Uncertainty Treatment in the Rule Interchange Format: From Encoding to Extension

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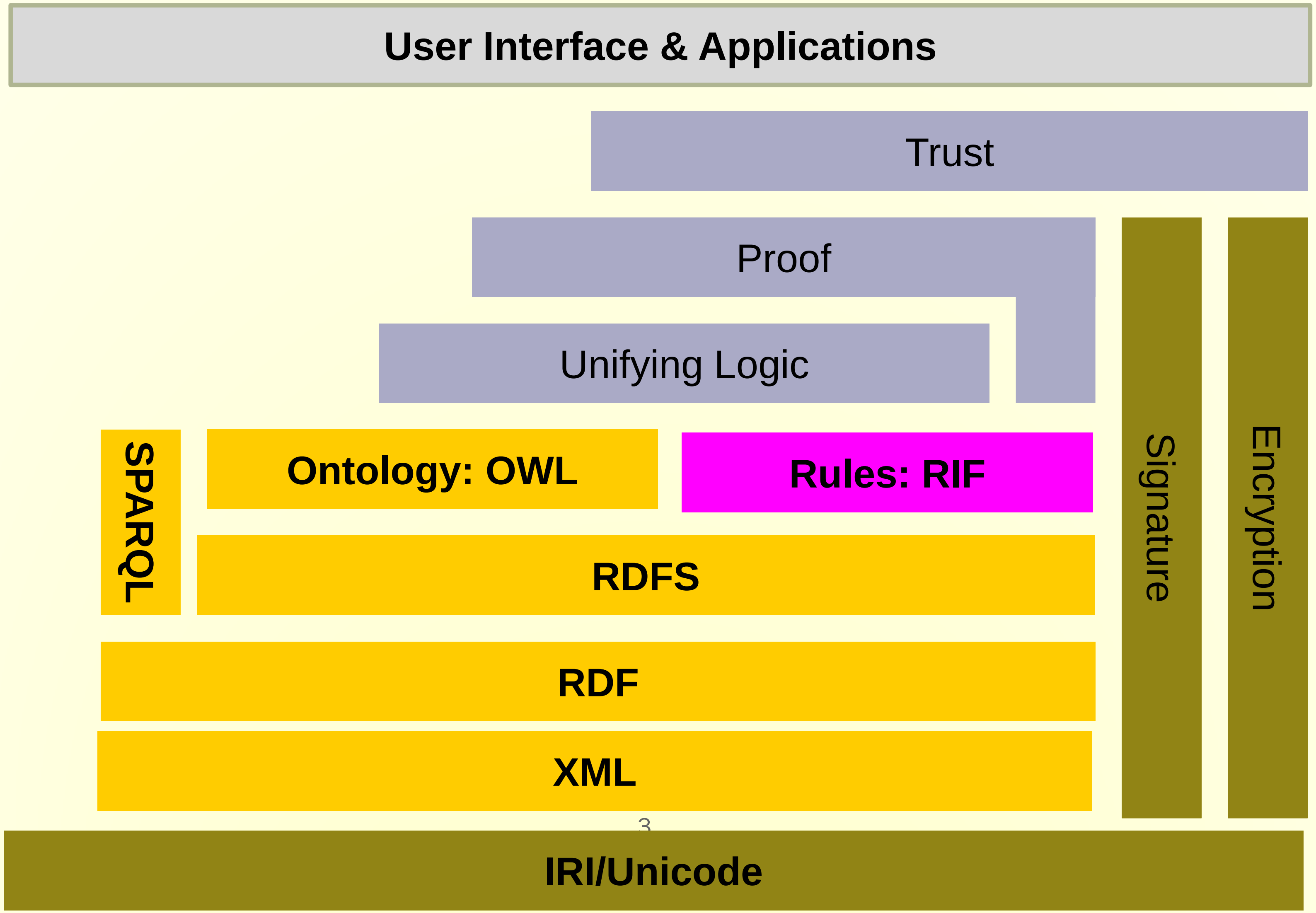
Talk Outline

