

An Ontology Mapping Approach to Integrating Earth Science Metadata

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Abstract

One of the main barriers to exploiting the great wealth of global earth science data available today is that researchers are unable to rapidly search and find data relevant to their studies. This data is spread across a large number of archives maintained by different institutions employing a bewildering array of different data description languages. In this paper, we describe a metadata federation approach designed to support queries across multiple earth science data archives without requiring adoption of a unified metadata standard. Our ontology-based approach employs a central metadata transformation facility capable of integrating heterogeneous metadata using a set of ‘translators’ and ‘wrappers’. This shifts the burden of federation from the data provider to the central metadata facility, acknowledging that not all data providers have the motivation or resources to comply with externally-imposed metadata standards. We demonstrate the feasibility of this approach with a proof-of-concept prototype that federates metadata across two earth science data archives – one containing NASA data and the other containing USDA data – despite the differences in their metadata languages.

Introduction

NASA’s earth science missions collect data that must often be used in combination with non-NASA data to answer complex science questions. Earth scientists must leverage data collected by NASA, as well as by other government agencies, public and private sector organizations, and foreign governments to accomplish their science objectives. One of the main barriers to using this great wealth of global earth science data effectively is that researchers are unable to rapidly search and find relevant data across multiple archives and different institutions. Each on-line archive has its own search mechanism and its own set of metadata keywords and values for describing stored datasets. As a result, finding data is a time-consuming exercise.

To address the problem of locating earth science data, NASA has developed the EOS Data Gateway [1] (EDG), which provides search services that range over all of NASA’s nine distributed active archive centers (DAACs) [2] containing NASA-funded data. Unfortunately, most

metadata federation schemes – including the scheme employed by the EDG – rely on the application of standards that place significant burdens on the data providers, who must modify their metadata management approach to be compliant. In particular, all of the DAACs are required to publish their metadata in a common format established by NASA. While it may be possible for NASA to mandate standards unilaterally for the projects it funds, this approach does not support integration with valuable non-NASA earth science datasets based upon on divergent metadata schemes.

In this paper, we describe a metadata federation approach that allows each data archive to publish its own metadata format without the burden of adopting an externally-imposed standard. This approach employs a central metadata transformation facility capable of integrating NASA metadata with metadata from external data sources using a set of ‘translators’ and ‘wrappers’. This shifts the burden of federation from the data provider to the central metadata facility, acknowledging that not all providers of useful data have the motivation or resources to comply with NASA metadata standards.

As a proof-of-concept, we are applying this approach to federate metadata from NASA’s Biogeochemical Dynamics data archive (BGC-DAAC) with metadata describing the USDA’s STEWARDS watershed data archive. The BGC-DAAC [3] holds most of the NASA’s terrestrial field experimental data, constituting 20% of all EOS products. The USDA’s Agricultural Research Service (ARS) has been collecting soil, water quality, and climate data in benchmark watersheds for almost a century, and has recently built the STEWARDS archive to hold the data [4]. The STEWARDS data is valuable to NASA researchers who can use the data to validate biogeochemical models and remote sensing observations; the NASA BGC-DAAC data is valuable to USDA researchers who require additional water and land cover data to improve the fidelity of their conservation effects assessment models.

Metadata Integration Framework

The challenge of metadata integration across multiple sources is to provide a scalable, maintainable approach without requiring data providers to alter their metadata curation or publishing methods. Our SemanticIntegrator framework [5] uses semantic integration techniques [6] to federate across a distributed set of data archives. SemanticIntegrator was initially designed to integrate various heterogeneous sources of planetary exploration data, including field-collected geology data, satellite imagery, GIS data, and physical/optical properties of minerals. To support integration, the framework requires that an ontology be developed to describe the metadata for each of the source data archives (SDAs) to be integrated. In addition, an overarching ontology must be developed that incorporates a comprehensive set of metadata distinctions found across the various sources. Conceptually, this ontology specifies a *virtual* data archive (VDA) that unites metadata across all of the SDAs.

