# RDF Declarative Description (RDD): A Language for Metadata

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## Abstract

*RDF Declarative Description (RDD) is a metadata modeling language which extends RDF(S) expressiveness by provision of generic means for succinct and uniform representation of metadata, their relationships, rules and axioms. Through its expressive mechanism, RDD can directly represent all RDF-based languages such as OIL and DAML-family markup languages (e.g., DAML+OIL and DAML-S), and hence allows their intended meanings to be determined directly without employment of other formalisms. Therefore, RDD readily enables interchangeability, interoperability as well as integrability of metadata applications, developed independently by different communities and exploiting different schemas and languages. Moreover, RDD is also equipped with computation and query-processing mechanisms.*

**Keywords:** *Metadata*, *RDF*, *RDF Schema*, *RDF Declarative Description*, *RDD language*.

## 1 Introduction

*Resource Description Framework* (*RDF*) [13] is a W3C's recommended framework for encoding, exchange and reuse of metadata, which offers foundations for syntactic and semantic interoperations among Web applications. Although *RDF Schema* (*RDFS*) [8] provides a simple ontological-modeling facility for descriptions of classes, properties and their hierarchies, its mechanism is still limited and lacks expressive power to describe Web resources and Web applications in that:

- it cannot represent ontological and domain axioms as well as relational algebraic properties, e.g., transitivity, symmetry of relations and inverse relations;
- it does not support an efficient and powerful computation mechanism; and
- it does not provide a query-processing mechanism.

In order to cope with such limitations, this paper develops *RDF Declarative Description* (*RDD*) language which employs RDF(S) and *Declarative Description* (*DD*) theory [1,2] as its underlying frameworks for description of metadata and for enhancement of RDF(S) expressive power. It allows ordinary RDF (metadata) elements, encoded in XML language and describing specific facts and relations among certain resources, to be directly represented. Moreover, it enhances the capability and expressiveness of ordinary RDF elements by additionally allowing expression of implicit complex resources as well as their relations, rules and axioms in terms of *RDF expressions*—an extension of RDF elements with variables—and *RDF clauses*.

An *RDD statement descriptor*, formulated as a set of ordinary RDF elements, RDF expressions with variables and RDF clauses, then provides sufficient, flexible and expressive means for describing and modeling a wide diversity of resources. Its semantics is formally and precisely defined as a set of ordinary RDF elements which are directly described by or derivable from the description itself.

**Table 1. Variable Types.**

| Variable Type | Variable Names Beginning with | Instantiation to |
|---|---|---|
| ***N-variables***: *Name-variables* | $N | Element types or attribute names |
| ***S-variables***: *String-variables* | $S | Strings |
| ***P-variables***: *Attribute-value-pair-variables* | $P | Sequences of zero or more attribute-value pairs |
| ***E-variables***: *RDF-expression-variables* | $E | Sequences of zero or more RDF expressions |
| ***I-variables***: *Intermediate-expression-variables* | $I | Parts of RDF expressions |

Moreover, RDD also supports formulation and evaluation of queries which not only allows pattern matching and selective retrieval, but also supports inquiries about implicit information contained in RDF metadata.

Section 2 formalizes RDD language, Section 3 presents an RDD approach to metadata modeling, Section 4 demonstrates an example of modeling and querying a metadata application, Section 5 reviews current, related works, and Section 6 concludes.

## 2 RDF Declarative Description (RDD)

By employment of DD theory [1,2] (cf. Appendix for its fundamental concepts), RDF—the framework for representation of metadata—will be extended with modeling and reasoning services. First, a formal definition of RDF expressions will be given, followed by a formalization of an *RDF specialization system*—a mathematical abstraction characterizing the data structure of RDF expressions. Based on such a structure, RDD language will be developed.

### 2.1 RDF specialization system

Ordinary RDF elements are *ground* (variable-free) and take one of the forms:

- $<t\ \ a_1=v_1 \ldots a_m=v_m/>$,
- $<t\ \ a_1=v_1 \ldots a_m=v_m> v_{m+1} </t>$,
- $<t\ \ a_1=v_1 \ldots a_m=v_m> e_1 \ldots e_n </t>$,

where $m, n \geq 0$, $t$ is an element name, the $a_i$ are distinct attribute names, the $v_i$ are strings, and the $e_i$ are RDF elements.

In order to represent implicit information and to enhance RDF elements' expressiveness, their definition will be extended by incorporation of variables and then called *RDF expressions*. Every component of an RDF expression—the expression itself, its element name, attribute names and values, pairs of attribute-value, contents, sub-expressions as well as some partial structures—can contain variables. Table 1 defines all variable types and their usages.

An *RDF expression alphabet* $\Sigma_R$ then comprises the symbols in the sets of names $N$, characters $C$ as well as the sets of those five types of variables.