- Introduction and Motivation
- DLP and Representation in RIF
- Encoding Uncertainty in RIF
  - Fuzzy LP
  - Using RIF Functions
  - Using RIF Predicates
- Uncertainty Extension of RIF
  - Definition of Truth Values and Truth Valuation
  - Proposed RIF-URD
- Fuzzy Description Logic Programs and Their Representation in RIF
- Conclusions and Future Work

Semantic Web Layer Cake

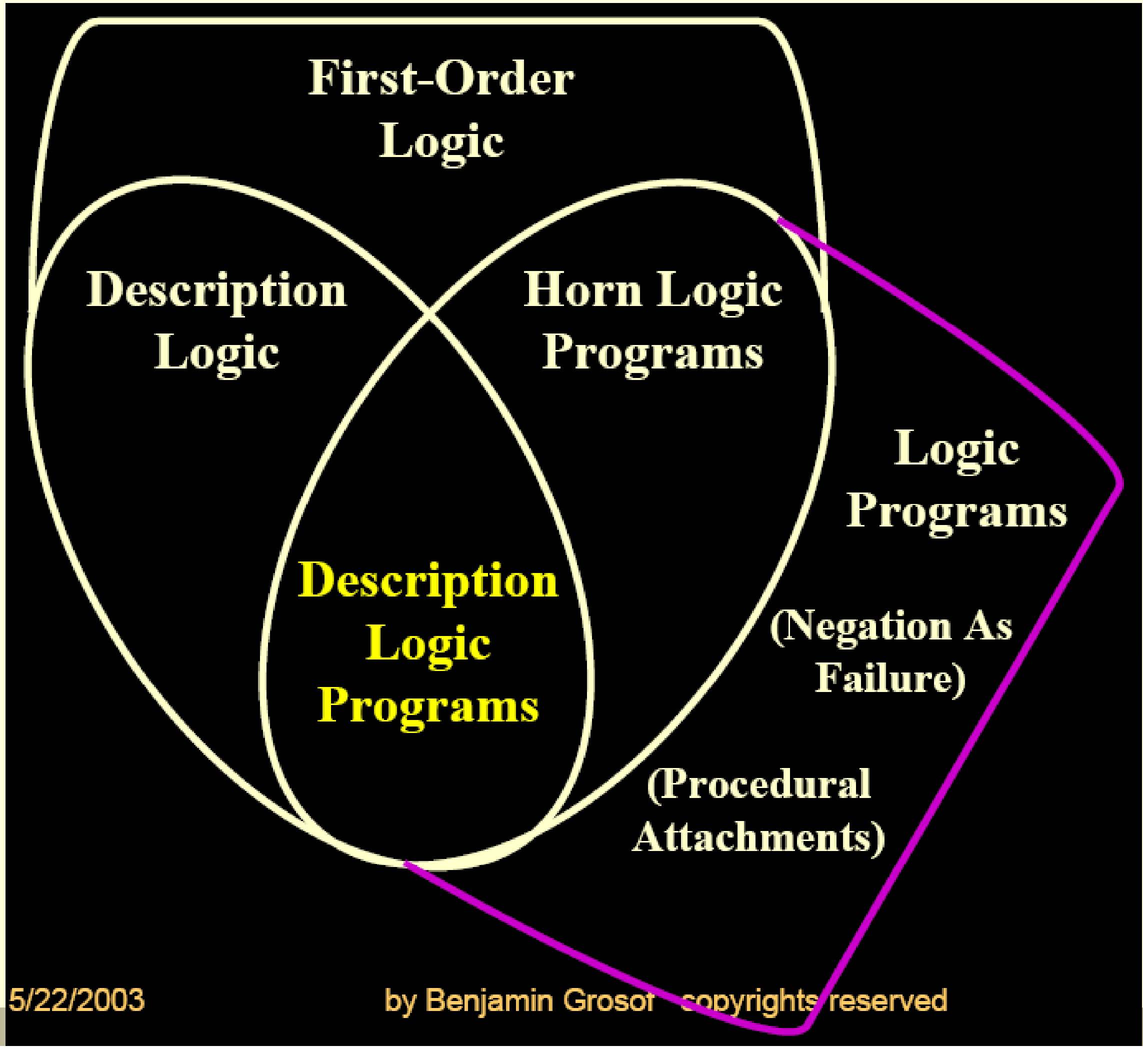


RIF Background

- Literally *hundreds* of rule system implementations
- RIF: Rule Interchange Format
- RIF defines
  - a basic logic dialect: RIF-BLD
  - a framework in the form of a menu of syntactic and semantic features that can be combined into different specializations: RIF-FLD
