe\_doe)$ is not provable (no rule has $Author$ in the head).
  - Do not conclude $nonAuthor(joe\_doe)$ from T:

    Models of T exist in which $Author(joe\_doe)$ is true and $NonAuthor(joe\_doe)$ is false.

Strong vs. Classical Negation

$$P: \quad person(X) \leftarrow author(X). \qquad \mathcal{T}: \quad \forall X. (Author(X) \supset Person(X)) \wedge$$
$$-person(joe\_doe). \qquad \neg Person(joe\_doe).$$

- Conclude $\neg Author(joe\_doe)$ from T;
- Do not conclude $-author(joe\_doe)$ from P
- strong negation can be seen as negation under OWA but in a single model setting, where knowledge might be incomplete (neither A nor $-A$ is true).

  Different from classical logic (*Tertium not datur*)
- Note: there is no contraposition in LP!

  $$-author(X) \leftarrow -person(X).$$

  is not equivalent to

  $$person(X) \leftarrow author(X).$$

Treatment of Equality

- In LP, usally we have *Unique Names Assumption (UNA)*:
  Syntactically different ground terms are different objects.
- This holds for the customary Herbrand interpretations considered in LP

$$knowsOtherPeople(X) \leftarrow knows(X,Y), X \neq Y.$$
$$knows(``http://polleres.net/foaf.rdf\#me'', ``http://www.polleres.net/foaf.rdf\#me'').$$

Under LP semantics ("$\neq$" amounts to "$not =$"), conclude

$$knowsOtherPeople(``http://polleres.net/foaf.rdf\#me'')$$

- RDF and OWL consider also non-Herbrand interpretations; no UNA
- OWL allows to relate objects using `owl:sameAs` and `owl:differentFrom`

Existential Quantification

- Furthermore, there are related problems with existential quantifiers:

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

(in DL Syntax, $Person \sqsubseteq \exists hasNationality$)

Skolemization of Y in the consequent

$$\mathcal{T}: \quad \forall X.\,(Person(X) \supset hasNationality(X, f_Y(X)))$$

- equi-satisfiable formula, could be seen as LP rule
- however,
  - LP dialect may exclude function symbols (e.g., Datalog)
  - if so, Herbrand semantics can not be applied
  - LP models become necessarily infinite
- Recent interest in handling function symbols in ASP, e.g. [Bonatti, 2004], [Baselice *et al.*, 2007], [Simkus and Eiter, 2007] + references

Decidability Enforcement

- Obstacle: the LP and DL worlds face undecidability issues from two completely different angles.
- LP: for function-free LPs, ground entailment can be determined by checking subsets of a *finite* Herbrand base
- DL: sometimes exploit that models have a particular form (e.g, tree-shaped models), or that DL can be recast to a decidable fragment of FOL.

  But: DL $\mathcal{SHOIN}$ lacks the tree-model and finite-model property.
- Levy and Rousset's pioneering work 1998: Combinations of Horn logic and very simple DLs are undecidable

Decidability Enforcement (ctd.)

- Problems with recursion and *unsafety* of rules

  Recall: rule r is *safe*, if each variable in r occurs in a positive literal in r's body

- Variants of safety are a key tool for decidability of some combinations.

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

Example

$$uncleOf(X, Y) \leftarrow parentOf(Z, Y), brotherOf(X, Z).$$

is not role-safe; its variant

$$\begin{aligned} uncleOf(X, Y) \leftarrow & parentOf(Z, Y), brotherOf(X, Z), \\ & \color{red}{person(X), person(Y)}, \end{aligned}$$

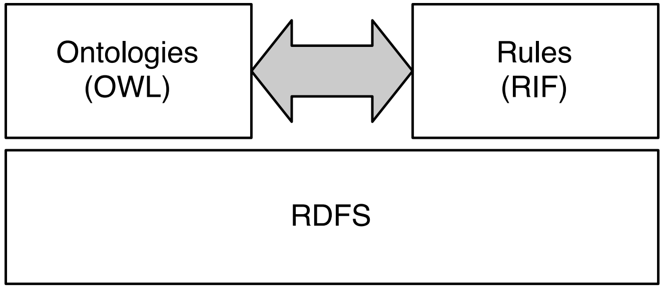
where $person$ is for facts in P, is role-safe.

