Metadata Management in Grid Database Federation

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Metadata management is a common issue in many types of information systems. In the field of integrating distributed database resources to build database federation, because of the heterogeneous nature of various database systems, the task of metadata management can be more complex than in a homogenous environment. The fast growing grid technology provides new approaches for database federation and brings new challenges for metadata management. This survey provides an in-depth view of past and on-going research on metadata management in the construction of grid-based database federation from 1998 to 2006. In this survey, we present our investigation of Metadata related standards, different metadata management solutions such as OGSA-DAI, Metadata Catalog (MCAT) and Metadata Catalog Service (MCS). We also put some emphasis on recent ontology-based metadata management approaches that allow knowledge-oriented data integration.

Categories and Subject Descriptors: A.1 [**Introductory and Survey**]: ; H.2.4 [**Databases Management**]: Systems; H.2.5 [**Heterogeneous Databases**]: On Combining the Knowledge of Heterogeneous Information Repositories; H.4.0 [**Information Systems Applications**]: General

General Terms: Metadata, Grid

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Contents

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1. INTRODUCTION

Metadata is information that describes data [Baru et al. 1998]. It is widely used by various systems components to provide wide-ranged support for process automation, user-machine interaction and decision support. A metadata management system is used to maintain the metadata and provide interfaces for other system components to access the metadata. In this survey, we investigate different metadata management strategies that could be used in federated database systems in grid environments. From the aspects of database federation and grid systems, they both have distinct requirements for metadata management. In the remaining of sections we will investigate these requirements based on previous surveys and existing technologies.

Because of the complexity of the problem, we believe that it is helpful to look at the metadata management problem from a more general point of view first, and then combine the heterogeneity characteristics brought by grid environments into our investigation. Standards are also very important when designing a complex system. Therefore we will present some studies of metadata standards and metadata related standards in grid community.

The rest of the survey is organized as follows: Section 2 covers the general discussion about metadata standards and scope of metadata management systems in Grid Database Federation. Section 3 covers different metadata management solutions in the Information Grid community. Section 4 reviews the investigated solutions and presents the existing gaps. Section 5 presents our conclusion. The References section lists the full bibliography and Appendix I contains all annotated bibliography of 24 selected papers.

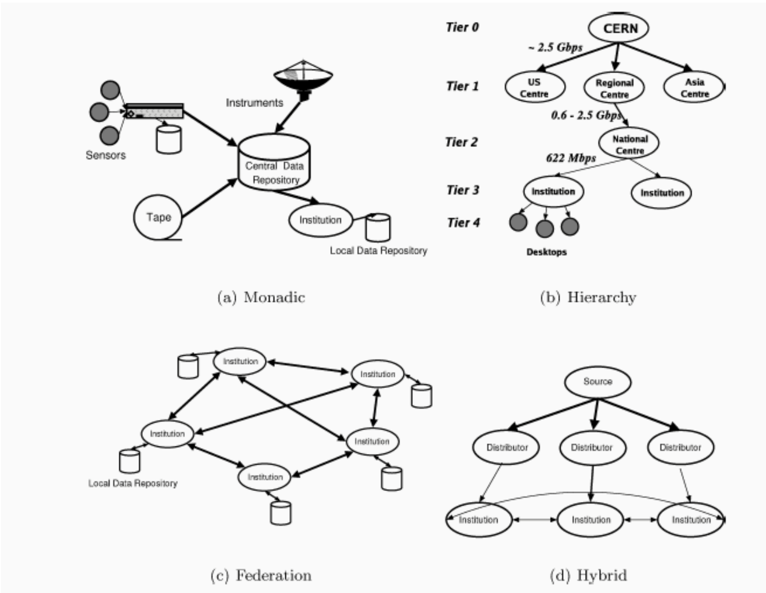
2. GENERAL DISCUSSION

2.1 Database Federation

The evolution of database federation has gone through a long history with the impetus of fast-evolving database and computer network technology. In 1990, Sheth and Larson presented a comprehensive research on the federated database system [Sheth and Larson 1990]. They state that a federated database system is a collection of cooperative database systems and has two distinct characteristics: 1) It contains autonomous and possibly heterogeneous component database systems that operate at lower end and provide support for specific application systems (legacy systems), 2) It has the availability to provide an integrated view that hides the heterogeneity of underlying database components at the upper end.

These characteristics require metadata management system to have the ability to generalize distributed and heterogeneous local database schema into a consistent global schema and allow the mapping between global schema and local database schema or between different local database schemas.

Database federation system can be either vender specific or non-vender specific. Example non-grid database federation systems include IBM Federated Database System [Haas et al. 2005] and Oracle 10g Federated Solution [ORACLE 2004].



(a) Monadic (b) Hierarchy

(c) Federation (d) Hybrid

Fig. 1. Possible Data Grid Models [Venugopal et al 2006, 16]

2.2 Information Grid

As stated in [Foster and Kesselman 2004], Grid technology allows the integration of distributed resources connected by a network to solve large-scale computation problems. Because of its ability to meet the requirement for resource sharing and problem solving in dynamic, multi-institutional virtual organizations, it is regarded as a natural approach for building general, cross platform, and non-vender specific solutions for database federation. Up to now, various attempts have been made to enable integrated data access over distributed multiple databases.

2.2.1 *Grid Taxonomy.* The term "Information Grid" came from the taxonomy of Data Grid and e-Science.

In [Venugopal et al. 2006], Venugopal et al present taxonomy of data grids. They claims that in contrast with Computational Grids, Data Grids primarily deal with providing services and infrastructure for distributed data-intensive applications that need to access, transfer, and modify massive datasets stored in distributed storage resources. In this paper, the authors classify Data Grid into four models: Monadic, Hierarchy, Federation and Hybrid [Figure 1], and claim that the Federation model is prevalent in Data Grids created by institutions that wish to share data in already existing databases. (From section 3.3.5 and 3.3.6 we could see that Hierarchy model can also been used in Grid Database Federation.)

Typical application of the Federation model are focused in database intense applications like the virtual observatory and bioinformatics, such as BioInformatics Research Network (BIRN) [2005] in the United States and e-Science program in UK [Fox and Walker 2003]. In UK e-Science program, this typical research field is called Information Grids.

In Information Grid community, metadata is also very important. Through summarizing the requirements of database federation and information grid, [Antonioletti et al. 2005] claims that grid-based database access is a metadata-driven access. To construct database federation under grid environment, rich set of metadata should be processed. The functionality of metadata management system should be extended by considering the requirement from both grid infrastructure and the inherited idiosyncrasy of database systems.

2.2.2 *Standards for Databases on the Grid.* To construct Grid Database Federation, It is very important to standardize the interfaces between the infrastructure, the managed resources and their consumers. The major activities of Global Grid Forum (now Open Grid Forum) are to produce documents describing best practices, technical specifications, user experiences, and implementation guidelines for distributed and grid computing environments. [Malaika et al. 2003]

Currently data-related groups in OGF are:

(1) DAIS-WG (Data Access and Integration Services Working Group), which is to produce the specification that describes a service-based interface for accessing and integrating data in existing relational and XML databases on the grid.
(2) OREP (OGSA Replication Services) group, which focuses on data replication technologies for the grid.
(3) DFDL (Data Format and Description Language) working group, which is to define the general language for describing and labeling the structure of data streams.

As to metadata management, Malaika et al claim that many standard activities are correlated with activities outside GGF, and states that current work are focused in defining and refining standards to: 1) Describe service data used by Data Resource Manager, 2) Describe database characteristics (data resources), 3) Describe representing relational database content, 4) Represent the query results in XML.

2.3 Metadata Management in General

Metadata Management has been widely discussed in different areas, such as data warehouse, digital library, education, scientific and business oriented area. In [Shaon 2005], the author summarizes these discussions and presents a comprehensive survey on metadata management from the aspect of metadata standards, metadata management systems, and potential collaborators. Some viewpoints of the author are listed as follows:

2.3.1 *Category of Metadata.* The author classifies metadata into three categories:

(1) Administrative Metadata, which provides information about the life-cycle of a digital object, and information regarding acquisition information, version control, archiving policy, audit trail, access rights, provenance, ownership and reproduction tracking etc.
(2) Descriptive Metadata, which is information about a digital resource, such as identifying information, intellectual entities, annotation details, keywords etc.

(3) Structural Metadata, which presents information in regards to the internal organization of a digital object and also include information on relationships among different components or sections of a complex digital object for the purposes of navigation.

2.3.2 *Metadata Storage.* The author claims that metadata can be stored along with the resource it describes or in separate location. The storage strategy depends on the type of metadata and its integrity requirement.

2.3.3 *Metadata Standards.* The author claims that various metadata standards can be classified based on whether they specify content, format or use. Commonly used metadata standards include:

(1) Dublin Code [DCMI], which provides a simple element set for describing a wide range of resources.
(2) LDAP Data Interchange Format [LDIF-RFC], which defines a data format used by Light Directory Access Protocol to describe directory structures and data objects.
(3) Resource Description Framework [RDF-W3C], which is a triple-based language (subject, predicates and objects) for representing metadata and constructing semantic data model.

2.3.4 *General Tasks of Metadata Management.* In [Ashfaq 2005], the author claims that the metadata management system should solve the following problems: 1) What data do we have? (data management, storage) 2) What does it mean? (description) 3) Where is it? (resource discovery) 4) How did it get there? (registration, data provenance) 5) How did I get it? (interoperability, authentication and rights management)

Additionally, [Shaon 2005] claims that long-term metadata curation, which includes quality assurance, auditing and versioning, are also important issues for metadata management.

2.4 Metadata Management in Grid Database Federation

2.4.1 *Heterogeneity.* As to Grid Based Federated Database systems, one major goal of metadata management system is to handle the heterogeneity and allow interoperability between different grid members by providing the degree of transparency to users who access the information. Heterogeneity exists at different levels in a distributed system. In [Koutrika 2005], the author identifies four different types of heterogeneity in the case of data sources within digital libraries. These types heterogeneity applies to all kinds of grid systems.

(1) System heterogeneity arises from different hardware platforms and operating systems.
(2) Syntactic heterogeneity arises from the presence of different protocols and encodings used with the system.
(3) Structural heterogeneity originates from the data organized according to different models and schemas.

(4) Semantic heterogeneity originates from different meanings given to the same data, especially because of the use of different metadata schemas for categorizing the data.

2.4.2 *Service Oriented Architecture.* As [Foster and Kesselman 2004] stated, Service Oriented Architecture is considered an important solution for interpretability and to solve the problem of the high degree of heterogeneity. In the past several years, Grid technology is under rapidly progressing of maturation and standardization around the banner of the Open Grid Services Architecture. OGSA builds upon standard web services and extending its power by introducing transient, stateful service instances (Grid Service). It allows maximum interoperability between different system components. Within OGSA, including metadata management, everything is represented as a Grid Service.

