Chapter 3

Semantic Web Service Description

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3.1 Introduction

The convergence of semantic Web with service oriented computing is manifested by Semantic Web Services (SWS) technology. It addresses the major challenge of automated, interoperable and meaningful coordination of Web Services to be carried out by intelligent software agents. In this chapter, we briefly discuss prominent SWS description frameworks, that are the standard SAWSDL, OWL-S and WSML[1]. This is complemented by main critics of Semantic Web Services, and selected references to further readings on the subject.

3.2 Issues of Semantic Service Description

Each semantic service description framework can be characterised with respect to (a) what kind of service semantics are described, (b) in what language or formalism, (c) allowing for what kind of reasoning upon the abstract service descriptions? Further, we distinguish between an abstract Web Service, that is the description of the computational entity of the service, and a concrete service as one of its instances or invocations that provide the actual value to the user [21]. In this sense, abstract service descriptions are considered complete but not necessarily correct: There might be concrete service instances that are models of the capability description of the abstract service but can actually not be delivered by the provider.

[1]Due to space limitations other description frameworks like SWSL (Semantic Web Service Language) and the DIANE service description language are excluded.

3.2.1 Functional and Non-Functional Service Semantics

In general, the functionality of a service can be described in terms of what it does, and how it actually works. Both aspects of its functional semantics (or capability) are captured by a service profile, respectively, service process model. The profile describes the signature of the service in terms of its input (I) and output (O) parameters, and its preconditions (P) and effects (E) that are supposed to hold before or after executing the service in a given world state, and some additional provenance information such as the service name, its business domain and provider. The process model of atomic or composite services describes how the service works in terms of the interplay between data and control flow based on a common set of workflow or control constructs like sequence, split+join, choice, and others.

This general distinction between profile and process model semantics is common to structured Web Service description frameworks, while differences are in the naming and formal representation of what part of service semantics. We can further differentiate between stateless (IO), respectively, state-based (PE) abstract service descriptions representing the set of its instances, that are concrete services providing value to the user. The non-functional service semantics are usually described with respect to a quality of service (QoS) model including delivery constraints, cost model with rules for pricing, repudiation, availability, and privacy policy.

3.2.2 Structured Representation of Service Semantics

A domain-independent and structured representation of service semantics is offered by upper (top-level) service ontologies and languages such as OWL-S and WSML with formal logic groundings, or SAWSDL which comes, in essence, without any formal semantics. Neither OWL-S nor WSML provide any agreed formal but intuitive, standard workflow-based semantics of the service process model (orchestration and choreography). Alternatively, for abstract service descriptions grounded in WSDL, the process model can be intuitively mapped to BPEL orchestrations with certain formal semantics.

3.2.3 Monolithic Representation of Service Semantics

The formal specification of service semantics agnostic to any structured service description format can be achieved, for example, by means of a specific set of concept and role axioms in an appropriate logic (cf. Section 3.6). Since the service capability is described by means of one single service concept, this representation of service semantics is called monolithic and allows to determine the semantic relations between service descriptions fully within the underlying logical formalism based on concept satisfaction, subsumption and entailment. However, it does not provide any further information on how the service actually works in terms of the process model nor any description of non-functional semantics.

3.2.4 Data Semantics

The domain-dependent semantics of service profile parameters (also called data semantics) are described in terms of concepts, roles (and rules) taken from shared domain, task, or application ontologies. These ontologies are defined in a formal semantic Web language like OWL, WSML or SWRL. If different ontologies are used, agents are supposed to automatically resolve the structural and semantic heterogeneities for interoperation to facilitate better Web Service discovery and composition. This process of ontology matching is usually restricted to ontologies specified in the same language, otherwise appropriate inter-ontology mappings have to be provided to the agents.

In subsequent sections, we briefly introduce prominent approaches to both types of service representation. For structured semantic service descriptions, we focus on OWL-S, WSML, and SAWSDL, and omit to discuss alternatives like DSD (DIANE service description format) and SWSL (Semantic Web Service Language).

3.2.5 Reasoning about Semantic Service Descriptions

The basic idea of formally grounded descriptions of Web Services is to allow agents to better understand the functional and non-functional semantics through appropriate logic-based reasoning. For this purpose, it is commonly assumed that the applied type of logic reasoning complies with the underlying semantic service description framework. Further, the concept expressions used to specify the data semantics of service input and output parameters are assumed to build up from basic concepts and roles taken from formal application or domain ontologies which the requester and provider commonly refer to. We survey approaches to non-logic-based, logic-based, and hybrid reasoning means for Semantic Web Service discovery, and composition planning in the next chapter.

3.3 SAWSDL

The standard language WSDL for Web Services operates at the mere syntactic level as it lacks any declarative semantics needed to meaningfully represent and reason upon them by means of logical inferencing. In a first response to this problem, the W3C Working Group on Semantic Annotations for WSDL and XML Schema (SAWSDL) developed mechanisms with which semantic annotations can be added to WSDL components. The SAWSDL specification became a W3C candidate recommendation on January 26, 2007[2], and eventually a W3C recommendation on August 28, 2007.

[2]http://www.w3.org/2002/ws/sawsdl/

3.3.1 Annotating WSDL Components

Unlike OWL-S or WSML, SAWSDL does not specify a new language or top-level ontology for semantic service description but simply provides mechanisms by which ontological concepts that are defined outside WSDL service documents can be referenced to semantically annotate WSDL description elements. Based on its predecessor and W3C member submission WSDL-S[3] in 2005, the key design principles for SAWSDL are that (a) the specification enables semantic annotations of Web Services using and building on the existing extensibility framework of WSDL; (b) it is agnostic to semantic (ontology) representation languages; and (c) it enables semantic annotations for Web Services not only for discovering Web Services but also for invoking them.

Based on these design principles, SAWSDL defines the following three new extensibility attributes to WSDL 2.0 elements for their semantic annotation:

- An extension attribute, named `modelReference`, to specify the association between a WSDL component and a concept in some semantic (domain) model. This modelReference attribute is used to annotate XML Schema complex type definitions, simple type definitions, element declarations, and attribute declarations as well as WSDL interfaces, operations, and faults. Each modelReference identifies the concept in a semantic model that describes the element to which it is attached.

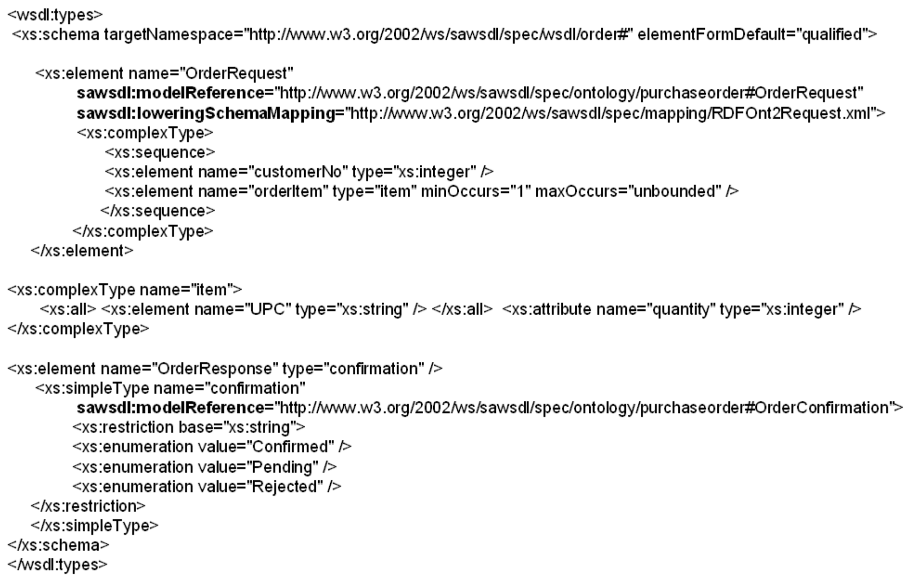
- Two extension attributes (`liftingSchemaMapping` and `loweringSchemaMapping`) are added to the set of XML Schema element declarations, complex type definitions and simple type definitions. Both allow to specify mappings between semantic data in the domain referenced by modelReference and XML, which can be used during service invocation.

An example of a SAWSDL service, that is a semantically annotated WSDL service with references to external ontologies describing the semantics of WSDL elements, is given in Figure 3.1: The semantics of the service input parameter of type “OrderRequest” is defined by an equally named concept specified in an ontology “purchaseorder” which is referenced (URI) by the element tag “modelReference” attached to “OrderRequest”. It is also annotated with a tag A tag “loweringSchemaMapping” which value (URI) points to a data type mapping, in this case an XML document, which shows how the elements of this type can be mapped from the referenced semantic data model (here RDFS) to XMLS used in WSDL.

3.3.2 Limitations

Major critic of SAWSDL is that it comes, as a mere syntactic extension of WSDL, without any formal semantics. In contrast to OWL-S and (in part) WSML, there is

[3]http://www.w3.org/Submission/WSDL-S/



```
<wsdl:types>
 <xs:schema targetNamespace="http://www.w3.org/2002/ws/sawsdl/spec/wsdl/order#" elementFormDefault="qualified">

    <xs:element name="OrderRequest"
           sawsdl:modelReference="http://www.w3.org/2002/ws/sawsdl/spec/ontology/purchaseorder#OrderRequest"
           sawsdl:loweringSchemaMapping="http://www.w3.org/2002/ws/sawsdl/spec/mapping/RDFOnt2Request.xml">
           <xs:complexType>
               <xs:sequence>
               <xs:element name="customerNo" type="xs:integer" />
               <xs:element name="orderItem" type="item" minOccurs="1" maxOccurs="unbounded" />
              </xs:sequence>
          </xs:complexType>
   </xs:element>

<xs:complexType name="item">
     <xs:all> <xs:element name="UPC" type="xs:string" /> </xs:all>  <xs:attribute name="quantity" type="xs:integer" />
</xs:complexType>

<xs:element name="OrderResponse" type="confirmation" />
    <xs:simpleType name="confirmation"
           sawsdl:modelReference="http://www.w3.org/2002/ws/sawsdl/spec/ontology/purchaseorder#OrderConfirmation">
          <xs:restriction base="xs:string">
          <xs:enumeration value="Confirmed" />
          <xs:enumeration value="Pending" />
          <xs:enumeration value="Rejected" />
   </xs:restriction>
   </xs:simpleType>
</xs:schema>
</wsdl:types>
```

Figure 3.1: Example of semantic annotation of WSDL elements in SAWSDL.

no defined formal grounding of neither the XML-based WSDL service components nor the referenced external metadata sources (via modelReference). Quoting from the SAWSDL specification: "Again, if the XML structures expected by the client and by the service differ, schema mappings can translate the XML structures into the semantic model where any mismatches can be understood and resolved." This makes any form of logic-based discovery and composition of SAWSDL service descriptions in the semantic Web rather obsolete but calls for "magic" mediators outside the framework to resolve the semantic heterogeneities.

Another problem with SAWSDL today is its –apart from the METEOR-S framework by the developers of SAWSDL (WSDL-S) and related ongoing development efforts at IBM– still very limited software support compared to the considerable investments made in research and development of software for more advanced frameworks like OWL-S and WSMO world wide. However, the recent announcement of SAWSDL as a W3C recommendation does not only support a standardized evolution of the W3C Web Service framework in principle (rather than a revolutionary technology switch to far more advanced technologies like OWL-S or WSML) but certainly will push software development in support of SAWSDL and reinforce research on refactoring these frameworks with respect to SAWSDL.

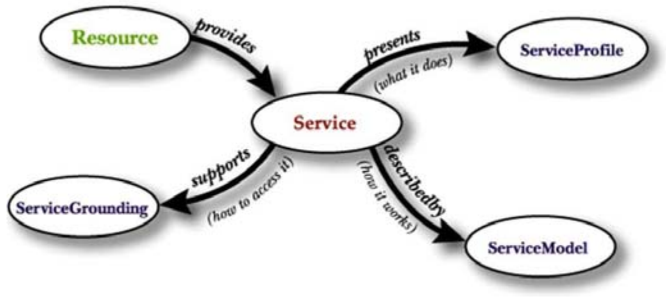


Figure 3.2: OWL-S service description elements.

3.4 OWL-S

OWL-S is an upper ontology used to describe the semantics of services based on the W3C standard ontology OWL and is grounded in WSDL. It has its roots in the DAML Service Ontology (DAML-S) released in 2001, and became a W3C candidate recommendation in 2005. OWL-S builds on top of OWL and consists of three main upper ontologies: the Profile, the Process Model, and the Grounding (cf. Figure 3.2).

In the following, we briefly summarize the underlying standard ontology language OWL and then present each of the main elements of OWL-S service descriptions.

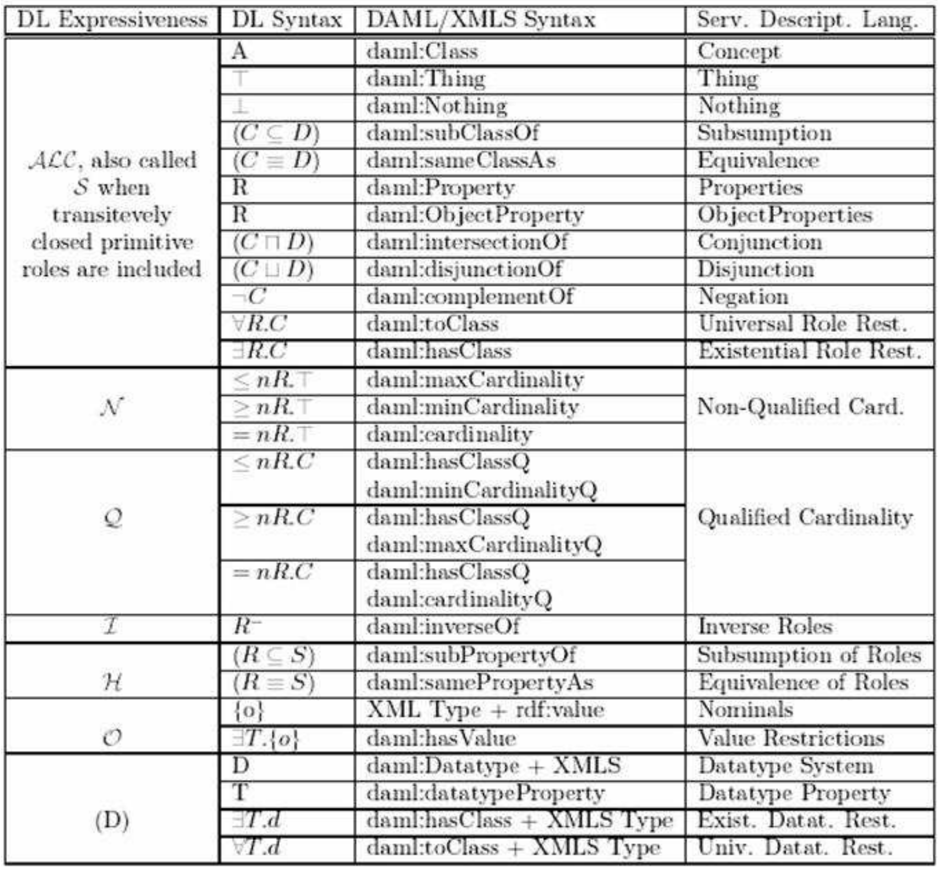
3.4.1 Background: OWL

The standard ontology language for the semantic Web is OWL [2, 4, 12] which is formally grounded in description logics (DL). OWL has its roots in the joint initiative DAML+OIL of researchers from the US and Europe in 2000 to develop a formal annotation or mark-up language for the Web. Only three years later, OWL became a W3C recommendation, and has been widely adopted by both industry and academics since then. The current version of OWL is OWL 1.1[4].

Variants

OWL comes in several variants, that are OWL-Full, OWL-DL, and OWL-Lite. Each variant corresponds to a DL of different expressivity and complexity. OWL-Lite and OWL-DL are an abstract syntactic form of the description logic SHIF(D), respectively, SHOIN(D). The most expressive variant OWL-Full provides full compatibility with RDFS and covers the expressivity of SHOIQ(D) which offers not only simple data types (D) but primitive transitive roles in qualified role cardinality restrictions (Q), and derived classes together with non-primitive roles Figure 3.3.

[4]http://www.w3.org/Submission/2006/10/



DL Expressiveness	DL Syntax	DAML/XMLS Syntax	Serv. Descript. Lang.
$\mathcal{ALC}$, also called $\mathcal{S}$ when transitevely closed primitive roles are included	A	daml:Class	Concept
	$\top$	daml:Thing	Thing
	$\perp$	daml:Nothing	Nothing
	$(C \subseteq D)$	daml:subClassOf	Subsumption
	$(C \equiv D)$	daml:sameClassAs	Equivalence
	R	daml:Property	Properties
	R	daml:ObjectProperty	ObjectProperties
	$(C \sqcap D)$	daml:intersectionOf	Conjunction
	$(C \sqcup D)$	daml:disjunctionOf	Disjunction
	$\neg C$	daml:complementOf	Negation
	$\forall R.C$	daml:toClass	Universal Role Rest.
	$\exists R.C$	daml:hasClass	Existential Role Rest.
$\mathcal{N}$	$\leq nR.\top$	daml:maxCardinality	Non-Qualified Card.
	$\geq nR.\top$	daml:minCardinality	
	$= nR.\top$	daml:cardinality	
$\mathcal{Q}$	$\leq nR.C$	daml:hasClassQ daml:minCardinalityQ	Qualified Cardinality
	$\geq nR.C$	daml:hasClassQ daml:maxCardinalityQ	
	$= nR.C$	daml:hasClassQ daml:cardinalityQ	
$\mathcal{I}$	R^-	daml:inverseOf	Inverse Roles
$\mathcal{H}$	$(R \subseteq S)$	daml:subPropertyOf	Subsumption of Roles
	$(R \equiv S)$	daml:samePropertyAs	Equivalence of Roles
$\mathcal{O}$	{o}	XML Type + rdf:value	Nominals
	$\exists T.\{o\}$	daml:hasValue	Value Restrictions
(D)	D	daml:Datatype + XMLS	Datatype System
	T	daml:datatypeProperty	Datatype Property
	$\exists T.d$	daml:hasClass + XMLS Type	Exist. Datat. Rest.
	$\forall T.d$	daml:toClass + XMLS Type	Univ. Datat. Rest.

