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Grid resource discovery based on semantically linked virtual organizations

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Locating desirable resources and information from a large-scale grid is challenging due to the considerable diversity, large number, dynamic behavior, and geographical distribution of the resources. In this paper, we propose an efficient discovery framework which organizes a grid network by a semantically linked overlay representing the semantic relationships between grid participants. Specifically, we use a semantics-aware topology construction method to group similar nodes to form a semantic small-world. With the small-world topology constructed, resource-discovery queries will be propagated only between semantically related nodes, which greatly improves the efficiency and accuracy of resource discovery in grids. Moreover, we propose a novel algorithm for efficient resource information integration and searching over the semantic small-worlds. Our experiments with simulations substantiate that this framework significantly improve the search expressiveness, efficiency, scalability, and precision.

1. Introduction

Grid computing is a virtualized distributed computing environment aimed at enabling the sharing of geographically distributed resources. Grid resources have traditionally consisted of dedicated super-computers, clusters, or storage units. With the present ubiquitous network connections and the growing computational and storage capabilities of modern everyday-use computers, more resources such as PCs, devices (e.g., PDAs and sensors), applications, and services are on grid networks. Grid is expected to evolve from a computing and data management facility to a pervasive, world-wide resource-sharing infrastructure. To fully utilize the wide range of resources in the grid, effective resource discovery mechanisms are required. However, resource discovery in large-scale semantic grids is very challenging due to the potentially large number of resources, and their diverse, distributed, and dynamic nature. In addition, it is equally difficult to integrate the information sources with a heterogeneous representation format.

The provision of an *information service* [1], as currently envisaged by the grid community, is a first step towards the discovery of distributed resources. However, a large part of these efforts have been focused on "getting it to work," without directly addressing issues of scalability, reliability, and information quality [2]. For example, classical grids always use centralized or static hierarchical models to discover resources. The Globus Toolkit [3] is a famous example. Globus users can get a node's resource information by directly querying a server application running on that node, or querying dedicated information servers that retrieve and publish the resource information of the organization. Although interactions between these information servers are supported, the general-purpose decentralized service discovery mechanism is still absent. To discover resources in a more dynamic, large-scale, and distributed environment, peer-to-peer (P2P) techniques have been used in resent research (e.g., [4,5]). P2P systems offer many benefits, such as adaptation, self-organization, fault-tolerance, and load-balancing, but they also present several challenges that remain obstacles to their widespread acceptance and usage in grids: First, current P2P systems offer limited data management facilities; in most cases, searching information relies on simple identifiers or Information Retrieval (IR)-style string matching. This limitation is acceptable for file-sharing applications, but in order to support complex resource discovery in semantic grids, we need richer facilities for exchanging, querying and integrating structured and semi-structured data. Second, most P2P systems specialize in a single functionality, for example, music sharing. More work needs to be done to support the sharing of varieties of resources in grids. Moreover, designing a good search mechanism is difficult in P2P systems because of the scale of the system and the unreliability of individual peers.

This paper seeks to provide a general solution to the above-mentioned problem. It proposes a framework to share and discover resources on an unprecedented scale, and for geographically distributed groups to work together in ways that were previously impossible. To get enlightened by the recently proposed Semantic Link Network (SLN) [6,7], we propose a distributed semantics-based discovery framework. We make use of SLN model to enable rich semantic representation, reasoning, execution, and to construct a "semantic small-world" structure—OntoSum. OntoSum is based on the observation that query transferring in social networks

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is made possible by locally available knowledge about acquaintances. Because of the similarity between grid networks and social networks and the fact that human users of grid networks direct grid nodes' links, we argue that grid networks can also utilize this phenomenon to discover resources. Peers in OntoSum use their ontology summary to represent their expertise; they learn and store knowledge about other peers with a view to their potential for answering prospective queries. This way, the network topology is reconfigured with respect to peers' semantic properties. This reconfiguration partitions the large unorganized search space into multiple well-organized semantically related sub-spaces, which we call semantic virtual organizations. Semantic virtual organizations help to discriminatively distribute resource information and queries to related nodes, thus reducing the search space and improving scalability. To further improve the efficiency of searching the virtual organizations, we propose a semantics-based resource-integrating and routing algorithm RDV (representing for Resource Distance-Vector-based), in which resource semantic metadata is decomposed into different coarse-grained elements, and then these elements are indexed with different schemes to improve scalability. We evaluate the performance of our system with extensive simulation experiments, the results of which confirm the effectiveness of the design.

The remainder of this paper is organized as follows: Section 2 presents the concept, property and construction of a semantic small-world architecture—OntoSum. Section 3 explains how resource discovery is performed in OntoSum. Section 4 proposes a comprehensive semantics-based query routing algorithm, RDV, which works as an improved routing algorithm to forward queries inside OntoSum clusters. Simulation experimental results are given in Section 5. Related work and concluding remarks are provided in Sections 6 and 7, respectively.

