Integrating XML Data Sources using RDF/S Schemas: The ICS-FORTH Semantic Web Integration Middleware (SWIM)

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Need for Data Integration on the Semantic Web

- The bulk of existing Web data is not yet in RDF/S (or any other form suitable for the SW)
  - Data physically stored in relational DBs and/or published as virtual XML
  - SW applications require viewing data as virtual RDF
  - valid instances of domain or application-specific RDF/S schemas

- Need the ability to manipulate data with high-level query or view languages (RQL, RVL)
  - How to do it?
    - republish XML as RDF
    - publish relational data as RDF
    - do both
Motivation: Republish XML as RDF

Semantic Web

RDF Schema (community ontology) → RDF Data

SW MIDDLEWARE Mapping → Reformulation

“Semistructured” Web

XML DTD or Schema (community sources) → XPath, XQuery

V. Christophides

Semantic Web Integration Middleware (SWIM)

- Practical concerns:
  - XML publishing systems often provide an XML query interface
  - SW middleware can function as an alternative to the XML publishing systems;
  - SW middleware provides direct access to underlying DBMSs
  - SW middleware may also be required to integrate DBMS data with data in native XML storage
- SW middleware data integration services:
  - Specify mappings: XML → RDF, RDB → RDF
  - Verify conformance to the semantics of employed schemas
  - Reformulate queries (i.e., compose RQL queries with mappings to produce XML or RDB queries)
  - Provide further abstractions of RDF data/schemas (RVL views)
  - Compose queries with views
Motivating Example

Semantic Web

"Semistructured" Web

```
<!DOCTYPE Museums [
<!ELEMENT Museums (Museum*)>
<!ELEMENT Museum (name, address?, Collection*)>
<!ELEMENT Collection (Artifact*)>
<!ATTLIST Collection kind (painting|sculpture) "painting">
<!ELEMENT name (#PCDATA)>
<!ELEMENT address (#PCDATA)>
<!ELEMENT Artifact (title, Artist)>
<!ELEMENT title (#PCDATA)>
<!ELEMENT Artist (school?)>
<!ATTLIST Artist name ID #IMPLIED>
<!ATTLIST Artist ref IDREF #IMPLIED>
<!ELEMENT school (#PCDATA)>
]>
```

```
<Museums>
  <Museum>
    <Name>Louvre</Name>
    <Collection kind="Sculpture">
      <Artifact>
        <title>Equestrian Statue</title>
        <Artist name="Leonardo Da Vinci"/>
      </Artifact>
      <Artifact>
        <title>Madonna with two angels</title>
        <Artist name="Giovanni di Agostino"/>
      </Artifact>
    </Collection>
    <Collection kind="Painting">
      <Artifact>
        <title>La Joconde</title>
        <Artist ref="#Leonardo Da Vinci"/>
      </Artifact>
    </Collection>
  </Museum>
</Museums>
```

```
<RDF>
  <Sculptor rdf:about="#Vinci">
    <name>Leonardo Da Vinci</name>
    <exhibits rdf:about="#Louvre"/>
  </Sculptor>
  <Sculptor rdf:about="#Agostino">
    <name>Giovanni di Agostino</name>
    <exhibits rdf:about="#Louvre"/>
  </Sculptor>
  <Painter rdf:about="#Vinci">
    <name>Leonardo Da Vinci</name>
    <exhibits rdf:about="#Louvre"/>
  </Painter>
  <Museum rdf:about="#Louvre">
    <denom>Louvre</denom>
  </Museum>
</RDF>
```
Various Forms of Heterogeneity

Data Model
- XML labeled tree (labels at nodes) vs RDF labeled graph (labels at nodes and edges)
- Nesting vs subsumption
- Tight vs loose coupling with document physical support

Categorization
- Unlike our XML DTD, our RDF schema represents Painter and Sculptor as subclasses of Artist

Type
- In our RDF schema we have Sculptors (Painters), while in our XML DTD there are collections of kind “Sculpture” (“Painting”)

Representation
- In our XML DTD Artifacts contain information about their Artists, while our RDF schema Artists exhibit in a Museum

Name
- XML Museum name vs denomination
SWIM Logic Framework (SWLF)

- Several reasons for representing RQL queries/views using a Datalog framework along with constraints:
  - Reducing the RDF-XML query reformulation problem to the relational equivalent exploits background theory on relational query optimization
    - query containment & minimization,
    - query composition,
    - query rewriting using views
  - are solvable for a fairly large class of queries in the presence of certain classes of constraints
- A robust formalism to rely on: union of conjunctive queries (linear Datalog) of the form $\bigvee_{i=1}^{l} \phi_i(\bar{x}_i, \bar{\psi}_i)$ interpreted as:
  $$\bigvee_{i=1}^{l} \exists \bar{\psi}_i, \phi_i(\bar{x}_i, \bar{\psi}_i)$$

SWIM Logic Framework (SWLF)

- The constraints considered in SWIM are disjunctive embedded dependencies (DEDs) of the form:
  $$\forall \bar{x} \left[ \phi(\bar{x}) \rightarrow \bigvee_{i=1}^{l} \exists \bar{\psi}_i, \phi'_i(\bar{x}, \bar{\psi}_i) \right]$$
  - DEDs restrictions:
    - No negation
    - No recursion
- Our first order logic (SWLF) representation for RDF/S schemas and resource descriptions consists of:
  - predicates capturing RDF/S schema classes and properties
  - a set of constraints (DEDs) capturing RDF/S semantics
RDF/S Representation in SWLF

