Integrating Agents, Ontologies, and Semantic Web Services for Collaboration on the Semantic Web

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Abstract

In fact, the vision of the Semantic Web proclaims seamless support for automated collaboration over the Web. Collaboration is concerned with cooperative interaction of individuals for achieving complex objectives; appropriate technologies for automated collaboration support on the Semantic Web need to reflect the nature of collaboration on the one hand, and, on the other, to comply with several technical requirements arising for Semantic Web technology. This paper presents an approach for combing agent technology, ontologies, and Semantic Web Services into a coherent, integrated technology for automated collaboration support on the Semantic Web.

1 Introduction

In order to indicate the vision of the Semantic Web as the next evolution step of the Internet, [Berners-Lee et al, 2001] give the following every day's life example. The siblings Pete and Lucy need to arrange doctoral treatments for their mother; each of them has a personal agent that performs tasks automatically. In order to fix appointments at the doctor and organize transportation, Pete's and Lucy's agents interact and coordinate their actions; they determine a suitable doctor and arrange appointments automatically, they elaborate transportation plans with regard to Pete and Lucy's time schedules, and exchange information on several issues. All information applied by the agents is exchanged over the Internet; also, computational facilities as well as information repositories used by the agents are accessed over the Internet.

In fact, this example proclaims the Semantic Web as a worldwide infrastructure for automated collaboration support. Collaboration refers to cooperative interactions of individuals for achieving complex objectives, wherefore automated support along with information interchange and processing over the Web is envisioned. As stated later in the referenced article, three key technologies are identified for realizing this vision: agents for representing real-world entities and automated task resolution on behalf of their owner, ontologies for semantically enhanced information exchange and processing over the Web, and Web Services as computational facilities accessible on the Web. These need to be integrated into a coherent technical framework.

We observe numerous research results and ongoing efforts for each of the identified key technologies. Research on intelligent agents has produced several results on agent architectures and multi-agent systems as a novel system design paradigm; recently addressed issues are semantic interoperability and advanced agent coordination mechanisms. Ontologies are widely recognized as an appropriate knowledge representation technique; standard ontology languages are recommended, and several research efforts are concerned with ontology technologies for the Semantic Web. While the current Web Service technology stack around UDDI, WSDL, and SOAP provides initial support for Web Service usage and application development, the emerging concept of Semantic Web Services combines Semantic Web and Web Service technologies in order to provide advanced facilities for automated discovery, composition, contracting, and execution of Web Services. However, a framework that coherently integrates these technologies do does not exist.

The basic setting for automated collaboration support on the Semantic Web appears to be intuitively: agents shall serve as electronic representatives of real-world entities that interact in a cooperative manner to solve the objectives of their owner; agents should be able to access and interchanged semantically annotated information over the Web, and to utilize Web Services as computational facilities. However, a sophisticated technology framework needs to define a proper model of agency that reflects collaborating real world entities along with mechanisms for determining agents as appropriate collaboration partners as well as resources to be applied for automated collaboration execution, and to support ontologies as the underlying data model with respect to semantic interoperability on the Web. This paper presents an approach towards an integrated technology framework for collaboration support on the Semantic Web.

The paper is structured as follows: Section 2 reveals the characteristics of collaboration and examines proper technology support; Section 3 presents our framework for collaboration on the Semantic Web, including the conceptual model, the system elements definition, and the collaboration management techniques developed; Section 4 examines a running example; Section 5 discusses related work, and Section 6 concludes the paper.

2 Collaboration and Technology Support

In order to motivate our approach and determine the state of the art in respective technologies, the following examines the epistemology of collaboration and existing support from agent and web technology in order to derive requirements for Semantic Web collaboration technologies.

2.1 What is Collaboration?

Collaboration is an essential asset of human society, denoting cooperative interaction of individuals in order to achieve complex objectives. Unfortunately, this is an intangible subject wherefore an overall theoretical model does not exists that could serve as the conceptual basis for designing prosperous technology support. Hence, we need to examine related academic disciplines in order to determine the inherent characteristics of collaboration.

