The Yin/Yang Web: A Unified Model for XML Syntax and RDF Semantics

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Abstract

XML is the W3C standard document format for *writing* and *exchanging* information on the Web. RDF is the W3C standard model for *describing the semantics* and *reasoning about* information on the Web. Unfortunately, RDF and XML—although very close to each other—are based on two different paradigms. We argue that in order to lead the Semantic Web to its full potential, the syntax and the semantics of information need to work together. To this end, we develop a model theory for the XML XQuery 1.0 and XPath 2.0 Data Model, which provides a unified model for both XML and RDF. This unified model can serve as the basis for Web applications that deal with both data and semantics. We illustrate the use of this model on a concrete information integration scenario. Our approach enables each side of the fence to benefit from the other, notably, we show how the RDF world can take advantage of XML Schema description and XML query languages, and how the XML world can take advantage of the reasoning capabilities available for RDF. Our approach can also serve as a foundation for the next layer of the Semantic Web, the ontology layer, and we present a layering of an ontology language on top of our approach.

Keywords

Semantic Web, RDF, XML, Syntax, Semantics, Data Model, RDF Schema, XML Schema, XQuery.

I. Introduction

As the W3C standard document format for *writing* and *exchanging* information on the Web, XML [1] is mostly concerned about syntax. However, syntax does not make sense without semantics, and many recent activities aim at adding more semantic capabilities to XML. Most notably, the XML Infoset [2] offers an abstract information model for XML; XML Schema [3] allows users to describe XML vocabularies, structures, and relationships; and XQuery [4] allows users to ask questions, manipulate, or reason about XML documents.

As the W3C standard model for *describing the semantics* and *reasoning about* information on the Web, RDF [5] is mostly concerned about semantics. However, semantics is not very useful in a computer system without a syntax, and many recent activities aim at providing a syntactic grounding for RDF. Most notably, RDF uses an XML serialization; and several query languages for RDF [6], [7] have already been proposed as well.

Many XML application scenarios require the use of semantic tools. For instance, data integration relies on the ability to build a common ontology between multiple sources [8], [9], [10]. Development of a domain's XML dialect (e.g., ebXML or VoiceXML [11]) is greatly simplified by the use of modeling methodologies based on rich semantic descriptions [12], [13]. Many RDF application scenarios require the access to existing information sources that are providing XML interfaces. For instance, semantic descriptions for Web services cannot be made without taking into account the format in which messages will be exchanged between these services.

Indeed, the coming Semantic Web is usually envisioned as a layer cake, like the one shown on Figure 1, in which the semantic layer is not independent from, but *is relying on* the syntactic layer. Unfortunately, XML and RDF, which are respectively supposed to form the ground for the syntactic (or data), and semantics (or meaning) layer of the Web, are currently based on different models, and are developed within separate activities. As a result, very few tools can actually be used jointly between XML and RDF.

We argue that syntax and semantics are the Yin and the Yang of the Web, and should be complementary to each other rather than independent—or worse, incompatible—from one another. Users facing the above applications need to deal with syntax and semantics in a unified way. We argue that rather than two Webs: one Syntactic Web and one Semantic Web, these users need one Web that encompasses both syntax and semantics: the Yin/Yang Web.

In this paper, we propose an architecture for a unified Web based on a common model theory for XML and RDF. Although RDF and XML have been two distinct activities, we will see that there is enough commonality between them to design, and implement, such a common model. There are several difficulties in the way though, due to the fact that RDF and XML viewpoints are not fully compatible. Notably, XML is ordered while RDF is not, XML uses a tree model while RDF uses a graph model, RDF distinguishes between classes (e.g., a company) and properties (e.g., the name of a company) while XML does not (e.g., company and names would both be elements). Our main contribution is a model theory that encompasses XML and RDF model properties in order to be able to represent, and reason about, both uniformly. We call this model the Yin/Yang model.

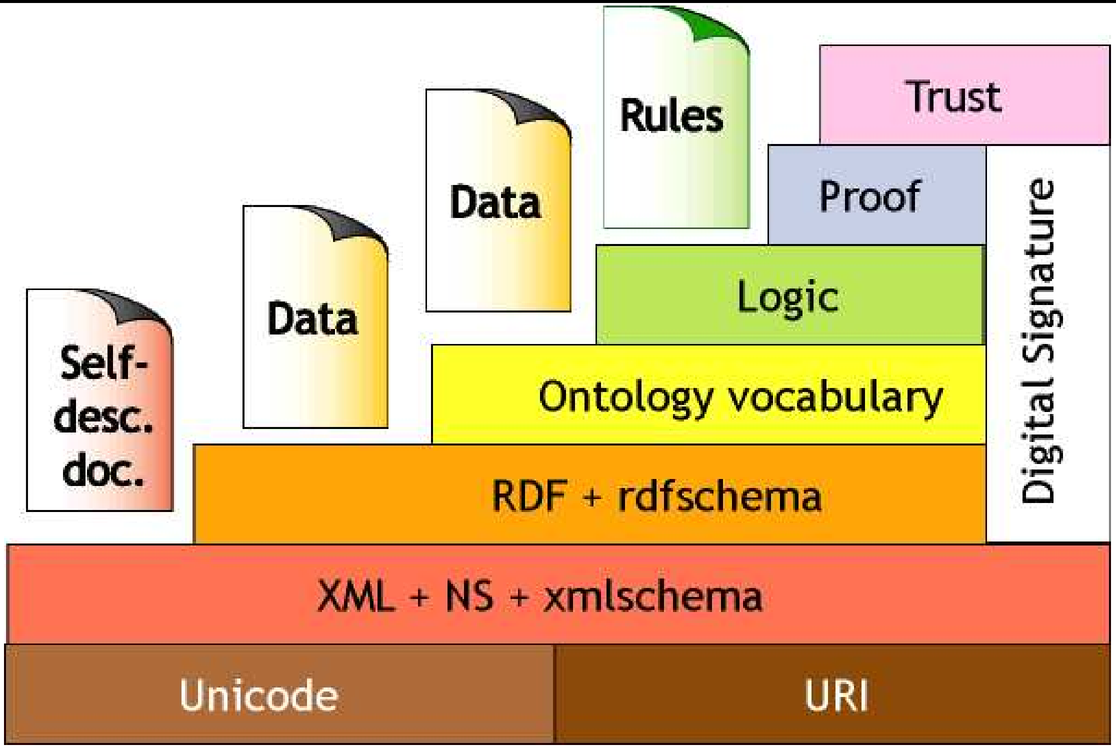


Fig. 1. The Semantic Web Layer Cake (figure courtesy of Tim Berners-Lee)

As soon as a common model exists, many more interesting but difficult questions arise. In particular, how XML Schema and RDFS interact, how one can query both XML and RDF, etc. A complete solution would indeed address these, but is still beyond the scope of this paper. We will show, however, how the Yin/Yang model enables some new exciting possibilities with respect to schema, typing and querying.

More precisely, we make the following technical contributions:

• We develop an integrated model for XML and RDF based on a model theory for the XQuery 1.0 and XPath 2.0 Data Model [14].

• We explain the relationship between our model theory and previous RDF/S model theories. Most of the existing semantics is captured, and we point out and explain the few existing discrepancies.

• We show how one can perform semantic reasoning in our integrated model theory. Note that the semantics of RDFS only supports limited reasoning capabilities.

• We show several new possibilities offered through our integrated model theory. Notably, we give some ideas as to how to capture some aspects of the XML Schema in the model theory for reasoning purposes. We also show how one can apply XQuery on a mix of RDF and XML descriptions, and we explain how XML querying can benefit from an RDF reasoner.

• We describe an implementation of our model theory on top of the XQuery data model. Because this uses the XQuery data model, building a Yin/Yang implementation with a reasoner can be done in a much simpler fashion than previous RDF implementation approaches.

• Finally, we show how the next layer of the Semantic Web, the ontology layer, can be layered on our foundation by giving a model-theoretic semantics for this layer using our notion of model theory.

A. *Ins and Outs*

The Yin/Yang model provides access to both data structures, through the XQuery data model, and their corresponding semantics, through the model theory.

On the syntactic side, applications have full access to the XQuery data model, hence there is no loss of information for data-oriented applications. Applications can even take advantage of *some* of the semantic-based features of the model by treating XQuery data model constructs in accordance with the meaning provided by the model theory. Syntactic processing is done entirely within the XML framework, as a result, the RDF parsetype extension is not handled. Also, the RDF shorthand that is inconsistent with XML is treated in the XML fashion, not in RDF fashion.

On the semantic side, our model theory integrates the two different world-views of XML and RDF with minimal loss of information. Our model theory allows for both the ordered view of documents from XML and the unordered view of information from RDF. It does not require the RDF distinction between classes and properties, allowing arbitrary XML, but the distinction between classes and properties, if present, can be recovered from the model theory. It includes a complete treatment of RDF typing, where type links are treated the same as other links, even when there is no distinction between classes and properties and incorporates XML names into RDF types. It allows for the identification of nodes, turning the tree view of XML into the graph model of RDF.