Each data archive ontology consists of:

- a set of entities pertinent to the archives (e.g., *fieldSites*, *instruments*, *measurements*, *PIs*, *dataGranules*, *projects*);
- a set of attributes defined for each archive entity (e.g., *sensorType*, *collectionDate*, *collectionMethod*, *dataUnits*, *PIcontactInformation*);
- a set of semantic relationships that establish cross-linkages among the archive entities (e.g., *PI leads project*, *measurement collectedBy instrument*, *measurement collectedAt fieldSite*); and
- a set of logical axioms that allow for specific forms of automated reasoning, classification, and constraint maintenance over the archive entities, attributes, and relationships (e.g., “*all fieldSites are dataCollectionSites*”, “*measurements must be collectedAt dataCollectionSites*”, “*only PIs can lead projects*”).

In essence, an ontology provides a vocabulary for describing data, constraints on data, and implications of the data.

The metadata languages defined for the VDA and the individual SDAs generally will be distinct, and will exhibit (potentially significant) differences. At a minimum, different terms (“dataset”, “collection”, “fileset”) will be used to express the same metadata concept in different archives. To accommodate these differences, translation will be necessary to pose the same query in a manner that is compatible with the different archives. We use the VDA ontology as a mediating language through which all queries must pass; a query can be posed using the metadata query language for a given SDA and then translated into the query languages for all other SDAs by passing through

the VDA. A set of translation rules specifies how to translate to and from the VDA language. These translation rules are interpreted and executed by a Data Source Mediator (DSM), the central module of SemanticIntegrator. Wrappers are created to receive translated ontology language queries and resolve these into actual queries appropriate to the native SDA query API (e.g., web services, HTTP request, database connectors, or other specialized APIs). A summary of this metadata integration framework is shown in Figure 1.

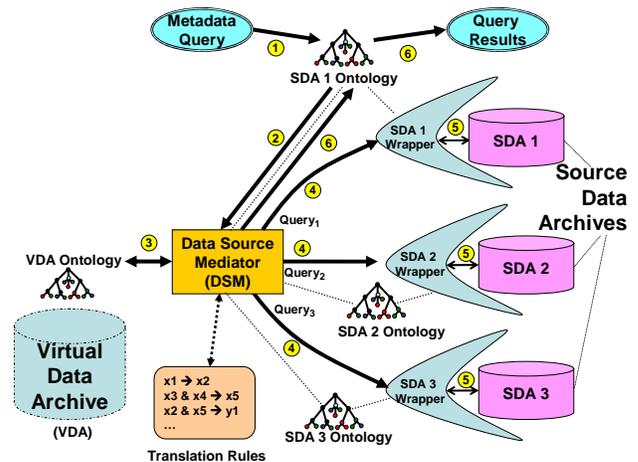


Figure 1 – Metadata Integration Framework: (1) Metadata query is issued using terms from SDA#1 ontology. (2) Query is transmitted to DSM, which uses translation rules to reformat query in terms of the VDA ontology (3). DSM translation rules next rewrite VDA query in terms of SDA#2 and SDA#3 ontologies, and queries for all three SDAs are sent to their respective wrappers (4). Finally wrappers query the SDAs archives to retrieve metadata (5) and transmit results back through DSM (6), which translates results back into the SDA#1 ontology language.

A key feature of this approach is that the individual SDA requires no modification to participate in federation by the VDA. All that is required is a means of programmatically querying the SDA. The wrapper, translation rules, and ontology can be developed in a manner independent of the SDA’s internal infrastructure and without the commitment of dedicated SDA resources and personnel, if none are available.

To simplify translation among the VDA and SDA metadata languages, they are each expressed in RDF [7], which will serve as a *lingua franca* for metadata interchange. RDF is a simple ontology language for expressing metadata relationships using triples of the form <subject predicate object>. For example, one might express the fact that a dataset contains temperature data collected in 1993 from Wilbur, Kansas in RDF as follows:

<dataset1 containsData tempData1> &
 <tempData1 measures temperature> &
 <tempData1 collectionYear 1993> &
 <tempData1 collectionPlace WilburKansas>

Application of Framework to Integrating USDA and NASA Metadata

In this section, we describe how the metadata integration framework can be applied to search metadata across two SDAs:

- **USDA/ARS STEWARDS:** The STEWARDS (Sustaining the Earth's Watersheds Agricultural Research Data System) archive [4] is being developed by a team of USDA ARS researchers to aggregate information on climate, water, and soil as well as on management and economic practices for 14 benchmark U.S. watersheds participating in the Conservation Effects Assessment Project (CEAP) [8]. Data for these watersheds have been collected from the early 20th century onward in varying formats. Each watershed measures, collects, and records data using differing procedures and employs slightly different terminology; this makes it very challenging to compare data across watersheds and generate meaningful analyses. The watershed data, which have never been centralized, are being collected and stored as part of the STEWARDS project to prepare the way for performing data integration and cross-watershed evaluations studies. The data and metadata are stored in relational database tables and are presented using ArcInfo [9], a web-based GIS interface.
- **NASA BGC-DAAC:** This archive, managed by the Oak Ridge National Laboratory (ORNL), is the primary source for NASA biogeochemical and ecological data and models useful in environmental research. Data held in the BGC-DAAC have been collected and archived from field observations, aircraft surveys, satellite collection, and from computer model output. These data are typically stored in investigator-supplied files that are maintained on the ORNL DAAC servers. The BGC-DAAC metadata is harvested from various descriptive files uploaded by science project personnel and stored in a relational database. The metadata, which is published in XML format [10], contain key information about the research, specific projects, sensors, parameters, time periods, site locations, and science terms associated with the data.

Applying the SemanticIntegrator framework to integrate metadata across these two archives involved the following steps:

1. Develop ontologies to represent the STEWARDS and BGC-DAAC archives.
2. Develop a cross-cutting ontology (the VDA Ontology) to serve as an interlingua for

transformations between the STEWARDS and BGC-DAAC archives.

3. Engineer a set of translation rules to convert statements (i.e., RDF triples) in the STEWARDS or BGC-DAAC ontologies into statements in the VDA ontology, and vice versa.
4. Implement wrappers to convert ontology queries expressed in terms of either the STEWARDS or BGC-DAAC ontologies into native metadata queries that can be posed against the actual archive metadata; a reverse wrapper must also be implemented to convert retrieved metadata results back into a set of RDF triples.

VDA Ontology

The VDA Ontology (Figure 2) captures common concepts that are important to describing both the STEWARDS and BGC-DAAC data. For this proof-of-concept demonstration, we generalized beyond the native metadata representations present in either STEWARDS or BGC-DAAC when designing the VDA Ontology, but we did not put a great deal of effort into creating an ontology that was very comprehensive or semantically principled. The VDA Ontology incorporates various types of scientific measurements, scientific units, spatial and temporal extents, geopolitical representations, and other concepts related to data collection and storage, including the social structures that support these activities. Although we did not base the VDA Ontology on any existing ontologies, incorporation of concepts from SWEET [11] would be a logical option to consider going forward.



Figure 2 – Virtual Data Archive (VDA) Ontology

BGC-DAAC Ontology

We derived the BGC-DAAC Ontology (Figure 3) directly from the metadata language used by ORNL to describe the data. We hand-coded the ontology, including only concepts, attributes, and relations directly analogous to the XML elements specified in the BGC-DAAC metadata language. (The metadata language specification was supplied to us by ORNL, and is based on metadata standards published by the Federal Geographic Data Committee (FGDC) [12].) The ontology incorporates project and contact information, keywords that cover the general nature of the scientific measurements collected, information about where and when the data were collected, citations to publications describing the data collection activity, and other information (See Figure 3).

