Behavioural description based web service composition using abstraction and refinement

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Abstract: The web service composition problem with respect to behavioural descriptions deals with the automatic synthesis of a coordinator web service that controls a set of web services to reach a goal state. Despite its importance, however, solving the problem for a general case (when the coordinator has only partial observations) remains doubly exponential in the number of variables in web service descriptions. Toward this challenge, we propose two novel (signature preserving and subsuming) approximation-based approaches using abstraction and refinement. Given a set of web service behavioural descriptions and a reachability goal, we automatically construct abstract web services which have less variables using over-approximation. If our method identifies a coordinator web service, the coordinator is guaranteed to control the given web services to reach the goal state no matter how they behave. Otherwise, our method refines the current abstraction by adding some variables that have strong dependency on the goal variables.

Keywords: WSC; web service composition; computational complexity; partial observation; behavioural description; abstraction; refinement.

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1 Introduction

Web services are software systems designed to support machine to machine interoperation over the internet. When a single web service does not satisfy a given requirement entirely, one needs to use a composition of web services. In particular, the *Web Service Composition (WSC)* problem that we focus on in this paper is defined as: *given a set of (behavioural descriptions of) web services, W, and a reachability goal, G, how to automatically synthesise a coordinator web service, c, that controls W to satisfy G.* In this paper, a behavioural description of a web service is a formal specification on how the web service executes internally and externally by interacting with users; e.g. describing what output value it returns for a given input and its state, and how it changes its internal state.

Despite abundant research on the WSC problem, only a few (e.g. Traverso and Pistore, 2004; Pistore et al., 2005a; Pistore et al., 2005b) employ realistic models with partial observation. Our previous work (Kil et al., 2008) showed that: (a) the WSC problem for a restricted case (when the synthesised coordinator web service, c, has *full observation* for all variables) is EXP-hard, and (b) the WSC problem for a general case (when c has *partial observation)* is 2-EXP-hard. These results imply that more focus should be put on the study of approximate solutions to the WSC problem. Toward this challenge, in this paper, we propose two approximation-based algorithms using 'abstraction and refinement' (Clarke et al., 1994). To the best of our knowledge, it is the

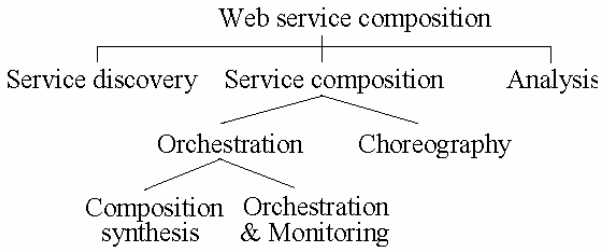
first attempt to apply an abstraction technique to the WSC problem. Even, in *planning under partial observation* (Bertoli and Pistore, 2004; Rintanen, 2004) which has a strong connection to the WSC problem, no study has attempted to apply abstraction techniques.

The first step is to reduce the original web services to the abstract ones with fewer variables. If we identify a coordinator that controls the abstract web services to satisfy a given goal, the coordinator can control the original web services to satisfy the goal since the abstract web services 'over-approximate' the concrete ones. Otherwise, we refine the abstract web services by adding variables, and repeat to find a solution. For the abstraction, we propose two methods – *signature-preserving abstraction* and *signature-subsuming abstraction.* Finally, we report the performance of our tool using three sets of realistic problems (i.e. 8 instances), comparing it with a basic algorithm (Traverso and Pistore, 2004) without abstraction/refinement. Our experiment shows that our proposal outperforms the basic algorithm. Finally, it is worth pointing out that our approach can be readily adopted for other WSC techniques such as knowledge-level composition (Pistore et al., 2005a).

2 Background

The WSC is required when a client request cannot be fulfilled by a single pre-existing web service. In such a case, one prefers integrating existing web services to satisfy the request. In the work of Alonso et al. (2003), this new value-added service and a process to generate the service are named as a *composite service* and *composition,* respectively. The essential activities of the WSC problem are illustrated in Figure 1.

Figure 1 The activities of web service composition problem.