Figure 3.3: DL constructors of OWL variants (SHIF, SHOIN, SHOIQ)

The syntactic transformation from OWL-Lite and OWL-DL ontologies to corresponding DL knowledge bases is of polynomial complexity.

Relation to RDFS The abstract syntax of OWL can be mapped to the normative syntax of RDF[5]. OWL adds constructors to RDFS for building class and property descriptions (vocabulary) and new axioms (constraints) with model-theoretic semantics. That is, OWL extends the expressivity of RDFS. In particular, the RDFS fragment of OWL-DL does not permit, for example, stating that a property P is transitive or the inverse of another property Q, and using intersection (union) within (sub-)class descriptions, or universal/existential quantifications within super-/subclasses [13].

It has been shown only recently [20], that the formal semantics of a sublanguage of RDFS is compatible with that of the corresponding fragment of OWL-DL such that RDFS could indeed serve as a foundational language of the semantic Web layer stack. Though checking whether a RDF graph is an OWL ontology and upgrading from RDFS to OWL remains hard in practice. For a detailed treatment of this subject, we refer to [7].

Complexity

For OWL-Lite and OWL-DL, concept satisfiability and ABox consistency is decidable in EXPTIME complete, respectively, NEXPTIME complete [11, 25]. Though SHOIQ(D) with primitive non-transitive roles is intractably co-NEXPTIME hard [25][6], its variant with non-primitive transitive roles, hence OWL-Full, is undecidable [4][7]. The same even holds for the subset SHN+ of OWL-DL with role cardinality restrictions (N) and role hierarchies (H).

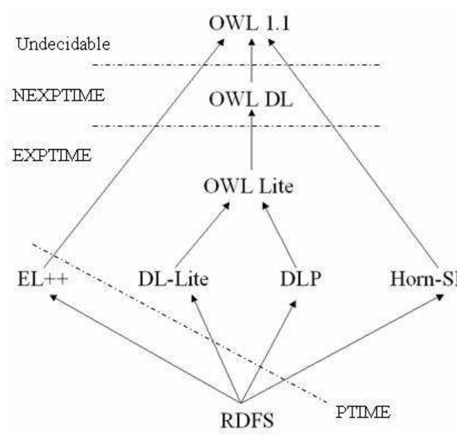
Figure 3.4 shows the relation of OWL to other prominent (polynomially reducable) tractable DL subsets like EL++, Horn-SHIQ, and DLPs (Description Logic Programs) together with related complexity results [2].

As mentioned above, efficient query answering over DL knowledge bases with large ABoxes (instance stores) and static TBoxes is of particular interest in practice. Unfortunately, OWL can be considered insufficient for this purpose in general: Conjunctive query answering (CQA) for SHIQ and SHIF underlying OWL-Lite is decidable but only in time exponential in the size of the knowledge base (taxonomic complexity) and double exponential in the size of the query [7] (query and

[5]RDFS statements are equivalent to DL axioms of the form $C \sqsubseteq D$, $\top \sqsubseteq \forall P : C$, $\top \sqsubseteq \forall P^{-}.C$, $P \sqsubseteq Q$, $a : C$ and $(a, b) : P$.

[6]Reasoning with data types and values (D) can be separated from reasoning with classes and individuals by allowing the DL reasoner to access a datatype oracle that can answer simple questions with respect to data types and values; this way, the language remains decidable if data type and value reasoning is decidable, i.e., if the oracle can guarantee to answer all questions of the relevant kind for supported datatypes.

[7]Allowing relationships to be asserted between property chains, like the rule that an uncle is precisely a parents brother, would make OWL entailment reduced to concept satisfiability undecidable.



		taxonomic	data	query	combined
EL++	A:	PTIMEc	PTIMEc	-	PTIMEc
	B:	?	PTIMEh	?	?
DLP	A:	EXPTIME	PTIMEc	-	EXPTIME
	B:	EXPTIME	PTIMEc	EXPTIME	EXPTIME
Horn-SHIQ	A:	EXPTIMEc	PTIMEc	-	EXPTIMEc
	B:	d/?	d/?	d/?	d/?
RDFS	A‘:	PTIME	LOGSPACE	-	PTIME
	B:	PTIME	LOGSPACE	d/?	d/?

A = Ontology Consistency, Concept Satisfiability, Concept Subsumption, Instance Checking
A‘ = Concept Subsumption, Instance Checking
B = Conjunctive Query Answering
? = Open problem,
d/? = Decidable, complexity bounds unknown
- = not applicable, h/c = hard/complete

Figure 3.4: Tractable fragments of OWL ([2])

combined complexity); the CQA complexity for OWL-DL is still unknown.

Another important inference on OWL ontologies is defined in terms of ontology entailment: Ontology O_1 entails another O_2, $O_1 \models O_2$, iff all interpretations that satisfy O_1 also satisfy O_2 in the DL sense. For both OWL-DL (SHOIN(D)) and OWL-Lite (SHIF(D)), ontology entailment checking can be polynomially reduced to the checking of the satisfiability of the corresponding DL knowledge bases O_1, O_2 (ontology consistency checking) which is decidable for both variants.

3.4.2 Service Profile

The OWL-S profile ontology is used to describe what the service does, and is meant to be mainly used for the purpose of service discovery. An OWL-S service profile or signature encompasses its functional parameters, i.e. hasInput, hasOutput, precondition and effect (IOPEs), as well as non-functional parameters such as serviceName, serviceCategory, qualityRating, textDescription, and meta-data (actor) about the service provider and other known requesters. Please note that, in contrast to OWL-S 1.0, in OWL-S 1.1 the service IOPE parameters are defined in the process model with unique references to these definitions from the profile (cf. Figure 3.5).

Inputs and outputs relate to data channels, where data flows between processes. Preconditions specify facts of the world (state) that must be asserted in order for an agent to execute a service. Effects characterize facts that become asserted given a successful execution of the service in the physical world (state). Whereas the semantics of each input and output parameter is defined as an OWL

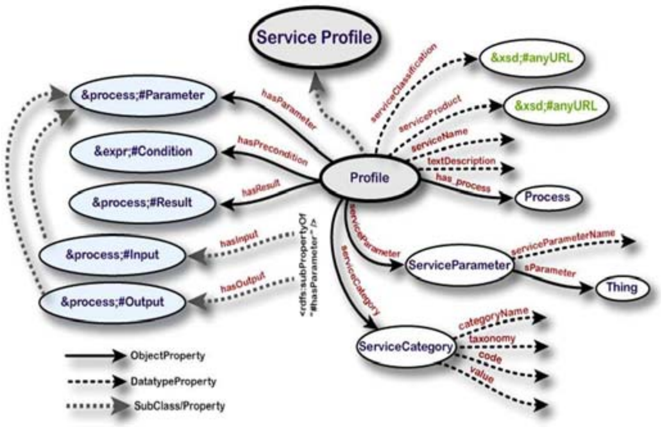


Figure 3.5: OWL-S service profile structure.

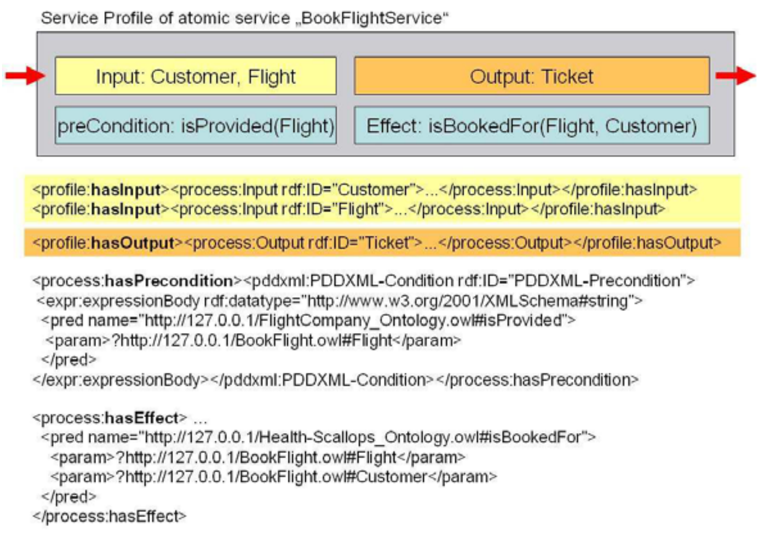
concept formally specified in a given ontology, typically in decidable OWL-DL or OWL-Lite, the preconditions and effects can be expressed in any appropriate logic (rule) language such as KIF, PDDL, and SWRL. Besides, the profile class can be subclassed and specialized, thus supporting the creation of profile taxonomies which subsequently describe different classes of services. An example of a Semantic Web Service profile in OWL-S 1.1 is given in figure 3.6.

3.4.3 Service Process Model

An OWL-S process model describes the composition (choreography and orchestration) of one or more services, that is the controlled enactment of constituent processes with respective communication pattern. In OWL-S this is captured by a common subset of workflow features like split+join, sequence, and choice (cf. Figure 3.7). Originally, the process model was not intended for service discovery but the profile by the OWL-S coalition.

More concrete, a process in OWL-S can be atomic, simple, or composite. An atomic process is a single, black-box process description with exposed IOPEs. Simple processes provide a means of describing service or process abstractions which have no specific binding to a physical service, thus have to be realized by an atomic process, e.g. through service discovery and dynamic binding at runtime, or expanded into a composite process. The process model of the example OWL-S service above is provided in Figure 3.8.

Composite processes are hierarchically defined workflows, consisting of atomic, simple and other composite processes. These process workflows are constructed using a number of different control flow operators including Sequence, Unordered (lists), Choice, If-then-else, Iterate, Repeat-until, Repeat-while, Split, and Split+Join. In OWL-S 1.1, the process model also specifies the inputs, outputs, preconditions,


Service Profile of atomic service „BookFlightService“
Input: Customer, Flight
Output: Ticket
preCondition: isProvided(Flight)
Effect: isBookedFor(Flight, Customer)

```
<profile:hasInput><process:Input rdf:ID="Customer">...</process:Input></profile:hasInput>
<profile:hasInput><process:Input rdf:ID="Flight">...</process:Input></profile:hasInput>

<profile:hasOutput><process:Output rdf:ID="Ticket">...</process:Output></profile:hasOutput>

<process:hasPrecondition><pddxml:PDDXML-Condition rdf:ID="PDDXML-Precondition">
 <expr:expressionBody rdf:datatype="http://www.w3.org/2001/XMLSchema#string">
  <pred name="http://127.0.0.1/FlightCompany_Ontology.owl#isProvided">
   <param>?http://127.0.0.1/BookFlight.owl#Flight</param>
  </pred>
</expr:expressionBody></pddxml:PDDXML-Condition></process:hasPrecondition>

<process:hasEffect> ...
  <pred name="http://127.0.0.1/Health-Scallops_Ontology.owl#isBookedFor">
    <param>?http://127.0.0.1/BookFlight.owl#Flight</param>
    <param>?http://127.0.0.1/BookFlight.owl#Customer</param>
  </pred>
</process:hasEffect>
```

Figure 3.6: Example of OWL-S 1.1 service profile.

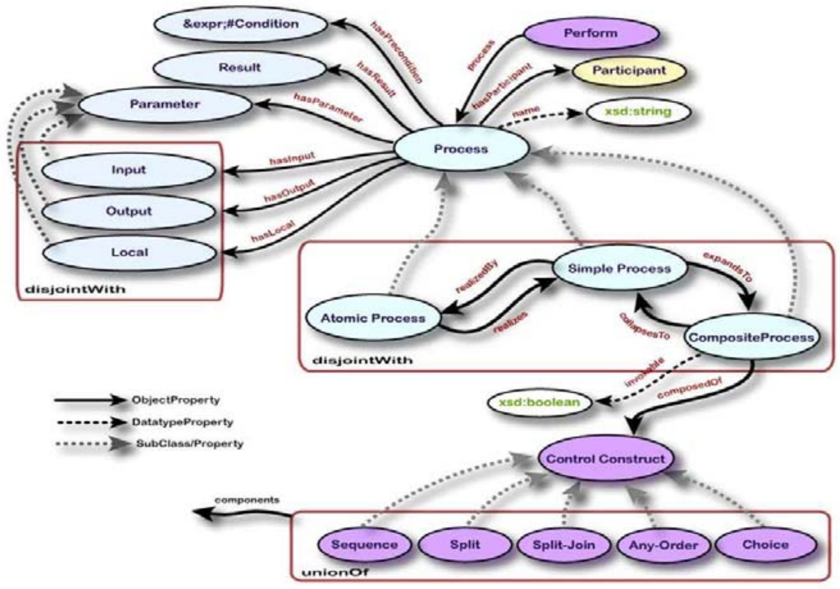
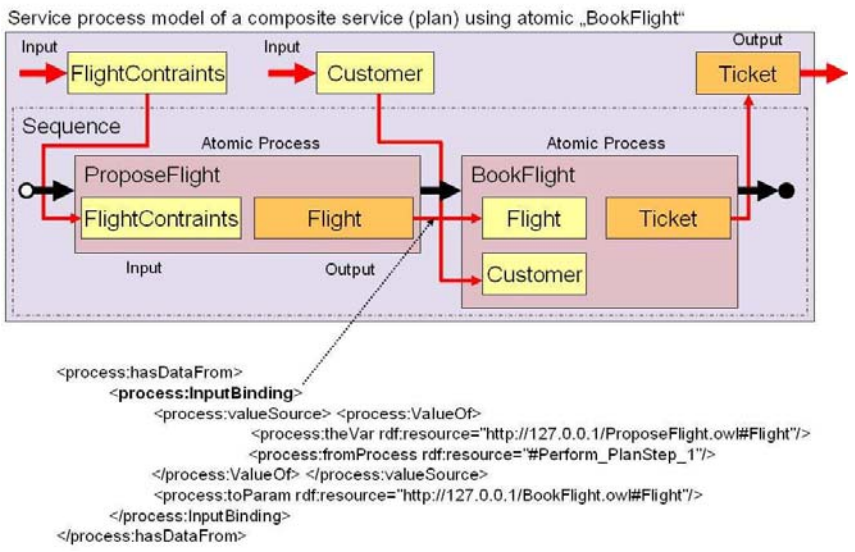


Figure 3.7: OWL-S service process model.



```
<process:hasDataFrom>
        <process:InputBinding>
                <process:valueSource> <process:ValueOf>
                                <process:theVar rdf:resource="http://127.0.0.1/ProposeFlight.owl#Flight"/>
                                <process:fromProcess rdf:resource="#Perform_PlanStep_1"/>
                </process:ValueOf> </process:valueSource>
                <process:toParam rdf:resource="http://127.0.0.1/BookFlight.owl#Flight"/>
        </process:InputBinding>
</process:hasDataFrom>
```

Figure 3.8: Example of OWL-S service process model.

and effects of all processes that are part of a composed service, which are referenced in the profiles of the respective services[8]. An OWL-S process model of a composite service can also specify that its output is equal to some output of one of its subprocesses whenever the composite process gets instantiated. Moreover, for a composite process with a Sequence control construct, the output of one subprocess can be defined to be an input to another subprocess (binding).

Unfortunately, the semantics of the OWL-S process model are left undefined in the official OWL-S documents. Though there are proposals to specify these semantics in terms of, for example, the situation calculus [18], and the logic programming language GOLOG based on this calculus [19].

3.4.4 Service Grounding

The grounding of a given OWL-S service description provides a pragmatic binding between the logic-based and XMLS-based service definitions for the purpose of facilitating service execution. Such a grounding of OWL-S services can be, in principle, arbitrary but has been exemplified for a grounding in WSDL to pragmatically connect OWL-S to an existing Web Service standard (cf. Figure 3.9).

In particular, the OWL-S process model of a service is mapped to a WSDL description through a thin (incomplete) grounding: Each atomic process is mapped

[8]This is in opposite to OWL-S 1.0, where the IOPES are defined in the profile and referenced in the process model.