  - other specializations

Motivation

- DL and LP cover different but overlapping areas of knowledge representation



Motivation

- DL and LP cover different but overlapping areas of knowledge representation
- DL cannot represent “more than one free variable at a time”
- LP/Horn Logic cannot represent a disjunction or an existential in the head

Motivation

- DL and LP cover different but overlapping areas of knowledge representation
- Handling uncertain knowledge is becoming a critical research direction for the (Semantic) Web

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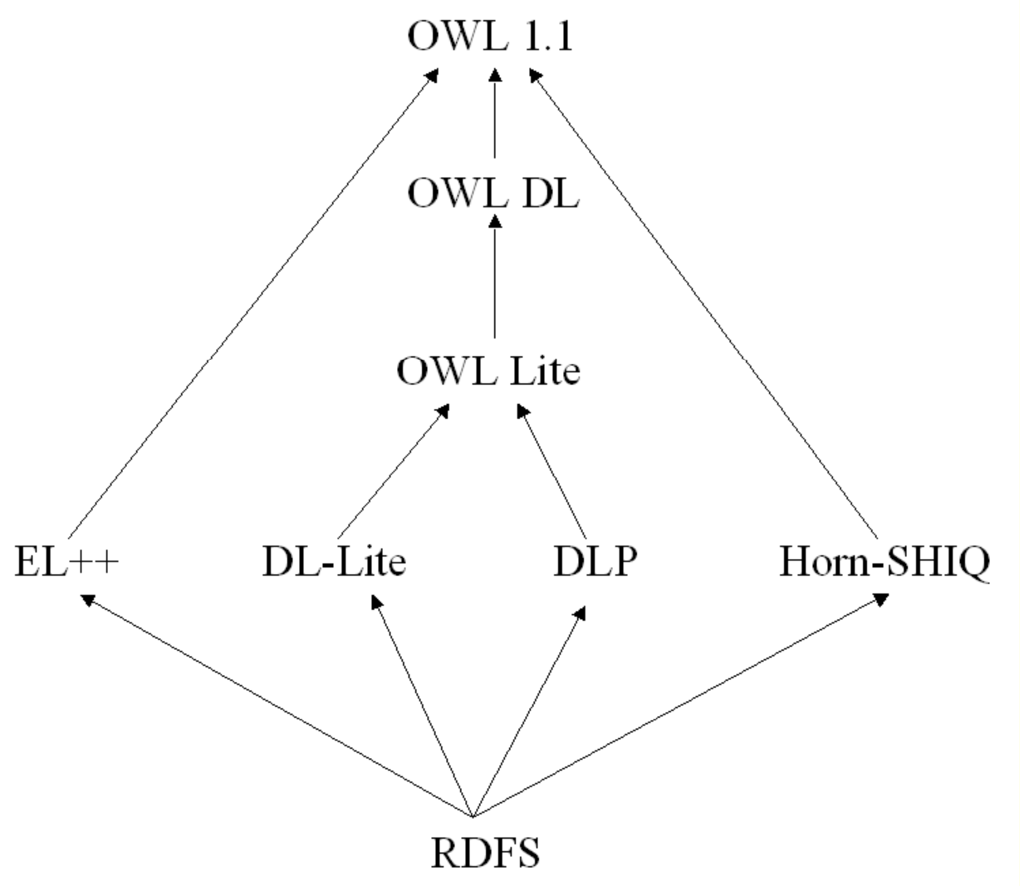
DLP Expressive Power and DLP mappings

