A SEMANTIC DATA MEDIATOR FRAMEWORK TO SUPPORT AUTOMATION OF WEB SERVICES DATA MEDIATION

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To my husband Mr. Sugumaran and
sons Sarveshaah and Avhineshah

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ABSTRACT

Most businesses nowadays use Web Services (WS) technology as a platform to facilitate interaction between service providers and requestors. Data mediators in these services play an important role in ensuring successful interactions; however, the Semantic Web Service (SWS) still faces great challenges in providing the mediation actions that are necessary for smooth WS interactions and is thus open for further research exploration and automation in discovery, selection and composition. Many existing data mediation approaches focus on automated ontology mapping that provides only limited discussions on mediating actual instances. As such, current approaches suffer from insufficient mediation knowledge for related domains to mediate messages correctly at run time. The objective of this thesis is to construct a data mediation framework for the SWS and its associated processes that can establish data mediation automatically for WS interactions at run-time. The Semantic Data Mediator Framework (SDMF) is proposed to manage interactions between source messages and target messages by expressing the data mediation knowledge of developers in the form of semantic knowledge representation. The research steps in *engineering method* research methodology are adopted to identify the required improvement and design the SMDF data mediation solution. A data mediation component that mediates messages during a WS interaction between scholarly databases and local universities is developed using the proposed SDMF. The evaluation results on the semantic data mediator component using the SDMF are benchmarked with an existing middleware application that is used to support the data mediation. The evaluation results prove that semantic descriptions of the Web service message content through the SDMF are able to enhance the correctness and automation during the run time of a WS interaction.

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ABSTRAK

Kebanyakan perniagaan kini menggunakan teknologi Perkhidmatan Web (PW) sebagai platform untuk membolehkan interaksi antara pembekal dan peminta perkhidmatan. Pengantara data dalam PW memainkan peranan penting untuk memastikan interaksi yang berkesan. Perkhidmatan Web Semantik (PWS) telah memberi ruang yang lebih banyak kepada penerokaan penyelidikan ke arah mengautomasikan pemilihan, penemuan dan komposisi PW. Walaubagaimanpun, PWS masih menghadapi cabaran yang besar dalam menyediakan tindakan pengantaraan yang diperlukan bagi melancarkan interaksi PW. Kebanyakan pendekatan pengantaraan data yang sedia ada, memberi tumpuan kepada pemetaan ontologi secara automatik dan hanya menyediakan perbincangan secara terhad bagi pengantaraan data dengan nilai sebenar. Oleh yang demikian, pengetahuan pengantaraan data semasa bagi sesuatu domain tidak mencukupi untuk menjana pengantara mesej secara automatik pada masa larian. Objektif tesis ini adalah untuk membina rangka kerja pengantaraan data bagi PWS dan proses yang berkaitan dengannya bagi mewujudkan pengantara data secara automatik semasa interaksi PW. Rangka kerja Pengantara Data Semantik (RPDS) adalah dicadangkan untuk menguruskan interaksi antara mesej sumber dan mesej sasaran dengan menyatakan data pengantaraan pengetahuan untuk pembangun sistem mewakilkannya sebagai pengetahuan semantik. Langkah-langkah yang terkandung dalam kaedah kejuruteraan telah digunakan sebagai kaedah penyelidikan untuk mengenalpasti penambahbaikan yang diperlukan dan merekabentuk pengantaraan data RPDS. Satu komponen pengantaraan data yang berfungsi sebagai pengantara mesej PW semasa interaksi antara pangkalan data ilmiah dan universiti tempatan telah dibangunkan menggunakan RPDS. Hasil penilaian ke atas komponen pengantaraan semantik data menggunakan RPDS diukur dengan membandingkan dengan aplikasi perisian tengah yang sedia ada untuk menyokong pengantaraan data. Keputusan penilaian membuktikan bahawa perwakilan pengetahuan semantik bagi kandungan mesej PW melalui RPDS dapat dipertingkatkan ketepatannya dan mengautomasikan interaksi PW.

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ARM	-	Association Rule Mining
ASM	-	Abstract State Machine
DMRO	-	Data Mediation Rule Ontology
DMSWS	-	Data Mediation Semantic Web Service
FOL	-	First Order Logic
GRA	-	General Reachability Analysis
HTML	-	Hyper Text Markup Language
IOPE	-	Input, Output, Precondition and Effect
OWL	-	Web Ontology Language
RDF	-	Resource Definition Framework
RDFS	-	Resource Definition Framework (Scheme)
SAWSDL	-	Semantic Annotation for WSDL
SDMF	-	Semantic Data Mediator Framework
SOAP	-	Simple Object Access Protocol
SPA	-	Specific Protocol Analysis
SWRL	-	Semantic Web Rule Language
SWS	-	Semantic Web Service
UDDI	-	Universal Description, Discovery, and Integration
W3C	-	World Wide Web Consortium
WS	-	Web Service
WSDL	-	Web Services Description Language
WSMF	-	Web Service Modelling Framework
WSML	-	Web Service Modelling Language
WSMO	-	Web Service Modelling Ontology
WSMX	-	Web Service Execution Environment
WWW	-	World Wide Web

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CHAPTER 1

INTRODUCTION

This chapter begins with a brief introduction on the subject of the research, i.e. using the Semantic Data Mediator Framework (SDMF) in supporting automation during the Web Service instance transformation. Various important aspects of the research as a whole are explained. Firstly, the background and statement of the problem are elaborated. This is then followed by the objectives and scope of this research. The final section contains the significance of this research and brief descriptions of some important terms that are used in this research.

1.1. Background of the Problem

It is important to have an overview of the background of the problem before investigating it. Therefore, this section begins with a brief introduction of Web Service (WS), Semantic Web Service (SWS) and interaction mismatches that support problem statements of this study. It is then followed by issues and challenges in instance transformation within the SWS data mediation.

