

Combining safe rules and ontologies by interfacing of reasoners

Uwe Aßmann, Jakob Henriksson, Jan Małuszyński

PPSWR06, Budva, Montenegro, 10th June 2006

The objective

- Define a scheme that
from given
 - Rule language R (e.g. Datalog, Xcerpt)
 - Logical language S (e.g. OWL-DL, ...)constructs
 - A language R_S integrating R and S:
 - + Syntax, Semantics of R_S : from syntax and semantics of R and S
 - + A (complete) reasoner for R_S
by interfacing the reasoners of R and S

Outline

- Motivating example
- The scheme
 - Principles and restrictions
 - An instance:
 - + Datalog + OWL-DL
 - + Prototype: interfacing XSB and a DL reasoner
- Conclusions
- Related work

Motivating example

Rule component Π :

r_1 : price-in-usa(X ,high) \leftarrow
made-by(X , Y),
NoFellowCompany(Y).

r_2 : price-in-usa(X ,high) \leftarrow
made-by(X , Y),
Associate(Y , Z),
American(Z),
monopoly-in-usa(Y , X).

r_3 : made-by(a , b).

r_4 : monopoly-in-usa(b , a).

DL component Σ :

T-Box:

European \cap American $\subseteq \perp$
EuropeanAssociate $\equiv \exists$ Associate.European
AmericanAssociate $\equiv \exists$ Associate.American
NoFellowCompany $\equiv \forall$ Associate. \neg American
InternationalCompany \equiv EuropeanAssociate \cup
AmericanAssociate

A-Box:

InternationalCompany(b)

Ref: A.Levy and M C.Rousset.CARIN:A Representation Language Combining Horn rules and Description Logics. Artificial Intelligence 104(1 2):165 –209, 1998.

Motivating example

Rule component Π :

r_1 : price-in-usa(X ,high) \leftarrow
 made-by(X , Y),
 NoFellowCompany(Y).

r_2 : price-in-usa(X ,high) \leftarrow
 made-by(X , Y),
 Associate(Y , Z),
 American(Z),
 monopoly-in-usa(Y , X).

r_3 : made-by(a , b).

r_4 : monopoly-in-usa(b , a).

DL component Σ :

T-Box:

European \cap American $\subseteq \perp$
 EuropeanAssociate $\equiv \exists$ Associate.European
 AmericanAssociate $\equiv \exists$ Associate.American
 NoFellowCompany $\equiv \forall$ Associate. \neg American
 InternationalCompany \equiv EuropeanAssociate \cup
 AmericanAssociate

A-Box:

InternationalCompany(b)

Constraining the extent of
 the head predicate in
 models of the rule-base

With constraint domain

Motivating example

- $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$?

Rule component Π :

r_1 : $\text{price-in-usa}(X, \text{high}) \leftarrow$
 $\text{made-by}(X, Y),$
 $\text{NoFellowCompany}(Y).$

r_2 : $\text{price-in-usa}(X, \text{high}) \leftarrow$
 $\text{made-by}(X, Y),$
 $\text{Associate}(Y, Z),$
 $\text{American}(Z),$
 $\text{monopoly-in-usa}(Y, X).$

r_3 : $\text{made-by}(a, b).$

r_4 : $\text{monopoly-in-usa}(b, a).$

DL component Σ :

T-Box:

$\text{European} \cap \text{American} \subseteq \perp$
 $\text{EuropeanAssociate} \equiv \exists \text{Associate}. \text{European}$
 $\text{AmericanAssociate} \equiv \exists \text{Associate}. \text{American}$
 $\text{NoFellowCompany} \equiv \forall \text{Associate}. \neg \text{American}$
 $\text{InternationalCompany} \equiv \text{EuropeanAssociate} \cup \text{AmericanAssociate}$

A-Box:

$\text{InternationalCompany}(b)$

Motivating example

- $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$?