2. Semantic small-world

A widely-held belief pertaining to social networks is that any two people in the world are connected via a chain of six acquaintances (*six-degrees of separation*) [8]. The famous Milgram's experiments illustrated that individuals with only a local knowledge of the network (i.e., their immediate acquaintances) may successfully construct acquaintance chains of short length, leading to networks with "small-world" characteristics. Small-world networks exhibit special properties, namely, a small average diameter and a high degree of clustering. A small diameter corresponds to a small separation between peers, while a high clustering signals tight communities. Small world graphs contain inherent community structure, where similar nodes are grouped together in some meaningful way. Intuitively, a network satisfying the small-world properties would allow peers to reach each other via short paths while maximizing the efficiency of communication within the clustered communities.

We draw inspiration from small-world networks and organize nodes in our system to form a small-world topology, particularly from a semantic perspective. Our objective is to make the system's dynamic topology match the semantic clustering of peers, i.e., there is a high degree of semantic similarity between peers within the clustered community; this would allow queries to be quickly propagated among relevant peers as soon as one of them is reached. To construct the semantic small world network depicted above, we follow the idea of the Kleinberg experiment [9]: each node keeps many close neighbors (short-range contacts), as well as a small number of distant neighbors (long-range contacts). The distance metric in our system is determined by nodes' semantic similarity. With the semantics-based small-world constructed, a query can be efficiently resolved in the semantic cluster neighborhood through short semantic paths.

2.1. Semantic basics

A major focus of our discovery solution is to provide an intelligent semantic search to overcome the problem of traditional keyword-based search. We employ ontology domain knowledge and SLN to assist in the search process, so that queries can be properly interpreted according to their meanings in a specific domain with the inherent relations between concepts also being considered.

2.1.1. Ontology-based metadata representation

Metadata, the data about data, is a crucial element of a discovery infrastructure. Effective metadata requires shared representations of knowledge as the basic vocabulary from which metadata statements can be asserted. An ontology, "a shared and common understanding of a domain" [10], is precisely intended to convey that kind of shared understanding. Therefore, we use ontologies to represent resource metadata semantics. An ontological representation defines concepts and relationships. To cope with the openness and extensibility requirements, we adopt two W3C recommendations: the Resource Description Framework (RDF) [11] and the Web Ontology Language (OWL) [12] as our ontology language. We concentrate on RDF's property of making statements about resources in the form of *subject–predicate–object* expressions, called *triples* in RDF terminology. The *subject* denotes the resource which has a Universal Resource Identifier (URI). The *predicate* denotes traits or aspects of the resource and expresses a relationship between the *subject* and the *object*. The *object* is the actual value, which can either be a resource or a literal. The concept of triple is very important in our work, because our metadata indexing scheme is based on this triple representation.

In our system the ontology knowledge is represented by OWL-DL and is separated into two parts: the terminological box (T-Box) and the assertion box (A-Box) as defined in the description logic terminology. The purpose of distinguishing between the T-Box and A-Box is to enable different coarse-grained indexing based on these two cases. The T-Box is a finite set of terminological axioms, which includes all axioms for concept definition and descriptions of domain structure. The A-Box is a finite set of assertional axioms, which includes a set of axioms for the descriptions of concrete data and relations. Separating the T-Box and A-Box enables different coarse-grained knowledge indexing, thus increasing the scalability of the system.

2.1.2. Semantic links

For many reasons, different people and organizations tend to use different ontologies. Therefore, we have to deal with situations where various local ontologies developed independently are required to be integrated as means for extracting information from the local ones. Semantic links provides a layer from which several ontologies could be accessed and hence information could be exchanged in a semantically sound manner. Semantic links relates the entities of two ontologies that share the same domain of discourse in such a way that the logical structure and the intended interpretations of the ontologies are respected. We adopt the semantic links defined by Zhuge in [13]. In particular, a semantic link between two ontologies can be one of the following types:

1. *Equal-to*, denoted by $Pi\text{—}equ \rightarrow Pj$, says that Pi is semantically equal to Pj. The equal-to link is reflexive, symmetric, and transitive.
2. *Similar-to*, denoted by $Pi - (sim, sd) \rightarrow Pj$, says that Pi is semantically similar to Pj to the degree sd.
3. *Reference*, denoted by $Pi - ref \rightarrow Pj$, says that Pi refers semantically to Pj.
4. *Implication*, denoted by $Pi - imp \rightarrow Pj$, says that Pi semantically implies Pj. The implication link is transitive and can