The RuleML Family of Web Rule Languages

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Introduction

- Rules are central to the Semantic Web
- Rule interchange in an open format is important for e-Business
- RuleML is the de facto open language standard for rule interchange/markup
- Collaborating with W3C (RIF), OMG (PRR, SBVR), OASIS, DARPA-DAML, EU-REWEPSE, and other standards/gov't bodies
RuleML Enables ...

Rule
modelling
markup
translation
interchange
execution
publication
archiving
in
UML
RDF
XML
ASCII
RuleML Identifies ...

- Expressive sublanguages
  - for Web rules
  - started with
    - *Derivation* rules: extend SQL views
    - *Reaction* rules: extend SQL triggers
  - to empower their subcommunities
RuleML Specifies ...

- Derivation rules via XML Schema:
  - All sublanguages: (OO) RuleML 0.91
  - First Order Logic: FOL RuleML 0.91
  - With Ontology language: SWRL 0.7
    - A Semantic Web Rule Language Combining OWL (W3C) and RuleML
  - With Web Services language: SWSL 0.9

- Translators in & out (e.g. Jess) via XSLT
Modular Schemas

“RuleML is a **family** of sublanguages whose **root** allows access to the language as a whole and whose **members** allow to identify customized subsets of the language.”

- **RuleML**: Rule Markup Language
  - RuleML derivation rules (shown here) and production rules defined in XML Schema Definition (XSD)
  - Each XSD of the family corresponds to the expressive class of a specific RuleML sublanguage
- The most recent schema specification of RuleML is always available at [http://www.ruleml.org/spec](http://www.ruleml.org/spec)
- Current release: RuleML 0.91
- Previews: [http://wiki.ruleml.org/XSD_Workplan](http://wiki.ruleml.org/XSD_Workplan)
Schema Modularization

- XSD URIs identify expressive classes
  - Receivers of a rulebase can validate applicability of tools (such as Datalog vs. Hornlog interpreters)
  - Associated with semantic classes (such as function-free vs. function-containing Herbrand models)
- Modularization (Official Model)
  - Aggregation: e.g., Datalog part of Hornlog
  - Generalization: e.g., Bindatalog is a Datalog
- **Rectangles** are sublanguages
  - Inheritance between schemas
- **Ovals** are auxiliary modules
  - Elementary, including only element and/or attribute definitions
  - Become part of sublanguages

E.g., in http://www.ruleml.org/0.91/xsd/hornlog.xsd
<xs:redefine schemaLocation="datalog.xsd">
<xs:include schemaLocation="modules/cterm_module.xsd"/>

Bring Datalog to the Semantic Web

- Start with n-ary relations (not binary properties)
- Keep variable typing optional (reuse RDFS’ subClassOf taxonomies as sort lattices)
- Allow signature declarations of arities and types
- Employ function-free facts as well as Horn rules (rather than 1\textsuperscript{st}: RDF descriptions; 2\textsuperscript{nd}: RDF rules)
- Use function-free Herbrand model semantics (querying stays decidable)
- Provide three syntactic levels:
  - User-oriented: Prolog-like, but with “?”-variables
  - Abstract: MOF/UML diagrams
  - XML serialization: Datalog RuleML
Business Rule: Positional

"The **discount** for a **customer** buying a **product** is 5 percent if the **customer** is **premium** and the **product** is **regular**."
Extend Datalog for the Semantic Web (I)

- Allow slots as name→filler pairs in Atoms (cf. F-logic’s methods and RDF’s properties)
- Extend optional types and signatures for slots
- Add optional object identifiers (oids) to atoms
- Separate Data literals from Individual constants
"The **discount** for a *customer* buying a *product* is 5 percent if the *customer* is **premium** and the *product* is **regular**."
Extend Datalog for the Semantic Web (II)

- Permit IRI webizing for **Data** (XML Schema Part 2), **Individuals** (RDF’s **resources**), **Relations**, **slot** names, types (RDFS’ classes), and **oids** (RDF’s **about**)
- Introduce **Module** (scope) construct for clauses (cf. RDF’s named graphs)
- Add scoped-default (**Naf**), strong (**Neg**), scoped-default-of-strong negation (unscoped: cf. **ERDF**)
- Integrate with Description Logics
  - Homogeneous (SWRL, Datalog RuleML + OWL-DL)
  - Hybrid (AL-log, Datalog^{DL}, DL+log, ...)
Bring Horn Logic to the Semantic Web