An RDF expression on $\Sigma_R$ takes formally one of the following forms:

- *evar*,
- $<t\ \ a_1=v_1 \ldots a_m=v_m\ \ pvar_1 \ldots pvar_k />$,
- $<t\ \ a_1=v_1 \ldots a_m=v_m\ \ pvar_1 \ldots pvar_k> v_{m+1} </t>$,
- $<t\ \ a_1=v_1 \ldots a_m=v_m\ \ pvar_1 \ldots pvar_k> e_1 \ldots e_n </t>$,
- $<ivar> e_1 \ldots e_n </ivar>$,

where - *evar* is an *E*-variable,
- $k, m, n \geq 0$,
- $t$, $a_i$ are names or *N*-variables,
- $pvar_i$ is a *P*-variable,
- $v_i$ is a string or an *S*-variable,
- *ivar* is an *I*-variable,
- $e_i$ is an RDF expression on $\Sigma_R$.

The orders of the attribute-value pairs $a_1=v_1 \ldots a_m=v_m$, of the *P*-variables $pvar_1 \ldots pvar_k$ and of the expressions $e_1 \ldots e_n$ are immaterial. Only the order of the expressions $e_1 \ldots e_n$ contained in an rdf:Seq-expression is important.

RDF expressions without variables are called *ground RDF expressions* or simply *RDF elements*, those with variables *non-ground RDF expressions*. An expression of the second, the third or the fourth form is referred to as a *t-expression*, while that of the fifth form as an *ivar-expression*. A ground *t*-expression will also be called a *t-element*. An *I*-variable is employed to represent an RDF expression when its structure or nesting pattern is not fully known. For example, the expression $<ivar> e_1 \ldots e_n </ivar>$, where $e_i$ are expressions, represents a set of RDF expressions which contain the sub-expression sequence $e_1 \ldots e_n$ to an arbitrary depth. As a more concrete example, consider the expression:

```
<$I:ivar>
   <$N:relation rdf:resource="http://ait.ac.th"/>
</$I:ivar>
```

which represents a class of resources with certain (possibly indirect) relations to the resource "http://ait.ac.th". For instance, it can represent

```
<Person rdf:about="p_01">
   <Name>Jack</Name>
   <Education>
      <Degree>
         <Name>MEng</Name>
         <Institute
            rdf:resource="http://ait.ac.th"/>
      </Degree>
   </Education>
</Person>
```

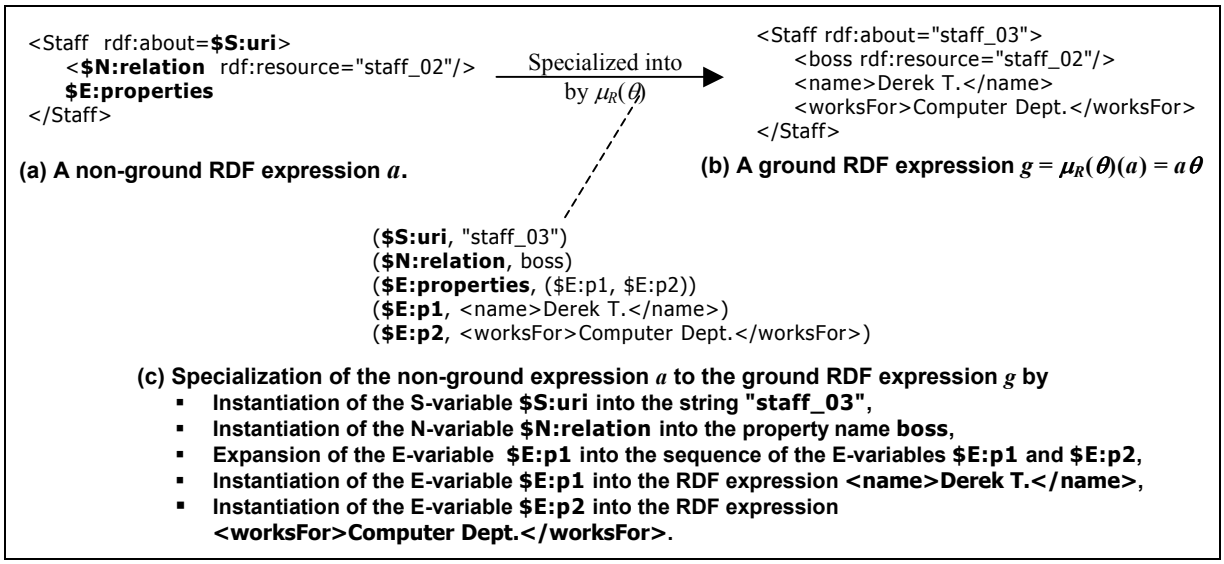


**Figure 1. Specialization of a non-ground RDF expression in $\mathcal{A}_R$ into a ground RDF expression in $\mathcal{G}_R$ by the operator $\mu_R$ using a specialization $\theta$ in $\mathcal{S}_R$.**

which specializes the *I*-variable $I:ivar into the description of the Person p_01 with an Education property indicating that such a Person has a degree MEng from the institute identified by "http://ait.ac.th".

Figure 1-a illustrates another example of a non-ground RDF expression which represents a class of Staff resources with some direct relation to the resource referred to by "staff_02"; however, the name of such a relation as well as the identifiers (URIs) and other properties of the resources in the class are unknown and are represented by an *N*-variable $N:relation, an *S*-variable $S:uri and an *E*-variable $E:properties, respectively. It will be seen later in this sub-section that such a non-ground expression can be specialized into a ground RDF expression of Figure 1-b.