Rule component Π :

r_1 : $\text{price-in-usa}(\mathbf{a}, \text{high}) \leftarrow$
 $\text{made-by}(\mathbf{a}, \mathbf{b}),$
 $\text{NoFellowCompany}(\mathbf{b}).$

r_2 : $\text{price-in-usa}(X, \text{high}) \leftarrow$
 $\text{made-by}(X, Y),$
 $\text{Associate}(Y, Z),$
 $\text{American}(Z),$
 $\text{monopoly-in-usa}(Y, X).$

r_3 : $\text{made-by}(a, b).$
 r_4 : $\text{monopoly-in-usa}(b, a).$

DL component Σ :

T-Box:

$\text{European} \cap \text{American} \sqsubseteq \perp$
 $\text{EuropeanAssociate} \equiv \exists \text{Associate}. \text{European}$
 $\text{AmericanAssociate} \equiv \exists \text{Associate}. \text{American}$
 $\text{NoFellowCompany} \sqsubseteq \text{InternationalCompany}$
 $\text{InternationalCompany} \equiv \text{EuropeanAssociate} \cup \text{AmericanAssociate}$

$\Sigma \not\models \text{NoFellowCompany}(b)$

A-Box:

$\text{InternationalCompany}(b)$

Motivating example

- $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$?

Rule component Π :

r_1 : $\text{price-in-usa}(X, \text{high}) \leftarrow$
 $\text{made-by}(X, Y),$
 $\text{NoFellowCompany}(Y).$

r_2 : $\text{price-in-usa}(\mathbf{a}, \text{high}) \leftarrow$
 $\text{made-by}(\mathbf{a}, \mathbf{b}),$
 $\text{Associate}(\mathbf{b}, _Z),$
 $\text{American}(_Z),$
 $\text{monopoly-in-usa}(\mathbf{b}, \mathbf{a}).$

r_3 : $\text{made-by}(a, b).$

r_4 : $\text{monopoly-in-usa}(b, a).$

DL component Σ :

T-Box:

$\text{European} \cap \text{American} \sqsubseteq \perp$

$\text{EuropeanAssociate} \equiv \exists \text{Associate}. \text{European}$

$\text{AmericanAssociate} \equiv \exists \text{Associate}. \text{American}$

$\text{NoFellowCompany} \sqsubseteq \text{Associate} \sqcup \text{American}$

$\text{InternationalCompany} \sqsubseteq \text{EuropeanAssociate} \cup$

AmericanAssociate

$\Sigma \not\models \exists (\text{Associate}(\mathbf{b}, _Z) \wedge$
 $\text{American}(_Z))$

A-Box:

$\text{InternationalCompany}(b)$

Motivating example

- $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$?

Rule component Π :

r_1 : $\text{price-in-usa}(\mathbf{a}, \text{high}) \leftarrow$
 $\text{made-by}(\mathbf{a}, \mathbf{b}),$
 $\text{NoFellowCompany}(\mathbf{b}).$

r_2 : $\text{price-in-usa}(\mathbf{a}, \text{high}) \leftarrow$
 $\text{made-by}(\mathbf{a}, \mathbf{b}),$
 $\text{Associate}(\mathbf{b}, _Z),$
 $\text{American}(_Z),$
 $\text{monopoly-in-usa}(\mathbf{b}, \mathbf{a}).$

r_3 : $\text{made-by}(\mathbf{a}, \mathbf{b}).$

r_4 : $\text{monopoly-in-usa}(\mathbf{b}, \mathbf{a}).$

DL component Σ :

T-Box:

But:

$\text{European} \cap \text{American} \sqsubseteq \perp$

$\Sigma \models \text{NoFellowCompany}(\mathbf{b})$

$\text{European} \sqsubseteq \text{Associate} \sqcap \text{American}$

$\text{AmericanAssociate} \equiv \exists \text{Associate}.\text{American}$

$\text{NoFellowCompany} \equiv \forall \text{Associate}.\neg \text{American}$

$\text{InternationalCompany} \equiv \text{EuropeanAssociate} \cup \text{AmericanAssociate}$

$\exists (\text{Associate}(\mathbf{b}, _Z) \wedge$
 $\text{American}(_Z))$

A-Box:

$\text{InternationalCompany}(\mathbf{b})$

Motivating example

- $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$

Rule component Π :

r_1 : $\text{price-in-usa}(\mathbf{a}, \text{high}) \leftarrow$
 $\text{made-by}(\mathbf{a}, \mathbf{b}),$
 $\text{NoFellowCompany}(\mathbf{b}).$

r_2 : $\text{price-in-usa}(\mathbf{a}, \text{high}) \leftarrow$
 $\text{made-by}(\mathbf{a}, \mathbf{b}),$
 $\text{Associate}(\mathbf{b}, _Z),$
 $\text{American}(_Z),$
 $\text{monopoly-in-usa}(\mathbf{b}, \mathbf{a}).$

r_3 : $\text{made-by}(a, b).$

r_4 : $\text{monopoly-in-usa}(b, a).$

DL component Σ :

T-Box:

Thus:

$\text{European} \cap \text{American} \sqsubseteq \perp$

$\text{European} \sqcap \text{Associate} \equiv \neg \text{Associate} : \text{European}$

$\text{American} \sqcap \text{Associate} \equiv \neg \text{Associate} : \text{American}$

$\text{NoFellowCompany} \equiv \forall \text{Associate}. \neg \text{American}$

$\text{InternationalCompany} \equiv \text{EuropeanAssociate} \cup \text{AmericanAssociate}$

A-Box:

$\text{InternationalCompany}(b)$

$\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$

Rules we consider

HEAD ← BODY

- HEAD is some basic construct (*atom*)
- BODY is a set of atoms
- **Safety**: head variables appear in the body
- Examples:
 - + Datalog: atomic formulae
 - + Xcerpt: *Query terms* and *Construct terms*

Semantics of rules

- Fixpoint semantics

- Rules derive ground atoms from given ground atoms
 - + *matching* of body atoms vs. given atoms gives substitution θ
 - + θ applied to head \Rightarrow derived atom

$$T_P(S) = \{ H\theta \mid (H \leftarrow B_1, \dots, B_n) \in P \text{ and } (B_1, \dots, B_n) \text{ matches some } A_1, \dots, A_n \text{ in } S \text{ with result } \theta \}$$

- T_P monotonic, $T_P(S) \subseteq T_P(S')$ for any $S \subseteq S'$
- **Semantics of program P:** least fixpoint of T_P

Examples of rule languages

- The class includes:
 - Logical rule languages, e.g.
 - + **Datalog** (without negation)
 - + Semantics of program: set of Datalog atoms
 - + least Herbrand model
 - Rule languages lacking logical semantics, e.g.
 - + **Xcerpt** (negation-free subset)
 - + Semantics of program: set of Xcerpt data terms

Extended rules

HEAD \leftarrow BODY, C

- C formula of an *external theory* in logical language L
- Ground atoms associated with a constraint
 - + A;C where A ground atom, C formula of L
- Extend T_P operator

$$T_P(S) = \{ H\theta; (C\theta \wedge C_1 \wedge \dots \wedge C_n) \mid (H \leftarrow B_1, \dots, B_n, C) \in P \text{ and} \\ \text{for some } A_1;C_1, \dots, A_n;C_n \text{ in } S \\ (B_1, \dots, B_n) \textit{ matches } A_1, \dots, A_n \text{ with result } \theta \}$$

Semantics of extended rules

- Restrict model of underlying rule program
 - A constraint C , wrt. an external theory Σ , can be:
 1. True in all models of Σ ($\Sigma \models C$)
 2. False in all models of Σ ($\Sigma \models \neg C$)
 3. None of above:
satisfiable, but false in some models of Σ
- $M(P) = \{ A \mid A \in \text{lfp}(T_P) \text{ and } \Sigma \models C_A \}$
- C_A is the disjunction of all constraints of A

Instance: Datalog + OWL-DL

- Restrictions:
 - Only OWL concepts
- Requirements
 - (1) Collect constraints from Datalog in XSB
 - (2) Solve disjunctive DL constraints in existing reasoner

(1) Collecting constraints

- Existing rule reasoners not aware of “external” predicates
 - How re-use rule reasoners?
 - How collect constraints?
 - Must be solved specifically for each language and rule reasoner
 - Here: **Datalog** in **XSB**

Π

r_1 : price-in-usa(X,high) ←
made-by(X,Y),
NoFellowCompany(Y).

r_2 : price-in-usa(X,high) ←
made-by(X,Y),
Associate(Y,Z),
American(Z),
monopoly-in-usa(Y,X).

r_3 : made-by(a,b).

r_4 : monopoly-in-usa(b,a).

(1) Collecting constraints

■ Collecting constraints in XSB

Π

```
price-in-usa(X,high) :-  
  made-by(X,Y),  
  NoFellowCompany(Y).
```

```
price-in-usa(X,high) :-  
  made-by(X,Y),  
  Associate(Y,Z),  
  American(Z),  
  monopoly-in-usa(Y,X).
```

```
made-by(a,b).  
monopoly-in-usa(b,a).
```

Π'

```
price-in-usa(X,high,[NoFellowCompany(Y)|A]) :-  
  made-by(X,Y,A).
```

```
price-in-usa(X,high,[Associate(Y,Z),American(Z)|A]) :-  
  made-by(X,Y,A1),  
  monopoly-in-usa(Y,X,A2),  
  append(A1,A2,A).
```

```
made-by(a,b,[]).  
monopoly-in-usa(b,a,[]).
```