[Fox and Walker 2003] presents the following scenario of a service-oriented grid system: A service might contain metadata that describes its capabilities, interfaces, provenance, performance, security and access policies, and the metadata could be distributed at all levels of the Grid. A service could also publish its metadata to metadata repositories that can then be queried to discover resources and services that have specified characteristics. As to the task of metadata services, the author claims that metadata services are divided in registry, information aggregation, metadata (Semantic Grid), curation and provenance areas.

2.4.3 *Semantic Grid.* Both [Fox and Walker 2003] and [Foster and Kesselman 2004] emphasis the importance of introducing knowledge service into metadata management in order to give machines the capability to make well-informed decisions about data and processes based on logical inferences. Semantic Grid is a term used to describe a metadata-rich environment for grid computing. The integration of grid and semantic web meta-data and ontology technologies has been considered as a major trend in metadata management.

3. SURVEY OF RESEARCH

3.1 Basic Middleware Components

3.1.1 *Open Grid Service Architecture - Data Access and Integration.* OGSA-DAI is a project started from February 2002 and supported by the UK e-Science Core Program [Fox and Walker 2003]. It provides OGSA standardized interfaces to access both relational databases and XML databases.

In [Atkinson et al. 2003], the authors present a formal specification of hierarchy and functionalities of a Grid Data Access and Integration middleware within the context under DAIS-WG of GGF. The authors state the need of middleware toolkit for integrating database systems into grid. As to metadata, the author claims that four types of Metadata are important for the development of Grid data access and integration services: Technical metadata, Contextual metadata, Derived metadata and Mapping metadata.

A more comprehensive presentation of the OGSA-DAI middleware toolkit is presented in [Antonioletti et al. 2005]. In this paper, the authors states that the toolkit has the following features that meets the requirements from both grid and database community:

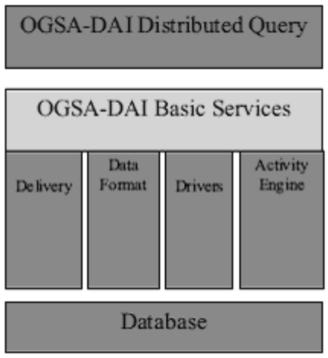


Fig. 2. Architecture of OGSA-DAI Product Family [Antonioletti et al 2005, 366]

(1) Data access is deployed as OGSA standardized service called Grid Data Service, a service can invoke underlying functional components defined as activities.
(2) Compatible with the grid security interface.
(3) Providing metadata activity to access the database schema in both static and dynamic manner.
(4) Providing functionalities to maintain the sessions for the communication with different databases.
(5) Providing support for using document-based request to specify a collection of activities and coordinating the delivery of result data over the grid via Grid Data Service.

The architecture of OGSA-DAI is shown as [Figure 2]. The authors claim that the OGSA-DAI project has become the de facto standard for grid based database interaction and is helpful to extend the functionalities of other data grids. The authors also introduce OGSA-DQP toolkit that builds on top of OGSA-DAI to provide database schema integration and distributed database query service. Both OGSA-DAI and OGSA-DQP has been widely used to build many grid higher-level Grid data management systems, such as SRB or Chimera.

Further enhancements of this middleware are stated in [Atkinson et al. 2003], which include sessions, transactions, distributed query performances, configurability of data services etc. [Fox and Walker 2003] also claims that metadata services will probably be implemented as optimized OGSA-DAI database services.

3.1.2 *Universal Description, Discovery, and Integration (UDDI).* Universal Description Discovery & Integration is an OASIS standard that currently evolved to its 3.0.2 version. As [UDDI2004 2004] claimed, the focus of UDDI is the definition of a set of services supporting the description and discovery of 1) businesses, organizations, and other Web services providers; 2) available web services, and 3) the technical interfaces which may be used to access those services. UDDI is based on a common set of industry standards, including HTTP, XML, XML Schema, and SOAP, it provides an interoperable, foundational infrastructure for a web services-based software environment for both publicly available services and services only exposed internally within an organization.

3.1.3 *Monitoring and Discovery System (MDS).* As [Foster 2005] stated, the Monitoring and Discovery System (MDS) is a suite of web services to monitor and discover resources and services for Globus Toolkit. It allows users to discover what resources are considered part of a Virtual Organization (VO) and to monitor those resources. "MDS services provide query and subscription interfaces to arbitrarily detailed resource data and a trigger interface that can be configured to take action when pre-configured trouble conditions are met". Current version of MDS-4 is provided with the Globus Toolkit 4. It provides the following functionalities: 1) query WSRF services for resource property information, 2) execute a program to acquire data, and 3) interface with third-party monitoring systems.

3.1.4 *Summary.* From section 3.1.1 to 3.1.3, we investigated existing grid data access and integration middleware OGSA-DAI and two ways for service registration and discovery - UDDI and MDS. The OGSA-DAI and DQP middleware has been widely used in grid based database integration. These tools can provide basic support for managing metadata repositories while major gaps on sessions, transactions, distributed query performances, and configurability of data services etc are still need to be fulfilled.

A criticism about UDDI and MDS is that they can store essentially no useful semantic information about the grid or web services and so it is very hard to ensure that one is choosing a service with both the correct functionality and with matching interfaces [Fox and Walker 2003].

From upper summary, one can see that it is not enough to construct a metadata management system by simply using the upper middleware and toolkits. For a Grid Database Federation system, it is essential to allow automatic service discovery and assembly. Further development includes enhancing these tools to allow knowledge representation and intelligent search by introducing ontology support. For example, in [Mirza and Kojima 2006], we can see the progress that extends existing MDS service by using semantic information for automatic service discovery.

3.2 Existing Metadata Catalogue Systems

3.2.1 *Metadata Catalogue (MCAT).* The Metadata Catalogue (MCAT) is a metadata management system that provides service APIs for managing both descriptive and system metadata of San Diego Supercomputer Center (SDSC) Storage Resource Broker (SRB) system.

The system is first presented by [Baru et al. 1998]. The Storage Resource Broker middleware is used in National Partnership for Advanced Computational Infrastructure (NPACI) project funded by the NSF to integrate heterogeneous storage systems such as relational database systems and file systems. In this paper, the authors claims that MCAT is used to maintain two kinds of metadata: 1) System metadata which provides location and access control information, 2) Descriptive metadata which describes the contents of entire data collections and/or individual data items.

The MCAT catalog is implemented in relational database and can be used under three usage scenarios: local resource, federated servers and SRB agents. MCAT provides a set of client APIs for accessing/updating metadata and data resources

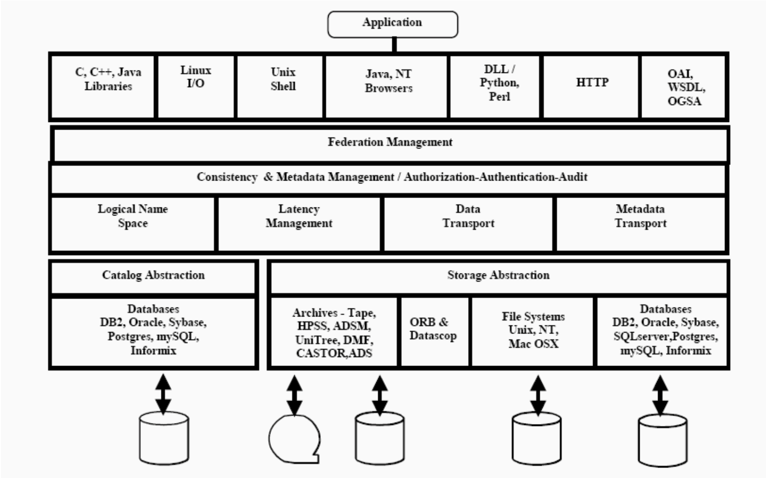


Fig. 3. Architecture of Storage Resource Broker [Venugopal et al 2006, 16]

of SRB system. A generic framework is used to support various types of storage resources and OS platforms.

In [Rajasekar et al. 2002], a MySRB system is presented that extends SRB system by introducing a web-based interface to it is presented. From the aspect of metadata management, MySRB "provides a very rich set of operations for creating, maintaining, viewing and searching different types of metadata for SRB objects as well as collections". For MySRB, metadata is classified as 1) system-defined metadata, 2) user-defined metadata, 3) type-oriented (domain-oriented) metadata, 4) file-based metadata, and 5) annotations and commentary metadata. The metadata is stored in MCAT and can be used to generate query user interface in an ad-hoc manner.

[Rajasekar et al. 2003] demonstrates the use of the combination of SRB and its metadata management system MCAT in mass storage as Grid Bricks. The author claims that Grid Bricks provide an attractive cost effective storage environment for persistent access to large collections to support the picking of individual digital entities.

In [Rajasekar et al. 2004] and [Moore et al. 2004], SRB and MCAT has become more sophisticated to support federated environment. [Figure 3] shows the recent architecture of SRB/MCAT. From the federated metadata management point of view, the authors introduced 10 models used in data grid federation and claim that these models are based on three generic federation models - Peer-to-peer federation model, Replication federation model and Hierarchical federation model and currently the federated SRB - zoneSRB has implemented all these models.

[Venugopal et al. 2006] has analyzed these federation models in their survey which provides a taxonomy of data grid systems and claims that the criteria of selecting from these models is based on the degree of autonomy of each site, constraints on cross-registration of users, degree of replication of data, and degree of synchronization. [Antonioletti et al. 2005] also claims that the SRB system could

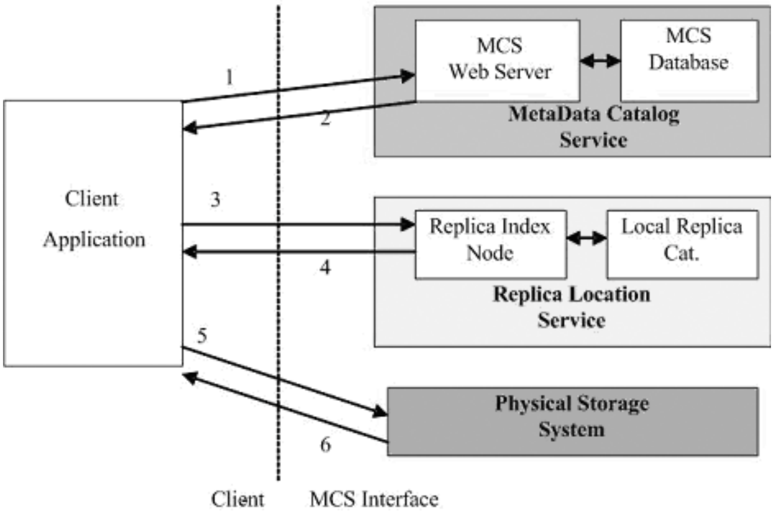


Fig. 4. Architecture of Metadata Catalog Service [Singh et al 2003, 4]

use OGSA-DAI middleware either to access structured data resources, or to provide access to the metadata from MCAT.