From socio-economical theories we learn that collaboration is a constitutional feature of society. As the facilities needed to achieve a complex objective typically are distributed among the members of society, collaboration is required; with respect to efficiency of labor divided between several entities, appropriate management structures are required [Mankiw, 2000]. Communication, i.e. interchange of information is the central means for collaboration as it enables individuals to co-align their activities to collaborative objectives. As for collaboration, a commonly accepted theory of communication does not exist. However, [Habermas, 1981] defines *communicative competence* as the prerequisite for successful communication: this is given if each communication partner can express himself comprehensively with respect to syntax and semantics of speech, and if all partners are willing to achieve a successful information interchange.

Psychology provides insights on the behavior of individuals that participate in collaborations. Freud's theory of mind distinguishes three interdependent elements (*id-ego-superego*) that determine both the internal decision process and the external visible behavior of an individual. The *theory of goal congruency* explains the motivation of an individual for participating in collaborative interactions if its personal objectives can be achieved therein, i.e. if the interaction of several individuals can result in a status of the world that satisfies the individual objectives of each participant [Martin and Stewart, 2001]. Technologies for supporting collaborative interactions between real-world entities should reflect these characteristics appropriately.

2.2 Agent and Web Technology

Agent and Web technology are the basis for automated collaboration support on the Semantic Web. While agent technology develops systems wherein autonomous agents reside that satisfy their particular objectives by interacting in a collaborative manner, the Web provides a world wide infrastructure for information provision and communication. The following briefly examines the state of the art in both with regard to collaboration support.

Following [Wooldridge, 2002], the foundation of agent technology are models of agency that define the structure and usage of agents in a system. Four inherent properties of agents are defined on basis of socio-psychological models: *autonomy*, *social abilities*, *re-activity*, and *pro-activeness*. While technical realizations of agent architecture cover a wider range, a common characteristic are goal-driven agent architectures. A goal represents the objective that an agent wants to achieve; it is specified in a machine-processable language to allow automated detection of appropriate computational facilities for resolving a goal. Intelligent agents require an appropriate runtime environment that allows agent to communicate and collaborate, referred to as multi-agent systems (MAS). In general, these are comprised of directories for agents, services for multi-agent coordination and interoperation, and a communication system for information interchange between agents.

Recent research issues in agent technologies are semantic interoperability and agent coordination [Luck et al., 2003]. The former refers to terminological consistency between interacting agents, which is given if agents use the same or at least homogeneous terminology for information interchange. Therefore, agent communication languages apply ontologies as semantic terminology definitions for the content of messages. However, determining if interacting agents use homogeneous ontologies is not trivial [Payne et al., 2001]; in fact, this is a main research issue addressed in ontology technologies for the Semantic Web. Agent coordination is concerned with the establishment, execution, and control of agent interactions. Therefore, semantic techniques on basis of declarative descriptions of agents and resources are envisioned [Sycara et al., 1999].

Although the World Wide Web provides a world wide infrastructure for information provision and communication, the initial web technology stack has substantial drawbacks with regard to automated web content processing. Consequently, the Semantic Web and Web Services are envisioned as the next evolution step of web technology that shall overcome these deficiencies. The key technology for the Semantic Web is ontologies: every resource and every data element interchanged shall be described on basis of ontologies. While standards for the lower levels of the Semantic Web language layer cake have been recommended by standardization bodies, current research efforts address appropriate technologies for ontology management (i.e. editing, storage, and retrieval, evolution support) as well as ontology integration [Fensel, 2003].