Instantiation of those various types of variables is defined by *basic specialization*, each of which has the form ($v$, $w$) where $v$ specifies the name of the variable to be specialized and $w$ the specializing value. For example, ($S:s1, $S:s2), ($N:relation, boss) and ($E:properties, ($E:p1, $E:p2)) are basic specializations which rename the *S*-variable $S:s1 to $S:s2, instantiate the *N*-variable $N:relation into the element name boss, and expand the *E*-variable $E:properties into the sequence of the *E*-variables $E:p1 and $E:p2, respectively.

There are four types of basic specializations:

1. Rename variables.
2. Expand a *P*- or an *E*-variable into a sequence of variables of their respective types.
3. Remove *P*- or *E*-variables.
4. Instantiate variables to RDF expressions or components of RDF expressions which correspond to the types of the variables.

Denote a sequence of zero or more basic specializations by a *specialization*.

The data structure and the specialization of RDF expressions are characterized by a mathematical abstraction

$$\Gamma_R = \langle \mathcal{A}_R, \mathcal{G}_R, \mathcal{S}_R, \mu_R \rangle,$$

called **RDF Specialization System**, where

- $\mathcal{A}_R$ is the set of all RDF expressions on $\Sigma_R$,
- $\mathcal{G}_R$ is the subset of $\mathcal{A}_R$ which comprises all ground RDF expressions in $\mathcal{A}_R$,
- $\mathcal{S}_R$ is the set of all *specializations* which reflect the data structure of the RDF expressions in $\mathcal{A}_R$,
- $\mu_R$ is the *specialization operator* which determines, for each specialization $s$ in $\mathcal{S}_R$, the change of each RDF expression $a$ in $\mathcal{A}_R$ caused by $s$.

Note that a specialization in $\mathcal{S}_R$ will often be denoted by a Greek letter such as $\theta$, and when $\mu_R$ is clear from the context, for $\theta \in \mathcal{S}_R$, $\mu_R(\theta)(a)$ will be written simply as $a\theta$.

Consider Figure 1-c for an example of a specialization in $\mathcal{S}_R$ and its application to an RDF expression by the specialization operator $\mu_R$.

### 2.2 RDD language

After the RDF specialization system $\Gamma_R$ has been developed, RDD language and its related concepts can now be defined.

A *constraint* on $\Gamma_R$, useful for defining a restriction on RDF expressions or components of RDF expressions, is a formula $q(a_1, \ldots, a_n)$, where $n > 0$, $q$ is a *constraint predicate* and $a_i$ an RDF expression in $\mathcal{A}_R$. Application of $\theta \in \mathcal{S}_R$ to a constraint $q(a_1, \ldots, a_n)$ yields $q(a_1\theta, \ldots, a_n\theta)$. Given a *ground constraint* $q(g_1, \ldots, g_n)$, $g_i \in \mathcal{G}_R$, its truth or falsity is predetermined.

Given two RDF expressions $a_1$ and $a_2$, define GT($a_1$, $a_2$) as a constraint which will be true, iff $a_1$, $a_2$ are RDF elements of the forms <Num>$v_1$</Num>, and <Num>$v_2$</Num>, respectively, where $v_1$, $v_2$ are numbers and $v_1 > v_2$. Obviously, a constraint

GT(<Num>8</Num>,<Num>4</Num>)

is a true ground constraint in *Tcon*. In addition, for some $a_1$, $a_2$, $a_3 \in \mathcal{A}_R$, let Mul($a_1$, $a_2$, $a_3$) be a constraint which will be true iff $a_1$, $a_2$ and $a_3$ are RDF elements of the forms:

<Num>$n_1$</Num>,
<Multiplier>$n_2$</Multiplier>, and
<Result>$n_3$</Result>,

respectively, where $n_1$, $n_2$, $n_3$ are numbers, and $n_3$ is the result of multiplying $n_1$ and $n_2$, i.e., $n_3 = n_1 \times n_2$.

An *RDF declarative description* on $\Gamma_R$, simply called an *RDD description*, is a set of *RDF clauses*, each of which has the form:

$$H \leftarrow B_1, B_2, ..., B_n$$

where $n \geq 0$, $H$ is an RDF expression in $\mathcal{A}_R$, and $B_i$ is an RDF expression in $\mathcal{A}_R$, or a *constraint* on $\Gamma_R$. The order of the $B_i$ is immaterial. $H$ is called the *head* and ($B_1$, ..., $B_n$) the *body* of the clause. Such a clause, if $n = 0$, is called a *unit clause*, if $n > 0$, a *non-unit clause*. When it is clear from the context, a unit clause ($H \leftarrow$) will be simply written as $H$. Therefore, an RDF document, containing a set of RDF elements and describing certain resources, is directly mapped onto an RDD description comprising solely ground RDF unit clauses.