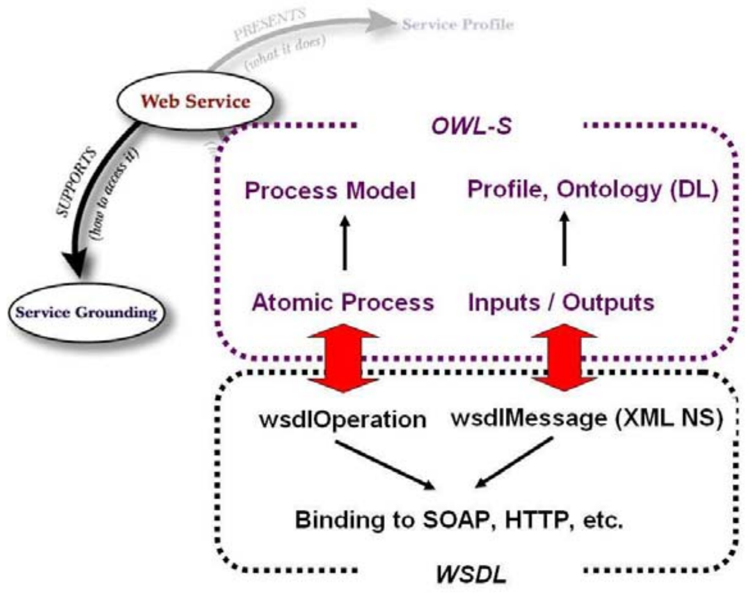


Figure 3.9: Grounding of OWL-S in WSDL.

to a WSDL operation, and the OWL-S properties used to represent inputs and outputs are grounded in terms of respectively named XML data types of corresponding input and output messages. Unlike OWL-S, WSDL cannot be used to express pre-conditions or effects of executing services. Any atomic or composite OWL-S service with a grounding in WSDL is executable either by direct invocation of the (service) program that is referenced in the WSDL file, or by a BPEL engine that processes the WSDL groundings of simple or orchestrated Semantic Web Services.

3.4.5 Software Support

One prominent software portal of the semantic Web community is SemWebCentral[9] developed by InfoEther and BBN Technologies within the DAML program in 2004 with BBN continuing to maintain it today. As a consequence, it comes at no surprise that this portal offers a large variety of tools for OWL and OWL-S service coordination as well as OWL and rule processing. Examples of publicly available software support of developing, searching, and composing OWL-S services are as follows.

[9]http://projects.semwebcentral.org/

- *Development.*
  OWL-S IDE integrated development environment[10], the OWL-S 1.1 API[11] with the OWL-DL reasoner Pellet[12] and OWL-S editors.
- *Discovery.*
  OWL-S service matchmakers OWLS-UDDI[13], OWLSM[14] and OWLS-MX[15] with test collection OWLS-TC2.
- *Composition.*
  OWL-S service composition planners OWLS-XPlan[16], GOAL[17].

3.4.6 Limitations

Main critics of OWL-S concern its limited expressiveness of service descriptions in practice which, in fact, corresponds to that of its underlying description logic OWL-DL. Only static and deterministic aspects of the world can be described in OWL-DL, since it does not cover any notion of time and change, nor uncertainty. Besides, in contrast to WSDL, an OWL-S process model cannot contain any number of completely unrelated operations.

However, OWL-S bases on existing W3C Web standards, in particular the Web Services protocol stack: It extends OWL and has a grounding in WSDL. Furthermore, the large set of available tools and applications of OWL-S services, as well as ongoing research on semantic Web rule languages on top of OWL such as SWRL and variants still support the adoption of OWL-S for Semantic Web Services, though this might be endangered by the choice of SAWSDL as a W3C standard just recently.

3.5 WSML

The WSMO (Web Service Modelling Ontology) framework[18] provides a conceptual model and a formal language WSML (Web Service Modeling Language)[19] for the semantic markup of Web Services together with a reference implementation WSMX (Web Service Execution Environment). Historically, WSMO evolved from the Web Service Modeling Framework (WSMF) as a result of several European Commission funded research projects in the domain of Semantic Web Services like

[10]http://projects.semwebcentral.org/projects/owl-s-ide/
[11]http://projects.semwebcentral.org/projects/owl-s-api/
[12]http://projects.semwebcentral.org/projects/pellet/
[13]http://projects.semwebcentral.org/projects/mm-client/
[14]http://projects.semwebcentral.org/projects/owlsm/
[15]http://projects.semwebcentral.org/projects/owls-mx/
[16]http://projects.semwebcentral.org/projects/owls-xplan/
[17]http://www.smartweb-project.de
[18]http://www.wsmo.org/TR/d2/v1.4/20061106
[19]http://www.wsmo.org/TR/d16/d16.1/v0.21/20051005/

DIP, ASG, Super, TripCom, KnowledgeWeb and SEKT in the ESSI (European Semantic Systems Initiative) project cluster[20].

3.5.1 WSMO Conceptual Model in Brief

WSMO offers four key components to model different aspects of Semantic Web Services in WSML: Ontologies, goals, services, and mediators. Goals in goal repositories specify objectives that a client might have when searching for a relevant Web Service. WSMO ontologies in WSML provide the formal logic-based grounding of information used by all other modeling components. Mediators bypass interoperability problems that appear between all these components at data (mediation of data structures), protocol (mediation of message exchange protocols), and process level (mediation of business logics) to “allow for loose coupling between Web Services, goals (requests), and ontologies”. Each of these components, called top-level elements of the WSMO conceptual model, can be assigned non-functional properties to be taken from the Dublin Core metadata standard by recommendation. More details and examples of services and goals are given below.

WSML is particularly designed for describing a Semantic Web Service in terms of its functionality (service capability), imported ontologies in WSML, and the interface through which it can be accessed for the purpose of orchestration and choreography. The formal semantics of elements within the description of goals and services capabilities (pre- and postconditions) are specified as logical axioms and constraints in ontologies using one of five WSML variants.

3.5.2 WSML Variants

The syntax of WSML is mainly derived from F-Logic extended with more verbose keywords and varies with respect to the logical expressions allowed to describe the semantics of service and goal description elements. WSML has a normative human-readable syntax, as well as an XML and an RDF syntax for exchange between machines. The language comes in different variants each grounded on a particular logic with different expressivity and computational complexity, namely, DL (WSML-DL), LP (WSML-Flight, WSML-Rule), and nonmonotonic logic (WSML-Full) (cf. Figure 3.10).

1. **WSML-Core** corresponds with the intersection of DL (SHIQ(D)) and definite Horn logic with datatype support, and is grounded on description logic programming (DLP) [9]. The semantics of WSML-Core is defined through direct mapping to function-free Horn logic with satisfiability of WSML-Core expressions under model-theoretic semantics and classical entailment relation of PL1. It is fully compliant with a subset of OWL-DL, and is extended both in the direction of DL (WSML-DL) and LP (WSML-Flight).

[20]http://www.sdkcluster.org/

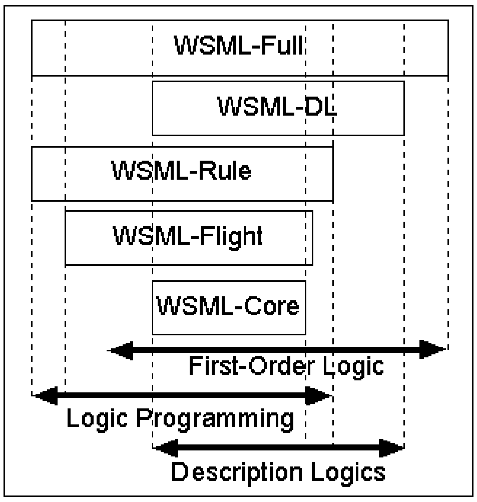


Figure 3.10: WSML language variants.

2. **WSML-DL** is a decidable DL variant of F-Logic, extending WSML-Core to SHIQ(D) that subsumes SHIF(D) underlying OWL-Lite and is subsumed by SHOIN(D) underlying OWL-DL. The model-theoretic semantics of WSML-DL generalizes that of WSML-Core and is defined through a mapping to function-free PL1 with equality. WSML-DL provides only limited modeling of restrictions (no closed world constraints) and no arbitrary rules.

3. **WSML-Flight** is a decidable Datalog variant of F-Logic (function-free, non-recursive and DL-safe rules). Its modeling primitives allow to specify different aspects of attributes, such as value constraints and integrity constraints (via built-ins), while safe Datalog rules extended with inequality and (locally) stratified negation allow efficient decidable reasoning. In other words, in WSML-FLight, concepts, instances and attributes are interpreted as objects in F-Logic with (nonmonotonic) default negation under perfect model semantics [22] of locally stratified F-Logic programs with ground entailment.

4. **WSML-Rule** extends WSML-Flight to a fully-fledged LP language, i.e. with function symbols and allowing arbitrary, unsafe rules with inequality and unstratified negation. It also provides meta modeling such as treating concepts as instances, but does not feature existentials, classical (monotonic) negation, and equality reasoning. The semantics of WSML-Rule is defined in the same way as WSML-Flight but through a mapping to full LP, that is to the Horn fragment of F-Logic extended with inequality and default negation under well-founded semantics [26] in the body of the rule instead of through a mapping to Datalog. In brief, the semantics of WSML-Rule bases on the well-founded semantics applied to the LP fragment of F-Logic [27].

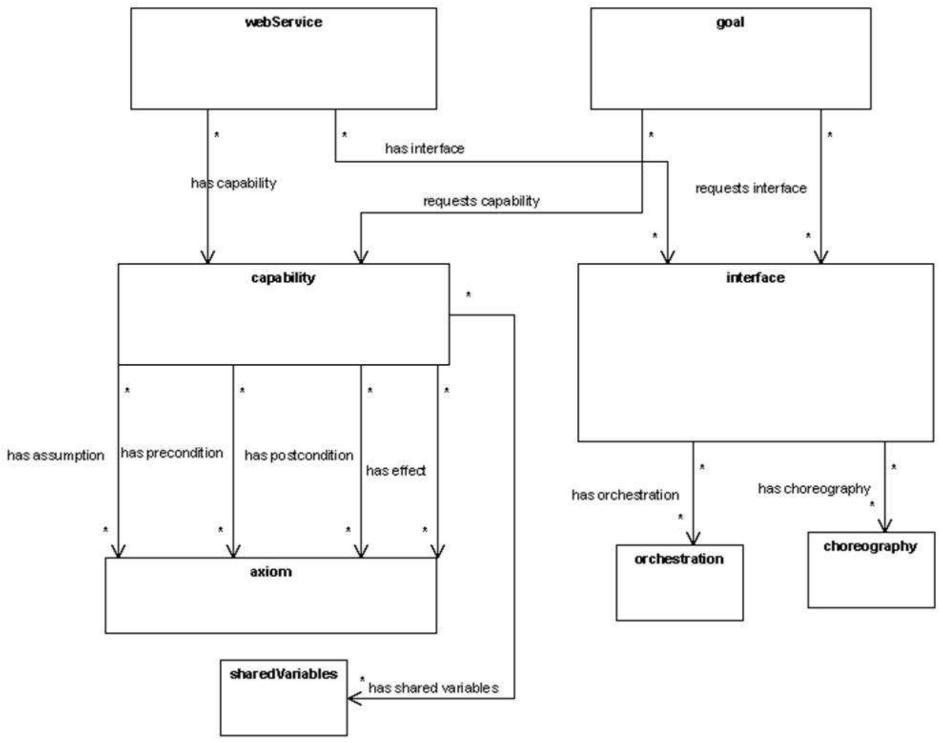


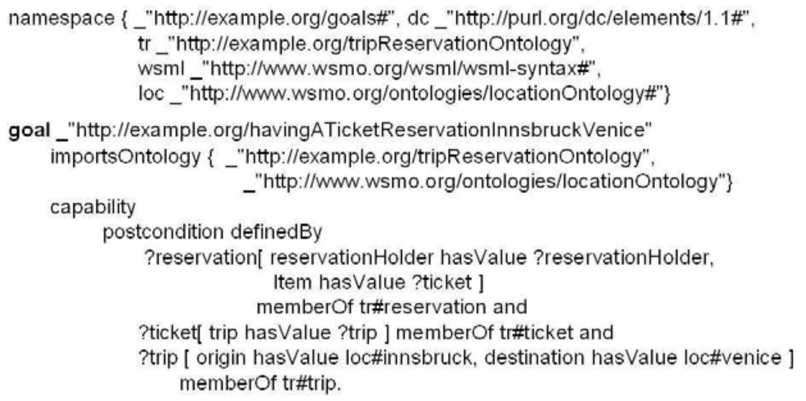
Figure 3.11: WSML service and goal description.

5. **WSML-Full** shall unify the DL and LP paradigms as a superset of FOL with non-monotonic extensions to support the nonmonotonic negation of WSML-Rule via Default Logic, Circumscription or Autoepistemic Logic. However, neither syntax nor semantics of WSML-Full have been completely defined yet.

In general, the description of the semantics of a service and request (goal) in WSML is structured into the parts of the service capability, the service interface used for orchestration and choreography, and the shared variables.

3.5.3 Goal

Like in OWL-S, a goal in WSMO represents the desired WSML service which is indicated with a special keyword "goal" instead of "webservice" in front of the service description. A goal refers to a desired state that can be described by help of a (world state) ontology. Such an ontology provides a basic vocabulary for specifying the formal semantics of service parameters and transition rules (TBox), and a set of concept and role instances (ABox) which may change their values from



```
namespace { _"http://example.org/goals#", dc _"http://purl.org/dc/elements/1.1#",
                tr _"http://example.org/tripReservationOntology",
                wsml _"http://www.wsmo.org/wsml/wsml-syntax#",
                loc _"http://www.wsmo.org/ontologies/locationOntology#"}

goal _"http://example.org/havingATicketReservationInnsbruckVenice"
     importsOntology {  _"http://example.org/tripReservationOntology",
                        _"http://www.wsmo.org/ontologies/locationOntology"}
     capability
           postcondition definedBy
                 ?reservation[ reservationHolder hasValue ?reservationHolder,
                               Item hasValue ?ticket ]
                             memberOf tr#reservation and
                 ?ticket[ trip hasValue ?trip ] memberOf tr#ticket and
                 ?trip [ origin hasValue loc#innsbruck, destination hasValue loc#venice ]
                      memberOf tr#trip.
```

Figure 3.12: Example of a service request (goal) in WSML.

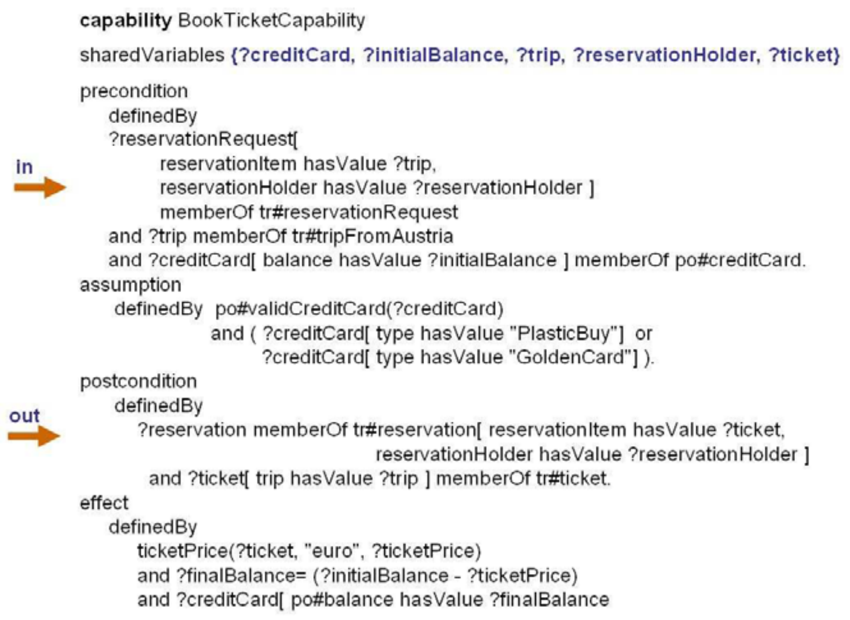
one world state to the other. It also specifies possible read-write access rights to instances and their grounding. A state is the dynamic set of instances of concepts, relations and functions of given state ontology at a certain point of time. The interpretation of a goal (and service) in WSML is not unique: The user may want to express that either all, or only some of the objects that are contained in the described set are requested [15].

Figure 3.12 gives an example of a goal in WSML to find a service, which as a result of its execution, offers to reserve a ticket for the desired trip. In this case, the only element of the capability the user is interested in, is the postcondition of the desired service.

3.5.4 Service Capability

A WSML service capability describes the state-based functionality of a service in terms of its precondition (conditions over the information space), postcondition (result of service execution delivered to the user), assumption (conditions over the world state to met before service execution), and effect (how does the execution change the world state). Roughly speaking, a WSML service capability consists of references to logical expressions in a WSML variant that are named by the scope (precondition, postcondition, assumption, effect, capability) they intend to describe. It also specifies non-functional properties and all-quantified shared variables (with the service capability as scope) for which the logical conjunction of precondition and assumption entails that of the postcondition and the effect.