Web Services have been proclaimed to enable access and usage of computational facilities over the Internet. As current Web Service technologies around UDDI, WSDL, and SOAP provide only limited support for dynamic and automated Web Service usage, the emerging concept of Semantic Web Services aims at more sophisticated technologies. Based on exhaustive semantic description frameworks, intelligent mechanisms are envisioned for automated discovery, composition, contracting, and execution of Web Services [Fensel and Bussler, 2002]. Applying ontologies as the underlying data model, we can understand Semantic Web Services as an integrated technology for realizing the vision of the Semantic Web. The most prominent frameworks are OWL-S that defines an exhaustive ontology for describing Web Services [OWL-S, 2004], and WSMO that defines Ontologies, Goals, Web Services, and Mediators as top-level elements for Semantic Web Services [Roman et al., 2005]. We observe that Semantic Web Service technologies for automated discovery, composition, mediation, contracting, and semantic execution support address the same aspects as interoperability and coordination within agent systems.

Summarizing, agent technology provides methodologies and architectural approaches that reflect the epistemology for collaborative interactions in the real world, while emerging Web technologies will provide a world wide infrastructure for communication and information exchange with support for semantically enhanced information processing and distributed computing over the Web.

2.3 Collaboration Technology Requirements

We identify seven requirements for sophisticated technologies for collaboration support on the Semantic Web. These integrate technical design principles from agent and Web technology with respect to the epistemology of collaboration outlined above.

1. Agents as Symmetric Collaboration Entities
Software agents should act automatically as electronic representatives on behalf of real-world entities that are involved in collaborative interactions. Agents should be structured symmetrically in order to overcome the deficiencies of the traditional requester-provider model.

2. Goal Driven Architecture
In accordance to agent architectures, collaboration systems should realize goal-driven architectures. Goals should allow specification of objectives that are to be resolved in a collaboration. With respect to sophisticated support from the user perspective, goals should be decoupled from technical usage requests.

3. Web Compliance
Information exchange and communication of the Internet must be supported. To ensure scalability and compatibility to Web technologies, collaboration system architectures need to comply with the design principles of the Web.

4. Ontologies as Data Model
Information used and interchanged in collaborative interactions should be based on ontologies in order to ensure semantic interoperability between machines. This means that every data element in resource descriptions or interchanged between resources is to be based on ontologies.

5. Strict Decoupling and Strong Mediation
Decoupling denotes that resources are defined independently without regard to possible interactions with other resources; mediation refers to handling of possibly occurring mismatches that occur between resources that are ought to interoperate. Decoupling and mediation are reciprocal principles for handling heterogeneity in Semantic Web Services [Fensel and Bussler, 2002].

6. Semantic Collaboration Management
Collaboration management, i.e. establishment, execution, and control of collaborations need to rely on a theoretic model that properly reflects the characteristics of collaboration. In order to ensure precision and high quality collaboration support, semantically enabled techniques should be applied for collaboration establishment and execution.

7. Maximal Automation
The collaboration process should be automated to the highest extent possible, with respect to human-machine interaction as well as to machine-machine interaction.

3 Integrated Collaboration Framework

On basis of the preceding examinations, the following presents our integrated framework for collaboration support on the Semantic Web. Section 3.1 introduces the conceptual model, Section 3.2 explains the specification of the core elements, and Section 3.3 presents the collaboration management process along with the techniques applied.

3.1 Conceptual Model

Figure 1 shows the conceptual model. In accordance to the requirements determined above, agents act as electronic representatives of real-world entities involved in collaborative interactions. Agents carry goals that are to be resolved in collaborations, use so-called Collaboration Services as computational facilities for participating in collaborations that are executed automatically over the Semantic Web, and autonomously control their collaboration behavior.

For collaborative problem solving, several real world entities specify their individual objectives independently of each other and delegate these as goals to their respective agent for automated resolution. An agent can be assigned with several different goals, whereby each goal is to be solved in a separate collaboration. Agents are considered as potential collaboration partners if they have compatible goals, meaning that a collaborative interaction can resolve the individual goals of the agents.