1.1.1. Issues in Web Service Interactions

Web service is a growing technology that has been widely adopted by many organizations. It has provided a medium for communication between the service

provider and the service requestor in the business environment. Generally, the capability of an offered service will be matched with the goal of the requested service from various perspectives in order to discover and select the matched services. However, there is no assurance that these matched services can work well due to the various message mismatches which only are discovered during the actual invocation phase. These mismatches occur in the web services environment due to the significant increase in the number of web services and the distributed nature of the web services themselves. Both the service provider and the requestor are unable to achieve their business goals when there are message mismatches during their web service interactions.

There are five types of mismatches during message interactions namely Extra Messages (EM), Wrong Order Messages (WOM), One to Many Messages (OMM), Many to One Messages (MOM) and Missing Messages (MM). Data level mismatches which occur from the differences in structure, type and naming conventions of the data elements in interacting messages can lead to these mismatches. In order to solve these interaction mismatches, five types of mediation actions have been proposed and these are: stop, merge, split, generate, and reorder [1]. The original messages are split, merged, or reordered according to the required interaction. New messages may even be generated from the original messages in order to conform to the required interaction patterns. Therefore, there is a need for a data mediator to support the proposed mediation actions.

The role of the semantic in web service has played an important part in this communication by allowing automatic discovery, selection and composition between the service provider and the requestor. Data incompatibility can also occur between web services during composition, negation and invocation so therefore, there is a need for the data mediator to solve the data incompatibility problem between the service provider and the service requestor. The data mediator is an important application in problem solving, since it is an important component in automating the SWS discovery, composition and invocation processes. Most of the SWS frameworks like the Web Service Modelling Ontology (WSMO), the Semantic Markup for Web Service (OWL-S) and the Web Service Semantic (WSDL-S) are

using the ontology-based techniques like ontology mapping, ontology alignment and ontology merging to solve the data incompatibility problem [2-6].

1.1.2. Issues of Instance Transformation in Data Mediation

There are two phases in implementation of the data mediation in the SWS namely the design-time and the run-time. A developer's involvement in the design-time process and the output from this phase will be executed automatically during the run-time. There are two further sub-components in the data mediation component in the SWS namely, the ontology mapping and the instance transformation. The existing approaches focus on creating the ontology mapping automatically; and only provide limited discussion on the instance transformation component.

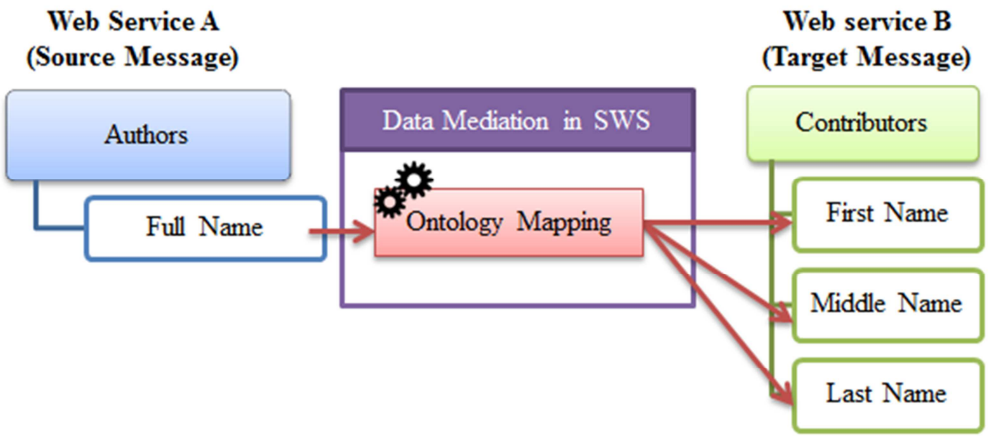

Figure 1.1: Ontology mapping that supports data mediation

The current data mediation approach in SWS is illustrated by using a simple scenario as shown in Figure 1.1. It can be assumed that there is an OMM mismatch between the two Web services namely A and B which require a data mediator to split the message. Web service A contains the full name attributes of the Authors' ontology, whereas Web service B is expecting three attributes termed as first name, middle name and last name which are linked to another ontology known as the Contributors as shown in Figure 1.1.

The existing approaches in the SWS only focus on generating the ontology mapping for one-to-many message mismatches. Various techniques to generate attributes mapping between full name to first name, middle name and last name to support web services interaction are used by the researcher. In this scenario, the data mediation must be able to split a single message into three messages.

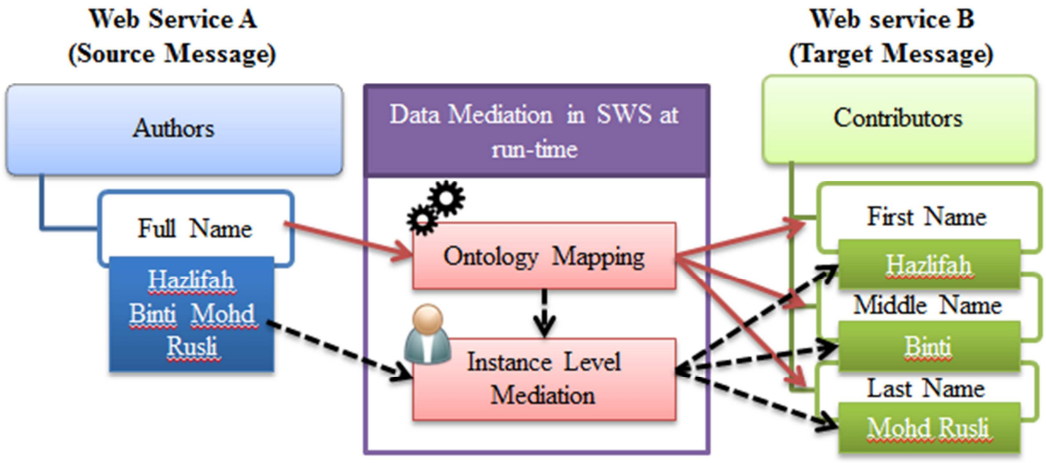

Figure 1.2: Role of Developer in Assisting Instance Level Matching in Data Mediation

The machines that support the SWS interaction need to understand the actual instance to ensure that the message can be mediated correctly according to the content and the provided mapping as shown in Figure 1.2. It shows the role of the developer in the data mediation to understand the content of the messages and split them meaningfully for the provided data mediation scenario. It can be assumed that the author ontology contains an instance of full name, “Hazlifah Binti Mohd Rusli”. In this case the machines are unable to split the author’s full name by just basing on the ontology mapping.