- Augment Datalog with uninterpreted **Functions** and their **Expressions**; also for extended Datalog
- Augment Datalog’s Herbrand model semantics with such **Functions** (querying becomes undecidable)
- Extend Datalog syntaxes
  - XML Schema of Hornlog RuleML inherits and augments XML Schema of Datalog RuleML
- Add **Equality** and **interpreted Functions** (XML serialization: attribute in="yes")
- Reuse XQuery/XPath functions and operators as built-ins
Specify a First-Order Logic Web Language

- Layer on top of either
  - Disjunctive Datalog: or in the head generalizing Datalog
  - Disjunctive Horn Logic: or in head of near-Horn clauses

- Alternatively, layer on top of either
  - Disjunctive Datalog with restricted strong negation
  - Disjunctive Horn Logic with restricted strong negation

- Permit unrestricted or, and, strong negation, and quantifiers forall and exists to obtain FOL

- Use semantics of classical FOL model theory

- Extend Hornlog RuleML syntax to FOL RuleML
Equality for Functions

- Functional programming (FP) plays increasing Web role: MathML, XSLT, XQuery
- Functional RuleML employs orthogonal notions freely combinable with Relational RuleML
- Also solves a Relational RuleML issue, where the following ‘child-of-parent’ elements are separated:
  - Constructor (\texttt{Ctor}) of a complex term (\texttt{Cterm})
  - User-defined function (\texttt{Fun}) of a call (\texttt{Nano})
- Proceed to a logic with equality
Function Interpretedness (I)

- Different notions of ‘function’ in LP and FP:
  - LP: *Uninterpreted functions* denote unspecified values when applied to arguments, not using function definitions
  - FP: *Interpreted functions* compute specified returned values when applied to arguments, using function definitions

- E.g.: `first-born`: Man × Woman → Human
  - Uninterpreted: `first-born(John, Mary)` denotes first-born
  - Interpreted: using `first-born(John, Mary) = Jory`, so the application returns `Jory`
Function Interpretedness (II)

- Uninterpreted `<Ctor>` vs. interpreted `<Fun>` functions now distinguished with attribute values: `<Fun in="no">` vs. `<Fun in="yes">`
- Function applications with `Cterm` vs. `Nano` then uniformly become `Expr`essions
- Two versions of example marked up as follows (where "u" stands for "no" or "yes"):

```
<Expr>
  <Fun in="u">first-born</Fun>
  <Ind>John</Ind>
  <Ind>Mary</Ind>
</Expr>
```
Unconditional Equations

- Modified `<Equal>` element permits both symmetric and oriented equations
- E.g.: `first-born(John, Mary) = Jory` can now be marked up thus:

```xml
<Equal oriented="yes">
  <lhs>
    <Expr>
      <Fun in="yes">first-born</Fun>
      <Ind>John</Ind>
      <Ind>Mary</Ind>
    </Expr>
  </lhs>
  <rhs>
    <Ind>Jory</Ind>
  </rhs>
</Equal>
```
Conditional Equations

- Use `<Equal>` as the conclusion of an `<Implies>`, whose condition may employ other equations.

  E.g.: \( ?B = \text{birth-year}(?P) \Rightarrow \text{age}(?P) = \text{subtract}(\text{this-year}(), ?B) \)
Accommodate SWSL-Rules

- **HiLog:** Higher-order **Variables**, **Constants**, and **Hterms** (complex terms and atomic formulas at the same time)
- **Equal:** As in Horn Logic with (unoriented) **Equality**
- **Frames:**
  - Value molecules: **Atoms** with an **oid**, an optional **Rel** class, and zero or more name-\(\rightarrow\)filler instance **slots**
  - Signature molecules: name-\(\rightarrow\)filler class **slots**, which can have \{**min**: **max**\} cardinality constraints
- **Reification:** A formula (e.g., a rule) embedded in a **Reify** element is treated (e.g., unified) as a term
- **Skolems:** Unnamed, represent new individual constants (like RDF's blank nodes); otherwise, uniquely named ones
HiLog Examples: Hterms (I)

- First-order terms: \( f(a, ?X) \)

\[
\langle \text{Hterm} \rangle \\
\langle \text{op} \rangle \langle \text{Con} \rangle f \langle /\text{Con} \rangle \langle /\text{op} \rangle \\
\langle \text{Con} \rangle a \langle /\text{Con} \rangle \\
\langle \text{Var} \rangle X \langle /\text{Var} \rangle
\langle /\text{Hterm} \rangle
\]