- RDF/S schemas and resource descriptions are represented by the following predicates:
  - **CLASS**(name: Class): All the RDF/S schema classes (name)
  - **C_SUB**((subC:Class, class:Class)): Class subC is a subclass of class
  - **PROP**(subject:Class, predicate:Property, object:Class): All the RDF/S schema properties (predicate) with domain (subject) and range (object) restrictions
  - **P_SUB**((subP:Property, prop:Property)): Property subP is a subproperty of prop
  - **C_EXT**(class:Class, inst:Resource): Resource inst belongs to extent of class
  - **P_EXT**(subject:Resource, predicate:Property, object:Resource): Resources subject and object belong to the extent of property predicate

From RDF/S Schemas to SWLF: Example

- Some of the relations for the RDF schema above:

**CLASS**
- Artist
- Artifact
- Painter
- Painting

**PROP**
- Artist Name String
- Artifact Title String
- Artist Creates Artifact
- Painter Paints Painting

**P_SUB**
- paints creates

**C_SUB**
- Painter Artist
General RDF Constraints

- **Basic constraints:**
  1. Every resource in the extent of a class implies the existence of the corresponding class
     \[ \forall c, x \ ( C_{EXT}(c, x) \rightarrow CLASS(c) ) \]
  2. Every statement in the extent of a property implies the existence of the corresponding property
     \[ \forall x, p, y \ ( P_{EXT}(x, p, y) \rightarrow \exists c, d \ PROP(c, p, d) ) \]
  3. Every subclass of a class is also a class
     \[ \forall c_1, c_2 \ ( C_{SUB}(c_1, c_2) \rightarrow CLASS(c_1) \land CLASS(c_2) ) \]
  4. Every sub-property of a property is also a property
     \[ \forall p, q \ ( P_{SUB}(p, q) \rightarrow \exists a, b, c, d \ ( PROP(a, p, b) \land PROP(c, q, d) ) \]
  5. The domain & range of every property is a class
     \[ \forall c_1, c_2 \ ( PROP(c_1, p, c_2) \rightarrow CLASS(c_1) \land CLASS(c_2) ) \]
  6. The domain & range of every property is unique
     \[ \forall a_1, a_2, b_1, b_2 \ ( PROP(a_1, p, b_1) \land PROP(a_2, p, b_2) \rightarrow a_1 = a_2 \land b_1 = b_2 ) \]

- **SUB constraints**
  1. Every class is a subclass of itself and the subclass relationship is transitive
     \[ \forall c \ ( CLASS(c) \rightarrow C_{SUB}(c, c) ) \] (subclass reflexivity)
  2. \[ \forall c_1, c_2, c_3 \ ( C_{SUB}(c_1, c_2) \land C_{SUB}(c_2, c_3) \rightarrow C_{SUB}(c_1, c_3) ) \] (subclass transitivity)
General RDF Constraints

Every property is a sub-property of itself and the sub-property relationship is transitive.

1. \( \forall a, p, b \ ( \text{PROP}(a, p, b) \rightarrow \text{P_SUB}(p, p) ) \) (subproperty reflexivity)

2. \( \forall p_1, p_2, p_3 \ ( \text{P_SUB}(p_1, p_2) \land \text{P_SUB}(p_2, p_3) \rightarrow \text{P_SUB}(p_1, p_3) ) \) (subproperty transitivity)

In a valid RDF description schema the domain (range) of every sub-property is subsumed by the domain (range) of its super-property.

- Domain-range constraints
  1. \( \forall a, p, b, c, q, d \ ( \text{P_SUB}(q, p) \land \text{PROP}(a, p, b) \land \text{PROP}(c, q, d) \rightarrow \text{C_SUB}(c, a) \land \text{C_SUB}(d, b) ) \) (subproperty-subclass compatibility)
General RDF Constraints

In a valid RDF description base the subject/object resources in every statement are instances of the property’s domain/range classes (either direct or a subclass’ instances).

∀a, p, b, x, y (PROP(a, p, b) ∧ P_EXT(x, p, y) → ∃c, d (C_SUB(c, a) ∧ C_SUB(d, b) ∧ C_EXT(c, x) ∧ C_EXT(d, y) )

(property-class extent compatibility)

SWLF Semantics vs. RDF-MT

RDF-MT does not consider different sorts of resources
- SWLF distinguish between classes, properties and their corresponding instances

- Additional SWLF Constraints
  - SWLF 6th basic constraint stating that each property has exactly one domain & range
  - SWLF 1st domain-range constraint stating that the domain (range) of every sub-property is subsumed by the domain (range) of its super-property

- These additional SWLF constraints degrease the complexity of RQL/RVL query containment and minimization algorithms
  - result to optimal query reformulations
XML Representation in SWLF

- Semi-structured XML data are represented by the following basic predicates:
  - T(e: int, l: String): e is the integer that identifies a node (in the XML tree) with label l.
  - C(s: int, t: int): there is a parent – child relation between nodes with identifiers s, t respectively (s is the father).
  - D(s: int, t: int): there is an ancestor – descendant relation between nodes with identifiers s, t respectively (s is the ancestor).
  - A(e:int, n:String, v:String): there is an attribute with identifier e, name n and value v.
  - Txt(e: int, str: string): node with identifier e has as content the string str.
  - E(s: int, t: int, l:label): there is a parent – child relation between nodes with identifiers s and t and additionally node with identifier t has a label l.

