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-REWERSE, and other standards/gov'nt bodies

RuleML Enables ...

Rule { modelling / markup / translation / **interchange** / execution / publication / archiving } in { UML / RDF / **XML** / ASCII }

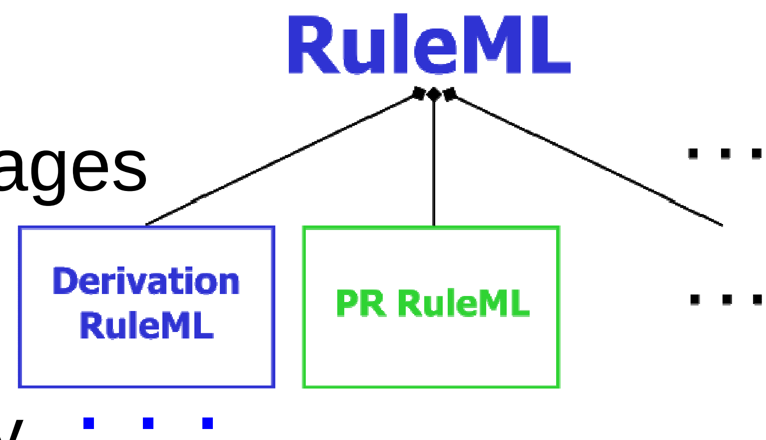
RuleML Identifies ...

- 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

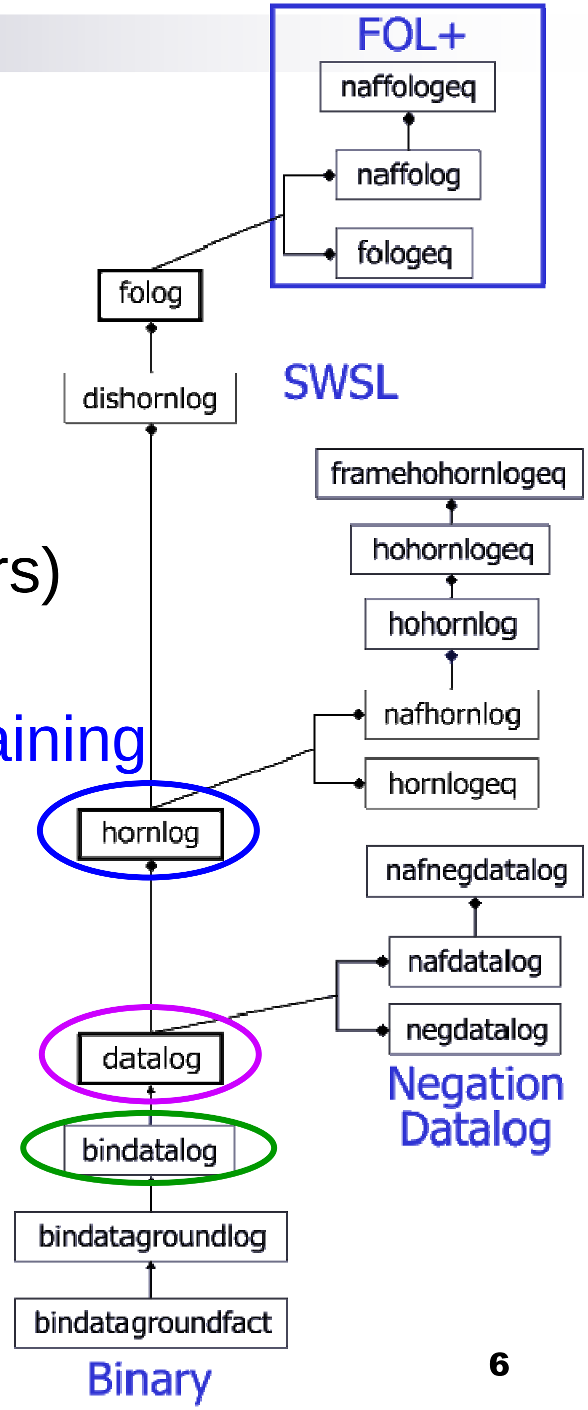


"RuleML is a **family** of sublanguages whose **root** allows access to the language as a whole and whose **members** allow to identify customized subsets of the language."