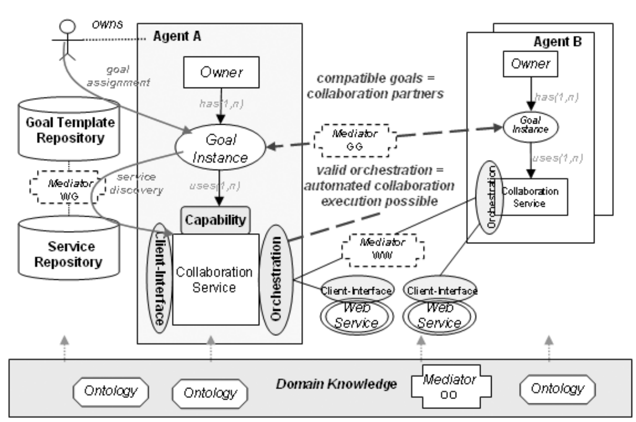

Figure 1: Conceptual Model

Collaboration Services, a special type of Web Service, provide the computational facilities that agents use for participating in automatically executed collaborations. They enable automated communication and information interchange with other agents over the Semantic Web as well as usage of other Web resources. Suitable Collaboration Services are dynamically detected or constructed for each collaboration; a service is considered to be usable by an agent if it can resolve the goal assigned to the agent. A collaboration is executed by the interaction of the Collaboration Services used by collaborating agents. Therefore, the services used by collaborating agents need to have compatible interaction behaviors.

Ontologies provide the underlying data model, i.e. that all element definitions are based on ontologies and all data interchanged are ontology instances. Mediators resolve possibly occurring mismatches between elements that need to interoperate for collaboration execution, whereby we distinguish different mediator types: *OO Mediators* resolve mismatches between heterogeneous ontologies, *GG Mediators* establish goal compatibility between goals that are not compatible a priori, *WG Mediators* make Collaboration Services usable for agents that are not usable a priori, and *WW Mediators* establish interaction behavior compatibility of Collaboration Services if this is not given a priori.

3.2 Element Specifications

The framework is comprised of five main elements: Ontologies, Agents, Goals, Collaboration Services, and Mediators. Each element has a clearly defined semantic description for supporting automated, semantically enabled collaboration management. Ontologies consist of concepts, relations, axioms, and instances defined in conventional ontology specification languages. The concept of mediators in our approach is aligned with WSMO [Mocan et al., 2005], so that mediation techniques and facilities developed for Semantic Web Services can be applied. In consequence, we here only expose the specification and usage of agents, goals, and collaboration services that we extend from existing approaches.

Model of Agency. The purpose of agents in our framework is to serve as electronic representatives of real-world entities that aim at achieving individual objectives by collaborative interactions, thereby minimizing human intervention in the collaboration process. An agent is assigned with several goals for automated resolution during its lifetime, it uses Collaboration Services as the facilities for participating in automatically executed collaborations, and it autonomously manages its behavior in the system. Goals and services are assigned, respectively detected dynamically to an agent during system runtime. All information of agents is based on ontologies, so that terminological consistency as well as semantic interoperability with other agents and resources is supported.

This is an extension of so-called *collaborative interface agents* [Lashkari et al., 1994]. Re- and pro-activity of such agents is allocated in the interaction with their respective owner as well as in the interaction with other agents. In our framework, the former is realized in task delegation via goal assignment, while the latter is realized as collaborative interaction of agents via Web Services. Agents are structured symmetrically in order to subjugate the restrictions of requester-provider models. Each agent individually manages its collaborative behavior by utilizing services for semantic collaboration management as explained further in Section 3.3 Agents use ontologies as the underlying data model in order to assure semantic interoperability, and use Web Services as the computational facilities for automated collaboration execution as requested in [Lyell et al, 2003].

This model of agency allows computerizing the collaborative behavior of real world entities as delegation and automated resolution of tasks, performed by symmetrically structured agents that interact over the Semantic Web. With respect to the requirements determined above as well as on agents for the Semantic Web stated in [Payne et al., 2002], this appears to be a sophisticated model of agency for collaboration on the Semantic Web.