1.2. Problem Statement

As explained in the problem background, ontology mapping itself is insufficient to handle the mediation actions. The existing automatic ontology mapping approaches in the SWS still requires the assistance of the developer to split the messages correctly according to the generated mapping. Thus, existing ontology mapping approaches in the SWS do not guarantee that the source messages can to be split into target messages correctly without the developer's role at run time.

The existing approaches use handlers to store and send messages based on the interaction mismatch patterns. These approaches are only able to resolve the interaction mismatches due to the EM and WOM. They could stop the extra messages and reorder the incorrect messages. However, it requires further data mediation functionalities to support the OMM, MOM and MM mismatches. The existing semantics in the web service only focus on generating the ontology that describes each concept or class in a web service. The ontological descriptions of the concepts need to be extended to describe the content of the messages/instances. The ontological descriptions on the message content and the message manipulations are able to support mediation action such as splitting, merging and generating new messages during instance transformation.

The following are the challenges of the instance transformation to support meaningful data mediation for OMM, MOM and MM type interaction mismatches automatically and correctly at run-time:-

(a) Need to describe the content of the provided source message using ontology.

(b) Need to apply correct message manipulation to produce the required target message.

(c) Need to transform the content descriptions and message manipulation into the SWS environment.

1.3. Research Questions

The ultimate goal to of this research is to provide automated data mediation approach during instance transformation to support OMM, MOM and MM mismatches in web service interactions using the WSMO elements. The output of this research is expected to increase the correctness and automation in other tasks in the SWS such as composition, negation, testing and invocation. The general research question is as follows:

How to enhance the existing data mediator to support interaction message mismatches automatically during the instance transformation?

The following research questions are formulated to address the stated general research question and the discussed problems in this research area.

(a) **RQ1**: What are the elements that are required in supporting the instance level data mediation during a web service interaction?

(b) **RQ2**: How to represent a domain expert's data mediation knowledge into a machine readable form?

  (i) How to describe a message content using ontology?

  (ii) How to describe message manipulations using ontology?

  (iii) How to query the ontology to extract the required messages according to the mediation actions?

(c) **RQ3**: What are the required components and processes involved in building the proposed SDMF?

(d) **RQ4**: How to build the SDMF to support instance level data mediation during web service interaction?

(e) **RQ5**: How to evaluate validity of the proposed approach to support instance level data mediation?

1.4. Objectives of the Study

The objectives of this study have been derived from the problem statement above. The objectives of this research are to:

(a) to study and investigate issues in Web services interactions associated to data mediation

(b) to develop a SDMF using the Data Mediation Rule Ontology (DMRO) and the Data Mediation Semantic Web Service (DMSWS).

(c) to evaluate the correctness of data retrieved from the DMRO using the Pellet Reasoner for splitting message and benchmark them with existing data mediation middleware applications.

1.5. Scopes of the Study

This section describes the limitations and the boundaries of this study. Below are the scopes of this research:-

(a) This research only focuses on three interaction mismatches in the web services namely OMM, MOM and MM mismatches and the respected mediation actions.

(b) This research describes all the activities and processes in developing ontology termed as the DMRO which describes the message content and the message manipulation to support mediation actions.

(c) The DMRO that describes the message content is modelled based on the knowledge extracted from a relational database and focuses on the string manipulations that support the mediation actions.

(d) This research also illustrates how the DMRO can be implemented as a SWS web service using the WSMO elements.

(e) This approach only evaluates based on two quality issues namely the automation and the correctness.

1.6. Significance of the Study

Related work on data mediation was analysed in the existing SWS Frameworks namely the WSMO, the OWL-S and the SAWSDL. Early data mediation effort in the Web services is found in [7] which introduces the mapping rules between the RDF scheme in the Triple Space Computing. This effort is extended by the WSMO data mediation initiatives which focus on the ontology alignment [5, 8, 9].

The WSMO initiatives generate mapping rules in the form of axioms based on the abstract mappings identified by the developers at the time of design. They demonstrate that the source instances that can be transformed into the target instances via posting query and retrieving answers from the mapping rules at the time of execution. However, the data mediation effort is found to focus only on the generating alignment between the attributes that are placed at different levels within the ontology. It describes implicitly the data mediation effort that involves splitting and merging messages during the mediation process.

Secondly, in the OWL-S, the data mediation that supports the mediation process is not explained in detail and is only mentioned as an external service [10]. The researchers however, have concluded on the need of better support for data mediation in order to allow real life Web service mediation [11]. Finally, data mediation efforts in the SAWSDL introduces the use of the context-based data type ranking algorithm to generate scheme mapping between the Web service messages [12]. Further discussion on data mediation to support process mediation actions is however not provided by the researchers [13].

Due to these limitations in the existing data mediation efforts in the SWS frameworks, this research has proposed the SDMF. This framework highlights how a semantically described message content using the OWL ontology and SWRL rule language can be useful in modelling mediation actions automatically and correctly. This research has also presented all the activities and processes in designing the SMDF which consists of the DMRO and the DMSWS. The DMRO is modelled

from the relational database with guidance from domain experts to express message content using the OWL and the SWRL at design-time. Then, the tested and evaluated DMRO is transformed into SWS using the WSML language to support the mediation action during the instance transformation at run-time. Below are some of the significant contributions of this research:-

(a) This research proposes the SDMF as it is able to overcome the existing data mediation problem in understanding the message content in order to mediate the web service message correctly. It extracts the required data mediation knowledge from the input resources such as database and developers/domain experts and uses the generated knowledge to mediate the messages correctly.