3.2.2 *Metadata Catalog Service (MCS).* Metadata Catalog Service (MCS) is a metadata catalog service that stores descriptive information (metadata) about logical data items. It has been developed as part of the Grid Physics Network (GriPhyN) and US National Virtual Observatory (NVO) projects and has been used in many other projects such as the Earth System Grid (ESG) project, the Laser Interferometer Gravitational-Wave Observatory (LIGO) project and the workflow mapping system Pegasus. The aim of these projects is to support large-scale scientific experiments. MCS is a standalone catalog that stores information about logical data items (e.g., files).

In [Singh et al. 2003], the author claims that the MCS is a grid based metadata service (web service) provider that has the following features: 1) Separates the logical metadata service from services for physical storage metadata or replica metadata, 2) Provides a general metadata schema. 3) Provide extensions for user-defined metadata attributes that could be used to support application-specific metadata ontologies, 4) Provide API for storing and querying metadata.

[Figure 4] displays a usage scenario of MCS:

(1) The client application queries the MCS based on some attributes of the desired data.
(2) The MCS returns the logical file names of one or more data items corresponding to those attributes.
(3) The client application next queries the Replica Location Service with the logical file names.
(4) The RLS returns the physical file names of the requested files to the client

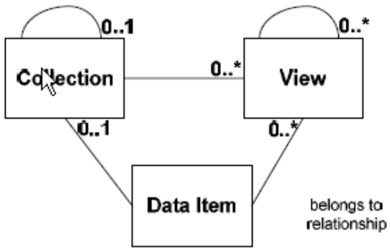


Fig. 5. Data Model For MCS [Deelman et al 2004, 4]

application.

(5) The client application then contacts the physical storage system where the file resides.

(6) The file is returned by the physical storage system.

The authors state that their work is induced from their previous work [Chervenak et al. 2002] that is a Replica Location Service that exclusively contains metadata information related to data replication, and also borrowed ideas from MCAT Metadata Catalog of the Storage Resource Broker (SRB) [see section 3.2.1]. The authors claim that Metadata Catalog Service differs from MCAT significantly in the architectural model. MCAT is implemented in tight integration with other components of SRB and cannot be used as a stand-alone component. MCAT stores logical metadata and physical metadata as well as attributes that describe resources, users and methods, while MCS is one component in a layered Grid architecture. It contains only logical metadata attributes. The authors also claims MCS is similar in its design and function to RepMec (Replica Metadata) catalog [Guy et al. 2002] developed by the European DataGrid's Reptor project.

In [Deelman et al. 2004], the authors present a new implementation of MCS that is based on OGSA-DAI middleware. The adoption of OGSA standards gives MCS the scalability to integrate with other grid services, sharing the same service discovery mechanism and security and support the federation of multiple databases.

The authors address more concern of using MCS from 1) the need to store and share the metadata, 2) the need to organize the metadata in a logical fashion for ease of publication and discovery, 3) the need to customize the view of the data by individuals, and 4) the need to support metadata about large-scale data set, and present the discussion on the data model, user model, authorization policies, schema flexibility and metadata interface. The data model of MCS is shown as [Figure 5].

The Data Item is the basic object within MCS. A collection is defined by a collaboration to aggregate a set of data items or other collections and provide convenient access with a single name. A view allows data items and collections to be organized by members of the collaboration into groups that are relevant to them.

The authors state that their future work is to extend the centralized metadata service to distributed service in order to provide better performance and scalability, and to use query mediation and planning techniques combined with ontology-based attribute models to query across multiple MCS instances. In this direction, [Cai et al. 2004] has introduced a Peer-to-Peer RDF Repository for Distributed Metadata Management.

3.2.3 *MagCat.* As stated in [Sousa et al. 2006], MagCat is a metadata service, developed in the context of the MAG (Mobile Agents Technology for Grid Computing Environments) grid middleware. It is currently being developed at the Computer Science Department of the Federal University of Maranhao, Brazil. The authors states that their system has the following contributions: 1) an extensible metadata schema that is domain-independent, 2) a language used for accomplishing data publication and discovery, 3) a well defined ontology for a metadata service, 4) an independence of the storage system used to keep the metadata, 5) a data model based on files that allows the grouping of data in collections and views, 6) allows metadata to be managed in distributed way.

The author claims that some of their ideas are come from MCS [see section 3.2.2]. The data model is similar to MCS's data model. The authors state that current MagCat implementation consists of the CatalogManager, SchemaManager, and DataManager agents, which provide the basic functionalities for publishing and discovering metadata, and schema extensibility. It also uses LDAP for features such as distribution, replication, synchronization, and security.

In this paper, the authors also present their comparison between MagCAT and other metadata management systems - MCS and MCAT. They claim that MagCat differs significantly from MCS [Singh et al. 2003] regarding its architecture and development paradigm, which includes:

(1) MCS provides a central metadata service, MagCat inherits the intrinsic LDAP distributed architecture, and deals with replica management and synchronization.
(2) MagCat was developed based on an agent paradigm while MCS is based on web service model.
(3) MCS uses a relational database system to store its metadata, while MagCat is independent of storage system.

As compared with MCAT [Baru et al. 1998], MagCat is independent of grid Middleware.

Future work stated by the authors include to integrate the access to the Open Grid Service Architecture Data Access Integration (OGSA-DAI) into the DataManager agent and to investigate the use of agent mobility heuristics in order to reduce the cost of data transfer in the grid and to realize of evaluating performance the architecture.

3.2.4 *Summary.* From Section 3.2.1 to 3.2.3, all the above mentioned metadata management systems are designed for integrating distributed data sources lies in heterogeneity of data structures, institutional policies, discovery and replication. We summarize the comparison of these three metadata catalogue systems as [Table I].

From the view of building Grid Database Federation, These metadata catalogue systems can be used for metadata management. However, these systems are mostly

Table I. Comparison of three metadata catalogue systems

	MCAT	MCS	MagCat
Architecture	Client API	Service oriented	Agent based
Metadata storage	Relational Database	Relational Database	Flexible
Metadata distribution support	Distributed	Centralized	Distributed
Data described	File and Database	File	File
Coupling with host system	Tight	Loose	Loose
Performance	Not mentioned	Need improve	Not mentioned
OGSA support	In plan	Yes	In plan

taking care of file based data rather than database systems. They do not provide much support on relational database schema mapping and generate global schema for database federation. Therefore, new approaches of metadata management need to be incorporated to meet this requirement.

3.3 Semantic Rich Metadata Management systems

As mentioned in [section 2.1], the construction of Grid Database Federation requires metadata management system to be able to generalize distributed and heterogeneous local database schema into a consistent global schema, generate maps between different schemas and manage the semantic correlation on items have the same semantic meaning. This requires intensely use of schema transforming technologies and semantic web technologies. In the following survey we will investigate different approaches in this area.

3.3.1 *Schema Federation of Distributed Databases.* Schema matching problem is to find correspondences between elements of two database schemas. It can be used in Federated Database systems to generate distributed query automatically. In [Do and Rahm 2002], a schema matching system called COMA has been presented and it has the following features: 1) supports simple and hybrid match algorithms to find similar correspondent elements, 2) supports both automatic and interactive match finding, 3) able to reuse previous matches.

The author also provides a three-step procedure to calculate combined similarity by combining results from different matching methods: Aggregation (generate similarity matrix), match selection and calculate combined similarity.

The author defines a set of indexes to evaluate the matching results, and states that the innovated matching reuse approach does improves the matching precision.

Inspired by COMA system, [Bernstein et al. 2004] also present a schema matching system called Protoplasm (a PROTOtype PLAtform for Schema Matching). The authors claim that their work overcomes the fragility problem of existing schema matching algorithms by enforcing industrial-strength and the ability of customization. Important contribution of this project include: 1) defined Schema Matching Model Graph (SMM Graph) as the internal representation of input schemas, which is implemented using XML, 2) defined Graph Document Object Model (GDOM) for navigating the SMM Graph, 3) defined XGPath to query the SMM model, 4) using Similarity Matrix to hold the degree of similarity between items (nodes and/or edges) of two SMM graphs, 4) declared a set of extensible operator interfaces to

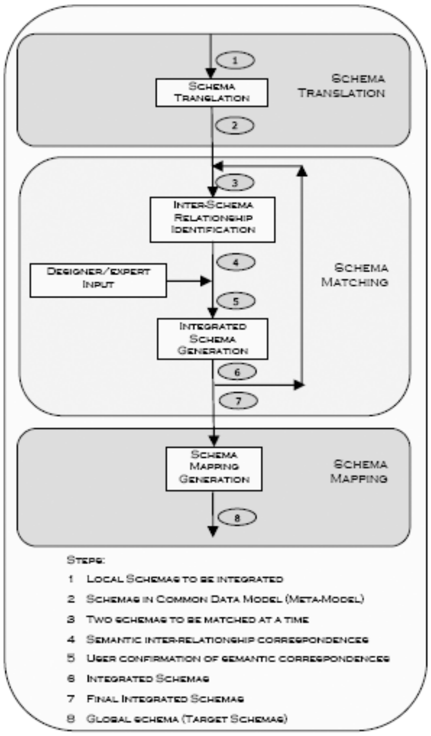


Fig. 6. Architecture of Schema Federation [Al-Hussaini et al 2005, 4]

carry out individual schema matching tasks, 5) a strategy mechanism has been provided to define a control flow of operators for a matching process.

The authors claim that they have used various approaches to optimize calculation and memory usage overhead for the matching algorithms, and state that further works include more effort to enhance mapping reusability, including more features such as Natural language processing, Machine learning, data mining etc and more flexible and friendly user interface.

Inspired by both COMA and Protoplasm project, and awaring the scalability problem of these systems, [Al-Hussaini et al. 2005] present a Service-based Approach to Schema Federation (SASF, Figure 6) to integrate heterogeneous database schemes and use it to support query generation in a federated database system. The authors address the difficulty of schema federation lies in the requirement of maintaining a consistent view of global schema over the distributed and autonomously managed source schemas. To solve the problem of schema matching problem in distributed environment, the authors designed three services: Schema Transaction which translates source schema into common data model; Schema Matching which finds semantic correspondences between two sets of schema elements and generate integrated schema, using either manual or automatic approaches; Schema Mapping which maps the integrated schema elements to their original data sources. Corresponding these three modules, three services have been implemented and the whole

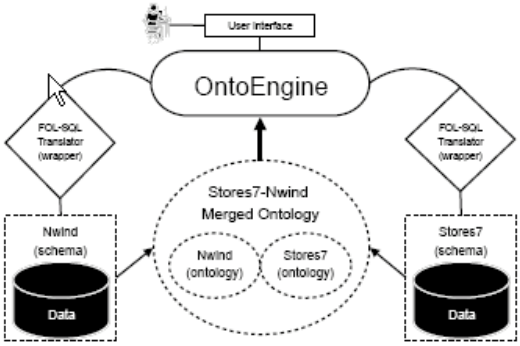


Fig. 7. Architecture of OntoGate [Dou and LePendu 2006, 464]

framework is able to work on top of OGSA-DQP [Section 3.1.1].