- 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
- Current release: RuleML 0.91
- Previews: http://wiki.ruleml.org/XSD_Workplan

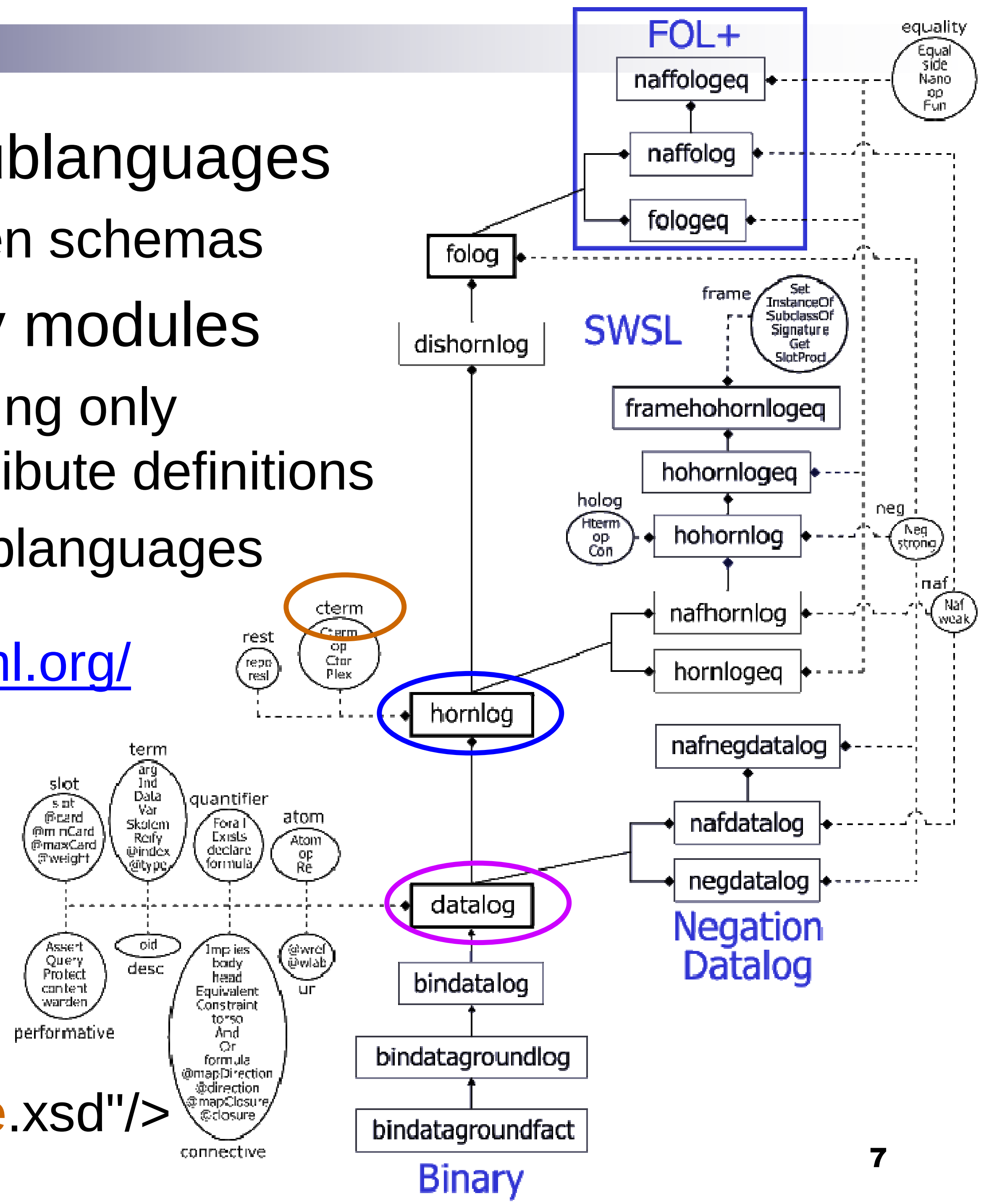
Schema Modularization

- 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"/>

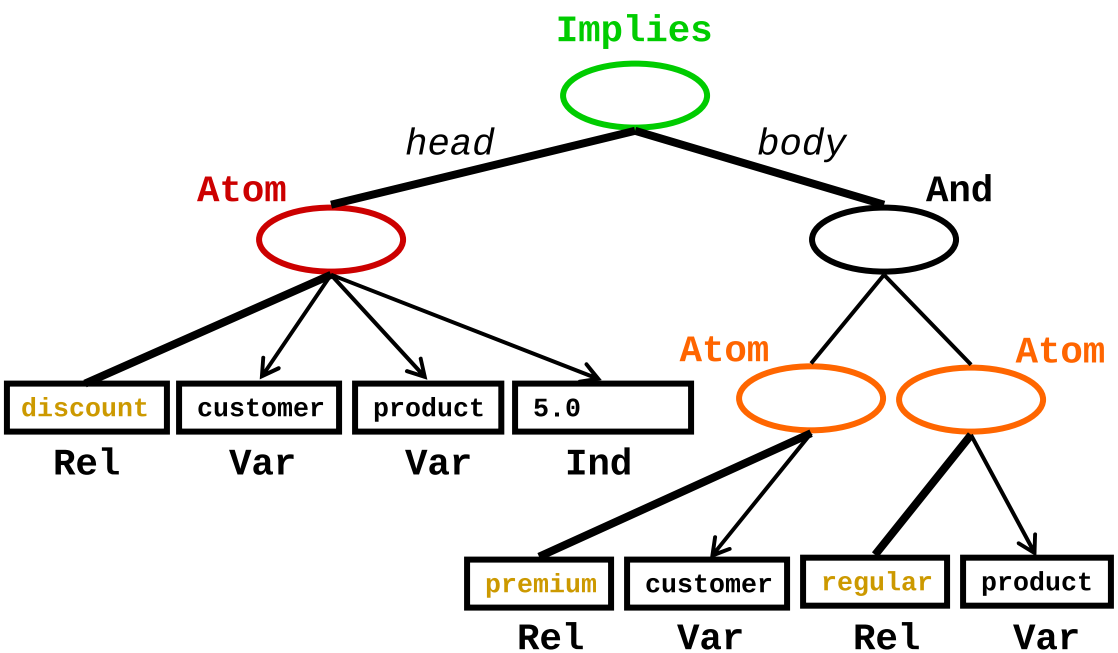


Bring Datalog to the Semantic Web

- Start with n-ary relations (not binary properties)
- Keep **Var**iable 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 1st: RDF descriptions; 2nd: 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**."