At first, *service discovery* is to find out one or a set of web service appropriate to a given request. How to locate a web service is also an inseparable issue in the discovery. For this, many researchers have focused on a centralised UDDI registry (2004, http://uddi.xml.org/) as an effective method to solve a web service discovery problem. UDDI (2004, see http://uddi.xml.org/), a standard for centralised repositories, stores information describing web services produced by service providers, and is queried by service requesters. As an alternative of UDDI, specialised portals, such as XMethods (http://www.xmethod.com), BindingPoint (2006, see http://www.bindingpoint.com), RemoteMethods (see http://www.remotemethods.com) or eSynaps (see http://www.robtex.com/dns/esynaps.com.html) appear. They gather web services via the manual registration and support a keyword-based service search by focused crawlers. However, as the number of web services grows, such a centralised approach quickly becomes

impractical. As a result, systems building on ontology and/or using Peer-to-Peer (P2P) technologies have been introduced (e.g. Hypercube ontology-based P2P system (Schlosser et al., 2002) and the Speed-R; see http://webster.cs.uga.edu/mulye/ SemEnt/ Speed-R.html).

Next, *service composition* integrates the existing services for a given request. Since various research fields tackle the composition problem with their own flavours, the vocabulary representing the design issues in the composition is mixed in many literatures. Here, we identify these terms for general understanding of the composition issues:

- *Orchestration vs. choreography:* Both of orchestration and choreography describe how web services can interact at the message level, including the business logic and execution order of the interactions. However, orchestration methods aim at synthesising a new web service called a *coordinator* which has a specialised role of controlling the other services by properly exchanging messages. WS-BPEL (see http://docs.oasis-open.org/wsbpel/2.0/wsbpel-v2.0.pdf) is an example of a standard language for orchestration. Choreography, on the other hand, is more collaborative in nature where each party involved in the process describes its own role for one shared goal. Accordingly, the execution of the composition is distributed to all participating web services. As a result, a specification generated by the orchestration identifies the execution steps for the participating services while a choreography specification describes the set of allowable conversation for a composite web service. The difference in the topology of the composite service clearly explains why orchestration methods are called centralised or mediated-based approaches whereas choreography methods are called distributed or peer-to-peer.
- *Composition synthesis vs. orchestration*: Orchestration is frequently used with a limited meaning by separating a composition synthesis in the literatures (Alonso et al., 2003; Hull, 2003; Haas, 2004; Berardi et al., 2005). Composition synthesis concerns how to generate a specification of how to coordinate the participating services, whereas orchestration here takes into account how to coordinate the various participating services by executing the specification generated by the composition synthesis. It also includes the functionality to monitor control and data-flow among the participants for the correct execution of the composite service.

In this paper, we deal with the composition synthesis. However, the service composition is more generally used as a representative, we use the term *web service composition problem,* instead of composition synthesis.

In addition, there are other issues that give an influence to the design of a composite service. Both *static* and *dynamic* compositions present the clear difference in service selection timing. In the static composition method, we can decide the services to be composed at design time. On the other hand, in the dynamic composition, it can happen at run time.

Finally, *analysis (verification)* in Figure 1 is particularly necessary since, by using automatic algorithms, a composite service is to be created from pre-existing services. The ultimate goal is to ensure that the eventual execution of a composite service produces the desired behaviour. Ideally, one would be able to statically verify properties (e.g. in a temporal logic) for composite services. There have been various attempts at developing such analysis methods for web services and workflow systems.

3 Related work

On the WSC problem, extensive research (e.g. McIlraith and Son, 2002; Sirin et al., 2004; Traverso and Pistore, 2004; Pistore et al., 2005a; Pistore et al., 2005b; Nam et al., 2008) has been carried out. In this section, we review some of the representative works.

First, automated planning techniques are mainly applied to solve the WSC problem due to its similarity to the planning problem. The work of McIlraith and Son (2002) presents a composition method to use logical inferencing techniques where a service capability specified in DAML-S is translated into situation calculus and Golog. Golog is designed for the specification and execution of complex actions. Hierarchical Task Network (HTN) planning (Sirin et al., 2004) allows the expression of aggregate behaviours. As an input, a planner takes composite processes representing how to compose a sequence of single step actions and tries to find a collection of atomic process instances which form an execution path for top-level composite process. However, these works consider neither non-determinism nor partial observability.