Goal Definition. Goals are semantically described specifications of objectives that real-world entities want to achieve in a collaboration by delegation to an agent for automated resolution. In order to facilitate maximal automation, we distinguish two types of Goals: *Goal Templates* and *Goal Instances*. A Goal Template is a predefined schema of a goal, whereof several Goal Instances are created of during runtime that denote the concrete goal assigned to an agent. Goal Templates denote the final state of the world that is considered to be satisfying a user's objective. With respect to openness and incompleteness of the Web, this is described by *postconditions* that specify conditions on the objects expected to be received as computational results and by *effects* that specify conditions on the world that shall to hold when the goal is resolved. A Goal Instance inherits the definition of its Goal Template, refines the postcondition and effects with regard to the concrete user objective, and carries additional information for automated service usage. A *submission* that contains ontology instances as the information that is intended to be submitted as input to a service, a *result* that holds the information returned as output after service usage, and *preferences and policies* that define conditions and restrictions collaboration partners, usable resources, on the goal resolution process. For the latter, the restrictions are defined as snippets of processes descriptions in the spirit of extended goal descriptions defined in [Pistore and Traverso, 2002].

This goal definition allows precisely specifying the objective to be achieved from a user perspective without regard to its technical resolution. In WSMO, OWL-S, as well as in formal software description, goals are defined as service descriptions from the requester perspective which contradicts the aim of decoupling goal definitions from technical usage requests and limits the applicability to requester-provider models. Goal definitions in agent systems mostly are predicates on the information space of an agent. In contrast, our goal definition provides an ontological model of the goal description elements, thus allowing concise handling of goals in the resolution process.

Collaboration Services. Services in our framework provide the computational facility an agent uses for participating in an automatically executed collaboration. They enable agent *A* to interact with an agent *B* via their respective Collaboration Services and allow usage of other resources needed for automated collaboration execution. An agent serves as the client for a Collaboration Service in association with the Goal Instance that is to be resolved in a collaboration. Figure 2 shows the service usage model.

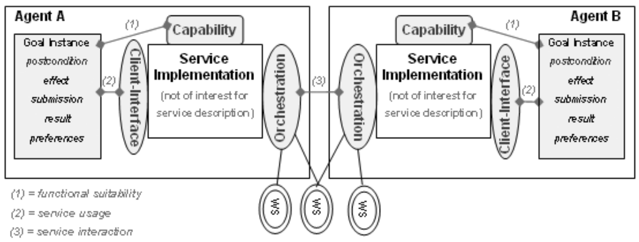

Figure 2: Service Usage Model

We define a semantic service description model for enable automated, semantically enabled detection and usage of Collaboration Services. Despite of non-functional properties for resource management, the *capability* provides a functional service description used to determine usability of a service by an agent; the *client interface* describes how the service can be automatically used by an agent via a Goal Instance; and the *orchestration* describes how the service functionality is achieved by the interaction with other agents via their Collaboration Services as well as with other utilized Web Services and resources. As a suitable basis, Collaboration Service descriptions rely on WSMO Web Service descriptions. A capability describes the service functionality by conditions on the pre- and post-state in order to determine usability of the service; WSMO service capabilities allow this, while OWL-S service profiles combine functionality descriptions with in- and outputs. Besides, WSMO provides a formal, ontology-based model for describing the dynamics of service usage and interaction on basis of Abstract State Machines [Scicluna et al., 2005] that we use for describing the client interface and the orchestration of Collaboration Services.

We consider Collaboration Services as a special kind of Web Services as they have very similar characteristics. They are computational facilities that allow information interchange and interaction between agents over the Web as well as usage of other Web resources in order to achieve their functionality. However, our service usage model differs from current architectural models for Web Services wherein Web Services are understood as both an objective of the provider and a computational facility. In our framework, real-world entities are represented by agents with goals as objective definitions, while Collaboration Services are only computational facilities that carry a semantic description in order to enable automated service detection and usage.