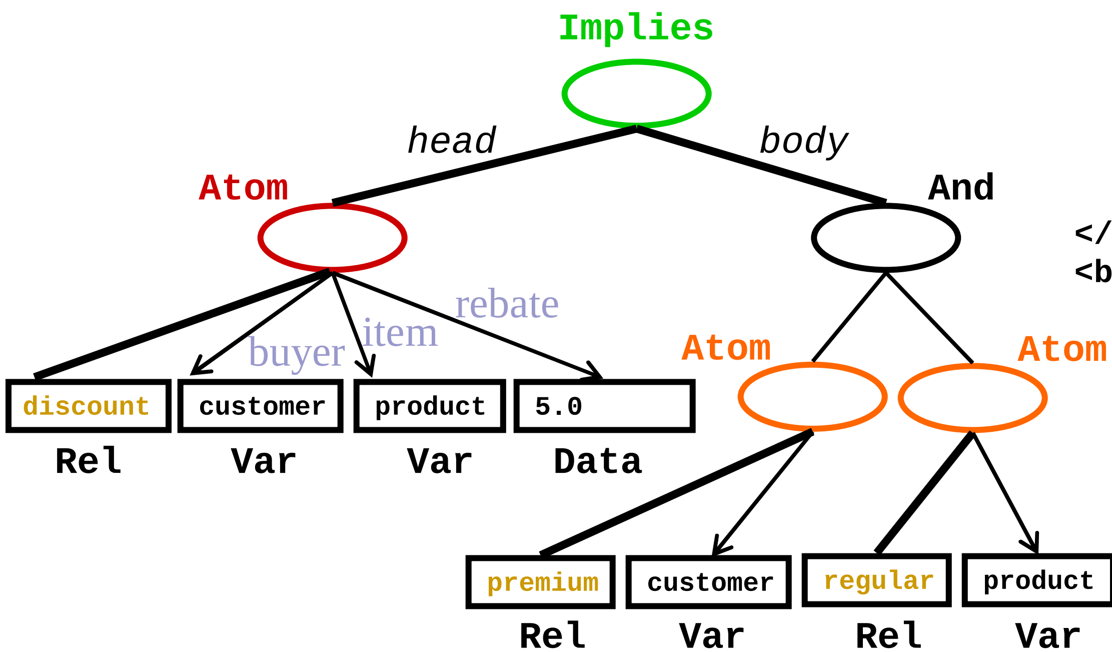

```
<Implies>
  <head>
    <Atom>
      <Rel>discount</Rel>
      <Var>customer</Var>
      <Var>product</Var>
      <Ind>5.0</Ind>
    </Atom>
  </head>
  <body>
    <And>
      <Atom>
        <Rel>premium</Rel>
        <Var>customer</Var>
      </Atom>
      <Atom>
        <Rel>regular</Rel>
        <Var>product</Var>
      </Atom>
    </And>
  </body>
</Implies>
```

Extend Datalog for the Semantic Web (I)

