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Title	Automated Collaboration on the Semantic Web
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Publication Date	2005

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Abstract. We understand the vision of the Semantic Web to proclaim seamless and automated collaboration of the Internet. Collaboration is concerned with cooperative interaction of individuals in order to achieve complex objectives; appropriate technologies for collaboration support need to reflect the nature of collaboration, and to comply with several technical requirements with respect to automated and semantically enabled collaboration support. This paper presents a framework for collaboration support on the Semantic Web that coherently integrates agent technology, ontologies, and Semantic Web services.

1 Introduction

Three technologies are proclaimed for enabling the Semantic Web: 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. But what is the underlying application scenario that denotes the requirements for appropriately integrating these technologies? In fact, the Semantic Web proclaims a worldwide infrastructure for automated collaboration support. Collaboration means cooperative interactions of individuals for achieving complex objectives, wherefore automated support along with information interchange and processing over the Web is envisioned. This paper presents a coherently integrated framework for automated collaboration support on the Semantic Web.

The vision of the Semantic Web is motivated in [1] by the following every day's life example. The siblings Pete P and Lucy L need to arrange doctoral treatments for their mother M ; both Pete and Lucy have their personal 'Semantic Web agents', $A(P)$ and $A(L)$. Lucy assigns her agent the task of automatically arranging an appointment with a suitable doctor for the medical treatment that M needs; Lucy also informs Pete, and he agrees to take over chauffeuring M to the doctor. $A(L)$ performs several tasks automatically: finding a doctor that is capable of performing the medical treatment that M needs, selecting those doctors with a good ranking, that are in a radius of 20 miles from M 's home and support her insurance, and finally presenting a complete plan incl. appointment time and transportation information. Then, $A(L)$ interacts with $A(P)$ to check whether the proposed plan is fine with Pete. Pete denies, and makes his agent $A(P)$ determining a different plan that better fits to his calendar. $A(P)$ finds such

a plan and communicates this to $A(L)$. After confirmation of all involved agents and real-world entities, $A(P)$ books the appointment with the agent $A(D)$ of the chosen doctor; this is added to the calendars of the involved parties.

In fact, this example proclaims automated collaboration support on the Web. But how such a system for collaboration support on the Semantic Web really work? That is, how does an agent know which agent to interact with, and which resources to apply, how can semantically correct information interchange be ensured, and how to ensure interoperability of interacting agents and used resources? Neglecting technical details at this point, we observe the following requirements for a technology assemble that enables automated collaboration support on the Semantic Web: there are real-world entities that need to collaborate in order to achieve their individual objectives; each real-world entity might have a personal ‘Semantic Web Agent’ that act as electronic representatives on behalf of their owner. An agent receives tasks by delegation from their owner, creates a plan for solving the task, is capable of interchanging information with other agents, and utilizes other resources needed for automated goal resolution. All information interchange between agents, their owners, and resources used should take place over the Web. Following the vision of the Semantic Web, all data interchanged should be based on ontologies as formal, machine-processable terminology definitions to ensure semantic interoperability, and agents should be able to utilize Web services as computational facilities accessible over the Web. Finally, suitable mechanisms are needed for automatically establishing and executing collaborations between agents. The aim of the work presented here is to elaborate a concise and complete technology framework that utilizes semantic technologies for high-quality, automated collaboration support on the Semantic Web.

This paper summarizes the core aspects of our work and is structured as follows: Section 2 examines the characteristics of collaboration and existing technology support, Section 3 presents the framework developed, including the conceptual model, the system element definitions, and the process and techniques for collaboration management, Section 4 presents the prototype implementation and use case testing, Section 5 discusses related work, and Section 6 concludes the paper.

2 Collaboration and Technology Support

In order to derive requirements for Semantic Web collaboration technologies, the following examines the epistemology of collaboration and existing support from agent and web technology.

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 exist 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 economical, sociological, and psychological theories we learn that collaboration is a constitutional feature of society due to the need for division of labor in order to achieve complex objectives [12]; communication means information interchange in order to enable collaboration, whereby perfect communication hardly achievable between humans [7]; individual behavior results

from internal motivations and decisions, whereby participation in collaborative group interactions is determined by the congruency of individual objectives [15].