Given an RDD description $P$, its meaning, denoted by $\mathcal{M}(P)$ (cf. Appendix), is the set of all RDF elements which are directly described by and are derivable from the unit and the non-unit clauses in $P$, respectively, i.e.:

- Given a unit clause ($H \leftarrow$ ) in $P$, for $\theta \in \mathcal{S}_R$:
  $H\theta \in \mathcal{M}(P)$ if $H\theta$ is a ground RDF expression.
- Given a non-unit clause
  $$(H \leftarrow B_1, ..., B_i, B_{i+1}, ..., B_n)$$
  in $P$, assuming without loss of generality that $B_1$, ..., $B_i$ are RDF expressions and $B_{i+1}$, ..., $B_n$ constraints, for $\theta \in \mathcal{S}_R$:
  $H\theta \in \mathcal{M}(P)$ if
  - $H\theta$ is a ground RDF expression,
  - $B_1\theta$,..., $B_i\theta \in \mathcal{M}(P)$,
  - $B_{i+1}\theta$, ... ,$B_n\theta$ are true constraints.

## 3 RDD: a metadata modeling language

In RDD language, metadata expressed in terms of RDF elements are directly represented by ground RDF expressions in $\mathcal{G}_R$, while classes of RDF metadata which share certain similar components and structures are modeled by RDF expressions with variables as shown in Figure 1-a.

A collection of RDF metadata describing certain specific facts and relations among resources of a real-world domain is then modeled as a set of RDF expressions. Ontological and domain axioms as well as implicit relations and their algebraic properties, such as transitivity, symmetry and inverse, are expressed as RDF clauses.

Hence, a particular metadata application domain is readily modeled as an RDD description which comprises a set of RDF expressions, describing explicit, complex objects and their relations in the domain, together with a set of RDF clauses, representing the domain's axioms as well as certain implicit relations. Its semantics is a set of RDF elements, which are explicit in the domain, together with all the derived ones, which are inferred from the specified axioms and relations.

Besides provision of a simple, yet expressive mechanism to model metadata, RDD also provides a facility to formulate and evaluate queries. Basically, a query is represented by an RDD description containing one or more RDF non-unit clauses. The head of each clause describes the structure of the query result, while its body specifies the pattern as well as the selection condition of the query.

Evaluation of a query is carried out by employment of *Equivalent Transformation* (*ET*) [2,3] (cf. Appendix)—a new computational model for solving problem based on *semantics-preserving* transformations. Given a description $P$ specifying a collection of metadata elements as well as a set of their relations and axioms within some particular domain, a query represented by a description $Q$ is evaluated by transforming the description ($P \cup Q$) successively into a simpler but equivalent description, from which the answers to the query can be obtained easily and directly. More precisely, such a description ($P \cup Q$) will be successively transformed until it becomes the description ($P \cup Q'$), where $Q'$ consists of only *ground unit clauses* and $\mathcal{M}(P \cup Q) = \mathcal{M}(P \cup Q')$. In order to guarantee the correctness of the computation, only equivalent transformations can be applied at every step. The unfolding transformation, a widely-used program transformation in conventional logic programming, is a kind of equivalent transformation. Other kinds of equivalent transformation can also be devised, especially for improvement of computation efficiency.

## 4 Example: metadata modeling

*DAML+OIL* [11] is an RDF-based language which extends RDFS by a richer set of modeling constructs for description of ontological axioms as well as algebraic properties of relations. This example demonstrates an RDD approach to representing and querying a metadata application by employment of DAML+OIL to model the application's schema and

```
<daml:Class rdf:ID="Staff"/>
<daml:Class rdf:ID="JuniorStaff">
    <rdfs:subClassOf rdf:resource="Staff"/>
</daml:Class>
<daml:Class rdf:ID="SeniorStaff">
    <rdfs:subClassOf rdf:resource="Staff"/>
</daml:Class>
<daml:Property rdf:ID="name"/>
<daml:Property rdf:ID="worksFor"/>
<daml:Property rdf:ID="salary"/>
<daml:TransitiveProperty rdf:ID="boss"/>
<daml:Property rdf:ID="contractPeriod"/>
<SeniorStaff rdf:about="staff_01">
    <name>Somchai P.</name>
    <worksFor>Sales Dept.</worksFor>
    <salary>5000</salary>
</SeniorStaff>
<SeniorStaff about="staff_02">
    <name>Sawat K.</name>
    <worksFor>Computer Dept.</worksFor>
    <salary>7000</salary>
</SeniorStaff>
<SeniorStaff  about="staff_03">
    <name>Derek T.</name>
    <worksFor>Computer Dept.</worksFor>
    <salary>6000</salary>
    <boss rdf:resource="staff_02"/>
</SeniorStaff>
<JuniorStaff  about="staff_04">
    <name>Arunee I.</name>
    <worksFor>Computer Dept.</worksFor>
    <salary>3000</salary>
    <boss rdf:resource="staff_03"/>
</JuniorStaff>
```

**Figure 2. Modeling of an application's schema and data.**

to describe the application's data and objects. The example will first show that by RDD language, instances of DAML+OIL can be directly expressed without a necessity for translation or modification and their semantics can be precisely determined. It will then demonstrate the expressive power of RDD language by modeling a particular domain axiom which is essential in the application but inexpressible by DAML+OIL. Finally, an example of a query about information implicit in the application will be given.