- Variables over function symbols: \( ?X(a, ?Y) \)

\[
\langle \text{Hterm} \rangle \\
\langle \text{op} \rangle \langle \text{Var} \rangle X \langle /\text{Var} \rangle \langle /\text{op} \rangle \\
\langle \text{Con} \rangle a \langle /\text{Con} \rangle \\
\langle \text{Var} \rangle Y \langle /\text{Var} \rangle
\langle /\text{Hterm} \rangle
\]
Parameterized function symbols: \( f(?X, a)(b, ?X(c)) \)

\[
\begin{align*}
\langle \text{Hterm} \rangle \\
\langle \text{op} \rangle \\
\quad \langle \text{Hterm} \rangle \\
\quad \langle \text{op} \rangle \langle \text{Con} \rangle f \langle /\text{Con} \rangle \langle /\text{op} \rangle \\
\quad \langle \text{Var} \rangle X \langle /\text{Var} \rangle \\
\quad \langle \text{Con} \rangle a \langle /\text{Con} \rangle \\
\quad \langle /\text{Hterm} \rangle \\
\langle /\text{op} \rangle \\
\langle \text{Con} \rangle b \langle /\text{Con} \rangle \\
\langle \text{Hterm} \rangle \\
\quad \langle \text{op} \rangle \langle \text{Var} \rangle X \langle /\text{Var} \rangle \langle /\text{op} \rangle \\
\quad \langle \text{Con} \rangle c \langle /\text{Con} \rangle \\
\quad \langle /\text{Hterm} \rangle \\
\langle /\text{Hterm} \rangle
\end{align*}
\]
Equality Example

- Equality ::= in rule head: $f(a, ?X) := g(?Y, b) :- p(?X, ?Y)$.

```xml
<Implies>
<head>
  <Equal>
    <Hterm>
      <op><Con>f</Con></op>
      <Con>a</Con>
      <Var>X</Var>
    </Hterm>
    <Hterm>
      <op><Con>g</Con></op>
      <Var>Y</Var>
      <Con>b</Con>
    </Hterm>
  </Equal>
</head>
<body>
  <Hterm>
    <op><Con>p</Con></op>
    <Var>X</Var>
    <Var>Y</Var>
  </Hterm>
</body>
</Implies>
```
Frame Example: Value Molecule

- Parameterized-name -> filler slot: o[f(a,b) -> 3]

```xml
<Atom>
  <oid><Con>o</Con></oid>
  <slot>
    <Hterm>
      <op><Con>f</Con></op>
      <Con>a</Con>
      <Con>b</Con>
    </Hterm>
    <Con>3</Con>
  </slot>
</Atom>
```
Reification Example: Reified Rule

- Rule as slot filler:  
  \[ \text{john} [\text{believes} \rightarrow \{ p(?X) \text{ implies } q(?X) \}] \].
  
  ```xml
  <Hterm>
    <oid>john</oid>
    <slot>
      <Con>believes</Con>
      <Reify>
        <Implies>
          <body>
            <Hterm>
              <op><Con>p</Con></op>
              <Var>X</Var>
            </Hterm>
          </body>
          <head>
            <Hterm>
              <op><Con>q</Con></op>
              <Var>X</Var>
            </Hterm>
          </head>
        </Implies>
        </Reify>
      </slot>
    </Hterm>
  ```
Skolem Examples (I):

- Named **Skolem**: holds(a, _#1) and between(1, _#1, 5).

    \[
    \text{<And>}
    \begin{align*}
    \text{<Hterm>}
    & \text{<op><Con>holds</Con>}</op> \\
    & \text{<Con>a</Con>} \\
    & \text{<Skolem>1</Skolem>}
    \end{align*}
    \text{</Hterm>}
    \begin{align*}
    \text{<Hterm>}
    & \text{<op><Con>between</Con>}</op> \\
    & \text{<Con>1</Con>} \\
    & \text{<Skolem>1</Skolem>} \\
    & \text{<Con>5</Con>}
    \end{align*}
    \text{</Hterm>}
    \text{</And>}
    \]
Skolem Examples (II):

- Unamed Skolem: holds(a,_#) and between(1,_#,5).

```xml
<And>
  <Hterm>
    <op><Con>holds</Con></op>
    <Con>a</Con>
    <Skolem/>
  </Hterm>
  <Hterm>
    <op><Con>between</Con></op>
    <Con>1</Con>
    <Skolem/>
    <Con>5</Con>
  </Hterm>
</And>
```
Proceed towards Modal Logics

- Modal operators **generically** viewed as special *Relation*s at least one of whose arguments is a proposition represented as an *Atom* with an uninterpreted *Relation* (including another modal operator, but not an arbitrary formula)
  - *Alethic* **necessary** (□) and **possible** (◇)
  - *Deontic* **must** and **may** (e.g., in business rules)
  - Open for *temporal* (e.g., when planning/diagnosing reactive rules), *epistemic* (e.g., in authentication rules), and further modal operators
- Towards a **unified framework** for multi-modal logic based on Kripke-style possible worlds semantics
Modal Examples: Alethic Operator

- Necessity: **□prime(1)**

```xml
<Atom>
  <Rel modal="yes">necessary</Rel>
  <Atom>
    <Rel in="no">prime</Rel>
    <Data>1</Data>
  </Atom>
</Atom>
```
Modal Examples: Epistemic Operator

- Knowledge: \texttt{k\texttt{nows}(\texttt{Mary,material(\texttt{moon,rock}))}}

\begin{verbatim}
<Atom>
  <Rel modal="yes">knows</Rel>
  <Ind>Mary</Ind>
  <Atom>
    <Rel in="no">material</Rel>
    <Indymoon</Ind>
    <Ind>rock</Ind>
  </Atom>
</Atom>
\end{verbatim}
Modal Examples: Epistemic Reasoning

- Veridicality axiom: $\text{Knows}_{\text{Agent}} \text{proposition} \rightarrow \text{proposition}$

\[
\text{Knows}_{\text{Mary}} \text{material}(\text{moon, rock}) \rightarrow \text{material}(\text{moon, rock})
\]

Serialization in previous slide

\[
\text{Atom}\]

\[
\text{Rel in="yes">material</Rel>} \quad \text{<!-- "yes" is default -->}
\]

\[
\text{Ind>moon</Ind>}
\]

\[
\text{Ind>rock</Ind>}
\]

\[
\text{Atom>}
\]
Modal Examples: Nested Operators

- Knowledge of Necessity: \( \text{knows}(\text{Mary}, \square \text{prime}(1)) \)

\[
<\text{Atom}>
  <\text{Rel modal="yes">knows</Rel}>
  <\text{Ind}>Mary</Ind>
  <\text{Atom}>
    <\text{Rel modal="yes" in="no">necessary</Rel}>
    <\text{Atom}>
      <\text{Rel in="no">prime</Rel}>
      <\text{Data}>1</Data>
    </\text{Atom}>
  </\text{Atom}>
</\text{Atom}>
\]
Protect Knowledge Bases by Integrity Constraints

- A knowledge base KB is a formula in any of our logic languages.
- An integrity constraint IC is also a formula in any of our logic languages, which may be chosen independently from KB.
- KB obeys IC iff KB entails IC (Reiter 1984, 1987).
  - Entailment notion of 1987 uses epistemic modal operator.
- Serialization: `<Entails> KB IC </Entails>`
Integrity Constraint Example: Rule with $\exists$-Head

- Adapted from (Reiter 1987):
  \[ IC = \{ (\forall x)\text{emp}(x) \Rightarrow (\exists y)\text{ssn}(x,y) \} \]

- $KB_1 = \{\text{emp}(\text{Mary})\}$  \hspace{1cm} $KB_1$ violates IC
- $KB_2 = \{\text{emp}(\text{Mary}), \text{ssn}(\text{Mary, 1223})\}$  \hspace{1cm} $KB_2$ obeys IC

\[ \langle\text{Entails}\rangle KB_1 IC \langle/\text{Entails}\rangle \]

$KB_1$:
<Atom>
  <Rel>emp</Rel>
  <Ind>Mary</Ind>
</Atom>

$KB_2$:
<Rulebase>
  <Atom>
    <Rel>emp</Rel>
    <Ind>Mary</Ind>
  </Atom>
  <Atom>
    <Rel>ssn</Rel>
    <Ind>Mary</Ind>
    <Data>1223</Data>
  </Atom>
</Rulebase>

IC:
<Forall>
  <Var>x</Var>
  <Implies>
    <Atom>
      <Rel>emp</Rel>
      <Var>x</Var>
    </Atom>
    <Exists>
      <Var>y</Var>
      <Atom>
        <Rel>ssn</Rel>
        <Var>x</Var>
        <Var>y</Var>
      </Atom>
    </Exists>
  </Implies>
</Forall>
Approach Production and Reaction Rules

- Share Condition (C) part with earlier languages as proposed for the RIF Condition Language
- Develop Action (A) part of Production Rules via a taxonomy of actions on KBs (Assert, Retract, ...), on local or remote hosts, or on the surroundings
- Develop Event (E) part of Reaction Rules via a corresponding taxonomy
- Create CA and ECA families bottom-up and map to relevant languages for Semantic Web Services
- Serialized: `<Reaction> E C A </Reaction>`
- See [http://ibis.in.tum.de/research/ReactionRuleML](http://ibis.in.tum.de/research/ReactionRuleML)
RDF Rules

- RDF-like Rules: Important RuleML sublanguage
  - Datalog: Relational databases augmented by views
  - RDF Properties: Slots permit non-positional, keyed arguments
  - RDF URIs/IRIs: Anchors provide object identity via webzing through URIs/IRIs
    - oids: Can be Individuals, Variables, etc.
    - iris: Now used for both RDF’s about and resource
  - RDF Blank Nodes: F-logic/Flora-2 Skolem-constant approach
    - E.g., Skolem generator ‘_’ becomes <Skolem/>
“For a product whose price is greater than 200 and whose weight is less than 50, no shipping is billed.”

<Implies>
  <body>
    <And>
      <Atom>
        <oid><Var>x</Var></oid>
        <Rel>product</Rel>
        <slot><Ind iri=":price"/><Var>y</Var></slot>
        <slot><Ind iri=":weight"/><Var>z</Var></slot>
      </Atom>
      <Atom>
        <Rel iri="swrlb:greaterThan"/><Var>y</Var><Data>200</Data>
      </Atom>
      <Atom>
        <Rel iri="swrlb:lessThan"/><Var>z</Var><Data>50</Data>
      </Atom>
    </And>
  </body>
  <head>
    <Atom>
      <oid><Var>x</Var></oid>
      <Rel>product</Rel>
      <slot><Ind iri=":shipping"/><Data>0</Data></slot>
    </Atom>
  </head>
</Implies>
Bidirectional Interpreters in Java

- Two varieties of reasoning engines
  - **Top-Down**: backward chaining
  - **Bottom-Up**: forward chaining

- jDREW: *Java Deductive Reasoning Engine for the Web* includes both TD and BU
  - [http://www.jdrew.org](http://www.jdrew.org)

- OO jDREW: *Object-Oriented* extension to jDREW
  - [http://www.jdrew.org/ooj jdrew](http://www.jdrew.org/ooj jdrew)

- Java Web Start online demo available at
  - [http://www.jdrew.org/ooj jdrew/demo.html](http://www.jdrew.org/ooj jdrew/demo.html)
OO jDREW Slots

- Normalized atoms and complex terms
  - oids (object identifier)
  - Positional parameters (in their original order)
  - Positional rest terms
  - Slotted parameters (in the order encountered)
  - Slotted rest terms

- Efficient unification algorithm
  - Linear O(m+n): instead of O(m*n)
    - No need for positional order
    - Slots internally sorted
  - Steps:
    - Scan two lists of parameters
      - Matching up roles and positions for positional parameters
      - Unifying those parameters
    - Add unmatched roles to list of rest terms
    - Generate dynamically a Plex (RuleML’s closest equivalent to a list) for a collection of rest terms
discount(?customer, ?product, percent5) :- premium(?customer), regular(?product).

premium(PeterMiller).
regular(Honda).

premium(cust->PeterMiller).
regular(prod->Honda).
OO jDREW Types

- Order-sorted type system
  - RDF Schema: lightweight taxonomies of the Semantic Web
  - To specify a partial order for a set of classes in RDFS

- Advantages
  - Having the appropriate types specified for the parameters
  - To restrict the search space
  - Faster and more robust system than when reducing types to unary predicate calls in the body

- Limitations
  - Only modeling the taxonomic relationships between classes
  - Not modeling properties with domain and range restrictions
base_price(customer->[sex->male;!?]; vehicle->:Van; price->725:Integer).
OO jDREW OIDs

- **oid**: Object Identifier
- Currently: symbolic names
  - In `<Atom>` & `<Implies>`
  - Planned: **iri** attribute
- E.g., give name to fact `keep(Mary, ?object)`.

```xml
<Atom>
  <oid><Ind mary-12</Ind></oid>
  <Rel>keep</Rel>
  <Ind>Mary</Ind>
  <Var>object</Var>
</Atom>

<Atom>
  <oid><Ind iri="http://mkb.ca"/></oid>
  <Rel>keep</Rel>
  <Ind>Mary</Ind>
  <Var>object</Var>
</Atom>

<Atom>
  <oid><Var>object</Var></oid>
  <Rel>keep</Rel>
  <Ind>Mary</Ind>
  <Var>object</Var>
</Atom>
```
Conclusions

- **RuleML** is modular family, whose root allows to access the language as a whole and whose members allow customized subsets
- New members joining, e.g. **Fuzzy RuleML**
- Concrete & abstract syntax of RuleML
  - Specified by modular XSD (shown here) & MOF
- Formal semantics of OO Hornlog RuleML
  - Implemented by OO jDREW BU & TD
- Interoperability/Interchange of/with RuleML
  - Realized by translators, primarily via XSLT