Hybrid Approaches: Taxonomy

- Different approaches to a semantics for a hybrid KB $\mathcal{KB} = \langle \mathcal{T}, P \rangle$
  - Strict semantic separation (loose coupling)
  - Tight semantic integration
  - Full integration
- Surveys and discussion (selection):
  - KNOWLEDGEWEB [Pan *et al.*, 2004]
  - REWERSE [Antoniou *et al.*, 2005]
  - ReasoningWeb [Rosati, 2006a], [Eiter *et al.*, 2006]

Loose Coupling

- Strict semantic separation between rules / ontology



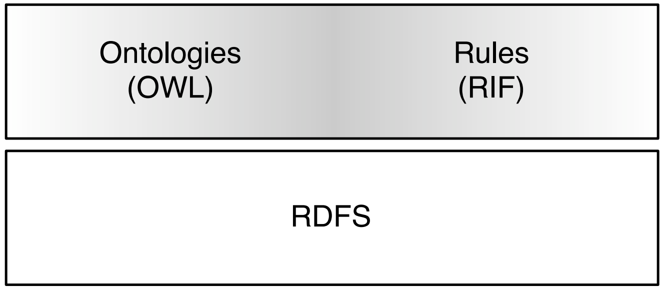
  - View rule base P and FO theory $\mathcal{T}$ as separate, independent components. $\Sigma_{\mathcal{T}}$ and Σ_P do (a priori) not share meaning.
  - They are connected through a minimal "safe interface" for exchanging knowledge (formulas, usually ground atoms).

- Well-suited for practical implementation on top of existing LP and DL reasoners.

Examples

nonmonotonic dl-programs [Eiter *et al.*, 2004][Eiter *et al.*, 2008];
defeasible logic+DLs [Wang *et al.*, 2004] (,**TRIPLE** [Sintek and Decker, 2002])

Tight Semantic Integration

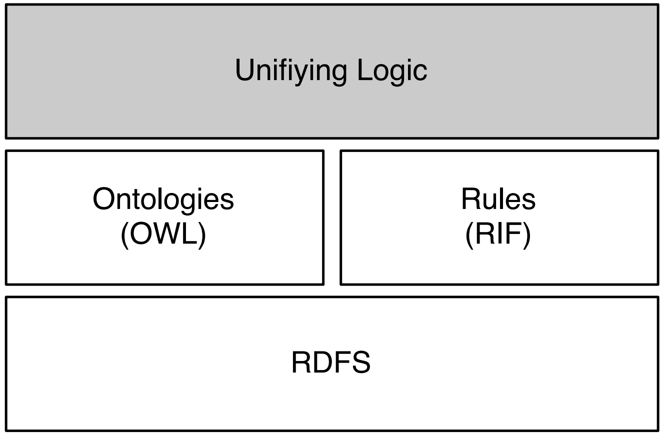


- Integrate FOL statements and the logic program to a large extent, but keep predicates of $\Sigma_{\mathcal{T}}$ and Σ_P separate.
- Build an *integrated model* M as the "union" of a model M_o of the FO theory $\mathcal{T}$ and a model M_l of P with the same domain.
- ensure *"safe interaction"* between M_o and M_l

Examples

CARIN [Levy and Rousset, 1998], **DLP** [Grosof *et al.*, 2003], **DL-safe rules** [Motik *et al.*, 2005], **R-hybrid KBs** [Rosati, 1999], [Rosati, 2005a] **R$^+$-hybrid KBs,** $\mathcal{DL}+log$ [Rosati, 2005b],[Rosati, 2006b]

Full Integration



- No principled separation between $\Sigma_{\mathcal{T}}$, Σ_P (but special axioms)

Examples

- Hybrid MKNF knowledge bases [Motik and Rosati, 2007a]
- FO-Autoepistemic Logic [de Bruijn *et al.*, 2007a]
- Open Answer Set Programs [Heymans *et al.*, 2007]
- Quantified Equilibrium Logic [de Bruijn *et al.*, 2007b]

- Related precursors: *Terminological Default Logic* [Baader and Hollunder, 1995], *DLs of Minimal Knowledge* [Donini *et al.*, 2002]

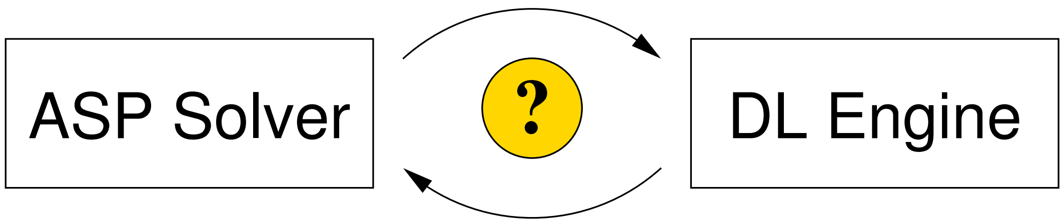
Sample Combination Approaches

- Briefly review some concrete approaches
- Consider one representative from each class
  - nonmonotonic dl-programs [Eiter *et al.*, 2004], [Eiter *et al.*, 2008]
  - $\mathcal{DL}+log$ [Rosati, 2006b]
  - Hybrid MKNF knowledge bases [Motik and Rosati, 2007a], [Motik and Rosati, 2007b]
- Comparison of these approaches

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

- 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 test $C \sqsubseteq D$; etc (recent extension: conjunctive queries)
- **Important**: Possible to modify the extensional part (ABox) of $\mathcal{T}$, by adding positive ($\uplus$) or negative ($\cupdot$) assertions, before querying
- Q evaluates to true iff the modified $\mathcal{T}$ proves Q.