**Modeling the application's schema and data:** Figure 2 illustrates an example of a DAML+OIL document which defines the application's schema and describes certain explicit information about each data object of the application. Obviously, such a document is an RDD description which contains merely unit clauses and will be referred to as $P_1$.

**Modeling relational algebraic properties and ontological axioms:** In order to define the meanings of those DAML+OIL modeling constructs (i.e., subClassOf and transitiveProperty), which are employed by Figure 2 and include some notion of implication, the RDF clauses $C_1$–$C_3$ of Figure 3 are formulated. Denote the set of these clauses by an RDD description $P_2$, i.e., $P_2 = \{C_1, C_2, C_3\}$. Note that the meanings of other DAML+OIL modeling constructs such as domain, range, inverseOf, intersectionOf and equivalentTo can also be defined in terms of RDF clauses in a similar manner.

**Modeling domain axioms:** The RDF clause $C_4$ of Figure 4 illustrates an example of modeling a domain axiom. It defines additional relationships among the properties salary, worksFor, bonus and contractPeriod of the class SeniorStaff. Donote the set of the clause $C_4$ by an RDD description $P_3$, i.e., $P_3 = \{C_4\}$.

Let $P$ be the union of the descriptions $P_1$, $P_2$ and $P_3$ which model (i) the application's schema and data, (ii) relational algebraic properties and ontological axioms, and (iii) domain axioms, respectively. Thus, $P$ becomes immediately a model of the application, and the meaning of $P$, $\mathcal{M}(P)$, includes not only the information explicit in the application, i.e., those elements of $P_1$, but also the following implicit information, which is uncovered by the clauses of the descriptions $P_2$ and $P_3$:

- The resources referred to by staff_01, staff_02, staff_03 and staff_04 are instances of the class Staff.
- The Staff referred to by staff_02 is a boss of the Staff referred to by staff_04.
- The contractPeriod of the SeniorStaff referred to by staff_02 is a 2-year term and that SeniorStaff will receive a bonus of 14000.
- The contractPeriod of the SeniorStaff referred to by staff_03 is a 2-year term and that SeniorStaff will receive a bonus of 12000.

**Formulating and evaluating a query:** The clause $C_q$ of Figure 5 represents a query, which selects all SeniorStaff who get a bonus of more than 10000, and then lists their names and bonuses.

Using unfolding transformation, the description

$$P \cup \{C_q\}$$

can be transformed into the description

$$P \cup \{C_{q1}, C_{q2}\},$$

where $C_{q1}$ and $C_{q2}$ are the following unit clauses

$C_{q1}$:
```
<BigBonusStaff>
    <name>Sawat K.</name>
    <bonus>14000</bonus>
</BigBonusStaff>     ← .
```

$C_{q2}$:
```
<BigBonusStaff>
    <name>Derek T.</name>
    <bonus>12000</bonus>
</BigBonusStaff>     ← .
```

Thus, one can directly draw that the head elements of $C_{q1}$ and $C_{q2}$ are the answers to the given query. Moreover, since only unfolding transformation, which always preserves the equivalence of declarative descriptions, is used, the two obtained answers are guaranteed to be correct.

```
C1: <daml:Class rdf:ID=$S:classA>                                  % subClassOf Transitivity
      <rdfs:subClassOf rdf:resource=$S:classC/>                    % Property: If A is a subclass of B
      $E:A_properties                                              % and B is a subclass of some broader
    </daml:Class>                                                  % class C, this implies that A is also a
        ← <daml:Class rdf:ID=$S:classA>                            % subclass of C.
            <rdfs:subClassOf rdf:resource=$S:classB/>
            $E:A_properties
          </daml:Class>,
          <daml:Class rdf:ID=$S:classB>
            <rdfs:subClassOf rdf:resource=$S:classC/>
            $E:B_properties
          </daml:Class>.

C2: <$S:classB rdf:about=$S:resourceX>                             % The meaning of subClassOf
      $E:X_properties                                              % construct: If a class A is declared
    </$S:classB>                                                   % as a subclass of another class B,
        ← <daml:Class rdf:ID=$S:classA>                            % then every resource which is an
            <rdfs:subClassOf rdf:resource=$S:classB/>              % instance of the class A will also be
            $E:A_properties                                        % an instance of the class B.
          </daml:Class>,
          <$S:classA rdf:about=$S:resourceX>
            $E:X_properties
          </$N:classA>.

C3: <$N:classA rdf:about=$S:resourceX>                             % The meaning of Transitive-
      <$S:propertyP rdf:resource=$S:resourceZ/>                    % Property construct: For a
    </$N:classA>                                                   % TransitiveProperty P, if a propertyP
        ← <daml:TransitiveProperty rdf:ID=$S:propertyP>,           % of a resource X is a resource Y and
          <$N:classA rdf:about=$S:resourceX>                       % that of the resource Y is a resource
            <$S:propertyP rdf:resource=$S:resourceY/>              % Z, then one can imply that a
            $E:X_properties                                        % property P of a resource X is also
          </$N:classA>,                                            % the resource Z.
          <$N:classB rdf:about=$S:resourceY>
            <$S:propertyP rdf:resource=$S:resourceZ/>
            $E:Y_properties
          </$N:classB>.
```

** **Note:** When an *S*-variable is used as an element name of an RDF expression, that variable can only be specialized into a valid element name, but not into any arbitrary string. For instance, an expression <**$S:classA** rdf:about="X"/> can be specialized into <**Staff** rdf:about="X"/> but not into <**"An arbitrary string"** rdf:about="X"/>.