3.3 Semantic Collaboration Management

Each agent individually manages its collaborative behavior by establishing and executing collaborations for resolving its assigned goals. Therefore, agents follow the collaboration management process shown in Figure 3. While the functional components for collaboration establishment and execution are provided as external Web Services (gray boxes in the figure), each agent controls the establishment and execution of collaborations autonomously.

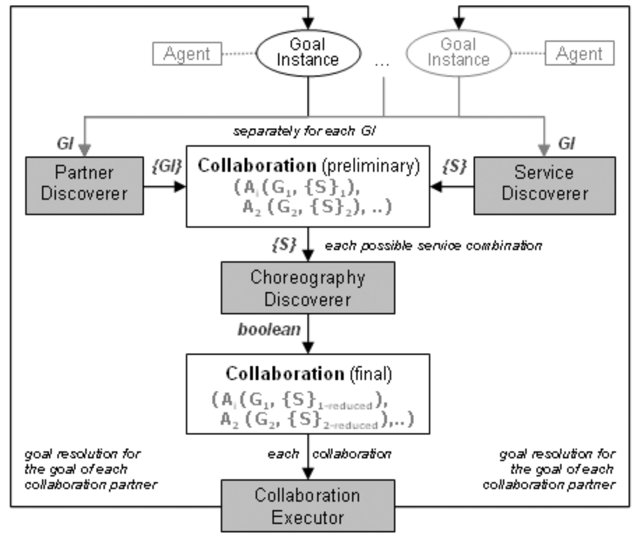

Figure 3: Collaboration Management Process

Collaboration establishment is concerned with creating potentially successful collaborations. Therefore, agents use three distinct discovery components: the *Partner Discoverer* detects potential collaboration partners, the *Service Discoverer* detects usable Collaboration Services for the agent, and the *Choreography Discoverer* determines existence of a valid interaction protocol for the Collaboration Services of the collaboration partners. As a detailed description of the mechanisms exceeds the scope of this paper, the following only outlines the realization of the collaboration management components.

Partner Discovery. Detection of agents as appropriate collaboration partners is achieved by determining compatibility of their respective goals. With regard to the theory of goal congruency, this is given if a collaboration of the agents results in resolution of the goals of all participants. For determining this, goal postconditions and effects are described by actions that are to be performed on objects of interest. Actions and their compatibility are defined in a special action-resource ontology that allows determination of goals with compatible actions, while we realize semantic matchmaking for object definitions. We refer to [Stollberg et al., 2005] for a more detailed discussion.

Service Discovery. Service discovery determines usability of a Web Service that allows participation in an automated collaboration. This is given if the action defined in a service description is equal to the one of a goal to be resolved in a collaboration, and if the service is capable of providing objects that can satisfy the objective defined in the goal. This is realized on the same basis as partner discovery, whereby we determine action equality on basis of the action-resource ontology perform object matchmaking between the service capability and the respective goal description elements. Partner and service discovery are performed concurrently and independent of each other; their respective discovery results are combined into a preliminary collaboration that contains the agents as collaboration partners, their goals, and usable Collaboration Services.

Choreography Discovery. This determines existence of a valid interaction protocol for the interaction of the Collaboration Services used by the partners. Based on previous work [Martens, 2003], we therefore need to determine whether there exists a valid choreography for the services. This is given if (1) the services' orchestrations use homogeneous ontologies, (2) the information to be interchanged, i.e. the content of communicative acts is compatible, and (3) the communication protocol of the choreography is sound, meaning that there is at least one start state, and a termination state can be reached without any additional input. This can be determined on basis of the formal orchestration description, as we present in [Stollberg, 2005] in more detail.

The Collaboration Execution Environment provides the technical environment used by agents for executing collaborations, along with facilities for executing management and control as well as post-execution processing. Collaborations are executed by the interaction of Collaboration Services and the other resources used. The execution of is performed remotely, by the agent submitting the input defined in the Goal Instance. Execution management and control is concerned with scheduling collaboration executions, ensuring accessibility of the required resources, and ensuring that equivalent collaborations are only executed once. After successful execution of a collaboration, the resolution of the goals of the participating agents is inspected: if the objects held in the result of the Goal Instance satisfy the postcondition and effects, then the goal is considered to the resolved.