Traverso and Pistore (2004), Pistore et al. (2005a) and Pistore et al. (2005b) have defined WSC over a planning domain where uncertainty on a state and a non-deterministic action are allowed, and presented algorithms which take into account service behaviours and complex goals. They extend the previous work in order to handle asynchronous, message-based interaction between domains and plans (Pistore et al., 2005b). However, they do not consider the complexity of the WSC problem. Recently, Fan et al. (2008) investigate the complexity of the WSC based on query rewriting using views, but do not include a more realistic non-deterministic web service in their setting. Furthermore, even though some work considered planning with abstraction, there has been no work that applied an abstraction technique to the WSC problem. Huang et al. (2007) propose a method to reduce observation variables for strong plans. This technique, however, cannot identify such variables until a plan is fully constructed. Armano et al. (2003) employ abstraction techniques for a hierarchical planner, and Smith et al. (2007) present an abstraction technique to generate exponentially smaller POMDP. Therefore, their techniques cannot be applied to our setting.

Recently, some works (Meyer et al., 2007; Yu et al., 2008; Brogi, 2010) focus on service process behaviours for fully automatic composition. Brogi (2010) for instance discusses the requirement of service behaviour representation in web services and the potential advantages of exploiting this behavioural information for service discovery and composition. The Adaptive Services Grid (ASG) project (Meyer et al., 2007) presents how dynamic adaptation strategies can support an automated selection, composition and binding of services during run-time. Yu et al. (2008) synthesise the process model from automata of the rules, by using path finding, branching structure identification and parallel structure identification.

In addition to the aforementioned research, our work is also related to the following: for example, game theory (Reif, 1984; Thomas, 2002), open system synthesis with temporal logics (Pnueli and Rosner, 1989; Antoniotti, 1995; Vardi, 1995; Kupferman and Vardi, 1997) and automated planning (Herzi et al., 2000; Bertoli and Pistore, 2004; Rintanen, 2004; Moffitt, 2007).

First, the WSC problem has a close connection to game theory. Since the coordinator cannot control the non-determinism of a given set of web services and has to decide inputs to web services only with outputs from them, this problem can be considered as a

two-player game with partial observation where the coordinator wants to win over the web services. Reif (1984) has proved that the problem of determining the outcome of universal games from a given initial position is 2-EXP-hard. Thomas (2002) has surveyed the algorithmic theory of infinite games, and its role in automatic programme synthesis and verification.

For open systems, next, various controller synthesis problems have been studied with temporal logics (Pnueli, 1981; Emerson, 1990). Most have considered linear time logics (Pnueli, 1981) and often involved dealing with incomplete information due to partial observation (Pnueli and Rosner, 1989; Vardi, 1995). For branching-time cases, Antoniotti (1995) has studied the synthesis of memoryless controllers with maximal environments. Kupferman and Vardi (1997) have studied the open system synthesis under partial observation, and proved that the problem with a specification in CTL (CTL*) (Emerson, 1990) is EXP-complete (2-EXP-complete, respectively).

Finally, the WSC problem is related to automated planning under partial observation (Herzi et al., 2000; Bertoli and Pistore, 2004; Rintanen, 2004; Moffitt, 2007). Herzig et al. (2000) have proposed a dynamic logic EDL for planning under partial observability. In the work of Bertoli and Pistore (2004), a fully automatic planning tool, MBP, has been developed for this setting based on belief-states. The complexity of planning under partial observability has been studied in the work of Rintanen (2004). Moffitt (2007) has explored a means to both model and reason about partial observability within the scope of constraint-based temporal reasoning.

The current paper is a revised and expanded version of our previous work (Kil et al., 2009); compared with the previous work, it also includes the explanation for background, related work, more detail examples, and discussion (i.e. the different with abstraction technique of model checking field).