(1) Collecting constraints

- Query $\leftarrow price-in-usa(a, high, \mathbf{C})$ wrt. Π' :

$\mathbf{C} = [NoFellowCompany(b)]$

$\mathbf{C} = [Associate(b, _Z), American(_Z)]$

Π'

```
price-in-usa(X,high,[NoFellowCompany(Y)|A]) :-  
  made-by(X,Y,A).
```

```
price-in-usa(X,high,[Associate(Y,Z),  
                    American(Z)|A]) :-  
  made-by(X,Y,A1),  
  monopoly-in-usa(Y,X,A2),  
  append(A1,A2,A).
```

```
made-by(a,b,[]).
```

```
monopoly-in-usa(b,a,[]).
```

ground(Π)

```
r1: price-in-usa(a,high) ←  
  made-by(a,b),  
  NoFellowCompany(b).
```

```
r2: price-in-usa(a,high) ←  
  made-by(a,b),  
  Associate(b,\_Z),  
  American(\_Z),  
  monopoly-in-usa(b,a).
```

```
r3: made-by(a,b).
```

```
r4: monopoly-in-usa(b,a).
```

(2) Disjunctive DL constraints

- Conjunctive query languages available
 - RacerPro, DQLServer, KAON2, Pellet etc.
- Disjunctive:
 - Service not directly supported

$\Sigma \models \text{AmericanAssociate}(a) \vee \text{NoFellowCompany}(b)$

\Rightarrow

$\Sigma \cup \{ a : \neg \text{AmericanAssociate}, b : \neg \text{NoFellowCompany} \}$
unsatisfiable?

Ref: Horrocks, I, Sattler U. Tessaris S and Tobies S. Query containment using a DLR Abox. LTCS-Report 99-15, LuFG Theoretical Computer Science, RWTH Aachen, Germany.

(2) Disjunctive DL constraints

- Disjunctions of conjunctive queries

$$\Sigma \models \text{NoFellowCompany}(a) \vee (\text{EuropeanAssociate}(b) \wedge \text{American}(b))$$

– DNF \Rightarrow CNF:

$$\Sigma \models (\text{NoFellowCompany}(a) \vee \text{EuropeanAssociate}(b)) \wedge (\text{NoFellowCompany}(a) \vee \text{American}(b))$$

(1) $\Sigma \cup \{ a:\neg\text{NoFellowCompany}, b:\neg\text{EuropeanAssociate} \}$

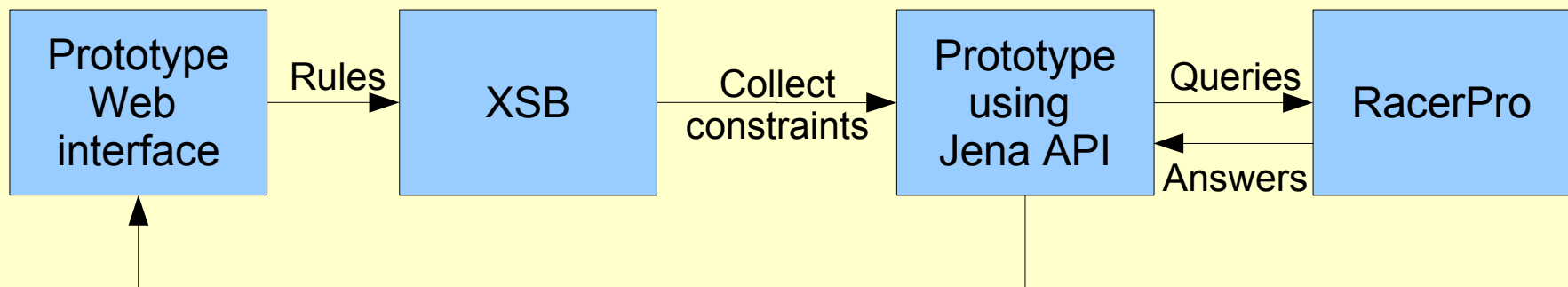
(2) $\Sigma \cup \{ a:\neg\text{NoFellowCompany}, b:\neg\text{American} \}$

– Answer “**yes**” if (1) and (2) are unsatisfiable

Ref: Horrocks, I, Sattler U. Tessaris S and Tobies S. Query containment using a DLR Abox. LTCS-Report 99-15, LuFG Theoretical Computer Science, RWTH Aachen, Germany.