**Figure 3. Modeling of ontological axioms and relational algebraic properties.**

```
C4: <SeniorStaff rdf:about=$S:staff>                               % The clause C4 defines additional
      <worksFor>Computer Dept.</worksFor>                          % relationships among the properties
      <salary>$S:salary</salary>                                   % worksFor, salary, bonus and
      <bonus>$S:bonus</bonus>                                      % contractPeriod of the class
      <contractPeriod>2 years</contractPeriod>                     % SeniorStaff, by asserting that for
      $E:staff_properties                                          % every SeniorStaff of the Computer
    </SeniorStaff>                                                 % Department, his/her contractPeriod
        ← <SeniorStaff rdf:about=$S:staff>                         % is 2 years and he/she will receive a
            <worksFor>Computer Dept.</worksFor>                    % double-salary bonus.
            <salary>$S:salary</salary>
            $E:staff_properties
          </SeniorStaff>,
          Mul(<Num>$S:salary</Num>, <Multiplier>2</Multiplier>,
              <Result>$S:bonus</Result>).
```

**Figure 4. Modeling of domain axioms.**

```
Cq: <BigBonusStaff>                                                % The clause Cq represents a query
      <name>$S:name</name>                                         % which lists the name and bonus of
      <bonus>$S:bonus</bonus>                                      % each SeniorStaff who gets a bonus
    </BigBonusStaff>                                               % of more than 10000.
        ← <SeniorStaff rdf:about=$S:staff>
            <name>$S:name</name>
            <bonus>$S:bonus</bonus>
            $E:staff_properties
          </SeniorStaff>,
          GT(<Num>$S:bonus</Num>, <Num>10000</Num>).
```

**Figure 5. Modeling of a query.**

R1: bonus(S, B)
← type(S, "SeniorStaff"),
worksFor(S,"Computer Dept."),
salary(S,SAL),
mul(SAL, "2", B).

R2: contractPeriod(S,"2 years")
← type(S, "SeniorStaff"),
worksFor(S,"Computer Dept."),
salary(S,SAL),
mul(SAL, 2, B).

**(a) Corresponding logical formulae.**

```
<Procedure>
  <Head>
    <Predicate name="bonus">
      <rdf:Seq>
        <rdf:li><Variable>S</Variable></rdf:li>
        <rdf:li><Variable>B</Variable></rdf:li>
      </rdf:Seq>
    </Predicate>
  </Head>
  <Body>
    <and>
      <Predicates>
        <rdf:Seq>
          <rdf:li>
            <Predicate name="type">
              <rdf:Seq>
                <rdf:li><Variable>S</Variable></rdf:li>
                <rdf:li><Constant>SeniorStaff</Constant>
                </rdf:li>
              </rdf:Seq>
            </Predicate>
          </rdf:li>
          ...
        </rdf:Seq>
      </Predicates>
    </and>
  </Body>
<Procedure>
```

**(b) Example of a metalog program representing the rule R1 in (a).**

**Figure 6. Metalog's representation of the domain axiom of Figure 4.**

## 5 Related works

*DAML+OIL* [11] is the most improved ontology markup language, which has been defined on the basis of RDF(S) and *OIL* [7,10], in order to provide an expressive set of modeling constructs. However, its mechanism is insufficient to model metadata, since it can represent only a limited set of ontological axioms and relational algebraic properties, while lacking an ability to express arbitrary rules and domain axioms.

As demonstrated by the example of Section 4, RDD language can be employed to enhance the expressiveness of DAML+OIL. Besides allowing the semantics of each DAML+OIL modeling construct to be precisely determined, RDD also provides sufficient means to describe additional rules and axioms in terms of RDF non-unit clauses.

*DAML-S* [5,15] is a recently proposed, DAML-family markup language for description of Web service properties, capabilities and functionalities. Instances of DAML-S, encoded in RDF/XML serialization, can be directly represented by RDD language as RDF unit clauses. Based on DAML-S syntax and constructs, an RDD approach to modeling and implementing Web services is being developed. In essence, such an approach will enable the automation of the following tasks:

- service advertisement and discovery,
- negotiation,
- service invocation and execution,
- service composition and integration, and
- service customization.

*SquishQL* [16]—the most recent, improved query language for RDF—is an SQL-like language with SELECT-FROM-WHERE-style syntax. Its query mechanism is based on subgraph matching, where patterns and query selection criteria are expressed in terms of RDF triples of subject, predicate and object. Based on SquishQL, several RDF query engines have been developed [16,9]. Apart from the simple ontological-modeling facility provided by RDFS, these engines do not allow additional descriptions of rules, axioms and relational algebraic properties. Thus, their sole inference service is based on class and property hierarchies.