The authors claim that compared with other schema matching methods, the SASF presented approach solves some of the long-standing issues in schema matching by using both schema-level and instance-level information to discover semantic correspondences. Besides this, user feedback is also used to ensure schema matching to its maximum precision. The schema matching approach can discover all cardinalities of relationships, i.e. 1:1, 1:n, n:1 and n:m.

The authors state that schema matching on all attributes will be a time-consuming task. The advantage of SASF is it enables user to choose subsets of interested attributes to confine the scale of schema matching. Hence the cost could be dramatically reduced.

Future work mentioned in this paper includes making SASF adaptable to evolving source schema and reducing the cost for re-generation of global schema. The authors mention that further effort is to reduce the cost of re-generation is to solve the redundancy brought by redundant attributes.

3.3.2 *OntoGrate: Ontology-based Databases Integration using Schema Mapping.* In [Dou and LePendu 2006], the authors present a way to solve the schema mapping and data integration problem when integrating autonomous database systems. They claim that they have developed an ontology-based, first order logic approach to integrate heterogeneous relational databases, which is called inferential data integration. The system is called OntoGrate system [Figure 7]. In this project, the author introduces Web-PDDL [`http://marzapan.cs.uoregon.edu/web-pddl.pdf`] ontology language to represent the database definition and inference axioms between different database schemas. Two components have been constructed, the SQL wrapper can be used to translate Web-PDDL script into SQL query and translate SQL record set into Web-PDDL facts; the OntoEngine maps Web-PDDL based database schema of one database into the form of another database using first-order logic.

According to the paper, experiment shows that the system demonstrates adequate performance for query answering however the performance of data translation is still need to be improved.

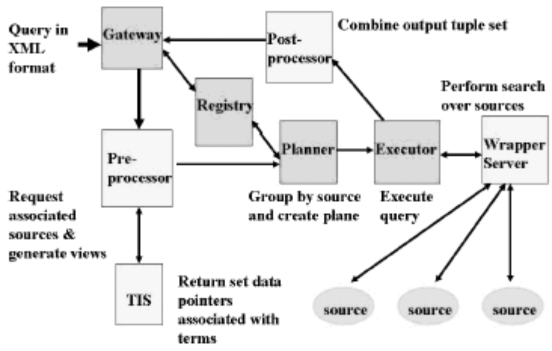


Fig. 8. Architecture of the mediator [Astakhov et al 2006, 3]

Stated future work includes testing OntoGrate system against biomedical databases, extending OntoGrate to integrate databases, XML files and Semantic Web resources, and continue to improve the performance of data translation.

3.3.3 *Semantic Mediator used in BIRN.* Biomedical Informatics Research Network (BIRN `http://www.nbirn.net`) is a multi-institutional bioinformatics network which contains distributed heterogeneous data sources. To integrate these data sources, [Astakhov et al. 2005],[Astakhov et al. 2006] present a data integration mediation system [Figure 8]. Through this framework, one could "Query Through an Ontology" without regarding the heterogeneity of distributed data sources. The framework is composed by the following components: 1) semantic components include Ontology (which is a term-graph having nodes represents domain-specific vocabulary and edges represents relations), 2) Term-index source (a database for mapping between data and ontology terms), 3) mapping relations (which provides integrated views over data sources) and 4) a XML based query language. The system uses the following parts: Gateway, Registry, Preprocessor, Planner, Executor, Wrapper Services and Postprocessor to process a submitted XML query, generate query plan automatically, submit executable plans to different sources via wrapper services and translate the result into unified format. The authors claim that the performance is acceptable.

Future work includes introducing reasoning and explanation by developing a Graph Query Engine and expanding the mediator to support handle spatial data related to image information.

3.3.4 *OnBrowser.* In [Cannataro et al. 2005], the authors state the problem about the lack of approaches for integrating ontology management systems on the Grid (in which knowledge could be coded in different application domains), and present the design of an ontology manager - OnBrowser [Figure 9]. The prototype toolkit uses OWL as ontology language, uses Jena toolkit for ontology API support and uses RDQL as query language.

The authors claim that OnBrowser could provide the following supports: 1) Ontology life-cycle management, 2) Ontology query language, 3) Ontology reasoning and 4) Ontology browsing via user interface. In addition, the authors claim that

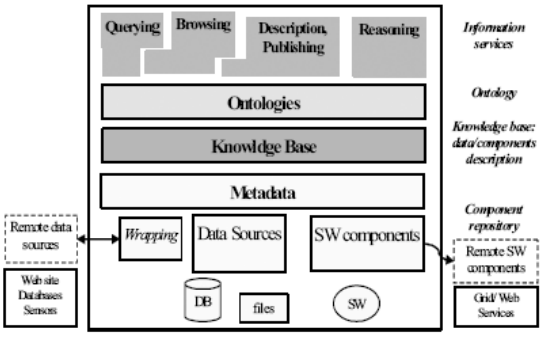


Fig. 9. Architecture of OnBrowser [Cannataro et al 2005, 2]

it could manage a distributed ontology setting through partitioning, replication, or hybrid approaches. In the end, the authors state that they have been applied OnBrowser to enhance application workflow formulation and editing in PROTEUS project, which is a Grid-based Problem Solving Environment for bioinformatics applications.

The authors state that OnBrowser is still in its partial implementation state. Further work is to fully implement its design and the goal is to allow the access through programming interfaces to knowledge objects stored in ontologies on the Grid.

3.3.5 *DartGrid.* DartGrid is a data integration toolkit using technology from semantic web and grid. It is a framework for constructing Ontology-based Database Virtual Organizations. The purpose of this toolkit is to overcome the difficulty of dynamic integrating distributed databases. This framework is developed by Zhejiang University of China and has been used to build VO for Traditional Chinese Medicine (TCM).

The toolkit was first introduced in 2004. In [Wu et al. 2004], the authors present an explicit definition of Ontology-based Database Virtual Organization and its proposed elements, and presented DartGrid that uses domain ontologies and webservice to organize distributed databases.

This author states that they have implemented the following web services and tools: 1) a semantic browser for user interaction, 2) a set of semantic services: Semantic Registry Service(SeRS), Data Semantic Service and Ontology Service, 3) Q3 and RDF based semantic query and Semantic Query Service (SeQS) that maps conceptual, semantic based query into local database query languages (SQL, XQuery etc). They claim that DartGrid significantly promotes the sharing and integration of database resources and greatly facilitates the cooperation in the preferable web mode.

The authors claim that their new approach is related to three different fields: knowledge-based query processing in distributed information system, semantic web query systems and Data Grid.

In [Chen et al. 2004] I, more details about Q3 and RDF semantic query engine are revealed, which includes Q3 query construction, query spreading, Q3 query to

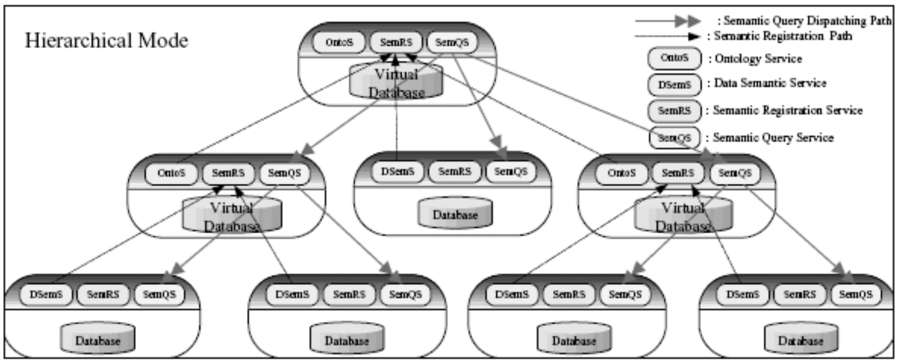


Fig. 10. Multi-tiered DartGrid Architecture [Chen et al 2004 II, 2]

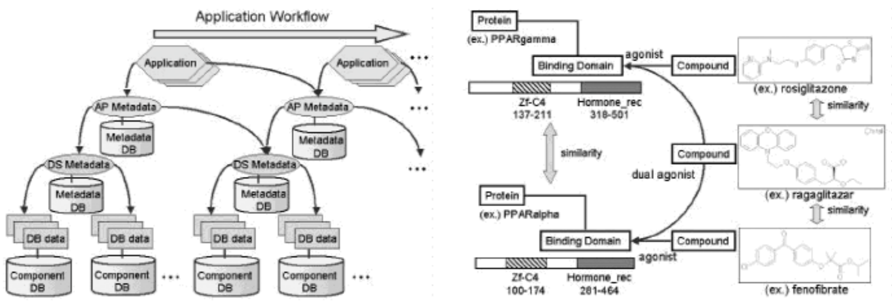


Fig. 11. Architecture of BioGrid [Nakamura 2004, 5]

SQL query rewriting and query result presentation.

In [Chen et al. 2004] II, the authors present the multi-tiered architecture of DartGrid [Figure 10], In DartGrid, a set of rules is defined to convert relation database schema (source data schema) into RDF/OWL ontology; a multi-tiered hierarchy is defined for database registration; semantic mapping policy is also used to map the lower-tiered schema (source data schema or mediated schema) into upper-tiered schema (mediated schema).

The authors state that there are still unsolved issues on mapping relational database schema into RDF/OWL semantic and lists three of them. 1) Redundancy among different database schemas, 2) Inconsistence between two database schemas, 3) Alternative ways to map n-ary (n>2) relation into RDF/OWL model.

3.3.6 *BioGrid - Metadata based Database Federation.* BioGrid is a project hold by Osaka University, Japan. The goal of this project is to build a Metadata-based database federation and to integrate distributed bio-databases that belong to different domains, and to produce a development platform where knowledge, techniques, and technologies regarding both IT and life science can easily converge so that bio-researchers and scientists can perform their analyses seamlessly.