4 A Running Example

We have implemented a prototypical realization of our framework within the Semantic Web Fred system, see project homepage: http://swf.deri.at. For demonstrating our approach, especially with regard to collaboration management by agents, the following exemplifies a simple collaboration scenario from an exhaustive use case in the domain of purchasing as the essential collaborative activity of society (see [Stollberg, 2004] for details on this).

We define several buyers, sellers, service providers, as well as a marketplace provider as the participants in the use case. Goal Templates are defined for sellers and buyers, and service providers offer Collaboration Services that can be used by buyer and seller agents for automated collaboration execution. At some point in time, several buyer agents have been assigned with a goal for purchasing some product; also, several seller agents carry goals for selling products. Let's consider a buyer agent B that shall purchase 'a brown chair made of wood'; it specifies the action *buy*, the postcondition specifies a purchase contract for a brown chair made of wood, and the effect defines that the purchased chair shall be delivered to the home address of the owner of B. As potential collaboration partners, there are several seller agents $S_1 - S_n$ that carry goals with the action *sell* and respective object definitions in the postcondition and effects: S_1 might be a private seller that wants to vend a specific chair, and S_k might be a furniture store that offers several chairs for purchasing.

When agent B initiates the collaboration establishment process, partner discovery detects several sellers $S_1 - S_n$ as potential collaboration partners that carry goals with compatible actions and matching objective definitions. Assuming that service discovery detects usable Web Services for each agent B, S_1,…, S_n and choreography discovery determines existence of a valid choreography for these, we retrieve a set of collaborations (B, S_1), (B, S_2), etc. that each can resolve the individual goals of the collaboration partners. As outlined above, collaboration establishment is performed independently for each Goal Instance assigned to an agent. Hence, agent S_1 my concurrently perform collaboration establishment for its goal. Thereof, we attain possible collaborations (S_1, B), (S_1, B_2),…, (S_1, B_m), whereby B_2, B_m denote other buyer agents that are determined as other collaboration partners for S_1. All established collaborations are handed over to the collaboration execution environment, wherein the execution management ensures that the collaboration between B and S_1 is only executed once. As soon as a collaboration execution has successfully solved the goal of an agent, all other collaborations that encompass this goal are terminated.

This example exposes the overall workflow of the automated collaboration process in our system. The symmetric design of agents as collaboration partners allows determining accurate collaborations, whereby semantic resource descriptions and discovery techniques applied from Semantic Web Service technologies allow correct and precise collaboration establishment. This properly reflects the nature of real-world collaborative interactions, and we beneficially combine agent and Web technology.

5 Related Work

We are not aware of any other framework that combines agent technology, ontologies, and Semantic Web Services for automated collaboration support on the Semantic Web comparable to our approach. Nevertheless, we observe several approaches that address related aspects.

The RETSINA system [Sycara et al. 2003] as well as the Open Agent Architecture OOA [Martin et al., 1999] are agent systems that apply semantic techniques for agent coordination. The former distinguishes different agent types: interface agents for user interaction, task agents that create task resolution strategies and control the execution of these; information agents provide access to information sources or computational facilities; and middle agents that determine other agents as appropriate interaction partners on basis of semantic filtering. The OAA also defines different agent types, whereby so-called *facilitators* handle agent coordination by establishing and controlling agent interactions on basis of semantic matchmaking techniques. The system architectures and techniques for agent coordination are similar to the collaboration management process of our framework; however, both systems define general purpose agent system architectures but do not provide automated support for real-world collaborations as aspired within our work.