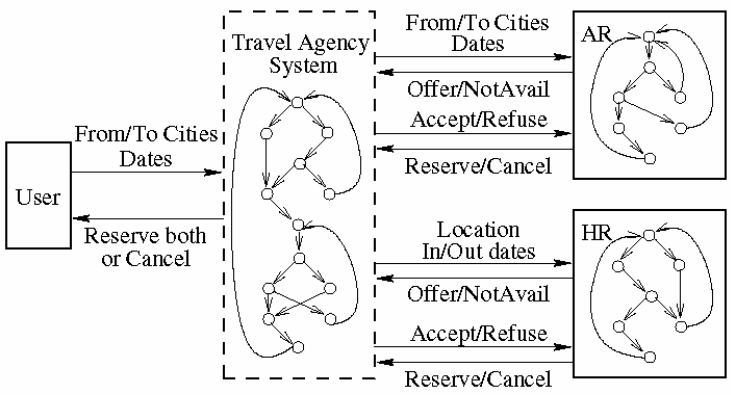
4 Web service composition

Example 1 (Travel agency system): Clients want to reserve both a flight ticket and a hotel room for a particular destination and a period. However, there exist only an airline reservation (AR) web service and a hotel reservation (HR) web service separately. Clearly, we want to combine these web services rather than implementing a new one. One way to combine them is to automatically construct a coordinator web service which communicates with them to book ticket of both a flight as well as a hotel room. Figure 2 illustrates this example. The AR service receives a request including departing/returning dates, an origin and a destination, and then checks if the number of available seats for flights is greater than 0. If so, it returns the flight information and its price; otherwise, it returns ‘Not Available’. Once offering the price, it waits for ‘Accept’ or ‘Refuse’ from its environment (in this case, a coordinator to be constructed). According to the answer, it processes the reservation. Likewise, the HR service is requested with check-in/check-out dates and a location, and then checks the number of available rooms. If there is available accommodation, it returns the room information and its price; otherwise, it returns ‘Not Available’ AR then processes a reply ‘Accept’ or ‘Refuse’ from its environment.

The coordinator web service to be constructed receives from a user a request including departing/returning dates, an origin and a destination, and tries to achieve a goal, ‘reserve both a flight ticket and a hotel room or cancel it’, by controlling these two web services. For every output from AR and HR, the coordinator has to decide one input

to them as the next action based on only output values (since in run-time it cannot access the internal variables in AR and HR, e.g. the number of available seats in flights), and it should accomplish the aim eventually. The coordinator can obviously be represented by a deterministic state-transition system.

Figure 2 Travel agency system



Definition 1 (Web service): *A (behavioural description of a) web service w is a 5-tuple* $(X, X^I, X^O, Init, T)$ *with the following components:*

- X *is a finite set of variables that w controls. A state s of w is a valuation for every variable in X. We denote a set of all states as S.*
- X^I *is a finite set of input variables that w reads from the outside;* $X \cap X^I = \varnothing$ *and every variable* $x \in \cup X^I$ *has a finite domain (e.g. Boolean, bounded integers, or enumerated types). A state in for inputs is a valuation for every variable in* X^I*. We denote a set of all input states as* S^I*.*
- $X^O \subseteq X$ *is a finite set of output variables that other web services can read. Let us denote a set of input and output variables by* X^{IO} *(i.e.* $X^{IO} = X^I \cup X^O$*) and a set of all variables by* X^A *(i.e,* $X^A = X \cup X^I$*).*
- *Init(X) is an initial predicate over X. Init(s) = true if and only if s is an initial state.*
- $T(X, X^I, X^I)$ *is a transition predicate over* $X \cup X^I \cup X'$*. For a set X of variables, we denote the set of primed variables of X as* $X' = \{x' \mid x'$ *for each* $x \in X\}$*, which represents a set of variables encoding successor- states.* $T(s, in, s')$ *is true if and only if s′ can be a next state when the input in* $\in S^I$ *is received at the state s. T can define a non-deterministic transition relation.*

While the formalism for web services by Traverso and Pistore (2004) is based on an explicit state-transition system using a set of states, we *symbolically* define web services by a set of variables, which is more compact.

Example 2: Consider a simple version of a web service *w* for the airline reservation in Example 1, and assume that clients can request (reserve or refuse) a flight ticket by an action req_1 or req_2 (*accept* or *refuse,* respectively). The web service *w* can be represented as (X, X^I, X^O, Int, T) where:

- X = {`state, avail, reply, confirm, f_num, tr_num`} *where* `state` *has the domain* $\{q_1, q_2\}$, `avail` *is Boolean*, `reply` *has the domain* {*undecided, offer, notAvail*}, `confirm` *has the domain* {*undecided, reserve, cancel*}, `f_num` *(flight number) has the domain* $\{f_1, f_2\}$, and `tr_num` (*transaction number*) *has the domain* $\{t_1, t_2\}$.
- X^I = {`action`} *where* `action` *has the domain* {req_1, req_2, *accept*, *refuse*}.
- X^O = {`reply, confirm, f_num`}.
- *Init(X)* = (`state` = q_1) $\wedge$ (`reply` = *undecided*) $\wedge$ (`confirm` = *undecided*).
- $T(X, X^I, X') \equiv$