Figure 3.13 provides an example of a Web Service capability specified in WSML. This example service offers information about trips starting in Austria and requires the name of the person and credit card details for making the reservation. The assumption is that the credit card information provided by the requester must designate a valid credit card that should be of type either PlasticBuy or



```
capability BookTicketCapability
sharedVariables {?creditCard, ?initialBalance, ?trip, ?reservationHolder, ?ticket}
precondition
    definedBy
    ?reservationRequest[
           reservationItem hasValue ?trip,
           reservationHolder hasValue ?reservationHolder ]
           memberOf tr#reservationRequest
    and ?trip memberOf tr#tripFromAustria
    and ?creditCard[ balance hasValue ?initialBalance ] memberOf po#creditCard.
assumption
     definedBy  po#validCreditCard(?creditCard)
                  and ( ?creditCard[ type hasValue "PlasticBuy"]  or
                         ?creditCard[ type hasValue "GoldenCard"] ).
postcondition
     definedBy
        ?reservation memberOf tr#reservation[ reservationItem hasValue ?ticket,
                                        reservationHolder hasValue ?reservationHolder ]
         and ?ticket[ trip hasValue ?trip ] memberOf tr#ticket.
effect
    definedBy
        ticketPrice(?ticket, "euro", ?ticketPrice)
        and ?finalBalance= (?initialBalance - ?ticketPrice)
        and ?creditCard[ po#balance hasValue ?finalBalance
```

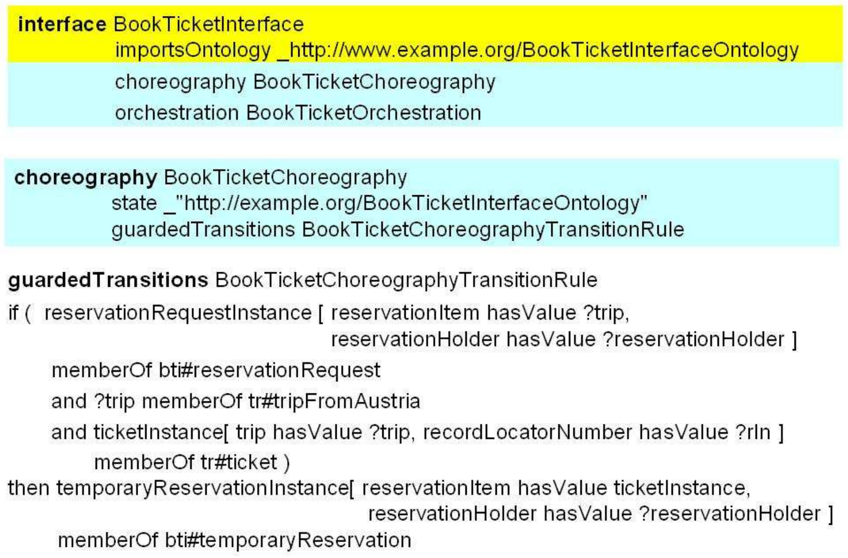
Figure 3.13: Example of service capability in WSML.

GoldenCard. The postcondition specifies that a reservation containing the details of a ticket for the desired trip and the reservation holder is the result of the successful execution of the Web Service. Finally, the effect in the world state is that the credit card is charged with the cost of the ticket.

3.5.5 Service Interface

A WSML service interface contains the description of how the overall functionality of the Web Service is achieved by means of cooperation of different Web Service providers (orchestration) and the description of the communication pattern that allows to one to consume the functionality of the Web Service (choreography). A choreography description has two parts: the state and the guarded transitions. As mentioned above, a state is represented by an WSMO ontology, while guarded transitions are if-then rules that specify conditional transitions between states in the abstract state space.

Figure 3.14 provides an example of a service interface with choreography, and a guarded transition rule which requires the following to hold: If a reservation request instance exists (it has been already received, since the corresponding concept in the state ontology currently has the mode “in”) with the request for a trip starting in Austria, and there exists a ticket instance for the desired trip in the Web Service instance store, then create a temporary reservation for that ticket.



```
interface BookTicketInterface
          importsOntology _http://www.example.org/BookTicketInterfaceOntology
          choreography BookTicketChoreography
          orchestration BookTicketOrchestration

choreography BookTicketChoreography
          state _"http://example.org/BookTicketInterfaceOntology"
          guardedTransitions BookTicketChoreographyTransitionRule

guardedTransitions BookTicketChoreographyTransitionRule
if (  reservationRequestInstance [ reservationItem hasValue ?trip,
                                   reservationHolder hasValue ?reservationHolder ]
     memberOf bti#reservationRequest
     and ?trip memberOf tr#tripFromAustria
     and ticketInstance[ trip hasValue ?trip, recordLocatorNumber hasValue ?rln ]
          memberOf tr#ticket )
then temporaryReservationInstance[ reservationItem hasValue ticketInstance,
                                   reservationHolder hasValue ?reservationHolder ]
      memberOf bti#temporaryReservation
```

Figure 3.14: Example of WSML service interface.

3.5.6 Software Support

The project web site www.wsmo.org provides, for example, a comprehensive set of links to software tools for developing WSMO oriented services (in WSML) most of which available under open source related licenses at sourceforge.net. Examples include the WSMO4J API[21], the WSMO studio[22] with WSML service editor, WSML-DL and WSML-Rule reasoner, WSML validator, and the WSMX service execution environment[23].

Remarkably, there are still neither implemented semantic WSML service composition planners nor full-fledged WSML service matchmakers available apart from a rather simple keyword-based and non-functional (QoS) parameter oriented WSML service discovery engine as part of the WSMX suite, and the hybrid matchmaker WSMO-MX. This situation of weak software support of services in WSML, however, could drastically improve in near future for various reasons of both politics and science.

3.5.7 Limitations

The WSMO conceptual model and its language WSML is an important step forward in the SWS domain as it explicitly overcomes some but not all limits of

[21]http://wsmo4j.sourceforge.net/
[22]http://www.wsmostudio.org/download.html
[23]http://sourceforge.net/projects/wsmx/

OWL-S. Unfortunately, the development of WSMO and, in particular, WSML has been originally at the cost of its connection to the W3C Web Service standard stack at that time. This raised serious concerns by the W3C summarized in its official response to the WSMO submission in 2005 from which we quote[24]: "The submission represents a development, but one which has been done in isolation of the W3C standards. It does not use the RDFS concepts of Class and Property for its ontology, and does not connect to the WSDL definitions of services, or other parts of the Web Services Architecture. These differences are not clearly explained or justified. The notion of choreography in WSMO is obviously very far from the definition and scope presented in WS-CDL. The document only gives little detail about mediators, which seem to be the essential contribution in the submission." To date, however, the connection of WSML with WSDL and SAWSDL (WSDL-S) has been established in part, and is under joint investigation by both WSMO and SAWSDL initiatives in relevant working and incubator groups of the standardisation bodies OASIS and W3C.

Another main critic on WSML concerns the lack of formal semantics of service capabilities in both the WSMO working draft as of 2006, and the WSML specification submitted to the Web consortium W3C in 2005. Recently, this problem has been partly solved by means of a semi-monolithic FOL-based representation of functional service semantics over abstract state spaces and (guarded) state space transitions by service execution traces [23]. Though, the formal semantics of the WSML service (orchestration and choreography) interface part is still missing — which is not worse than the missing process model semantics of OWL-S.

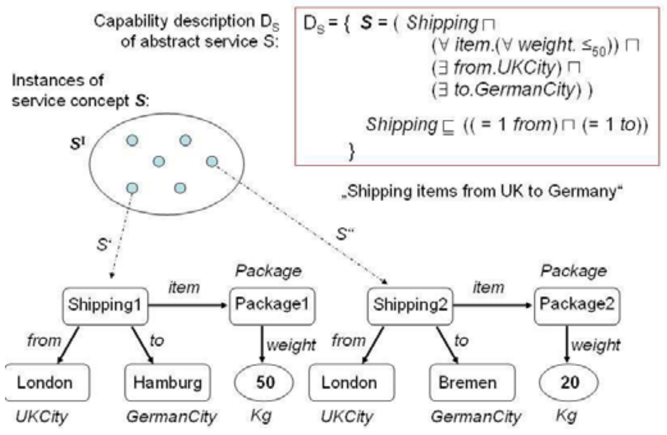
Further, principled guidelines for developing the proposed types of WSMO mediators for services and goals in concrete terms are missing. Besides, the software support for WSML services provided by the WSMO initiative appears reasonable with a fair number of downloads but is still not comparable to that of OWL-S in terms of both quantity and diversity.

Finally, as with OWL-S, it remains to be shown whether the revolutionary but rather academic WSMO framework will be adopted by major business stakeholders within their service application landscapes in practice. In general, this also relates to the key concern of insufficient scaling of logic-based reasoning to the Web scale as mentioned in the previous chapter.

3.6 Monolithic DL-Based Service Descriptions

As mentioned above, an alternative to formally specifying the functional semantics of a Web Service agnostic to any structured service description formats like OWL-S, SAWSDL, or WSML, is the pure DL-based approach: The abstract service semantics is defined through an appropriate set of concept and role axioms in a given description logic. Any instantiation of this service concept corresponds to a concrete service with concrete service properties. That is, the extension S^I

[24]http://www.w3.org/Submission/2005/06/Comment



Capability description D_S of abstract service S:
D_S = { S = (Shipping ⊓ (∀ item.(∀ weight. ≤50)) ⊓ (∃ from.UKCity) ⊓ (∃ to.GermanCity))
Shipping ⊑ ((= 1 from) ⊓ (= 1 to)) }
„Shipping items from UK to Germany"
Instances of service concept S:
S'
S'
S''
Shipping1
item
Package
Package1
from
to
weight
London
Hamburg
50
UKCity
GermanCity
Kg
Shipping2
item
Package
Package2
from
to
weight
London
Bremen
20
UKCity
GermanCity
Kg

Figure 3.15: Example of a monolithic DL-based semantic service description.

of a service concept S representing the abstract service to be described in an interpretation I of the concept over a given domain contains all service instances the provider of S is willing to accept for contracting with a potential requester of S. An example of a monolithic DL-based description of an abstract service and possible service instances is shown in Figure 3.15 ([8]).

In this example, the functional semantics or capability of the abstract Web Service S is described by a set D_S of two DL concept axioms: The service concept S for the shipping of items with a weight less than or equal to 50kg from cities in the UK to cities in Germany; the concept *Shipping* (used to define S) which assures that instances of S specify exactly one location for origin and destination of the shipping. Semantic relations between such monolithically described service semantics can be determined fully within the underlying logical formalism, that is by DL-based inferencing. For a more detailed treatment of this topic, we refer to [8].

3.7 Critics

Main critics of Semantic Web Services (SWS) range from limitations of proposed frameworks via the lack of appropriate means of service coordination and software support to the legitimation of the research field as a whole. As one consequence, SWS technology still appears too immature for getting adopted by both common Web users and developers in practice, and industry for its commercial use on a large scale.

Do we really need formal service semantics? Some recent critics of SWS technology argue against the significance of its claimed benefits for practical Web

Service applications in general. Key justification of this argument, is related to the general critics on semantic Web technologies. In fact, the need of having formal logic-based semantics specified for Web Services in practical human-centred applications is often questioned: It is completely unclear whether the complete lack of formal service semantics turns out to be rather negligible, or crucial for what kinds of service applications for the common Web user in practice, and on which scale.

Just recently, van Harmelen and Fensel [6] argued for a more tolerant and scalable semantic Web reasoning based on approximated rather than strict logic-based reasoning. This is in perfect line with experimental results available for hybrid SWS matchmakers that combine both logic and approximated reasoning like the OWLS-MX [16], the WSMO-MX [14] and the syntactic OWLS-iMatcher [1].

Where are all the Semantic Web Services? Another interesting question concerns the current reality of SWS technology in use. According to a recent survey of publicly available Semantic Web Service descriptions in the surface Web [17], revealed that not more than around 1500 indexed semantic services in OWL-S, WSML, WSDL-S or SAWSDL are accessible in the Web of which only about one hundred are deployed outside special test collections like the OWLS-TC[25]. Though we expect the majority of Semantic Web Services being maintained in private project repositories and sites of the deep Web [10], it certainly does not reflect the strong research efforts carried out in the SWS domain world wide.

Of course, one might argue that this comes at no surprise in two ways. First, SWS technology is immature (with a standard announced just recently, that is SAWSDL) which still provides insufficient common ground supporting its exploitation by end users. Though this is certainly true, the other related side of this argument is that massive research and development of the field around the globe should have produced a considerable amount of even publicly visible Semantic Web Service descriptions within the past half dozen of years.

Second, one might argue that it is not clear whether the surface Web and academic publications are the right place to look for Semantic Web Service descriptions, as many of them would be intended for internal or inter-enterprise use but not visible for the public. Though this is one possible reason of the low numbers reported above, it indicates some lack of visibility to the common Web user to date.

Where are the easy to use SWS tools for the public? As with semantic Web application building in general, apart from the project prototypes and systems there is hardly any easy to use software support off the shelves available to the common user for developing, reusing and sharing her own Semantic Web Services — which might hamper the current confluence of the field with the Web 2.0 into the so called service Web 3.0 in practice.

[25]projects.semwebcentral.org/projects/owls-tc/

How to efficiently coordinate Semantic Web Services? Despite tremendous progress made in the field in European and national funded research projects like DIP, Super, CASCOM, Scallops and SmartWeb, there still is plenty of room for further investigating the characteristics, potential, and limits of SWS coordination in both theory and practice. The Semantic Web Services Challenge[26] attempts to qualitatively measure the minimal amount of programming required to adapt the semantics of given systems to new services. This acknowledges that the complete automation of composing previously unknown services is impossible, rather being a kind of Holy Grail of modern semantic technologies. Besides, the comparative evaluation of developed SWS discovery tools is currently hard, if not impossible, to perform since the required large scale service retrieval test collections are still missing even for the standard SAWSDL. Related to this, there are no large scale experimental results on the scalability of proposed service coordination means in practice available.

Apart from the problem of scalable and efficient SWS discovery and composition, another open problem of SWS coordination as a whole is privacy preservation. Though there are quite a few approaches to user data privacy preservation for each of the individual coordination processes (discovery, composition, and negotiation), there is no integrated approach that allows to coherently secure SWS coordination activities.

3.8 Discussion

This chapter briefly introduced prominent frameworks of describing services in the semantic Web together with some major critics of the domain. Overall, the interdisciplinary, vivid research and development of the semantic Web did accomplish an impressive record in both theory and applications within just a few years since its advent in 2000. Though we identified several major gaps to bridge before the still immature Semantic Web Services technology will make it to the common user of the Web, the ongoing convergence of the semantic Web, Web 2.0, and services into a so called service Web 3.0 indicates its potential for future Web application services. In the next chapter, we survey prominent approaches to semantic discovery and composition planning of services in the semantic Web.

Further readings For more comprehensive information on Semantic Web Services in general, we refer to the accessible readings on the subject [24, 3, 5]. Examples of major funded research projects on Semantic Web Services are

- the European funded integrated projects DIP[27] and ASG (Adaptive semantic services grid technologies)[28]

[26]http://sws-challenge.org
[27]dip.semanticweb.org/
[28]asg-platform.org

- SmartWeb — Mobile multi-modal provision of Semantic Web Services[29],
- SCALLOPS[30] — Secure Semantic Web Service coordination,
- the European funded specific targeted research projects CASCOM[31], ARTEMIS[32] — Semantic Web Services for e-health applications (mobile, P2P)

For more information about Semantic Web Service description frameworks, we refer to the respective documents submitted to the W3C:

- OWL-S[33]
- WSMO[34]
- SAWSDL[35]
- Semantic Web Services Framework SWSF[36] with SWSL-Rule[37] for monolithic FOL-based service representation by means of different variants of rule languages (DLP, HiLog, etc).

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[31]http://www.ist-cascom.org
[32]http://www.srdc.metu.edu.tr/webpage/projects/artemis/
[33]http://www.w3.org/Submission/OWL-S/
[34]www.w3.org/Submission/WSMO/
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[37]www.w3.org/Submission/SWSF-SWSL/)

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Chapter 4

Semantic Web Service Coordination

Matthias Klusch

4.1 Introduction

Semantic service coordination aims at the coherent and efficient discovery, composition, negotiation, and execution of Semantic Web Services in a given environment and application context. What makes coordination of services in the semantic Web different from its counterpart in the Web is its far more advanced degree of automation through means of logic-based reasoning on heterogeneous service and data semantics.

In this chapter, we only focus on approaches to semantic discovery and composition planning of Semantic Web Services, and briefly comment on their interrelationships and selected open problems of both fields. For reasons of space limitations, the set of presented examples is representative but not exhaustive.

4.2 Semantic Service Discovery

Semantic service discovery is the process of locating existing Web Services based on the description of their functional and non-functional semantics. Discovery scenarios typically occur when one is trying to reuse an existing piece of functionality (represented as a Web Service) in building new or enhanced business processes. Both service oriented computing and the semantic Web envision intelligent agents to proactively pursue this task on behalf of their clients.

Service discovery can be performed in different ways depending on the service description framework, on means of service selection, and on its coordination through assisted mediation or in a peer-to-peer fashion. In general, any semantic service discovery framework needs to have the following components [34].

- Service description: Formal means to describe the functional and non-functional semantics of Web Services.
- Service selection: Reasoning mechanisms for service matching, that is the pairwise comparison of service descriptions in terms of their semantic relevance to the query, and ranking of the results based on partially or totally ordered degrees of matching and preferences.
- Discovery architecture: Environmental assumptions on (centralized, decentralized) network topology, service information storage (e.g. distribution of services, ontologies, registries) and location mechanisms, and functionality of agents involved (e.g. service requester, provider, middle agents).

In the following, we survey existing approaches to semantic service selection and discovery architectures.