Our model theory does, however, eliminate as irrelevant XML comments and process instructions as well as the lexical form of typed text nodes, and does not distinguish between XML elements and attributes. Further, it does not handle most of the XML Schema structural information, at least for now.

B. *Related work*

This discussion about the relationship between syntax and semantics is not new. Several attempts have been made to provide a unified view of XML and RDF. Tim Berners-Lee [16] was one of the first to point out the reasons for the differences between XML and RDF. Also we acknowledge the fact that RDF and XML serve different purposes, we believe this difference must not prevent syntactic and semantic interoperability, which is an important user need. Sergey Melnik [17] created a version of RDF that can handle arbitrary

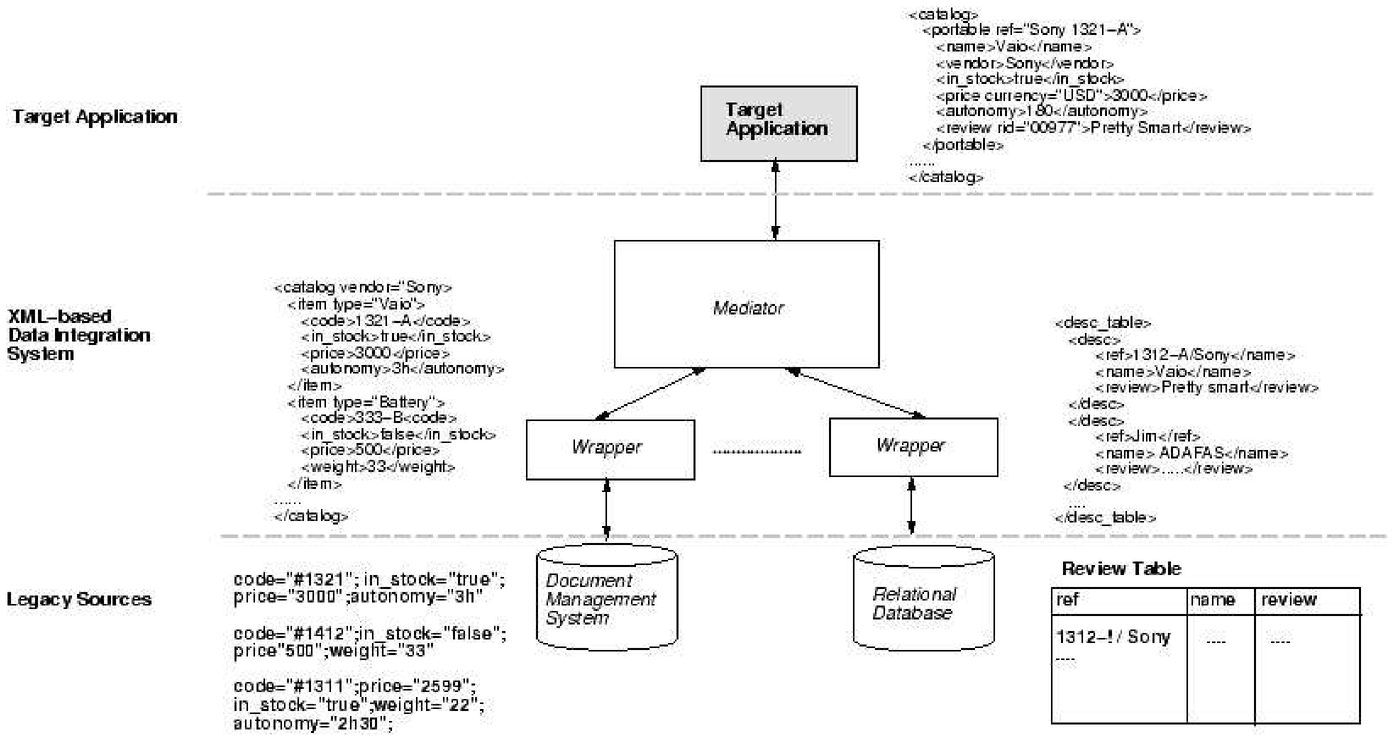
XML, but uses information on how to handle the parts of XML constructs that do not fit well into the RDF model. Harold Boley [18] has a data model that can be used for both XML and RDF. However, his approach requires changes to XML to unify it with RDF. He also stops at the data model and does not proceed to a model theory. Fundulaki et al [20] acknowledge the need for integrating syntax and semantics, but require the development of user-defined rules in order to cope with the discrepancy between XML and RDF. Robie et al [21] also address the need for applications to query semantics, but map the syntax into the semantics, hence requiring the need to hard-code some of the semantic aspects in functions. To the best of our knowledge, our approach is the first one that allows XML data access and RDF semantic reasoning in a common framework.

II. Using syntax and semantics on the Web

We start by giving an application scenario that illustrates the need for tight integration between syntax and semantics on the Web. In this scenario, a computer retailer wants to build its store's information system from multiple hardware and software vendors' catalogs (e.g., Sony, IBM), and a product's review database maintained by a third party (e.g., http://www.epinions.com/).

Information integration is an important application of XML. Recently, a number of companies [22], [23] and research projects [24], [25], [26], [27], [28] have been working on building XML-based data integration systems. These systems rely on the ability to represent any kind of legacy information in XML, and on XML high-level languages, such as XQuery [4], to merge their information under a common schema. Figure 2 shows the architecture of a typical data integration system, where *wrappers* are used to map legacy information into XML, and a *mediator* is used to perform the integration. We refer the reader to the related work on how to use XML query languages to specify such data integration [24], [25], [26], [27], [28].

Still, information integration cannot be fully solved without addressing semantic issues. For instance, one needs to define a global ontology for all information involved in the sources, and also to understand how similar information is represented in different ways on each source [8], [9], [10]. In our scenario, the retailer might want to organize his data according to a product hierarchy where `Product` would be the root of the hierarchy. Then `Portable` and `Desktop` would represent major categories of products, `PDA` and `Laptop` be sub-categories of `Portable`, etc. Each product would have a name and a reference number, while portables would have an autonomy. In order to work on the web, modern semantic integration platforms [20] are relying on RDF/S, to describe such an ontology. However, each vendor's catalog provides a different set of information for their products, for instance the Sony catalog indicates the autonomy of each laptop, while the IBM indicates a battery reference. Also the classifications within the catalogs differ, for instance Sony



```
<catalog>
  <portable ref="Sony 1321–A">
    <name>Vaio</name>
    <vendor>Sony</vendor>
    <in_stock>true</in_stock>
    <price currency="USD">3000</price>
    <autonomy>180</autonomy>
    <review rid="00977">Pretty Smart</review>
  </portable>
......
</catalog>
```

```
<catalog vendor="Sony>
  <item type="Vaio">
    <code>1321–A</code>
    <in_stock>true</in_stock>
    <price>3000</price>
    <autonomy>3h</autonomy>
  </item>
  <item type="Battery">
    <code>333–B<code>
    <in_stock>false</in_stock>
    <price>500</price>
    <weight>33</weight>
  </item>
......
</catalog>
```

```
<desc_table>
  <desc>
      <ref>1312–A/Sony</name>
      <name>Vaio</name>
      <review>Pretty smart</review>
  </desc>
  </desc>
      <ref>Jim</ref>
      <name> ADAFAS</name>
      <review>.....</review>
  </desc>
  ....
</desc_table>
```

```
code="#1321"; in_stock="true";
price="3000";autonomy="3h"

code="#1412";in_stock="false";
price"500";weight="33"

code="#1311";price="2599";
in_stock="true";weight="22";
autonomy="2h30";
```

Review Table

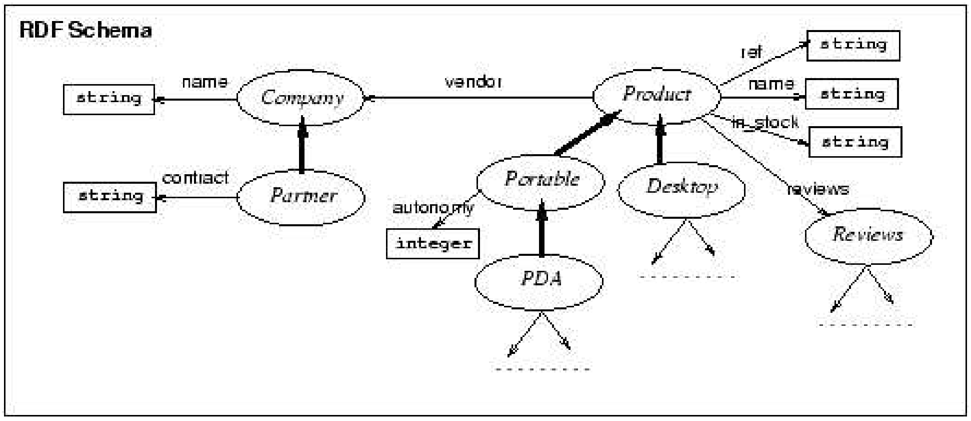
ref	name	review
1312–! / Sony	....	....