2.1 Collaboration Support in Agent and Web Technologies

As the basis for automated collaboration support on the Semantic Web, agent technology develops systems wherein autonomous agents reside that satisfy their particular objectives by interacting in a collaborative manner, while the Web provides a world wide infrastructure for information provision and communication.

Following [26], the foundation of agent technology is models of agency that define the structure and usage of agents in a system. While technical realizations of agent architecture cover a wide range, a common characteristic are goal-driven agent architectures. A goal represents the objective that an agent wants to achieve, specified in a machine-processable language to allow automated detection of facilities for goal resolution. A recent research issue in agent technology is semantic interoperability, i.e. terminological consistency between interacting agents that is given if agents use homogeneous terminology for information interchange. Although agent communication languages apply ontologies as terminology definitions, determining semantic interoperability is not trivial [16]; in fact, this is a main research issue addressed within Semantic Web ontology techniques. Agent coordination is concerned with the establishment, execution, and control of agent interactions, wherefore semantic techniques on basis of declarative descriptions of agents and resources are used [24].

Although the Internet 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. To overcome these deficiencies, ontologies and Web services are envisioned as the basis for next generation Web technologies: every resource and very 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, current research efforts address appropriate technologies for ontology management (i.e. editing, storage, and retrieval, evolution support) as well as ontology integration (mapping, merging, alignment) [6]. Contemporarily, 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 [5]; the most prominent frameworks are OWL-S [25] and the Web service Modeling Ontology WSMO [18]. 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.

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.

2.2 Principles for Next Generation Collaboration Technology

Derived from agent and Web technology design principles and with respect to the epistemology of collaboration, we identify seven technological requirements for sophisticated collaboration support on the Semantic Web.

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 [5].

6. Semantic Collaboration Management

The collaboration management process (establishment, execution, and execution control of collaborations) needs to reflect the characteristics of collaboration; semantically enabled techniques should be applied to ensure precision and high quality collaboration support.

7. Maximal Automation

The collaboration process should be automated to the highest extend possible for human-machine interaction as well as for machine-machine interaction.

3 Framework for Automated Collaboration on the Semantic Web

With respect to the requirements determined, the following presents our integrated framework for collaboration support on the Semantic Web. This includes the conceptual model, the definition and usage of the main elements, and the automated collaboration management process implemented by agents.

3.1 Conceptual Model

Figure 1 shows the overall conceptual model. In accordance to the requirements defined above, agents act as electronic representatives of real-world entities involved in collaborative interactions; agents carry Goal Instances that are to be resolved in collaborations, and use Collaboration Services as computational facilities for automatically executing collaborations via service interaction. Ontologies provide the data model throughout the whole system (all elements definitions are based on ontologies, and all data interchanged between elements are ontology instances); different mediators resolve possibly occurring mismatches between elements that shall interoperate.