From XML Data to SWLF: Example

```
(myXMLroot)
(e1 in E) (e2 in E) (e3 in E) (d1 in D) (t1 in T)
(e1.s = myXMLroot) and (e1.l = "Artist") and (e2.s = e1.t) and (e2.l = "name") and (d1.s = e1.t) and (d1.t = t1.e) (t1.l = "exhibits") and (e4.s = t1.e) and (e4.l = "Museum")
```
General XML Constraints

**Basic Constraints**

1. **every y that is a child of x implies that y is a descendant of x**
   \[ \forall x,y \ [C(x, y) \rightarrow D(x, y)] \text{ or } \forall x,y,l \ [E(x, y, l) \rightarrow D(x, y)] \] (base)

2. **every y that is a descendant of x and every z is a descendant of y implies that z is a descendant of x**
   \[ \forall x,y,z \ [D(x, y) \land D(y, z) \rightarrow D(x, z)] \] (transitivity)

3. **every node is a descendant of itself**
   \[ \forall x,l \ [T(x, l) \rightarrow D(x, x)] \text{ or } \forall x,y,l \ [E(y, x, l) \rightarrow D(x, x)] \] (reflexivity)

4. **every x that is a descendant of y and y is a descendant of x then x and y are the same node**
   \[ \forall x,y \ [D(x, y) \land D(y, x) \rightarrow x=y] \] (anti-symmetry)

5. **every x that is child of y and y is child of x then x and y are the same node**
   \[ \forall x,y \ [C(x, y) \land C(y, x) \rightarrow x=y] \text{ or } \forall x,y,l \ [E(x, y, l) \land E(y, y, l) \rightarrow x=y] \] (one parent)

6. **every y that is a child of x implies that both x, y are nodes**
   \[ \forall x,y \ [C(x, y) \rightarrow \exists z,k,l1,l2 \ [T(x, l1) \lor E(z, x, l1) \land T(y, l2) \lor E(k, y, l2)]] \] (nodes)

7. **every y that is descendant of x implies that x, y are nodes**
   \[ \forall x,y \ [D(x, y) \rightarrow \exists z,k,l1,l2 \ [T(x, l1) \lor E(z, x, l1) \land T(y, l2) \lor E(k, y, l2)]] \] (nodes)

8. **every node has at most one tag**
   \[ \forall x,l1,l2 \ [T(x, l1) \land T(x, l2) \rightarrow l1=l2] \text{ or } \forall x,y,l1,l2 \ [E(y, x, l1) \land E(y, x, l2) \rightarrow l1=l2] \text{ or } \forall x,y,l1,l2 \ [E(y, x, l1) \land T(x, l2) \rightarrow l1=l2] \] (one tag)

9. **every attribute has at most one value**
   \[ \forall x,n,v1,v2 \ [A(x, n, v1) \land A(x, n, v2) \rightarrow v1=v2] \] (one attribute)

10. **there exist only one root node**
   \[ \forall x,y \ [\text{Root}(x) \land \text{Root}(y) \rightarrow x=y] \] (one root)
General XML Constraints

- every y that is root and it is descendant of x then x is root too
  \[ \forall x,y \ [D(x, y) \land \text{Root}(y) \rightarrow \text{Root}(x)] \] (top root)
- every z that is descendant of both x and y then x and y have a descendant relationship or are the same node
  \[ \forall x,y,z \ [D(x, z) \land D(y, z) \rightarrow x=y \lor D(x, y) \lor D(y,x)] \] (linear)
- every y that is a child of x and there is a node z between them then z is the same node with either x or y
  \[ \forall x,y,z \ [C(x, y) \land D(x, z) \land D(z, y) \rightarrow x=z \lor y=z] \] or \[ \forall x,y,z,l \ [E(x, y, l) \land D(x,z) \land D(z,y) \rightarrow x=z \lor y=z] \] (choice)

SWIM Mapping Rules

- SWIM rules map XML fragments to RDF/S classes & properties:
  \[ \phi_{RPred}(\overline{X}) = \neg \phi_{XPred}(\overline{X'}) \]
  \[ \phi_{RPred}(\overline{X}) : \text{conjunction of SWLF RDF/S predicates (C_EXT, P_EXT)} \]
  \[ \phi_{XPred}(\overline{X'}) : \text{conjunction of SWLF XML predicates (Root, T, C, D, E, Txt)} \]
  \[ \overline{X} \subseteq \overline{X'} \] are variables
- SWIM adopts the GLAV approach by representing mappings in terms of constraints of the following form:
  \[ \forall \overline{X} \left[ \phi_{RPred}(\overline{X}) \rightarrow \bigvee_{i=1}^{l} \exists \overline{\psi}, \phi_{RPred}(\overline{X}, \overline{\psi}) \right] \] GAV
  \[ \forall \overline{X} \left[ \phi_{XPred}(\overline{X}) \rightarrow \bigvee_{i=1}^{l} \exists \overline{\psi}, \phi_{XPred}(\overline{X}, \overline{\psi}) \right] \] LAV
SWIM Mapping Examples

- XML tags correspond to RDF/S class (unique URIs for resource instances) or literal nodes

```
<!DOCTYPE Artist [ 
  <!ELEMENT Artist (#PCDATA)> ]>
```

- Mapping an XML node to an RDF/S class node
  \[ C_{EXT}(\text{Artist}, x) :- \\{/\text{Artist}\}(x). \]
  \[ \forall ce \text{ in } C_{EXT} \exists a,s,x \text{ Root}(a), \exists D(a,s), \exists T(s,“\text{Artist}”), \exists \text{Txt}(s,x), \text{ce.class} = “\text{Artist}”, \text{ce.inst} = x. \]
  \[ \forall a,s,x \text{ Root}(a), D(a,s), T(s,“\text{Artist}”), \text{Txt}(s,x) \exists ce \text{ in } C_{EXT} \text{ce.class} = “\text{Artist}”, \text{ce.inst} = x. \]

- XML attributes (atomic types) or textual elements are mapped to properties with range of type literal

```
<!DOCTYPE Artist [ 
  <!ATTLIST Artist name CDATA #REQUIRED> 
  <!ELEMENT born (#PCDATA)> ]>
```

- Mapping an XML path to an RDF/S property edge
  \[ C_{EXT}(\text{Artist}, x) :- \\{/\text{Artist}\}(k), \\{./@name\}(k, x). \]
  \[ P_{EXT}(x, \text{has\_Name}, y) :- \\{/\text{Artist}\}(k), \\{./@name\}(k, y), x = y. \]
XML complex elements are additionally mapped to RDF properties with range class

```xml
<!DOCTYPE Artist [ 
<!ELEMENT Artist (born, address?)> 
<!ATTLIST Artist name CDATA #REQUIRED> 
<!ELEMENT born (#PCDATA)> 
<!ELEMENT address (city)> 
<!ATTLIST address street CDATA #REQUIRED> 
<!ELEMENT city (#PCDATA)> ]>
```

Mappings:

- C_EXT(Artist, x):- {//Artist}(k), {./@name}(k, x).
- C_EXT(Address, x):- {//address}(k), {.@street}(k, x).
- P_EXT(x, has_address, y):- {//Artist}(k), {./@name}(k, x), {./address/@street}(k, y).

XPath Fragment employed in SWIM Mappings

- SWIM mappings from XML to RDF/S rely on XPath 2.0
- We employ the following fragment of XPath 2.0:
  - Contains all navigational axes except axes for those about siblings (following, preceding, ...)(document order is disregarded)
  - Contains wildcard * only for attributes (no to:a/*/b, but yes to:a/@*) (higher complexity)
  - Accepts abbreviated syntax (a/b instead of a/child::b)
- Additionally we are able to employ non interpreted functions (e.g. for handling strings like concat, split) in order to establish more expressive mappings (e.g., involving complex keys)
Basic steps:
- RQL query patterns are translated into a SWLF conjunctive query
- SWLF query is chased in order to be composed with the RDF/S schema information and constraints
- SWLF query is backchased in order to be minimized in terms of the P_EXT and C_EXT predicates
- Further chasing is used in order to compose the minimized SWLF query with the mappings
- Then the resulting query is minimized once more with the help of additional constraints (if any) from the data sources
- The SWLF reformulated query is finally translated into XPath or XQuery in order to be executed by the XML data sources

XML vs. RDF Schema

```
<!DOCTYPE Museums [
  <!ELEMENT Museums (Museum*)>
  <!ELEMENT Museum (name, address?, Collection*)>
  <!ELEMENT Collection (Artifact*)>
  <!ATTLIST Collection kind (painting|sculpture) "painting">
  <!ELEMENT name (#PCDATA)>
  <!ELEMENT address (#PCDATA)>
  <!ELEMENT Artifact (title, Artist)>
  <!ELEMENT title (#PCDATA)>
  <!ELEMENT Artist (school?)>
  <!ATTLIST Artist name ID #IMPLIED>
  <!ATTLIST Artist ref IDREF #IMPLIED>
  <!ELEMENT school (#PCDATA)>
]
```
XML vs. RDF Data

<Art>
  <Museum>Louvre</Museum>
  <Collection kind="Sculpture">
    <Artifact>
      <title>Equestrian Statue</title>
      <Artist name="Leonardo Da Vinci"/>
    </Artifact>
  </Collection>
  <Collection kind="Painting">
    <Artifact>
      <title>La Joconde</title>
      <Artist ref="#Leonardo Da Vinci"/>
    </Artifact>
  </Collection>
</Art>

<RDF>
  <Sculptor rdf:about="#Vinci">
    <name>Leonardo Da Vinci</name>
    <exhibits rdf:about="#Louvre"/>
  </Sculptor>
  <Sculptor rdf:about="#Agostino">
    <name>Giovanni di Agostino</name>
    <exhibits rdf:about="#Louvre"/>
  </Sculptor>
  <Painter rdf:about="#Vinci">
    <name>Leonardo Da Vinci</name>
    <exhibits rdf:about="#Louvre"/>
  </Painter>
  <Museum rdf:about="#Louvre">
    <denom>Louvre</denom>
  </Museum>
</RDF>

RDF/S Facts & XML -> RDF/S Mappings

FACTS
CLASS(Artist).
CLASS(Painter).
CLASS(Sculptor).
CLASS(Museum).
C_SUB(Painter, Artist).
C_SUB(Sculptor, Artist).
PROP(Artist, exhibits, Museum).
PROP(Artist, name, String).
PROP(Museum, denom, String).
PROP(Sculptor, school, String).

MAPPINGS
C_EXT(Artist, x) :- {//Collection}(k),
  ./@kind(k,s), ./Artist/@name(k,x),
  s="Sculpture".
C_EXT(Artist, x) :- {//Collection}(k),
  ./@kind(k,s), ./Artist/@name(k,x),
  s="Painting".
C_EXT(Sculptor, x) :- {//Collection}(k),
  ./@kind(k,s), ./Artist/@name(k,x),
  s="Sculpture".
C_EXT(Sculptor, x) :- {//Collection}(k),
  ./@kind(k,s), ./Artist/@name(k,x),
  s="Painting".
C_EXT(Museum, x) :- {//Museum}(k),
  ./name(k,x).
P_EXT(x, exhibits, y) :- {//Museum}(k),
  ./Collection/Artist/@name(k,x),
  ./name(k,y), x=y.
P_EXT(x, exhibits, y) :- {//Museum}(k),
  ./Collection/Artist/@ref(k,x),
  ./name(k,y), x=y.
A Full Example

Given our example RDF schema we pose the following RQL query:

Find artists exhibiting in Louvre

SELECT X
FROM {X}exhibits{Y}, {Y}denom{Z}
WHERE Z = "Louvre"

The class and property patterns of this RQL query will be translated:

\[
\text{ans}(x) :\ - \ \text{P\_SUB}(A, \text{exhibits}), \ \text{P\_EXT}(x, A, y), \ \\
\text{P\_SUB}(B, \text{denom}), \ \text{P\_EXT}(y, B, z), \ \\
z = \text{"Louvre"}.
\]

Chase starts...

Taking into consideration the facts about subproperties and subclasses:

\[
\text{ans}(x) :\ - \ \text{P\_SUB}(A, \text{exhibits}), \ \text{P\_EXT}(x, A, y), \ \\
\text{P\_SUB}(B, \text{denom}), \ \text{P\_EXT}(y, B, z), \ \\
A = \text{exhibits}, \ B = \text{denom}, \ z = \text{"Louvre"}.
\]

Eliminating some trivial predicates and applying the property domain/range constraint:

\[
\forall x, p, y \ ( \text{P\_EXT}(x, p, y) \rightarrow \exists c, d \ \\
\text{PROP}(c, p, d))
\]

\[
\text{ans}(x) :\ - \ \text{P\_EXT}(x, A, y), \ \text{P\_EXT}(y, B, z), \ \\
\text{PROP}(s, A, t), \ \text{PROP}(m, B, k), \ A = \text{exhibits}, \ \\
B = \text{denom}, \ z = \text{"Louvre"}.
\]
Due to facts about properties:

\[ \text{ans}(x) : \text{P\_EXT}(x, A, y), \text{P\_EXT}(y, B, z) \]

\[ \text{PROP}(s, A, t), \text{PROP}(m, B, k), \]
\[ A = \text{exhibits}, B = \text{denom}, \]
\[ s = \text{Artist}, t = \text{Museum}, m = \text{Museum}, \]
\[ k = \text{String}, z = \text{"Louvre"}. \]

Apply the property instance domain/range constraint:

\[ \text{ans}(x) : \text{P\_EXT}(x, A, y), \text{P\_EXT}(y, B, z), \]
\[ \text{PROP}(s, A, t), \text{PROP}(m, B, k), \]
\[ \text{C\_SUB}(a, s), \text{C\_EXT}(a, x), \text{C\_SUB}(b, t), \text{C\_EXT}(b, y), \]
\[ \text{C\_SUB}(c, m), \text{C\_EXT}(c, y), \text{C\_SUB}(d, k), \text{C\_EXT}(d, z), \]
\[ A = \text{exhibits}, B = \text{denom}, \]
\[ s = \text{Artist}, t = \text{Museum}, m = \text{Museum}, k = \text{String}, z = \text{"Louvre"}. \]

Using the facts about subclasses of class Artist we get the following:

\[ \text{ans}(x) : \text{P\_EXT}(x, \text{exhibits}, y), \text{P\_EXT}(y, \text{denom}, z), \]
\[ \text{C\_EXT}(\text{Artist}, x), \text{C\_EXT}(\text{Museum}, y), z = \text{"Louvre"}. \]
\[ \text{U} \]
\[ \text{ans}(x) : \text{P\_EXT}(x, \text{exhibits}, y), \text{P\_EXT}(y, \text{denom}, z), \]
\[ \text{C\_EXT}(\text{Painter}, x), \text{C\_EXT}(\text{Museum}, y), z = \text{"Louvre"}. \]
\[ \text{U} \]
\[ \text{ans}(x) : \text{P\_EXT}(x, \text{exhibits}, y), \text{P\_EXT}(y, \text{denom}, z), \]
\[ \text{C\_EXT}(\text{Sculptor}, x), \text{C\_EXT}(\text{Museum}, y), z = \text{"Louvre"}. \]

At this point chase has finished and the result of the backchase is given in an abbreviated form.
A Full Example

- Further chasing is used in order to compose the minimized SWLF query with the mappings

```
ans(x):-{/Museum}(k), {./name}(k,y),
{/Museum}(m), {./name}(m,y), z=y, z="Louvre"
{/Museum}(s), {./name}(s,y), {./Collection//Artist/@name}(s,x),
{/Collection}(n), {/@kind}(n,q), {./Artist/@name}(n,x), q=Sculpture.
U
...{/Collection}(n), {/@kind}(n,q), {./Artist/@name}(n,x), q=Painting.
U
ans(x):-{/Museum}(k), {./name}(k,y),
{/Museum}(m), {./name}(m,y), z=y, z="Louvre"
{/Museum}(s), {./name}(s,y), {./Collection//Artist/@ref}(s,x),
{/Collection}(n), {/@kind}(n,q), {./Artist/@name}(n,x), q=Sculpture.
U
...{/Collection}(n), {/@kind}(n,q), {./Artist/@name}(n,x), q=Painting.
```

Towards More Efficient Reformulations

- Until now the RQL query has been reformulated with the use of general constraints that are part of the semantics of both the RDF & XML data models

- However, using additional constraints from the XML data sources we are able to perform more efficient reformulation
  - XML, for example, gives us the ability to specify keys and keyrefs, as well as value enumerations for attributes

- Such additional constraints can improve our reformulations by eliminating redundant queries (previous example) or by simplifying the generated queries (“cutting” some predicates)
A Full Example (cont.)

The fact that attribute kind of the Collection is an enumerated type can be encoded in SWIM as a constraint:

\[ \forall x_1, x_2. \text{root}(x_1), \text{D}(x_1, x_2), \text{T}(x_2, \text{"Collection"}) \rightarrow \exists x_3, v. \text{C}(x_2, x_3), \text{A}(x_3, \text{"kind"}, v), v = \text{"Painting"} \text{ or } \text{C}(x_2, x_3), \text{A}(x_3, \text{"kind"}, v), v = \text{"Sculpture"} \]

Every collection has a kind which can be either "painting" or "sculpture"

A Full Example

Further backchasing with the help of the constraint defined previously

\[
\text{ans}(x):= \{\text{//Museum}(k), \{./\text{name}(k, y)\}, \{\text{//Museum}(m), \{./\text{name}(m, y)\}, z = y \}
\{\text{//Museum}(s), \{./\text{name}(s, y)\}, \{\text{//Collection}//\text{Artist}//\text{@name}(s, x)\}, \{\text{//Collection}(n), \{\text{//Artist}//\text{@name}(n, x)\}, z = \text{"Louvre"}. \}
\]

U

\[
\text{ans}(x):= \{\text{//Museum}(k), \{./\text{name}(k, y)\}, \{\text{//Museum}(m), \{./\text{name}(m, y)\}, z = y \}
\{\text{//Museum}(s), \{./\text{name}(s, y)\}, \{\text{//Collection}//\text{Artist}//\text{@ref}(s, x)\}, \{\text{//Collection}(n), \{\text{//Artist}//\text{@name}(n, x)\}, z = \text{"Louvre"}. \}
\]
A Full Example (cont.)

- Constraints for elements or attributes defined as key or keyref in XML Schema

```
<key name="name">
    <selector xpath="//Museum"/>
    <field xpath="name"/>
</key>

<key ref="name">
    <selector xpath="//Artist"/>
    <field xpath="@name"/>
</key>

<keyref name="refer"
    refer="aname">
    <selector xpath="//Collection//Artist"/>
    <field xpath="ref"/>
</keyref>
```

Taking advantage of XML Constraints

- The definition of key constraints is encoded in SWIM as follows:

```
∀ x1, x2 [root(x1), D(x1,x2), T(x2, "Museum") → ∃ x3, v E(x2,x3, "name")]
∀ x1, x2, x3, x4, x5, v1, v2 [root(x1), D(x1, x2), T(x2, "Museum"), D(x1, x3), T(x3, "Museum"), E(x2, x4, "name"), Txt(x4, v1), E(x3, x5, "name"), Txt(x5, v2), v1 = v2 → x2 = x3]
∀ x1, x2, x3, v1, x4, v2 [root(x1), D(x1, x2), T(x2, "Museum"), E(x2, x3, "name"), Txt(x3, v1), E(x2, x4, "name"), Txt(x4, v2) → v1 = v2]
```

- Every Museum has at least one "name"
- For every two Museums having the same "name" then these Museums are the same
- For every Museum having two "name"s then these "name"s are equal
Taking advantage of XML Constraints

- The definition of a keyref constraint is encoded in SWIM as follows:

\[
\forall x_1, x_2, x_3, a \ [\text{root}(x_1), D(x_1, x_2), T(x_2, "Artist"), C(x_2, x_3), A(x_3, "ref", a) \rightarrow \exists x_4, x_5, x_6, v \ D(x_1, x_4), T(x_4, "Collection"), D(x_4, x_5), T(x_5, "Artist"), C(x_5, x_6), A(x_6, "name", v), v = a]
\]

For every Artist having an attribute "ref" there exist a Collection with a descendant called Artist, which has an attribute "name" such that the value of "ref" is equal to the value of "name".

A Full Example (cont.)

- The previous query was reformulated into:

\[
\text{ans}(x) :- \{\text{//Museum}(k), \{./name\}(k,y), \{\text{//Museum}(m), \{./name\}(m,y), z = y, z = "Louvre", \{\text{//Museum}(s), \{./name\}(s,y), \{./Collection//Artist/@name\}(s,x), \{\text{//Collection}(n), \{./Artist/@name\}(n,x).}
\]

\[
\text{U} \text{ans}(x) :- \{\text{//Museum}(k), \{./name\}(k,y), \{\text{//Museum}(m), \{./name\}(m,y), z = y, z = "Louvre", \{\text{//Museum}(s), \{./name\}(s,y), \{./Collection//Artist/@ref\}(s,x), \{\text{//Collection}(n), \{./Artist/@name\}(n,x).
\]

- Keyref constraint will add to the second query the following:

\[
\{\text{//Collection}(w), \{./Artist/@name\}(w,o), o = x.
\]
A Full Example (cont.)

- The previous query was reformulated into (with keys):

  \[
  \text{ans}(x) : \begin{cases}
  \text{//Museum}(k), \{./\text{name}(k,y)\}, \\
  \text{//Museum}(m), \{./\text{name}(m,y)\}, z=y, z=\text{“Louvre”}, \\
  \text{//Museum}(s), \{./\text{name}(s,y)\}, \text{//Collection//Artist/@name}(s,x), \\
  \text{//Collection}(n), \{./\text{Artist/@name}(n,x)\}.
  \end{cases}
  \]

- And finally the first query is a superset of the second one. So...

  \[
  \text{ans}(x) : \begin{cases}
  \text{//Museum}(s), \{./\text{name}(s,y)\}, \text{//Collection//Artist/@name}(s,x), \\
  y=\text{“Louvre”}.
  \end{cases}
  \]
Translating SWIM Queries into XPath/XQuery

- The previous query should be translated into a query language that is appropriate for retrieving data from XML sources.

- Two target XML query languages:
  - XPath (for some RQL queries)
  - XQuery (for all RQL queries)

- **XPath**:
  
  //Museum[./name="Louvre"]//Artist/@name

  <name>Giovanni di Agostino</name>

  <name>Leonardo Da Vinci</name>

XPath Translation

- XPath returns nodes, so the result is not an XML document and of course not an RDF description (as desired).
- XPath 1.0 is not able to project over two node values
  - i.e., return both first and last name of an Artist.
- XPath 1.0 does not support explicit quantification
  - i.e., to concatenate first and last name of each Artist.
- XPath 2.0 is able to express more complex queries due to the fact that can use for, let, ... and variable bindings.

- So ...
  - XPath 1.0 only for simple RQL queries (projections on one variable) and simple XML constraints (no complex keys).
XQuery Translation

XQuery:

```xml
<RDF>
  <Bag>
    { for $var0 in document(“art.xml"
      for $var1 in $var0//Museum
      for $var2 in $var1/name
      for $var3 in $var1//Artist
      for $var4 in $var3/@name
      where ($var2/text()="Louvre")
      return
        <li>{$var4/text()}</li>
    }
  </Bag>
</RDF>
```

The result of this query will be:

```xml
<RDF>
  <Bag>
    <li>Giovanni di Agostino</li>
    <li>Leonardo Da Vinci</li>
    ...
  </Bag>
</RDF>
```

- XQuery 1.0 is used for the above transformation
- XQuery has the ability to construct elements and produce a well-formed or valid XML document
- With appropriate tag selection in the return clause we can return a valid RDF description according to the employed RDF/S schema
Expressiveness of SWIM Mappings

- Mappings are specified through simple or complex XPath or RQL path expressions:

  Mapping an XML path to an RDF/S property
  \[ P_{-}EXT(x, \text{has}\_Name, y) \]:- {\text{Artist}}(x), {./Name}(x, y) \]

- Mapping an XML subpath to an RDF/S property
  \[ P_{-}EXT(x, \text{exhibits}, y) \]:- {\text{Artist}}(k), {./fName}(k, a), {./lName}(k, b), {./exhibits/Museum/denom}(k, y) \mid \text{concat}(x, a, b). \]
Expressiveness of SWIM Mappings

» Mapping an XML tree to an RDF/S property

\[ P_{\text{EXT}}(x, \text{exhibits}, y) :\quad \{/\text{Museum}\}(a), \{./\text{Collection}\}(a,k), \{./\text{type}\}(k, s), \{./\text{Artifact/@id}\}(k, x), \{./\text{name}\}(a,y), \]
\[ s = \text{“Sculptures”}. \]

V. Christophides

Expressiveness of SWIM Mappings

» Mapping an XML tree to an RDF/S path

\[ P_{\text{EXT}}(x, \text{exhibits}, y), P_{\text{EXT}}(y, \text{has_artifact}, z) :\quad \{/\text{Artist}\}(k), \{./\text{name}\}(k, x), \{./\text{artifact_name}\}(k, y). \]

V. Christophides
The ICS-FORTH SWIM Architecture

SWIM Implementation using MARS

- The MARS system (UPenn&UCSD) was originally designed for query optimization/reformulation over (object) relational databases:
  - Checking for query containment,
  - Checking query equivalence,
  - Minimizing queries