Fig. 2. XML-based data integration

has separate categories for laptop and palmtop, while IBM has a single category for portable computers, etc. This often implies that the resulting global ontology will be a fairly complex hierarchy with many different classes, and properties for these classes. Understanding the relationship between these classes then becomes essential.

As sources export their data in XML, integration into that common ontology is more easily specified using an XML language like XQuery. This results in a mismatch between the data produced in XML and the ontology description in RDF/S. Figure 3 shows an example of an RDFS graph describing the target semantics, and of an integrated XML document generated from the sources. A first use of a unified XML and RDF model is to provide the ability to relate the integrated XML information with its intended meaning in RDF. In section IV we will see how our model theory can be used to understand the relationship between the XML document and its intended semantics in RDF.

It is important to note that the XML document resulting from integration reflects some of the semantic hierarchy of the ontology. Assuming the target application wants to access all the computers that have certain characteristics, one should be able to write an XML query to do that. However at the XML level, the connection between the element names (e.g., `desktop`, `laptop` and `computers`) would not be available to an XML query processor without knowledge of the semantics layer. In section V we will see how one can use our model theory to perform such semantic querying for XML documents.



```
<catalog>
   <portable ref="Sony 1321-A">
      <vendor co="Sony"/>
      <name>Vaio</name>
      <in_stock>true</in_stock>
      <price currency="USD">3000</price>
      <autonomy>180</autonomy>
      <review rid="00977">Pretty Smart</review>
      <accessories>
         <battery ref="IBM X111"/>
         <docking_station ref="IBM X112"/>
         <battery ref="Sony 333-B"/>
      </accessories>
   </portable>
   <PDA ref="Compaq 4XDF">
      <name>iPAQ</name>
      <vendor co="IBM"/>
      <in_stock>inorder</in_stock>
      <price currency="USD">500</price>
      <weight>33</weight>
   </PDA>
   .....
<catalog>

<companies>
   <company co="Sony">
      <name>Sony<name/> <tel>555-13-13</tel>
   </company>
   <partner>
      <name>IBM<name/> <tel>555-13-13</tel> <contract>013</contract>
   </partner>
   ...
</companies>
```

Fig. 3. RDF Schema vs. XML Data

A. Other Scenarios for the Yin/Yang Web

We took the data integration example for ease of exposure and the striking need for interaction between the semantic and the data worlds. But there is no shortage of important applications for the Yin/Yang Web.

A.1 XML Dialects

The development of domain-specific dialects is an important activity area around XML. Witness of that activity, the Oasis consortium [11] hosts several dozens of dialects that describe information from almost all possible domains of human knowledge (e.g., music, theology), industry segments (e.g., car manufacturing, voice interface), or specific transversal activities (e.g., Web presentation with XHTML, calendars).

These dialects allow communities to share information in a common syntax. Yet, this common syntax is only a means to share information with an agreed upon semantics. It is therefore essential to develop that dialect based on a mutually shared understanding. Semantic modeling tools [12], [13] provide services to define ontologies for a given application or domain. After the modeling phase, this usually results in a concrete XML Schema, in which part of the semantics is either lost (e.g., the distinction between an entity and a relationship) or deprecated (e.g., typed references to objects can be preserved only as integrity constraints). In the Yin/Yang Web, the applications can be given full access to the data (XML), structure (XML Schema), but also (part of) its intended semantics (using RDF/S or the ontology language we specify in Section VII).

A.2 Web services

High-level service description languages can be written in a semantic language (for instance DAML-S in DAML+OIL). Lower-level activities, including passing messages between services, instead use XML, possibly including XML Schema validation. In the Yin/Yang Web, these two levels can be firmly joined and clearly related to each other.

III. The Yin/Yang Approach

A. Processing information on the Web

When an application gathers some information from the Web, this information is usually accessed as a document, most often in XML syntax. This document goes through several stages before the actual meaning of the information is accessible to the application. According to current W3C architectures, initial stages fall into the category of producing an abstract syntax tree for a document, resulting in one of the various data models, such as the XQuery data model [14] for data or documents, or the RDF model [5], for semantic information. Each stage in these processes produces an abstraction of the original document, and can both remove information that is deemed irrelevant (such as non-significant white space) and add implied information (such as typing information). Although they perform very similar tasks, there are significant differences between the initial processing stages of XML documents and of RDF documents.

- After parsing, XML documents are usually validated against a DTD or XML Schema. As well as checking that all and only the indicated constraints are verified, this process also adds some important information to the documents, such as default values, datatypes, some derivation information, etc. This result in a *post-schema validation infoset*, which can then be loaded into the XQuery data model for querying. XQuery data model structures provide a tree representation of the XML document and can be accessed by applications via a functional interface.
- Parsing RDF documents results in an RDF graph structure, similar to the XQuery data model, but a graph instead of a tree. This graph structure is given semantics by means of a model theory [29]. Many RDFS constructs, such as its subclass property, result in constraints in the model theory, such as requiring that certain kinds of relationships are transitive. The model theory does not specify how these semantic constraints are to be implemented. The model theory also does not provide a data structure that can be accessed. On the other hand, access to the semantic information in a document can be performed via software that implements logical operations on the the model theory, such as entailment.

The existence of these two distinct models, along with distinct processing stages for XML and for RDF is the main reason that prevents applications from dealing with information both at a data level and at a semantic level. In addition, due to the similarity of processing in both cases, there is significant duplication of work. Our approach eliminates this duplication by using as much XML processing as possible before moving to semantic processing. In a nutshell, we first build an instance of the XQuery data model for XML, RDF and even RDFS documents. This already supports structural manipulation for data-oriented applications over XML, RDF or RDF schema information. Then, we use that data model in a model theory in order to support semantic reasoning. The stages in the Yin/Yang model are described on Figure 4.

Our processing architecture has the following advantages. It builds on existing XML processors as much as possible, which reduces the work required to develop a semantic processor. It provides tight coupling between the data layers and the semantic layers. It allows data applications to benefit from semantic reasoning. It allows semantic-based applications to access data consistently. Before we explain more about the Yin/Yang model itself, we briefly give some background information on the XQuery data model and on model theory.

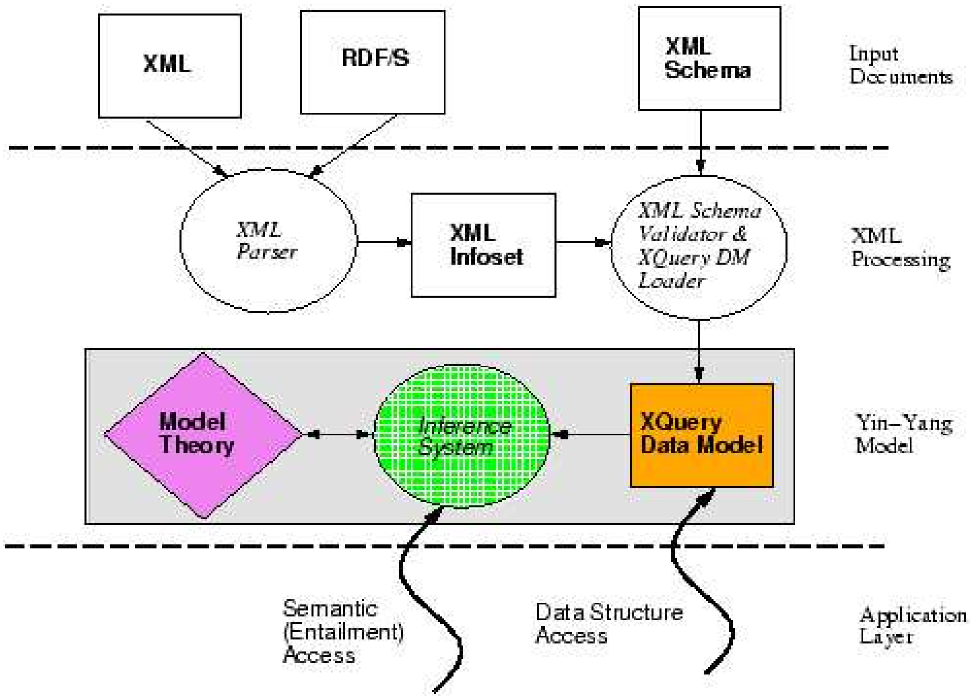


Fig. 4. Yin/Yang model

B. From Syntax to Data Model

For our purposes a data model is a collection of data types that can be used to construct an abstract view of a web document (or collection of documents), along with functions that allow access to the information contained in values belonging to these types. Data models generally also have construction functions, but we will not be talking much about the construction of the data model and so will mostly ignore them.

The XQuery 1.0 and XPath 2.0 Data Model (henceforth "data model") represents an XML document as a collection of nodes of different kinds, arranged in a tree. For example, an element node in the data model, which corresponds to an XML element information item has accessors for its name, parent, namespaces, attributes, and children, as one would expect. The data model includes other types of nodes, such as attribute nodes, namespace nodes, comment nodes, and text nodes.