(b) Current SWS initiatives only focus on developing ontology that describes the concepts and classes. This research has proposed ways to describe message content using ontology. It also demonstrates how the message manipulation functionality can be embedded into the ontology and reasoning tools which can be used to retrieve the target messages.

(c) The role of the SDMF can replace the work of developers or data entry clerks to support automation in service discovery, selection, process mediation and composition in SWS.

(d) The DMRO that captures common data mediation knowledge can be reused for other web services interactions for a different service provider and requestor.

1.7. Glossary

This section explains some of the terms that have used in this research. The detailed explanation for each of these terms is provided in the Literature Review section.

- **Web Service** – a software system or technology which describes the services using the XML and these services can be accessed by other software systems using the XML based messages via web. It consists

of three important components which are the WSDL, the UDDI and the SOAP.

- **Semantic Web Service** –a new paradigm that brings semantic descriptions to data and behaviour of web services. It has evolved from the integration of the Semantic Web and Web Service technologies. The current research on SWS focuses on automation of discovery, selection, mediation and composition of the Web Services.
- **Interaction message mismatches** – interaction message mismatches are similar to solvable message mismatches [14] and unspecified reception in the web services interaction as mentioned by [15]. There are five types of interaction message mismatches namely the EM, WOM, OMM, MOM and MM.
- **Mediation Actions** – refers to the solutions or actions for each interaction message mismatches that are mentioned earlier. There are five mediation actions namely stop or hide, inverse order, split, merge and generate.
- **Data mediation** – a component of the SWS that resolves data mismatches in the WS interaction. It contains two important components which are the Ontology Mapping and the Instance Transformation.
- **Instance transformation** – a component that uses the mappings created by the ontology mapping component to assign correct target instance to the respected source instance during run-time.
- **Message manipulations** – refers to built-in functions in the database that manipulates data according to the required structure. There are three main categories in message manipulations that are required in the web services namely the aggregate, the string and the date/time manipulation functions.
- **Web Service Modelling Ontology (WSMO)** – a formal SWS framework that provides semantic descriptions to all the related aspects of the web service. The WSMO consists of four core elements namely the *Goal*, the W*eb Service*, the *Mediator* and the *Ontology*.

- **Web Service Modelling Toolkit (WSMT)** – is an ontology engineering toolkit for the WSMO framework. It provides graphical interface to assist domain experts in creating ontology mapping between source and target ontology [16].
- **Web Service Modelling Language (WSML)** – a concrete formal language of the WSMO framework that is used to describe the *Goal*, the W*eb the Service*, the *Mediator* and the *Ontology* elements.
- **Ontology** - Ontology refers to a formalization of the knowledge in the domain. It is able to interweave human and computer understanding of symbols. Basic building blocks of ontology design include: classes or concepts, properties of each concept describing various features and attributes of the concept such as restrictions or axioms, instances and relationships.
- **Protégé** – is a Java-based open source a stand- alone application that allows a user to load and save the OWL and the RDF based ontology [17]. It also allows the user to edit and visualize classes and properties of ontology and semantic rule languages such as the SWRL.
- **Semantic Web Rule Language (SWRL)** – helps to extend expressivity of the OWL by adding rules to the existing ontology. The SWRL rules contain unary predicates for describing classes and data types, binary predicates for properties, and some special built-in n-ary predicates [18].

1.8. Thesis Outline

This research discusses some specific issues of data mediation in the SWS approaches during message interactions. It also highlights the limitation of the existing approaches in resolving interaction mismatches at instance transformation. It describes a proposed SDMF that enhances automation and correctness of the existing approaches. The SDMF uses the OWL ontology and the SWRL rules to describe the message content and the required message manipulation and then transform them into the WSMO elements. This thesis is organised as follows:-

Chapter 2: It discusses the literature reviewed on the SWS and interaction mismatches. It begins with some preliminary studies that describe message mismatches in the web service interaction and the data mediation actions that support these interaction mismatches. This is followed by a discussion on the instance transformation component in data mediation. Also in this section the methods and elements that support instance transformation of data mediation in the WSMO framework are discussed.

Chapter 3: This chapter provides a survey on the-state-of-art data mediation approaches that support the interaction mismatches. A comparative evaluation on eight important elements of the message mediator is also presented in this section. The outcome of this survey highlights the need for further research in enhancing the semantic description of the web service messages to support data mediation. The final section presents the architecture and implementation of the data mediation to interaction mismatches in the WSMO framework. This section highlights on the elements of the WSMO that needs to be improved to overcome the existing limitation.

Chapter 4: It describes the research design, procedure and activities which are used in this research. It also discusses on the research instruments, the evaluation criteria, assumptions and limitations that have been adopted and observed in this research.

Chapter 5: presents a conceptual model of the proposed SDMF. It begins with the motivation of this research; summarises the limitations of the existing approaches; and analysis on the required elements to overcome the limitations. This is followed by a detailed discussion on the proposed SDMF. It explains the two main components in the SDMF, DMRO and DMSWS; and the six important procedures involved in modelling this framework.

Chapter 6: It explains the design and implementation of the SDMF. The design and implementation of the DMRO and DMSWS components are discussed in detail by elaborating the three important processes namely knowledge extraction; knowledge representation and evaluation; and knowledge modelling into the SWS. All the procedures that are related to these three design and implementation processes are also explained in detail.

Chapter 7: It explains the evaluation on the correctness and automation of the proposed SDMF in detail. Firstly a motivating scenario that requires data mediation at runtime between the Bibliographic Scholarly Database (BSD) organisations and the Higher Learning Institutions (HLI) in Malaysia are selected. The instance data mediation component that supports data mediation in this motivating scenario has been built using the proposed SDMF. Secondly, a middleware application that is currently used to support data mediation between the service provider and requestor is analysed and used as the benchmark. The results that are retrieved from the existing middleware application and the DMRO component of the SDMF are verified by domain experts and output from the database. Both the proposed SDMF and the existing middleware applications are measured using precision, recall and the F-measure measurements.