LP syntax	DL syntax
$D(x) \leftarrow C(x)$	$C \sqsubseteq D$
$D(x) \leftarrow C(x),$ $C(x) \leftarrow D(x)$	$C \equiv D$
$C(y) \leftarrow R(x,y)$	$\top \sqsubseteq \forall R.C$
$C(x) \leftarrow R(x,y)$	$\top \sqsubseteq \forall R^{-}.C$
$C(a)$	$C(a)$
$R(a,b)$	$R(a,b)$
$R(x,y) \leftarrow P(x,y),$ $P(x,y) \leftarrow R(x,y)$	$P \equiv R$
$R(x,y) \leftarrow P(y,x),$ $P(y,x) \leftarrow R(x,y)$	$P \equiv R^{-}$
$R(x,z) \leftarrow R(x,y), R(y,z)$	$R^{+} \sqsubseteq R$
$P(x,y) \leftarrow R(x,y)$	$R \sqsubseteq P$

$D(x) \leftarrow C_1(x) \wedge C_2(x)$	$C_1 \sqcap C_2 \sqsubseteq D$
$P(x,y) \leftarrow R_1(x,y) \wedge R_2(x,y)$	$R_1 \sqcap R_2 \sqsubseteq P$
$C_1(x) \leftarrow D(x),$ $C_2(x) \leftarrow D(x)$	$D \sqsubseteq C_1 \sqcap C_2$
$D(x) \leftarrow C_1(x),$ $D(x) \leftarrow C_2(x)$	$C_1 \sqcup C_2 \sqsubseteq D$
$D(y) \leftarrow R(x,y) \wedge C(x)$	$C \sqsubseteq \forall R.D$
$D(x) \leftarrow R(x,y) \wedge C(y)$	$\exists R.C \sqsubseteq D$

DLP



- *Figure . Relationship between the fragments (profiles) of OWL 1.1*
- *http://www.webont.org/owl/1.1/tractable.html*

DLP comprises basic RDFS & more

- RDFS subset of DL permits the following statements:
  - Subclass, Domain, Range, Subproperty (also SameClass, SameProperty)
  - instance of class, instance of property
- more DL statements beyond RDFS:
  - Intersection in class descriptions
  - Transitive or symmetric property, inverse property
  - Disjunction or Existential in a *subclass expression*
  - Universal in a *superclass expression*

DLP limitations

- Does not allow using disjunction or existential in a superclass expression.

  E.g., $C \sqsubseteq D_1 \sqcup D_2$, $C \sqsubseteq \exists P.D$
- A universal restriction as a subclass of an inclusion axiom

  E.g. $\forall P.D \sqsubseteq C$
- Negation ($\neg$) and cardinality restrictions ($\leq$,$\geq$)

OWL 2 RL

- Created by W3C OWL Working Group
- Is a syntactic profile of OWL 2 DL
- Based on Description Logic Programs (DLP)
- Syntactic restrictions
- http://www.w3.org/2007/OWL/wiki/Profiles#OWL_2_RL

RIF-BLD Overview

- Definite Horn rules
- Functions
- Equality (in conclusion and condition)
- Internationalized resource identifiers (IRIs)
- XML syntax
- Presentation syntax
- Published “Last Call” draft in July
- Slides 14-17 are adapted from Chris Welty’s talk on RIF-BLD

Rules

- IF <condition> THEN <conclusion>
  - <condition> aka rule body, antecedant
  - <conclusion> aka rule head, consquent
- BLD rule:
  - **Forall** var* (<conclusion> **:-** <condition>)
  - Conclusions may contain conjunction
  - Conditions may contain conjunction, disjunction, and existential
- Restrictions on conclusion
  - No existential, disjunction, external functions