- Allow slots as name**`->`**filler pairs in **`Atom`**s (cf. F-logic's methods and RDF's properties)
- Extend optional types and signatures for slots
- Add optional object identifiers (**`oid`**s) to atoms
- Separate **`Data`** literals from **`Ind`**ividual constants

Business Rule: Slotted (for OO)

"The **discount** for a *customer* buying a *product* is 5 percent if the *customer* is **premium** and the *product* is **regular**."




```
<Implies>
  <head>
    <Atom>
      <Rel>discount</Rel>
      <slot><Ind>buyer</Ind><Var>customer</Var></slot>
      <slot><Ind>item</Ind><Var>product</Var></slot>
      <slot><Ind>rebate</Ind><Data>5.0</Data></slot>
    </Atom>
  </head>
  <body>
    <And>
      <Atom>
        <Rel>premium</Rel>
        <Var>customer</Var>
      </Atom>
      <Atom>
        <Rel>regular</Rel>
        <Var>product</Var>
      </Atom>
    </And>
  </body>
</Implies>
```

Extend Datalog for the Semantic Web (II)

- Permit IRI webizing for **`Data`** (XML Schema Part 2), **`Ind`**ividuals (RDF's **`resource`**s), **`Rel`**ations, **`slot`** names, types (RDFS' classes), and **`oid`**s (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 **`Fun`**ctions and their **`Expr`**essions; also for extended Datalog
- Augment Datalog's Herbrand model semantics with such **`Fun`**ctions (querying becomes undecidable)
- Extend Datalog syntaxes
  - XML Schema of Hornlog RuleML inherits and augments XML Schema of Datalog RuleML
- Add **`Equal`**ity and **`in`**terpreted **`Fun`**ctions (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 **`Neg`**ation
  - Disjunctive Horn Logic with restricted strong **`Neg`**
- Permit unrestricted **`Or`**, **`And`**, strong **`Neg`**, 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 (**`Ctor`**) of a complex term (**`Cterm`**)
  - User-defined function (**`Fun`**) of a call (**`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:

```
<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 = birth-year(?P)`** ⇒ **`age(?P) = subtract(this-year(),?B)`**

```
<Implies>
 <Equal oriented="no">
   <Var>B</Var>
   <Expr>
     <Fun in="yes">birth-year</Fun>
     <Var>P</Var>
   </Expr>
 </Equal>
 <Equal oriented="yes">
   <Expr>
     <Fun in="yes">age</Fun>
     <Var>P</Var>
   </Expr>
   <Expr>
    <Fun in="yes">subtract</Fun>
    <Expr>
      <Fun in="yes">this-year</Fun>
    </Expr>
    <Var>B</Var>
   </Expr>
 </Equal>
</Implies>
```

Accommodate SWSL-Rules

- HiLog: Higher-order **`Var`**iables, **`Con`**stants, and **`Hterm`**s (complex terms and atomic formulas at the same time)
- **`Equal`**: As in Horn Logic with (un**`oriented`**) **`Equal`**ity
- Frames:
  - Value molecules: **`Atom`**s with an **`oid`**, an optional **`Rel`** class, and zero or more name**`->`**filler instance **`slot`**s
  - Signature molecules: name**`=>`**filler class **`slot`**s, 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
- **`Skolem`**s: Unnamed, represent new individual constants (like RDF's blank nodes); otherwise, uniquely named ones

HiLog Examples: Hterms (I)

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

```
<Hterm>
  <op><Con>f</Con></op>
  <Con>a</Con>
  <Var>X</Var>
</Hterm>
```

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

```
<Hterm>
  <op><Var>X</Var></op>
  <Con>a</Con>
  <Var>Y</Var>
</Hterm>
```

HiLog Examples: Hterms (II)

- Parameterized function symbols: **`f(?X,a)(b,?X(c))`**

```
<Hterm>
  <op>
    <Hterm>
      <op><Con>f</Con></op>
      <Var>X</Var>
      <Con>a</Con>
    </Hterm>
  </op>
  <Con>b</Con>
  <Hterm>
    <op><Var>X</Var></op>
    <Con>c</Con>
  </Hterm>
</Hterm>
```

Equality Example

- **Equal**ity **:=:** in rule head: **`f(a,?X):=:g(?Y,b) :- p(?X,?Y).`**

```
<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]**

```
<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: **`john[believes -> ${p(?X) implies q(?X)}].`**

```
<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).**

```
<And>
  <Hterm>
    <op><Con>holds</Con></op>
    <Con>a</Con>
    <Skolem>1</Skolem>
  </Hterm>
  <Hterm>
    <op><Con>between</Con></op>
    <Con>1</Con>
    <Skolem>1</Skolem>
    <Con>5</Con>
  </Hterm>
</And>
```