*Metalog* [14] and *SiLRi* (*Simple Logic-based RDF Interpreter*) [6] employ logic programming and F-logic (Frame-Logic) theories, respectively, in order to provide both query and reasoning services for RDF. In these two approaches, RDF metadata elements must be translated into sets of corresponding representation in their original frameworks, i.e., into sets of binary predicates and F-logic formulae. Querying and reasoning about RDF metadata are then performed on these corresponding translations instead of direct operation on RDF elements.

Figure 6 shows metalog representation of the axiom of Figure 4. Clearly, its mechanism appears to

```
"staff_01": SeniorStaff [ name → "Somchai P.",
                          worksFor → "Computer Dept.",
                          salary → "7000"]
```

**(a) The DAML+OIL statement of Figure 2.**

```
S: SeniorStaff [ bonus → B, contractPeriod → "2 years"]
    ← S: SeniorStaff [ worksFor → "Computer Dept.",
                       salary → R],
      (B = R * 2).
```

**(b) The domain axiom of Figure 4.**

**Figure 7. F-logic expressions.**

```
C_set: <rdf:Bag ID="comp-dept-staff">
         $E:namelist
       </rdf:Bag>
     ← <xdd:SetOf>
         <xdd:Set>$E:namelist</xdd:Set>
         <xdd:Constructor>
           <rdf:li>$S:name</rdf:li>
         </xdd:Constructor>
         <xdd:Pattern>
           <Staff rdf:about=$S:X>
             <name>$S:name</name>
             <worksFor>
               Computer Dept.
             </worksFor>
             $E:staff_properties
           </Staff>
         </xdd:Pattern>
       </xdd:SetOf>.
```

**Figure 8. Modeling of an aggregation query.**

be unnatural and difficult to interpret, whence it is not a good candidate for a metadata language.

Figure 7 illustrates corresponding SiLRi (F-logic) expressions of the given DAML+OIL statement of Figure 2 and the domain axiom of Figure 4. Despite its declarativeness and abilities to formulate various kinds of axioms and queries, SiLRi's expressive power is still insufficient to represent RDF containers [6]—bags (rdf:Bag), sequences (rdf:Seq) and alternatives (rdf:Alt)—because in F-logic, sets are not treated as objects and cannot have attributes.

Moreover, axioms and queries involving such concepts of RDF containers are inexpressible. For example, it is unable to handle a query which returns an RDF:Bag listing names of all Staff working for the computer department. By RDD language, Figure 8 formulates this query as the RDF clause $C_{set}$, which employs the concept of *set aggregation* for construction of an RDF:Bag. The xdd:SetOf-expression in $C_{set}$'s body states that for each Staff $X$ of the computer department (xdd:Pattern sub-expression), the variable $E:namelist (xdd:Set sub-expression) aggregates an rdf:li-element listing $X$'s name, represented by $S:name (xdd:Constructor sub-expression). The theoretical details of this concept are beyond the scope of this paper, but are provided by [4].

# 6 Conclusions

By integration of the RDF data model, DD theory and ET computational paradigm, this paper has developed a solid, practical framework for a uniform representation of and reasoning with RDF metadata. The developed framework derives metadata description facilities, exchangeability and interoperability from the RDF data model, expressiveness from DD theory and an efficient computational mechanism from ET paradigm.

In order to demonstrate its usefulness and practicability in real applications, the framework has been employed to model a resource discovery problem as well as to develop a unified foundation for *software configuration management* [12]. Their Web-based prototype systems have also been implemented, using *ETC* [3]—a compiler under the ET paradigm.

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# Appendix: Declarative Description Theory

This section recalls certain fundamental definitions of *Declarative Description* (*DD*) theory [1,2]—an axiomatic theory inspired by the concept of conventional logic programs with an attempt to cover a wider variety of data domains. The data structure of a given data domain is characterized by a mathematical abstraction, called a *specialization system*. Despite its simplicity, the specialization system provides a sufficient structure for the definition of *declarative descriptions* and their *meanings*. Thus, by appropriate construction of a specialization system for a given data domain, a framework for the representation and computation of data in that domain can be directly obtained. Correspondingly, in Section 2, DD theory is employed to develop the theory of RDF declarative descriptions.

## A.1 Specialization systems

**Definition 1 (Specialization System)** Let $\mathcal{A}$, $\mathcal{G}$ and $\mathcal{S}$ be sets of *objects*, *ground objects*, and *specializations*, respectively, and $\mu$ be a mapping from $\mathcal{S}$ to *partial_map*($\mathcal{A}$ ) (i.e., the set of all partial mappings on $\mathcal{A}$ ). The quadruple $\langle \mathcal{A}, \mathcal{G}, \mathcal{S}, \mu \rangle$ is a specialization system under the conditions:

1. $\forall s_1, s_2 \in \mathcal{S}, \exists s \in \mathcal{S} : \mu(s) = \mu(s_1) \circ \mu(s_2)$,
2. $\exists s \in \mathcal{S}, \forall a \in \mathcal{A} : \mu(s)(a) = a$,
3. $\mathcal{G} \subset \mathcal{A}$,

where $\mu(s_1) \circ \mu(s_2)$ is the composite mapping of the partial mappings $\mu(s_1)$ and $\mu(s_2)$. The set $\mathcal{G}$ is called the *interpretation domain*. □

In the sequel, let $\Gamma = \langle \mathcal{A}, \mathcal{G}, \mathcal{S}, \mu \rangle$ be a specialization system. When $\mu$ is clear from the context, for $\theta \in \mathcal{S}$, $\mu(\theta)(a)$ will be written simply as $a\theta$. If there exists $b$ such that $a\theta = b$, then $\theta$ is said to be applicable to $a$, and $a$ is specialized into $b$ by $\theta$.

