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PAIRSE: A Privacy-Preserving Service-Oriented Data Integration System

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ABSTRACT

Privacy is among the key challenges to data integration in many sectors, including healthcare, e-government, etc. The PAIRSE project aims at providing a flexible, loosely-coupled and privacy-preserving data integration system in P2P environments. The project exploits recent Web standards and technologies such as Web services and ontologies to export data from autonomous data providers as reusable services, and proposes the use of service composition as a viable solution to answer data integration needs on the fly. The project proposed new composition algorithms and service/composition execution models that preserve privacy of data manipulated by services and compositions. The proposed integration system was demonstrated at EDBT 2013 and VLDB 2011.

1. INTRODUCTION

Data integration has been a long-standing challenge for the database community. This is motivated by the number of contexts in which the need for a flexible data integration mechanism has become critical, including Web and enterprise data integration, scientific data exploration, data exchange in government agencies, etc.

Much of the literature on data integration across autonomous data sources has tacitly assumed that data on the side of each data source can be revealed and shared with other sources. In practice, however, data integration scenarios are often hampered by legitimate and widespread data privacy concerns. In the healthcare application domain for example, medical data are subject to many legislations (e.g., [2, 1]) around the world that restrict collection, processing, and disclosure of personal data, and hold data holders accountable for any unintended data disclosure or misuse.

The PAIRSE project addresses the challenge of flexible and privacy-preserving data integration in peer-to-peer environments. Driven by the recent trends of using SOA-oriented architectures for data integration in modern enterprises, PAIRSE assumes that data sources are exposed to the data sharing environment as Web services. This type of services is commonly known as data services [11], where data services provide a well documented, platform (and source) independent, interoperable method of interacting with data. PAIRSE proposes a service composition-based approach for on-demand data integration; i.e., heterogeneous data services from autonomous service providers are selected and composed on the fly to answer users’ queries. Data privacy preservation is a key objective of PAIRSE. Users in PAIRSE are allowed only to access the information they are entitled to for a given purpose.

PAIRSE focuses on modeling, discovering, selecting and composing data services to efficiently answer users’ queries. The contributions of PAIRSE, which was demonstrated at EDBT 2013 [5] and VLDB 2011 [9], are summarized as follows:

- **Semantic description model for data services**: The semantics of data services should be explicitly represented to automate their discovery, selection and composition. We modeled data services as “RDF Views” over domain ontologies to formally define their semantics [7]. The service description files (e.g., WSDLs) are annotated with these RDF views.

- **Query resolution by automatic service composition**: Queries in PAIRSE are resolved by automatically selecting and composing data services. We exploited mature query rewriting techniques to devise a novel service composition algorithm [7, 9]. The algorithm relieves users from having to manually select and com-
pose services, tasks that would generally require important programming skills. We proposed also an efficient algorithm to locate relevant services in a P2P environment [14].

- **Privacy preservation**: We proposed a privacy preserving composition model [5, 8, 16]. Our model allows services providers to locally enforce their privacy and security policies when their services are invoked. In addition, it prevents services in a composition from learning any information about the data that each other holds, beyond what is permitted.

The rest of the paper is organized as follows. Section 2 gives an overview of our integration system. Section 3 describes our semantic modeling of data services. Section 4 presents our composition approach. Section 5 presents our techniques to privacy preservation. Section 6 applies our work in two application domains, and summarizes obtained results. Section 7 concludes the paper.

2. **PAIRSE’S ARCHITECTURE**

The PAIRSE data integration system has a hybrid peer-to-peer infrastructure [14], where peers form communities of interest, called Virtual Organizations VOs. Each VO has a common domain ontology modeling its expertise, and peer members that may have relations with members from other VOs. Relations between peers exist only if there is a mapping between the ontologies of their respective VOs. PAIRSE does not impose any constraint on the topology graph formed by the ontologies and the different mappings. Peers export their (shareable) data sources as data services.