Concerning determination of appropriate collaboration partners and resources, so-called multi-agent collaboration theories define formal models for determining symmetrically structured agents as potential collaboration partners. The *Joint Intentions theory* [Levesque et al. 1990] defines individuals to be appropriate collaboration partners if they aim at achieving the same status of an object of interest. In contrast, the notion of goal compatibility that we apply for partner discovery defines collaboration partners by congruency of their individual objectives, meaning that an interaction can resolve the individual goals because of specific similarities. We think that this better reflects the nature of individual behavior in collaborative interactions. The *Shared Plan theory* [Grosz and Sidner, 1990] states that several individuals can successfully collaborate if they have a common goal, agree on a sequence of actions to accomplish this, each individual is able to perform collaborative actions, and each individual commits to the overall success of the collaboration. This coincides with the model of collaboration that underlies our framework. We understand a collaboration as an interaction of several entities that each have an individual objective, and they need facilities that embody the interaction behavior for collaboration execution; if these are compatible, then the collaboration can be executed successfully. The commitment for participating in a collaboration is denoted by creation of a goal.

Regarding the integration of agent and Web technology, we observe several approaches that extend agent technologies with Web technologies [Decker et al, 1997], [Zou et al., 2003]; also, the usage of Web Services as computational facilities for agents has been recommended [Dale et al., 2003]. However, these approaches only present partial technology integrations, as they adopt Web technologies and incorporate this into agent technologies. But for an appropriate integration, it is necessary to drill up each technology group, inspect the functional usability of existing building blocks, and then assimilate these into a coherent framework as we have presented here.

Examining conceptual architecture models for Web Service-based systems, we observe that the underlying model implicitly assumes automation of collaborative interactions of real-world entities as the essential system functionality. The W3C Web Service Architecture [Booth et al., 2004] denotes service requesters and providers as real-world entities concerned with Web Service usage and provision; a requester wants to use a Web Service for achieving some objective, and a provider wants its service to be consumed in order to achieve his business objectives. [Preist, 2004] extends this by denoting requester and provider agents, denoting that the real-world entities can or should be represented by electronic agents for automating Web Service usage. Moreover, this paper outlines the different associations of the term 'Web Service': it is understood as a business service that provides added value functionality in a domain, as well as computational facility usable over the Internet. This ambiguity might be caused by lack of experience and missing applications for Web Services. Our approach overcomes this, as objectives of collaboration partners are allocated in agents and goals, while services only provide a computational facility. In this respect, our conceptual model may contribute to a better understanding of the application scenarios and thus the design of Semantic Web and Web Service technologies.

6 Conclusions

This paper has presented an approach for integrating agents, ontologies, and Semantic Web Services into a coherent framework for automated collaboration support on the Semantic Web. Collaboration is concerned with cooperative interactions of individuals in order to achieve complex objectives. Analyzing the vision of the Semantic Web in this regard, we observe that it actually proclaims seamless and automated support for collaboration on the Web.

Agents, ontologies, and Web Services have been identified as the enabling technologies for the Semantic Web at an early stage. However, these have to be integrated concisely, wherefore a sophisticated understanding of the application context is required. Understanding automated collaboration support as the essential functionality of the Semantic Web, we have examined the inherent characteristics of collaboration from related academic disciplines. On this basis and with respect to technical requirements, we have designed an appropriate technology framework for collaboration on the Semantic Web.

The conceptual model defines a model of agency wherein agents act as electronic representatives of real-world entities that are involved in collaborative goal resolution. An agent is a collaborative interface agent that interacts with its owner as well as with other agents in order to achieve its individual objectives. Tasks are delegated to agents are defined as goals, and Web Services are used as the computational facilities for automated collaborative interaction of agents. We use ontologies as the underlying data model throughout the whole system in order to support semantic interoperability, and we use mediators to handle possible occurring heterogeneities between resources that are ought to interoperate. Thereby, we apply methodologies and architectural aspects from agent technology, while resource definitions and semantically enabled collaboration management techniques are based on techniques developed for Semantic Web Services.

Concluding, we have presented an integrated technology framework that allows realizing the vision of the Semantic Web and can serve as a basis for future design of Semantic Web and Web Service technologies.

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