Skolem Examples (II):

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

```
<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 **`Rel`**ations at least one of whose arguments is a proposition represented as an **`Atom`** with an uninterpreted **`Rel`**ation (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)**

```
<Atom>
  <Rel modal="yes">necessary</Rel>
  <Atom>
    <Rel in="no">prime</Rel>
    <Data>1</Data>
  </Atom>
</Atom>
```

Modal Examples: Epistemic Operator

- Knowledge: **knows(Mary,material(moon,rock))**

```
<Atom>
  <Rel modal="yes">knows</Rel>
  <Ind>Mary</Ind>
  <Atom>
    <Rel in="no">material</Rel>
    <Ind>moon</Ind>
    <Ind>rock</Ind>
  </Atom>
</Atom>
```

Modal Examples: Epistemic Reasoning

- Veridicality axiom: $Knows_{Agent}\, proposition \rightarrow proposition$

  $Knows_{Mary}$ **`material(moon,rock)`** → **`material(moon,rock)`**

Serialization in previous slide

→

```
<Atom>
  <Rel in="yes">material</Rel>  <!-- "yes" is default -->
  <Ind>moon</Ind>
  <Ind>rock</Ind>
</Atom>
```

Modal Examples: Nested Operators

- Knowledge of Necessity: **knows(Mary,□prime(1))**

```
<Atom>
  <Rel modal="yes">knows</Rel>
  <Ind>Mary</Ind>
  <Atom>
    <Rel modal="yes" in="no">necessary</Rel>
    <Atom>
      <Rel in="no">prime</Rel>
      <Data>1</Data>
    </Atom>
  </Atom>
</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 ∃-Head

- Adapted from (Reiter 1987):
  IC = {$(\forall x) emp(x) \Rightarrow (\exists y) ssn(x,y)$}
  KB_1 = {**emp(Mary)**} — KB_1 violates IC
  KB_2 = {**emp(Mary), ssn(Mary,1223)**} — KB_2 obeys IC

<**Entails**> KB_i IC </**Entails**>

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 TG

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 **`O`**bject **`id`**entity via webzing through URIs/IRIs
    - **`oid`**s: Can be **`Ind`**ividuals, **`Var`**iables, etc.
    - **`iri`**s: 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.”