## A.2 Declarative descriptions and their declarative semantics

A declarative description on $\Gamma$ and other related concepts can now be defined.

Let a set $\mathcal{K}$ comprise constraint predicates. A *constraint* on $\Gamma$ is a formula $q(a_1, \ldots, a_n)$, where $q$ is a constraint predicate in $\mathcal{K}$ and $a_i$ an object in $\mathcal{A}$. Given a ground constraint $q(g_1, \ldots, g_n)$, $g_i \in \mathcal{G}$, its truth and falsity are predetermined. Denote the set of all true ground constraints by *Tcon*. A specialization $\theta$ is applicable to a constraint $q(a_1, \ldots, a_n)$ if $\theta$ is applicable to $a_1, \ldots, a_n$. The result of $q(a_1, \ldots, a_n)\theta$ is the constraint $q(a_1\theta, \ldots, a_n\theta)$; and $q(a_1, \ldots, a_n)$ is said to be specialized into $q(a_1\theta, \ldots, a_n\theta)$ by $\theta$.

**Definition 2 (Declarative Description)** A *clause* on $\Gamma$ is a formula of the form:

$$H \leftarrow B_1, B_2, ..., B_n$$

where $n \geq 0$, $H$ is an object in $\mathcal{A}$ and $B_i$ an object in $\mathcal{A}$ or a constraint on $\Gamma$. $H$ is called the *head* and ($B_1$, $B_2$, ..., $B_n$) the *body* of the clause. A *declarative description* or simply a *description* on $\Gamma$ is a (possibly infinite) set of clauses on $\Gamma$. □

The head of $C$ will be denoted by *head*($C$) and the set of all objects and constraints in the body of $C$ by *object*($C$) and *con*($C$), respectively. Let *body*($C$) = *object*($C$) ∪ *con*($C$). A clause $C'$ is an *instance* of $C$ iff there is a specialization $\theta \in \mathcal{S}$ such that $\theta$ is applicable to $H, B_1, B_2, ..., B_n$ and $C' = C\theta = (H\theta \leftarrow B_1\theta, B_2\theta, ..., B_n\theta)$. A clause $C$ is a *ground clause* iff $C$ comprises only ground objects and ground constraints.

Let $P$ be a declarative description on $\Gamma$. Associated with $P$ is the mapping $T_P$ on $2^{\mathcal{G}}$ defined by: For each $X \subset \mathcal{G}$, a ground object $g$ is contained in $T_P(X)$ iff there exist a clause $C \in P$ and a specialization $\theta \in \mathcal{S}$ such that $C\theta$ is a ground clause the head of which is $g$ and all the objects and constraints in the body of which belong to $X$ and *Tcon*, respectively, i.e.:

$$T_P(X) = \{ head(C\theta) \mid C \in P,\ \theta \in \mathcal{S},\ C\theta \text{ is a ground clause},\ object(C\theta) \subset X,\ con(C\theta) \subset Tcon \}$$

Based on $T_P$, the meaning of $P$ can now be defined.

**Definition 3 (Semantics of a Declarative Description)** Let $P$ be a declarative description on $\Gamma$. The meaning of $P$, denoted by $\mathcal{M}(P)$, is defined by

$$\mathcal{M}(P) = \bigcup_{n=1}^{\infty} [T_P]^n(\varnothing)$$

where $\varnothing$ is the empty set, and $[T_P]^1(\varnothing) = T_P(\varnothing)$ and $[T_P]^n(\varnothing) = T_P([T_P]^{n-1}(\varnothing))$ for each $n > 1$. □

### A.3 Equivalent Transformations

*Equivalent Transformation* (*ET*) [2,3] is a new computational model based on semantics-preserving transformations (*equivalent transformations*) of declarative descriptions. Computation by means of ET is carried out by successive transformation of a given description $P_1$ into $P_2$, $P_3$, … until a desirable description $P_n$ is obtained; in the transformation process, the semantics of each description must be preserved, i.e., $\mathcal{M}(P_1) = \mathcal{M}(P_2) = \mathcal{M}(P_3) = \ldots = \mathcal{M}(P_n)$.

In order to guarantee the correctness of the computation, only equivalent transformations are applied at every step. The unfolding transformation, a widely-used program transformation in conventional logic programming, is a kind of equivalent transformation. Other kinds of equivalent transformation can also be devised, especially for improvement of computation efficiency. Thus, ET provides a more flexible, efficient computational framework.