The strategic view of this project was first presented by [Nakamura et al. 2004]. In this paper, Nakamura presents a hierarchical structured database federation model

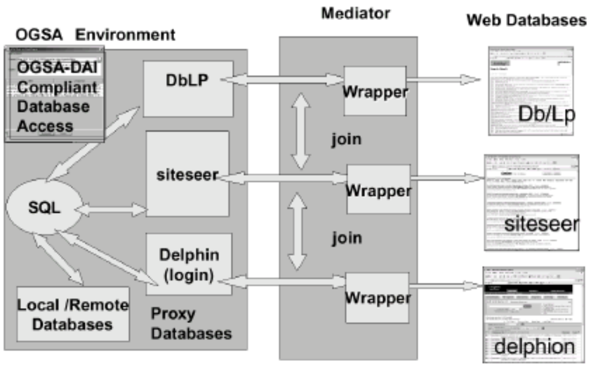


Fig. 12. Architecture of OGSA-WebDB [Kojima and Mirza 2004, 2]

[Figure 11] managed by multi-tied metadata repository. The metadata in this paper has been classified into two types: the Application-Metadata which plays a role for the mediation between applications and databases and Data Service Metadata which is used for hiding the heterogeneity of various records of biology-related databases. The author also presents a preliminary platform called BioPfuga, which could provide a schematic view of the Data Grid based on this metadata model.

Further architecture and implementation details are revealed in [Tohsato et al. 2005] and [Kitajima et al. 2004]. In [Tohsato et al. 2005], the author claims that they have ported the system to work in a practical Grid environment, using the Globus Toolkit 3 with OGSA-DAI in order to provide better scalability through standardization. In [Kitajima et al. 2004], the design of meta-databases for integrating database information on disease, proteins (drug targets) and ligands (lead compounds) has been presented, a workflow mechanism for drug identification is also implemented based on the metadata-based database federation.

3.3.7 *Database Grid.* The Database Grid project [DatabaseGrid] is a project of Grid Technology Research Center of AIST (National Institute of Advanced Industrial Science and Technology), Japan. The purpose of this project is to provide a uniform view for heterogeneous database resources in grid environment. This project has many subprojects:

In [Kojima 2006], the author presented the OGSA-DAI-RDF middleware that extends OGSA-DAI access to RDF database systems including Sesame and Jena. Several OGSA-DAI activities for handling RDF data and ontology are implemented. The middleware supports using SPARQL query language to query ontology-based metadata repository.

In [Pahlevi and Kojima 2004],[Kojima and Mirza 2004] and [Mirza and Kojima 2004], the authors present a project called OGSA-WebDB [Figure 12] that makes existing web database (WebDB) resources grid-ready. The goal of this project is to automate the query on different web databases by using a unified SQL interface. The middleware wraps the existing large amounts of heterogeneous web databases using SQL wrappers and OGSA-DAI. It enables grid applications to integrate data

Table II. Contribution of existing technologies in Grid Database Federation

Existing technologies	Basic grid services: Connectivity, Delivery etc	Metadata Repository	Schema Mapping	Distributed Query Processing	Schema Matching	Knowledge-Based Automatic Query Generation
OGSA-DAI	√					
OGSA-DQP			√	√		
UDDI	√					
MDS	√					
MCAT	√	√				
MCS	√	√				
MagCat	√	√				
COMA and Protoplasm			√		√	
SASF			√	√	√	
OntoGate			√	√		√
BIRN mediator			√	√		√
OnBrowser			?	?	?	√
OGSA-DAI-RDF	√	√				
OGSA-WebDB	√	√	√	√		
DartGrid (framework)	√	√	√	√	√	√
BioGrid (framework)	√	√	√	√	√	√

from local databases with data from web databases.

As mentioned by the authors, the system has three components: proxy database, mediator and wrappers. 1) the proxy databases are local databases that are used to delegate external web databases and store the extracted information from web DB, 2) the mediator converts SQL query into search conditions to the web databases, 3) the wrapper is used to convert the result data from various external web DBs into mediator recognizable format using schema mapping approach. The mediator could also use a simple dynamic query-processing scheme to join multiple web databases.

3.3.8 *Summary.* From section 3.3.1 to 3.3.6, one can see that various approaches have been used to allow distributed query processing and ontology based query. Major projects are focused on three areas: multi-database schema mediation, semantic web service and extending existing grid data access middleware. To construct a federated grid database system, these approaches can be integrated at different level. One can refer to [Table II] for contributions of existing technologies mentioned in above sections that can be used in Grid Database Federation.

From the upper approaches one can see that many approaches are using OGSA-

DAI and DQP to integrate heterogeneous distributed databases. This middleware provides OGSA standard based data integration hence we can expect that there will have more Grid Database Federation related projects be built on this basis.

4. CONCLUDING COMMENTS

In this survey we have reviewed the nature of federated databases, metadata standards and the status of the information grid community. We understand that grid technology provides a natural platform for constructing database federation. Due to the complex nature of database schema and the complex status of heterogeneity, the metadata management system is facing challenges from both grid infrastructure and the database systems.

Through reviewing the existing shortcomings of current Information Grids from the aspect of metadata management, we can see the trend of adopting the Service-Oriented Architecture to solve the heterogeneity problem, and using semantic web technology for representing data models and intelligent schema mediation. Next we identified several metadata related middleware that can be used in Grid Database Federation. And then reviewed several existing metadata catalogues used in grids. We put more focus on different approaches used in database schema mapping and ontology-based data mediation because these technologies are very important to integrate heterogeneous database schemas and allow distributed query processing. Finally we reviewed several existing grid database integration projects.

Through investigating existing grid-based data integration middleware, metadata catalogues and various projects, we can see that there is no single metadata management system that meets all of the requirements for building Grid-based Database Federations. The metadata management components of current complete Grid Database Federation frameworks all borrow concepts from different domains such as Service-Oriented Architecture, multi-database schema integration and the semantic web. We evaluated the contributions of different approaches that can be used by metadata management systems in Grid Database Federation. We can expect that more Grid Database Federation related projects will be built on the basis of standardized middleware such as the OGSA-DAI toolkit, and the use of semantic web technologies into this area will be a notable subject for continuing research.

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Metadata Management in Grid Database Federation

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Course: 60-510, Survey, Fall 2006

University of Windsor
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A. ANNOTATED BIBLIOGRAPHY

A.1 [Al-Hussaini et al 2005]

Ref. Al-Hussaini,Leena, Viglas,Stratis, Atkinson,Malcolm. 2005. A Service-based Approach to Schema Federation of Distributed Databases. *UK. Technical Report EES-2006-01.* National e-Science Center, University of Edinburgh, UK, School of Informatics, University of Edinburgh.

In this paper, the authors address the difficulty of schema federation lies in the requirement of maintaining a consistent view of global schema over the distributed and autonomously managed source schemas. The authors present a Service-based Approach to Schema Federation (SASF) to integrate heterogeneous database schemes and use it to support query generation in a federated database system.

The authors mention that their work is inspired by existing schema matching systems including COMA system [Do and Rahm 2002] and Protoplasm project [Bernstein et al. 2004] and stated the scalability problem of these systems. To solve the problem of schema matching in distributed environment, the authors designed three services: Schema Transaction which translates source schema into common data model; Schema Matching which finds semantic correspondences between two sets of schema elements and generate integrated schema, using either manual or automatic approaches; Schema Mapping which maps the integrated schema elements to their original data sources. Corresponding these three modules, three services have been implemented and the whole framework is able to work on top of OGSA-DQP.

The authors claim that compared with other schema matching methods, the SASF presented approach solves some of the long-standing issues in schema matching by using both schema-level and instance-level information to discover semantic correspondences. Besides this, user feedback is also used to ensure schema matching to its maximum precision. The schema matching approach can discover all cardinalities of relationships, i.e. 1:1, 1:n, n:1 and n:m.

The authors state that schema matching on all attributes will be a time-consuming task. The advantage of SASF is it enables user to choose subsets of interested attributes to confine the scale of schema matching. Hence the cost could be dramatically reduced.

Future work mentioned in this paper includes making SASF adaptable to evolving source schema and reducing the cost for re-generation of global schema. The authors mention that further effort is to reduce the cost of re-generation is to solve the redundancy brought by redundant attributes.

A.2 [Antonioletti et al 2005]

Ref. Antonioletti, M. et al 2005. Design and Implementation of Grid Database Services in OGSA-DAI. *Concurrency and Computation: Practice and Experience*, vol. 17, no. 2-4, 357-376.

In this paper, the authors address the requirements to integrate disperse database systems into grid environment. The authors claim that Grid-based database access is metadata-driven access. The metadata management system should have the ability to cope with rich set of metadata categories like the following:

(1) Data schema that describes data structure and content information for data discovery or interpretation.

(2) System and administrative information for management or scheduling.

(3) Indexes or summaries for resource or access method selection.

(4) Provenance data (the origin of data) for data selection or evaluation.

This paper provides a panorama review of a service-oriented middleware OGSA-DAI project and also discussed the requirements for a grid-enabled database federation. It discusses the following concerns: How to enable the facilities that already supported by contemporary DBMS in a grid environment; metadata representation, registration, query, auto-generation and evolving; distributed query processing.

The authors present that OGSA-DAI partially provides solutions for these issues by providing standardized interfaces to access both relational database and XML database, using the grid security interface; providing metadata service to access the database schema in both static and dynamic manner; providing functionalities to maintain the sessions for the communication with different databases and enabling using document-based request to specify a collection of activities and coordinating the delivery of result data over the grid via Grid Data Service.

The authors compare their design with previous works, including:

(1) JDBC drivers that to connect different databases from low-level.

(2) Oracle 9i has tried to invoke web services within SQL queries and define web services via stored procedure, but it is only Oracle specific.

(3) Spitfire project by European Data Grid that developed a web service interface to access relational databases for metadata management, which supports fine-grained operations (i.e. single query).

The authors claim that the OGSA-DAI project has become the de facto standard for grid based database interaction and is helpful to extend the functionalities of other data grids. According to the paper, OGSA-DAI and its distributed query supportive package OGSA-DQP has been widely used to build many grid higher-level Grid data management systems, such as SRB or Chimera. Further works mentioned in the paper include WSRF & WSI mapping and further development on OGSA-DQP.

Further discussions on OGSA-DAI architecture can be read from [Atkinson et al. 2005].

A.3 [Asthfaq 2005]

Ref. Ashfaq, Sadaf. 2005. Design and Analysis of a GIS DataGrid System with Generalized Metadata Schema. *University of Windsor, Ms.C. Thesis 2005*, A84.

In this paper, the author states that up to that time, very little research has been done in the area of metadata management for the DataGrid System and presents a comprehensive design of a GIS DataGrid system using state-of-art software engineering technologies. The design of a metadata management subsystem in this project is presented from the following aspects: 1) Category of metadata, 2) Existing grid metadata catalogues - Metadata Catelogue(MCAT) for SRB [Rajasekar et al. 2004][Moore et al. 2004] and Metadata Catalogue Service(MCS) [Singh et al. 2003] and 3) Metadata standards.