PAIRSE follows a declarative approach to compose data services (Figure 1). Data services in each peer are modeled as RDF Views over domain ontologies to explicitly define their semantics. Users formulate their queries on domain ontologies using SPARQL query language. Then, our system exploits the defined RDF views (added as annotations to service description files) to select and compose the relevant services using an RDF query rewriting algorithm that we have devised for that purpose. Queries may necessitate the use of remote data services, in which case an efficient P2P service discovery algorithm [14] is used to locate and retrieve the descriptions of relevant services from remote peers. The system generates then an execution plan for the composition and executes it to provide the user with the requested data. As data services may manipulate privacy-sensitive information, PAIRSE proposed new service and composition execution models to preserve privacy.

3. **SEMANTIC MODELING AND SERVICE QUERYING**

In this section, we explain our service composition based approach to query resolution.

3.1 **Semantic Modeling of Data Services**

Modeling and explicitly specifying the semantics of data services are the first step towards the automation of service selection and composition.

In PAIRSE, we proposed in [7] to model data services as RDF Parameterized Views (RPVs) over domain ontologies. A parameterized RDF view uses concepts and relations whose meanings are formally defined in domain ontologies to define the semantic relationships between input and output parameters sets of a data service. A parameterized view is a technique that has been used to describe content and access methods in Global-as-View (GaV) integration architectures [13]. Figure 2 shows an RPV of a service returning the personal information (i.e., name and dates of birth) of patients admitted in a given medical center. Note that input parameters are prefixed with the symbol “$” and output parameters are prefixed with the symbol “?”.

RDF views may also specify constraints to characterize the data manipulated by their corresponding services. These constraints may have different forms, including simple interval constraints (e.g., $X \in [a, b]$, where $X$ is a variable used in an RDF view), and fuzzy constraints interpreted according to a fuzzy membership function (e.g., the medications returned by a service have “High” concentration of hydroxypropyl-$\beta$-cyclodextrin; i.e., $X$ is High, where the fuzzy term “High” is interpreted by a membership function specifying for each value of $X$ the degree to which it is high).

We adopted an approach similar to SAWSDL\(^1\) to

\(^1\)http://www.w3.org/2002/ws/sawsdl/
RDF schema constraints such as our query rewriting algorithm takes into account case of RDF/RDFS data integration. Specifically, XML data integration [13, 17], we considered the:

Compliance with the RDF/S data models: while previous data integration systems have focused on answering specific queries, PAIRSE has focused on answering parameterized queries. The key focus was on constructing compositions of services (i.e., parameterized integration plans) that are independent of a particular input value. For example, assume a parameterized query $Q(x, y)$ for the medications $y$ that may interact with a given medication $x$. Assume also two data services:

$$S_1(x, y), \quad x \in [1, 5] \text{ and } y \in [100, 150],$$
$$S_2(x, y), \quad x \in [6, 10] \text{ and } y \in [150, 200]$$

If $Q$ was a specific query ($Q_{x=2}$), then $S_2$ would not be considered in the rewriting (i.e., composition) as $x=2$ is not covered by $S_2$. In contrast, both of $S_1$ and $S_2$ are usable for $Q$, to cover as much as possible of the potential values of $x$. Our composition algorithm extends the previous ones with: (i) a probabilistic subsumption test to determine in a polynomial time the minimum number of services required to satisfy the value constraints that may be specified on query’s parameters [6], and (ii) a mechanism to optimize the generated composition plans based on value constraints specified in service descriptions [7].

Inclusion of user’s preferences: often the number of candidate compositions that may be used to answer the same query is very large. We proposed an approach [9] to compute the top-$k$ compositions based on user preferences. In our approach, we modeled user’s preferences using fuzzy sets. We match the (fuzzy) constraints of the relevant services to those of the query and determine their matching degrees using a set of matching methods from the fuzzy set theory. We then rank-order candidate services based on a fuzzification of Pareto dominance and compute the top-$k$ compositions.

4. PRIVACY PRESERVATION IN PAIRSE

In this section, we briefly present our models to preserve the privacy of manipulated data at the service and the composition levels.

4.1 Privacy-preserving Service Execution Model

Data returned by a data service may be subject to different security and privacy concerns. For example, different people may have different access rights over the same data item; data subjects\(^2\) may

\[^2\]We use the term data subject to mean the individual whose information is manipulated by data services.
Step 3: Enforcing security and privacy constraints. Services selected in the previous step are composed and executed using the conventional service execution process. The composition returns (i) the data items returned by the invoked service along with (ii) the data items necessary to evaluate the security and privacy constraints. We defined a privacy filter that evaluates the privacy constraints of the different items that are subject to privacy constraints in the view. Null values will be returned for items whose privacy constraints evaluate to False.