Chapter 8: It concludes this dissertation by describing the research achievements and contributions. This is followed by the research summary and suggestions for research future works.

REFERENCES

1. Cimpian, E. and A. Mocan. *WSMX process mediation based on choreographies*. 2005. Nancy, France: Springer Verlag.
2. Shafiq, O., et al. *Data mediation support for triple space computing*. 2006. Atlanta, GA, United states: Inst. of Elec. and Elec. Eng. Computer Society.
3. Fensel, D., M. Kerrigan, and M. Zaremba, *Mediation*, in *Implementing Semantic Web Services*. 2008. p. 211-231.
4. Nagarajan, M., et al., *Ontology driven data mediation in Web services.* International Journal of Web Services Research, 2007. **4**(4): p. 104-126.
5. Mocan, A. and E. Cimpian, *An ontology-based data mediation framework for semantic environments.* Semantic Web and Information Systems, 2007. **3**(2): p. 69-98.
6. Mocan, A. and E. Cimpian, *WSMX Data Mediation*, A. Mocan, Editor. 2005: Vienna. p. 32.
7. Shafiq, O., et al. *Data Mediation Support for Triple Space Computing*. in *2006 International Conference on Collaborative Computing: Networking, Applications and Worksharing, CollaborateCom*. 2006. Atlanta, GA, United states: Inst. of Elec. and Elec. Eng. Computer Society.
8. Mocan, A., E. Cimpian, and M. Kerrigan, *Applying Reasoning to Instance Transformation*, in *5th European Semantic Web Conference (ESWC)*. 2009: Tenerife Spain.
9. Mocan, A. and E. Cimpian. *WSMX Data Mediation*. 2005 11 Oct 2005 [cited 28 June 2011]; Available from: http://www.wsmo.org/TR/d13/d13.3/v0.2/20051011/.
10. Vaculin, R., R. Neruda, and K. Sycara, *The process mediation framework for semantic Web services.* International Journal of Agent-Oriented Software Engineering, 2009. **3**(1): p. 27-58.
11. Vaculin, R. and K. Sycara. *Towards automatic mediation of OWL-S process models*. in *Proceedings - 2007 IEEE International Conference on Web Services, ICWS 2007*. 2007. Salt Lake City, UT.
12. Wu, Z.X., et al., *Automatic composition of semantic web services using process mediation*, J. Cardoso, J. Cordeiro, and J. Filipe, Editors. 2007, LSDIS lab, University of Georgia. p. 453-461.
13. Gomadam, K., et al., *A Declarative Approach using SAWSDL and Semantic Templates Towards Process Mediation*, in *Semantic Web Services Challenge*. 2009. p. 101-118.

14. Fensel, D. and C. Bussler, *The Web Service Modeling Framework WSMF*. Electronic Commerce Research and Applications, 2002. **1**(2): p. 113-137.
15. Bordeaux, L., et al. *When are two web services compatible?* in *Lecture Notes in Computer Science*. 2005. Toronto, Ont.
16. Euzenat, J., A. Mocan, and F. Scharffe, *Ontology Alignments*, in *Ontology Management*. 2008. p. 177-206.
17. Waterfeld, W., et al., *Ontology Management Infrastructures*, in *Ontology Management*. 2008, Springer US. p. 59-87.
18. Horrocks, I., et al. *A Semantic Web Rule Language Combining OWL and RuleML*. 2004 [cited; Available from: http://www.w3.org/Submission/SWRL/.
19. Fensel, D., et al., *Web Services*, in *Enabling Semantic Web Services*. 2007. p. 37-54.
20. Berners-Lee, T., T. Fielding, and L. Masinter. *Uniform Resource Identifiers (URI): Generic Syntax", IETF RFC 2396*. 1998 [cited; Available from: http://www.ietf.org/rfc/rfc2396.txt.
21. Austin, D., et al. *Web Services Architecture Requirements*. 2004 [cited; Available from: http://www.w3.org/TR/wsa-reqs/.
22. Clement, L., et al. *UDDI Spec Technical Committee Draft*. 2004 19 Oct 2004 [cited; Available from: http://www.uddi.org/pubs/uddi_v3.htm.
23. Christensen, E., et al. *Web Services Description Language (WSDL) 1.1*. 2001 15 Mac 2001 [cited; Available from: http://www.w3.org/TR/wsdl.
24. Werner, C. and S. Fischer, *Architecture and Standardisation of Web Services*, in *Semantic Web Services*. 2007. p. 25-48.
25. Gudgin, M., et al. *SOAP Version 1.2 Part 1*. 2007 [cited; Available from: http://www.w3.org/TR/soap12-part1/.
26. Berners-Lee, T., J. Hendler, and O. Lassila, *The Semantic Web*, in *Scientific American*. 2001. p. 34-43.
27. Hepp, M., *Ontologies: State of the Art, Business Potential, and Grand Challenges*, in *Ontology Management*. 2008. p. 3-22.
28. Nicola, G. *Ontology and Terminology: how can formal ontology help concept modeling and terminology?* in *EAFT on Terminology, Concept Modeling and Ontology*. 2006.
29. *The Semantic Web*, in *Enabling Semantic Web Services*. 2007. p. 25-36.
30. Stephan, G., H. Pascal, and A. Andreas, *Knowledge Representation and Ontologies*, in *Semantic Web Services*. 2007. p. 51-105.
31. Cardoso, J., *The Semantic Web: A mythical story or a solid reality?*, in *Metadata and Semantics*. 2009. p. 253-257.
32. *Semantic Web Services*, in *Implementing Semantic Web Services*. 2008. p. 27-41.
33. Cardoso, J. and A. Sheth, *The Semantic Web and Its Applications*, in *Semantic Web Services, Processes and Applications*. 2006. p. 3-33.
34. Martin, D., et al. *OWL-S: Semantic Markup for Web Services* 2004 [cited; Available from: http://www.w3.org/Submission/OWL-S/.