The author claims that a metadata management system is proposed to answer the following questions: 1) What data do we have? 2) What does it mean? 3) Where is it? 4) How did it get there? And 5) How did I get it? The proposed GIS Metadata Management System incorporates Dublin core for general metadata and ISO 19115 for GIS specific metadata. Both LDAP and Relational Database based approach for storing metadata has been discussed. Other issues like automatic metadata generation, metadata replication in the distributed environment also been discussed in this thesis.

The author states that future work includes re-exam additional requirements, extend the design of metadata management system to reflect spatial data types and support intelligent query, detailed design of services, interfaces and fundamental components.

A.4 [Astakhov et al 2006]

Ref. Astakhov, V, Gupta, A, Grethe, J, Ross,E, Little, D, Yilmaz, A, Martone, M, Qian, X, Santini, S, Ellisman, M. 2006. Semantically Based Data Integration Environment for Biomedical Research. *Computer-Based Medical Systems, CBMS 2006.* 19th IEEE International Symposium, 171-176.

In this paper, the authors present a data integration mediation system which is a part of the Biomedical Informatics Research Network (BIRN;http://www.nbirn.net) project. The purpose of this system is to integrate distributed and heterogeneous bioinformatics data sources. Through this framework, one could "Query Through an Ontology" without regarding the heterogeneity of distributed data sources. The framework is composed by the following components: semantic components include

Ontology (which is a term-graph having nodes represents domain-specific vocabulary and edges represents relations); Term-index source (a database for mapping between data and ontology terms), mapping relations (which provides integrated views over data sources) and a XML based query language. The system uses the following parts: Gateway, Registry, Preprocessor, Planner, Executor, Wrapper Services and Postprocessor to process a submitted XML query, generate query plan automatically, submit executable plans to different sources via wrapper services and translate the result into unified format. The authors claim that the performance is acceptable. Future work includes introducing reasoning and explanation by developing a Graph Query Engine and expanding the mediator to support handle spatial data related to image information.

A.5 [Baru et al 1998]

Ref. Baru, C., Moore, R., Rajasekar, A., and Wan, M. 1998. The SDSC storage resource broker. In *Proceedings of the 1998 Conference of the Centre For Advanced Studies on Collaborative Research (Toronto, Ontario, Canada, November 30 - December 03, 1998).* S. A. MacKay and J. H. Johnson, Eds. IBM Centre for Advanced Studies Conference. IBM Press, 5.

In this paper, the authors present the design and implementation of the Storage Resource Broker middleware for the first time. The purpose of this middleware is to integrate heterogeneous storage systems such as relational database systems and file systems used in National Partnership for Advanced Computational Infrastructure (NPACI) project funded by the NSF.

The authors categorize the metadata into two kinds 1) System metadata which provides location and access control information and 2) Descriptive metadata which describes the contents of entire data collections and/or individual data items, and present a Metadata Catalogue (MCAT) system, which provides service APIs for managing both descriptive and system metadata of the system. The authors present three usage scenarios of MCAT: local resource, federated servers and SRB agents, and the use of client APIs to access metadata and data resources of SRB system.

The authors claim that their approach provides a generic framework compared with other vender specific approaches such as IBM Datalinks and supports more types of storage resources and OS platforms.

The authors claim that they will extend the system to make it support more metadata schemas, image data types and the research issues on metadata replication and partition to convert centralized MCAT to distributed MCAT.

A.6 [Bernstein et al 2004]

Ref. Bernstein, P., Melnik, S., Petropoulos, M. et al 2004. Industrial-strength schema matching. *SIGMOD Records, 33*:4, 38-43.

In this paper, in order to overcome the fragility of existing schema matching algorithms, the authors present a schema matching system called Protoplasm (a PROTOtype PLAtform for Schema Matching). The authors claim that their work overcomes the fragility problem by enforcing industrial-strength and the ability of customization. They claim that their work is inspired by COMA [Do and Rahm

2002]. Important aspects of this project include:

(1) Defined Schema Matching Model Graph (SMM Graph) as the internal representation of input schemas, which is implemented using XML.
(2) Defined Graph Document Object Model (GDOM) for navigating the SMM Graph.
(3) Defined XGPath to query the SMM model
(4) Using Similarity Matrix to hold the degree of similarity between items (nodes and/or edges) of two SMM graphs.
(5) Declares a set of extensible operator interfaces to carry out individual schema matching tasks.
(6) A strategy mechanism has been provided to define a control flow of operators for a matching process.

The authors claim that they have used various approaches to optimize calculation and memory usage overhead for the matching algorithms.

The authors state that further works include more effort to enhance mapping reusability, including more features such as Natural language processing, Machine learning, data mining etc and more flexible and friendly user interface. Later work referred to this paper includes [Al-Hussaini et al. 2005] in their work on building "A Service-based Approach to Schema Federation of Distributed Databases".

A.7 [Cannataro et al 2005]

Ref. Cannataro, M., Hiram Guzzi, P., Mazza, T., Veltri, P. 2005. Distributed management of ontologies on the grid. *Enabling Technologies: Infrastructure for Collaborative Enterprise.* 14th IEEE International Workshops, 261- 266.

In this paper, the authors state the problem about the lack of approaches for integrating ontology management systems on the Grid (in which knowledge could be coded in different application domains), and present the design of an ontology manager - OnBrowser. The prototype toolkit uses OWL as ontology language, uses Jena toolkit for ontology API support and uses RDQL as query language.

The authors claim that OnBrowser could provide the following supports: 1) Ontology life-cycle management, 2) Ontology query language, 3) Ontology reasoning, 4) Ontology browsing via user interface. In addition, the authors claim that it could manage a distributed ontology setting through partitioning, replication, or hybrid approaches. In the end, the authors state that they have been applied OnBrowser to enhance application workflow formulation and editing in PROTEUS project, which is a Grid-based Problem Solving Environment for bioinformatics applications.

The authors state that OnBrowser is still in its partial implementation state. Further work is to fully implement its design and the goal is to allow the access through programming interfaces to knowledge objects stored in ontologies on the Grid.

A.8 [Chen et al 2004 II]

Ref. Chen,Huajun, Wu,Zhaohui, Zheng,Guozhou, Mao,Yuxing. 2004. RDF-Based Schema Mediation for Database Grid. *grid*, 456-460.

In this paper, the authors provide an approach to integrate dispersed database resources by building a multi-tiered architecture, and also using RDF/OWL semantic to describe the different kinds of metadata in a unified form. The authors state that the project is originated from a project of building a data grid for traditional Chinese medicine (TCM), which needs to integrate heterogeneous relation databases in the grid.

The authors present a prototype system DartGrid; Defined a set of rules to convert relation database schema into RDF/OWL ontology called source data schema; Defined the multi-tiered registration hierarchy and semantic mapping policy that maps the lower-tiered schema (source data schema or mediated schema) into upper-tiered schema (mediated schema); Developed the mechanism for interactive Q3 query construction, query spreading, Q3 query to SQL query rewriting and query result presentation.

In this paper the authors state that they have done the following works:

(1) Semantic Browser: visualized Q3 query construction tool.
(2) A set of services was been implemented, including:
(3) Data Semantic Service: Convert relational schema into RDF/OWL;
(4) Ontology Service: Publishing ontology of the source data schema or the mediated schema;
(5) Semantic Registration Service: Mapping sub-tier data source ontology into mediated schema for current layer;
(6) Semantic Query Service: Semantic query distributor, SQL query generator & processor.

Related Works include OGSA-DAI grid data service [http://www.ogsadai.org.uk/], Pizza XML-XML mapping technology presented by [Halevy et al. 2003] and Edutella RDF query and storage service presented by [Nejdl et al. 2002].

The authors state there are still unsolved issues on mapping relational database schema into RDF/OWL semantic and lists three of them. 1) Redundancy among different database schemas, 2) Inconsistence between two database schemas, 3) Alternative ways to map n-ary (n>2) relation into RDF/OWL model.

A.9 [Deelman et al 2004]

Ref. Deelman, E., Singh, G., Atkinson, M.P., Chervenak, A., Chue Hong, N.P., Kesselman, C., Patil, S., Pearlman, L., Mei-Hui Su. 2004. Grid-based metadata services. Scientific and Statistical Database Management. In *Proceedings of 16th International Conference*, 393- 402.

In this paper, the authors present their farther work on MCS [Singh et al. 2003] which makes MCS conforms to OGSA standard. They claim that the boundary between metadata and data is to some extent arbitrary and may vary during a data object's lifetime, and presents more discussion on the requirements on the metadata service, which includes: 1) The need to store and share the metadata, 2) The need to organize the metadata in a logical fashion for ease of publication and discovery,

3) The need to customize the view of the data by individuals and 4) The need to support metadata about large-scale data sets.

The authors present a new implementation of MCS which is based on OGSA-DAI middleware and present the discussion on the data model, user model, authorization policies, schema flexibility and metadata interface. The author claims that their experiments indicate that the use of OGSA-DAI Grid Service expands the scalability vs. previous web service based approach. The new implementation of MCS has been used in several projects including Earth System Grid (ESG) application and Pegasus workflow management system.

The authors state that their future work is to extend the centralized metadata service to distributed service in order to provide better performance and scalability, and to use query mediation and planning techniques combined with ontology-based attribute models to query across multiple MCS instances.

A.10 [Do and Rahm 2002]

Ref. Do, H. and Rahm, E. 2002. COMA - A system for flexible combination of schema matching approaches. In:*Proc of the Int'l Conf on Very Large Data Bases(VLDB).* Hong Kong,China.

In this paper, the author provides a similarity-based approach to solve the schema matching problem, which is finding correspondences between elements of two schemas. A schema matching system called COMA has been presented and it has the following features: 1) supports simple and hybrid match algorithms to find similar correspondent elements, 2) supports both automatic and interactive match finding, and 3) able to reuse previous matches

The author also provides a three-step procedure to calculate combined similarity by combining results from different matching methods: Aggregation (generate similarity matrix), match selection and calculate combined similarity.

The author defines a set of indexes to evaluate the matching results, and states that the innovated matching reuse approach does improves the matching precision.

Later work inspired by this paper includes [Bernstein et al. 2004] and [Al-Hussaini et al. 2005].

A.11 [Dou and LePendu 2006]

Ref. Dou, D. and LePendu, P. 2006. Ontology-based integration for relational databases. In *Proceedings of the 2006 ACM Symposium on Applied Computing (Dijon, France, April 23 - 27, 2006). SAC '06.* ACM Press, New York, NY, 461-466. DOI= `http://doi.acm.org/10.1145/1141277.1141387`

This paper provides a way to solve the schema mapping and data integration problem when integrating autonomous database systems.