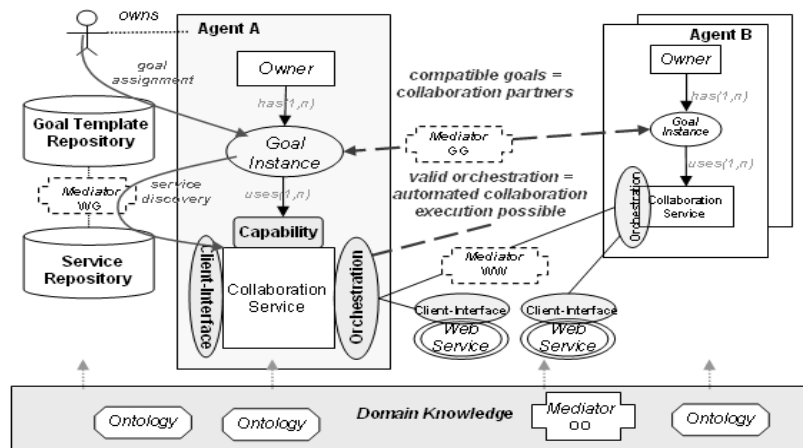


Fig. 1. Conceptual Model

The business process of the system is that first a real world entity specifies an objective to be achieved and delegates this to its respective agent as a goal for automated resolution. This is performed independently by each entity that intends to participate in a collaborative interaction. An agent can be assigned with several different goals throughout its life time, whereby each goal is to be solved in a separate collaboration. Collaborations are executed by the interaction of the Collaboration Services used by each participating agent. Therefore, the Goal Instance to be resolved and carried by an agent serves as the client of the Collaboration Service that achieves its functionality by interacting with Collaboration Services of collaboration partners and utilizing other Semantic Web resources.

Agents are considered as potential collaboration partners if they have compatible Goal Instances. A collaboration can be executed automatically if the orchestrations of the Collaboration Services used by each agent are valid, meaning if the Collaboration Services used by participating agents can interact and if other Semantic Web resources aggregated by the Collaboration Services can be utilized successfully.

3.2 Collaboration System Element Ontology (CSEO)

Our framework is comprised of five main elements: Ontologies, Agents, Goals, Collaboration Services, and Mediators. In order to support automated, semantically enabled collaboration management, we define semantic descriptions structures for each element. This is an extension of the Web service Modeling Ontology WSMO that defines Ontologies, Web services, Goals, and Mediators as core elements for Semantic Web services [18], thus providing an accurate basis for our needs. The following summarizes the element definitions, referring to [21] for detailed design discussion.

Ontologies. Ontologies provide the semantic terminology definitions used as the data model throughout the whole system. We apply WSMO ontology definitions, along with ontology integration and management techniques in order to ensure semantic interoperability and knowledge level information processing.

Agents. We define a proper model of agency of ‘Semantic Web agents’ as denoted in the motivating example. This is based on so-called *collaboration interface agents* [9] whose re- and pro-activity is allocated in the interaction with their owner as well as in the interaction with other agents. We extend this with ontologies as the data model, dynamic interaction with the agent owner for goal assignment, and the usage and dynamic detection of Collaboration Services as the agent facilities for participating in a collaboration automatically executed over the Semantic Web.

Goals. Goals represent the objective that a real-world entity wants to achieve in a collaboration by delegation to agents for automated resolution. In order to enable maximal automation, we distinguish two types of Goals: *Goal Templates* are predefined schemas whereof several and *Goal Instances* are created during runtime that denote the concrete goal assigned to an agent. Goal Templates are described as final desired states by *postconditions* (conditions on the objects expected to be received as computational results by service usage) and *effects* (conditions on the objects that are expected to exist in the world). 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 Collaboration Service usage, namely: a *submission* containing ontology instances that are intended to be submitted as input to a service, and a *result* that holds the information returned as output after service usage, and *preferences* on the goal resolution process.

Collaboration Services, short: CS, are the computational facilities that an agent uses for participating in a collaboration automatically executed over the Semantic Web. The client of a CS is the Goal Instance that is to be resolved and carried by the respective agent. For achieving its functionality, a CS interacts with the CSs of collaboration partners and utilizes other Semantic Web resources (e.g. Web services, information repositories, semantically annotated websites). CS are a special kind of Web services, thus defined as a sub-class of WSMO Web Services with the following description elements: a *capability* as the functional description, a *client interface* that describes the interaction behavior of a CS for consuming its functionality, and an *orchestration* that describes how the CS achieves its functionality by interacting with the CS of collaboration partners as well as with other Semantic Web resources.

Mediators. We apply the concept of mediators from WSMO for handling possibly occurring mismatches between elements that shall interoperate for collaboration execution. Therefore, we utilize different mediator types: *OO Mediators* resolve mismatches between heterogeneous ontologies, *GG Mediators* establish goal compatibil-

ity between goals that are not compatible a priori, *WG Mediators* make Web services usable for agents that are not usable a priori, and *WW Mediators* establish interoperability of services for collaboration execution if this is not given a priori.

3.3 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 2. 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.