35. Akkiraju, R., et al. *Web Service Semantics - WSDL-S*. 2005 [cited; Available from: http://www.w3.org/Submission/WSDL-S/.
36. Farrell, J. and H. Lausen, *Semantic Annotations for WSDL and XML Schema (SAWSDL)*, in *W3C Recommendation*. 2007.
37. Bruijn, J.d., et al. *Web Service Modeling Ontology (WSMO)*. 2005 [cited; Available from: http://www.w3.org/Submission/WSMO/.
38. Wang, H.H., et al., *A formal model of the Semantic Web Service Ontology (WSMO)*. Information Systems, 2012. **37**(1): p. 33-60.
39. Lausen, H., et al., *Description*, in *Semantic Web Services*. 2007. p. 179-209.
40. Fensel, D., M. Kerrigan, and M. Zaremba, *WSMO and WSML*, in *Implementing Semantic Web Services*, D. Fensel, M. Kerrigan, and M. Zaremba, Editors. 2008. p. 43-65.
41. Keyvan, M., et al., *A comparative evaluation of semantic web service discovery approaches*, in *Proceedings of the 12th International Conference on Information Integration and Web-based Applications & Services*. 2010, ACM: Paris, France.
42. Arroyo, S., M.A. Sicilia, and J.M. Dodero, *Choreography frameworks for business integration: Addressing heterogeneous semantics*. Computers in Industry, 2007. **58**(6): p. 487-503.
43. Yellin, D.M. and R.E. Strom, *Protocol specifications and component adaptors*. ACM Transactions on Programming Languages and Systems, 1997. **19**(2): p. 292-333.
44. Stollberg, M., E. Cimpian, and D. fensel. *Mediating Capabilities with Delta-Relations*. in *First International Workshop on Mediation in Semantic Web Services (MEDIATE 2005) conjuction with 3rd International Conference on Service-Oriented Computing (ICSOC 2005)*. 2005. Amsterdam, Netherlands
45. Motahari Nezhad, H.R., et al. *Semi-automated adaptation of service interactions*. in *16th International World Wide Web Conference, WWW2007*. 2007. Banff, AB.
46. Wei, T., et al., *Compatibility analysis and mediation-aided composition for BPEL services*, in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. 2007: Bangkok. p. 1062-1065.
47. Mateescu, R., P. Poizat, and G. Salaün, *Adaptation of Service Protocols Using Process Algebra and On-the-Fly Reduction Techniques*, in *Service-Oriented Computing – ICSOC 2008*. 2008. p. 84-99.
48. Dustdar, S., et al., *Adapt or Perish: Algebra and Visual Notation for Service Interface Adaptation*, in *Business Process Management*. 2006, Springer Berlin / Heidelberg. p. 65-80.
49. Cimpian, E. and A. Mocan, *Process Mediation In WSMX*, E. Cimpian, Editor. 2005: Vienna. p. 29.
50. Mizoguchi, R., et al., *Mediation Enabled Semantic Web Services Usage*, in *The Semantic Web – ASWC 2006*. 2006, Springer Berlin / Heidelberg. p. 459-473.

51. Li, X., et al., *A pattern-based approach to protocol mediation for web services composition.* Information and Software Technology, 2009. **52**(3): p. 304-323.
52. Camara, J., G. Salaun, and C. Canal, *Composition and run-time adaptation of mismatching behavioural interfaces.* Journal of Universal Computer Science, 2008. **14**(13): p. 2182-2211.
53. Brogi, A. and R. Popescu, *Service adaptation through trace inspection.* International Journal of Business Process Integration and Management, 2007. **2**: p. 9-16.
54. Kongdenfha, W., et al., *Mismatch patterns and adaptation aspects: A foundation for rapid development of web service adapters.* IEEE Transactions on Services Computing, 2009. **2**(2): p. 94-107.
55. Kuang, L., et al. *Towards adaptation of service interface semantics*. in *2009 IEEE International Conference on Web Services, ICWS 2009*. 2009. Los Angeles, CA.
56. Seguel, R., R. Eshuis, and P. Grefen. *Generating Minimal Protocol Adaptors for Loosely Coupled Services*. in *Web Services (ICWS), 2010 IEEE International Conference on*. 2010.
57. Wiederhold, G., *Mediators in the architecture of future information systems.* Computer, 1992. **25**(3): p. 38-49.
58. Grahne, G. and V. Kiricenko, *Process Mediation in Extended Roman Model*, in *First International Workshop on Mediation in Semantic Web Services (MEDIATE 2005) conjuction with 3rd International Conference on Service-Oriented Computing (ICSOC 2005)*, M. Hepp, et al., Editors. 2005: Amsterdam, Netherlands p. 17-33.
59. Scharffe, F., *Correspondence Patterns Representation*, in *Faculty of Mathematics, Computer Science and Physics*. 2009, University of Innsbruck: Austria. p. 237.
60. Wöhrer, A., et al., *Towards a Reference Model for the Runtime-Phase of Semantic Data Mediation*, in *Intelligent Distributed Computing IV*. 2010, Springer Berlin / Heidelberg. p. 89-95.
61. Shafiq, O., et al. *Resolving data heterogeneity issues in open distributed communication middleware*. in *Proceedings - 3rd International Conference on Internet and Web Applications and Services, ICIW 2008*. 2008. Athens.
62. Mocan, A., E. Cimpian, and M. kerrigan, *Formal Model for Ontology Mapping Creation*. 2006.
63. Euzenat, J.r.m. and P. Shvaiko, *Basic techniques*, in *Ontology Matching*. 2007, Springer Berlin Heidelberg. p. 73-116.
64. Euzenat, J.r.m. and P. Shvaiko, *Matching strategies* in *Ontology Matching*. 2007, Springer Berlin Heidelberg. p. 117-150.
65. Bruijn, J.d., et al., *Ontology Mediation, Merging, and Aligning*, in *Semantic Web Technologies*. 2006, John Wiley & Sons, Ltd. p. 95-113.
66. Nitzsche, J. and B. Norton, *Ontology-based data mediation in BPEL (For Semantic Web Services)*, in *Lecture Notes in Business Information*

Processing, D. Ardagna, M. Mecella, and J. Yang, Editors. 2009: Milano. p. 523-534.