The authors claim that they have developed an ontology-based, first order logic approach to integrate heterogeneous relational databases, which is called inferential data integration. The system is called OntoGrate system. In this project, the author introduces Web-PDDL [`http://marzapan.cs.uoregon.edu/web-pddl.pdf`] ontology language to represent the database definition and inference axioms between different database schemas. Two components have been constructed, the

SQL wrapper can be used to translate Web-PDDL script into SQL query and translate SQL record set into Web-PDDL facts; the OntoEngine maps Web-PDDL based database schema of one database into the form of another database using first-order logic.

According to the paper, the experiment is done based on query answering (invoking the backward chaining reasoner to reformulate the source query to the target one) and data translation (using the forward chaining reasoner and bridging axioms to translate that set of source facts into the target database schema). The authors state that the system demonstrates adequate performance for query answering however the performance of data translation is still need to be improved.

The authors claim that related work includes falls in three areas:

Schema mapping:

(1) [Dhamankar et al. 2004] in their paper "imap: Discovering complex mappings between database schemas"
(2) [Haas et al. 2005] in their paper "Clio Grows Up: From Research Prototype to Industrial Tool"
(3) [Rahm and Bernstein 2001] in their paper "Bernstein. A survey of approaches to automatic schema matching".

Database reverse engineering: [Stojanovic et al. 2002] in the paper "Migrating data-intensive web sites into the semantic web".

Data integration and logic inference: [Sheth and Larson 1990] in the paper "Federated database systems for managing distributed, heterogeneous, and autonomous databases".

The authors state the future work includes testing OntoGrate system against biomedical databases, extending OntoGrate to integrate databases, XML files and Semantic Web resources, and continue to improve the performance of data translation.

A.12 [Fox and Walker 2003]

Ref. Fox, G., Walker, D. 2003. e-Science Gap Analysis. *Technical report.* Indiana University and Cardiff University, UK e-Science Center.

This paper presents a comprehensive survey to identify the gaps between existing Grid technology in e-Science and the expected functionalities up to April 2003, and also proposes a list of possible development programs to fill these gaps. It overlaps with our survey on the topics of Semantic Grid, which is "Integration of Grid and Semantic Web meta-data and ontology technologies" and Information Grid, which is to Grid service access to distributed repositories. On the former, gaps listed by the authors include enable semantic interoperability of services; enhance existing directory services; meta-data reasoning; Service Data Element modeling; meta-data provenance. On the later, the gaps listed include federation support, filtering techniques, analyzing and integrating existing e-science frameworks, data curation and integrating metadata catalogs in variety of fields.

In metadata management area, the survey listed fundamental researches processing in the Council for the Central Laboratory of the Research Councils (CCLRC) e-Science Centre: 1) CCLRC Scientific Metadata Format, and 2) CCLRC cross-disciplinary DataPortal, "which allows searching various data facilities in parallel, exploring their metadata catalogues and accessing their data". And possible future projects (relative to 2003): 1) Key areas in Semantic Grid: ontology, annotation, maintenance, Intelligent Brokering and Service Discovery, 2) Service Registry from [ITInnovation], 3) Provenance Specification from [myGrid], and 4) Storage Resource Broker (SRB) evaluation, where SRB is a client-server based middle-ware [Baru et al. 1998].

In information grid area, the survey states that major development will be focused on OGSA-DAI middleware and its application in various grid projects.

A.13 [Kojima 2006]

Ref. Kojima,I. 2006. Design and Implementation of OGSA-DAI-RDF. *GGF16 3rd Semantic Grid Workshop.*

In this paper, the author presented a project that extends OGSA-DAI access to RDF database systems and is intend to provide a uniform view for heterogeneous database resources in grid environment. This project is a subproject of Database Grid project that is initiated by National Institute of Advanced Science and Technology (AIST) of Japan.

Through this project, the author expands the functionality of OGSA-DAI toolkit by providing a set of RDF related activities such as:

(1) SPARQL QueryStatement Activity: to support the query of RDF document using SPARQL query language.
(2) RDF ResourceManagement Activity: provides create and delete functionalities to manipulate RDF statements.
(3) RDF CollectionManagement Activity: provides supports to create, delete and list functionalities to RDF data repository.

The toolkit is developed based on java-based ontology toolkit Jena or Sesame. Because it is seamlessly integrated with OGSA-DAI, one can easily submit SPARQL queries and transfer query results using OGSA-DAI provided delivery mechanism over a distributed environment.

The author claims that this toolkit provides fundamental support for other parallel projects by providing a service-based interface for RDF databases. Related projects include: Semantic MDS, OGSA-WebDB and RDFCube (`http://www.dbgrid.org/`).

A.14 [Malaika et al 2003]

Ref. Malaika, S., Eisenberg, A., and Melton, J. 2003. Standards for databases on the grid. *SIGMOD Rec. 32*, 3 (Sep. 2003), 92-100. DOI= `http://doi.acm.org/10.1145/945721.945739`.

In this survey, the authors emphasize the importance of standardizing the interfaces between the infrastructure, the managed resources and their consumers on supporting any significant infrastructure over heterogeneous resources, and presents their work to help researchers to understand the hierarchy of the Global Grid Forum(now Open Grid Forum) and major activities currently proceeding in the work groups from the aspect of grid database integration.

The authors state that major functions of GGF are to produce documents describing best practices, technical specifications, user experiences, and implementation guidelines for distributed and grid computing environments. Currently data-related groups in GGF are:

(1) DAIS-WG (Data Access and Integration Services Working Group), which is to produce the specification that describes a service-based interface for accessing and integrating data in existing relational and XML databases on the grid.
(2) OREP (OGSA Replication Services) group, which focuses on data replication technologies for the grid.
(3) DFDL (Data Format and Description Language) working group, which is to define the general language for describing and labeling the structure of data streams.

They have their major concerns in data visualizing, data managing and data integrating area. Further more, the authors provide a list of data-related workgroups, related workgroups and describes their functions. As to metadata management, the authors claim that many standard activities are correlated with activities outside GGF, and states that current work are focused in defining and refining standards to: 1) Describe service data used by Data Resource Manager, 2) Describe database characteristics (data resources), 3) Describe representing relational database content, and 4) Represent the query results in XML.

[Cannataro et al. 2005] referred to this paper and presented a solution for managing distributed ontologies in grid.

A.15 [Nakamura 2004]

Ref. Nakamura, H., Date, S., Matsuda, H., Shimojo, S.: A Challenge towards Next-Generation Research Infrastructure for Advanced Life Science. *New Generation Computing*, 22 (2004), 157-166.

This paper addresses the requirements to integrate distributed bio-related database into grid environment. It presents the current status of BioGrid project held in by Osaka University, Japan and its future prospect and uses one whole section (Section 3) to present the blueprint of a Metadata-based database federation and its preliminary application.

The authors present a hierarchical structured database federation model managed by multi-tied metadata repository. The metadata in this paper has been classified into two types: the Application-Metadata which plays a role for the mediation between applications and databases and Data Service Metadata which is used for hiding the heterogeneity of various records of biology-related databases. The authors also present a preliminary platform BioPfuga, which could provide a schematic view of the DataGrid based on this metadata model.

The authors claim that the goal of the Biogrid project is to produce a development platform where knowledge, techniques, and technologies regarding both IT and life science can easily converge and bio-researchers and scientists can perform their analyses seamlessly. The authors also state that they were in the process of porting the system to work in a practical Grid environment, using the Globus Toolkit 3 with OGSA-DAI (Open Grid Services Architecture - Database Access and Integration), `http://www.ogsadai.org/`).

Based on this infrastructure, further works on the same project has been reported by [Tohsato et al. 2005] and in "Heterogeneous Database Federation Using Grid Technology for Drug Discovery Process", [Kitajima et al. 2004] in "Development of a database system for drug discovery by employing grid technology".

A.16 [Rajasekar et al 2002]

Ref. Rajasekar, A, Wan, M, Moore, R. 2002. MySRB & SRB: Components of a data Grid. In *Proceedings of the 11th IEEE International Symposium on High Performance Distributed Computing (HPDC-11).* IEEE Computer Society Press, Washington, DC, 301-310.

In this paper, the authors present their further work that extends SRB system [Baru et al. 1998] by introducing a web-based interface to it, which is called MySRB. They claims that MySRB provides user-friendly interface for user to access distributed collections brokered by the SRB. From the aspect of metadata management, MySRB "provides a very rich set of operations for creating, maintaining, viewing and searching different types of metadata for SRB objects as well as collections". For MySRB, metadata is classified as 1) system-defined metadata, 2) user-defined metadata, 3) type-oriented (domain-oriented) metadata, 4) file-based metadata, and 5) annotations and commentary metadata.

The authors present detailed description on how does MySRB cooperate with metadata catalogue system to allow user construct their queries and define new metadata and annotations. At last the authors claim that the SRB and MySRB architecture is a potent approach in the Data Grid Architecture for building distributed data collections, digital libraries, and persistent archives.

A.17 [Rajasekar et al 2004] and [Moore et al 2004]

Ref. Rajasekar, A., Wan, M., Moore, R., AND Schroeder, W. 2004. Data Grid federation. In *Proceedings of the 11th International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA'04).* Las Vegas, NV. CSREA Press, Las Vegas, NV.
Ref. Moore, R., Jagatheesan, A., Rajasekar, A., Wan, M., and Schroeder, W. 2004. Data Grid management systems. In Proceedings of the 21st IEEE Conference on Mass Storage Systems and Technologies UMSS'04, College Park, MD. IEEE Press, Los Alamitos, CA.

In these two papers, the authors present their further works that extend SRB and MCAT to meet the requirements of constructing federated systems. They introduced their data grid product held by San Diago Super Computer Centre at UCSD (SDSC) called Storage Resource Broker (SRB), its metadata management system Meta data Catalog (MCAT) and zoneSRB project which extends SRB into federated environment. From the federated metadata management point of view, the authors introduced 10 models used in data grid federation, including: Occasional Interchange, Replicated Catalog, Resource Interaction, Replicated Data Zones, Master-Slave Zones, Snow-Flake Zones, User and Data Replica Zones, Nomadic Zones - SRB in a Box, Free-floating Zones and Archival Zone/BackUp Zone. The authors claim that these models are based on three generic federation models - Peer-to-peer federation model, Replication federation model and Hierarchical federation model and currently zoneSRB has implemented all these models.

[Venugopal et al. 2006] referred these papers in their survey which provides a taxonomy of data grid systems and their further developing trend. [Antonioletti et al. 2005] also claims that the proposed SRB system could use could use their OGSA-DAI either to access structured data resources, or to provide access to the metadata from MCAT.

A.18 [Shaon 2005]

Ref: Shaon, Arif. 2005. Long-term Metadata Management & Quality Assurance in Digital Curation. Submitted In Partial Fulfilment Of The Requirements for the Degree Of MASTER OF SCIENCE In Network Centred Computing, E-Commerce in the Faculty Of Science. University of Reading. available as `http://epubs.cclrc.ac.uk/bitstream/897/MSc_Dissertation.pdf`.