- While early approaches on reformulation considered either materialized views or integrity constraints the Chase & Backchase algorithm implemented in MARS was the first that allowed proving completeness theorems considering both cases

- The key to its success was the ability to treat mappings between published & proprietary schemas defined using both the Global-As-View and Local-As-View integration approaches (GLAV)
SWIM Implementation using MARS

- MARS architecture and extensions
  - RQL query
  - RDF in RDB encoding
  - XML in RDB encoding
  - Additional constraints like keys, keyrefs (XML) and constraints that express the semantics of RDF
  - XML integrity constraints

  C&B
  - reformulated queries
  - RQL query

  GReX
  - built-in XML data model constraints

  Reformulated queries (multiple solutions)

  Transformation of queries into XPath/XQuery

GReX: Generic Relational encoding of XML, used internally to partially capture the intended model

Related Work

- STYX [Fundulaki 03 INRIA]
  - Integrates XML sources through extended ER schemas
  - Maps ER entities and (binary) relationships to XPath expressions (only attribute and child axes)
  - LAV approach

- PEPSINT [Cruz 04 Univ. of Illinois]
  - Integrates XML sources through RDF/S schemas
  - XML DTDs are first converted to an RDF/S schema and then these source schemas are mapped to a global one (RDF/S to RDF/S mappings of concepts and properties)
  - GAV approach

- Integration of XML sources with OWL [Lethi 04 IPSI]
  - Integrates XML sources through OWL global schemas
  - Maps XML Schema constructs to OWL concepts and properties (OWL union/intersection of concepts and properties, equivalence of classes and properties, inverse properties)
  - GAV approach
Summary and Future Work

- SWIM relies on state-of-the art relational database theory for SW data integration applications
  - XML and RDF/S data models
    - constructs are represented by first order predicates
    - semantics is captured by constraints (DED)
  - Sound and complete composition and reformulation of RQL queries (or RVL views) using XML → RDF (or RDB → RDF) mappings
    - Chase & Backchase Algorithm

- Extend SWIM functionality with
  - More expressive SW ontology constraints (e.g., OWL inverse properties, cardinality constraints)
  - More expressive RQL queries (e.g., schema querying)
  - Generate entire translation programs for SW Data Warehouses

Three Ways to Overcome Semantic Heterogeneity

1. Standardization: agree on common user-defined schemas/ontologies
   - great if no pre-existing applications
   - great if power player enforces it

2. Translation: create mappings among different schemas/ontologies
   - requires human interpretation and machine reasoning
   - mappings can be difficult, expensive to establish

3. Annotation: create relationships to agreed upon conceptualizations
   - requires human interpretation and machine reasoning
   - annotation can be difficult, expensive to establish
   - reasoning over the conceptualization can provide added value
Ontology Integration vs...

- Two mappings => Two translations
  - Mapping between ontology and the information they describe
  - Mapping between ontologies
  - Semantic relationships (e.g., equivalence) to specify translation of concept & property definitions between ontologies

Comparing Ontology Integration Approaches

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<thead>
<tr>
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<th>Single Ontology Approaches</th>
<th>Multiple Ontology Approaches</th>
<th>Hybrid Ontology Approaches</th>
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<td>Need for some adaptation in the global ontology</td>
<td>Providing a new source ontology; relating to other ontologies</td>
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<td>Comparing multiple ontologies</td>
<td>--</td>
<td>Difficult because of the lack of a common vocabulary</td>
<td>Simple because ontologies use a common vocabulary</td>
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vs Data Integration

- One mapping => One translation
  - From local to global schema or vise versa
  - Views (i.e., queries) to specify data translation from global to local schemas or vice versa

Comparing Data Integration Approaches

- Query answering
  - In GAV is simple (query unfolding, polynomial)
  - In LAV is more complex (answering queries with views NP-Complete)
- Source addition or removal
  - In GAV implies changes to the global schema specification
  - In LAV is simpler since new local source demands only to be described as view over the global schema
- Adding constraints to sources
  - LAV requires some extensions to the source descriptions
  - GAV requires modifications of the global schema description
GLAV

- In order to take advantage of both LAV and GAV, an other approach has been proposed: GLAV

- GLAV approach combines the expressive power of both LAV and GAV, allowing flexible schema definitions independent of the particular details of the sources

- In GLAV we can find both the previous expressions:
  \[
  \text{loc}_i(X) \rightarrow \text{gl}_1(X_1), \text{gl}_2(X_2), \ldots, \text{gl}_k(X_k) \quad \text{and} \\
  \text{loc}_1(X_1), \text{loc}_2(X_2), \ldots, \text{loc}_k(X_k) \rightarrow \text{gl}_l(X) \quad \text{or even} \\
  \text{loc}_1(X_1), \text{loc}_2(X_2), \ldots, \text{loc}_k(X_k) \rightarrow \text{gl}_1(X_1), \text{gl}_2(X_2), \ldots, \text{gl}_m(X_m)
  \]

Translations Between Different Data Models

- Exported schema
- Query in exported schema
- Data in global data model
- Local DM
- Native schema
- Query in native schema
- Data in local data model
### Complexity of View-based Query Answering

#### User Query

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<th>Source Descriptions</th>
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### Complexity of View-based Query Answering: Regular Path Queries

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