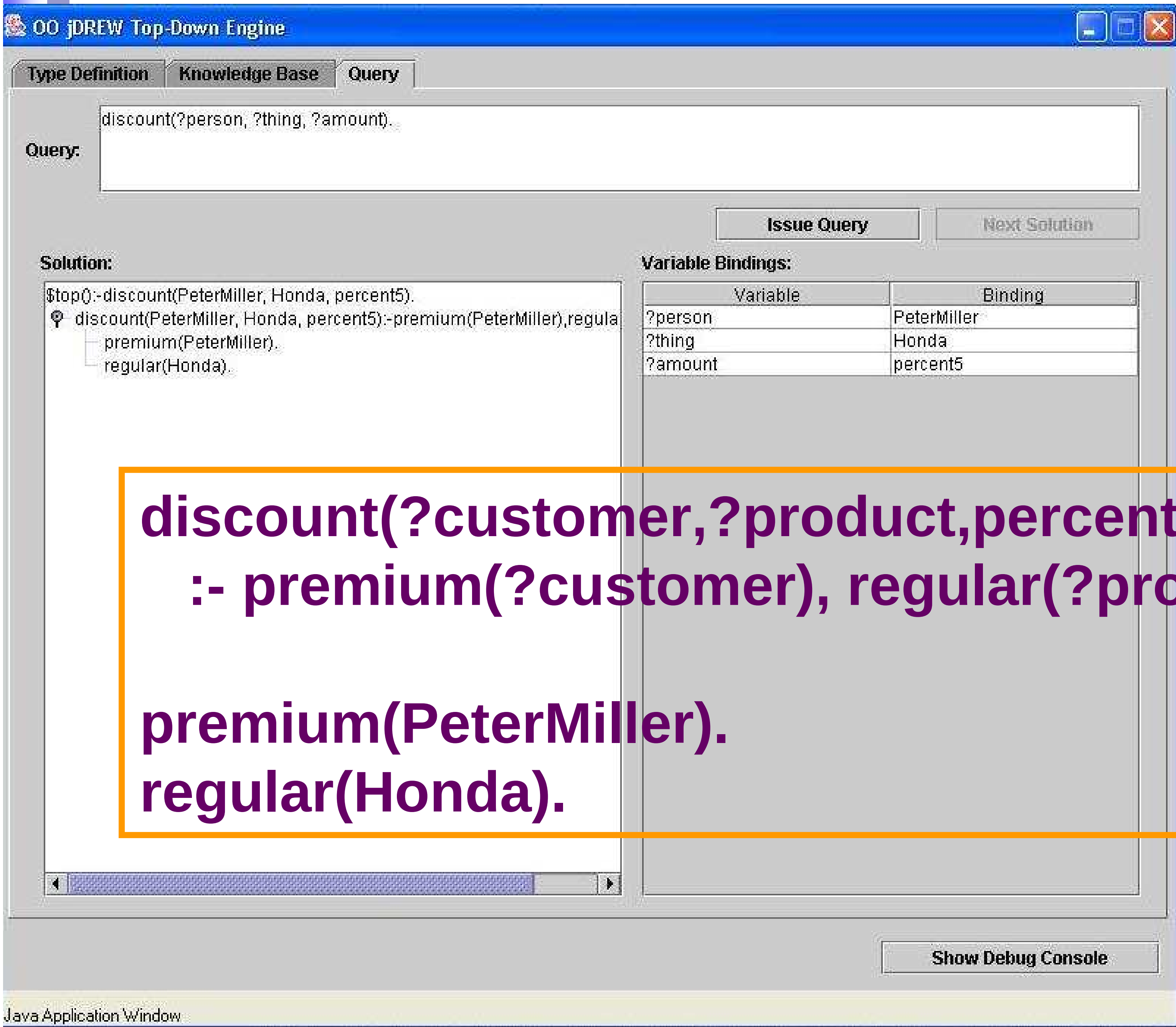
```
<Implies>
  <body>
    <And>
      <Atom>
        <oid><Var>x</Var></oid>
        <Rel>product</Rel>
        <slot><Ind iri=":price"/><Var>y</Var></slot>
        <slot><Ind iri=":weight"/><Var>z</Var></slot>
      </Atom>
      <Atom>
        <Rel iri="swrlb:greaterThan"/><Var>y</Var><Data>200</Data>
      </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
  - **T**op-**D**own: backward chaining
  - **B**ottom-**U**p: forward chaining