Examples

- $DL[Author](\text{“}joey''\text{)}$
- $DL[Author](X)$
- $DL[isAuthorOf \uplus my\_isauthorOf; Author](X)$

  add all assertions $isAuthorOf(c)$ to $\mathcal{T}$ where $my\_isAuthorOf(c)$ holds in P.
- $DL[Author \cupdot no\_author; Author](X)$

  add all assertions $\neg Author(c)$ to $\mathcal{T}$, such that $no\_author(c)$ holds in P.

dl-Programs

- More formally, dl-atoms have form $DL[\langle Add\rangle; Q](\vec{X})$, where
  - $\langle Add\rangle = S_1\, op_1\, p_1, \ldots, S_m\, op_m\, p_m$, is a list of additions $S_i\, op_i\, p_i$, where S_i is a concept/role, p_i a unary/binary LP predicate, and $op_i \in \{\uplus, \cup\!\!\!\!-\}$;
  - $Q(\vec{X})$ is the query ($\vec{X}$ contains variables and/or constants).
- dl-programs are hybrid KB with dl-atoms in rules

A *dl-program* is a pair $\mathcal{KB} = \langle \mathcal{T}, P\rangle$ where

- $\mathcal{T}$ is a FO theory corresponding to a DL knowledge base
- P consists of rules

$$a_1 \vee \cdots \vee a_l \leftarrow b_1, \ldots, b_k, not\; b_{k+1}, \ldots, not\; b_m,$$

where each a_i is a classical literal and each b_j is either a classical literal or a dl-atom (no function symbols)

Example: Reviewer selection [Eiter *et al.*, 2008] (adapted)

$$paper(p_1);\ kw(p_1, Semantic\_Web); \tag{1}$$

$$paper(p_2);\ kw(p_2, Bioinformatics);\ kw(p_2, ASP); \tag{2}$$

$$\begin{aligned} kw(P, K_2) \leftarrow\ & kw(P, K_1),\ DL[hasMember](S, K_1), \\ & DL[hasMember](S, K_2); \end{aligned} \tag{3}$$

$$paperArea(P, A) \leftarrow DL[keywords \uplus kw; inArea](P, A); \tag{4}$$

$$\begin{aligned} cand\_rev(X, P) \leftarrow\ & paperArea(P, A), DL[CandidateReviewer](X), \\ & DL[expert](X, A); \end{aligned} \tag{5}$$

$$assign(X, P) \leftarrow cand\_rev(X, P), not\ {-assign}(X, P); \tag{6}$$

$$-assign(Y, P) \leftarrow cand\_rev(Y, P), assign(X, P),\ X \neq Y; \tag{7}$$

$$has\_rev(P) \leftarrow assign(X, P); \tag{8}$$

$$error(P) \leftarrow paper(P), not\ has\_rev(P). \tag{9}$$

- Determine paper area with enhanced keyword info (key word clusters) (3), (4)
- Use ontology to determine candidate reviewers (5)
- (6)–(9) is a plain ASP selection program (choose one $cand\_rev$ per paper))

Answer Sets

- The semantis of dl-programs is defined in terms of *answer sets*, generalizing classical Answer Set Semantics [Gelfond and Lifschitz, 1991].
- As usual, ground the rules over constants C (=: $gr(P)$)
- C contains the constants in P and additional ones from $\mathcal{T}$ (by default, all occurring in $\mathcal{T}$),
- A *model* is a consistent set of classical ground literals M built from the predicates in P and the constants in C.
- 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 $\langle Add\rangle^M$
- M is a model of P, if it satisfies all rules of $gr(P)$

Answer Sets (ctd.)

- Single out special models of P as (strong) answer sets of KB
- Use a reduct sP^M akin to the Gelfond-Lifschitz reduct P^M
- In building P^M, treat dl-atoms like ordinary atoms:

  sP^M contains all rules obtained from $gr(P)$ by removing

  1. all rule instances

     $$a_1 \vee \cdots \vee a_l \leftarrow b_1, \ldots, b_k, not\, b_{k+1}, \ldots, not\, b_m$$

     such that for some b_j, where $j \in \{k+1, \ldots, m\}$, it holds that b_j is true in M (which for a classical literal b_j means $b_j \in M$), and
  2. all negation-as-failure literals $not\, b_j$ from the remaining rules.
- M is a *(strong) answer set* of KB iff M is the least model of sP^M (resp. a minimal model of sP^M, if rules are disjunctive).

Variants exist (different treatment of the dl-atoms).

Example: Reviewer selection (ctd.)

- Answer sets of $\mathcal{KB}$ depend on the instances of $hasMember$, $keywords$, $inArea$, $expert$ $CandidateReviewer$

- Suppose in $\mathcal{T}$ $expert(jim,$"A1"$)$, $expert(tim,$"A1"$)$, $expert(sue,$"A2"$)$ $ReviewerCandidate(jim)$, $ReviewerCandidate(tim)$, $ReviewerCandidate(sue,LP)$, $hasMember(c_1, ASP)$, $hasMember(c_1, LP)$ are true (named clusters)

- further, that $inArea(p_1,$"A1"$)$ is true and $inArea(p_2,$"A2"$)$ is true after asserting $keywords(p_2,LP)$.

- $$\begin{aligned} M = \{ & (1), (2), kw(p_2, LP), paperArea(p_1, \text{``}A1''), paperArea(p_2, \text{``}A2''), \\ & cand\_rev(p_1, jim), cand\_rev(p_1, tim), cand\_rev(p_2, sue), \\ & assign(jim, p_1), -assign(tim, p_1), assign(sue, p_2), \\ & has\_rev(p_1), has\_rev(p_2) \qquad \} \end{aligned}$$

  is an answer set of $\mathcal{KB}$.

Example: Reviewer selection (ctd.) /2

$$M = \{\ (1),(2),\ kw(p_2, LP),\ paperArea(p_1, \text{“}A1''),\ paperArea(p_2, \text{“}A2''),\\ cand\_rev(p_1, jim),\ cand\_rev(p_1, tim),\ cand\_rev(p_2, sue),\\ assign(jim, p_1),\ -assign(tim, p_1),\ assign(sue, p_2),\\ has\_rev(p_1),\ has\_rev(p_2)\ \}$$

- Part 0: Facts
- Part 1: kw, $paperArea$, (LP, ASP in same cluster)
- Part 2 $cand\_rev$
- Part 3: choice for $assign$; has_rev; reduct sP^M (relevant part)

Note: A second answer set is $M = \{\ldots -assign(jim, p_1), assign(tim, p_1) \ldots\}$

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-style and Reiter-style Default Logic over DL knowledge bases (for restricted fragments, to the effect of *Terminological Default Logic*).

    Front-end [Dao, 2008]

  - **Minimal Model Reasoning**

    Single out "minimal" models of a DL base

Example: Reviewer Candidate Selection using Defaults

$$\begin{aligned}\mathcal{T} \quad = \quad \{ \quad & \neg ex{:}ConflictingReviewer \sqsubseteq ex{:}CandidateReviewer, \\ & ex{:}Senior(joe),\ ex{:}Senior(bob),\ ex{:}ConflictingReviewer(bob)\,\}.\end{aligned}$$

- Besides known candidate reviewers, by default also every senior author is a candidate reviewer (unless a conflict is apparent)
- This is mimicked by the following dl-program:

$$\begin{aligned} r_0: \quad & cand\_rev(P) \leftarrow DL[ex{:}CandidateReviewer]; \\ r_1: \quad & cand\_rev(P) \leftarrow DL[ex{:}Senior](P), not\ conflict(P); \\ r_2: \quad & conflict(P) \leftarrow DL[ex{:}CandidateReviewer \uplus cand\_rev; \\ & \qquad\qquad ex{:}ConflictingReviewer](P). \end{aligned}$$

- Under Answer Set Semantics, r_2 effects maximal application of r_1.
- Single answer set: $M = \{\ cand\_rev(joe),\ conflict(bob)\ \}$; reduct sP^M

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

- [Rosati, 2006b] Latest in chain of extensions of the DL $\mathcal{ALC}$ with rules [$\mathcal{AL}$-log; R-, R$^+$-hybrid KBs]
- choices:
  - Distinguish predicates in Σ_P and $\Sigma_\mathcal{T}$ and (the latter may appear in rule heads); no function symbols
  - a 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 $\mathcal{T}$ and M of P when fixing classical atoms in P to $\mathcal{I}$.
  - No strong negation, weak negation limited to rule-predicates
  - Uses *weak (DL-)safety* to ensure decidability
  - Decidable, if certain union of conjunctive queries containment (CQ/UCQ) in $\mathcal{T}$ is decidable,

Weak (DL-)safety

Each variable X in a rule r must occur in some positive body atom of r, and this atom must have a rule predicate if X occurs in an atom with classical predicate in the head of r.

- Weak safety allows to *access unnamed individuals* in classical atoms (not directly possible in dl-programs)
- **Example.** Consider $\mathcal{KB} = \langle \mathcal{T}, P \rangle$, where
  - $\mathcal{T} = \{ author \sqsubseteq \exists isAuthorOf, author(turing) \}$
  - $P = \{ scientist(X) \leftarrow isAuthorOf(X, Y), not\ likes(X, astrology) \}$

  - the rule is weakly DL-safe
  - $scientist(turing)$ follows from $\mathcal{KB}$, even if publications of $turing$ are unknown!
- Note: the dl-rule

$$scientist(X) \leftarrow DL[isAuthorOf](X, Y), not\ likes(X, astrology)$$

would not entail $scientist(turing)$ (needs rewriting)

$\mathcal{DL}+log$: 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, using the Gelfond-Lifschitz reduct $P_{\mathcal{I}}^{M}$

Example

$$\mathcal{T} = \{\ Multilingual \sqsubseteq \neg Monolingual;\quad Multilingual \sqcup Monolingual \sqsubseteq Author$$
$$Author \sqsubseteq \exists isAuthorOf;\quad Author(joey)\ \}$$

$$P = \{\ novelist(X) \mid scientist(X) \leftarrow writer(X);$$
$$Monolingual(X) \leftarrow novelist(X);$$
$$Multilingual(X) \leftarrow scientist(X);$$
$$scientist(X) \leftarrow writer(X), isAuthorOf(X,Y), not\ likes(X, astrology);$$
$$writer(joey)\ \}$$

- Classical predicates $Monolingual$, $Multilingual$, $isAuthorOf$ occur in rules.
- Take $\mathcal{I}$ s.t. $\{Author(joey), Multilingual(joey)\}$ holds in it: $P_{\mathcal{I}}$

  $M_1 = \{writer(joey), scientist(joey)\}$: ${P_{\mathcal{I}}}_1^M$ has min. model $M_1 \Rightarrow$ stable
  $M_2 = \{writer(joey), novelist(joey)\}$: ${P_{\mathcal{I}}}_2^M$ hasn't min. model $M_2 \Rightarrow$ unstable
- Take $\mathcal{I}$ s.t. where $\{Monolingual(joey), Person(joey)\}$ holds in it: $P_{\mathcal{I}}$

  No stable model (in any such M, $likes(joey, astrology)$ must be false)

Full Integration: Hybrid MKNF

- Builds on a FO-version of the Lifschitz bimodal logic MKNF [Lifschitz, 1991]
- Rules r are of the form

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

  where the h_i, b_j are function-free FO atoms
  - $\mathbf{K}\phi \approx$ "ϕ is known to hold under the values of the not-atoms"
  - $\mathbf{not}\phi \approx$ "there is the possibility that ϕ is false".
- The FO part $\mathcal{T}$ is converted to a formula MKNF$(\mathcal{T}) = \mathbf{K}(\bigwedge_{\phi \in \mathcal{T}} \phi)$ (assuming finiteness)
- The approach faithfully extends LP and DL; it generalizes CARIN, $\mathcal{AL}$-log, and DL-safe rules;
- Allows "closed world glasses" on classical predicates, stating exceptions
- Decidable for decidable $\mathcal{T}$ under DL-safety

Hybrid MKNF: Semantics

- Kripke-style semantics for modal logics ("maximal" S5-models wrt. operator $\mathbf{K}$)
- Uses as $\mathcal{DL}+log$ a fixed, countably infinite domain and standard names (no function symbols), in fact Herbrand interpretations
- A *model* is a structure $(\mathcal{I}, \mathcal{M}, \mathcal{N})$, where $\mathcal{I}$ is an interpretation, and $\mathcal{M}, \mathcal{N}$ are *sets of interpretations* (possible worlds)
- at world $\mathcal{I}$, atoms, propositional combinations of formulas, and quantifiers are evaluated as usual in first-order logic.
  - $\mathbf{K}\phi$ evaluates to true at $\mathcal{I}$, if ϕ evaluates to true at each $\mathcal{I}' \in \mathcal{M}$ (S5 semantics);
  - $\mathbf{not}\,\phi$ evaluates to true at $\mathcal{I}$, if ϕ evaluates to false at some $\mathcal{I}' \in \mathcal{N}$.

Hybrid MKNF: Semantics (ctd.)

- $\mathcal{M}$ is an *MKNF model* of $\mathcal{KB} = \langle \mathcal{T}, P \rangle$, if
  1. the formula

     $$\text{MKNF}(\mathcal{KB}) = \text{MKNF}(\mathcal{T}) \wedge \text{MKNF}(P)$$

     is true in $(\mathcal{I}, \mathcal{M}, \mathcal{M})$ for each world $\mathcal{I} \in \mathcal{M}$ where MKNF(P) is the usual rewriting of P to FO logic (rewrite rules as universal implications), and
  2. no $\mathcal{M}' \supset \mathcal{M}$ exists such that MKNF$(\mathcal{KB})$ evaluates to true in $(\mathcal{I}, \mathcal{M}', \mathcal{M})$ for some world $\mathcal{I} \in \mathcal{M}'$
- Note: condition 2) implements the *Minimal Knowledge Principle*
- for modal-free ϕ, the formula $\mathbf{K}\phi$ is equivalent to ϕ
- $\mathbf{not}$ implements negation as failure

Hybrid MKNF: Example

$$\mathcal{T} = \{\ Multilingual \sqsubseteq \neg Monolingual; \quad Multilingual \sqcup Monolingual \sqsubseteq Author$$
$$Author \sqsubseteq \exists isAuthorOf; \quad Author(joey); \quad Lefthanded \sqsubseteq Author \quad \}$$

$$\begin{aligned} P = \{\ & \mathbf{K} novelist(X) \vee \mathbf{K} scientist(X) \leftarrow \mathbf{K} writer(X); \\ & \mathbf{K} Monolingual(X) \leftarrow \mathbf{K} novelist(X); \\ & \mathbf{K} Multilingual(X) \leftarrow \mathbf{K} scientist(X); \\ & \mathbf{K} scientist(X) \leftarrow \mathbf{K} writer(X), \mathbf{K} isAuthorOf(Y, X), \\ & \qquad\qquad not\ likes(X, astrology); \\ & \mathbf{K} writer(joey); \\ & \mathbf{K} Righthanded(X) \leftarrow \mathbf{K} Author(X), not\ Lefthanded(X) \quad \} \end{aligned}$$

- Authors are righthanded, if not lefthanded
- Assume that, by default, a person is not lefthanded
- conclude $Righthanded(joey)$ from $\mathcal{KB}$
- Not expressible in $\mathcal{DL}$+log in this way

Assessment (+ . . . yes, − . . . no, +∼ . . . yes, with some proviso)

	dl-programs	$\mathcal{DL}+log$	hybrid MKNF	SWRL
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	+	+	+	−
Special equality predicate	+∼	+∼	+	+
No uniqueness	−	−	−	+
Knowledge Interaction: from FO theory $\mathcal{T}$ to logic program P				
Per single model	−	+	−	+
Entailment	+	−	+	−
Knowledge Interaction: from logic program P to FO theory $\mathcal{T}$				
Per single model	−	+	+	+
Entailment	+	−	−	−
Decidability				
	+∼	+∼	+∼	−

- A number of criteria

Assessment /2

- **Predicate distinction:** indication of the level of coupling
- **Domain of discourse of P:** SWRL is an outlier, all other approaches are more or less close to Herbrand universes
- **Uniqueness of Names:** again, SWRL is different from the others

  In dl-programs and $\mathcal{DL}+log$, special equality predicates might defined as *congruence relations* in $\mathcal{KB}$
- **Knowledge interaction from $\mathcal{T}$ to P:** literals with "classical" predicate in a rule depend for a model M of P on a single model of/multiple model entailment from $\mathcal{T}$
- **Knowledge interaction from P to $\mathcal{T}$:**
  - *single-model interaction:* each model M of P *constrains* the models of $\mathcal{T}$ to ones where all classical predicates are larger than in M
  - *entailment based interaction:* positive conclusions about the classical predicates from a model M of P are added to $\mathcal{T}$

Further Aspects

Several extensions and further/alternative aspects have been considered (see lecture notes), including

- **Probabilistic ASP for SW**
- **Fuzzy ASP for SW**
- **Stable models for extended RDF/S**
- **Well-founded semantics**
- **Mapping of FOL/DL into LP**

- Grigoris Antoniou, Carlos Viegas Damásio, Benjamin Grosof, Ian Horrocks, Michael Kifer, Jan Maluszynski, and Peter F. Patel-Schneider.
  Combining Rules and Ontologies: A survey.
  Technical Report IST506779/Linköping/I3-D3/D/PU/a1, Linköping University, February 2005.
  IST-2004-506779 REWERSE Deliverable I3-D3. `http://rewerse.net/publications/`.

- F. Baader and B. Hollunder.
  Embedding defaults into terminological representation systems.
  J. Automated Reasoning, 14:149–180, 1995.

- Sabrina Baselice, Piero A. Bonatti, and Giovanni Criscuolo.
  On finitely recursive programs.
  In *Proceedings 23rd International Conference on Logic Programming (ICLP 2007)*, volume 4670 of *Lecture Notes in Computer Science*, pages 89–103. Springer, 2007.

- Piero A. Bonatti.
  Reasoning with infinite stable models.
  Artificial Intelligence, 156(1):75–111, 2004.

- Jos de Bruijn, Axel Polleres, Rubén Lara, and Dieter Fensel.
  OWL DL vs. OWL Flight: Conceptual modeling and reasoning on the semantic web.
  In *Proceedings of the 14th International World Wide Web Conference (WWW2005)*, pages 623–632, Chiba, Japan, 2005. ACM Press.

- Carlos Viegas Damásio, Anastasia Analyti, Grigoris Antoniou, and Gerd Wagner.
  Supporting open and closed world reasoning on the web.

In *PPSWR*, volume 4187 of *Lecture Notes in Computer Science*, pages 149–163. Springer, 2006.

Tran Minh Dao.
Default Reasoning on Top of Ontologies with DL-Programs.
Master's thesis, Vienna University of Technology, Karlsplatz 13, A-1040 Wien, June 2008.

Jos de Bruijn, Thomas Eiter, Axel Polleres, and Hans Tompits.
On representational issues about combinations of classical theories with nonmonotonic rules.
In *Proceedings of the 1st International Conference on Knowledge Science, Engineering and Management (KSEM'06)*, volume 4092 of *Lecture Notes in Computer Science (LNCS)*, pages 1–22, Guilin, China, 2006. Springer.

Jos de Bruijn, Thomas Eiter, Axel Polleres, and Hans Tompits.
Embedding non-ground logic programs into autoepistemic logic for knowledge base combination.
In M. Veloso, editor, *Proceedings 20th International Joint Conference on Artificial Intelligence (IJCAI 2007)*, pages 304–309. AAAI Press/IJCAI, 2007.

Jos de Bruijn, David Pearce, Axel Polleres, and Agustín Valverde.
Quantified equilibrium logic and hybrid rules.
In *Web Reasoning and Rule Systems, First International Conference, RR 2007, Innsbruck , Austria, June 7-8, 2007, Proceedings*, pages 58–72, 2007.

Francesco M. Donini, Daniele Nardi, and Riccardo Rosati.
Description logics of minimal knowledge and negation as failure.

ACM Trans. Comput. Log., 3(2):177–225, 2002.

T. Eiter, T. Lukasiewicz, R. Schindlauer, and H. Tompits.
Combining answer set programming with description logics for the Semantic Web.
In *Proceedings KR-2004*, pages 141–151, 2004.

Thomas Eiter, Giovambattista Ianni, Axel Polleres, Roman Schindlauer, and Hans Tompits.
Reasoning with rules and ontologies.
In Pedro Barahona, François Bry, Enrico Franconi, Ulrike Sattler, and Nicola Henze, editors, *Reasoning Web 2006*, volume 4126 of *LNCS*, pages 93–127. Springer, September 2006.

Thomas Eiter, Giovambattista Ianni, Thomas Lukasiewicz, Roman Schindlauer, and Hans Tompits.
Combining Answer Set Programming with Description Logics for the Semantic Web.
Artificial Intelligence, 172(12-13):1495–1539, 2008.
doi:10.1016/j.artint.2008.04.002.

M. Gelfond and V. Lifschitz.
Classical Negation in Logic Programs and Disjunctive Databases.
New Generation Computing, 9:365–385, 1991.

B. N. Grosof, I. Horrocks, R. Volz, and S. Decker.
Description logic programs: Combining logic programs with description logics.
In *Proceedings WWW-2003*, pages 48–57, 2003.

Stijn Heymans, Davy Van Nieuwenborgh, and Dirk Vermeir.

Open answer set programming for the semantic web.
J. Applied Logic, 5(1):144–169, 2007.

Ian Horrocks, Bijan Parsia, Peter Patel-schneider, and James Hendler.
Semantic web architecture: Stack or two towers.
In *Proc. of Principles and Practice of Semantic Web Reasoning. 3rd Int. WS, PPSWR 2005, Dagstuhl*, pages 37–41. Springer, 2005.

Michael Kifer, Jos de Bruijn, Harold Boley, and Dieter Fensel.
A realistic architecture for the semantic web.
In *Proceedings of the 1st International Conference on Rules and Rule Markup Languages for the Semantic Web (RuleML2005)*, number 3791 in Lecture Notes in Computer Science, pages 17–29, Galway, Ireland, November 2005. Springer.

A. Y. Levy and M.-C. Rousset.
Combining Horn Rules and Description Logics in CARIN.
Artificial Intelligence, 104(1-2):165–209, 1998.

Vladimir Lifschitz.
Nonmonotonic databases and epistemic queries.
In *Proceedings IJCAI-91*, pages 381–386, 1991.

Boris Motik and Riccardo Rosati.
A faithful integration of description logics with logic programming.
In *IJCAI 2007, Proceedings of the 20th International Joint Conference on Artificial Intelligence*, pages 477–482, 2007.

Botis Motik and Riccardo Rosati.

Closing semantic web ontologies.
Technical report, University of Manchester, March 2007.
Available from http://web.comlab.ox.ac.uk/oucl/work/boris.motik/publications/mr06closing-report.pdf.

Boris Motik, Ulrike Sattler, and Rudi Studer.
Query Answering for OWL-DL with Rules.
Journal of Web Semantics: Science, Services and Agents on the World Wide Web, 3(1):41–60, 2005.

Boris Motik, Ian Horrocks, Riccardo Rosati, and Ulrike Sattler.
Can OWL and logic programming live together happily ever after?
In *Proceedings ISWC-2006*, volume 4273 of *LNCS*, pages 501–514. Springer, 2006.

J. Z. Pan, E. Franconi, S. Tessaris, G. Stamou, V. Tzouvaras, L. Serafini, I. R. Horrocks, and B. Glimm.
Specification of Coordination of Rule and Ontology Languages.
Project Deliverable D2.5.1, KnowledgeWeb NoE, June 2004.

Axel Polleres, Cristina Feier, and Andreas Harth.
Rules with contextually scoped negation.
In *Proceedings ESWC-2006*, volume 4011 of *LNCS*, pages 332–347. Springer, 2006.

R. Rosati.
Towards Expressive KR Systems Integrating Datalog and Description Logics: Preliminary Report.

In *Proceedings of the 1999 International Workshop on Description Logics (DL '99)*, pages 160–164, 1999.

Riccardo Rosati.
On the Decidability and Complexity of Integrating Ontologies and Rules.
Journal of Web Semantics, 3(1):61–73, 2005.

Riccardo Rosati.
Semantic and computational advantages of the safe integration of ontologies and rules.
In *Principles and Practice of Semantic Web Reasoning, Third International Workshop, PPSWR 2005*, volume 3703 of *Lecture Notes in Computer Science*, pages 50–64. Springer, 2005.

Riccardo Rosati.
Integrating Ontologies and Rules: Semantic and Computational Issues.
In Pedro Barahona, François Bry, Enrico Franconi, Ulrike Sattler, and Nicola Henze, editors, *Reasoning Web, Second International Summer School 2006, Lissabon, Portugal, September 25-29, 2006, Tutorial Lectures*, volume 4126 of *LNCS*, pages 128–151. Springer, September 2006.

Riccardo Rosati.
$\mathcal{DL}+log$: Tight Integration of Description Logics and Disjunctive Datalog.
In *Proceedings of the Tenth International Conference on Principles of Knowledge Representation and Reasoning (KR 2006)*, pages 68–78. AAAI Press, 2006.

Mantas Simkus and Thomas Eiter.
FDNC: Decidable non-monotonic disjunctive logic programs with function symbols.

In *Logic for Programming, Artificial Intelligence, and Reasoning, 14th International Conference, LPAR*, pages 514–530, 2007.
Full paper Tech. Rep. INFSYS RR-1843-08-01, TU Vienna.
http://www.kr.tuwien.ac.at/research/reports/rr0801.pdf.

Michael Sintek and Stefan Decker.
TRIPLE - A Query, Inference, and Transformation Language for the Semantic Web.
In *Proceedings of the First International Semantic Web Conference* (*ISWC 2002*), volume 2342 of *Lecture Notes in Computer Science* (*LNCS*), pages 364–378, 2002.

Kewen Wang, David Billington, Jeff Blee, and Grigoris Antoniou.
Combining Description Logic and Defeasible Logic for the Semantic Web.
In *Proceedings of the ISWC 2004 Workshop on Rules and Rule Markup Languages for the Semantic Web* (*RuleML 2004*), volume 3323 of *Lecture Notes in Computer Science* (*LNCS*), pages 170–181. Springer Verlag, 2004.

Carey L. Williamson, Mary Ellen Zurko, Peter F. Patel-Schneider, and Prashant J. Shenoy, editors.
Proceedings of the 16th International Conference on World Wide Web, WWW 2007, Banff, Alberta, Canada, May 8-12, 2007. ACM, 2007.