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Personal View:

From Semantic Grid to Knowledge Service Cloud

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1 Introduction

The World Wide Web is a major breakthrough in the history of human communication and information sharing (Berners-Lee *et al.*, 2006). The Web has brought us a series of revolutionary tools, such as digital libraries, net meetings, e-mails, and data services, which have changed the face of scientific research and publishing. Scientists are increasingly relying on these tools to conduct their daily research, and to collaborate with their colleagues through distant communication and knowledge sharing. Despite all these accomplishments, there are still gaps between what can be done using the current Web and what need to be done in an e-Science environment (Buetow, 2005).

Computer scientists have long envisioned a ‘cyberinfrastructure for e-Science’ on top of the current Web infrastructure (Hey and Trefethen, 2005). Wright and Wang (2011) stated that cyberinfrastructure “integrates advanced computer, information, and communication technologies to empower computation-based and data-driven scientific practice and improve the synthesis and analysis of scientific data in a collaborative and shared fashion”. Various approaches have been taken to build such a cyberinfrastructure, including service-oriented computing (Papazoglou and Georgakopoulos, 2003; Bichier and Lin, 2006), Grid computing (Foster, 2002), and cloud computing (Armbrust *et al.*, 2010).

Computer scientists have advocated service-oriented approaches to e-Science for years (Foster, 2005). Papazoglou and Georgakopoulos (2003) defined service-oriented computing (SOC) as “the computing paradigm that utilizes services as fundamental elements for developing applications”. The application of SOC on the Web is manifested by Web services, which enable application programs to communicate in ways that are independent of specific platforms and languages, and therefore facilitate system interoperability (Papazoglou and Georgakopoulos, 2003). Web services can be used to implement a cyberinfrastructure according to Service-Oriented Architecture (SOA), which turns the development of e-Science applications into a pipeline of service development, service deployment, and service combination (Erl, 2008).

As an extension to SOC, Grid computing is also a major approach to building the cyberinfrastructure for e-Science (Foster, 2002). In essence, a Grid computing environment enables the integration of services and resources across distributed, heterogeneous, dynamic virtual organizations (Foster *et al.*, 2002). The most famous solution to Grid computing is the Globus Toolkit, which is an open source set of services and software libraries that support Grids and Grid applications (Foster, 2006). Grids have been successfully applied in many e-Science projects covering various areas of science, engineering, and medicine (Hey and Trefethen, 2005).

In addition to Grid computing, cloud computing is also a popular paradigm of distributed computing characterized by the delivery of storage capacity, computational capacity, and software as Web services, and the decoupling of service delivery from underlying technology (Armbrust *et al.*, 2010). Cloud computing has arisen from the improvements in software abstractions that hide the complexity of

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underlying hardware architectures from the programmer (Mika and Tummarello, 2008). As a pioneer of cloud computing, Google has contributed such fundamental technologies as the Google File System (Ghemawat *et al*., 2003), the MapReduce framework (Dean and Ghemawat, 2008), and the Big Table system (Chang *et al*., 2008). Cloud computing technologies have been fully implemented as an open source project named Apache Hadoop (a collection of related subprojects such as HDFS, HBase, and Pig), which accelerates the adoption of cloud computing in small and medium enterprises. Scientists and engineers have used cloud computing in research on a number of topics, including large-population genetic risk analysis, information retrieval, and particle physics (Fox, 2011). Recently, Delic and Walker (2008) identified a clear trend of applying cloud computing in academic environments.

According to Foster *et al*. (2008), Grid computing and cloud computing are closely related paradigms that share a lot of commonality in their vision, architecture, and technology. They also share some limitations, namely the inability to provide intelligent and autonomous services, the incompetency to address the heterogeneity of systems and data, and the lack of machine-understandable content. Mika and Tummarello (2008) identified the root cause of these limitations as the lack of 'Web semantics'.

The Semantic Web is an emerging technical movement target on Web semantics (Berners-Lee *et al*., 2006). The Semantic Web languages, such as Resource Description Framework (RDF), RDF Schema (RDFS), Web Ontology Language (OWL), and SPARQL, together with a rich set of pragmatic tools, enable a Web of data with semantics formally defined (Domingue *et al*., 2011). The reliability, effectiveness, and efficiency of these technologies have been proved in practical applications from various domains such as biology, medical science, healthcare, and pharmaceutics. As Semantic Web technologies are reaching maturity, computer scientists are exploring the possibilities of integrating Semantic Web technologies into other Web-based technologies (e.g., SOC, Grid computing, and cloud computing), to create more powerful integration solutions. In this paper, we will discuss three major trends of technical integration: Semantic Web Services (Payne and Lassila, 2004), the Semantic Grid (de Roure *et al*., 2001), and the Knowledge Service Cloud (KSC).

2 Semantic Web Services

On one hand, SOC is very effective in supporting the collaboration within a distributed and multidisciplinary team. On the other hand, the Semantic Web allows data and knowledge to be explicitly described in order to eliminate misunderstandings between team members. Therefore, Payne and Lassila (2004) proposed Semantic Web Services (SWS) as the integration of the two technical approaches. SWS is characterized by the use of shared ontologies, such as Web Service Modeling Ontology (WSMO) (Roman *et al*., 2005), to model various aspects of Web services, including service interfaces, service messages, and service structures, which enables the discovery, composition, and invocation of services in an automatic and ad-hoc manner (Burstein *et al*., 2005; Wang *et al*., 2007). While SWS technologies have several technical advantages, several real-world issues, such as authentication and authorization, must be solved before these technologies gain widespread use (Battle and Benson, 2008).