67. Fensel, D., et al., *Seekda: The Business Point of View* in *Semantic Web Services*. 2011, Springer Berlin Heidelberg. p. 325-351.
68. Stollberg, M., et al., *A Semantic Web Mediation Architecture*, in *Canadian Semantic Web*. 2006. p. 3-22.
69. Fensel, D., et al., *The Concepts of WSMO*, in *Enabling Semantic Web Services*. 2007. p. 63-81.
70. Tan, P.-N., M. Steinbach, and V. Kumar, *Introduction to Data Mining*. 2006: Addison Wesley.
71. Kotsiantis, S. and D. Kanellopoulos, *Association rules mining: A recent overview*. GESTS International Transactions on Computer Science and Engineering, 2006. **32**(1): p. 71-82.
72. Bellandi, A., et al. *Ontology-driven association rule extraction: A case study*. in *Context & Ontologies: Representation and Reasoning*. 2007.
73. Ghani, R. and A.E. Fano. *Using text mining to infer semantic attributes for retail data mining*. in *Data Mining, 2002. ICDM 2003. Proceedings. 2002 IEEE International Conference on*. 2002.
74. Gorodetsky, V., V. Samoylov, and S. Serebryakov. *Ontology–Based Context–Dependent Personalization Technology* in *Web Intelligence and Intelligent Agent Technology (WI-IAT), 2010 IEEE/WIC/ACM International Conference on*. 2010.
75. Man, L., D. Xiao-Yong, and W. Shan. *Learning ontology from relational database*. in *Machine Learning and Cybernetics, 2005. Proceedings of 2005 International Conference on*. 2005.
76. Santoso, H.A., S.-C. Haw, and Z.T. Abdul-Mehdi, *Ontology extraction from relational database: Concept hierarchy as background knowledge.* Knowledge-Based Systems, 2011. **24**(3): p. 457-464.
77. Justas, T. and V. Olegas, *Building ontologies from relational databases using reverse engineering methods*, in *Proceedings of the 2007 international conference on Computer systems and technologies*. 2007, ACM: Bulgaria.
78. Chen, H.-p., L. He, and B. Chen. *Research and Implementation of Ontology Automatic Construction Based on Relational Database*. in *Computer Science and Software Engineering, 2008 International Conference on*. 2008.
79. Albarrak, K.M. and E.H. Sibley. *Translating relational & Object-Relational Database models into OWL models*. in *Information Reuse & Integration, 2009. IRI '09. IEEE International Conference on*. 2009.
80. Fisher, M. and M. Dean, *Automapper: Relational database semantic translation using OWL and SWRL, OWLED 2008: OWL experiences and Directions, Karlsruhe Germany 2008*. 2008.
81. Jiuyun, X. and L. Weichong. *Using Relational Database to Build OWL Ontology from XML Data Sources*. in *Computational Intelligence and Security Workshops, 2007. CISW 2007. International Conference on*. 2007.

82. Cerbah, F. *Mining the Content of Relational Databases to Learn Ontologies with Deeper Taxonomies*. in *Web Intelligence and Intelligent Agent Technology, 2008. WI-IAT '08. IEEE/WIC/ACM International Conference on*. 2008.
83. Kjernsmo, K. and A. Passant (2009) *SPARQL New Features and Rationale*. **Volume**,
84. Toma, I., B. Bishop, and F. Fischer, *Defining the features of the WSMLRule v2.0 language*. 2009. p. 32.
85. Benatallah, B., et al. *Developing adapters for web services integration*. in *Lecture Notes in Computer Science*. 2005. Porto.
86. Cimpian, E. and A. Mocan, *WSMX process mediation based on choreographies*, in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. 2005: Nancy. p. 130-143.
87. Zhou, S. and Z. Sun. *Using WSMO to enable mediation of heterogeneous services and semi-automation of service discovery and execution in semantic SOA*. in *2009 International Conference on Web Information Systems and Mining, WISM 2009*. 2009. Shanghai.
88. Vaculin, R., R. Neruda, and K. Sycara, *Process Mediation: Requirements, Experiences and Challenges.* Electronic Business Interoperability: Concepts, Opportunities and Challenges, 2011: p. 77.
89. Brogi, A., R. Popescu, and M. Tanca, *Design and implementation of SATOR: A web service aggregator*. ACM Transactions on Software Engineering and Methodology, 2010. **19**(3).
90. Arroyo, S. and M.Ã. Sicilia, *Modeling learning technology interaction using Sophie: Main mappings and example usage scenarios*, in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. 2009: Chania, Crete. p. 128-136.
91. Tan, W., et al., *Data-driven service composition in enterprise SOA solutions: a Petri net approach.* Automation Science and Engineering, IEEE Transactions on, 2010. **7**(3): p. 686-694.
92. Ardissono, L., et al., *Interaction protocol mediation in web service composition.* International Journal of Web Engineering and Technology, 2010. **6**(1): p. 4-32.
93. Gierds, C., A.J. Mooij, and K. Wolf, *Reducing adapter synthesis to controller synthesis.* Services Computing, IEEE Transactions on, 2012. **5**(1): p. 72-85.
94. Li, X., et al., *A petri net approach to analyzing behavioral compatibility and similarity of web services.* Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on, 2011. **41**(3): p. 510-521.
95. Tan, W., Y. Fan, and M. Zhou, *A petri net-based method for compatibility analysis and composition of web services in business process execution language.* IEEE Transactions on Automation Science and Engineering, 2009. **6**(1): p. 94-106.