We demonstrated the validity of our model by extending the architecture of the famous service container AXIS² 2.0 with a new module implementing our privacy-preserving service execution model.

4.2 Privacy-preserving Composition Execution Model

Executing compositions may disclose confidential information to component services. Assume, for example, a composition of two services: $S_1$ returns HIV patients in a given city, and $S_2$ checks whether a given patient has been treated for psychiatric disorders. Such composition could be needed (by a pharmaceutical researcher) to investigate the connection between a chemical component present in HIV medicines and the development of severe psychiatric disorders. Assume also Bob is a common patient to $S_1$ and $S_2$. If $S_2$ is invoked with Bob’s identifier, and the provider of $S_2$ has an access to the composition plan (i.e., he knows that Bob was outputted by $S_1$), then he will infer that Bob is an HIV patient. On the other hand, if the data returned by $S_1$ were completely privacy-sanitized (e.g., by removing identifiers and sensitive information), then the composition could not be executed.

We proposed a privacy-preserving composition execution model in [5] that limits the information disclosed to services in a composition about the data that each other holds. Our model distinguishes between the following entities: (i) the services in the composition, (ii) the execution engine, and (iii) the recipient of final results. It relies on two key ideas: First, data services use the same order-preserving encryption scheme OPES [3] to encrypt the identifier attributes that are needed to connect data subjects across the different services. They are still free to protect non-identifier attributes with their own techniques (e.g., anonymization, etc.). This way the execution engine has only access to protected data and can still link data subjects across services using the encrypted identifier attributes (note that OPES allows for applying equality queries on encrypted

http://axis.apache.org/axis2/java/core/
in less than 4 seconds. In the context of parameterized queries, our experiments in [6] showed that our algorithm to find the minimum set of services introduced only a small cost at the composition construction time (i.e., in all experiments the algorithm required less than 10% of the time needed to rewrite the query), and improved substantially the composition execution time (i.e., in all experiments the composition execution time was reduced to less than 0.75% of the time needed without optimization), as it removes redundant services. In the context of preferences queries, our experiments in [9] considered that services can be grouped in classes. The experiments showed that the top-k compositions can be computed efficiently. For instance, for classes containing about 400 services, the top-k compositions are computed in less than 4 seconds.

5. IMPLEMENTATION AND EVALUATION

We evaluated our different techniques and algorithms in the healthcare and bioinformatics application domains. These domains have widely embraced Web standards, such as XML and Web services [12, 10], and are characterized by the need for a flexible and privacy-preserving data integration approach.

The cardiology hospital of Lyon provided us with access to two medical databases. The identities of patients in these databases were changed. We also generated synthetic medical data about the same patients. We implemented about /400/ data Web services on top of our real and synthetic data. Services were all deployed on an extended version of AXIS 2.0 implementing our service execution model. We built a medical ontology based on the building blocks and the data types defined in the HL7 standard, and used it for the annotation of service description files. To evaluate our techniques in the bioinformatics domain, we used a set of /300/ services from the BioCatalogue registry\(^4\).

Figure 4 (part a) shows the query interface to the PAIRSE. Users are assisted in formulating their SPARQL queries over domain ontologies. The figure shows (in part b) also the composition plan of a selected composition, along with the privacy-sanitized results (part c).

We conducted exhaustive experiments to evaluate the performance of our integration system. We summarize below obtained results\(^5\):

**Composition construction and execution:** Our experiments in [7] showed that our composition algorithm can handle hundreds of data services in a reasonable time. For example, for chain queries [13] and RPVs with a length of 3 or 4 object properties the algorithm was able to handle up to 400 services in less than 4 seconds.

6. CONCLUSION

The goal of the PAIRSE project was to develop new methods and techniques for flexible and privacy-preserving data integration. We have evaluated our composition-based approach in the healthcare and bioinformatics domains. The obtained results [5, 9, 7, 14, 8, 16, 6] are promising.

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