4.2.1 Classification of Semantic Web Service Matchmakers

Semantic service matching determines whether the semantics of a desired service (or goal) conform to that of an advertised service. This is at the very core of any semantic service discovery framework. Current approaches to semantic service matching can be classified according to

- what kinds and parts of service semantics are considered for matching, and
- how matching is actually be performed in terms of non-logic-based or logic-based reasoning on given service semantics or a hybrid combination of both, within or partly outside the respective service description framework (cf. Figure 4.1).

Non-Logic, Logic, and Hybrid Semantic Service Matching The majority of Semantic Web Service matchmakers performs logic-based semantic service matching. That is, they are keeping with the original idea of the semantic Web to determine semantic relations between resources including services based on logical inferencing on their annotations grounded in description logics (DL) and/or rules (cf. Chapter 3). In fact, the set of logic-based Semantic Web Service matchmakers for OWL-S and WSML still outnumbers the complete set of non-logic-based or hybrid semantic matchmakers available for any Semantic Web Service description format. Non-logic-based semantic matchmaker do not perform any logic-based reasoning but compute the degree of semantic matching of given pairs of abstract service descriptions based on, for example, syntactic similarity measurement, structured graph matching, or numeric concept distance computations over given ontologies.

Service Profile and Process Model Matching Most Semantic Web Service matchmakers perform service profile rather than service process model matching. Service

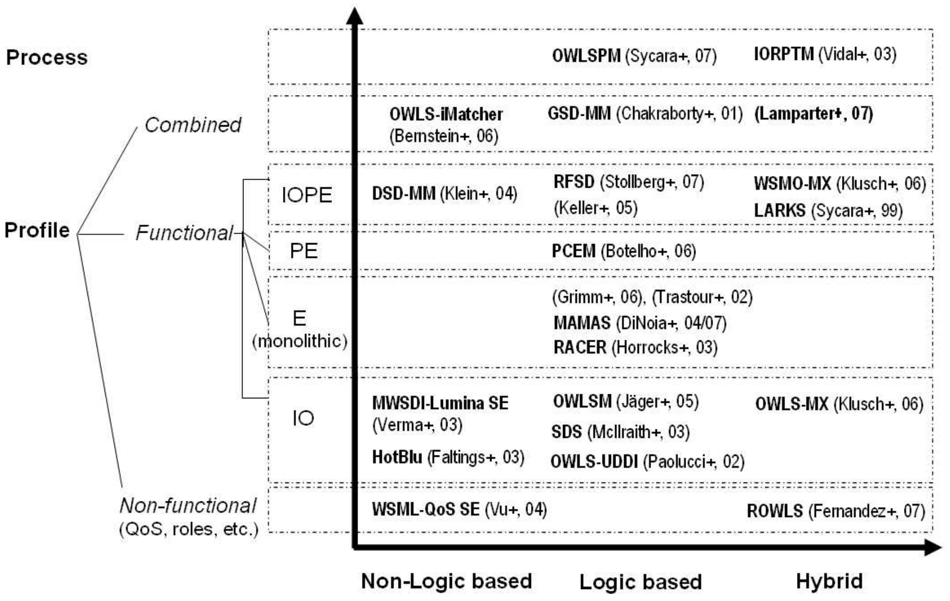

Figure 4.1: Categories of existing Semantic Web Service matchmakers.

profile matching (so called "black-box" service matching) determines the semantic correspondence between services based on the description of their profiles. The profile of a service describes what it actually does in terms of its signature, that is its input and output (IO), as well as preconditions (P) and effects or postconditions (E), and non-functional aspects such as the relevant business category, name, quality, privacy and pricing rules of the service. We classify additional context information for service matching such as the organisational (social or domain) roles, or geographic location of service requesters and providers in their interaction as non-functional.

Service process-oriented matching (so-called "glass-box" service matching) determines the extent to which the desired operational behavior of a given service in terms of its process control and data flow matches with that of another service. Like with service profile matching, we can distinguish between non-logic-based, logic-based and hybrid semantic process matching approaches depending on whether automated reasoning on operational semantics specified in some certain logic or process algebraic language (e.g. CCS, π-calculus) is performed, or not. An overview of relevant approaches to process mining for process discovery is given in [104].

Supported Semantic Web Service Description Formats Each of the implemented stand-alone Semantic Web Service matchmakers shown in Figure 4.1 supports only one of many existing Semantic Web Service description formats (cf. Chapter 3) as follows. This list is representative but not exhaustive.

- **OWL-S** matchmakers: Logic-based semantic matchmakers for OWL-S services are the OWLSM [42] and OWLS-UDDI [75] focussing on service input/output (IO) matching, and the PCEM [16] that converts given OWL-S services to PDDL actions for PROLOG-based matching of preconditions and effects. Further OWL-S matchmakers are, the hybrid service IO matchmaker OWLS-MX [53], the hybrid non-functional profile matchmaker ROWLS [31], and the non-logic-based service IOPE matchmaker OWLS-iMatcher [13]. An approach to logic-based OWL-S process model verification is in [103], an approach to the matching of process dependency graphs based on syntactic similarity measurements while [10] presents an approach to the matching of OWL-S process dependency graphs based on syntactic similarity measurements, and [11] proposes a hybrid matchmaker that recursively compares the DAML-S process model dependency graphs.

- **WSML** matchmakers: Implemented approaches to WSML service discovery include the hybrid semantic IOPE matchmaker WSMO-MX [46], and the non-logic-based search engine of the WSMO studio for non-functional (QoS-based) WSML service discovery in P2P networks [106]. Other approaches to logic-based WSML service IOPE matchmaking are presented in [45, 97], though it is unclear to what extent they have been implemented.

- **WSDL-S/SAWSDL** matchmakers: The METEOR-S WSDI discovery infrastructure [105] and the UDDI-based search component Lumina[1] are the only tool support of searching for SAWSDL services so far. While searching with Lumina is keyword-based, the MWSDI discovery of SAWSDL services relies on non-logic-based matching means.

- **Monolithic DL-based** matchmakers: Only very few matchmaker are agnostic to the above mentioned structured Semantic Web Service description formats without conversion by accepting monolithic descriptions of services in terms of a single service concept written in a given DL. In this case, semantic matching directly corresponds to DL inferencing, that is, semantic service matching is done exclusively within the logic theory such as performed by RACER [59], MaMaS[2] [26, 27], and in [35]. Recently, an implemented approach to matching of monolithic service descriptions in OWL-DL extended with (non-functional) pricing policies modeled in DL-safe SWRL rules according to given preferences using SPARQL queries to a service repository is presented in [56].

- **Others**: Non-logic-based service IOPE profile matchmakers for other structured service description formats are the DSD matchmaker [49] for DIANE

[1]lsdis.cs.uga.edu/projects/meteor-s/downloads/Lumina/
[2]sisinflab.poliba.it/MAMAS-tng/

services, the numeric service IO type matching based HotBlu matchmaker [23], and the hybrid service IOPE matchmaker LARKS for services in an equally named format [99].

In the following, we discuss each category of Semantic Web Service matching together with selected representative examples of the above mentioned Semantic Web Service matchmakers in more detail. This is complemented by a classification of existing service discovery architectures in which these matchmakers can be used in principle, or explicitly have been designed for. As stand-alone implementations, each of them classifies, in principle, as centralized service discovery system, though a few of them have been also tested for, or were originally developed for decentralized P2P service retrieval systems like the OWLS-MX and the OWLS-UDDI matchmaker, respectively, the WSMO-QoS search engine and the DReggie/GSD matchmaker[3].

4.2.2 Logic-Based Semantic Service Profile Matching

As mentioned above, logic-based semantic service matchmakers perform purely logical reasoning on service semantics. The majority of such matchmakers focus on comparing the formal profile semantics of a given pair of services. The concepts and/or rules used to define these semantics are specified in ontologies considered as first-order or rule-based background theories with a shared minimal vocabulary. Different ontologies of service providers and service requester have to be appropriately matched or aligned either at design time, or at runtime as part of the matching process.

Matching Degrees

The degree of logic-based matching of a given pair of semantic service profiles can be determined either (a) exclusively within the considered theory by means of logic reasoning, or (b) by a combination of logical inferences within the theory and algorithmic processing outside the theory. Prominent logic-based matching degrees are exact, plugin, subsumes, and disjoint which are defined differently depending on the parts of service semantics and kind of logic theory used to compute them.

For example, a software specification S plugs into (plug-in matches with) another specification R if the effect of S is more specific than that of R, and vice versa for the preconditions of S and R [109]. That is called a post plug-in match, if it is restricted to their effects. Unfortunately, this original notion of plug-in

[3]For reasons of readability, the implemented (stand-alone) Semantic Web Service matchmakers shown in Figure 4.1 each representing ako central discovery system per se are not again listed in Figure 4.2, and vice versa, that is, those matchmaking approaches being inherent part of the functionality of each node of decentralized discovery systems (but not available as stand-alone matchmaker) are not listed in Figure 4.1.

matching has been adopted quite differently by most logic-based Semantic Web Service matchmakers for both monolithic and structured service descriptions.

Monolithic Service Matching

Matching of monolithic DL-based service descriptions (cf. Chapter 3) is performed exclusively within the considered theory by classical means of DL reasoning.That is, each service concept describing the effect of corresponding Web Services in a description logic gets terminologically compared against a given query concept written in the same logic over a shared (matchmaker) ontology. This kind of logic-based service effect matching is simple but agnostic to any structure imposed by other Semantic Web Service formats like OWL-S or WSML.

For example, the post plug-in match of the effect of a service S with that of a service request R is defined as the DL entailment of concept subsumption of S by R over given knowledge base kb extended by the axioms of S and R ($kb \cup S \cup R \models S \sqsubseteq R$). That is, in every possible world or valid interpretation I of kb, the service provider's set S^I of (possible) service instances (represented by the monolithic description of the effect of S to the state space) is fully contained in the set R^I of instances acceptable to the requester ($S^I \subseteq R^I$). This assures the requester that each offered service instance is covered by her more generic request, hence S is definitely relevant, regardless of how unspecified issues in R are resolved.

In contrast, a logical service subsumes match ($kb \cup S \cup R \models R \sqsubseteq S$) assures the requester that her acceptable service instances are also acceptable to the provider, while for an intersection match the satisfiability of the conjunction of S and R (i.e., there exists an interpretation I of $kb \cup S \cup R$ such that $S^I \cap R^I \neq \emptyset$) identifies their compatibility with some underspecified constraints to agree upon. The latter is also called a potential match. An accessible account of logic-based matching filters under possible world semantics over the universe of concrete services (service instances) is given in [34].

The complexity of matching monolithic DL-based Semantic Web Service descriptions is equal to the combined DL complexity. Post plugin matching of service concepts in SHIQO$^+$ (with transitive non-primitive roles) has been shown to be undecidable [9] but decidable for OWL-DL, WSML-DL and DL-safe SWRL. Examples of monolithic service matchmakers are MAMAS [26, 27] and RACER for service concepts in OWL and DAML+OIL. Notably, they determine the post plugin matching degree inverse to its original definition in [109].

In MAMAS [22, 27], non-standard explanation services, that are abduction, a form of commonsense reasoning, and contraction, a typical belief revision operation, are devised as non-monotonic inferences for monolithic DL-based service matching. In particular, concept contraction computes an explanation concept G of why a request concept R is not compatible with service concept S, that is, $S \sqcap R$ is not satisfiable (no intersection or partial match), that is $(S \sqcap R) \sqsubseteq \bot$. For this purpose, it keeps the least specific concept expression K of concept R such that K

is still compatible with S, i.e. $\neg(K \sqcap S) \sqsubseteq \bot$. The remaining set G of constraints of R represents the desired explanation of mismatch.

If $S \sqcap R$ is satisfiable (potential match), concept abduction computes a concept expression K representing what is underspecified in service S (which constraints are *missing* in S) to completely satisfy a request R. That is, it determines a minimal explanation concept K for a failed concept subsumption $S \sqsubseteq (K \sqsubseteq)R$ ($S \sqcap K$ unsatisfied and $K \sqsubseteq R$). Both cases of approximated matching (partial, potential) are NP-hard for the simple description logic ALN. However, research in this direction has just begun and is, in part, related to research on non-monotonic reasoning with semantic Web (rule) languages.

Service Specification Matching

Service specification or profile PE matching determines the logic based semantic relation between service preconditions and effects. For example, the original notion of plug-in matching of two software components S, R requires that the logic-based definition of the effect or postcondition of S logically implies that of R, while the precondition of S is more general than that of R [109]. In other words, a logic-based semantic plug-in match of service advertisement S with service request R requires (in every model of given knowledge base kb) the service effect to be more specific, and its precondition more general than requested. Depending on the Semantic Web Service description framework (cf. Chapter 3), the specification of preconditions and effects ranges from, for example, decidable def-Horn (DLP), WSML-DL, OWL-DL to undecidable SWRL, KIF and F-Logic(LP).

For example, the logic-based service PE matchmaker PCEM (cf. Chapter 10) exploits tuProlog for exact matching of service preconditions or effects (checking if there is a possibly empty variable substitution such that, when applied to one or both propositions, this results into two equal expressions), or domain specific inference rules (for computing subPartOf relations) represented in Prolog (cf. Chapter 10).

Other examples are the IOPE matchmakers. The hybrid semantic WSML matchmaker WSMO-MX [46] is checking approximated query containment over finite service instance bases for WSML service constraints in undecidable F-Logic(LP) using OntoBroker. The IOPE matchmaker RFSD [97] uses the VAMPIRE theorem prover for matching pairs of preconditions and effects in FOL, while the hybrid IOPE matchmaker LARKS [99] performs polynomial theta-subsumption checking of preconditions and postconditions in def-Horn for this purpose. There are no non-logic-based or hybrid semantic service profile PE matchmaker available yet.

Service Signature and IOPE Matching

logic-based semantic service signature or profile IO matching is the stateless matching of declarative data semantics of service input and output parameters by a combination of logical inferences within the theory and algorithmic processing outside the theory. For example, the logic-based plug-in matching of state-based service specifications can be adopted to the plugin matching of stateless service signatures: Service S is expected to return more specific output data whose logically defined semantics is equivalent or subsumed by those of the desired output in request R, and requires more generic input data than requested in R.

More concrete, the signature of S plugs into the signature of request R iff $\forall\ \textsc{in}_S\ \exists\ \textsc{in}_R\colon \textsc{in}_S \overset{\cdot}{\geq} \textsc{in}_R \wedge \forall\ \textsc{out}_R\ \exists\ \textsc{out}_S\colon \textsc{out}_S \in \mathrm{LSC}(\textsc{out}_R)$, with $LSC(C)$ the set of least specific concepts (direct children) C' of C, i.e. C' is a immediate sub-concept of C in the shared (matchmaker) ontology. The quantified constraint that S may require less input than specified in R guarantees at a minimum that S is, in principle, executable with the input provided by the user in R iff the corresponding input concept definitions are equivalently mapped to WSDL input messages and corresponding service signature data types.

Examples of Semantic Web Service matchmakers that perform logic-based semantic signature matching only are the OWLSM [42] and the OWLS-UDDI [75]. Though the latter determines signature plug-in matching inverse to the original definition and restricted to the output. [45, 97] propose approaches to logic-based semantic IOPE matching of Web Services. In general, logic-based matching of stateless service descriptions with I/O concepts and conjunctive constraints on their relationship specified in SHOIN has been proven decidable though intractable [39]. This indicates the respective decidability of IOPE matching for OWL-S (with OWL-DL) and WSML (with WSML-DL).

4.2.3 Non-logic-based Semantic Profile Matching

As mentioned above, non-logic-based Semantic Web Service matchmaker do not perform any logical inferencing on service semantics. Instead, they compute the degree of semantic matching of given pairs of service descriptions based on, for example, syntactic similarity measurement, structured graph matching, or numeric concept distance computations over given ontologies. There is a wide range of means of text similarity metrics from information retrieval, approximated pattern discovery, and data clustering from data mining, or ranked keyword, and structured XML search with XQuery, XIRQL or TeXQuery [36, 5]. In this sense, non-logic based semantic service matching means exploit semantics that are implicit in, for example, patterns, subgraphs, or relative frequencies of terms used in the service descriptions, rather than declarative IOPE semantics explicitly specified in the considered logic.

One example is the OWLS-iMatcher [13] which imprecisely queries a set of OWL-S service profiles that are stored as RDF graphs in a RDF database with an extension of RDQL, called iRDQL, based on four (token and edit-based) syntactic similarity metrics from information retrieval. The imprecise querying of RDF resources with similarity joins bases on TFIDF and the Levenshtein metric. The results are ranked according to the numerical scores of these syntactic similarity measurements, and a user-defined threshold.

The DSD matchmaker [49, 55] performs, in essence, graph matching over pairs of state-based service descriptions in the object oriented service description language DSD (with variables and declarative object sets) without any logic-based semantics. The matching process determines what assignment of IOPE variables is necessary such that the state-based service offer is included in the set (of service instances) defined by the request, and returns a numeric (fuzzy) degree of DSD service matching.

4.2.4 Hybrid Semantic Profile Matching

Syntactic matching techniques are first class candidates for the development of hybrid semantic service profile matching solutions that combine means of both crisp logic-based and non-logic-based semantic matching where each alone would fail. Indeed, first experimental results of evaluating the performance of both non-logic-based and hybrid semantic service matchmakers (OWLS-MX, OWLS-iMatcher) show that crisp logic-based semantic service selection can be significantly outperformed by the former under certain conditions.

LARKS [99] has been the first hybrid semantic IOPE matchmaker while OWLS-MX [53] was the first hybrid semantic IO matchmaker for OWL-S services. OWLS-MX complements crisp logic-based reasoning with approximate reasoning by use of selected token-based IR similarity metrics for services.

WSMO-MX [46] is the first hybrid semantic matchmaker for services written in an LP extension of WSML-Rule, called WSML-MX. The hybrid service matching scheme of WSMO-MX is a combination of ideas of hybrid semantic matching of the OWLS-MX, the object-oriented graph matching of the DSD-MM, and the concept of intentional matching of services proposed in [45]. WSMO-MX synthesizes means of both logic programming and approximate reasoning, and applies different filters to retrieve services that are relevant to a given query with respect to strictly ordered degrees of hybrid semantic matching. These degrees are recursively computed by aggregated valuations of (a) ontology-based type matching, (b) logical constraint matching in F-logic, (c) relation matching, and (d) syntactic similarity measurement as well. Evaluation of WSMO-MX is ongoing work.

It is not yet known, however, what kind of approximative (hybrid) service matching will scale best to the size of the Web in practice, if at all. Research in this direction is in perfect line with the just recent call in [30] for a general shift in semantic Web research towards scalable, approximative rather than strict logic-based reasoning.

4.2.5 Logic-based Semantic Process Matching

Semantic matching of service process models, in general, is very uncommon, and not intended by the designers of current Semantic Web Service description formats. Besides, the semantics of process models in OWL-S or WSML have not been formally defined yet, while neither SAWSDL nor monolithic service descriptions offer any process model. This problem can be partly solved by intuitively rewriting the process model descriptions in an appropriate logic with automated proof system and respective analysis tool support.

For example, in [103], OWL-S service process models are mapped into (intuitively) equivalent logical Promela statements that are then efficiently evaluated by the SPIN model checker[4]. This allows to verify the correctness of a given service process model in terms of consistency and liveness properties of an advertised service like the Delivery process always executes after the Buy process. The results of such service process model checking can be exploited for limited process oriented OWL-S service selection; this is a topic of ongoing research.

Alternatively, the matching of process models of OWL-S services that are grounded in WSDL can be reduced to the matching of corresponding orchestrations in BPEL. As mentioned in Chapter 3, the OWL-S process model captures a common subset of workflow features that can be intuitively mapped to BPEL which offers an all-inclusive superset of such features (e.g. structured process activities in BPEL like Assignment, Fault Handler, Terminate are not available in OWL-S) [8]. Though BPEL has been given no formal semantics either yet, there are a few approaches to fill this gap based on Petri nets [63] and abstract state machines [29] that allow to formally verify liveness properties of BPEL orchestrations [66].

4.2.6 Non-logic-based and Hybrid Semantic Process Model Matching

Non-logic-based business process matching can be applied to appropriately transformed pairs of Semantic Web Service process models. For example, an approach to the matching of process dependency graphs based on syntactic similarity measurements is presented in [10]. [11] proposes a hybrid matchmaker (IO-RPTM) that recursively compares the DAML-S process model dependency graphs based on given workflow operations and logical match between IO parameter concepts of connected (sub-)service nodes of the process graphs. On the other hand, means of functional service process matching can be exploited to search for a set of relevant subservices of a single composite service.

4.2.7 Semantic Service Discovery Architectures

Existing Semantic Web Service discovery architectures and systems in the literature can be broadly categorized as centralized and decentralized by the way they handle service information storage and location in the considered service

[4]A model checker verifies if a given system (service process) model satisfies a desirable property. If the property does not hold, it returns a counter-example of an execution where the property fails.

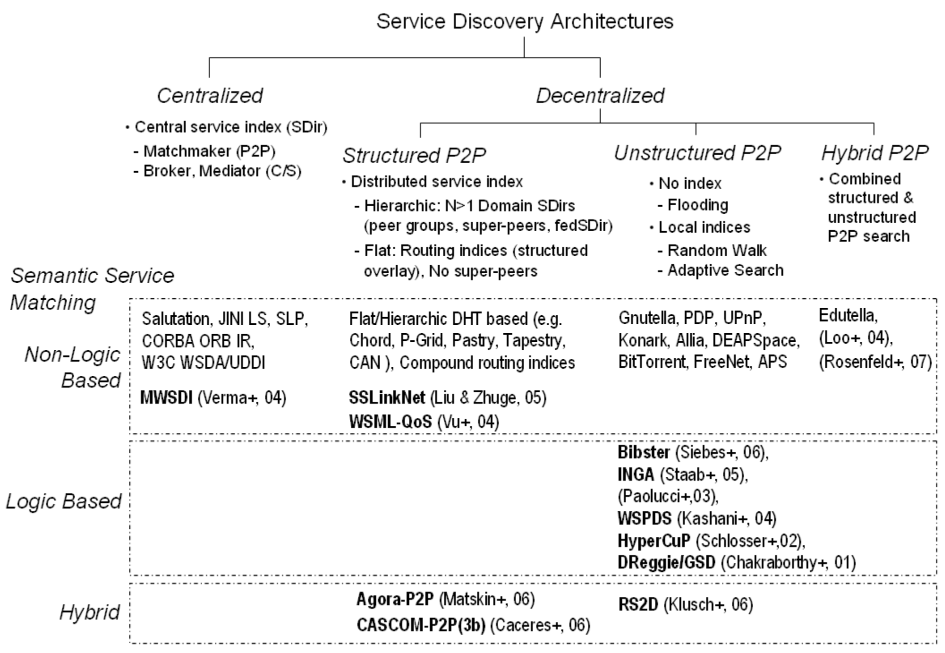
Service Discovery Architectures
Centralized
• Central service index (SDir)
- Matchmaker (P2P)
- Broker, Mediator (C/S)
Decentralized
Structured P2P
• Distributed service index
- Hierarchic: N>1 Domain SDirs (peer groups, super-peers, fedSDir)
- Flat: Routing indices (structured overlay), No super-peers
Unstructured P2P
• No index
- Flooding
• Local indices
- Random Walk
- Adaptive Search
Hybrid P2P
• Combined structured & unstructured P2P search
Semantic Service Matching
Non-Logic Based
Salutation, JINI LS, SLP, CORBA ORB IR, W3C WSDA/UDDI
MWSDI (Verma+, 04)
Flat/Hierarchic DHT based (e.g. Chord, P-Grid, Pastry, Tapestry, CAN), Compound routing indices
SSLinkNet (Liu & Zhuge, 05)
WSML-QoS (Vu+, 04)
Gnutella, PDP, UPnP, Konark, Allia, DEAPSpace, BitTorrent, FreeNet, APS
Edutella, (Loo+, 04), (Rosenfeld+, 07)
Logic Based
Bibster (Siebes+, 06),
INGA (Staab+, 05),
(Paolucci+,03),
WSPDS (Kashani+, 04)
HyperCuP (Schlosser+,02),
DReggie/GSD (Chakraborthy+, 01)
Hybrid
Agora-P2P (Matskin+, 06)
CASCOM-P2P(3b) (Caceres+, 06)
RS2D (Klusch+, 06)

Figure 4.2: Categories of Semantic Web Service discovery architectures and systems.

network [4, 34]. A classification of implemented Semantic Web Service discovery systems is given in Figure 4.2.

Centralized service discovery systems rely on one single, possibly replicated, global directory service (repository, registry) maintained by a distinguished so called super-peer or middle agent like matchmaker, broker or mediator agent [52]. Contrary, decentralized service discovery systems rely on distributing service storage information over several peers in a structured, unstructured or hybrid P2P network.

Semantic service discovery systems can be further classified with respect to the kind of semantic service matching means used by the intelligent agents in the network. For example, the exact keyword-based service location mechanisms of all contemporary P2P systems like JINI, SLP, Gnutella flooding, and DHT (distributed hash table) can be complemented or replaced by sophisticated logic-based semantic matching means to improve the quality of the search result.

As mentioned above, due to its generic functionality, any service matchmaker (cf. Figure 4.1) can be used in arbitrary discovery architectures and systems. In the extremes, a matchmaker can either serve as a central service directory (index) or look-up service, or can be integrated into each peer of an unstructured P2P service network to support an informed adaptive service search like in RS2D [12].

In fact, a few means of semantic service matching were originally developed for decentralized semantic P2P service retrieval in different applications.

Centralized Semantic P2P Service Discovery

In centralized semantic P2P service systems, a dedicated central service directory or matchmaker returns a list of providers of semantically relevant services to the requester. Contrary to centralized client-server middleware or brokering, the requester then directly interacts with selected providers for service provision [52]. The advantage of such centralized discovery architectures is a fast resource or service lookup time, though the central look-up server or registry like in JINI or the CORBA ORB interface registry is a single point of failure that can be only partially mitigated by replication and caching strategies.

An application of centralized P2P service discovery is the Napster music file sharing system, and the SETI@home system that is exploiting a vast set of distributed computional resources world wide to search for extraterrestrial signals. From the Semantic Web Service discovery perspective, each of the above mentioned stand-alone Semantic Web Service matchmakers, in principle, realizes a centralized logic-based semantic service discovery system by itself. For example, the SCALLOPS e-health service coordination system uses the hybrid semantic matchmaker OWLS-MX as a central matchmaker for the selection of relevant e-health services in a medical emergency assistance application. The same matchmaker is distributed to each peer of an unstructured P2P network for decentralized OWL-S service discovery [12].

MWSDI [105] is a centralized semantic P2P service system with non-logic-based semantic service signature matching. Each peer in the system maintains one domain specific WSDL-S (SAWSDL) service registry and respective ontologies; multiple peers can form a domain oriented group. However, a distinguished central gateway or super-peer provides a global registries ontology (GRO) that maintains the complete taxonomy of all domain registries, the mappings between WSDL-S service I/O message types and concepts from shared domain ontologies in the system, associates registries to them, and serves as central look-up service for all peers. This central super-peer is replicated in form of so called auxiliary peers for reasons of scalability. For service location, any client peer (user) selects the relevant domain registries via the central GRO at the super-peer which then performs non-logic-based semantic matching (structural XMLS graph matching, NGram-based syntactic similarity, synonyms/hyponyms/hypernyms in the GRO) of service input and output concepts with those of the desired service. However, it would be hard to build the GRO, and difficult for the user to query the GRO without knowing its details in advance.

Decentralized Semantic P2P Service Discovery

Decentralized semantic service discovery systems rely on service information storage and location mechanisms that are distributed over all peers in structured, unstructured or hybrid P2P networks.

Structured Semantic P2P Service Systems Structured P2P systems have no central directory server but a significant amount of structure of the network topology (overlay) which is tightly controlled. Resources are placed neither at random peers nor in one central directory but at specified locations for efficient querying. In other words, the service index of the system is distributed to all peers according to a given structured overlay enforcing a deterministic content distribution which can be used for routing point queries.

Prominent examples of structured P2P systems are those with flat DHT-based resource distribution and location mechanism like Chord rings, Pastry, Tapestry, CAN, P-Grid and P2PAlvis, and structured hierarchic P2P systems. Flat DHT-based systems allow to route queries with certain keys to particular peers containing the desired data. But to provide this functionality all new content in the network has to be published at the peer responsible for the respective key, if new data on a peer arrives, or a new peer joins the network.

In structured hierarchical or N-super-peer P2P systems (N>1), peers are organized in N domain oriented groups with possibly heterogeneous service location mechanisms (e.g hierarchic DHT, that is, one group with Chord ring overlay, another one with P-Grid overlay, etc.). Each group is represented by one super-peer hosting the group/domain service index. The set of super-peers, in turn, can be hierarchically structured with federated service directories in a super-peer top level overlay of the network. Peers within a group query its super-peer which interacts with other super-peers to route the query to relevant peer groups for response. The functionality of a super-peer of one peer group is not necessarily fixed, but, in case of node failure, transferable to a new peer of that group. Typically JXTA, a collection of P2P protocols, is used to realize super-peer based P2P systems, though it does not enforce such architectures.

Examples of decentralized Semantic Web Service discovery in structured P2P networks are [106], WSPDS [44], SSLinkNet [60], CASCOM-P2P$_{3b}$ [17] and Agora-P2P [54, 61]. SSLinkNet, and Agora-P2P combine keyword-based service discovery in the underlying Chord ring, respectively, P-Grid system with semantic service profile matching. The CASCOM and Agora-P2P systems are demonstrated for semantic OWL-S (DAML-S) service discovery, while SSLinkNet and WSPDS perform a P2P search for conventional Web Services.

In the SSLinkNet [60], a Chord ring-based search is complemented by forwarding the same Web Service request by the identified peers to relevant neighbors based on a given semantic service link network. The semantic links between services are determined by non-logic-based semantic service matching, and are used to derive semantic relationships between service provider peers based on heuristic rules.

Similarly, the AGORA-P2P system [54, 61] uses a Chord ring as the underlying infrastructure for a distributed storage of information about OWL-S services over peers. Service input and output concept names are syntactically hashed as literals to unique integer keys such that peers holding the same key are offering services with equal literals in a circular key space. A service request is characterized as a syntactic multi-key query against this Chord ring. Both systems, SSLinkNet and AGORA-P2P, do not cope with the known problem of efficiently preserving the stability of Chord rings in dynamic environments.

The generic CASCOM semantic service coordination architecture has been instantiated in terms of a hierarchic structured P2P network with N interacting super-peers each hosting a domain service registry that make up a federated Web Service directory. Each peer within a group can complement a keyword-based preselection of OWL-S services in their super-peer domain registries with a more complex semantic matching by a selected hybrid or logic-based semantic OWL-S matchmaker (ROWL-S, PCEM or OWLS-MX) on demand. Both, the simple service discovery agent and Semantic Web Service matchmaking module are integrated into each peer (cf. Chapter 10).

Service discovery in structured P2P networks can provide search guarantees, in the sense of total service recall in the network, while simultaneously minimizing messaging overhead. However, this challenge has not been fully explored for unstructured P2P networks yet.

Unstructured Semantic P2P Service Systems In unstructured P2P systems, peers initially have no index nor any precise control over the network topology (overlay) or file placement based on any knowledge of the topology. That is, they do not rely on any structured network overlay for query routing as they have no inherent restrictions on the type of service discovery they can perform.

For example, resources in unstructured P2P systems like Gnutella or Morpheus are located by means of network flooding: Each peer broadcasts a given query in BFS manner to all neighbour peers within a certain radius (TTL) until a service is found, or the given query TTL is zero. Such network flooding is extremely resilient to network dynamics (peers entering and leaving the system), but generates high network traffic.

This problem can be mitigated by a Random Walk search where each peer builds a local index about available services of its direct neighbour peers over time and randomly forwards a query to one of them in DFS manner until the service is found[5] as well as replication and caching strategies based on, for example, access frequencies and popularity of services [65]. Approaches to informed probabilistic adaptive P2P search like in APS [102] improve on such random walks based on estimations over dynamically observed service location information stored in the

[5]This is valid in case the length of the random walk is equal to the number of peers flooded with bounded TTL or hops).

local indices of peers. In contrast to the structured P2P search, this only provides probabilistic search guarantees, that is incomplete recall.

In any case, the majority of unstructured P2P service systems only performs keyword-based service matching and does not exploit any qualitative results from logic-based or hybrid semantic service matching to improve the quality of an informed search. In fact, only a few system are available for logic-based or hybrid Semantic Web Service retrieval such as DReggie/GSD [20, 21], HyperCuP [89], Sem-WSPDS [44], [76], Bibster [37], INGA [62], and RS2D [12]. These systems differ in the way of how peers perform flooding or adaptive query routing based on evolving local knowledge about the semantic overlay, that is knowledge about the semantic relationships between distributed services and ontologies in unstructured P2P networks. Besides, all existing system implementations, except INGA and Bibster, perform semantic service IO profile matching for OWL-S (DAML-S), while HyperCuP peers dynamically build a semantic overlay based on monolithic service concepts.

For example, [76] proposes the discovery of relevant DAML-S services in unstructured P2P networks based on both the Gnutella P2P discovery process and a complementary logic-based service matching process (OWLS-UDDI matchmaker) over the returned answer set. However, the broadcast or flooding-based search in unstructured P2P networks like Gnutella is known to suffer from traffic and load balancing problems.

Though Bibster and INGA have not been explicitly designed for Semantic Web Service discovery, they could be used for this purpose. In INGA [62], peers dynamically adapt the network topology, driven by the dynamically observed history of successful or semantically similar queries, and a dynamic shortcut selection strategy, which forwards queries to a community of peers that are likely to best answer given queries. The observed results are used by each peer for maintaining a bounded local (recommender) index storing semantically labelled topic specific routing shortcuts (that connect peers sharing similar interests).

Similarly, in Bibster [37] peers have prior knowledge about a fixed semantic overlay network that is initially built by means of a special first round advertisement and local caching policy. Each peer only stores those advertisements that are semantically close to at least one of their own services, and then selects for given queries only those two neighbours with top ranked expertise according to the semantic overlay it knows in prior. Further, prior knowledge about other peers ontologies as well as their mapping to local ontologies is assumed. This is similar to the ontology-based service query routing in HyperCuP [89].

In RS2D [12], contrary to Bibster and DReggie/GSD, the peers perform an adaptive probabilistic risk-driven search for relevant OWL-S services without any fixed or prior knowledge about the semantic overlay. Each peer uses an integrated OWLS-MX matchmaker for hybrid semantic IO matching of local services with given query, and dynamically learns the average query-answer behaviour of its direct neighbours in the network. The decision to whom to forward a given semantic service request is then driven by the estimated mixed individual Bayes' conditional risk of routing failure in terms of both semantic loss and high communication costs. Peers are dynamically maintaining their local service (matchmaker) ontology-based on observations of the results which, in particular, renders RS2D independent from the use of any fixed global ontology for semantic annotation like in DReggie/GSD.

Semantic Hybrid P2P Service Systems Hybrid P2P search infrastructures combine both structured and unstructured location mechanisms. For example, Edutella combines a super-peer network with routing indices and an efficient broadcast. In [64] a flat DHT approach is used to locate rare items, and flooding techniques are used for searching highly replicated items. A similar approach of hybrid P2P query routing that adaptively switches between different kinds of structured and unstructured search together with preliminary experimental results are reported in [88]. However, there are no hybrid P2P systems for semantic service discovery available yet.

Despite recent advances in the converging technologies of semantic Web and P2P computing [96], the scalability of semantic service discovery in structured, unstructured or hybrid P2P networks such as those for real-time mobile ad-hoc network applications is one major open problem. Research in this direction has just started. Preliminary solutions to this challenge vary in the expressivity of semantic service description, and the complexity of semantic matching means ranging from computationally heavy Semantic Web Service matchmakers like OWLS-MX in SCALLOPS and CASCOM, to those with a streamlined DL reasoner such as Krhype [48] suitable for thin clients on mobile devices in IASON [32]. An example analysis of semantic service discovery architectures for realizing a mobile e-health application is given in [19].

4.3 Semantic Service Composition Planning

Semantic Web Service composition is the act of taking several semantically annotated component services, and bundling them together to meet the needs of a given customer. Automating this process is desirable to improve speed and efficiency of customer response, and, in the semantic Web, supported by the formal grounding of service and data annotations in logics.

4.3.1 Web Service Composition

In general, Web Service composition is similar to the composition of workflows such that existing techniques for workflow pattern generation, composition, and management can be partially reused for this purpose [38]. Typically, the user has to specify an abstract workflow of the required composite Web Service including both the set of nodes (desired services) and the control and data flow between these nodes of the workflow network. The concrete services instantiating these nodes are bound at runtime according to the abstract node descriptions, also called “search recipes” [18]. In particular, the mainstream approach to composition is to have a single entity responsible for manually scripting such workflows (orchestration and choreography) between WSDL services of different business partners in BPEL [77, 1]. This is largely motivated by industry to work for service composition in legally contracted business partner coalitions — in which there is, unlike in open service environment, only very limited need for automated service composition planning, if at all. Besides, neither WSDL nor BPEL or any other workflow languages like UML2 or YAWL have formal semantics which would allow for an automated logic-based composition.

In fact, the majority of existing composition planners for Semantic Web Services draws its inspiration from the vast literature on logic-based AI planning [78]. In the following, we focus on these approaches to Semantic Web Service composition, and comment on the interleaving of service composition planning with discovery, and distributed plan execution. Please note that, the set of presented examples of Semantic Web Service composition planners is representative but not exhaustive.

4.3.2 AI-Planning-Based Web Service Composition

The service composition problem roughly corresponds to the state-based planning problem (I, A, G) in AI to devise a sound, complete, and executable plan which satisfies a given goal state G by executing a sequence of services as actions in A from a given initial world state I. Classical AI planning focuses on the description of services as deterministic state transition (actions) with preconditions, and state altering (physical) effects that are applicable to states based on the evaluation of preconditions and yield new states where the effects are valid. Further, classical planning is performed under the assumption of closed world with complete, fully observable initial states.

The goal and all logic-based semantic service concepts (IO parameter values, preconditions and effects) defined in a formal ontology (domain or background theory) and outside are converted to one declarative (FOL) planning domain and problem description that serves a given logic-based AI planner as input. In particular, service outputs are encoded as special non-state altering knowledge effects, and inputs as special preconditions. The standard language for this purpose is PDDL (Planning Domain Description Language) but alternative representation formalisms are, for example, the situation calculus [68], linear logic [86], high-level logic programming languages based on this calculus like GOLOG [67], Petri nets, or HTN planning tasks and methods [93].

However, as pointed out in [95], the naive adoption of classical AI planning for service compositions has severe limits. In particular, they are insufficient for planning under uncertainty in open service environments where (a) the initial state is incomplete, and (b) actions may have several possible (conditional) outcomes and effects that are modeled in the domain but not deterministically known at planning time, or unknown outcomes at all that can be determined only at run-time. We survey implemented functional and process level composition planner for Semantic Web Services that rely on either classical planning or planning under uncertainty in the following.

4.3.3 Classification of Semantic Service Composition Planners

In general, any AI planning framework for Semantic Web Service composition can be characterized by

- the representation of the planning domain and problem to allow for automated reasoning on actions and states,
- the planning method applied to solve the given composition problem in the domain, and
- the service semantics that are used for this purpose.

We can classify existing Semantic Web Service composition planners according to the latter two criteria, which yields the following classes.

- Dynamic or static Semantic Web Service composition planners depending on whether the plan generation and execution are inherently interleaved in the sense that actions can be executed at planning time, or not.
- Functional level or process level Semantic Web Service composition planners depending on whether the plan generation relies on service profile (data flow/IOPE) semantics only, or process model semantics in addition (data and control flown) [57].

Figure 4.3 shows the respective classification of existing Semantic Web Service composition planners.

Static and Dynamic Composition

In summary, the majority of Semantic Web Service composition planners such as GOAL [80], MetaComp (cf. Chapter 11), PLCP [83], RPCLM-SCP [57] and AGORA-SCP [86] are static classical planners. Approaches to dynamic composition planning with different degrees of interleaving plan generation and execution are rare. Unlike the static case, restricted dynamic composition planners allow the execution of information gathering but no world state altering services, hence are capable of planning under uncertainty about action outcomes at planning time. Examples of such composition planners are SHOP2 [91, 93], GOLOG-SCP [67] and OWLS-XPlan1 [50].

Advanced and reactive dynamic composition planners in stochastic domains even take non-deterministic world state changes into account during planning. While advanced dynamic planners like OWLS-XPlan2 [51] are capable of heuristic replanning subject to partially observed (but not caused) state changes that affect

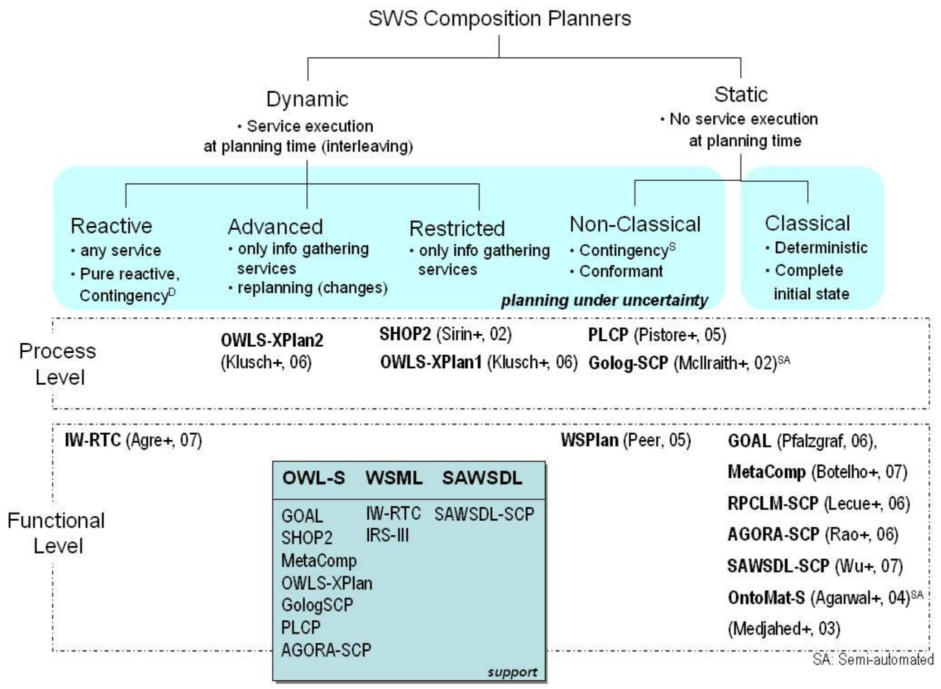

Figure 4.3: Classes of Semantic Web Service composition planners.

the current plan at planning time, their reactive counterparts like INFRAWEBS-RTC [3] fully interleave their plan generation and execution in the fashion of dynamic contingency and real-time planning.

Functional and Process Level Composition

As shown in Figure 4.3, most Semantic Web Service composition planners perform functional level or service profile based composition (FLC) planning. FLC planning considers services as atomic or composite black-box actions which functionality can solely be described in terms of their inputs, outputs, preconditions, and effects, and which can be executed in a simple request-response without interaction patterns. Examples of FLC planners are GOAL [80], SAWSDL-SCP [107] and OntoMat-S [2].

Process level composition (PLC) planning extends FLC planning in the sense that it also the internal complex behavior of existing services into account. Prominent examples are SHOP2 [93], PLCP [81, 83] and OWLS-XPlan [50, 51]. Both kinds of composition planning exploit semantic profile or process matching means that is either inherent to the AI planning mechanism, or provided by a connected stand-alone matchmaker.

Support of Semantic Web Service Description Frameworks

Remarkably, most implemented Semantic Web Service composition planners support OWL-S like GOAL, OWLS-XPlan, SHOP2, GologSCP and MetaComp, while there is considerably less support of the standard SAWSDL and WSML available to date. In fact, the SAWSDL-SCP planner [107] is the only one for SAWSDL, while the IW-RTC planner [3] is, apart from the semi-automated orchestration of WSML services in IRS-III, the only fully automated FLC planner for WSML yet.

Most composition planner feature an integrated conversion of Semantic Web Services, goals and ontologies into the internally used format of the planning domain and problem description, though a few others like the framework WSPlan [79] for static PDDL-based planning under uncertainty, and the recursive, progression-based causal-link matrix composition planner RPCLM-SCP [57] do not.

In the following, we discuss each category and selected examples of Semantic Web Service composition planners in more detail.

4.3.4 Functional Level Composition Planners

Intuitively, FLC planning generates a sequence of Semantic Web Services based on their profiles that exact or plug-in matches with the desired (goal) service. In particular, existing services S_i, S_{i+1} are chained in this plan such that the output of S_i matches with the input of S_{i+1}, while the preconditions of S_{i+1} are satisfied in the world state after execution of S_i. Depending on the considered Semantic Web Service description format (cf. Chapter 3), different approaches to logic-based, non-logic-based or hybrid semantic service profile IOPE matching are available for this purpose (cf. Figure 4.1).

In order to automatically search for a solution to the composition problem, FLC planners can exploit different AI planning techniques with inherent logic-based semantic profile IOPE or PE matching like WSPlan [79], respectively, MetaComp (cf. 11). The recursive forward-search planner GOAL [80] as well as the SAWSDL-SCP [107] apply non-logic-based semantic profile IO matching of OWL-S, respectively, SAWSDL services.

In AGORA-SCP [86], theorem proving with hybrid semantic profile IO matching is performed for OWL-S service composition: Both services and a request (theorem) are described in linear logic, related to classical FOL, while the SNARK theorem prover is used to prove that the request can be deduced from the set of services. The service composition plan then is extracted from the constructive proof.

The FLC planner in [69] uses proprietary composability rules for generating all possible plans of hybrid semantic profile IO matching services in a specific description format (CSSL). From these plans the requester has to select the one of best quality (QoS).

4.3.5 Process Level Semantic Service Composition Planners

Though FLC planning methods can address conditional outputs and effects of composite services with dynamic planning under uncertainty, considering services as black-boxes does not allow them to take the internal complex service behaviour into account at planning time. Such behavior is usually described as subservice interactions by means of control constructs including conditional and iterative steps. This is the domain of process level composition (PLC) planning that extends FLC planning in the aforementioned sense.

However, only few approaches to process level composition planning for Semantic Web Services exist to date. For example, orchestration of WSML services in IRS-III [28] synthesizes abstract state machines to compose individual services in a given process flow defined in OCML[6]. Though, the functionality of the WSMX orchestration unit has not been completely defined yet.

Other automated PLC planners of OWL-S services exploit different AI planning techniques such as

- HTN (Hierarchical Task Network) planning of OWL-S process models converted to HTN methods like in SHOP2 [93],
- Neo-classical GRAPHPLAN-based planning mixed with HTN planning of OWL-S services converted to PDDL in OWLS-XPlan [50, 51],
- Value-based synthesis of OWL-S process models in a given plan template of situation calculus-based GOLOG programs [67, 68],
- Planning as model checking of OWL-S process models converted to equivalent state transition systems (STS) in the PLCP [81, 83].

In the following, we discuss each class of static and dynamic Semantic Web Service composition planners (in short: composition planners) together with selected examples, if available.

4.3.6 Static Semantic Service Composition Planners

The class of static AI planning-based composition covers approaches to both classical and non-classical planning under uncertainty.

Static Classical Planning

As mentioned above, classical AI planners perform (off-line) planning under the assumption of a closed, perfect world with deterministic actions and a complete initial state of a fully observable domain at design time. For example, Graphplan is a prominent classical AI planning algorithm that first performs a reachability

[6]kmi.open.ac.uk/projects/ocml/

analysis by constructing a plan graph, and then performs logic-based goal regression within this graph to find a plan that satisfies the goal. Classical AI planners are static since their plan generation and execution is strictly decoupled.

Examples of Static Classical Composition Planners

One example of a static classical Semantic Web Service composition planner is GOAL [80] developed in the SmartWeb project. GOAL composes extended OWL-S services by means of a classical recursive forward-search [33]. Both, the initial state and the goal state are derived from the semantic representation of the user's question (goal) obtained by a multimodal dialogue system in SmartWeb. At each stage of the planning process the set of services which input parameters are applicable to the current state is determined by signature (IO) matching through polynomial subgraph isomorphism checking [70]: The instance patterns of input parameters are matched against the graph representation of the state, and a service is applied to a plan state (simulated world state) by merging the instance patterns of its output parameters with the state. As a result, GOAL does not exploit any logical concept reasoning but structural service I/O graph matching to compose services. If plan generation fails, GOAL detects non-matching paths within instance patterns and consequently produces a clarification request (ako information gathering service) conveyed to the user by the dialogue system; on response by the user the planning process is restarted in total.

Static service composition in the AGORA-SCP service composition system [86] relies on linear logic (LL) theorem proving. The profiles of available DAML-S services are translated in to a set of LL axioms, and the service request is formulated as a LL theorem to be proven over this set. In case of success, the composition plan can be extracted from the proof, transformed to a DAML-S process model and executed as a BPEL script. The AGORA planner is the only approach to decentralized composition planning in structured P2P networks [54].

An example of a static classical Semantic Web Service composition planner based on a special logic-based PDDL planner is MetaComp which we describe in detail in Chapter 11.

Static Planning under Uncertainty

In general, work on planning under uncertainty in AI can be classified according to (a) the representation of uncertainty, that is whether uncertainty is modeled strictly logically, using disjunctions, or is modeled numerically (e.g. with probabilities), and (b) observability assumptions, that is whether the uncertain outcomes of actions are not observable via sensing actions (conformant planning); partially or fully observable via sensing actions (conditional or contingency planning) [24]. As mentioned above, we can have uncertainty in the initial states and in the outcome of action execution. Since the observation associated to a given state is not unique, it is also possible to model noisy sensing and lack of information. Information on action outcomes or state changes that affect the plan can be gathered either at planning time (dynamic) or thereafter (static) for replanning purposes.

Static Conditional or Contingency Planning. Static conditional or contingency planner like Cassandra and DTPOP devise a plan that accounts for each possible contingency that may arise in the planning domain. This corresponds to an optimal Markov policy in the POMDP framework for planning under uncertainty with probabilities, costs and rewards over a finite horizon. The contingency planner anticipates unexpected or uncertain outcomes of actions and events by means of planned sensing actions, and attempts to establish the goals for each different outcome of these actions through conditional branching of the plan in advance[7]. The plan execution is driven by the outcome of the integrated sensing subplans for conditional plan branches, and decoupled from its generation which classifies these planners as static.

Static Conformant planning. Conformant planners like the Conformant-FF, Buridan, and UDTPOP perform contingency planning without sensing actions. The problem of conformat planning to search for the best unconditional sequence of actions under uncertainty of intial state and action outcome can be formalized as fully non-observable MDP, as a particular case of POMDP, with a search space pruned by ignoring state observations in contingency planning. For example, conformant Graphplan planning (CGP) [94] expresses the uncertainty in the initial state as a set of completely specified possible worlds, and generates a plan graph for each of these possible worlds in parallel. For actions with uncertain outcomes the number of possible worlds is multiplied by the number of possible outcomes of the action. It then performs a regression (backward) search on them for a plan that satisfies the goal in all possible worlds which ensures that the plan can be executed without any sensory actions. Conformant planner are static in the sense that no action is executed at planning time.

Examples of Static Composition Planners under Uncertainty

The PLCP [82, 83] performs static PLC planning under uncertainty for OWL-S services. OWL-S service signatures and process models together with a given goal are converted to non-deterministic and partially observable state transition systems which are composed by a model checking-based planner (MBP)[81] to a new STS which implements the desired composed service. This STS eventually gets

[7]Examples of decision criteria according to which contingency branches are inserted in the (conventional) plan, and what the branch conditions should be at these points, are the maximum probability of failure, and the maximum expected future reward (utility) as a function of, for example, time and resource consumption. Uncertainty is often characterized by probability distributions over the possible values of planning domain predicates.

transformed to an executable service composition plan (in BPEL) with possible conditional and iterative behaviors. No action is executed at planning time, and uncertainty is resolved by sensing actions during plan execution.

An example of static FLC planning under uncertainty is the WSPlan framework [79] which provides the user with the option to plug in his own PDDL-based planner and to statically interleave planning (under uncertainty) with plan execution. Static interleaving refers to the cycle of plan generation, plan execution, and replanning based on the result of the executed sensing subplans (in the fashion of static conditional planning) until a sequential plan without sensing actions is generated that satifies the goal. There are no static classical PLC planner for Semantic Web Services with deterministic (sequential) process models of composite services only available.

4.3.7 Dynamic Composition Planners

The class of dynamic AI-planning-based composition covers approaches to restricted, advanced and reactive dynamic planning under uncertainty.

Restricted Dynamic Planning

Dynamic planning methods allow agents to inherently interleave plan generation and execution. In restricted dynamic planning, action execution at planning time is restricted to information gathering (book-keeping callbacks) about uncertain action outcomes. These special actions add new knowledge in form of ground facts to the partial observable initial state under the known IRP (Invocation and Reasonable Persistence) assumption [67] to ensure conflict avoidance[8]. Like in classical planning, however, world state altering services with physical effects (in opposite to knowledge effects of service outputs) are only simulated in local planning states and never get executed at planning time.

Examples of Restricted Dynamic Composition Planners

Prominent examples of restricted dynamic composition planners are SHOP2, and OWLS-XPlan1 [50] for OWL-S services of which we describe the latter in detail in Chapter 11. SHOP2 [91, 92] converts given OWL-S service process models into HTN methods and applies HTN planning interleaved with execution of information gathering actions to compose a sequence of services that satisfies the given task. Mapping any OWL-S process model to a situation calculus-based GOLOG program, the authors prove that the plans produced are correct in the sense that they are equivalent to the action sequences found in situation calculus.

[8]The IRP assumption states that (a) the information gathered by invoking the service once cannot be changed by external or subsequent actions, and (b) remains the same for repeating the same call during planning. That is, the incremental execution of callbacks would have the same effect when executing in prior to planning for extending the initial state which, in essence, closes the world for planning.

Advanced Dynamic Planning

Advanced dynamic planning methods allow in addition to react on arbitrary changes in the world state that may affect the current plan already during planning such as in OWLS-XPlan2. This is in contrast to static planning under uncertainty where sensing subplans of a plan are executed at run time only. However, in both restricted and advanced dynamic planning the interleaved execution of planning with world state altering services is prohibited to prevent obvious problems of planning inconsistencies and conflicts.

Examples of Advanced Dynamic Composition Planners

To the best of our knowledge, OWLS-XPlan2 [51] still is the only one implemented example of an advanced dynamic composition planner. OWLS-XPlan2 will be described in Chapter 11.

Reactive Dynamic Planning

Finally, reactive dynamic planning like in Brooks's subsumption architecture, RETE-based production rule planners, and the symbolic model checking-based planner SyPEM [14] allows the execution of arbitrary actions at planning time. Pure reactive planner produce a set of condition-action (if-then) or reaction rules for every possible situation that may be encountered, whether or not the circumstances that would lead to it can be envisaged or predicted. The inherently interleaved planning and execution is driven through the evaluation of state conditions at every single plan step to select the relevant if-then reaction rule and the immediate execution of the respective, possibly world state altering action; This cycle is repeated until the goal is hopefuly reached.

A variant of reactive dynamic planning is dynamic contingency planning like in XII and SAGE. In this case, a plan that is specified up to the information-gathering steps gets executed to that stage, and, once the information has been gathered, the rest of the plan is constructed. Interleaving planning and execution this way has the advantage that it is not necessary to plan for contingencies that do not actually arise. In contrast to pure reactive planners, reasoning is only performed at branch points predicted to be possible or likely.

In any case, reactive dynamic planning comes at the possible cost of plan optimality, and even plan existence, that is suboptimality and dead-end action planning or failure. The related ramification problem[9] is usually addressed either by restrictive assumptions on the nature of service effects on previous planning states [14] in safely explorable domains, or by integrated belief revision (TMS) in the planners knowledge base at severe computational costs.

[9]The problem of ensuring the consistency of the planners knowledge base and the reachability of the original goal in spite of (highly frequent) world state altering service execution during plan generation.

Examples of Reactive Dynamic Composition Planners

One example of an implemented reactive dynamic composition planner is the real-time composition planner IW-RTC [3] developed in the European research project INFRAWEBS. It successively composes pairs of keyword-based IO matching services, executes them and proceeds with planning until the given goal is reached. Unfortunately, the authors do not provide any detailed description of the composition and matching process nor complexity analysis.

Problems of Composition Planning under Uncertainty

One problem with adopting planning under uncertainty for semantic service composition is that the execution of information gathering (book keeping) or even world state altering services at design or planning time might not be charge free, if granted by providers at all. That is, the planning agent might produce significant costs for its users even without any return value in case of plan generation or execution failure. Another problem is the known insufficient scalability of conditional or conformant planning methods to planning domains at Web scale or business application environments with potentially hundreds of thousands of services and vast instance bases. Research on exploiting conditional or conformant planning methods for Semantic Web Service composition has just started.

4.3.8 FLC Planning of Monolithic DL-Based Services

Research on AI-based FLC planning with monolithic DL-based descriptions of services has just started. Intuitively, the corresponding AI planning (plan existence) problem for the composition of such services is as follows. Given an acyclic TBox T describing the domain or background theory in a DL, ABoxes S and G which interpretations I (consistent wrt T) over infinite sets of individual (object) names are describing, respectively the initial and goal state, and a set A of operators describing deterministic, parameterized actions α which precondition and effects are specified in the same DL and transform given interpretations of concepts and roles in T ($I \rightarrow_{\alpha}^{T} I'$), is there a sequence of actions (consistent with T)[10] obtained by instantiating operators with individuals which transforms S into G?

It has been shown in [9] that the standard reasoning problems on actions, that are executability[11] and projection[12], are decidable for description logics between ALC and ALCOIQ. Furthermore, it has been shown in [71] only recently that the plan existence problem for such actions in ALCOIQ is co-NEXPTIME decidable for finite sets of individuals used to instantiate the actions, while it is known to be PSPACE-complete for propositional STRIPS-style actions. In addition, the

[10] An action is consistent with TBox T, if for every model I of T there exists I' s.t. $I \rightarrow_{\alpha}^{T} I'$.

[11] Action executability is equal to the satisfaction of action preconditions in given world states: $I \models pre_1, \forall i, 1 \leq i \leq n, I'.I \rightarrow_{\alpha_1 \ldots \alpha_i}^{T} I' : I' \models pre_{i+1}$.

[12] Satisfaction of assertion ϕ as a consequence or conjunctive effect of applying actions to a given state: For all models I of S and T,$I'.I \rightarrow_{\alpha_1 \ldots \alpha_n}^{T} I' : I' \models \phi$

extended plan existence problem with infinitely countable set of individuals was proven undecidable, as it is for Datalog STRIPS actions, for actions specified in ALC_U with universal role U for assertions over the whole domain by reduction to the halting problem of deterministic Turing machines. However, there is no implemented composition planner for monolithic DL-based services available to date.

4.4 Interrelations

Though semantic service discovery and composition planning are active fields of research by themselves, they are mainly treated separatedly in the literature. In the following, we discuss the principled relationships between them.

4.4.1 Discovery and Composition Planning

What if the search for relevant existing services fails? In this case, service matchmaker agents may attempt to compose services together to satisfy the given service request. In fact, functional IOPE or process oriented semantic service matching is inherent part of the functionality of FLC or PLC planners that is either integrated into the planner itself or outsourced to respective matchmakers with which the planner interacts on demand; though most existing Semantic Web Service matchmakers are used as stand alone tools for service discovery only (cf. Figure 4.1).

¿From the view of composition planning, semantic service discovery is of importance for the following reasons.

- Discovery means provide the complete set of initially available services as a prerequisite of composition planning. This set of services together with related ontologies forms the basis of the initial and goal state to be specified in the planning domain description format used by the planner.
- Selection of semantically relevant (e.g. equivalent or plug-in matching) services that are also execution compatible after or even during (re-)planning on demand.

In other words, semantic service matching can be used by the composition planning tool to intially set and prune the search space of potential services by selecting relevant services in prior to, interleaved with, or after planning (re-planning). However, there is no agreed strategy for a-priori pruning the set of potential services accessible to the planner for composing. Heuristic pre-filtering of services can be performed, for example, against non-functional criteria such as observed quality of service, relevant application and business domains, and user and organisational roles like in ROWLS [31]. To enable fast replanning in case of detected (temporarily) unavailability of planned services, or optimization of the plan quality, the composition planner can also exploit respectively precomputed lists of semantically equivalent or plug-in services for each service sorted delivered by a matchmaker.

Likewisely, from the view of semantic service discovery, the composition of complex services is of importance if none of the registered services satisfies the given request. In this case, the matchmaker agent can delegate its task to a composition planner for successfully generating a composite service for the given query.

Examples There are only a few implemented approaches that explicitly interleave semantic matching with composition planning.

In [58], logic-based service matching is extended with concept abduction to provide explanations of mismatches between pairs of service profiles that are iteratively used as constructive feedback during composition planning and replanning when searching for alternative services to bridge identified semantic gaps between considered IOPE profiles of services in the current plan step. A similar abduction-based matchmaking approach is presented in [26]. This scenario of explicitly interleaved discovery and composition has been implemented and tested in a non-public France Telecom research project.

In [55], the functional level composition of services specified in the DIANE service description language DSD is explicitly integrated with a DSD matchmaker module that matches service requests asking for multiple connected effects of configurable services. By using a value propagation mechanism and a cut of possible (not actual) parameter value fillings for service descriptions that cover multiple effects the authors avoid exponential complexity for determining an optimal configuration of plug-in matching service advertisements used for a composition.

In [15], the syntactic functional level service composition is based on partial matching of numerically encoded service IO data types in a service directory. Unfortunately, the justification of the proposed numeric codings for matching services appears questionable, though it was shown to efficiently work for certain applications.

The composition planner OWLS-XPlan2 [87] integrates IOPE matching and calls the component OWLS-MXP of the matchmaker OWLS-MX 1.1 to check the compatibility of input/output data types of sequenced services at each plan step. This ensures the principled executablity of the generated sequential plan at the service grounding level.

The UMBC interactive OWL-S service composer [92] uses the OWLS-UDDI matchmaker to help users filter and select relevant services while building the composition plan. At each plan step, the composer provides the user with advertised services that plug-in or exact match with the current service selection yielding an incremental backward IO chaining of services in the plan.

The Agora-P2P service composition system [54] is the only approach to decentralized Semantic Web Service composition planning. It uses a Chord ring to publish and locate OWL-S service descriptions keyword-based while linear logic theorem proving and logic-based semantic service IO matching is applied to compose (and therefore search for relevant subservices of) the desired service.

4.4.2 Composition Planning and Execution

The semantic compatibility of subsequent services in a plan does not guarantee their correct execution in concrete terms on the grounding level. A plan is called correct, if it produces a state that satifies the given goal [57]. The principled plan executability, also called execution composability of a plan requires its data flow to be ensured during plan execution on the service grounding level [69]. This can be verified through complete (XMLS) message data type checking of semantically matching I/O parameters of every pair of subsequent services involved in the plan. For example, OWLS-XPlan2 calls a special matchmaker module that checks plan execution compatibility at each plan step during planning.

The consistent, central or decentral plan execution can be achieved by means of classical (distributed) transaction theory and systems. An advanced and implemented approach to distributed Semantic Web Service composition plan execution is presented, for example, in Chapter 12 (Semantic Web Service Execution) and [73]. However, the availability of non-local services that are not owned by the planning agent can be, in principle, refused by autonomous service providers without any prior commitment at any time. This calls for effective replanning based on alternative semantic matching services delivered by the matchmaker to the composition planner prior to, or during planning such as in OWLS-XPlan2.

4.4.3 Negotiation

Services may not be for free but pay per use. In particular, requester agents might be charged for every single invocation of services at discovery or planning time. Besides, the service pricing is often private which makes it hard, if not infeasible, for any search or composition agent to determine the total expenses of coordinated service value provision to its user.

Standard solution is to negotiate service level agreements and contracting of relevant services based on non-functional service parameters such as QoS, pricing, and reputation between service requester and provider agents involved [108]. Usually, such negotiation takes place after service discovery depending on service configurations and user preferences, followed by contracting [84]. Most existing Semantic Web Service frameworks offer slots for non-functional provenance information as part of their service description.

However, the problem of how to dynamically interleave composition (re-)planning and negotiation remains open. Related work draw upon means of parallel auctioning [85], and coalition forming [74] of planning agents in different competitive settings.

4.5 Open Problems

The research field of Semantic Web Service coordination is in its infancies. Hence, it comes at no surprise that there are many open problems of both semantic service discovery and composition planning that call for intensive further investigation in the domain. Some major open problems of semantic service discovery are the following.

- *Approximated matching.* How to deal with uncertain, vague or incomplete information about the functionality of available services and user preferences for service discovery? Fuzzy, probability, and possibility theory are first class candidates for the design of approximated (hybrid) semantic service matching algorithms to solve this problem. In particular, efficient reasoners for respective extensions of semantic Web (rule) languages like probabilistic pOWL, fuzzyOWL, or pDatalog can be applied to reason upon semantic service annotations under uncertainty and with preferences.

  However, there are no such semantic service matchmakers available yet. Apart from the first hybrid matchmakers for OWL-S and WSML services, OWLS-MX and WSMO-MX, the same holds for the integrated use of means of statistical analysis from data mining or information retrieval for approximative matching of semantic service descriptions.

- *Scalability.* How to reasonably trade off the leveraging of expensive logic-based service discovery means with practical requirements of resource bounded, just-in-time and light-weight service discovery in mobile ad-hoc or unstructured P2P service networks? What kind of approximated and/or adaptive semantic service discovery techniques scale best for what environment (network, user contxt, services distribution, etc) and application at hand? The required very large scale, comparative performance experiments under practical real-world conditions have not been conducted yet.

- *Adaptive discovery.* How to leverage semantic service discovery by means of machine learning and human-agent interaction? Though a variety of adaptive personal recommender and user interface agents have been developed in the field, none of the currently implemented semantic Web Service matchmakers is capable of flexibly adapting to its changing user, network, and application environment.

- *Privacy.* How to protect the privacy of individual user profile data that are explicit or implicit in service requests submitted to a central matchmaker, or relevant service providers? Approaches to privacy preserving Semantic Web Service discovery are still very rare, and research in this direction appears somewhat stagnant. Amongst the most powerful solutions proposed are the Rei language for annotating OWL-S services with privacy and authorization policies [25, 43], and the information flow analysis based checking of the privacy preservation of sequential OWL-S service plans [40, 41]. However, nothing is known about the scalability of these solutions in practice yet.

- *Lack of tool support and test collections.* Current easy to use tool support of Semantic Web Service discovery is still lagging behind the theoretical advancements, though there are differences to what extent this is valid for what service description framework (cf. Figure 4.1). In particular, there is no official test collection for evaluating the retrieval performance of service discovery approaches (matchmakers, search engines) for the standard SAWSDL and WSML, while there are two publicly available for OWL-S (OWLS-TC2, SWS-TC). There are no solutions for the integrated matching of different services that are specified in different languages like SAWSDL, OWL-S and WSML. Relevant work on refactoring OWL-S and WSML to the standard SAWSDL is ongoing.

Some major challenges of research and development in the domain of Semantic Web Service composition planning are as follows.

- Scalable and resource efficient approaches to service composition planning under uncertainty and their use in real-world applications of the Web 3.0 and in intelligent pervasive service applications of the so called "Internet of Things" that is envisioned to interlink all kinds of computing devices without limit on the global scale.
- Efficient means of distributed composition planning of Semantic Web Services in peer-to-peer and grid computing environments.
- Easy to use tools for the common user to support discovery, negotiation, composition and execution Semantic Web Services in one framework for different Semantic Web Service formats like the standard SAWSDL, and non-standards like OWL-S, WSML, and SWSL.
- Interleaving of service composition planning with negotiation in competitive settings.

4.6 Discussion

This chapter provided a brief romp through the fields of Semantic Web Service discovery and composition planning. We classified existing approaches, discussed representative examples and commented on the interrelationships between both service coordination activities. Despite fast paced research and development in the past years world wide, Semantic Web Service technology still is commonly considered immature with many open theoretical and practical problems as mentioned above. However, its current convergence with Web 2.0 towards a service Web 3.0 in an envisioned Internet of Things helds promise to effectively revolutionize computing applications for our everday life.

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