96. Mateescu, R., P. Poizat, and G. Salaun. *Behavioral adaptation of component compositions based on process algebra encodings*. in *ASE'07 - 2007 ACM/IEEE International Conference on Automated Software Engineering*. 2007. Atlanta, GA.
97. Zhou, Z., et al. *Formal verification of mediated web service interactions considering client's expected behaviours*. in *2009 5th International Conference on Collaborative Computing: Networking, Applications and Worksharing, CollaborateCom 2009*. 2009. Washington, DC.
98. Cimpian, E., *Message-based Semantic Process Mediation*, in *Faculty Science*. 2010, National University of Ireland Galway: Ireland. p. 198.
99. Cimpian, E. and A. Mocan. *Process Mediation in WSMX*. 2005 8 July 2005 [cited 28 June 2011]; Available from: http://www.wsmo.org/TR/d13/d13.7/v0.1/.
100. Vitvar, T., et al., *Mediation using WSMO, WSML and WSMX*, in *Semantic Web Services Challenge*. 2009. p. 31-49.
101. Zhou, Z., et al. *Developing process mediator for supporting mediated Web service interactions*. in *Proceedings of the 6th IEEE European Conference on Web Services, ECOWS'08*. 2008. Dublin.
102. Cabral, L., et al. *IRS-III: A broker for semantic web services based applications*. 2006. Athens, GA, United states: Springer Verlag.
103. Zhou, Z., et al., *Process mediation based on triple space computing*, in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. 2008: Shenyang. p. 672-683.
104. Domingue, J., et al., *IRS-III: A broker-based approach to semantic Web services.* Web Semantics, 2008. **6**(2): p. 109-132.
105. Victor, R.B., *The Experimental Paradigm in Software Engineering*, in *Proceedings of the International Workshop on Experimental Software Engineering Issues: Critical Assessment and Future Directions*. 1993, Springer-Verlag.
106. Shaw, M., *What makes good research in software engineering?* International Journal on Software Tools for Technology Transfer (STTT), 2002. **4**(1): p. 1-7.
107. Euzenat, J.r.m. and P. Shvaiko, *Evaluation of matching systems*, in *Ontology Matching*. 2007, Springer Berlin Heidelberg. p. 193-216.
108. Euzenat, J. *Semantic precision and recall for ontology alignment evaluation*. 2007.
109. Bellahsene, Z., et al., *On Evaluating Schema Matching and Mapping*, in *Schema Matching and Mapping*. 2011, Springer Berlin Heidelberg. p. 253-291.
110. Buitelaar, P., et al., *Ontology-based information extraction and integration from heterogeneous data sources.* International Journal of Human-Computer Studies, 2008. **66**(11): p. 759-788.

111. Hitzler, P., et al., *Ontologies and Rules*, in *Handbook on Ontologies*. 2009, Springer Berlin Heidelberg. p. 111-132.
112. O'Connor, M., et al., *Querying the Semantic Web with SWRL* Advances in Rule Interchange and Applications, 2007. **4824**: p. 155-159.
113. Kitchenham, B.A., *Evaluating software engineering methods and tools - part 3: selecting an appropriate evaluation methods - practical issues.* ACM SIGSOFT Software Engineering Notes, 1996. **21**(4): p. 9-12.
114. Kitchenham, B., S. Linkman, and D. Law, *DESMET: a methodology for evaluating software engineering methods and tools.* Computing & Control Engineering Journal, 1997. **8**(3): p. 120-126.
115. Ghawi, R. and N. Cullot. *Database-to-ontology mapping generation for semantic interoperability*. in *VDBLâ€™07 conference, VLDB Endowment ACM*. 2007.
116. Xu, Z., S. Zhang, and Y. Dong. *Mapping between relational database schema and OWL ontology for deep annotation*. in *Proceedings of the 2006 IEEE/WIC/ACM international Conference on Web intelligence*. 2006: IEEE Computer Society.
117. Horridge, M., *A Practical Guide To Building OWL Ontologies Using Protege 4 and CO-ODE Tools*. 2011, The University Of Manchester.
118. Antoniou, G., et al., *Combining Rules and Ontologies. A survey*. 2005.
119. de Bruijn, J., et al., *The Web Service Modeling Language WSML: An Overview*, in *The Semantic Web: Research and Applications*. 2006, Springer Berlin / Heidelberg. p. 590-604.
120. O'Connor, M., M. Musen, and A. Das, *Using the Semantic Web Rule Language in the Development of Ontology-Driven Applications*, in *Handbook of Research on Emerging Rule-Based Languages and Technologies: Open Solutions and Approaches*. 2009, IGI Global. p. 525-539.
121. Aßmann, U., et al., *Combining Safe Rules and Ontologies by Interfacing of Reasoners*, in *Principles and Practice of Semantic Web Reasoning*. 2006, Springer Berlin / Heidelberg. p. 33-47.
122. Sirin, E., et al., *Pellet: A practical OWL-DL reasoner*. Web Semantics: Science, Services and Agents on the World Wide Web, 2007. **5**(2): p. 51-53.
123. Susan Elliott, S., E. Steve, and C.H. Richard, *Using benchmarking to advance research: a challenge to software engineering*, in *Proceedings of the 25th International Conference on Software Engineering*. 2003, IEEE Computer Society: Portland, Oregon.
124. Despres, S. and H. Zargayouna. *Evaluation of knowledge based applications: benchmark and guidelines*. in *Signal-Image Technology & Internet-Based Systems (SITIS), 2009 Fifth International Conference on*. 2009: IEEE.
125. Kirchhoff, L., et al. *Using social network analysis to enhance information retrieval systems*. in *Applications of Social Network Analysis (ASNA)*. 2008. Zurich.
126. Fabrizio, S., *Machine learning in automated text categorization.* ACM Comput. Surv., 2002. **34**(1): p. 1-47.

127. O'Connor, M., et al., *Supporting Rule System Interoperability on the Semantic Web with SWRL*. The Semantic Web – ISWC 2005, 2005. **3729**: p. 974-986.