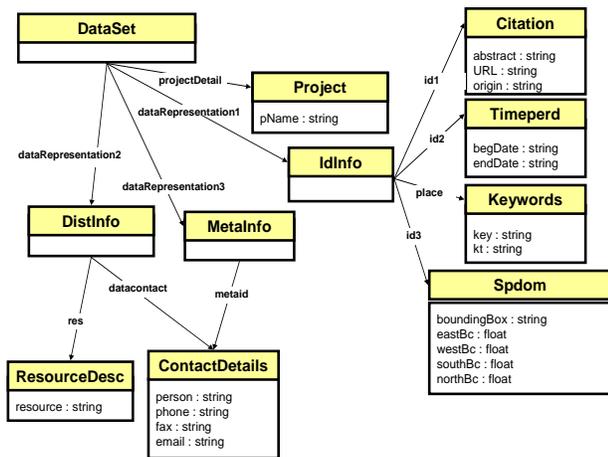


Figure 3 – Ontology for BGC-DAAC Data Archive

STEWARDS Ontology

Unlike the BGC-DAAC archives, STEWARDS was not designed to incorporate a distinct metadata language. Both its metadata and data are being stored in tables within a relational database. These tables will eventually hold information covering 14 water sheds over a 20-year timespan. The STEWARDS metadata is much more fine-grained than the BGC-DAAC metadata, and includes comprehensive descriptions of all measurements as well the data collection methodology. To create the BGC-DAAC Ontology (Figure 4), we imported the relational database schema provided by the USDA into RDF using the Protégé DataMaster plugin [13]. The import procedure automatically converts relational database tables into classes and table columns into slots. (Columns that are foreign keys get converted into links between classes.)

Translation Rules

The mapping between SDA and VDA ontologies is performed via a set of ontology translation rules. These rules are executed by the Data Source Mediator (DSM – Figure 1), which utilizes the Jess rule engine [14] to support inferencing and query rewriting. The DSM also serves as a registry that maintains information about the different data archives being integrated. Translation rules are simple if-then rules, where each clause takes the form of an RDF triple. Following are two simple translation rules:

R1:
 if
 (?Project1 daac:pName ?Name1)
 then
 (?Project1 vda:projectName ?Name1)

R2:
 if
 (?Loc1 stewards:locationName ?Name2)
 then
 (?Loc1 vda:projectName ?Name2)

Each of these rules derives the value of the projectName property, which is defined in the VDA ontology. R1 infers this value from the pName property of a project instance in the BGC-DAAC ontology, whereas R2 infers the same property based on the locationName of a location instance in the STEWARDS ontology. These two rules highlight some differences in how data storage is conceptualized in these different archives. Although the BGC-DAAC archive includes the notion of a project, the STEWARDS archive does not. The closest to the ‘project’ concept in the STEWARDS archive is the notion of a watershed ‘location’. For each watershed location, there exist a number of field sites with associated datasets. Similarly, for each project in the BGC-DAAC,

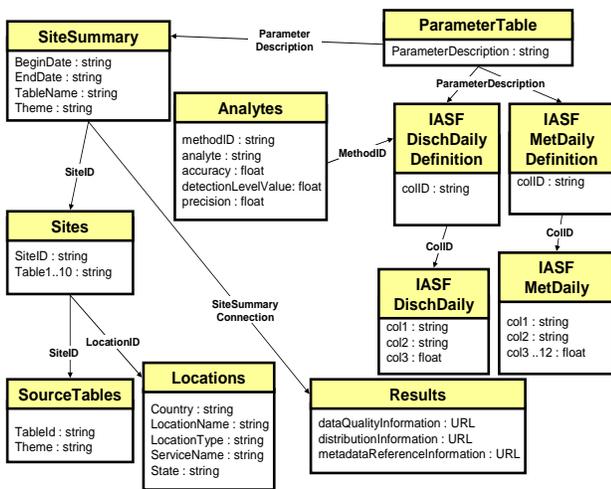


Figure 4 – Ontology for STEWARDS Data Archive

investigators carry out measurements at multiple sites, and multiple datasets are associated with each site.

Rules R1 and R2 are invoked via backchaining when the following query is issued:

```
Q1: (* vda:projectName *)
```

Q1 infers the vda:projectName property for all vda:ScientificProject instances based on the property values stored in the STEWARDS and BGC-DAAC archives.