- jDREW: *Java Deductive Reasoning Engine for the Web* includes both TD and BU
  http://www.jdrew.org
- OO jDREW: *Object-Oriented* extension to jDREW
  http://www.jdrew.org/oojdrew
- Java Web Start online demo available at
  http://www.jdrew.org/oojdrew/demo.html

OO jDREW Slots

- Normalized atoms and complex terms
  - **oid**s (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

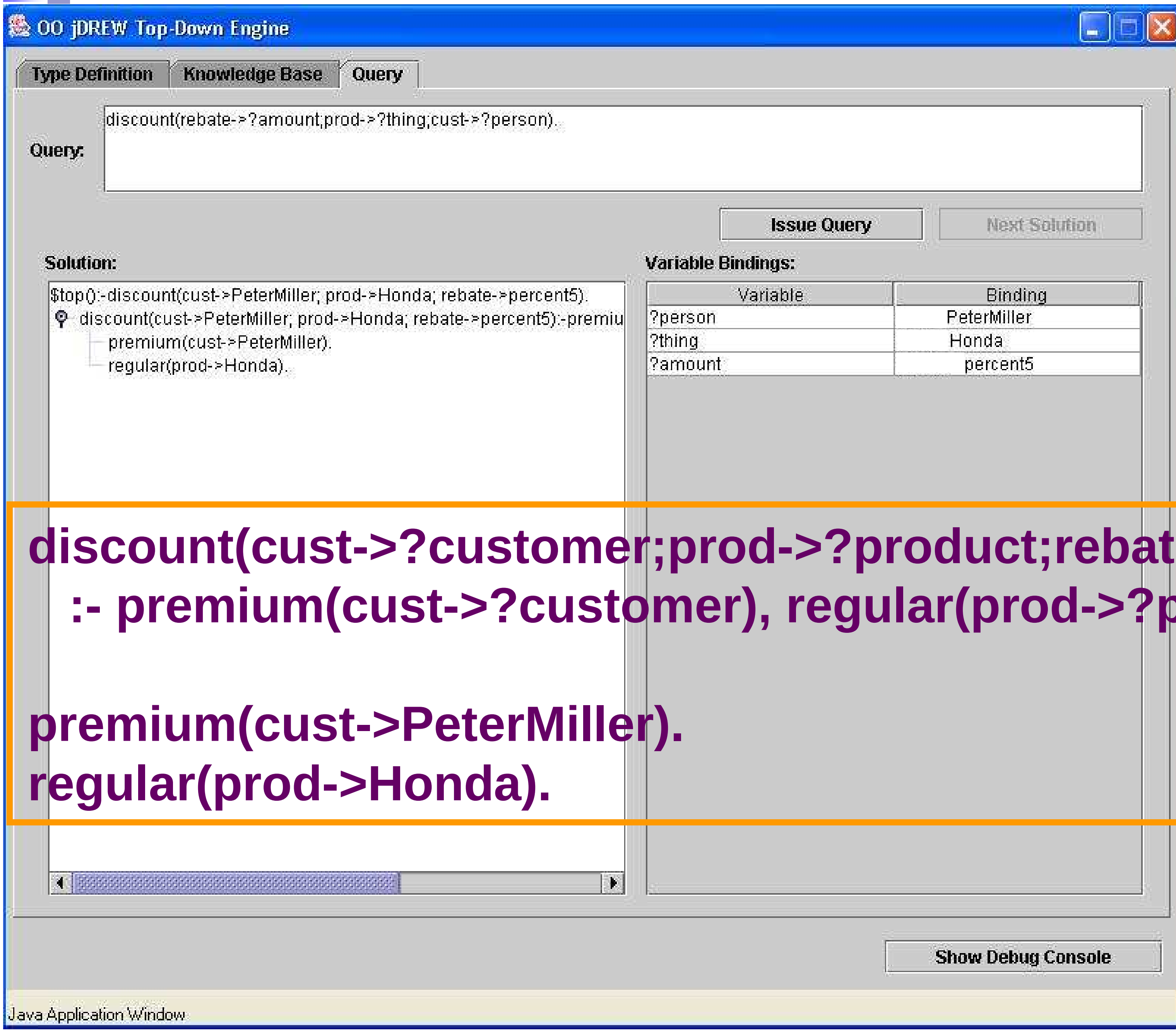


discount(?customer,?product,percent5)
:- premium(?customer), regular(?product).

premium(PeterMiller).
regular(Honda).