One reason that we are using this data model is that it contains support for DTD and XML Schema validation. To access information gathered from validation, the data model provides accessors for the XML Schema type associated with many kinds of nodes, and, if the type is a simple XML Schema datatype, to the sequence of typed values resulting from XML Schema processing of the text within the node (for element nodes) or the value of the node (for attribute nodes).

So the first phase of the processing of an XML document or collection of documents, so far as we are concerned, results in the tree or forest of nodes in the data model. This processing includes not only the parsing of the document, but also DTD and XML Schema validation and decoration.

C. From Data Model to Semantics

The next phase of our approach is to move from the data model into the semantic realm. We do this by adopting conventions from model theory, a branch of mathematics that is used to provide meaning for many logics and representation formalisms, and has recently been applied to several web-related formalisms, namely RDF [29]. and DAML+OIL [30].

One of the particularities of our approach is the choice of relying on two distinct paradigms: data model for data, and model theory for semantics. There are several fundamental differences between data models and model theory approaches that justify that choice.

Information retention: Data models tend to retain almost all of the information in the input document, such as comments and the exact form of typed values. In model theory, on the other hand, there is a decision made on just which kind of information to retain, and which kind of information is ignored. It is typical in model theories to use sets instead of sequences and thus to ignore the order in which information is presented.

Direction of flow: In data models there is a process of generating a data model from an input document and thus the result is constructed from the input. In model theory, on the other hand, the interpretations are simply mathematical objects that are not constructed at all. Instead there is a relationship between syntax constructs and interpretations that determines which interpretations are compatible with a document. Generally there are many interpretations that are so compatible, not just one.

Schema vs. Data: Data model approaches make a fundamental distinction between schema and data. In model theory, both schema and data are part of a model on which one can perform reasoning. As shown on Figure 4, this allows us to deal with both RDF and RDFS in a common way, while some aspects of XML Schema will remain out of the scope of the inference system.

D. Using model theory for reasoning

In a model theory, we end up with not just a single interpretation or model, but instead a collection of interpretations or models. These models can be thought of as the different ways that the world can be while still remaining compatible with the information in the input document.

What is generally done next in model theory is to define a relationship between input syntax called entailment, which can be read as "follows from". A collection of sentences (or documents), called the antecedents, entails a sentence (or document), called the consequent, if every interpretation that is a model for each element of the collection is also a model for the consequent. This relationship can be read as "if the world is compatible with each antecedent, then it is also compatible with the consequent" or "if each antecedent is true then so is the consequent." Another way of saying this is that entailment captures what information is implicit in a document.

It is possible to think of entailment as a version of relational retrieval where the query specifies explicit values for all elements of the tuple, i.e., there is at most one possible answer. Generalizations of entailment have been used that allow open variables in the consequent, resulting in a version of entailment close to retrieval.

Note again, that the *kind of* reasoning that can be achieved depends on the expressive power of the semantics description language.

IV. The Yin/Yang Model Theory

A. Processing of input documents

Our model theory starts with a tree structure composed of a set of nodes, N, in the XQuery 1.0 and XPath 2.0 Data Model [14]. This tree structure corresponds to an XML or RDF document (or collection of documents) that have already been through a serious amount of processing, notably parsing and schema validation. Each tree node, n, is assumed to have a mapping, $UTS(n)$ which is the map from strings to qualified names, given the namespace declarations in scope at the node.

B. Example

Consider the following pieces of an XML document (actually RDF with an XML Schema datatype extension):

```
<Laptop rdf:about="Vaio505G">
   <manufacturer rdf:resource="Sony"/>
   <price xsi:type="xsd:integer">3000</price>
</Laptop>

<rdf:Description rdf:about="Sony"
                 home="www.sony.com">
   <rdf:type>
      <rdf:Description rdf:about="Company">
   </rdf:type>
</rdf:Description>
```

This document is parsed and then loaded into the XQuery data model. This results in the following data set, written here in a simple data structure where nodes are represented as tuples containing the relevant bits of information prefixed with a node identifier:

```
1:<Laptop,attributes=[ 2:<rdf:about,"Vaio505G">],
  elements=
    [ 3:<manufacturer,
          attributes=
           [ 4:<rdf:resource,"Sony">]>,
      5:<price,
          attributes=
           [ 6:<xsi:type,"xsd:integer">],
          elements=
           [ 7:<"3000">]>]>
8:<rdf:Description,
  attributes=
    [ 9:<rdf:about,"Sony">,
      10:<home,"www.sony.com">],
  elements=
    [ 11:<rdf:type,
          elements=
           [ 12:<rdf:Description,
               attributes=
                 [ 13:<rdf:about,"Company">]>]>]>
```

This structure can then be accessed using the XQuery data model accessor operations on nodes, can be queried using XQuery, etc.

C. Resources, Names, Values, and Datatypes

Our Yin/Yang model theory assumes a universe of resources and data values. For simplicity, we make the assumption that QNames are suitable as RDF identifiers, but readers could read the document substituting RDF identifiers for QNames. (A full treatment of RDF identifiers is somewhat messy so a simpler treatment is used here.) The construction `rdf:`*name* refers to the QName with local name *name* and URI (the rdf URI): http://www.w3.org/1999/02/22-rdf-syntax-ns.

Definition IV.1: We call L the lexical space of strings, and U the value space of QNames, i.e., pairs of URIs and local parts. We call DT the subset of U corresponding to XML Schema primitive datatypes, and DV the union of the value spaces of the XML Schema primitive datatypes. In RDF elements of DV are generally called literals. The function $DTC : DT \rightarrow \mathcal{P}(DV)$, (where $\mathcal{P}$ is the powerset operator), maps XML Schema primitive datatypes to their value spaces and $DTS : DT \rightarrow (L \rightarrow DV)$, maps XML Schema primitive datatypes to their lexical to value maps. We define the union of the datatype mappings $XTS : L \rightarrow \mathcal{P}(DV)$, where $v \in XTS(l)$ iff $v = DTS(dt)(l)$ for some XML Schema datatype dt.

D. Yin/Yang Interpretations

Interpretations are the essential component of our model theory. An interpretation corresponds to one possible way the world could be, hence encoding a certain meaning for the information manipulated by an application. Interpretations give information about resources and related resources through relationships and semantic constraints. For instance, one resource may be a $Laptop$, related to another resource $Sony$ through a $manufacturer$ property. We define a notion of interpretation that is suitable for both XML and RDF documents, through the XQuery data model.

Definition IV.2: An *interpretation* I is a six-tuple:
$\langle R, E, EXT, CEXT, O, S \rangle$, where:
R is a set of resources,
E is a set of relationships,
$EXT : E \rightarrow R \times (R \cup DV)$ maps relationships to the resources they relate,
$CEXT : R \rightarrow \mathcal{P}(R \cup DV)$ maps class resources to their extensions,
$O : R \rightarrow \mathcal{P}(E \times E)$ provides a local order on the relationships, and
$S : U \rightarrow R$ is a partial map from QNames to resources.

An interpretation can be thought of as a multigraph with an ordering on the edges. Resources (R) form the nodes of the graph. Edges of the graph are formed from relationships (E) and EXT. For instance, a relationship:

$$e1 \in E \text{ with } EXT(e1) = \langle Vaio505G, manufacturer \rangle$$

indicates that the resource $Vaio505G$ is related to the resource $manufacturer$, and a relationship:

$$e2 \in E \text{ with } EXT(e2) = \langle manufacturer, Sony \rangle$$

indicates that the resource $manufacturer$ is related to the resource $Sony$. We remark that there is no distinction at this point between $Sony$, as an instance of a class, and $manufacturer$, which is a property. This allows the model theory to represent arbitrary XML documents, while we will see we can still recover the traditional RDF semantics.

S provides a mapping between syntax (QNames) and their denotation (resources). S gives a means to identify these entities using QNames. There is no requirement that all resources have corresponding QNames, nor is there a requirement that QNames are all mapped to different resources.

$CEXT$ provides typing information for resources.[1] For instance, assuming the resource `Sony` is in `CEXT(Company)` then the resource `Sony` is of type `Company`. Loosely speaking, in RDF terms $CEXT$ serves for both property and class extensions. Or, considered another way, a property is presented as a type whose values and related tuples identify arcs in the traditional RDF graph structure.

Finally, O provides ordering information between the relationships that are related to a common resource. This information is not usually part of RDF model theories [29], but it is important to capture document order in XML documents. We add one special attribute to RDF, `rdf:order`, to indicate whether a node should have its outgoing relationships ordered. This is not an ideal solution. We have considered adding a flag to the semantics to indicate ordering, but decided to use this simple method for now.

Definition IV.3: In order for an interpretation to to be an *RDF interpretation*, the above six-tuple must also satisfy the following additional conditions:

• $O(r)$ is a strict partial order, used to order to the outgoing edges for each node.

• If $\langle x, y\rangle \in O(r)$ then $EXT(x)$ and $EXT(y)$ have r as their first element.

• $CEXT(S(\texttt{rdf}:\texttt{Description})) = R$

• $CEXT(S(\texttt{rdf}:\texttt{Property})) \subseteq R$

• $S(\texttt{rdf}:\texttt{type}) \in CEXT(S(\texttt{rdf}:\texttt{Property}))$

• If $\langle x, y\rangle \in EXT$, $y \in CEXT(S(\texttt{rdf}:\texttt{type}))$, and $\langle y, z\rangle \in EXT$
then $x \in CEXT(z)$.

• If $x \in CEXT(z)$ and $x \in R$ then
$\exists\, y \in R : \langle x, y\rangle \in EXT \;\wedge\; y \in CEXT(S(\texttt{rdf}:\texttt{type})) \;\wedge\; \langle y, z\rangle \in EXT$.

• If $d \in DT$ then $CEXT(S(d)) = DTC(d)$, provided that S is defined on d.

The first and second conditions say that $O(r)$ is a strict ordering over the relationships emanating from r. The third, fourth, and fifth conditions provide part of the meaning for some of the built-in RDF vocabulary.

The sixth and seventh conditions relate the two ways of providing typing for resources, one via $CEXT$ and one via `rdf:type` links. This is needed because `rdf:type` is part of both the theory and the metatheory of RDF. As part of the theory of RDF, `rdf:type` is given a denotation, and relationships impinge on it.

[1] It would be possible to define $CEXT$ in terms of `rdf:type`, as is done in RDF. We have chosen to make $CEXT$ a part of the semantics to emphasize its importance.

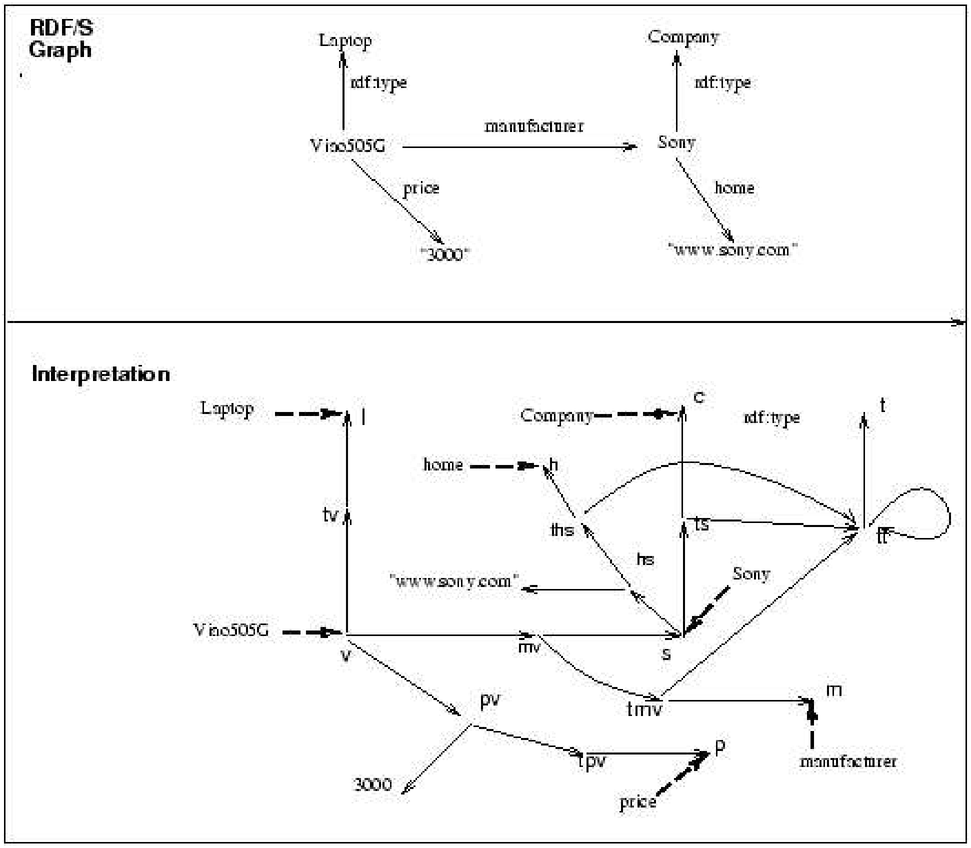


Fig. 5. RDF Graph and a corresponding interpretation

As part of the metatheory of RDF, these relationships impose conditions on the extension ($CEXT$) of RDF classes. The sixth condition goes from `rdf:type` links to `CEXT` for all resources and data values whereas the seventh condition goes the other way, but not for data values.

The eighth condition provides meaning for XML Schema primitive datatypes. It ensures that the extension of a resource that corresponds to an XML Schema primitive datatype is the value space of that datatype.

E. Example

In Figure 5 we present an RDF graph (the original method for providing meaning to RDF documents) and *part of* an interpretation. The interpretation is presented in the form of a graph. Most nodes are resources, i.e., elements of R; the node with 3000 next to it is the integer 3000 and the node with "www.sony.com" next to it is a string, both data values. (The labels on resource nodes are just so that they can be referred to in the text below.) The mapping S is given by the dashed arrows from QNames to the nodes. Relationships in the interpretation (E and EXT) are shown as links between the resources. Finally $CEXT$ contains $CEXT(l) = \{v\}$, $CEXT(c) = \{s\}$, $CEXT(p) = \{pv\}$, $CEXT(m) = \{mv\}$, $CEXT(h) = \{hs\}$,

$CEXT(t) \supset \{tv, ts, tmv, tpv, ths, tt\}$. This is only a partial representation of an interpretation as it does not incorporate `rdf:Description` and `rdf:Property`, relationships to them, and $CEXT$ for them. Nor does the graph specify the ordering relationships that come from the document order.

As an abbreviation, we will use a triple notation, saying that $\langle s, p, o\rangle$ is in I iff there is some resource $r \in R$ such that $\langle s, r\rangle \in EXT$, $\langle r, o\rangle \in EXT$, and $r \in CEXT(p)$. For example to indicate that $Vaio505G$ is related to $Sony$ through a $manufacturer$ resource we will use $\langle Vaio505G, manufacturer, Sony\rangle$.

F. *Recovering RDF meaning*

As one can see in Figure 5, RDF graphs make a clear distinction between classes and properties, while this distinction is not present in our model theory in order to deal with XML documents. Still, RDF graphs correspond to a precise subset of our interpretations. In a nutshell, RDF graphs corresponds to interpretations in which a proper alternation between classes and properties exists.

This statement is made more precise by the following definition.

Definition IV.4: Given an interpretation:

$I = (R, E, EXT, CEXT, O, S)$ let

- $P = \{x : \exists y\ x \in CEXT(y) \wedge y \in CEXT(\texttt{rdf : Property})\}$
- $E' = E\ -\{e : \exists y\ EXT(e) = \langle y, S(\texttt{rdf : type})\rangle\}$

  $-\{e : \exists x, y, e'\ EXT(e) = \langle x, y\rangle \wedge EXT(e') = \langle y, S(\texttt{rdf : type})\rangle\}$

If P makes E' bipartite, i.e., all $EXT(e')$ for $e' \in E'$ either originate or terminate, but not both, in P, and also for each $x \in P$ there is exactly one $e' \in E'$ with $EXT(e')$ of the form (x, y) for some y and exactly one $e' \in E'$ with $EXT(e')$ of the form (y, x) for some y, then I is a *bipartite interpretation*.

A bipartite interpretation can be turned into an interpretation in the RDF model theory [29] by:

- taking each pair of relationships $\langle e', e''\rangle \in E'$

where $EXT(e') = (x, p)$, $EXT(e'') = (p, z)$, and p in P

- replacing it with (x, z) in $IEXT(r)$ for each r such that $p \in CEXT(r)$
- then adding $(x, c) \in IEXT(S(\texttt{rdf : type}))$ for each x in $CEXT(c)$ for x not in P.

G. *Models of XML and RDF documents*

Now that we have defined our notion of interpretation, we need to explain how instances of the XQuery data model correspond to these interpretations.

Intuitively, each node in the XQuery data model is mapped to a resource in the interpretation, and EXT relationships are built according to the original tree structure of the XQuery data model instance. On top of that the specific XML Schema and RDF attributes `xsi:type`, `rdf:ID`, `rdf:about`, `rdf:type`, `rdf:resource`, and `rdf:order` are treated specially in order to build a theory of RDF documents that reflects their intended meaning.

Definition IV.5:

An interpretation $I = \langle R, E, EXT, CEXT, O, S \rangle$ is a *model* for a data set N if S is defined on all names in N, and there are mappings $M : N \to R \cup DV$ and $MA : N' \to DV$, where N' consists of the attribute nodes in N. Further, the interpretation and mapping have to satisfy the following conditions. (Although there are a lot of conditions here, they all really boil down to doing the obvious thing.)

- For each $n \in N$ an element node,
  - $M(n) \in R$ and $M(n) \in CEXT(S(name(n)))$
  - If n has an attribute with name `rdf:ID` and string-value u then $M(n) = S(UTS(n)(u))$.
  - If n has an attribute with name `rdf:about` and string-value u then $M(n) = S(UTS(n)(u))$. (This treats `rdf:ID` and `rdf:about` as exactly the same which is not quite correct but a full treatment would have to address the messy differences between QNames and RDF identifiers.)
  - If n has an attribute with name `rdf:resource` and string-value u then there is an $e \in E$ with $EXT(e) = \langle M(n), S(UTS(n)(u)) \rangle$.
  - If n has an attribute with name `rdf:type` and string-value u then $\langle M(n), S(UTS(n)(u)) \rangle \in CEXT$.
  - For each attribute node, n', of n, except for attributes with any of the specific names above, then there is an $e \in E$ with $EXT(e) = \langle M(n), M(n') \rangle$.
  - If n has a simple type, dt, then
    - for each of the k typed-values, v_i, of n there is an $e_i \in E$ with:

$$EXT(e_i) = \langle M(n), DTS(d)(string - value(v_i)) \rangle.$$

    - if n has no attribute with name `rdf:order` and value `"false"` then: $\langle ei, ej \rangle \in O$ for $1 \leq i < j \leq k$.
  - If n does not have a simple type, then
    - for each of the k element or text children nodes, n', of n, in document order there is an $e_i \in E$ with $EXT(e_i) = \langle M(n), M(n') \rangle$.
    - if n has no attribute with name `rdf:order` and value `"false"` then $\langle ei, ej \rangle \in O$ for $1 \leq i < j \leq k$.

- For each $n \in N$ a text node $M(n) \in DV$ and $M(n) \in XTS(string - value(n))$
- For each $n \in N$ an attribute node, except for attributes with any of the specific names above,
  - $M(n) \in R$ and $M(n) \in CEXT(S(name(n)))$
  - $MA(n) \in DV$ and $MA(n) \in XTS(string - value(n))$
  - There is some $e \in E$ with $EXT(e) = \langle M(n), MA(n) \rangle$.
  - If n has a simple type, dt, then $MA(n) = DTS(dt)(string - value(n))$
- For each $n \in N$ a reference node, $M(n) = M(deference(n))$.

Definition IV.6: An *RDF model I* for N is an RDF interpretation I that is a model for N.

H. Example

Now the interpretation in Figure 5 is a model for the document above under the mapping $M(1) = v$, $M(3) = mv$, $M(5) = pv$, $M(7) = 3000$, $M(8) = s$, $M(11) = ts$, $M(12) = c$, $M(10) = hs$, and $MA(10) = "www.sony.com"$. The other nodes are "structural nodes" and thus do not have a mapping. As XML Schema datatypes only show up in the "structural" nodes, they do not need to be present.

I. Entailment

Finally, we are now ready to define a notion of entailment for XML and RDF data sets.

Definition IV.7: A data set N *entails* another data set N' iff every RDF model of N is also an RDF model of N'. A collection of data sets entails another data set N' iff every RDF model of every element of the collection is also an RDF model of N'.

As we will see in Section V, entailment is the main reasoning tool that we will use at the application level. Entailment captures valid reasoning, in that if a data set N' is entailed by another N, the information in N' in implicitly present in N.

J. Dealing with RDF Schema

RDF Schema (RDFS) is an extension of RDF that has a vocabulary for stating relationships between classes and properties as well as some built-in meaning for this vocabulary.

We handle the RDFS vocabulary by requiring that an RDFS interpretation include the following triples. (Actually there is more RDFS vocabulary than given below, such as rdfs:comment. This other vocabulary does not matter to our approach and can be easily handled. To conserve space we do not include it here.)

```
<S(rdf:Description),     S(rdf:type),          S(rdfs:Class)>
<S(rdf:Description),     S(rdfs:subClassOf), S(rdfs:Resource)>
```

```
<S(rdfs:Resource),      S(rdfs:subClassOf), S(rdf:Description)>
<S(rdfs:Resource),      S(rdf:type),        S(rdfs:Class)>
<S(rdf:Property),       S(rdf:type),        S(rdfs:Class)>
<S(rdfs:Class),         S(rdf:type),        S(rdfs:Class)>
<S(rdfs:Literal),       S(rdf:type),        S(rdfs:Class)>
<S(rdf:type),           S(rdf:type),        S(rdf:Property)>
<S(rdfs:subClassOf),    S(rdf:type),        S(rdf:Property)>
<S(rdfs:subPropertyOf), S(rdf:type),        S(rdf:Property)>
<S(rdfs:Class),         S(rdfs:subClassOf), S(rdfs:Resource)>
<S(rdf:type),           S(rdfs:range),      S(rdfs:Class)>
<S(rdfs:subClassOf),    S(rdfs:domain),     S(rdfs:Class)>
<S(rdfs:subClassOf),    S(rdfs:range),      S(rdfs:Class)>
<S(rdfs:subPropertyOf), S(rdfs:domain),     S(rdf:Property)>
<S(rdfs:subPropertyOf), S(rdfs:range),      S(rdf:Property)>
<S(rdfs:range),         S(rdfs:domain),     S(rdf:Property)>
<S(rdfs:range),         S(rdfs:range),      S(rdfs:Class)>
<S(rdfs:domain),        S(rdfs:domain),     S(rdf:Property)>
<S(rdfs:domain),        S(rdfs:range),      S(rdfs:Class)>
```

RDFS interpretations also must meet the following additional constraints:

- $CEXT(S(\mathtt{rdfs:Resource})) = R$
- $CEXT(S(\mathtt{rdfs:Literal})) = DV$
- If $x \in CEXT(y)$ and $\langle y, S(\mathtt{rdfs:subClassOf}), z\rangle \in I$, then $x \in CEXT(z)$.
- If $\langle x, S(\mathtt{rdfs:subClassOf}), y\rangle \in I$ and $\langle y, S(\mathtt{rdfs:subClassOf}), z\rangle \in I$,

then $\langle x, S(\mathtt{rdfs:subClassOf}), z\rangle \in I$.

- If $\langle x, r, y\rangle \in I$ and $\langle r, S(\mathtt{rdfs:subPropertyOf}), s\rangle \in I$, then $\langle x, s, y\rangle \in I$.
- If $\langle x, S(\mathtt{rdfs:subPropertyOf}), y\rangle \in I$ and $\langle y, S(\mathtt{rdfs:subPropertyOf}), z\rangle \in I$,

then $\langle x, S(\mathtt{rdfs:subPropertyOf}), z\rangle \in I$.

- If $\langle x, p, y\rangle \in I$ and $\langle p, S(\mathtt{rdfs:range}), c\rangle \in I$ then $y \in CEXT(c)$.
- If $\langle x, p, y\rangle \in I$ and $\langle p, S(\mathtt{rdfs:domain}), c\rangle \in I$ then $x \in CEXT(c)$.

Now the RDFS analogues of RDF models and RDF entailment are defined in the obvious way.

Definition IV.8: An RDFS model for a data set N is an RDFS interpretation that is a model for N. A data set N RDFS-entails another data set N' iff every RDFS model of N is also a RDFS model of N'. A collection of data sets RDFS-entails another data set N' iff every RDFS model of every element of the collection is also a RDFS model of N'.

K. Caveats

This is quite a bit of machinery. Some of it is required to handle the two ways, XML and RDF, of looking at the world, and some of it is required to handle the vocabulary of RDF. We feel that this model theory captures the important parts of XML and RDF, but there are some aspects of both XML and RDF that it is missing.

The model theory explicitly discards as irrelevant most of the formatting aspects of the initial document. Similarly it also discards as irrelevant the lexical form of elements that have XML Schema datatypes. There is no way of recovering the exact character sequence of the initial document from the model theory.

Just about the only significant aspect of XML documents that are not handled in the model theory is the distinction between attributes and elements. This is discarded to obtain consistency with RDF.

On the RDF side our scheme does not handle certain RDF constructs. The meaning of reification in RDF and RDF containers have not yet been determined, so the model theory does not address them. One RDF shorthand form, collapsing the properties of an unnamed RDF resource into the enclosing XML element, changes the XML meaning of a document and thus cannot be handled by the model theory. As syntax processing is completely handled by XML, our scheme cannot handle the RDF `parsetype` extension.

V. Applications

We can now go back to our catalog example from Figure 2. Remember that the data integration is done in two steps. On the semantic side, one needs to design and build a global ontology for the information manipulated by the target application. On the data side, one accesses data from various information providers using XML, resulting in a mismatch between data and semantics, as illustrated on Figure 3.

A. Semantic Consequences

The first result of our integration is that the semantic consequences of the RDF Schema information are applied to the the XML data. For example, the `Compaq 4XDF` is a `portable` because that information is entailed from the fact that it is a `PDA` and the class relationships in the RDF Schema information. This entailed information is available to applications that access the data model view.

We are still exploring the various capabilities that a powerful inference system can support in the XML world. Still, there are two important remarks to be made. First, it is always possible to import more information for reasoning. For instance, it is quite common that various terminologies or vocabularies will be used between the data sources, and in the ontology. Following Fundulaki [10], RDFS – hence our model theory – is expressive enough to capture standard thesaurus descriptions, and incorporate them in the reasoning. For instance, if one would use `manufacturer` instead of `vendor`, the system would still be able to figure our semantics relationships and inconsistencies, assuming these are declared as homonyms in the thesaurus.

B. Querying RDF

A second important application of the Yin/Yang model is related to querying RDF with XQuery. Robie et al [21] propose one approach to query RDF and topic maps documents using XQuery. One of the benefits they gain is the ability to query both XML and RDF information in a uniform framework. A difficulty of their approach lies in the inability of the XQuery data model to incorporate the semantic features of RDF . To solve that problem, [21] uses special-purpose functions in XQuery that perform some part of the reasoning.

In the Yin/Yang model, one now has access to both the data model representation and the semantics of the RDF information. Hence, one can use XQuery to access the data structure of the RDF document, while using entailment to access its semantics. For instance, the following function from [21] performs a recursive access on the class hierarchy in order to figure out whether an entity is an instance of a given class.

```
define function rdf:instance-of-class
  ( ListOfDescription $t,
    charstring $base-name )
returns ListOfDescription
 {
   ( $t[rdf:type = $base-name],
     for $i in $t[rdfs:subClassOf = $base-name]
     return
       rdf:instance-of-class($t, string($i/@rdf:about)) )
}
```

This function can be defined directly through entailment in the following way:

```
define function rdf:instance-of-class
  ( ListOfDescription $t,
    charstring $base-name )
returns ListOfDescription
```

```
{
   for $d in $t
   where
     entails($yin:yang,
             <rdf:Description rdf:about={$d}>
              <rdf:type>
               <rdf:Description rdf:about={$base-name}>
              </rdf:type>
             </rdf:Description>)
  return $d
}
```

This function returns only those descriptions `$d` in `$t` such that the current semantics (represented as a global variable `$yin:yang`) entails the statement (written in rdf syntax) that `$d` is of class `$base-name`.

Indeed, model theory and entailment provide a precise formal foundation for the techniques presented in [21]. Entailment also enables more complex reasoning, that cannot be captured by a finite set of functions. For instance, one can ask whether all companies with a contract are partners with the following entailment query (note the use of parenthesis in the XQuery syntax to separate parameters of the function).

```
  entails( ( $yin:yang,
             <rdf:Description rdf:about={$d}>
               <rdf:type>
                 <rdf:Description rdf:about="Company">
                 <contract>{$c}</contract>
               </rdf:type>
             </rdf:Description> ) ,

            ( <rdf:Description rdf:about={$d}>
               <rdf:type>
                 <rdf:Description rdf:about="Partner">
               </rdf:type>
             </rdf:Description> )
         )
```

A somewhat interesting remark is that our work would also allow a converse approach to the one of Robie et al, by using an RDF query language such as RQL [6] on the model theory representation of XML documents, hence allowing to query both XML and RDF with an RDF query language. Note again that we are just starting to explore the possibilities provided by such semantics reasoning in RDF as well as in XML. We cannot go into more details due to space limitation, but we believe these simple examples are giving some ideas of the many interesting possibilities revealed by our approach.

C. Semantic Integrity

Another interesting question to ask as a user is whether the data built through the integration system is semantically consistent with the target ontology. If there are no models for both the RDF Schema information and the XML data then there is some semantic inconsistency between them.

Unfortunately, RDF Schema is too weak to provide this sort of reasoning. For example, if a mistake in the input causes a resource to be both a Company and a Product, this is not a semantic error, as Company and Product are not necessarily disjoint. This disjointness cannot be enforced in RDF Schema. Adding disjointness reasoning to our approach would require more powerful semantic formalisms, such as the DAML+OIL ontology language [31].

There are also other forms of reasoning we are not able to do due to the expressive power limitations of RDF Schema. We cannot perform any recognition on the information, such as determining that an IBM computer that has a portable property belongs to the same category as a SONY laptop. Again such inference is available in newer proposals for the Semantic Web, such as DAML+OIL.

VI. Implementation

The approach we have outlined has several implementation advantages. First and foremost, as the initial stages of processing for both XML and RDF documents are the same, there is no need to have a syntax processor for RDF. Second, the approach integrates XML Schema datatypes, eliminating the need for a separate datatype implementation for RDF.

As a result, an implementation of the entire Yin/Yang model can be quickly and easily written, by exploiting tools for the XQuery data model. In fact, we have written an initial reference implementation of the scheme in OCaml [32]. This implementation builds on the Galax XQuery engine [33] and data model implementation, and our implementation on top of it is only about 300 lines of code.

Although our implementation is not complete, it provides the core of what is needed for a complete system based on our scheme: the mapping from the XQuery data model and the entailment algorithm. This implementation is currently available from the authors.

The implementation uses the fact that a canonical model exists for our scheme. This is a traditional implementation technique for semantic reasoners. Given a collection of XML and RDF documents, the implementation builds a canonical model for them. This canonical model can then be used to determine whether another document is entailed by the original documents.

VII. Adding the Ontology Layer

The above development of our approach only handles the bottom layers of the Semantic Web. However, it is possible to easily add the ontology layer to our approach.

One interesting complication with the ontology layer, is that it is already partly present in the lower layers. First, RDFS is a (very) limited ontology language, as it can be used to create classes and place these classes in a class hierarchy. RDFS can also be used to place properties in a property hierarchy and provide domains and ranges for these properties.

Second, and more interestingly, XML Schema also has ontology implications. Much of what XML Schema does is to create analogues of classes and properties, and to provide some sort of meaning for these classes and properties. However, XML Schema is only used to restrict the form of XML documents - ontology implications of XML Schema come about only via this restriction. In our framework it is possible for XML Schema to have a direct effect on models, separate from their use in restricting the form of documents.

Our extended approach is illustrated in Figure 6, which is an extension of Figure 4. The additions consist of a direct connection from XML Schemas and ontology documents to the model theory. We first treat the ontology language in some detail and then sketch how the direct connection from XML Schema document to the model theory would work.

A. *Our Vision for a Web Ontology Language*

The ontology layer goes beyond what can be specified in XML Schemas. The W3C Web Ontology working group is producing a web ontology language, called OWL. We present our vision of how a language like OWL could be used to provide ontology information in our framework. We will call this language SWOL, to distinguish it from OWL.

SWOL is actually close to a description logic [15], as is OWL. There are actually many possibilities for SWOL, just as there are many description logics, varying in expressive power from frame-like formalisms up to very powerful ontology formalisms. The particular expressive power of the W3C-recommended SWOL is under consideration by the W3C Web Ontology Working Group (although they are working from an RDF

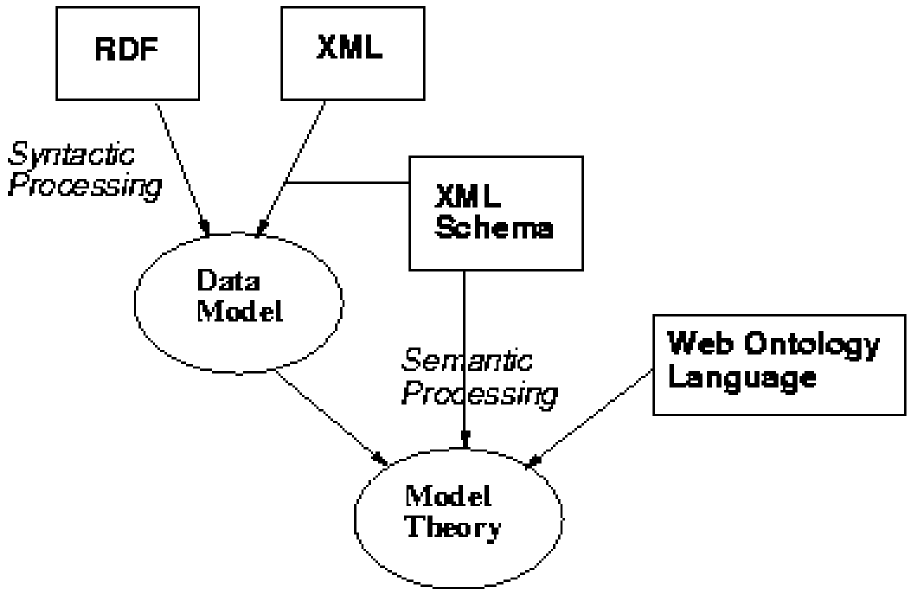


Fig. 6. From Documents to Model Theory

base).

The syntax of SWOL is less important for this discussion than its semantics. We will thus only present a syntax for SWOL by means of examples.

The following SWOL document contains information about a class, named `Organization`. Elements of this class, organizations, have a name, in the form of a string. Elements of the class also can have purchases, each of which must belong to the PurchaseOrderType.

```
<swol:class name="Organization" complete="no">
  <swol:exists>
    <swol:class name="name"/>
    <swol:class name="xsd:String"/>
  </swol:exists>
  <swol:all>
    <swol:class name="purchase"/>
    <swol:class name="PurchaseOrderType"/>
  </swol:all>
</swol:class>
```

We can think of a SWOL document as a collection of several axioms of this sort.

B. Models of SWOL documents

SWOL documents are written in XML and go through XML syntactic processing, resulting in a data set. The resulting data set is then subject to semantic interpretation. However, as we do not give a complete definition of SWOL syntax, we will define the semantics of SWOL documents by means of document fragments.

Definition VII.1: An interpretation $I = \langle R, E, EXT, CEXT, O, S \rangle$ is a *model* for a SWOL ontology document O if S is defined on all names in O. Further, the interpretation has to satisfy the following conditions:

1. For each axiom in O of the form

```
<swol:class name="n" complete="yes"> d1 ...  dn </swol:class>
```

$CEXT(S(n)) = I(d1) \sqcap \ldots \sqcap I(dn)$.

2. For each axiom in O of the form

```
<swol:class name="n" complete="no"> d1 ...  dn </swol:class>
```

$CEXT(S(n)) \leq I(d1) \sqcap \ldots \sqcap I(dn)$.

where $I(d)$ (d is called a description) is defined as

1. If d is `<swol:class name="n"/>`

then $I(d) = CEXT(S(n))$.

2. If d is `<swol:intersect> d1 ...dn </swol:intersect>`

then $I(d) = I(d1) \cap \ldots \cap I(dn)$.

3. If d is `<swol:union> d1 ...dn </swol:union>`

then $I(d) = I(d1) \cup \ldots \cup I(dn)$.

4. If d is `<swol:complement> d1 </swol:complement>`

then $I(d) = R - I(d1)$.

5. If d is `<swol:all> d1 d2 </swol:all>`

then $I(d) = \{r \in R : \forall \langle r, s \rangle \in EXT, s \in I(d1) \rightarrow s \in I(d2)\}$.

6. If d is `<swol:exists> d1 ...dn </swol:exists>`

then $I(d) = \{r \in R : \exists \langle r, s \rangle \in EXT, s \in I(di), 1 \leq i \leq n\}$.

More-powerful versions of SWOL would have more possibilities for axioms and descriptions, but would have still have their meaning defined in this way.

C. Multiple Sources of Information

Our notions of models and entailment above are not restricted to single documents, or even documents all of one kind. In fact, most of the interesting information sources will consist of several documents

- one or more XML (or RDF) documents containing base facts,
- zero or more XML Schema documents, brought in by the XML documents, and
- zero or more SWOL Ontology documents, brought in by explicit directives.

The first two kinds of documents are processed into data models, which are then given meaning in the semantics, whereas the third is given meaning directly.

So, an interpretation is a model of a collection of data sets and a collection of SWOL Ontology documents if is a model of each each of the data sets and each of the ontology documents separately.

D. Giving Direct Meaning to XML Schema Documents

So far the only meaning we have given to XML Schema documents is their effect on the creation of XQuery data models. However, it is possible (but not necessary) to also have XML Schema documents have a direct relationship to the model theory.

Whether one wants to do this depends on one's view of the status of XML Schema. If XML Schema definitions only constrain the form of XML documents then there should not be a direct connection between XML Schema documents and the model theory. In this view the definitions in an XML Schema document are *local*, that is, their import should only be felt by XML documents that directly reference the XML Schema document. Two different XML documents could use the same element names but give them different meaning, by using different XML Schema documents. So, for example, one XML document could use one XML Schema document for purchases and another XML document could use a different XML Schema document, with a different definition of purchases, even though they both used the same (qualified) element names.

On the other hand, one might want to require that all purchases have similar meaning, although maybe not similar form. In this view the XML Schema document that defines the purchase schema would not just affect one (or more) XML documents, but would have a direct and global impact on the model theory.

XML Schema is a (very) large specification, so the details of how interpretations can model XML Schema documents are beyond the scope of this paper but the general outline is clear.

Definition VII.2: An interpretation $I = \langle R, E, EXT, CEXT, O, S \rangle$ is a *model* for a XML Schema ontology document O if S is defined on all names in O. Further, for each global complex type, element, or attribute definition in O with name n, $CEXT(S(n))$ contains only those resources that have the pieces in the definition, in the correct order, and with the correct characteristics, but also, possibly, other pieces.

Not all the components of an XML Schema document have direct model-theoretic implications. In particular, default information does not give rise to any conditions, although, of course it *does* have model-theoretic effects through its effects on the data model.

In this way XML Schema documents can be added to the inputs of SWOL and end up with very similar status to SWOL ontology documents. XML Schema documents and SWOL ontology documents can even refer to definitions or axioms from the other kind of document and everything still works well.

VIII. Example

A simple example that shows how all this fits together and gives some hint as to the power of the scheme can be constructed on top of the purchase order example in the XML Schema primer [19] [2].

We assume the existence of a collection of different purchaseOrders and PurchaseOrderTypes each defined in a different XML Schema document, with different URLs. We will assume that each of these documents have a namespace, pos-i. Without loss of generality, we will assume that the different XML Schema documents use the same internal name for their top-level components.

We can use SWOL to define the Organization class, containing resources that have purchases that belong to the PurchaseOrderType.

```
<swol:class name="Organization" defined="no">
  <swol:all>
    <swol:class name="purchase">
    <swol:class name="PurchaseOrderType">
  </swol:all>
  ...
</swol:class>
```

This PurchaseOrderType is then defined as a generalization of the various PurchaseOrderTypes via

```
<swol:class name="pos-i:PurchaseOrderType" defined="no">
  <swol:class name="PurchaseOrderType" />
</swol:class>
```

We can then create a document that ties together various purchase orders, again, each in its own document with its own name, here given as po-i.

```
<Organization rdf:ID="foo">
  <purchase rdf:ID="po-1:">
  <purchase rdf:ID="po-2:">
  ...
</Organization>
```

[2] http://www.w3.org/TR/xmlschema-0/#po.xml

However, all we have so far is a collection of purchase orders with no combined way of accessing the information in them, because they each have different elements names (because of their differing namespaces). To unify these elements, we have to provide a generalization of the different element names, as in

```
<swol:class name="pos-i:shipTo" defined="no">
  <swol:class name="shipTo" />
</swol:class>
<swol:class name="pos-i:items" defined="no">
  <swol:class name="items" />
</swol:class>
...
```

Now the various fields of the different PurchaseOrderTypes are considered to be sub-categories of the combined PurchaseOrderType we have created.

So far, we have not done much more than could have been done with RDF Schema, if RDF Schema was modified to deal with XML data and XML Schema types. However, we *can* go further. For example, we can say that our PurchaseOrderType can only be one of the other PurchaseOrderTypes, and nothing else, via:

```
<swol:class name="PurchaseOrderType" defined="yes">
  <swol:union>
    <swol:class name="pos-1:PurchaseOrderType" />
    ...
    <swol:class name="pos-n:PurchaseOrderType" />
  </swol:union>
</swol:class>
```

Using this, and other, facilities from SWOL, we can take information from disparate XML documents, using disparate XML Schema types, and access it in a uniform manner, resulting in a Semantic Web version of the World-Wide Web.

There are, of course, some things that we cannot do with SWOL, as SWOL is only a limited ontology language. In particular, arbitrary inferencing will have to wait for the next level of this vision of the Semantic Web.

IX. Future Work and Conclusion

Our work aims at providing both the data and semantics access required by many of the new Web applications. We have presented an original framework and model for a Web that integrates both syntax and semantics: the Yin/Yang Web. This unified Web is obtained through a tighter integration between XML and RDF, and we believe such integration is essential for the coming Semantic Web envisioned by many.

We see this work as foundational, and at this point it is raising many new interesting, but probably difficult, questions. We need to complete the integration of XML Schema into our model. When the OWL ontology language has been designed we need to modify SWOL to be as close as possible to it.

On the querying side, we believe both XML and RDF users could benefit from the proposed framework and we intend to explore that in more depth. Notably, it is not clear to us whether it would be more suitable to query the Yin/Yang Web by extending an XML Query language such as XQuery, by extending an RDF query language, such as RQL, or by designing a unified language that would provide some features of both.

Other extensions to our scheme are also possible, potentially leading to a unified semantics for the entire Semantic Web layer cake. As our model theory is somewhat different from the standard logical model theories, some work will be required create a compatible model theory for logics like first-order logic.

Even though we have only made a beginning, we believe that the Yin/Yang Web is an important step in the process of truely building the foundations of the Semantic Web. We have created a semantic framework for all of XML. This framework also applies to RDF, with the exception of some of its problematic features, resulting in a true integration between XML and RDF. Our scheme also integrates XML Schema, providing a very general integration between XML Schema datatypes and RDF, and extends at least to the ontology level of the Semantic Web.

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