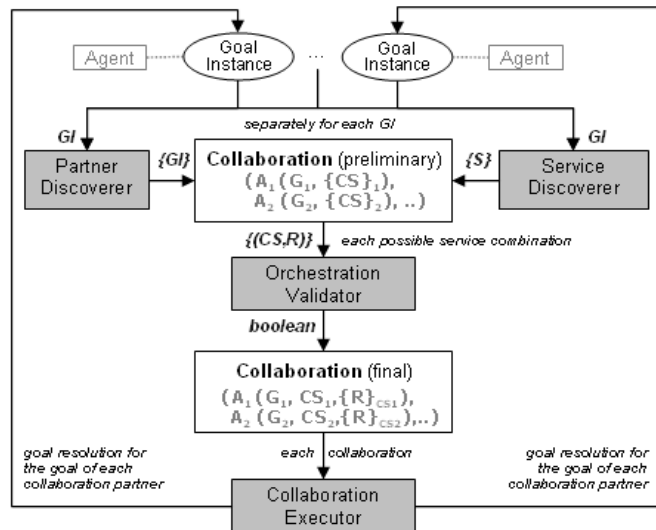


Fig. 2. Collaboration Management Process

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 Collaboration Services usable by an agent for participating in an automatically executed collaboration, and the *Orchestration Validator* determines existence of valid interaction protocols between the Collaboration Services of all collaboration participants and other Semantic Web resources utilized. Each component realizes respective techniques envisioned for Semantic Web services. We only outline the realization of the components as a detailed description of the mechanisms exceeds the scope of this paper. We discuss an example in the next section.

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 [15], this is given if a collaboration of the agents results in resolution of the goals of all participants. For determining this, goals denote an action

that is to be performed for solving the objective of the agent owner, while the post-condition and effect define conditions on the object of interest of the objective. Actions and their compatibility is defined in a special action-resource ontology that allows determination of goals with compatible actions, while we realize set-based matchmaking as defined in [8] for object matchmaking.

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. Service discovery 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 agents, their goals, and usable services. [20] explains the realization of partner and service discovery in more detail.

Orchestration Validation. This determines existence of a valid interaction protocol between Collaboration Services and other Semantic Web resources for automatically executing a collaboration. We therefore determine whether there exists a valid interaction protocol for every interaction to be performed. This is given if (1) the resources use homogeneous ontologies, (2) the information to be interchanged, i.e. the content of communicative acts is compatible, and (3) the communication protocol 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 service interface descriptions as we present in [21] in more detail.

Collaboration Execution Environment. The collaboration execution environment provides the technical environment for executing collaborations along with facilities for execution management and control. Collaborations are executed via the orchestrations of the Collaboration Services used by the collaborating agents. All services are invoked by submitting the input defined in the Goal Instance of the agent, and executed remotely over the Web. Execution management and control schedules collaboration executions, provides accesses to the required resources, and ensures that equivalent collaborations are only executed once. After successful execution of a collaboration, each participating agent inspects the resolution status of its goals. If the objects held in the result of the Goal Instance satisfy the postcondition and effects, then the goal is considered to be resolved.

4 Prototype Implementation and Use Case Testing

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 in society.

The real world entities participating in the use case are buyers, sellers, service providers, and a marketplace provider. Defined in [19] in detail, Goal Templates are given 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_j 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.

Initiating collaboration establishment for agent B , 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 Collaboration Services for each agent B, S_1, \dots, S_n and the orchestration validator determines existence of a valid interaction protocol for these, we retrieve a set of collaborations $(B, S_1), (B, S_2), \dots$ 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 some agent. Hence, while determining possible collaborations for B , collaboration establishment is concurrently performed for the goal of S_j . Thereof, we attain possible collaborations $(S_j, B), (S_j, B_2), \dots, (S_j, B_m)$, whereby B_2, B_m denote other buyer agents that are determined as other collaboration partners for S_j . All established collaborations are handed over to the collaboration execution environment, wherein the execution management ensures that the collaboration between B and S_j is only executed once; as soon as a collaboration execution has successfully solved the goal of an agent, all other collaborations that encompass these goals 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 reflects the nature of real-world collaborative interactions properly and beneficially combines 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.

Regarding the integration of agent and Web technology, we observe several approaches that extend agent technologies with Web technologies, e.g. [4]; also, the usage of Web services as computational facilities for agents has been recommended [3]. 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 assimilate these into a coherent framework as we have presented here. Besides, a remarkable shortcoming of existing Web service technologies is the lack of ontology support, as Web service usage and invocation is mostly performed via SOAP on basis of WSDL interface descriptions (e.g. grounding in OWL-S or Web service usage in BPEL4WS and WS-CDL). These technologies only support interchange of XML data, so that the ontological information are lost. For realizing the vision of the Semantic Web, it is crucial to overcome this by communication technologies with inherent ontology support [6].

With respect to the overall system architecture, we observe similar approaches in agent systems as well as in architectural models envisioned for Semantic Web and Web service-based systems. Both the RETSINA system [23] and the Open Agent Architecture OOA [14] are agent systems that apply semantic techniques for agent coordination. Both define different agent types as the functional system building blocks, whereby the coordination facilities for agent interactions are provided by specialized agents provide as centralized components, similar to the collaboration management components in our framework. 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 [2] denotes service requesters and providers as real-world entities concerned with Web service usage and provision. [17] extends this by denoting that the real-world entities can or should be represented by electronic agents for automating Web service usage; further, this paper outlines the different associations of the term 'Web service': it is understood as a business service that provides an 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 framework overcomes this as objectives of collaboration partners are allocated in agents and goals while Web services only provide a computational facility.

With regard to ongoing standardization efforts, we presume that standard recommendations for semantically describing Web services and related aspects will emerge from existing frameworks like OWL-S and WSMO. Our framework is based on the latter, as it provides a concise ontological model for the core aspects of Semantic Web services, including four out of the five elements of our framework.

Several approaches are related to the semantic collaboration establishment applied in our framework. For instance, the *Joint Intentions theory* [10] 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. Semantic matchmaking techniques as we utilize for partner and service discovery have been developed in several preceding efforts, e.g. [24], [11]; we extend these by the differentiation of action and object knowledge in resource descriptions and by using a theorem prover for matchmaking realization, see [20] for details. Based on previous work [13], we have developed an approach for determining interoperability of Web services on basis of formal interface descriptions, depicting a starting point for automated Web services contracting techniques.

6 Conclusions

This paper has summarized the approach and core aspects of a framework that coherently integrates agents, ontologies, and Semantic Web services for automated collaboration support on the Semantic Web. Collaboration is concerned with cooperative interactions of individuals in order to achieve complex objectives. Understanding automated collaboration support as the essential functionality of the Semantic Web, we have examined the inherent characteristics of collaboration from related academic disciplines as the conceptual basis for properly integrating the key technologies identified for the Semantic Web.

The presented framework 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 Collaboration Services provide the computational facilities for automated collaborative interaction of agents that allow automated interaction with other agents as well as utilizing Semantic Web resources for achieving the service functionality. 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. For automated collaboration management, we apply methodologies and architectural aspects from agent technology while our element definitions as well as our semantically enabled collaboration management components realize techniques currently under development for Semantic Web services.

Summarizing, the presented framework presents an integrated technology 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. Regarding future Web application engineering, we have experienced in our project work that users and system developers regard exhaustive tool support that 'hides' logical aspects as very important. For example, end-user interfaces are requested that allow creation and edition of goals without enforcing the user to formulate logical expressions; for developers, tool support is requested that minimizes the effort for creation of resource description and deployment. This shows that 'conventional system developers' regard tool support and automation for system development and maintenance as very important, which we think this is a crucial aspect for success and usage of Semantic Web technologies.

Acknowledgements

This work presented is supported by the EU funding under the DIP project (FP6 - 507483) and by the Science Foundation Ireland under Grant No. SFI/02/CE1/I131. We would like to thank the Quarto Software GmbH, Vienna, for fruitful cooperation in the SWF project funded by the Vienna city government.

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