positional

POSL syntax



slotted

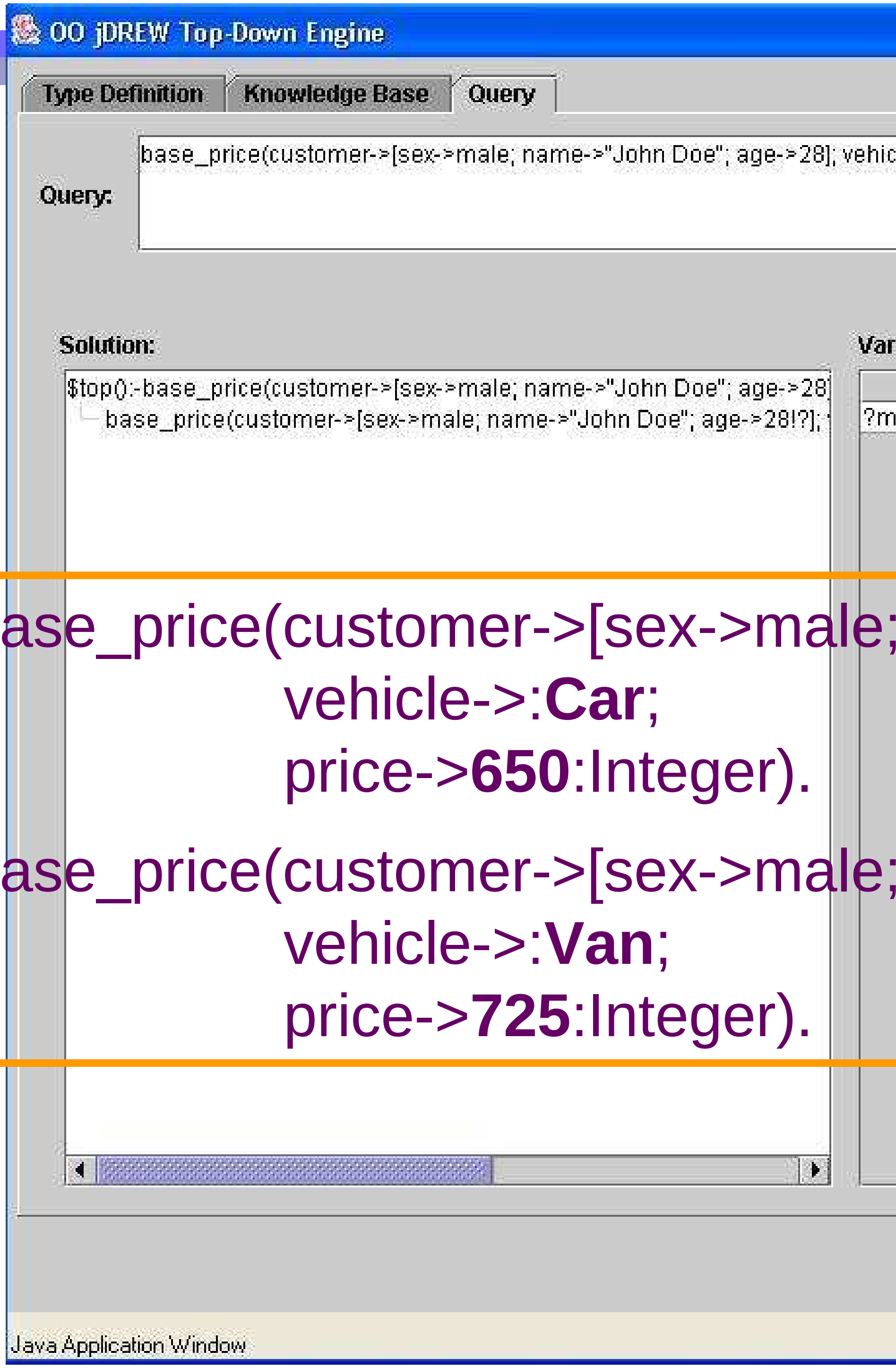
POSL syntax

discount(cust->?customer;prod->?product;rebate->percent5)
:- premium(cust->?customer), regular(prod->?product).

premium(cust->PeterMiller).
regular(prod->Honda).

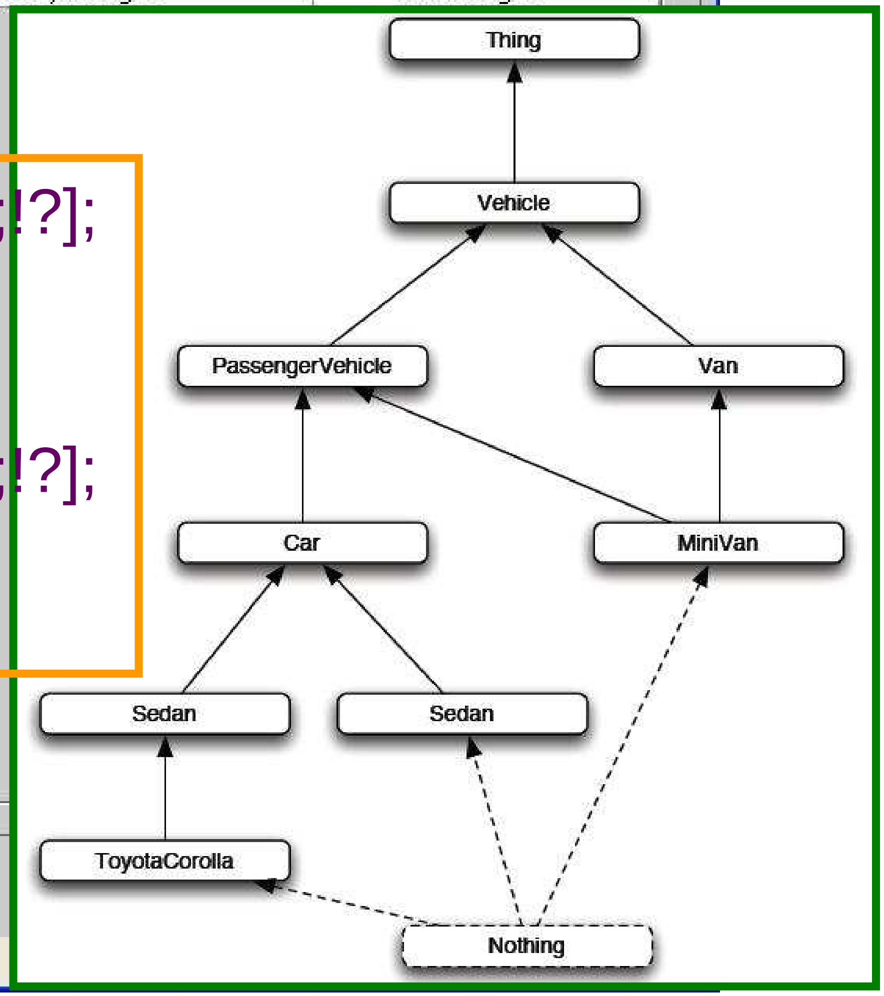
OO jDREW Types

- 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->:**Car**;
price->**650**:Integer).

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).

```
<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