Document Structure (in presentation syntax)

- Groups occur in Documents
  - Document(
  - Group(Forall ?x (Q(?x) :- P(?x))
  - Forall ?x (Q(?x) :- R(?x)))
  - Group(Forall ?y (R(?y) :- ex:op(?y))))
- Rules occur in Groups
  - Group(Forall ?x (Q(?x) :- P(?x))
  - Forall ?x (Q(?x) :- R(?x)))

DLP in RIF

LP syntax	DL syntax	RIF
$D(x) \leftarrow C(x)$	$C \sqsubseteq D$	Forall ?x (D(?x) :- C(?x))
$D(x) \leftarrow C(x)$, $C(x) \leftarrow D(x)$	$C \equiv D$	Forall ?x (D(?x) :- C(?x)) Forall ?x (C(?x) :- D(?x))
$C(y) \leftarrow R(x,y)$	$\top \sqsubseteq \forall R.C$	Forall ?x ?y (C(?y) :- R(?x ?y))
$C(x) \leftarrow R(x,y)$	$\top \sqsubseteq \forall R^{-}.C$	Forall ?x ?y (C(?x) :- R(?x ?y))
$D(x) \leftarrow C_1(x) \wedge C_2(x)$	$C_1 \sqcap C_2 \sqsubseteq D$	Forall ?x (D(?x) :- And(C_1(?x) C_2(?x)))
$C_1(x) \leftarrow D(x)$, $C_2(x) \leftarrow D(x)$	$D \sqsubseteq C_1 \sqcap C_2$	Forall ?x (C_1(?x) :- D(?x)) Forall ?x (C_2(?x) :- D(?x))
$D(x) \leftarrow C_1(x)$, $D(x) \leftarrow C_2(x)$	$C_1 \sqcup C_2 \sqsubseteq D$	Forall ?x (D(?x) :- C_1(?x)) Forall ?x (D(?x) :- C_2(?x))
$D(y) \leftarrow R(x,y) \wedge C(x)$	$C \sqsubseteq \forall R.D$	Forall ?x ?y (D(?y) :- And(R(?x ?y) C(?x)))
$D(x) \leftarrow R(x,y) \wedge C(y)$	$\exists R.C \sqsubseteq D$	Forall ?x ?y (D(?x) :- And(R(?x ?y) C(?y)))

