Semantic Web Service Composition: The Web Service Challenge Perspective

Thomas Weise, M. Brian Blake, and Steffen Bleul

Abstract Service-oriented architecture (SOA) is a software design paradigm for creating highly modular, distributed applications. Web services can implement well-defined, atomic functions which can be composed into high-level business processes. The composition of clearly separable modules is one of the key advantages of SOAs. This article provides an overview of research, challenges, and competitions in this domain. We first define and discuss the general notions of syntactical and semantic discovery/composition and the corresponding quality of service (QoS) features. One focus of this chapter is the Web Service Challenge (WSC), which has established an extensive body of knowledge and community of researchers in the area of web service composition. We discuss the structure, requirements, and utilities provided in the scope of this competition. The paper furthermore includes a detailed literature review of the activities of the WSC event in context of the related initiatives.

This is a preview version of the book chapter [1] (see page 38 for the reference). Read the full piece at `http://dx.doi.org/10.1007/978-1-4614-7518-7_7`.

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1 Introduction

Service-oriented architectures (SOAs) [2, 3, 4] represent a promising paradigm for realizing business processes within enterprise software systems. The modularity of services that underlie SOAs enable an infrastructure that is easy to maintain, extend, improve, and interconnect. To fully enable the flexibility of SOA environments, approaches must be developed that compose multiple services into higher-level business processes. Services are building blocks in implementing business processes in companies and to integrate heterogeneous resources and external systems [5].

The composition of services within companies implements processes such as ordering, billing, accounting, and information dissemination. Each service within the process realizes a specific task. The communication between services is realized with messages, either directly or by using a middleware. Compositions of services are normally defined in a process execution language such WS-BPEL [6, 7] and a message choreography language like WS-CDL [8]. The automatic execution of specifications provided in such languages is then performed by process execution engines.

Service oriented architectures evolve by replacing services with more effective substitutes. These substitutes may offer extended functionality or enhanced quality of service (QoS) (i.e., reduced response time or higher throughput). When organizations collaborate on their offerings, services offer flexibility in outsourcing software capabilities to external entities.

Consequently, service discovery and service composition [5, 9] are essential functionalities in service oriented architectures. In this paper, we review the developments in automated web service composition during the last five years. This work leverages the research activities and results of the Web Service Challenge (WSC) [10]. The WSC initiative was the first effort that attempts to enhance the state-of-the-art in service composition through annual “side-by-side” community evaluation.

2 Automatic Web Service Composition

2.1 *Syntactic Discovery*

The syntactic description of a function in an imperative language like `C`, `Java`, or `C#` contains the input and output data types, as sketched in Listing 1.From a simplified perspective, a web service w can be described in the same way, by a set $w.T_I$ of input types t_i and a set $w.T_O$ of output data types t_o. Syntactic web service discovery means finding web services whose input and output parameter types *exactly* fit to the types T_G of available input data and which produce output data *exactly* fitting to a set of required types T_N.

```
Title getBookTitle(ISBN bookId) {
  ...
  }
```

Fig. 1: Example for a syntactical interface.

A discovery request R can be fully specified as a tuple $R = (R.T_G, R.T_N, R.W)$ of the set $R.T_G$ of types of the known data elements, the set $R.T_N$ of types which should be found, and a web service repository $R.W$. Notice that in a software system, the service repository is not part of the user's request, but part of the data accessible by the algorithm. From algorithmic perspective, however, it is part of the input of the discovery procedure. The goal of solving the request R is to discover a service $w \in R.W$ for which can be executed with the given parameters and produces instances of the wanted types as output, i.e., fulfills the predicate $valid_{synD}(w,R)$ defined in Equation 1.

$$valid_{synD}(w,R) \Leftrightarrow (w \in R.W) \wedge (\forall t_i \in w.T_I \Rightarrow t_i \in R.T_G) \wedge (\forall t_o \in R.T_N \Rightarrow t_o \in w.T_O) \quad (1)$$

2.2 Syntactical Composition

Service composition also permits combining multiple services in order to fulfill the requirements of a user-based request. Such a composition C is a directed acyclic graph (DAC) describing the order in which the services must be executed. It consists of a set $C.W$ of services and a strict partial order $C.pred$ defined on them (where $w' \in C.pred(w)$ means that $w' \in C.W$ must be executed before $w \in C.W$). For a valid syntactic composition $valid_{synC}(C,R)$ defined in Equation 2 must hold. In [11], Oh, Lee, and Kumara show that the syntactical service composition is *NP*-complete.

$$\begin{aligned} valid_{synC}(C,R) \Leftrightarrow\ & (\forall w \in C.W \Rightarrow w \in R.W) && \wedge \\ & \left(\forall w \in C.W, t_i \in w.T_I \Rightarrow t_i \in \left[R.T_G \cup \textstyle\bigcup_{\forall w' \in C.pred(w)} w'.T_O\right]\right) && \wedge \\ & (\forall t_o \in R.T_N \Rightarrow t_o \in [\textstyle\bigcup_{\forall w \in C.W} w.T_O]) \end{aligned} \quad (2)$$

2.3 Semantic Composition

Semantic composition takes into account that besides primitive types (such as numbers or Boolean values), type systems usually support hierarchical compositions of types.[1] In Equation 1, the parameter type `ISBN` could be a class. In the publishing industry, the `ISBN`s are used to uniquely identify media. Because of the shortage of remaining unused identifies the ten-digit `ISBN-10` have been superseded by the new thirteen-digit `ISBN-13`s. The `ISBN` class could be subclassed to

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[1] Also, formal representations of pre and post conditions may be considered during the matching process.

`ISBN-10` and `ISBN-13`. Instances of all three classes could be passed to the function `getBookTitle`.

Semantic composition takes such type hierarchies into account by representing the types as concepts in an ontology. This ontology can again be described as DAG. The composition request is thus complemented with a subsumption predicate $R.subs$ where $t' \in R.subs(t)$ means that type t' subsumes type t. In a class hierarchy known from Object Oriented Programming, the type `ISBN` could subsume both, `ISBN-10` and `ISBN-13`. `ISBN-10` and `ISBN-13` are then specializations of `ISBN`.

A service w can be executed if for each of input types $t_i' \in w.T_I$, at least one instance of either t_i' directly or any type t_i with $t_i' \in subs(t_i)$ is available. For simplicity, let us $R.subs^\star(T)$ be the joint set of all subsumed types of the types $t \in T$. Then, a valid solution for the semantic service composition request R fulfills Equation 3. A syntactic composer can be extended to support semantic composition by replacing the "equals" operation applied to (syntactical) parameter names with a subsumption check. Such a check can be performed in $\mathbf{O}(1)$ if all the subsumed concepts are stored in a hash map built upon loading the type taxonomy.

$$\begin{aligned} valid_{semC}(C,R) \Leftrightarrow\ & (\forall w \in C.W \Rightarrow w \in R.W) && \wedge \\ & \left(\forall w \in C.W, t_i \in w.T_I \Rightarrow t_i \in subs^\star\left(R.T_G \cup \bigcup\nolimits_{\forall w' \in C.pred(w)} w'.T_O\right)\right) && \wedge \\ & \left(\forall t_o \in R.T_N \Rightarrow t_o \in subs^\star\left(\bigcup\nolimits_{\forall w \in C.W} w.T_O\right)\right) \end{aligned} \quad (3)$$

2.4 QoS-based Composition

Currently, discovery and composition tasks predominantly consist of AI *planning problems* [12] which can be solved with informed (heuristic) or uninformed (exhaustive) local search methods [13, 14]. However, in a SOA, not only the functionality of a business process itself is of interest but also nonfunctional criteria such as quality of service (QoS) [15, 16]. This especially holds for enterprise mash-up, i.e., software systems which partly rely on services provided by external vendors. QoS may be modeled with semantic conditions, but can also be considered as orthogonal objective – i.e., it is possible to perform syntactic composition with regard to QoS. In usual composition scenarios, however, QoS and semantics are closely linked together.

When QoS is considered together with functionality, service composition becomes a (constrained combinatorial) *optimization problem* [17]. The validity criterion *valid* now becomes a feasibility constraint whereas the QoS parameters can be considered as objective functions. Both, the constraint and the objectives can be combined to a single heuristic guiding, for example, an A* search. However, depending on the size of the service repository $R.W$, the number of non-functional criteria, and the expected number of involved services, optimization algorithms such as Evolutionary Algorithms [18, 19, 20, 17], Simulated Annealing [21, 22, 17], Tabu Search [23, 24, 17], or other metaheuristics [17, 25, 26] become feasible approaches. Especially multi-objective Evolutionary Algorithms are promising, since they are able to return multiple solutions in one run which can represent a trade-off between the objectives (i.e., one composition could have a high runtime at lower costs whereas another one may be more costly but also faster) from which a human operator might pick the most suitable one(s).

3 History and Impact of the WSC

3.1 History

The Web Service Challenge (WSC) is an event for researchers investigating software engineering concerns in the area of efficient automatic web service composition algorithms. Since 2005, this annual forum has attracted 44 contributions from 97 authors. As shown in Table 1, the challenges proposed in the WSC evolved from the general concept of syntactical web service composition in 2005 to semantic composition involving QoS optimization in 2009. At the same time, the forum leverages standardized data formats such as WSDL [77], OWL [78, 79], WS-BPEL [6, 7], and WSLA [80, 81].

The first Web Service Challenge in 2005 focused on syntactic service composition. Simple XML [82] data formats were used to describe the challenge. Techniques from Artificial Intelligence, often based on heuristic or uninformed searches, were prevalent. In the following year, a semantic composition challenge was added. The type taxonomy was represented as XSD schema [83]. The solutions to these challenges were sequences of services. In 2007, the WSC further developed – the type taxonomies were represented in the OWL format and the challenge included the ability to evaluate services that can be executed in parallel. Another major change was that the composition systems were required to be implemented as Web Services.

Generally, semantic web service composition [5] has been achieved with hierachical task network planning [84, 85], Petri Nets [86], situation calculus (e.g., with Golog) [86, 87, 88], uninformed search [89], with planning based on rule-based expert systems [90], via model checking [91, 92], with semi-automatic procedures [93], and Genetic Programming [94]. As can be seen in Table 1, the techniques developed within the framework of the Web Service Challenge are even more wide spread and include, for example, agent-based methodologies [52], but also more low-level techniques from AI such as heuristic search [36] which proved to be especially efficient.

In 2008, the WSC event introduced challenge datasets with structured data types. More importantly, the solutions could contain arbitrarily nested and parallel processes, as well as choices between different possible processes. Therefore, WS-BPEL was adopted as solution format. From this point on, the entries to the WSC – composition services – could theoretically be plugged directly into existing SOAs. Finally in 2009, QoS criteria were introduced. The goal was extended beyond the synthesis of valid compositions to also find valid compositions with maximal throughput and minimal response time. WSLA was chosen in order to represent these quality dimensions in the input data. In 2010, the WSC event featured

Table 1: The Web Service Challenge (WS-Challenge, WSC) [27]

— I. Web Service Challenge 2005 [27, 28] —
(Syntactical Web Service Composition)

1. **Huang et al. [29]:** Hashing, Depth-limited Search
2. **Oh et al. [30]:** Bloom Filter Hash, $A^\star$ search
3. **Bharadwaj et al. [31]:** Agents, Modal Logic, Prolog
4. **Greenwood et al. [32]:** Topic Map, Multi-Agent System
5. **Dorn et al. [33]:** Partial Order Planning

— II. Web Service Challenge 2006 [34] —
(Semantic Web Service Composition, Taxonomy represented as XSD)

6. **Aiello et al. [35]:** Hashing, Greedy Search
7. **Bleul et al. [36]:** Hashing, Tree Data Structures, Multi-Threading, Greedy Search, Iterative Deepening Depth-First Search
8. **Kona et al. [37]:** Depth-First Search, Prolog
9. **Oh et al. [38]:** AI, Planning, Breadth-First Search
10. **Dorn et al. [39]:** Answer Set Programming
11. **Ramasamy [40]:** Hashing, Bi-Directional Search Depth-First Search
12. **Colasuonno et al. [41]:** Description Logic Reasoning
13. **Akkiraju et al. [42]:** Hashing, Metric Planning via Greedy Search
14. **Xu et al. [43]:** Inverted Table Index, Breadth-First Search
15. **Zhang et al. [44]:** Trees, String Prefix Matching, Breadth-First Search
16. **Makhzan and Lin [45]:** Syntactic Composition only, Hashing, Depth-limited Search

— III. Web Service Challenge 2007 [46] —
(WSC'06 + OWL for Taxonomy, Concurrency, Composer as Service)

17. **Juszcyk et al. [47]:** Table-based Index, Greedy Search
18. **Gu et al. [48]:** Inverted Table Index, Breadth-First Search
19. **Bleul et al. [49]:** Hashing, Tree Data Structures, Multi-Threading, Greedy Search, Genetic Algorithm, Iterative Deepening Depth-First Search
20. **Kona et al. [50]:** Breadth-First Search, Prolog, Constraint Logic Programming over Finite Domains (CLP(FD))
21. **Zhang et al. [51]:** Breadth-First Search, Greedy Search, Indexing using B-Trees, Least Recently Used Memory Management
22. **Buhler et al. [52]:** Triple-Store, Multi-Agent System
23. **Oh et al. [53]:** Inverted Index, AI, Planning

— IV. Web Service Challenge 2008 [54] —
(WSC'07 + Structured Data Types, BPEL, Multi-Objective Composition)

24. **Nam et al. [55]:** Tranformation to Satisfieability (SAT) Problem, Iterative Application of a SAT Solver
25. **Yan et al. [56]:** And/Or Graph, Depth-First Search
26. **Yan and Zheng [57]:** Breadth-First Search in a Planning Graph
27. **Buhler and Thomas [58]:** Triple-Store, Multi-Agent System
28. **Yoo et al. [59]:** Integer Linear Programming, Non-Functional Objectives, Constraints
29. **Weise et al. [60]:** Hashing, Tree Data Structures, Multi-Threading, Greedy Search, Genetic Algorithm, Iterative Deepening Depth-First Search
30. **Aiello et al. [61]:** Greedy Depth-First Search
31. **Raman et al. [62]:** Greedy Search, Indexing using B-Trees, Least Recently Used Memory Management

— V. Web Service Challenge 2009 [63] —
(WSC'08 + Quality of Service, WSLA)

32. **Aiello et al. [64]:** Greedy Search, Priority Queue
33. **Bartalos and Bieliková [65]:** Depth-First Search
34. **Zhang et al. [66]:** Service Classes, Indexing using B-Trees, Greedy Search, Iterative Deepening Depth-First Search
35. **Rainer and Dorn [67]:** Planning Domain Description Language (PDDL), Graphplan
36. **Nam et al. [68]:** Planning, Dynamic Programming, Learning Depth-First Search
37. **Cui et al. [69]:** Matrix Representation, Topological Network Analysis. Multi-Criteria Integer Programming, Depth-First Search
38. **Oh et al. [70]:** Planning, $A^\star$ search
39. **Huang et al. [71]:** Dynamic Programming, Integer Programming, Pruning, Multi-Threading
40. **Yan et al. [72]:** Service Layer Representation, Two Steps: Solution Finding, Service Number Reduction

— VI. Web Service Challenge 2010 [73] —
(WSC'09 + Larger Scale Test Sets)

41. **Luo et al. [74]:** Greedy Search
42. **Degeler et al. [75]:** Greedy Search, Priority Queue
43. **Ma et al. [76]:** Service Layer Representation, Two Steps: Solution Finding, Service Number Reduction; Dynamic Programming

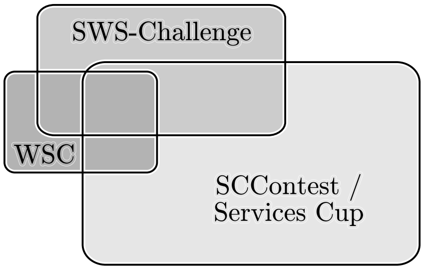

Fig. 2: The relation between WSC, SWS, and SC Contest.

much larger and complex challenge tasks whereas the involved formats remained the same. Since 2005, the scale of the challenge datasets has steadily increased, leading to rather large-scale testsets comprising service repositories with 40 000 services, ontologies with 20 000 concepts, and compositions comprising a minimum of 50 services.

3.2 Impact

Because of its structure, evolution, and relevance, the Web Service Challenge has become a major reference in both, the research and the industrial service composition community. The developers of widely-recognized systems such as ADDO [49, 16], MOVE [95], and jUDDI+ [41] used the WSC as reference for their work.

In 2012, checking Google Scholar (and Microsoft Academic Search) for citations of the competition lead papers and entries reveales 119 (72) references to the 2005 challenge, 119 (67) for the 2006 one, 85 (31) for 2007, 62 (23) for 2008, and 70 (20) for 2009. Adding up these numbers, there are more than 450 (210) citations of the WSC or works that competed in its context – which emphasizes its large influence on the community.

4 Related Events

Since the conception of the WSC approach, other derivative events have emerged: the SWS Challenge and the SC Contest. The later events have focused on other aspects of the service composition. In total, 293 researchers are involved in the three challenges, but only five of them contributed to more than one family of competitions. The relation of the challenge themes is illustrated in Figure 2.

Table 2: The Semantic Web Service Challenge (SWS-Challenge) [96]

— I. 1st Semantic Web Services Challenge Workshop (Stanford, USA, 2006) [97] —
(Phase I: Discovery, Interoperability, Mediation)

1. **Brambilla et al. [98]:** WebML + Glue: Visual Modeling, Automatic Code Generation, WSMO Ontology, Service Discovery
2. **Chopra et al. [99]:** OWL-P: Business Processes in Open Systems, multi-agent system, Business Partners = Agents, OWL
3. **Cimpian et al. [100]:** WSMX: WSMO, Data Mediation, Semantic Lifting and Lowering of Messages
4. **Gomadam et al. [101]:** METEOR-S: Protocol and Data Mediation
5. **Pokraev et al. [102]:** Service Mediation
6. **Kubczak et al. [103]:** jABC: UML, Web Service Wrappers for Mediation, Visual Modeling
7. **Küster et al. [104]:** DIANE: Description Language (DSD), Interaction Modeling, Service Mediation, BPEL
8. **Maximilien [105]:** Human-based Service Mediation, Data and Process Abstraction

— II. 2nd Semantic Web Services Challenge Workshop (Budva, Republic of Montenegro, 2006) [106] —
(Phase II: Adaptation, Changes in SOA)

9. **Haselwanter et al. [107]:** WSMX Middleware: Semantic Enriching of Schemas, Data and Process Mediation, WSMO, WSML
10. **Brambilla et al. [108]:** WebML + Glue: Visual Modeling, Service Discovery
11. **Küster et al. [109]:** DIANE: Description Language (DSD), Matchmaking, Middleware
12. **Kubczak et al. [110]:** jABC: Web Service Wrappers for Mediation

— III. 3rd Semantic Web Services Challenge Workshop (Athens, USA, 2006) [111] —
(Phase III: Same as Phase II)

13. **Brambilla et al. [112]:** WebML + Glue: Entity Relationship, UML, WSMO, WebRatio, F-Logic
14. **Zaremba et al. [113]:** WSMX Middleware: WSMO, WSML, WSMX
15. **Küster and König-Ries [114]:** DIANE: Description Language (DSD), Matchmaking, Middleware
16. **Kubczak et al. [115]:** jABC + jETI: GraphSIB, AXIS, miAamics

— IV. 4th Semantic Web Services Challenge Workshop (Innsbruck, Austria, 2007) [116] —
(SWS Phase III + Composition)

17. **Küster and König-Ries [117]:** DIANE: Description Language (DSD), Matchmaking, Middleware, Temporal Reasoning
18. **Kubczak et al. [118]:** jABC + jETI: AXIS, Velocity, JAXB, Java
19. **Brambilla et al. [119]:** WebML + Glue: Entity Relationship, UML, WSMO, WebRatio WS
20. **Moran et al. [120]:** WSMX Middleware: WSMO, WSML, WSMX

— V. Special Session at ICEIS (Madeira, Portugal, 2007) [121, 122] —

21. **Zaremba et al. [123]:** WSMX Middleware: WSMO, WSML, Entity Relationship Model, Service Mediation
22. **Margaria et al. [124]:** WebML + Webratio vs. jABC + jETI
23. **Küster et al. [125]:** DIANE (Fuzzy Sets) vs. SWE-ET (Glue + WebRatio, F-Logic); Modeling, Matchmaking, Dynamics
24. **Maximilien [126]:** Swashup: Ruby on Rails Mashup
25. **Wu et al. [127]:** METEOR-S: SAWSDL, GraphPlan

— VI. 5th Semantic Web Services Challenge Workshop (Silicon Valley, USA, 2007) [128] —

26. **Küster and König-Ries [129, 130]:** DIANE Middleware: Mediation, Fuzzy Sets, Service Discovery and Composition
27. **Kubczak et al. [131]:** jABC + jETI: Mediation, AXIS, GeneSys, JAXB
28. **Brambilla et al. [132]:** WebML/WebRatio + Glue: Entity Relationship, UML, WSMO
29. **Kubczak et al. [133]:** jABC + miAamics: Service Discovery
30. **Moran et al. [134]:** Service Discovery, WSMO, Constraint-based Service Composition

— VII. 6th Semantic Web Services Challenge Workshop (Tenerife, Spain, 2008) [135, 136] —

31. **Stuckenschmidt [137]:** Debugging of Ontologies: MUPSter, DION, RADON, Protegee, SWOOP
32. **Barnickel et al. [138]:** Semantic Mediation, Semantic Bridges
33. **Carenini et al. [139]:** New Scenarion Proposal: Logistics, Functional/Non-Functional Properties
34. **Margaria et al. [140]:** jABC: ABC/ETI, Mediator Synthesis, Semantic Linear-time Temporal Logic
35. **Kubczak et al. [141]:** jABC: Semantic Linear-time Temporal Logic, Abductive Logic Programming, Event Calculus, Model Checking, SAP's Goal-oriented Enterprise Management (GEM)
36. **Zaremba et al. [142]:** WSMX Middleware: WSMO, WSML, WSMX, KAON2 Reasoner, IRIS Reasoner, Service Mediation

— VIII. 7th Semantic Web Services Challenge Workshop (Karlsruhe, Germany, 2008) [143, 136] —
(New Discovery Scenario)

37. **Quartel et al. [144]:** COSMO: Model-Driven Architecture, Model Transformations
38. **Lemcke et al. [145]:** jABC + GEM: Service Mediation for "Purchase Order Mediation v2" and "Payment Problem"

— IX. 8th Semantic Web Services Challenge Workshop (Eindhoven, The Netherlands, 2009) [146] —

39. **Asuncion et al. [147]:** COSMO: Model-Driven Architecture, Model Transformation, Goal Modeling
40. **Palmonari et al. [148]:** Glue2: Semantic Service Discovery for the Logistics Management Scenario

Table 3: The IEEE International Services Computing Contest (SCContest) and Services Cup

— I. First IEEE International Services Computing Contest (Chicago, USA, 2006) [149] —
(Theme: SOA Methodologies and Tools to Better Solve Business Issues)

1. **Wei et al. [150]:** Geospatial Data, Grid Computing, Replication, Security, BPEL, SOA
2. **Bourcier et al. [151]:** Home Automation, OSGi, Smart Home, Ubiquitous Computing, Central Gateways
3. **Rosenberg et al. [152]:** VIDRE: Business Rules, Rules Engine, RuleML, Supply Chain Management
4. **Lorenzoli et al. [153]:** Self-Adaptive Web Service Integration (SAWI): Personal Mobility Manager, Self-Adaptation, WSDL
5. **Kart et al. [154]:** MIDAS: Supply Chain Management, SOA
6. **de Mello et al. [155]:** SOAR: SOA for Real-Estate Industry, Trust and Security Architecture

— II. Second IEEE International Services Computing Contest (Salt Lake City, USA, 2007) [156] —
(Theme: SOA Methodologies and Tools to Better Solve Business Issues)

7. **Kart et al. [157]:** e-Healthcare, Medicin, Multimedia, Security, Speech Recognition, Atom/RSS
8. **Dai et al. [158]:** (Dynamic) Supply Chain Management, Knowledge-Driven SOA

— III. Third IEEE International Services Computing Contest (Honolulu, USA, 2008) [159] —
(Theme: Business SOA and Services Mash-up)

9. **Ding et al. [160]:** Domain-Specific Query Language (DSQL) for Services Mash-Up, OWL-D, SQL-like language
10. **Zhu et al. [161]:** Rich Internet Application, Naval Shipping and Logistics, BPEL, Web 2.0
11. **Wang et al. [162]:** Semantic Mash-Up: Bayesian Networks, Ontologies, Tourism
12. **Jacob et al. [163]:** Mash-Up: News Industry, Data Augumentation for Celibrities, Text Mining, Web Crawling
13. **Ariga et al. [164]:** University-wide Web 2.0 Information/Service System, Service Mash-Ups
14. **Habich et al. [165]:** Open Service Process Platform: Web 2.0, Orchestration OSGi
15. **Jeyaverasingam and Yan [166]:** Mash-Up: Home Library Management System, Bar Code Scanning, ISBN
16. **Ma et al. [167]:** Combination of Geographical Information Systems (GIS) and Data, BPEL, XML, AJAX
17. **Harzallah et al. [168]:** Mash-Up: Forest Fires, GIS, Simulation
18. **Liang et al. [169]:** Rental Advising System, GIS, Service Wrappers and Mash-Ups
19. **Navabpour et al. [170]:** Mash-Up of Travel Planning Services: Bus, Flight, Train, Hotel
20. **Chodos and Stroulia [171]:** E-Commerce: Illustration of Products via Second Life, HTML Wrapping, REST

— IV. First Services Cup (Los Angeles, USA, 2009) [172] —
(No Specific Theme)

21. **Starlinger et al. [173]:** BioCreative MetaServer, BC-VisCon, Text Mining, Bioinformatics, Genetics
22. **Hoyer et al. [174]:** Enterprise Mash-Up, SAP, GUI, E-Commerce, Marketplaces
23. **Preißler et al. [175]:** Stream-based Event Processing in a SOA, Selling and Buying Stocks
24. **Ko et al. [176]:** Genesis: Dynamic Formulation of Abstract Business Processes, Business-OWL
25. **Hallal et al. [177]:** Web-based Business Application, Behavior Model Inference, SPIN, Promela, Weka, GraphViz
26. **AbuJarour et al. [178]:** Posr: Automatic Generation of User Interfaces and Services Wrapping existing Applications, Travel Planning

— V. Second Services Cup (Miami, USA, 2010) [179] —
(Theme: Cloud Computing)

27. **Li and Svärd [180]:** SIR: Text Correction, Human as a Service, REST-based SOA, Cloud Computing
28. **Yao et al. [181]:** Accountability, Cloud Computing, Logging
29. **Richly et al. [182]:** Cloud Computing, Cost Approximation: Neural Networks, MapReduce
30. **Vashishtha et al. [183]:** TAPoR: Text Mining, Digital Humanities, MapReduce
31. **Menzel et al. [184]:** Service Security Lab, Model Driven Architecture, Cloud Computing

The Semantic Web Service Challenge (SWS) has attracted 40 contributions from 72 authors, as listed in Table 2. It propagates the interaction of services, processes, and e-businesses in one specific scenario. Web service discovery and composition is involved in so far that, in order to wire two SOAs with each other and to adapt processes to changing requirements, services matching to the (new) requirements must be discovered and, if necessary, combined. These discovery or competition tasks are, however, of much smaller scale. Furthermore, the challenge requires the complete implementation of an application scenario. While this, on one hand, allows researchers to study "a system in action", it also requires much more work and does not allow for the research on singular, specific aspects of a SOA.

While earlier Web Service Challenges lacked rich semantics as compared to the Semantic Web Service Challenges [185, 186], in 2007, the WSC has supported OWL taxonomies and later, with WSC'08 , structured data types. The WSC represents a challenge which is theoretical enough to allow researchers to construct solutions as modules without needing to deal with the complete enterprise architecture at once. It is, however, also realistic enough to represent the challenges in such an architecture.

The International Services Computing Contest (SCContest), renamed to Services Cup in 2008, has attracted 31 contributions from 129 authors, as listed in Table 3. The SWS is more general than the WSC as it provides a well-defined task, although the task is less precise. The Services Cup, on the other hand, gives much more freedom to its participants: the organizers introduce a theme such as "Services Mash-Ups" or "Cloud Computing", from which the participants demonstrate capabilities. This challenge thus creates a venue for researchers from different areas in Web Services, it also makes the comparison of systems much more subjective.

Table 4: The International Workshop on Semantic Web Services and Web Process Composition (SWSWPC)

— I. First International Workshop on Semantic Web Services and Web Process Composition (San Diego, USA, 2004) [9] —

1. **Cardoso and Sheth [187]:** Semantic Web Service Composition: Travel Industry, QoS
2. **Cardoso et al. [188]:** Comparison: Academic and Industrial Research on Web Service Composition
3. **Benatallah and Nezhad [189]:** Semantic Service Interoperability: Content, Conversation, Policy
4. **Martin et al. [190]:** OWL-S
5. **Rao and Su [5]:** Automated Web Service Composition: Survey
6. **Rajasekaran et al. [191]:** METEOR-S: WSDL-S, Web Service Description and Discovery
7. **Biswas [192]:** End-User input for Compensations (Undoing) in Transactions composed of Web Services
8. **Olmedilla et al. [193]:** Semantics for Dynamic Service Discovery, WSMO
9. **Srinivasan et al. [194]:** Service Discovery, Matching: OWL-S/UDDI
10. **Mallya and Singh [195]:** Protocols for E-Businesses: Reasoning, Aggregation, Refinement/Subsumption
11. **Yu et al. [196]:** Web Portal Discovery, Semantic Web, Ontologies, UDDI, P2P
12. **Oldham et al. [197]:** METEOR-S: Annotation, Machine Learning, Weka, Classification of WSDL Descriptions

In 2004, the first workshop entirely dedicated to service composition took place co-located with ICWS in San Diego (see Table 4). This workshop merged into the conference as sessions into the following years.

5 The 2010 WSC

The 2010 WSC adopts the idea of Semantic Web Services with functional and non-functional characteristics. Web Services are specified with a semantic interface description as well as quality of service aspects. The task is to find a composition of services that produces a set of queried output parameters from a set of provided input parameters which is optimal in terms of (at least) one of the two QoS dimensions "Throughput" and "Response Time".

tb

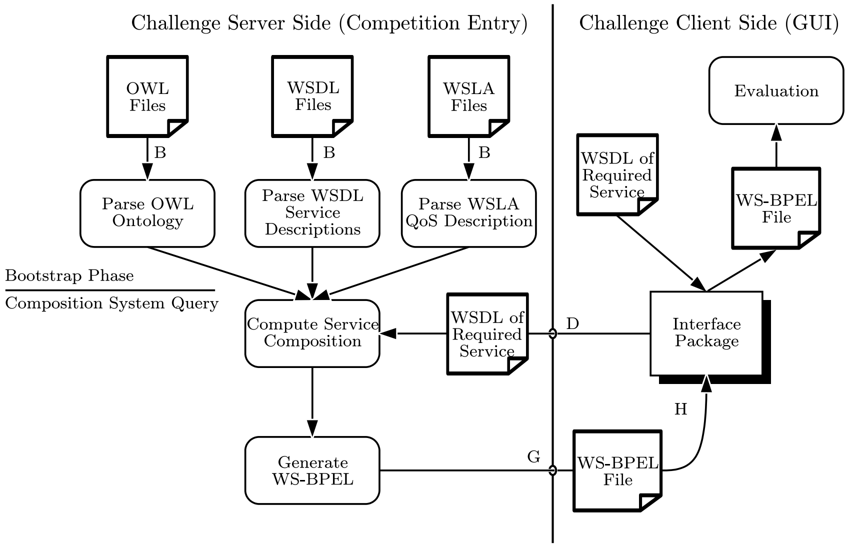

Fig. 3: Overview on the WSC system.

5.1 Software Suite

The WSC software suite (implemented in Java) is not limited to the competition, but it is also suitable for the evaluation of general web service composition systems. This suite includes:

1. A challenge generator [198, 63] which can generate composition tasks consisting of arbitrary numbers of services, semantic concepts, QoS annotations, and solutions (consisting of arbitrary numbers of services). This program creates both the challenge as well as suitable solutions (for reference).
2. A verifier/checker software [198, 63] that can check whether a given WS-BPEL process specification fulfills a composition task as well as computes its QoS properties.
3. Ten pre-defined composition challenges [198], ranging from small-scale to large-scale composition problems, along with example solutions obtained from three state-of-the art systems [74, 75, 76].
4. A GUI which can communicate which a composer via a SOAP-based Web Service Interface [199].
5. A skeleton implementation of a composition system in Java including an example competition system.
6. A full specification and documentation of all formats, protocols, and processes involved in the above.

The composer software is placed on the server side of the suite and started with a bootstrap procedure. First, the system is provided with the locations of the service descriptions. The WSDL file contains a set $R.W$ of semantically annotated services w along with annotations $w.T_I$ and $w.T_O$ of their respective input- and output parameters (see Section 2.3). Every service has an arbitrary number of parameters. The annotation with semantic individuals will not only be used for message parts, but for whole message structures specified with XSD. These structures can consist of simple elements, SOAP-Arrays [199], Lists, Structures, and Enumerations. The number of services ranged from 500 to 20 000 in the ten challenge tasks provided.

In addition to the WSDL file, the addresses of the OWL file and the WSLA data are also provided during the bootstrapping process. The OWL file contains the taxonomy of concepts, in other words, holds the type subsumption relationships $R.subs$. The 2010 WSC features ontologies with between 5000 and 100 000. Each WSLA file contains the QoS description of a Web Service as outlined in Section 2.4. During the bootstrapping process – sketched in the upper part of Figure 3 – the composers load the relevant information from these files.

The composition task will then be sent to the composer via a client-side GUI. After the bootstrapping on the server side is finished, the GUI queries the composition system with the challenge problem definition. The problem definition is provided in form of a semantically annotated WSDL file holding the description of the required functionality ($R.T_G$ and $R.T_N$).

The composer system then computes a solution – one or more service compositions – and answers in the solution format which is a subset of the WS-BPEL schema. When the WS-BPEL document is received by the GUI, it finishes its time measurement and afterwards evaluate the compositions themselves.

5.2 Suggested Composer Structure

As mentioned in the previous section, the WSC does not only provide the challenge framework but also a composer skeleton. This example system is plugged into the challenge framework as follows. In the bootstrap phase, the WSC *Client Application* submits the URLs *(A)* of the OWL taxonomy, the service repository WSDL files, and the WSLA data. The composition system then loads this data *(B)* with the *SAX-based Input Parser* and initializes the internal *Knowledge Base* and the *Service Registry (C)*. After this bootstrapping, the WSC client submits the URL of the WSDL query document *(D)*. Starting from this point, the parser loads the information to the *Composer (E)* which computes a solution *(F)*. The solutions are passed to the *SAX-based Output Writer (G)*. The client UI offers an internal Web Service as a callback interface (which is necessary to avoid communication timeouts). The composition system calls this callback Web Service in order to stream the composition result to the *Client Application (H)*. The evaluation of the result is done with the verifier/checker software.

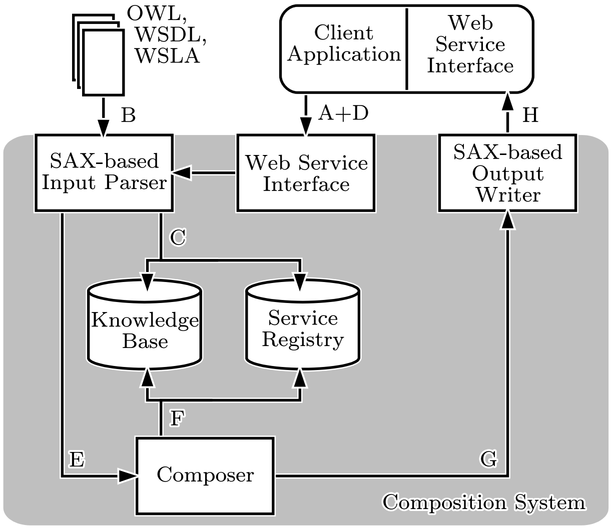

Fig. 4: The blueprint of the example composition system.

6 WSC-based Survey of Semantic Web Service Composition Techniques

As can be seen in Table 1, a wide variety of approaches to semantic web service composition have been applied and tested within the framework of the WSC. They can roughly be divided into the following categories:

6.1 Uninformed Search

Uninformed search algorithms [12] exhaustively search the space possible solutions until a valid composition is found. Here, depth-first search [37, 56, 65], breadth-first search [43, 44, 57], depth-limited search [29, 45], iterative deepening depth-first search [36, 49, 66], and bi-directional searches [40] are most commonly applied in Web Service Composition. In general, these methods implement the composition task as a graph search problem. Usually, the search is conducted backwards. Initially, the set N of needed parameters, i.e., the parameters required as output of the composition, is defined as:

$$N = R.T_N \tag{4}$$

Then, the set of promising services, services which can produce at least one of the needed parameters as output, is computed as:

$$P = \{w : (w \in R.W) \wedge \exists (t_o \in N) \wedge (t_o \in subs^{\star}(w.T_O))\} \quad (5)$$

According to the search pattern applied, e.g., depth-first search, breadth-first search, iterative deepening depth-first search, etc., service w is expanded, i.e., added to the composition and the set N of needed parameters is modified as follows:

$$N' = N \cap subs^{\star}(w.T_O) \cup \{t_i : (t_i \in w.t_i) \wedge (t_i \notin subs^{\star}(R.T_G))\} \quad (6)$$

At the end of this process, all parameters which can be covered by the outputs of the service no longer require additional processes, i.e., are not members of the new version N' of the set N. At this point, the input parameters of the service which are not provided by $R.T_G$ now become members of N' and are processed in the same manner as the wanted output parameters.

Breadth-first search methods first expends all services of the same depth before transitioning to another level. Depth-first search and its derived methods always expand the most recently discovered (unexpanded) service. This process is repeated iteratively until all services in the composition can be executed, i.e., until $N = \emptyset$. Uninformed algorithms therefore do not make use of any priority or heuristic information. For larger composition or problems with many alternative services that can produce required concepts, the runtime of these methods quickly increases and they become infeasible [13, 200].

6.2 Informed/Heuristic Search

Heuristic search methods, such as greedy search [35, 36, 42, 47, 51, 62] and $A^{\star}$ search [30, 70] are usually applied in a way similar to the uninformed search methods. These approaches initially find services w able to produce the wanted, user-specified composition output. They then traverse backwards in order to find services w' that can produce the inputs needed for w. However, while uninformed searches process the services in the order in which they are discovered, informed methods incorporate heuristics into their decision about which service should be expanded next. A common heuristic is to give priority to services that contain the largest number of parameters that may lead to the deletion of the most needed concepts or which lead to the fewest new needed concepts. The utilization of such heuristics can accelerate the search process by several orders of magnitude [13, 200].

6.3 Techniques from AI and Planning

A more high-level point of view is to consider Web Service Composition as a planning problem [38, 53, 57, 68, 67]. Partial order planning [33] and metric planning [42] are two leading techniques for planning. The partial order planning approach initially creates set of *actions* (which represent subsets of the overall composition solution) and a *partial order* of these actions. A metric planning approach creates a set of *states* defined by a set of propositional variables (a triple of propositions create an action). The assignment of numeric values for these variables allows an overall plan to be valuated based on a set of actions. AI planning methods require the translation of the composition problem into a representation which can be processed by a planning software. The advantage of this approach is that planners incorporate efficient and optimized algorithms. The drawback is that they cannot utilize knowledge like the web service composition-specific heuristics mentioned before. The leading approaches to web service composition use heuristic approaches to prune the search space prior to executing the planning algorithms. Strategies for increased performance would include removing web services with duplicative outputs or limit the expansion of planning graphs immediately after a proposition layer contains the necessary goal propositions.

6.4 Metaheuristic and Centralized Approaches

Metaheuristics [17, 25, 26] are randomized optimization methods which try to find solutions which are optimal according to one or multiple objective functions. They are similar to heuristic search algorithms in that they employ functions which evaluate and rate candidate solutions according to their utility. Different from the algorithms discussed in Section 6.2, however, they do not construct their solutions in a strictly iterative way.

A good example in the domain of Web Service Composition is the use of Evolutionary Algorithms (EAs) by Weise et al. [13, 13, 200, 49, 60]. EAs are population-based metaheuristics which, in a cycle, refine a set (the population) of candidate solutions. Weise et al. [13] first create a set of random initial compositions. Each composition is evaluated with a heuristic. In a randomized selection step, the best candidate solutions are chosen for further extension with a highest probability. Each composition then is either randomly mutated (by, e.g., expanding one of their services in order to satisfy its input parameters) or combined with another composition. After this reproduction step, the next cycle (generation) of the EA begins.

Such metaheuristics tend to be one order of magnitude slower than greedy search in the semantic composition problem [13, 200]. For QoS-based composition, however, they may be the most attractive approaches.

Dynamic Programming [68, 71, 76] is an approach which divides a problem into smaller sub-problems, solves these problems, and combines their solutions to a final result [201, 202]. These approaches are quite similar to divide and conquer strategies. Dynamic Programming can be used as programming paradigm to reduce the runtime of uninformed search significantly and reach the effectiveness of heuristic search methods [68].

Similar to metaheuristics, Integer (Linear) Programming (ILP) [59, 69, 71] can be used to treat the composition problem as a constrained optimization task with linear objective function(s). Here, a composition is represented as a vector of integer values. There exists a variety of highly-efficient algorithms for ILP [203].

6.5 Multi-Agent and Decentralized Approaches

So far, all approaches discussed assume the existence of one central repository and one central computer executing the algorithm. Multi-agent systems, in contrast, are decentralized by nature. Agents can synthesize compositions via cooperation in parallel [32, 52, 58]. Decentralized systems can more effectively adapt to (dynamic) distributed environments where services enter and exit the system unpredictably, can exploit the geographic distributions of computing resources, and are likely to scale better. Available and high capacity systems can be used to execute search algorithms, on-demand. However, decentralized approaches do not outperform centralized heuristic search approaches if the system is centralized and a single computer performs the composition.

7 Discussion

In this article, we presented a review on the Web Service Challenge, a competition that has had significant impact in the evolution of Service Oriented Architectures. We compared this challenge with related competitions and provided a survey of the works submitted to all competitions, in tabular and textual form.

The Web Service Challenge created a research community for automated semantic service composition and implementations of fast performing composition engines. After 2007, the focus of the challenge gradually changed from a solely scientific service indexing competition to a comprehensive and practice-oriented solution for Service-oriented Architectures.

As of 2009, it fosters the implementation of composers in a way that could directly be reused in an actual SOA. It now solely adopts standardized data formats such as WS-BPEL, WSDL, OWL, and WSLA. Its tasks are already highly practical, requiring the compositions to fulfill both functional and non-functional constraints.

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