As another illustration of the type of ontology translation rules necessary to support this earth science metadata integration task, consider rule R3 below. This rule creates measurement subclasses in the VDA ontology based on the science theme keywords assigned to datasets stored in the BGC-DAAC archive. For each keyword associated with a dataset, a corresponding subclass of measurement is inferred.

```
R3:
if
  (?Project1 daac:hasDataset ?Dataset1)
  (?Dataset1 daac:dataRepresentation1 ?Idinfo1)
  (?Idinfo1 daac:theme ?Keywords1)
  (?Keyword1 daac:kt ?key1)
then
  (?keyword1 rdfs:subClassOf vda:ScientificMeasurement)
```

Wrappers

For each source data archive, a separate wrapper is invoked by the DSM to satisfy metadata queries. These queries take the form of RDF triples with wildcards in either the subject or object position (cf. Q1 above). The wrapper translates ontology-based triple queries into native queries against the archives. The native queries may involve web service calls or other types of specialized API calls. ORNL is in the process of developing web services capable of providing access to BGC-DAAC metadata, and the USDA is planning to develop this capability. As these services are not yet functional, we obtained a portion of the metadata from both archives and stored it on our servers. The STEWARDS data were stored in a Microsoft Access database using a schema identical to the one STEWARDS uses for its data storage. The BGC-DAAC metadata were stored as XML files on our file server. We imported the metadata from STEWARDS and BGC-DAAC into separate Jena [15] repositories and built wrappers to query the metadata instances in those repositories. (Note: We used Jena as a matter of expediency, but our plan is to reimplement these wrappers so that they access the STEWARDS database and BGC-DAAC XML files directly, rather than through Jena. This would be a more in the spirit of the metadata integration framework pictured in Figure 1.) Eventually, when USDA and ORNL publish

their web services, the wrappers can be swapped out and replaced with new ones that access the actual metadata archives maintained by USDA and ORNL.

Query Interface

The query interface shown in Figure 5 allows the user to query both the STEWARDS and BGC-DAAC archive metadata using a unified interface. The user makes GUI selections to choose the archives to query, as well as the parameters, the spatial region of interest, and the time period. Upon clicking the “Display Datasets” button, the user is presented with a listing of datasets that meet these criteria along with metadata describing the datasets, including information about how to access the data.

What is significant about the interface lies behind the scenes. To populate the interface, the GUI backend formulates a series of STEWARDS ontology queries and forwards each to the DSM. The DSM transmits each query directly to the STEWARDS wrapper, which interrogates the STEWARDS archive and returns any matching results. The DSM also translates each STEWARDS query into a VDA ontology query and then into a BGC-DAAC ontology query. This query is passed to the BGC-DAAC wrapper, which interrogates the BGC-DAAC and returns matching results to be combined with the STEWARDS results. All necessary translations are encoded by rules within the DSM, so the USDA application developers are isolated from all details of interacting with the BGC-DAAC metadata language.

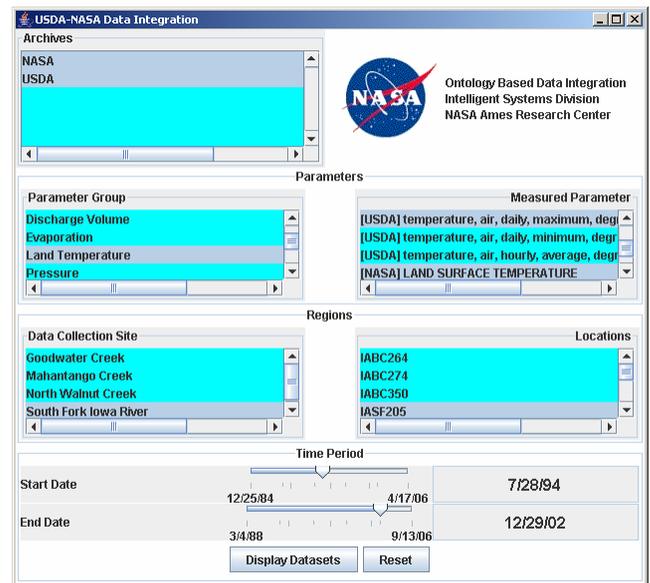


Figure 5 – Query interface

Conclusion

The scientific data collected during NASA's Earth observation missions and generated by NASA-sponsored earth science research are archived in different data archives across the country. Using metadata integration technology, we hope to enable NASA scientists to submit one query that searches across all NASA earth science data holdings, as well as key non-NASA data holdings – regardless of any differences in metadata standards employed. These benefits are symmetrical; scientists with access to non-NASA data should benefit similarly by improving their ability to query NASA's environmental holdings. This type of improved access to metadata can play a vital role by allowing scientists to discover new datasets to help them further their understanding of the Earth's environmental problems.

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