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Fuzzy LP

- Syntax of a fuzzy rule

$$H(\vec{x}) \leftarrow B_1(\vec{x}_1),\ \cdots,\ B_n(\vec{x}_n) \quad / c$$

- Semantics
  - The body: Gödel's semantics

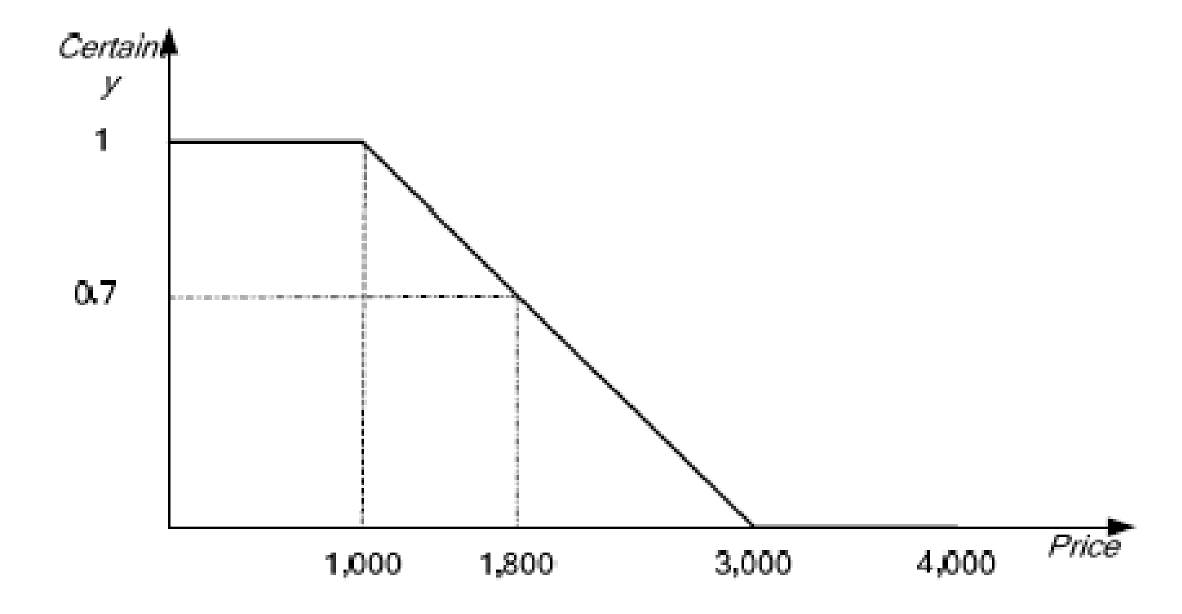
$$val((B_1, \cdots, B_n), H_I) = \min\{val(B_i, H_I) \mid i \in \{1, \cdots, n\}\}$$

  - The implication: product

$$val(H, H_I) = c \times val((B_1, \cdots, B_n), H_I)$$

Fuzzy LP example: cheapFlight

$$cheapFlight(x,y) \leftarrow affordableFlight(x,y) \quad / \, 0.9 \qquad (1)$$
$$affordableFlight(x,y) \quad / \, left\_shoulder0k4k1k3k(y) \qquad (2)$$



$$KB_{LP} \models cheapFlight(flight0001, 1800) \quad / \, 0.63$$

Encoding Uncertainty in RIF: Using RIF Functions

- Map all predicates to functions
- Use equality for letting the functions return uncertainty values
- A fuzzy rule in RIF-BLD $H(\vec{x}) \leftarrow B_1(\vec{x}_1), \; \cdots, B_n(\vec{x}_n) \quad / c$

```
Document(
  Group
  (     Forall ?x1 … ?xk (
          h(t1 … tr)=?ch :- And(b1(t1,1 … t1,s1)=?c1  ···  bn(tn,1 … tn,sn)=?cn
                               ?ct =External(numeric-minimum(?c1  ···  ?cn))
                               ?ch=External(numeric-multiply(c ?ct)) )
  )     )
```

- The semantics of the fuzzy rules is encoded using built-in functions from RIF_DTB and planned extensions

Example cheapFlight encoded in RIF-BLD

```
(* <http://example.org/fuzzy/membershipfunction > *)
Document(
   Group
   (      (* "Definition of membership function  left_shoulder(0,4000,1000,3000) "[] *)
      Forall ?y(
            left__shoulder0k4k1k3k(?y)=1 :- And(External(numeric-less-than-or-equal(0 ?y))
                                                   External(numeric-less-than-or-equal(?y 1000))))
      Forall ?y(
      left__shoulder0k4k1k3k(?y)=External(numeric-add(External(numeric-multiply(-0.0005 ?y)) 1.5))
            :- And(External(numeric-less-than(1000 ?y))
                   External(numeric-less-than-or-equal(?y 3000))))
      Forall ?y(
            left__shoulder0k4k1k3k(?y)=0 :- And(External(numeric-less-than(3000 ?y))
                                                   External(numeric-less-than-or-equal(?y 4000))))
         . .
   )    )
```

```
Document(
   Import (<http://example.org/fuzzy/membershipfunction >)
   Group
   (       Forall ?x ?y(
         cheapFlight(?x ?y)=?c_h :- And(affordableFlight(?x ?y)=?c_1
                                        ?c_h=External(numeric-multiply(0.4 ?c_1))))
      Forall ?x ?y(affordableFlight(?x ?y)=left__shoulder0k4k1k3k(?y))
   )    )
```

Encoding Uncertainty in RIF: Using RIF Predicates

- Make all n-ary predicates into (1+n)-ary predicates
- A fuzzy rule in RIF-BLD
- The semantics of the fuzzy rules is also encoded using built-in functions from RIF_DTB and planned extensions

```
Document(
   Group
   (     Forall ?x1 … ?xk (
            h(?ch t1 … tr) :- And(b1(?c1 t1,1 … t1,s1)  ···  bn(?cn tn,1 … tn,sn)
                                  ?ct =External(numeric-minimum(?c1  ···  ?cn))
                                  ?ch=External(numeric-multiply(c ?ct)) )
   )     )
```

Example cheapFlight encoded in RIF-BLD

```
Document(
   Import (<http://example.org/fuzzy/membershipfunction >)
   Group
   (
      Forall ?x ?y(
         cheapFlight(?ch ?x ?y) :- And(affordableFlight(?c1 ?x ?y)
                                       ?ch=External(numeric-multiply(0.4 ?c1)))
      )
      Forall ?x ?y(affordableFlight(?c1 ?x ?y) :- ?c1 =left__shoulder0k4k1k3k(?y))
   )      )
```

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Uncertainty Extension of RIF

- Set of Truth Values $\mathcal{TV}$ from FLD:
  the interval [0,1]
- Let $\leq$ denote the numerical truth order

Definition 1. (Set of truth values as a specialization of the set in RIF-FLD)

(1) The set TV is a complete lattice with respect to $\leq$, i.e., the least upper bound (lub) and the greatest lower bound (glb) exist for any subset of $\leq$.

(2) Antisymmetry. If $e_i \leq e_j$ and $e_j \leq e_i$ then $e_i = e_j$.

(3) Transitivity. If $e_i \leq e_j$ and $e_j \leq e_k$ then $e_i \leq e_k$.

(4) Totality. Any two elements should satisfy one of these two relations: $e_i \leq e_j$ or $e_j \leq e_i$.

(5) The set TV has an operator of negation, $\sim: TV \to TV$, such that

a). $\sim e_i = 1 - e_i$.

b). $\sim$ is self-inverse, i.e., $\sim\sim e_i = e_i$.

Uncertainty Extension of RIF

- Truth Valuation

Definition 2. (Truth valuation adapted from RIF-FLD). Truth valuation for well-formed formulas in RIF-URD is determined as in RIF-FLD, adapting the following three cases.

(8) Conjunction (glb_t becomes min): $TVal_I(And(B_1 \cdots B_n)) = \min(TVal(B_1) \cdots TVal(B_n))$.

(9) Disjunction (lub_t becomes max): $TVal_I(Or(B_1 \cdots B_n)) = \max(TVal(B_1) \cdots TVal(B_n))$

(11) Rule implication (t becomes 1, f becomes 0, condition valuation is multiplied with c):

$TVal_I(conclusion :- condition \quad / c) = 1$ if $TVal_I(conclusion) \geq c \times TVal_I(condition)$

$TVal_I(conclusion :- condition \quad / c) = 0$ if $TVal_I(conclusion) < c \times TVal_I(condition)$

RIF Uncertainty Rule Dialect: URD

- Proposed RIF-URD
- Rule
- Fact

Document(
Group
(
Forall $?x_1 \ldots ?x_k$ (
$h(t_1 \ldots t_r)$:- And($b_1(t_{1,1} \ldots t_{1,s1}) \cdots b_n(t_{n,1} \ldots t_{n,sn})$)
) / c
)

$h(t_1 \ldots t_r)$ / c

```
Document(
   Import (<http://example.org/fuzzy/membershipfunction >)
   Group
   (
      Forall ?x ?y(
            cheapFlight(?x ?y) :- affordableFlight(?x ?y)
      )   / 0.4
      Forall ?x ?y(affordableFlight(?x ?y))   / left__shoulder0k4k1k3k(?y)
   )      )
```

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fhDLP

- Mappings in fhDLP

LP syntax	DL syntax
$D(x) \leftarrow C_1(x), \cdots, C_n(x) \quad / c$	$\bigcap_{i=1}^{n} C_i \sqsubseteq D \quad = c$
$P(x,y) \leftarrow R_1(x,y), \cdots, R_n(x,y) \quad / c$	$\bigcap_{i=1}^{n} R_i \sqsubseteq P \quad = c$
$C(x) \leftarrow D(x) \quad / c_1,$ $D(x) \leftarrow C(x) \quad / c_2$	$C \equiv D \quad = \min(c_1, c_2)$
$R(x,y) \leftarrow P(x,y) \quad / c_1,$ $P(x,y) \leftarrow R(x,y) \quad / c_2$	$R \equiv P \quad = \min(c_1, c_2)$
$R(x,y) \leftarrow P(y,x) \quad / c_1,$ $P(y,x) \leftarrow R(x,y) \quad / c_2$	$P \equiv R^- \quad = \min(c_1, c_2)$
$C(y) \leftarrow R(x,y) \quad / c$	$\top \sqsubseteq \forall R.C \quad = c$
$C(x) \leftarrow R(x,y) \quad / c$	$\top \sqsubseteq \forall R^-.C \quad = c$
$R(x,z) \leftarrow R(x,y), R(y,z) \quad / c$	$R^+ \sqsubseteq R \quad = c$
$C(a) \quad / c$	$C(a) \quad = c$
$R(a,b) \quad / c$	$R(a,b) \quad = c$

fhDLP

Semantics

LP syntax	DL syntax	Semantics
$D(x) \leftarrow C_1(x), \cdots, C_n(x) \quad / c$	$\bigcap_{i=1}^{n} C_i \sqsubseteq D \quad = c$	$\forall x \in \Delta^H \quad val(D(x), H_I) \geq c \times \min\{val(C_i(x), H_I) \mid i \in \{1, \cdots, n\}\}$
$C(y) \leftarrow R(x, y) \quad / c$	$\mathrm{T} \sqsubseteq \forall R.C \quad = c$	$\forall x, y \in \Delta^H \quad val(C(y), H_I) \geq c \times val(R(x, y), H_I)$
$C(a) \quad / c$	$C(a) \quad = c$	$val(C(a), H_I) \geq c$

fhDLP in RIF functions, RIF predicates and RIF-URD

LP syntax	$P(x,y) \leftarrow R_1(x,y),\cdots,R_n(x,y) \quad / c$
DL syntax	$\bigcap_{i=1}^{n} R_i \sqsubseteq P \quad = c$
RIF function	Forall ?x ?y(P(?x ?y)=?c_h :- And(R$_1$(?x ?y)=?c_1 $\cdots$ R$_n$(?x ?y)=?c_n ?c_t =External(numeric-minimum(?c_1 $\cdots$?c_n)) ?c_h=External(numeric-multiply(c ?c_t)))
RIF predicate	Forall ?x ?y(P(?c_h ?x ?y) :- And(R$_1$(?c_1 ?x ?y) $\cdots$ R$_n$(?c_n ?x ?y) ?c_t =External(numeric-minimum(?c_1 $\cdots$?c_n)) ?c_h=External(numeric-multiply(c ?c_t)))
RIF-URD	Forall ?x ?y(P(?x ?y) :- And(R$_1$(?x ?y) $\cdots$ R$_n$(?x ?y))) / c

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Conclusions

- Presented two different principles of encoding uncertainty in RIF-BLD

- Proposed an extension of RIF leading to RIF-URD

- Presented fhDLP, a fuzzy extension to Description Logic Programs

Future Work

- Parameterize RIF-URD to support different theories of uncertainty in a unified manner

- Complement RIF-URD presentation syntax with RIF-URD XML syntax

- Explore further combination strategies of DL and LP

Questions?