This dissertation discusses the general requirements of a metadata management system, especially on the planning details for a long-term metadata curation project, which can be used for "long-term metadata management and its quality assurance with a broader objective of successful long-term data preservation". The author presents a comprehensive survey on existing metadata standards, metadata management systems, potential collaborators and the assessment of the long-term metadata curation project.

The author claims that long-term metadata curation is an important part of metadata management system that ensures the high quality, well-managed metadata and therefore essential for successful long-term high quality data preservation. However, most of existing publications on long-term preservation of digital information overlooked the fact that long-term curation strategy should also be designed for metadata that associates with the preserved resources. The author also claims that none of current metadata management projects intended for long-term metadata curation or management.

A.19 [Sheth and Larson 1990]

Ref. Sheth, A. P., Larson, J. A. 1990. Federated database systems for managing distributed, heterogeneous, and autonomous databases. *ACM Computing Surveys*, 22(3):183-236.

In this paper, the authors presented a comprehensive research on the federated database system. The authors declare that a federated database system is a collection of autonomous and possibly heterogeneous cooperating component database systems, and analyzed this kind of system from five aspects: the taxonomy if federated database systems, hierarchied schema types and processor types, developing methodology, developing tasks and distinct operations performed by federated database systems.

The authors state that FDBMS is a subset of multi-database systems. It is distinctly characterized by its autonomous feature. According to the integration level it can be classified to loosely-coupled and tightly-coupled and the latter can be further classified as single federation and multiple federation based on the federated schema.

In this paper, The authors state that the ANSI/X3/SPARC Standard three level data description is inadequate for federated database systems and extends it into five levels: local schema, component schema, export schema, federated schema and external schema. Additionally, the authors standardized a set of processors for translating and filtering the schemas and discussed the usage in different scenarios.

In the end, The authors claim that future work will be focused on semantic identifying and representing, automation and management tools, transaction management, improve efficiency in a autonomous environment and extend the data source to non-tradition data providers.

A.20 [Singh et al 2003]

Ref. Singh, G., Bharathi, S., Chervenak, A., Deelman, E., Kesselman, C., Manohar, M., Patil, S., and Pearlman, L. 2003. A Metadata Catalog Service for Data Intensive Applications. In *Proceedings of the 2003 ACM/IEEE Conference on Supercomputing (November 15 - 21, 2003).* Conference on High Performance Networking and Computing. IEEE Computer Society, Washington, DC, 33.

In this paper, the authors list the requirement of constructing a metadata service that allow effective accessing terabyte and petabyte of data sets consisting of millions of data items, and present a design of a Metadata Catalog Service (MCS) that "provides a mechanism for storing and accessing descriptive metadata and allows users to query for data items based on desired attributes". According to the paper, the MCS is a grid based metadata service provider that has the following features:

(1) Separates the logical metadata service from services for physical storage metadata or replica metadata.

(2) Provides a general metadata schema.

(3) Provide extensions for user-defined metadata attributes that could be used to support application-specific metadata ontologies.

(4) Provide API for storing and querying metadata.

The authors state that the Metadata Catalog Service implementation is based on open source web service and relational database technology, and has been used in the Earth System Grid (ESG) project, the Laser Interferometer Gravitational-Wave Observatory (LIGO) project and the workflow mapping system Pegasus.

The authors use a set of experiments to test the MCS and claims that although the use of web service to access database introduces a significant overhead, it does scales well for many of the supported operations as with increasing size of the database.

The authors state that their work is induced from their previous work [Chervenak et al. 2002] which is a Replica Location Service that exclusively contains metadata information related to data replication, and also borrowed ideas from MCAT Metadata Catalog of the Storage Resource Broker (SRB) from the San Diego Supercomputing Center [Baru et al. 1998][Rajasekar et al. 2002][Rajasekar et al. 2004][Moore et al. 2004]. The authors claim Metadata Catalog Service differs from MCAT significantly in the architectural model. MCAT is implemented in tight integration with other components of SRB and cannot be used as a standalone component. It stores both logical metadata and physical metadata as well as attributes that describe resources, users and methods, while MCS is one component in a layered Grid architecture. It contains only logical metadata attributes. The authors also claims MCS is similar in its design and function to RepMec (Replica Metadata) catalog [Guy et al. 2002] developed by the European DataGrid's Reptor project.

The authors claim their future work includes to make MCS more extensible and to provide a more general query model, using the OGSA Database Access and Integration (DAI) service, to enhance the authorization and authentication, to solve performance and reliability problems by moving centralized MCS implementation to a distributed implementation.

A.21 [Sousa et al 2006]

Ref. Sousa, Bysmarck Barros de, Silva, Francisco Jose da Silva e, Teixeira, Mario Meireles, Filho, Gilberto Cunha, 2006. MagCat: An Agent-based Metadata Service for Data Grids. *ccgrid, Sixth IEEE International Symposium on Cluster Computing and the Grid Workshops (CCGRIDW'06)*, 6.

In this paper, the authors point out the problem of integrating distributed data sources lies in heterogeneity of data structures, institutional policies, discovery and replication, a metadata management system is the key component to solve these problems. The authors present a multi-agent metadata management system called MagCAT that is used in the middleware system called Mobile Agents Technology for Grid Computing Environments. The authors states that their system has the following contributions: 1) an extensible metadata schema that is domain-inpendent, 2) a language used for accomplishing data publication and discovery, 3) a well defined ontology for a metadata service, 4) an independence of the storage system used to keep the metadata, 5) a data model based on files that allows the grouping of data in collections and views, and 6) allows metadata to be managed in distributed way.

The authors state that current MagCat implementation consists of the CatalogManager, SchemaManager, and DataManager agents, which provide the basic functionalities for publishing and discovering metadata, and schema extensibility. It also uses LDAP for features such as distribution, replication, synchronization, and security.

In this paper, the authors also present their comparison between MagCAT and other metadata management systems - MCS and MCAT. They claim that MagCat differs significantly from MCS [Singh et al. 2003] regarding its architecture and development paradigm, which includes:

(1) MCS provides a central metadata service, MagCat inherits the intrinsic LDAP distributed architecture, and deals with replica management and synchronization.
(2) MagCat was developed based on an agent paradigm while MCS is based on web service model.
(3) MCS uses a relational database system to store its metadata, while MagCat is independent of storage system.

As compared with MCAT [Baru et al. 1998], MagCat is independent of grid Middleware.

Future work stated by the authors include to integrate the access to the Open Grid Service Architecture Data Access Integration (OGSA-DAI) into the DataManager agent and to investigate the use of agent mobility heuristics in order to reduce the cost of data transfer in the grid and to realize of evaluating performance the architecture.

A.22 [Venugopal et al 2006]

Ref. Venugopal, S., Buyya, R., and Ramamohanarao, K. 2006. A taxonomy of Data Grids for distributed data sharing, management, and processing. *ACM Comput. Surv.* 38, 1 (Jun. 2006), 3. DOI= http://doi.acm.org/http://doi.acm.org/10.1145/1132952.1132955.

This paper presents the taxonomy of Data Grids based on various aspects: organization (Model, Scope, VO, Data Sources, Management), Data Transport (Function, Security, Fault Tolerance, Transfer Mode), Data replication and storage (Model, Topology, Storage Integration, Transfer protocol, Metadata, Update propagation, Catalog Organization), Resource Allocation and Scheduling (Application model, Scope, Data replication, Utility function, Locality).

From the survey we can see that database federation falls in the taxonomy of Data Grid based on adopted Model under Organization, i.e. the manner in which data sources are organized in a system. The authors state that the federation model [Rajasekar et al. 2004] is prevalent in Data Grids created by institutions that wish to share data in already existing databases, and presented an example of Data Grid called the BioInformatics Research Network (BIRN) [http://www.nbirn.net] in the United States. The authors also mentioned that [Moore et al. 2004] has a discussion about 10 different types of federations that are possible using the Storage Resource Broker (SRB) [Baru et al. 1998] in various configurations.

Stated future trends in Data Grid include: Increasing Collaboration, Wide adoption of SOA, introducing Market mechanisms and meet with enterprise requirements.

A.23 [Wu et al 2004]

Ref. Wu, Zhaohui, Chen, Huajun, et al 2004. DartGrid: Semantic-based Database Grid. *Lecture Notes in Computer Science 3036/2004*, 59 - 66.

This paper is intended to overcome the difficulty to integrate distributed databases dynamically and construct a Database Virtual Organization. It presents an explicit definition of Ontology-based Database Virtual Organization and its proposed elements and also presents a fundamental grid-based framework called DartGrid, which uses domain ontologies to organize distributed databases.

The author states that they have implemented the following web services and tools to achieve its designation goal:

(1) A Semantic Browser for user interaction.
(2) A Set of Semantic Services: Semantic Registry Service(SeRS), Data Semantic Service and Ontology Service.
(3) Q3 and RDF based semantic query and Semantic Query Service (SeQS) that maps conceptual, semantic based query into local database query languages (SQL, XQuery etc).

The framework has been used to build VO for Traditional Chinese Medicine (TCM).

The authors claim that this system significantly promotes the sharing and integration of their database resources and greatly facilitates their cooperation in their preferable web mode.

The authors claim that their new approach is related to three different fields: knowledge-based query processing in distributed information system, Information integration and Data Grid. Future work stated by the authors includes integrating more types of resources into their prototype. Succeeding works reported in the thread of this project include [Chen et al 2004 I] which presents more details about Q3 and RDF semantic query engine and [Chen et al 2004 II] which places more focus on the multi-tiered architecture.

A.24 [Dublin Core]

Dublin Core is a metadata standard promoted by Dublin Core Metadata Initiative [DCMI] in 1995. It defines a simple element set for describing a wide range of resources. Using Dublin Core, all metadata resources are described as terms, each term contains a set of properties that are also a set of Dublin Core standardized terms. The Dublin Core standardized terms could be:

(1) Elements, which are attributes of resources - characteristics that a resource may "have" such as Name, Title and URI etc.
(2) Qualifiers, including element refinements (adjective information that refines the term with narrower semantics), encoding schemes (contextual information or parsing rules that aid in the interpretation of a term value, such as date format).
(3) Vocabulary terms, which is also called the DCMI Type Vocabulary.

Each term has a Uniform Resource Identifier that uniquely identifies a term and all the properties give the term a commonly understood semantics. Metadata described using DCMI Terms can be expressed in different forms. It can be stored in relational databases or as documents in HTML/XHTML [Powell 2003], XML [Powell and Johnston 2003] or RDF format [Beckett et al. 2002].

***** This survey is completely my own work. *****

Signature: