Toward a Semantic Web Service Technology Roadmap

Daniel Bachlechner

Abstract—**Semantic Web services pledge the automation of core Web service tasks such as discovery, selection, composition, and execution. They are supposed to enable seamless interoperation between systems, whereby human intervention is kept at a minimum. Nevertheless, Semantic Web services have not yet been adopted by the industry. Within the scope of this work, we discuss the correspondence of the viewpoints of experts from academia and industry with respect to current challenges and the latest achievements in the field of Semantic Web service research. Our primary objective is to identify technology locks between industrial needs and research activities. Additionally, we take a first step toward the production of a technology roadmap with respect to Semantic Web services. The discourse is based on the findings of a comprehensive Delphi study which was conducted in early 2007. In order to also assess Semantic Web services in an organizational context, we occasionally focus on the technology's application as basis of integration architectures.**

Index Terms—**Delphi study, integration architectures, Semantic Web services, technology roadmap.**

I. Introduction

MANY enterprises employ multiple mission-critical, best-of-breed application systems from different vendors with different technologies and platforms [1]. They choose the best vendor for every operational area and connect the products via the interfaces they provide. This approach normally leads to highly complex systems, though. Nevertheless, until recently this strategy was considered a silver bullet when assembling business software.

Together with mergers and acquisitions, reorganizations, and leadership changes, which also cause considerable impact on IT infrastructures, best-of-breed solutions lead to extreme heterogeneity. Obviously, the operation of such application patchworks is extremely costly and complex. The maintenance of numerous vendor relations and the necessity of specific know-how usually are not justifiable. However, the integration of application systems within organizations and across organizational boundaries is essential to realize competitive advantages. Even if just a few critical systems cannot share their data effectively, they create information bottlenecks that often require human intervention to be solved. Only with properly deployed integration architectures can organizations focus their efforts on their value-creating core competencies.

Web services brought about a revolution by taking a remarkable step toward seamless integration of distributed software components. The importance of Web services as a cornerstone of service-oriented integration architectures is recognized and widely accepted by experts from industry and academia. Current Web service technology, however, operates at the syntactic level, is not suited for automatic processing, and, hence, still requires human interaction to a large extent. To better support the discovery of services and automate their composition into complex processes, a formal and standardized semantic description of services is needed.

Using Semantic Web technologies for the description of Web services appears to be a promising approach. Semantic Web services (SWS) pledge the automation of core Web service tasks such as discovery, selection, composition, and execution, thus enabling interoperation between systems, keeping human intervention to a minimum [2], [3]. The objective of SWSs is to combine services on the fly in order to achieve given goals. Based on goal descriptions and descriptions of available services, a complex service yielding the desired result should be composed automatically out of atomic building blocks [4].

Within the scope of this work, we discuss the correspondence of the viewpoints of experts from academia and industry, with respect to current developments in the field of SWS research and take a first step toward a technology roadmap. The main reason for the development of a technology roadmap is the identification of critical technologies and technology gaps with respect to SWSs. The discourse is based on the findings of a comprehensive Delphi study which was conducted in early 2007 [5]. In order to foster the practical relevance of our work, we assessed SWS research in an organizational context. For this purpose, we occasionally focus on the application of SWSs as basis of integration architectures.

Section II describes the status quo with respect to SWSs. After a brief discussion of the awareness of SWSs, the constituent technologies are detailed. Then, we describe the infrastructure necessary for the use of SWSs and finally introduce the most prominent SWS frameworks. In section III the research approach is described, highlighting the survey design, the questionnaire, the structure of the expert panel, and the survey system. The results of the survey are presented in section IV where we describe our findings with regard to the most important challenges SWS research is facing today, the most probable achievements that the SWS research community will make by 2012, the potential of SWSs with respect to integration architectures, and the availability of real-world

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D. Bachlechner is with the University of Innsbruck, Innsbruck, Austria (e-mail: daniel.bachlechner@uibk.ac.at).

case studies in which SWS-based integration architectures are used. Particular importance is attached to the correspondence of the viewpoints of experts from academia and industry. Section V first summarizes the major challenges and achievements with respect to SWSs and then takes a first step toward the production of a technology roadmap. We conclude by pointing out the main contributions of this work in section VI.

II. Semantic Web Services

A. Technology Awareness

SWS research has been receiving increasing attention during the past years. Several efforts are involved in SWS technology research and development, mostly gathered around OWL-S (Web Ontology Language for Services) [6] and WSMO (Web Service Modeling Ontology) [7], which are the most prominent SWS frameworks.

Since 2001, the number of publications devoted to SWSs is constantly growing. McIlraith *et al.* published one of the first scientific articles on SWSs [2]. A Google Scholar query for SWS-related articles results in 6 matches for the year 2001. For the years 2004 and 2005, Google Scholar lists 189 and 344 articles, respectively. A query for the year 2006 results in 426 matches and for the 2007 the search engine delivers 458 publications devoted to SWS. Bachlechner gathered similar numbers for the years 2001 though 2006 by querying the digital libraries operated by Elsevier, Springer, the Association for Computing Machinery (ACM), and the IEEE Computer Society, directly [5].

B. Constituent Technologies

Current Web technologies will not be replaced by Semantic Web technologies; the idea of a Semantic Web must rather be seen as some kind of upgrade. SWSs are the result from the combination of Web service and Semantic Web technologies. Both technologies are composed of sets of standards.

Web Services

The basic idea underlying Web services is to facilitate the use and integration of applications by making them independent from the technologies with which they have been implemented. A Web service should be accessible by clients regardless of the programming languages in which the service or the client have been implemented or the operating systems on which they are running. Moreover, Web services should be highly reusable and easily combinable. Services are seen as building blocks for processes that can be rearranged by business experts without involving developers. Finally, replacing one service with another service offering the same functionality should be straightforward.

Web services are inherently process-oriented. A service, or more precisely a service operation, is an action performed by a program. Processes can then be constructed by combining individual service operations. The W3C (World Wide Web Consortium) has established six working groups and one interest group concerned with the architecture of Web services within the scope of its Web Service Activity.

Four basic standards form the initial specification for Web services. They are explained elaborately in [8]. Three of them are generally accepted today: XSDL (XML Schema Definition Language) for describing data types, SOAP as a message format containing service requests and responses, and WSDL (Web Services Description Language) to describe service interfaces by specifying the protocol bindings and message formats required for interactions. The relevance of the fourth basic standard, UDDI (Universal Description, Discovery and Integration), is less unanimous. UDDI defines four core types of information that provide the data required to discover and use Web services [9], [10].

In addition to these basic standards, a host of standards that address specific aspects of Web service usage have been developed. Together, they form a Web service stack of standards. These standards deal with issues such as security, reliable messaging, choreography of services, and transactions. Standard compliance is essential for Web services because it is the key to achieving independence from technologies, vendors, and programming languages.

In spite of the advanced state of standardization, interoperability is not always guaranteed. Because existing standards are very extensive, software products often support only subsets of the complete standards. The WS-I Group (Web Services Interoperability) has been founded to overcome these challenges. Its purpose is to promote Web service interoperability across platforms, operating systems, and programming languages. Many software vendors have committed to ensuring that their products are WS-I profile compliant, and some products already offer functionality testing for WS-I profile compliance.

According to Vinoski, Web services currently present the most promising way to facilitate application integration based on Internet technologies [11]. Web services simply use the ubiquitous Internet infrastructure to apply proven approaches from mature middleware.

Semantic Web

Berners-Lee *et al.* first described the evolution of a Web that consists largely of documents for humans to read to one that includes data and information for computers to manipulate [12]. They state that the Semantic Web is a web of actionable information derived from data through a semantic theory for interpreting symbols. The semantic theory provides an account of meaning in which the logical connection of terms establishes interoperability between systems.

As per Antoniou and van Harmelen, the development of the Semantic Web has a lot of industry momentum and also governments started investing some time ago [13]. The Semantic Web is among the key action lines of Europe's Seventh Research Framework Programme (FP7) and the government of the United States of America established the

DAML (DARPA Agent Markup Language) program in 2000.

The rather unstructured HTML pages of the Web are sufficient for human readers, who use their background knowledge to identify relevant pieces of information. However, it is not straightforward to extract such information automatically. Programs that do this at present are usually hand-coded scripts, which are particularly tailored toward the websites from which they extract information. Reusability is low and maintenance is costly as the scripts must be updated as soon as the structure or the layout of the underlying website changes. It would be much easier if information on the Web contained information about itself. The Semantic Web aims to standardize information in a way that metadata can be added to the data which is currently put on websites.

The basic idea underlying the vision of the Semantic Web is to make websites machine-processable by structuring and enhancing the information contained in them. This allows for the creation of intelligent applications roaming the Internet and using the Web's information to offer all sorts of services [14].

The Semantic Web is supposed to give machines the ability to solve problems by performing operations on well-defined data. Information semantics and their conceptual associations are explicitly defined within the Semantic Web. Through explicit semantic definitions and meanings embedded in data, applications and systems become readily accessible to computer programs that can process them at high speed. To resolve semantic differences and to intelligently process information semantics are two of the main motivations driving the Semantic Web. To put it in a nutshell, the Semantic Web is an extension of the current Web in which information is given well-defined meaning, better enabling computers and people to work in cooperation [12].

So far, real-world applications of Semantic Web technologies are difficult to find. Most existing applications have been developed in academic contexts or research projects funded by public institutions. Work on Semantic Web languages and standards can only be seen as a first step. These standards provide formats in which metadata can be represented. They do not provide a set of metadata to be used, nor do they say anything about how metadata can be obtained.

The Semantic Web is primarily static as it aims at enhancing information representation in order to make automatic processing feasible. Combining it with the dynamic concept of Web services is thus facilitating its usage in process-oriented application contexts.

C. *Infrastructure and Usage*

A general SWS infrastructure is discussed comprehensively by Cabral *et al.* in [15]. They characterize the infrastructure along three orthogonal dimensions:

1) usage activities, which define functional requirements;
2) the architecture, which defines the components needed for accomplishing these activities; and
3) the service ontology, which aggregates all concept models related to the description of SWSs and constitutes the knowledge-level model of the information describing and supporting the usage of the services.

Arroyo and López-Cobo make usage activities of SWS infrastructures a subject of discussion in [16].

Usage Activities

Along with the core tasks, publication, selection, discovery, composition, execution, and mediation, the execution of SWSs requires various other important activities to be performed. Under the term execution support activities such as monitoring, compensation, replacement, and auditing are summarized [16].

In [15], the deployment of services and the management of service ontologies also are considered as usage activities. The deployment of a service by a provider is independent of the publishing of its semantic description because the same Web service can serve multiple purposes. Nevertheless, SWS infrastructures can provide a facility for the instant deployment of code for a given semantic description. The management of service ontologies is a cornerstone activity for SWSs due to the fact that it ensures that semantic service descriptions are created, accessed, and reused within the Semantic Web.

In [16], Arroyo and López-Cobo outline the Web service usage process as follows. Essential for a successful discovery is, according to them, that the publisher of a service registers the service at a registry and describes its capabilities. To discover a service, a requester must specify a goal and translate it into a machine-readable query. The goal is then decomposed into constituent subgoals and matched against the capabilities of the registered services. After that, the services that alone or in combination with others allow achieving the objective are selected.

Mediation is required during the discovery process to allow services described, using different domain knowledge, to be matched against a goal. A selection process is carried out to pick the most suitable service or services from the set of alternatives based on functional and nonfunctional properties. The list of preferred services is required for the process of service composition. In case composition is required because one service is not sufficient to acquire the goal, the list of services is assembled in a way that enables their interoperation. Again, mediation is required to overcome mismatches and to allow interoperation with regard to different data formats used in the message exchange protocols and specific business models. Finally, the service or set of services is executed at the expenses of the service provider. In case of composed services, execution requires additional support for monitoring, compensation, replacement, and auditing.

Monitoring controls the execution process. It is concerned with determining the current state of a service execution or finding out what state a service is in when a problem is reported. In case of a problem, compensation undoes or mitigates the unwanted effects of the execution and provides transactional support. To continue with normal execution, a new service or a combination of new services usually is required. Replacement facilitates the substitution of services by suitable equivalents. For that, the usage process is started from the beginning, trying to discover services or sets of services having capabilities that match those of the malfunctioning service. Auditing is the last step in the execution of a composed service. It verifies that a service execution occurred in the expected way.

Architecture

The SWS architecture is defined by a set of components that support the usage activities. Between a requester and a provider, components such as a register, a reasoner, a matchmaker, a decomposer and an invoker are needed. The components have different names and scopes across individual approaches. Security and trust mechanisms also are typically discussed under the architecture perspective.

The reasoner is used for all usage activities. It provides reasoning support for interpreting semantic descriptions and queries. The register provides the mechanisms for publishing and locating services in a semantic registry as well as functionalities for creating and editing service descriptions. The matchmaker mediates between the requester and the register during the processes of service discovery and selection. The decomposer is required to execute the composition model of composed services. The invoker mediates between requester and provider or decomposer and provider when invoking services.

Service Ontology

The service ontology represents the capabilities of Web services as well as the restrictions that have to be considered when using them. It integrates the information defined by Web service standards such as UDDI and WSDL with related domain knowledge. This includes functional capabilities such as inputs, output, preconditions, and post-conditions as well as nonfunctional capabilities such as category, cost, and quality of service. Provider related information such as company name and address, task or goal-related information, and domain knowledge defining, for instance, the types of the inputs of a service, are also included. The information can be distributed in several ontologies.

D. Prominent Frameworks

OWL-S and WSMO are the most prominent SWS frameworks. Both were submitted to the W3C to set up standardization efforts. Other related efforts are SWSF (Semantic Web Services Framework), outlined in [17], which also was submitted to the W3C, IRS (Internet Reasoning Service), and METEOR-S. IRS, described in [18], is the SWS framework of KMi at The Open University, which allows applications to semantically describe and execute Web services. IRS supports the provision of semantic reasoning services within the context of the Semantic Web. The METEOR-S project at the LSDIS Lab of the University of Georgia aims, according to [19], to extend current Web service standards with Semantic Web technologies to achieve greater dynamism and scalability. The SAWSDL (Semantic Annotations for WSDL) Working Group was started by the W3C in April 2006 with the objective of developing a mechanism to enable the semantic annotation of Web service descriptions. This mechanism takes advantage of the WSDL 2.0 extension mechanisms to build simple and generic support for adding semantic descriptions to Web services. The SAWSDL specification became a candidate recommendation in January 2007.

However, at this point in time, efforts in SWS technology research gather primarily around OWL-S and WSMO. Today, the main lines in research relate to the composition of SWSs, the establishment of a semantic environment for execution, and the reasoning needed for the automated discovery of services. Lara *et al.* provide a comprehensive conceptual comparison of OWL-S and WSMO in [20]. Cabral *et al.* discuss and compare OWL-S, WSMO and IRS in [15].

III. Research Approach

The main goal of the underlying study was to collect and quantify the opinions of clearly defined groups of practitioners and researchers on the potential of SWSs as basis for integration architectures that enable organizations to link their data processing systems efficiently. It was expected that an understanding of the relevance and applicability of SWS-based integration architectures would help to align future research efforts with industry needs effectively. Another goal was to make participating experts from academia and industry more sensitive to the progress and focus of SWS research in general and to take a first step toward a technology roadmap.

A Delphi study with experts from industry and academia seemed to be particularly suitable to achieve these goals. By means of Delphi studies, anonymous expert judgments are obtained in a series of survey rounds. After each round the panel is provided with controlled feedback about its responses in earlier rounds [22]. A basic limitation of the Delphi, as with many other forecasting methods, is its inability to make complex forecasts with multiple factors. Potential future outcomes are usually considered as if they had no effect on each other. Most events and developments, however, are in some way connected to each other. Hence, these interdependencies must be taken into consideration for more consistent and accurate forecasts. Despite these shortcomings, today, the method is a widely accepted tool for technology foresight and has been used successfully in many studies.

The Delphi method also is not new to Web-related research. In 2000, Beck, Glotz, and Vogelsang used the Delphi method to forecast the development of online communication. The results were published in [21]. Five years later, trends in the field of Semantic Web research were identified through the use of the Delphi method within the scope of the Knowledge Web project. The findings were published by Cuel *et al.* in the form of a project deliverable [22].

A. Survey Design

Within the scope of the study, the participating experts were provided with two questionnaires. The first questionnaire contained open-ended questions designed to capture the experts' views concerning SWS research in general and factors potentially affecting the relevance and applicability of SWS-based integration architectures in particular. The responses from the first round were aggregated into groups and classified by the unique issues that best summarized their contents. The second questionnaire was based on the responses from the first round. The participants were asked to review the aspects identified in the first round and rank them on structured bipolar rating scales ranging from 1 to 5, with 1 representing *Strong Disagreement* and 5 representing *Strong Agreement*. Two rounds were expected to be sufficient to attain a first impression concerning the opinions of the experts.

The Delphi study consisted of four parts, structured and formalized in a way that allowed for various analyses: a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, a requirements analysis, an analysis of expected effects, and a technology roadmap. Within the scope of this work, we focus exclusively on the technology roadmap.

B. Questionnaire

A technology roadmap intends to define and plan the necessary research to bring a product to its full potential. It focuses on forecasting the development and commercialization of a new or emerging technology [24]. The questions stated within the scope of the development of the technology roadmap for SWSs read as follows:

1) What challenges do you know of that SWS research is facing today?
2) What will be achieved in SWS research within the next five years?
3) What are problems of current integration architectures that you believe can be solved with SWSs?
4) Do you know of any real-world case studies where SWS-based integration architectures have been used?

Questions 1 and 2 are related to SWS research in general. Question 3 embodies an approach embracing the potential of SWSs, in particular with respect to the problems of current integration architectures. Question 4 was posed only in the first round of the survey because no real-world case studies were named by the experts who responded to this question. As expected, all responses described academic research projects rather than mature implementations in industry.

C. Expert Panel

The candidates were selected from academia and industry in similar proportion. Repeated involvement at major conferences and publication in at least one of the relevant fields were two of the main criteria used to find suitable representatives of the target population. The candidates were exclusively people involved in at least one of the major international conferences related to SWSs and associated technologies, enterprise integration architectures and middleware solutions. Additionally, book authors and members of widely recognized initiatives active in at least one of the related research fields were considered.

The 38 experts who participated in both rounds of the study were from all parts of the world and affiliated with major universities and enterprises. Whereas 21 of the experts had academic backgrounds, 17 had industrial ones. These numbers correspond well with Clayton's recommendation for an adequate panel size [25]. The expertise of the participants in the area of research was gathered to evaluate their technical qualification for the study. The expertise distribution grouped by backgrounds is shown in Fig. 2. The scale ranged from 1 to 5, with 1 representing *Novice* and 5 representing *Expert*. None of the participants ranked in the lowest category. According to Grupp, Blind, and Cuhls, having people with different levels of expertise in the panel reduces the risk of achieving too optimistic forecasts [26].

D. Survey System

Web-based surveys provide capabilities far beyond those of any other type of self-administered survey technique. They can be designed in ways that facilitate a dynamic interaction between respondents and the survey administrator, which is of particular interest for Delphi studies [27]. However, it always must be kept in mind that a survey corresponds to a level of technical sophistication that makes it possible for most users to respond. Within the scope of the development of the survey system used for the Delphi study, programming and design steps were taken to minimize the differences across respondents caused by different operating systems, Web browsers, and screen configurations.

IV. Results

The respondents rated up to 35 statements with respect to each of the questions stated. The participants were free to

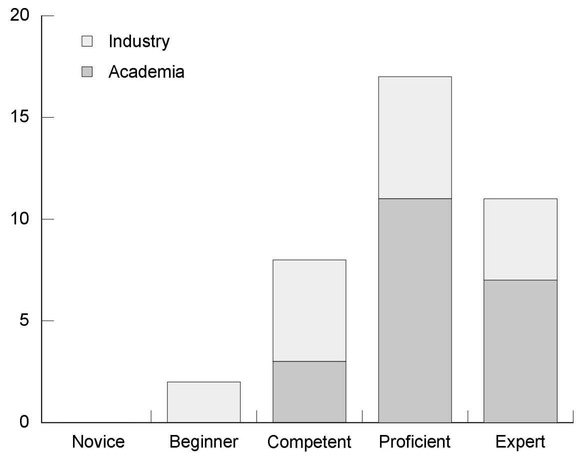

Fig. 2. Expertise distribution among the 38 experts who participated.

leave statements unrated or to check a *No Comment* box. The most important statements from respondents with either academic or industrial backgrounds are presented in tabular form. Statements are defined as *Most Important*, if the mean of their ratings is greater than or equal to 3.75 (i.e., more than 90% of the experts, on average, at least agreed to the statement). We also computed Fleiss' kappa κ for each statement in order to measure inter-rater reliability [28]. The mean of the κ values for the group of researchers is 0.32 and the one for the group of practitioners is 0.48. The respective standard deviations are 0.06 and 0.14. These κ values indicate moderate agreement within the groups. The most controversial statements comparing the two groups of respondents are illustrated by means of net diagrams. The five statements in which the difference of the means of the two groups of respondents is maximal are defined as *Most Controversial*.

A. *Major Challenges*

Tables I and II list the most important challenges SWS research is facing today from either an academic or an industrial perspective. The most important challenges from an academic perspective, with average ratings equal to or greater than 4, are the integration of SWSs into a broader set of technologies, the grounding of the research vision into reality, the unavailability of convincing case studies, the lack of skilled developers, and the limited maturity of the used technologies. The lack of effective tools, high complexity, the proof of cost-effectiveness, and the unclear benefits over traditional approaches are further challenges from an academic point of view. Finally, respondents with academic backgrounds perceive the integration into integrated development environments, the lack of suitable test environments, and the lack of effective semantics elicitation as major challenges SWS research is facing today.

TABLE I
MAJOR CHALLENGES FROM AN ACADEMIC PERSPECTIVE

Statement	Mean
Integration into a broader set of technologies	4.11
Grounding research vision into reality	4.11
Unavailability of convincing case studies	4.06
Lack of skilled developers	4.06
Immature technologies	4.00
Lack of effective tools	3.94
High complexity	3.89
Proof of cost effectiveness	3.89
Unclear benefit over traditional approaches	3.89
Integration into integrated development environments	3.87
Lack of suitable test environments	3.83
Lack of effective semantics elicitation	3.78

TABLE II
MAJOR CHALLENGES FROM AN INDUSTRIAL PERSPECTIVE

Statement	Mean
Market and vendor apathy	4.50
Lack of semantically-enabled services	4.40
Immature technologies	4.20
High complexity	4.10
Integration into integrated development environments	4.10
Agreement on standards	4.10
Lack of effective tools	4.00
Proof of cost-effectiveness	4.00
Scalability of ontologies	4.00
Unsatisfactory trust and reputation features	3.90
Scalability of reasoning	3.90
Slow process of adoption	3.90
Lack of suitable test environments	3.90
Lack of skilled developers	3.89
Unsatisfactory inconsistency detection	3.80
Lack of suitable languages	3.80
Grounding research vision into reality	3.80

From an industrial point of view, particularly the immaturity of SWS technologies, high complexity, the lack of effective tools, and the proof of cost-effectiveness play key roles regarding major challenges with average ratings equal to or greater than 4. Also the lack of suitable test environments, the lack of skilled developers, and the grounding of the research vision into reality are perceived as rather important from an industrial point of view.

The integration of SWSs into a broader set of technologies which is the most important research challenge from an academic viewpoint is, with an average rating of 3.30, only of limited importance for practitioners. Respondents with industrial backgrounds perceive the unavailability of convincing case studies, with an average rating of 3.50, as considerably less important than researchers. The unclear benefit over traditional approaches and the lack of effective semantics elicitation are, with average scores of 3.60, only slightly less important to practitioners than to researchers, though.

Practitioners perceive market and vendor apathy and the lack of semantically-enabled services as the most important challenges SWS research is facing today. Respondents with academic backgrounds rated them, with average scores of only 3.56 and 3.38, respectively, rather neutral. Both are also among the most controversial statements comparing the two groups of respondents. Agreement on standards, the scalability of ontologies as well as reasoning, and unsatisfactory trust and reputation features are further challenges from an industrial point of view. Whereas researchers are, with an average rating of 3.61, quite in line with practitioners regarding the scalability of ontologies, they attach to the scalability of reasoning and unsatisfactory trust and reputation features, with average scores of 3.22 and 3.39, respectively, considerably less importance than participants with industrial backgrounds. In the case of unsatisfactory trust and reputation features, the difference of the means is large enough to make it the most controversial statement with respect to SWS research challenges. Finally, respondents with industrial backgrounds perceive the slow process of adoption, unsatisfactory inconsistency detection, and the lack of suitable languages as major challenges SWS research is facing today. With an average rating of 3.50, the slow adoption process plays also a role for researchers. However, unsatisfactory inconsistency detection and the lack of suitable languages are, with average scores of 3.00 and 3.11, respectively, rated, at most, slightly

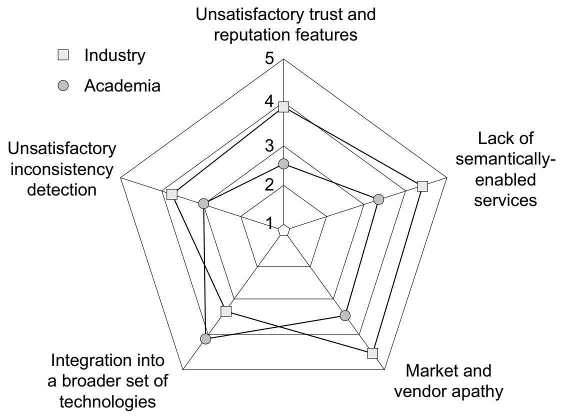

Fig. 3. Most controversial statements regarding challenges SWS research is facing today.

above average by participants with academic backgrounds. Unsatisfactory inconsistency detection is also among the most controversial statements with respect to challenges in the field of SWS research. Fig. 3 shows the most controversial challenges SWS research is facing today, comparing the two groups of respondents.

In the second round of the survey, an expert commented that one of the biggest challenges for SWS research is to show that the technologies work in practice. This is in line with challenges ranked in the top third, such as the grounding of the research vision into reality, the proof of cost-effectiveness, and market and vendor apathy. Furthermore, the present circumstances were compared with the situation 30 years ago, when the logic programming community was trying to sell programming tools based on Prolog. It was alleged that SWSs can only capture small niche markets in specific application domains. This concern, however, could not be brought in line with the overall impression gathered from the results of the study. The high rating of the unavailability of convincing case studies is in line with the responses to question 4.

B. Near- and Medium-Term Achievements

Table III lists the most probable achievements that the SWS research community will make within a timeframe of five years (i.e., by early 2012) from an academic perspective. Table IV lists the respective achievements from an industrial perspective. Improved service discovery capability and the availability of convincing cases studies will be achieved most likely by early 2012, according to both groups of respondents.

From an academic point of view, also integrated methodologies, open workbenches, and advanced ontology management systems will be available. Researchers are also convinced that the reasoning capability will be improved notably within the next five years. Practitioners generally agree with the researchers' ratings with respect to those statements. With an average score of 3.70, respondents with industrial backgrounds are quite in line with the ratings of the researchers regarding the improved reasoning capability. The ratings of the practitioners for the availability of advanced ontology management systems and open workbenches also are, with average scores of 3.60, only slightly below the values of the respondents with academic backgrounds. In principle, the same also holds for the availability of integrated methodologies, with an average rating of 3.50. Interestingly, the availability of integrated methodologies also is among the most controversial statements with respect to the most probable achievements that the SWS research community will make within a timeframe of five years.

From an industrial perspective, there will be a considerably higher awareness of SWSs in the industry by early 2012. Furthermore, practitioners expect serious improvements concerning the choreography and the orchestration capability. Respondents with industrial backgrounds also rated the availability of suitable languages, semantically-enabled services, and open system architectures quite high. Finally, practitioners are convinced that there will be industrial application of SWSs at a limited scale by early 2012.

With respect to the availability of open system architectures and semantically-enabled services as well as the limited-scale industrial application, researchers are quite in line with practitioners. Researchers rated the statements with average scores of 3.61 and 3.67, respectively, only slightly lower than the participants with industrial backgrounds. With an average rating of 3.61, researchers are not as convinced as practitioners that suitable languages will be available by early 2012. Interestingly, the two groups of respondents are not in line with respect to the improvements of the choreography and orchestration capability and the availability of higher awareness of SWSs in industry. In all three cases, respondents with industrial backgrounds rated the statements clearly higher than respondents with an academic perspective. Furthermore, all three statements are among the most controversial statements with respect to the most probable achievements that

TABLE III
FORTHCOMING ACHIEVEMENTS FROM AN ACADEMIC PERSPECTIVE

Statement	Mean
Improved service discovery capability	3.94
Availability of integrated methodologies	3.89
Availability of convincing cases studies	3.83
Availability of open workbenches	3.83
Availability of advanced ontology management systems	3.82
Improved reasoning capability	3.78

TABLE IV
FORTHCOMING ACHIEVEMENTS FROM AN INDUSTRIAL PERSPECTIVE

Statement	Mean
Availability of convincing cases studies	4.20
Higher awareness in industry	4.10
Availability of suitable languages	4.00
Improved service choreography capability	4.00
Improved service orchestration capability	4.00
Improved service discovery capability	3.90
Availability of semantically-enabled services	3.80
Availability of open system architectures	3.80
Limited-scale industrial application	3.80

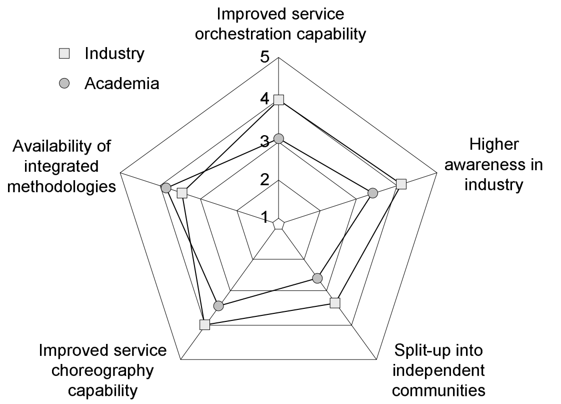

Fig. 4. Most controversial statements regarding achievements in SWS research within the next five years.

the SWS research community will make within a timeframe of five years. With average ratings of 3.39 and 3.17, respectively, researchers are not as convinced as practitioners that the choreography and orchestration capability will be improved notably within five years. The same holds for the awareness in industry. With an average score of 3.89, researchers rated the respective statement considerably lower than practitioners. The two groups of respondents are also not in line with respect to the future structure of the community. Whereas respondents with industrial backgrounds expect, with an average rating of 3.38, that the community will split up into independent communities, participants with an academic perspective, with average ratings of 2.69, do not expect that to happen. The respective statement is also among the most controversial statements shown in Fig. 4.

One expert doubted that SWS-based integration architectures will support a large degree of automation in design- and mediation-related activities in the near-term. He argued that in the initial phase of SWS adoption and deployment, it is neither necessary nor technically possible to support a large degree of automation. In the near- to medium-term, from the expert's point of view, human involvement will remain necessary and desirable for making final choices. This estimation is in line with the results of the study.

C. Potential of SWSs with respect to Integration Architectures

The respondents revealed many aspects of current integration architectures that could be improved by using SWSs. Tables V and VI list the problems of current integration architectures that can most probably be solved through the application of SWSs from an academic and an industrial perspective. According to both groups of respondents, SWSs can be used to solve problems regarding the automation of service discovery. The respondents are also in line concerning the potential of SWSs with respect to problems of current integration architectures such as the lack of semantic service descriptions, data mapping and sharing, and matching services from heterogeneous sources.

From an academic perspective, SWSs will help to solve problems known from traditional integration architectures with respect to the lack of semantic interoperability, the reuse of components, and limited flexibility. Respondents with industrial backgrounds are, with average ratings of 3.50 and 3.60, respectively, slightly less convinced that SWSs have the potential to solve problems with respect to the limited flexibility of integration architectures and the reuse of components. The opinions of the two groups of respondents are quite controversial with respect to the potential of SWSs to overcome problems associated with the lack of semantic interoperability. Practitioners rated the statement, with an average score of 3.60, considerably lower than researchers. Actually, the statement is among the most controversial statements regarding problems of current integration architectures that can probably be solved through the application of SWSs.

Respondents with industrial backgrounds expect that the application of SWSs will help to solve problems known from traditional integration architectures with respect to the agreement on standards. Interestingly, the researchers fully disagree. With an average score of 3.06, respondents with academic backgrounds rated the agreement on standards rather neutral. The difference of the means is large enough to make it the most controversial statement with respect to problems of current integration architectures that can probably be solved through the application of SWSs.

Fig. 5 shows the most controversial statements with respect to problems of current integration architectures that can probably be solved through the application of SWSs, comparing the two groups of respondents. Whereas practitioners see a potential in SWSs to help overcome market and vendor apathy with an average rating of 3.20, researchers clearly disagree with an average rating of 2.44. Regarding the problem of invalid standard implementations and the lack of

TABLE V
POTENTIAL WITH RESPECT TO INTEGRATION ARCHITECTURES FROM AN ACADEMIC PERSPECTIVE

Statement	Mean
Lack of semantic interoperability	4.22
Automation of service discovery	4.06
Matching of services from heterogeneous sources	4.00
Data mapping and sharing	4.00
Lack of semantic service descriptions	3.94
Reuse of components	3.82
Limited flexibility	3.81

TABLE VI
POTENTIAL WITH RESPECT TO INTEGRATION ARCHITECTURES FROM AN INDUSTRIAL PERSPECTIVE

Statement	Mean
Automation of service discovery	4.00
Lack of semantic service descriptions	4.00
Agreement on standards	4.00
Data mapping and sharing	3.90
Matching of services from heterogeneous sources	3.80

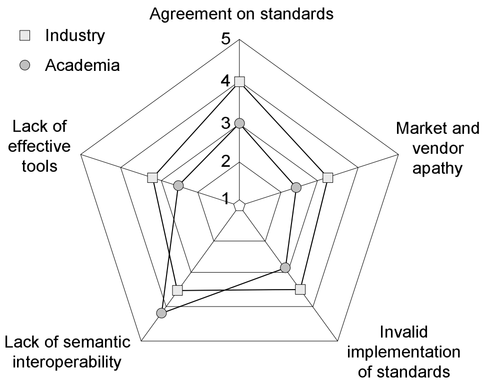

Fig. 5. Most controversial statements regarding problems of current integration architectures that may be solved with SWSs.

effective tools, the situation is similar. With an average rating of 3.60, respondents with industrial backgrounds expect that the application of SWSs will help to reduce invalid implementations of standards, whereas participants with academic backgrounds, with average ratings of 2.89, do not expect that. Researchers are, with average ratings of 2.63, considerably less convinced that SWSs have the potential to help overcome the lack of effective tools, known from current integration architectures, than practitioners with average ratings of 3.20.

According to an expert's comment, the SWS approach departs considerably from existing development paradigms without providing any clear and proven additional benefits to justify its use. The expert was also apprehensive about the fact that SWSs are confusing documentations created for human consumption. Many of the examples SWS researchers use are rather artificial because they try to capture things that are intended for human consumption as metadata. Nevertheless, because the availability of convincing case studies leads the list of the most important achievements in SWS research, it seems agreed that it is possible and of major importance to make convincing case studies available.

D. Real-World Case Studies

Most respondents who answered question 4, which was related to real-world case studies in which SWS-based integration architectures are used, declared that they did not know of any. Others reported that they knew only of pilots and prototypes in which integration architectures based on SWSs were used in experimental environments. One expert stated explicitly that up to now, SWS technologies have failed to show any practical applications in industry, except for some specific cases around service discovery. According to him, the reason is that many SWS prototypes either do not take scalability into account or try to capture semantics in a purely syntactic manner. No question, scalability plays a key role in integration architectures. It is also among the most important qualitative requirements identified within the scope of the Delphi study [5]. It seems plausible that most current integration architectures capture semantics, if they are available, in a purely syntactic manner. The results of the study, however, do not substantiate this assumption specifically.

Some respondents referred to research projects in which SWS technologies were used. The projects ATHENA (Advanced Technologies for Interoperability of Heterogeneous Enterprise Networks and their Application) and DIP (Data, Information, and Process Integration with Semantic Web Services) were mentioned most often in this regard. ATHENA was an integrated project sponsored by the European Commission, conducted from February 2004 to January 2007. The project aimed to enable enterprises to interoperate seamlessly with others and spanned the full spectrum from technology components to applications and services. Its multi-disciplinary research was particularly focused on industrial relevance. DIP was also an integrated project and ran from January 2004 to December 2006. The project took the vision of SWSs and worked on transforming it into a mature and scalable technology by defining and implementing additional layers of functionality on top of the existing Web service stack, and by mechanizing e-work and e-commerce relationships based on Semantic Web technologies. Other projects such as SWAD Europe, SWWS (Semantic Web-enabled Web Services) and MAPPER (Model-based Adaptive Product and Process Engineering) were also mentioned. The SWAD Europe project ran from May 2002 to October 2004 and was aimed at moving Semantic Web technologies into the mainstream of networked computing. By the end of the SWWS project in February 2005, the project partners had developed several prototype applications based on SWSs. MAPPER started in September 2005 and aims at supporting the increased cooperation and collaboration among enterprises during the product life-cycle. Of course, there are many more projects which are or were related to SWSs but which were not mentioned by the participants of the study.

Finally, respondents also stated that SWS-based integration architectures have already been introduced into bioinformatics. Projects such as BioMOBY and EMBRACE are beginning to adopt SWS-based methods. BioMOBY is a research project intended to generate an architecture for the discovery and distribution of biological data through Web services. The objective of EMBRACE is to draw together a broad group of experts throughout Europe involved in the use of IT in the biomolecular sciences to optimize information exploitation.

V. Discussion

We would like to emphasize once again that the Delphi method has the basic limitation that it cannot make complex forecasts with multiple factors. The method considers potential future outcomes as if they have no effect on each other. However, because most events and developments are in some way connected to each other, these interdependencies must be kept in mind when interpreting the results.

A. Challenges and Achievements

Considering both groups of respondents, immature technologies play the most important role with respect to challenges SWS research is facing today. Further challenges, such as the grounding of the research vision into reality, the proof of cost-effectiveness and market and vendor apathy, suggest that the industry is not yet convinced of the potential of SWSs. There is only a limited awareness of the benefits of approaches based on SWS over traditional approaches. Furthermore, SWS-based approaches are perceived as highly complex. The lack of skilled developers and effective tools are not only a cause but also a consequence of the almost nonexistent industrial adoption of SWSs.

With respect to the most probable achievements that the SWS research community will make within a timeframe of five years the experts are rather undecided. The fact that, considering both groups of respondents, none of the statements has an average rating equal to or greater than 4 is indicative for that. Expected achievements, such as the availability of convincing case studies or industrial application at a limited scale, suggest that the community is quite optimistic with respect to the potential of SWSs and the technology's wider acceptance in general. Particularly practitioners believe in a notably higher awareness of SWSs by early 2012. Researchers, however, rather expect the achievement of several technological improvements, such as improved service discovery and reasoning capability.

Integration architectures based on SWSs are expected to solve problems of current integration architectures particularly with respect to issues such as the automation of service discovery, the lack of semantic interoperability, and the matching of services from heterogeneous sources. The replacement of hardwired adapters and converters is expected to lead to higher flexibility. Considering both groups of respondents, reusability of components also plays a key role with respect to problems of current integration architectures that can most probably be solved through the application of SWSs.

According to Kungas and Matskin [29], in the past, the industry has been mostly interested in standardization and promotion of Web service technology, whereas academia has been looking for ways to fit the technology into other frameworks, such as the Semantic Web. In principle, our results are compatible with their findings with respect to the positions of industry and academia. As per our analysis, from an academic perspective, the integration of SWSs into a broader set of technologies is the major challenge for the research community today. Researchers expect the availability of integrated methodologies and convincing case studies within a timeframe of five years. Respondents with industrial backgrounds perceive market and vendor apathy to be the most important challenge SWS research is facing today. It seems that practitioners trace this fact back to issues such as the lack of agreement on standards and semantically-enabled services. The limited maturity of SWS technologies plays an important role for both groups of respondents. However, maturity of technologies is not expected by early 2012 by experts from academia and industry. The availability of consolidated architectures is more likely, though.

B. Technology Roadmap

A technology roadmap aims to analyze current and future trends in the context of a technology as well as related tools, methods, applications, and theories. This first step toward a technology roadmap considers an academic as well as an industrial perspective on SWSs in order to identify technology locks between industrial needs and research activities.

Fig. 6 shows the ten most important challenges the SWS research community is facing today, according to the ratings of both groups of respondents. Fig. 7 shows the most probable achievements that SWS research will make within a timeframe of five years. The ten most probable achievements considering the ratings of both groups of respondents are illustrated.

With respect to major challenges SWS research is facing today, respondents with academic and industrial backgrounds are mostly in line with each other. However, whereas market and vendor apathy is a critical challenge from an industrial perspective, researchers do not resemble that. By tendency, also practitioners worry about issues such as immature technologies, the integration of SWSs into integrated development environments, high complexity, and the proof of cost-effectiveness. The unavailability of convincing case studies is mostly for participants with academic backgrounds an important issue. For practitioners it does not play a remarkable role. By tendency, also the grounding of the research vision into reality and the lack of skilled developers are more important from an academic point of view.

With respect to the ten most probable achievements, the situation is similar but less conspicuous. As was expected, the

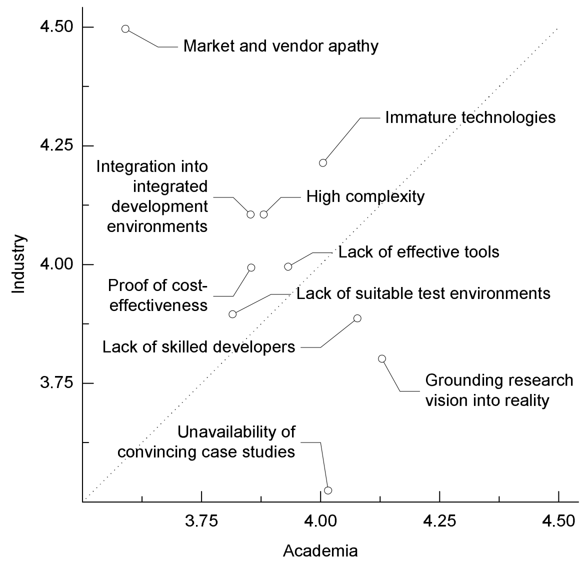

Fig. 6. Most important challenges SWS research is facing today considering the ratings of both groups of respondents.

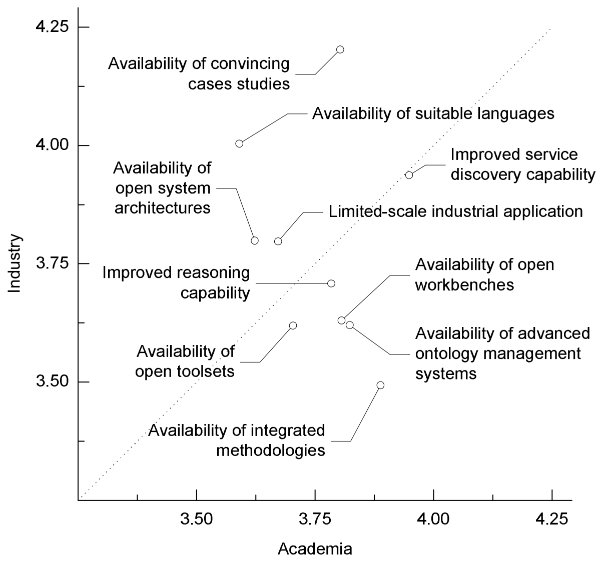

Fig. 7. Most probable achievements that SWS research will make within a timeframe of five years. The diagram shows the ten most probable achievements considering the ratings of both groups of respondents.

availability of convincing case studies is among the most probable achievements from an industrial viewpoint. By tendency, practitioners rather than researchers think that there will be limited-scale industrial application of SWSs by 2012. The availability of suitable languages also is an issue that respondents with industrial backgrounds rather perceive achievable than researchers. Integrated methodologies, advanced ontology management systems, and open workbenches will also be available by 2012, according to the participants. However, particularly researchers have confidence in the realization of these developments.

Cuel *et al.* identify critical aspects regarding the relationship between industrial needs and research activities in [22]. They state that researchers have only vague knowledge about organizational needs, technology impacts, and the potential of use cases. In contrast, practitioners are supposed to have only vague knowledge about the advantages deriving from the implementation of Semantic Web technologies. Furthermore, according to Cuel *et al.*, industry lacks insight with respect to the impact of Semantic Web technologies within organizations and across organizational borders. The work toward the production of a technology roadmap is particularly meaningful in combination with an analysis of the strengths, weaknesses, opportunities, and threats of SWS-based approaches. Bachlechner provides a comprehensive SWOT analysis of SWSs as basis of integration architectures in [30]. His findings, which rely on the same Delphi study as this work, are generally compatible with the ones of Cuel *et al.*, however, more specific. The limited consideration of business needs, the unavailability of convincing case studies, and the unproven cost-effectiveness are important factors restricting the use of integration architectures based on SWSs from an academic perspective. The assumption that the market does not understand values and capabilities of SWS-based integration architectures is of importance from an industrial point of view.

In essence, the use of integration architectures based on SWSs has a variety of profound business impacts. SWS-based integration architectures have a dramatic impact on the economics of enterprise integration. Because these architectures have not yet been adopted on an industrial scale, the exercise of caution is advisable. Besides high system complexity and the use of immature technologies, the lack of effective tools poses problems. It is not surprising that improved service definitions do not come without labor-intensive specification and modeling tasks. Furthermore, it is clear that there is still lack of agreement on the depth of descriptions. Finally, it is important to find the right balance satisfying high knowledge requirements and avoiding description overhead.

Currently, integration architectures based on SWSs are hardly used outside of experimental environments. However, we assume that SWS-based integration architectures are relevant to the integration market and will be applicable within a reasonable time. Without doubt, the majority of the used technologies is not yet satisfactorily mature. To bring SWS-based solutions, such as integration architectures, further, the problems regarding immature technologies and market and vendor apathy have to be addressed in particular. These problems are responsible for many weaknesses such as the high initial start-up efforts.

VI. Conclusion

Based on the results of the discussed part of the study, it seems plausible that SWSs will, at some point in time, be relevant with respect to certain integration problems. They will be dealing with one of the key bottlenecks in modern networked society: interoperability. We expect a strong demand for SWSs and integration technologies based on them as businesses react to the need for a higher level of integration and more agility. Making disparate systems share information cost-effectively is a key problem for many companies and represents billions of euros in technology spending, with a high percentage of worldwide IT budgets dedicated to enterprise integration projects. SWSs promise to integrate application services that are encapsulated in both old and new applications. Enterprises will not only be able to move information from application to application, but also to create composite applications by combining services found in any number of different local or remote application systems.

Regarding many aspects, the picture of integration architectures based on SWSs looks quite different from an academic point of view as compared with an industrial viewpoint. Unfortunately, the results of this analysis do not allow inferring a precise timing of the achievements to be made within the scope of SWS research. Analyzing SWSs with respect to major challenges, forthcoming achievements, and the potential in one of their most promising application areas, however, allows taking a first step toward the production of a technology roadmap.

In order to produce a more profound technology roadmap for SWSs, further research would be needed. To attain a first impression concerning the opinions of the experts, a two-round Delphi study was conducted. However, the moderate average κ values for both groups of respondents suggest the continuation of the Delphi process in order to attain more substantial agreement among the experts. Because most events and developments are in some way connected to each other, interdependencies must be kept in mind when interpreting the results of Delphi studies. Conducting a cross-impact analysis, for instance, would be a suitable method to identify mutually exclusive or conflicting scenarios. It would take the possibility into account that the occurrence of one development may change probabilities of other expected development.

Despite the fact that this work can only be seen as a first step toward a profound SWS technology roadmap, we hope that our discourse will serve as a basis to reduce the gap between research activities and industrial needs and, subsequently, to exploit the full potential of SWSs.

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