3 Semantic grid

Soon after the invention of the Semantic Web, de Roure *et al*. (2001) advocated "the application of Semantic Web technologies both on and in the Grid". While the original Grid focuses on the vision of computational capacity and storage as a utility, the Semantic Grid focuses on the sharing and reuse of knowledge. In this sense, the Semantic Grid is very similar to the notion of 'Knowledge Grid', which is "a mechanism that can synthesize knowledge from data through mining and reference methods and enable search engines to make references, answer questions, and draw conclusions from masses of data" (Berman, 2001). The research issues of the Semantic Grid include knowledge representation, knowledge integration, knowledge discovery, problem-solving, and automated reasoning in a Grid environment. The Semantic Grid has been applied in various domains such as traditional Chinese medicine and intelligent transportation (Wu and Chen, 2008). The success of the Semantic Grid encourages us to explore the potential marriage of the Semantic Web and cloud computing.

4 Knowledge Service Cloud

A KSC is characterized by providing 'knowledge as a service' for Web users anytime, anywhere, and via any device. A KSC is empowered by Web semantics: it both consumes knowledge and data from the Web of data, and incorporates Semantic Web technologies. A KSC is an open space that allows the voluntary participation of both humans and robots who can collaborate in knowledge creation.

A KSC makes heavy use of domain ontologies, to attach semantic annotations to documents and knowledge resources, and to specify the semantics of Web services. Ontologies also facilitate the construction of open knowledge services, which can be used by other parties in various knowledge-driven research applications. Here, we briefly discuss three classic types of knowledge services:

Knowledge sharing services facilitate Web users to set up ontology-based knowledge bases that store and manage domain knowledge (e.g., concepts, semantic relations, evidence, patterns, and rules), and to access and reason about their content.

Decision support services facilitate Web users to make informed decisions by retrieving relevant evidence and executing business rules. Take healthcare as an example. Decision support services include context-aware recommendation, reminder and alert, adverse drug event detection, report generation, clinical pathway, disease management, and so on. Clinical logics can be expressed as executable rules in Semantic Web languages, and embedded in rule engines that support these applications.

Knowledge discovery services facilitate Web users to discover actionable knowledge (patterns and rules) from the Web of data. Knowledge discovery experiments can be modeled as a tree of operators, each operator implemented with knowledge services or knowledge resources on the Web. Knowledge discovery services facilitate users "to leverage the power of amalgamation and serendipitous reuse" (Berners-Lee *et al*., 2006) provided by the Semantic Web.

Here, we propose a reference architecture of the KSC, containing four layers:

1. Ontology layer. This layer provides various services for the access of shared domain ontologies, enabling ontology engineering and management in a virtual organization. To achieve collective intelligence across organizations, large-scale ontologies are engineered mostly in a decentralized manner. The Semantic Web can merge these disparate ontologies and provide higher layers with a coherent ontology service. For example, the biomedical community has adopted the OWL to express domain ontologies. The legacy ontologies, traditionally represented in heterogeneous formats, are translated into Semantic Web languages such as OWL, and are integrated together in incremental steps. With these achievements, we can foresee a unified biomedical ontology available on the Semantic Web in the future.

2. Resource layer. This layer enables the integration and retrieval of knowledge resources within a virtual organization. A biomedical practitioner can manage, read, and use only a small subset of knowledge resources (academic papers, clinical records, etc.) generated by the entire community. These disparate resources can be aggregated by intelligent agents for integrative knowledge discovery. In addition, by extracting structured data from free-style documents, we can build a machine-understandable Web in a scalable manner.

3. Knowledge service layer. This layer wraps formal knowledge and reasoning capabilities as self-explained and reusable services, enabling the production and management of knowledge assets within a virtual organization. This layer contains intelligent agents that can collaborate with each other via knowledge services and assist humans in problem-solving. The intelligent agents could discover important Web resources, discern latent semantic associations, and/or interpret interesting patterns. Existing methods of reasoning, machine learning, and data mining can be adopted to implement these intelligent agents. These agents are developed in Semantic Web languages such as RDF/XML, OWL, and SPARQL, instead of SQL. This paradigm hides the complexity of domain logics and the underlying data structures, and can support more generic and powerful applications.

4. Application layer. This layer implements intelligent applications through the composition of knowledge services. This layer contains personalized agents that translate a researcher's problem-solving requirements into a series of service requests against lower layers. It also provides interactive mechanisms for the navigation and visualization of various forms of knowledge.

5 Conclusions

The scientific community is still searching for the ultimate technical solution to an e-Science infrastructure. Such an infrastructure will emerge from the integration of the Semantic Web, Grid computing, cloud computing, and potentially other technologies as well. The major character of this future e-Science infrastructure is 'knowledge as a service', which emphasizes supporting knowledge creation activities with intelligent services anytime, anywhere, and via any device.

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