Prototype

- Interfaces existing reasoners
 - Rule reasoner: **XSB**
 - Ontology reasoner: **DIG compliant DL reasoner**



+ Available at: <http://www.ida.liu.se/hswrl>

- Work in progress:
 - Allow roles in constraints through “*rolling-up*”

Conclusions

- Combining general class of rules with constraints
 - Rules are negation-free, fixpoint semantics
- Non-logical rule languages
 - E.g. Xcerpt
- Re-using existing reasoners
- Prototype integration:
 - Datalog + OWL-DL
 - Using: XSB + RacerPro

Related work

- Motivated by and extends \mathcal{AL} -Log
- ASP + DL [Eiter et. al.]
 - Negation
 - Bi-directional flow of information
- Safe hybrid KBs [Rosati]
 - Disjunctive Datalog
 - Ontological predicates in rule heads
- Different objectives from *language extensions*
 - E.g. SWRL [Horrocks et. al.], OWL-DL [Motik et. al.]

Future work

- How re-use existing rule reasoners?
- Eager interaction
- Other constraint languages
- Rules with negation

Combining safe rules and ontologies by interfacing of reasoners

Uwe Aßmann, Jakob Henriksson, Jan Małuszyński

PPSWR06, Budva, Montenegro, 10th June 2006

The objective

- Define a scheme that
from given
 - Rule language R (e.g. Datalog, Xcerpt)
 - Logical language S (e.g. OWL-DL, ...)constructs
 - A language R_S integrating R and S:
 - + Syntax, Semantics of R_S : from syntax and semantics of R and S
 - + A (complete) reasoner for R_S
by interfacing the reasoners of R and S

Outline

- **Motivating example**
- **The scheme**
 - Principles and restrictions
 - An instance:
 - + Datalog + OWL-DL
 - + Prototype: interfacing XSB and a DL reasoner
- **Conclusions**
- **Related work**

Motivating example

Rule component Π :

r_1 : price-in-usa(X,high) \leftarrow
made-by(X,Y),
NoFellowCompany(Y).

r_2 : price-in-usa(X,high) \leftarrow
made-by(X,Y),
Associate(Y,Z),
American(Z),
monopoly-in-usa(Y,X).

r_3 : made-by(a,b).

r_4 : monopoly-in-usa(b,a).

DL component Σ :

T-Box:

European \cap American $\subseteq \perp$
EuropeanAssociate $\equiv \exists$ Associate.European
AmericanAssociate $\equiv \exists$ Associate.American
NoFellowCompany $\equiv \forall$ Associate. \neg American
InternationalCompany \equiv EuropeanAssociate \cup
AmericanAssociate

A-Box:

InternationalCompany(b)

Ref: A.Levy and M.C.Rousset. CARIN: A Representation Language Combining Horn rules and Description Logics. Artificial Intelligence 104(1-2):165-209, 1998.

Motivating example

Rule component Π :

r_1 : price-in-usa(X,high) \leftarrow
 made-by(X,Y),
 NoFellowCompany(Y).
 r_2 : price-in-usa(X,high) \leftarrow
 made-by(X,Y),
 Associate(Y,Z),
 American(Z),
 monopoly-in-usa(Y,X).
 r_3 : made-by(a,b).
 r_4 : monopoly-in-usa(b,a).

DL component Σ :

T-Box:
 European \cap American $\sqsubseteq \perp$
 EuropeanAssociate $\equiv \exists$ Associate.European
 AmericanAssociate $\equiv \exists$ Associate.American
 NoFellowCompany $\equiv \forall$ Associate. \neg American
 InternationalCompany \equiv EuropeanAssociate \cup
 AmericanAssociate

A-Box:
 InternationalCompany(b)

Constraining the extent of
the head predicate in
models of the rule-base

With constraint domain

Motivating example

- $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$?

Rule component Π :

r_1 : $\text{price-in-usa}(X, \text{high}) \leftarrow$
 $\text{made-by}(X, Y),$
 $\text{NoFellowCompany}(Y).$

r_2 : $\text{price-in-usa}(X, \text{high}) \leftarrow$
 $\text{made-by}(X, Y),$
 $\text{Associate}(Y, Z),$
 $\text{American}(Z),$
 $\text{monopoly-in-usa}(Y, X).$

r_3 : $\text{made-by}(a, b).$
 r_4 : $\text{monopoly-in-usa}(b, a).$

DL component Σ :

T-Box:

$\text{European} \cap \text{American} \subseteq \perp$
 $\text{EuropeanAssociate} \equiv \exists \text{Associate}.\text{European}$
 $\text{AmericanAssociate} \equiv \exists \text{Associate}.\text{American}$
 $\text{NoFellowCompany} \equiv \forall \text{Associate}.\neg \text{American}$
 $\text{InternationalCompany} \equiv \text{EuropeanAssociate} \cup \text{AmericanAssociate}$

A-Box:

$\text{InternationalCompany}(b)$

Motivating example

- $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$?

Rule component Π :

r_1 : $\text{price-in-usa}(a, \text{high}) \leftarrow$
 $\text{made-by}(a, b),$
 $\text{NoFellowCompany}(b).$
 r_2 : $\text{price-in-usa}(X, \text{high}) \leftarrow$
 $\text{made-by}(X, Y),$
 $\text{Associate}(Y, Z),$
 $\text{American}(Z),$
 $\text{monopoly-in-usa}(Y, X).$
 r_3 : $\text{made-by}(a, b).$
 r_4 : $\text{monopoly-in-usa}(b, a).$

DL component Σ :

T-Box:
 $\text{European} \cap \text{American} \sqsubseteq \perp$
 $\text{EuropeanAssociate} \sqsubseteq \exists \text{Associate}.\text{European}$
 $\text{AmericanAssociate} \sqsubseteq \exists \text{Associate}.\text{American}$
 $\text{NoFellowCompany}(b) \sqsubseteq \exists \text{Associate}.\text{American}$
 $\text{InternationalCompany} \sqsubseteq \text{EuropeanAssociate} \cup \text{AmericanAssociate}$
A-Box:
 $\text{InternationalCompany}(b)$

Motivating example

- $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$?

Rule component Π :

```

r1: price-in-usa(x,high) ←
    made-by(x,y),
    NoFellowCompany(y).

r2: price-in-usa(a,high) ←
    made-by(a,b),
    Associate(b,_z),
    American(_z),
    monopoly-in-usa(b,a).

r3: made-by(a,b).
r4: monopoly-in-usa(b,a).
    
```

DL component Σ :

```

T-Box:
European ⊓ American ⊆ ⊥
EuropeanAssociate ≡ ∃Associate.European
AmericanAssociate ≡ ∃Associate.American
NoFellowCompany ≡ ∃Associate.(EuropeanAssociate ⊔ AmericanAssociate)
InternationalCompany ≡ EuropeanAssociate ⊔ AmericanAssociate

A-Box:
InternationalCompany(b)
    
```

$\Sigma \not\models \exists(\text{Associate}(b, _z) \wedge \text{American}(_z))$

Motivating example

- $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$?

Rule component Π :

r_1 : $\text{price-in-usa}(a, \text{high}) \leftarrow$
 $\text{made-by}(a, b),$
 $\text{NoFellowCompany}(b).$
 r_2 : $\text{price-in-usa}(a, \text{high}) \leftarrow$
 $\text{made-by}(a, b),$
 $\text{Associate}(b, _Z),$
 $\text{American}(_Z),$
 $\text{monopoly-in-usa}(b, a).$
 r_3 : $\text{made-by}(a, b).$
 r_4 : $\text{monopoly-in-usa}(b, a).$

DL component Σ :

$T\text{-Box:}$
But:
 $\Sigma \models \text{NoFellowCompany}(b) \wedge$
 $\exists(\text{Associate}(b, _Z) \wedge \text{American}(_Z))$
 $A\text{-Box:}$
 $\text{InternationalCompany}(b)$

Motivating example

- $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$

Rule component Π :

r_1 : $\text{price-in-usa}(a, \text{high}) \leftarrow$
 $\text{made-by}(a, b),$
 $\text{NoFellowCompany}(b).$
 r_2 : $\text{price-in-usa}(a, \text{high}) \leftarrow$
 $\text{made-by}(a, b),$
 $\text{Associate}(b, _Z),$
 $\text{American}(_Z),$
 $\text{monopoly-in-usa}(b, a).$
 r_3 : $\text{made-by}(a, b).$
 r_4 : $\text{monopoly-in-usa}(b, a).$

DL component Σ :

$T\text{-Box?}$
Thus:
 $\Pi \cup \Sigma \models \text{price-in-usa}(a, \text{high})$
 $\text{European} \cap \text{American} \sqsubseteq \perp$
 $\text{European} \cap \text{Associate} \sqsubseteq \perp$
 $\text{American} \cap \text{Associate} \sqsubseteq \perp$
 $\text{NoFellowCompany} \sqsubseteq \forall \text{Associate}, \neg \text{American}$
 $\text{InternationalCompany} \sqsubseteq \text{EuropeanAssociate} \cup \text{AmericanAssociate}$
 $A\text{-Box?}$
 $\text{InternationalCompany}(b)$

Rules we consider

HEAD ← BODY

- HEAD is some basic construct (*atom*)
- BODY is a set of atoms
- **Safety**: head variables appear in the body
- Examples:
 - + Datalog: atomic formulae
 - + Xcerpt: *Query terms* and *Construct terms*

Semantics of rules

- Fixpoint semantics

- Rules derive ground atoms from given ground atoms
 - + *matching* of body atoms vs. given atoms gives substitution θ
 - + θ applied to head \Rightarrow derived atom

$$T_P(S) = \{ H\theta \mid (H \leftarrow B_1, \dots, B_n) \in P \text{ and } (B_1, \dots, B_n) \text{ matches some } A_1, \dots, A_n \text{ in } S \text{ with result } \theta \}$$

- T_P monotonic, $T_P(S) \subseteq T_P(S')$ for any $S \subseteq S'$
- **Semantics of program P**: least fixpoint of T_P

1. Matching depends on the rule language

Examples of rule languages

- The class includes:
 - Logical rule languages, e.g.
 - + **Datalog** (without negation)
 - + Semantics of program: set of Datalog atoms
 - + least Herbrand model
 - Rule languages lacking logical semantics, e.g.
 - + **Xcerpt** (negation-free subset)
 - + Semantics of program: set of Xcerpt data terms

Extended rules

HEAD \leftarrow BODY, C

- C formula of an *external theory* in logical language L
- Ground atoms associated with a constraint
 - + A;C where A ground atom, C formula of L
- Extend T_p operator

$$T_p(S) = \{ H\theta; (C\theta \wedge C_1 \wedge \dots \wedge C_n) \mid (H \leftarrow B_1, \dots, B_n, C) \in P \text{ and} \\ \text{for some } A_1;C_1, \dots, A_n;C_n \text{ in } S \\ (B_1, \dots, B_n) \text{ matches } A_1, \dots, A_n \text{ with result } \theta \}$$

Semantics of extended rules

- Restrict model of underlying rule program
 - A *constraint* C , wrt. an external theory Σ , can be:
 1. True in all models of Σ ($\Sigma \models C$)
 2. False in all models of Σ ($\Sigma \models \neg C$)
 3. None of above:
satisfiable, but false in some models of Σ
- $M(P) = \{ A \mid A \in \text{lfp}(T_P) \text{ and } \Sigma \models C_A \}$
- C_A is the disjunction of all constraints of A

1. Refer to introductory example

Instance: Datalog + OWL-DL

- Restrictions:
 - Only OWL concepts

- Requirements
 - (1) Collect constraints from Datalog in XSB
 - (2) Solve disjunctive DL constraints in existing reasoner

(1) Collecting constraints

- Existing rule reasoners not aware of “external” predicates

- How re-use rule reasoners?
- How collect constraints?
- Must be solved specifically for each language and rule reasoner
- Here: **Datalog** in **XSB**

Π

r_1 : price-in-usa(X,high) \leftarrow
made-by(X,Y),
NoFellowCompany(Y).

r_2 : price-in-usa(X,high) \leftarrow
made-by(X,Y),
Associate(Y,Z),
American(Z),
monopoly-in-usa(Y,X).

r_3 : made-by(a,b).

r_4 : monopoly-in-usa(b,a).

(1) Collecting constraints

Collecting constraints in XSB

Π

```
price-in-usa(X,high) :-  
  made-by(X,Y),  
  NoFellowCompany(Y).
```

```
price-in-usa(X,high) :-  
  made-by(X,Y),  
  Associate(Y,Z),  
  American(Z),  
  monopoly-in-usa(Y,X).
```

```
made-by(a,b).  
monopoly-in-usa(b,a).
```

Π'

```
price-in-usa(X,high,[NoFellowCompany(Y)|A]) :-  
  made-by(X,Y,A).
```

```
price-in-usa(X,high,[Associate(Y,Z),American(Z)|A]) :-  
  made-by(X,Y,A1),  
  monopoly-in-usa(Y,X,A2),  
  append(A1,A2,A).
```

```
made-by(a,b,[]).  
monopoly-in-usa(b,a,[]).
```

(1) Collecting constraints

- Query $\leftarrow price-in-usa(a, high, \mathbf{C})$ wrt. Π' :

$\mathbf{C} = [\text{NoFellowCompany}(b)]$

$\mathbf{C} = [\text{Associate}(b, _Z), \text{American}(_Z)]$

Π'

```
price-in-usa(X, high, [NoFellowCompany(Y)|A]) :-  
  made-by(X, Y, A).  
  
price-in-usa(X, high, [Associate(Y, Z),  
                      American(Z)|A]) :-  
  made-by(X, Y, A1),  
  monopoly-in-usa(Y, X, A2),  
  append(A1, A2, A).  
  
made-by(a, b, []).  
monopoly-in-usa(b, a, []).
```

$\text{ground}(\Pi)$

```
r1: price-in-usa(a, high) ←  
  made-by(a, b),  
  NoFellowCompany(b).  
  
r2: price-in-usa(a, high) ←  
  made-by(a, b),  
  Associate(b, \_Z),  
  American(\_Z),  
  monopoly-in-usa(b, a).  
  
r3: made-by(a, b).  
r4: monopoly-in-usa(b, a).
```

(2) Disjunctive DL constraints

- Conjunctive query languages available
 - RacerPro, DQLServer, KAON2, Pellet etc.
- Disjunctive:
 - Service not directly supported

$\Sigma \models \text{AmericanAssociate}(a) \vee \text{NoFellowCompany}(b)$

\Rightarrow

$\Sigma \cup \{ a : \neg \text{AmericanAssociate}, b : \neg \text{NoFellowCompany} \}$
unsatisfiable?

Ref: Horrocks, I, Sattler U. Tessaris S and Tobies S. Query containment using a DLR Abox. LTCS-Report 99-15, LuFG Theoretical Computer Science, RWTH Aachen, Germany.

Jakob Henriksson, PPSWR06, Budva

10th June 2006

(2) Disjunctive DL constraints

- Disjunctions of conjunctive queries

$\Sigma \models \text{NoFellowCompany}(a) \vee$
 $\quad (\text{EuropeanAssociate}(b) \wedge \text{American}(b))$

– DNF \Rightarrow CNF:

$\Sigma \models (\text{NoFellowCompany}(a) \vee \text{EuropeanAssociate}(b))$
 $\quad \wedge (\text{NoFellowCompany}(a) \vee \text{American}(b))$

(1) $\Sigma \cup \{ a:\neg\text{NoFellowCompany}, b:\neg\text{EuropeanAssociate} \}$

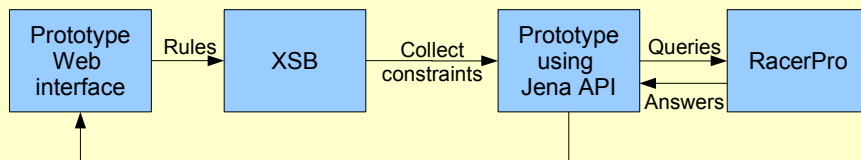
(2) $\Sigma \cup \{ a:\neg\text{NoFellowCompany}, b:\neg\text{American} \}$

– Answer “**yes**” if (1) and (2) are unsatisfiable

Ref: Horrocks, I, Sattler U. Tessaris S and Tobies S. Query containment using a DLR Abox. LTCS-Report 99-15, LuFG Theoretical Computer Science, RWTH Aachen, Germany.

Prototype

- Interfaces existing reasoners
 - Rule reasoner: **XSB**
 - Ontology reasoner: **DIG compliant DL reasoner**



+ Available at: <http://www.ida.liu.se/hswrl>

- Work in progress:
 - Allow roles in constraints through “*rolling-up*”

Conclusions

- Combining general class of rules with constraints
 - Rules are negation-free, fixpoint semantics
- Non-logical rule languages
 - E.g. Xcerpt
- Re-using existing reasoners
- Prototype integration:
 - Datalog + OWL-DL
 - Using: XSB + RacerPro

Related work

- Motivated by and extends \mathcal{AL} -Log
- ASP + DL [Eiter et. al.]
 - Negation
 - Bi-directional flow of information
- Safe hybrid KBs [Rosati]
 - Disjunctive Datalog
 - Ontological predicates in rule heads
- Different objectives from *language extensions*
 - E.g. SWRL [Horrocks et. al.], OWL-DL [Motik et. al.]

Future work

- How re-use existing rule reasoners?
- Eager interaction
- Other constraint languages
- Rules with negation