$$(((\texttt{state} = q_1) \wedge (\texttt{action} = req_1) \wedge (\texttt{avail} = true)) \rightarrow ((\texttt{state}' = q_2) \wedge (\texttt{reply}' = offer) \wedge (\texttt{tr\_num}' = t_1)))$$

$$\wedge (((\texttt{state} = q_1) \wedge (\texttt{action} = req_1)) \rightarrow (\texttt{f\_num}' = f_1))$$

$$\wedge \ldots$$

$$\wedge (((\texttt{state} = q_2) \wedge (\texttt{action} = accept)) \rightarrow ((\texttt{state}' = q_1) \wedge (\texttt{confirm}' = reserve)))$$

$$\wedge (((\texttt{state} = q_2) \wedge (\texttt{action} = refuse)) \rightarrow ((\texttt{state}' = q_1) \wedge (\texttt{confirm}' = cancel))).$$

Note that the process model for any web service described in semantic web languages (e.g. WS-BPEL or OWL-S) can be easily transformed into our representation above without any information loss if it has only finite domain variables and no recursion[1]. In the WSC problem, in this paper a given a set of available web services, *W*, every web service in *W* communicates only with their coordinator but not with each other.

Definition 2 (Set of web services): *Based on the assumption above, given a set* $W = \{w_1, \ldots, w_n\}$ *of web services where for each* $w_i(X_i, X_i^I, X_i^O, Init_i, T_i)$, X_i *is disjoint with every other* X_j *and* X_i^I *is disjoint with every other* X_j^I, *W also can be represented by a 5-tuple* (*X, X*^{I}*, X*^{O}*, Init, T) where* $X = X_1 \cup \cdots \cup X_n, X^I = X_1^1 \cup \ldots \cup X_n^I, X^O = X_1^O \cup \ldots \cup X_n^O$, $Init(X) = Init_1 \wedge \ldots \wedge Init_n$, *and* $T(X, X^I, X') = T_1 \wedge \cdots \wedge T_n$.

In the above definition, we assume that web services in *W* do not share the identical variable name. If this case happens, by simply adding unique prefix/suffix to the names, we can distinguish the variables.

Since a *coordinator web service* is also a web service, it is a 5-tuple $c\left(X_c, X_c^I, X_c^O, Init_c, T\right)_c$. In what follows, s_c denotes a state of a coordinator web service,

and S_c denotes a set of all states of a coordinator. Although T_c can define a non-deterministic transition relation, in this problem we want only a *deterministic* transition relation for *c*; i.e. for every coordinator state s_c and input *in*, there exists only one next coordinator state s_c' such that $T_c(s_c, in, s_c') = true$.

Example 3: Consider a simple coordinator web service c that communicates with AR in Example 2. The coordinator web service $c = \left(X_c, X_c^I, X_c^O, Int_c, T_c\right)$ can be represented with the following elements:

- X_c = {`c_state`, `action`} *where* `c_state` *has the domain* $\{s_1, s_2\}$, *and* `action` *has the domain* $\{req_1, req_2, accept, refuse\}$.
- X_c^I = {`reply`, `confirm`, `f_num`} *where* `reply` *has the domain {undecided, offer, notAvailable}*, `confirm` *has the domain* {*undecided, reserve, cancel*}, and `f_num` *has the domain* $\{f_1, f_2\}$.
- X_c^O = {action}.
- $Init_c(X_c) \equiv (\texttt{c\_state} = s_1) \wedge (\text{action} = req_1)$.
- $T_c(X_c, X_c^I, X_c' \equiv$

$$
\begin{aligned}
&(((\texttt{c\_state} = s_1) \wedge (reply = offer)) \rightarrow \\
&\qquad ((\texttt{c\_state}' = s_2) \wedge (action' = accept))) \\
&\wedge (((\texttt{c\_state} = s_1) \wedge (reply = notAvailable)) \rightarrow \\
&\qquad ((\texttt{c\_state}' = s_1) \wedge (\texttt{action}' = req_2))) \\
&\wedge (((\texttt{c\_state} = s_2) \wedge (\texttt{confirm} = reserve)) \rightarrow \\
&\qquad ((\texttt{c\_state}' = s_1) \wedge (\texttt{action}' = req_1))) \\
&\wedge (((\texttt{c\_state} = s_2) \wedge (\texttt{confirm} = cancel)) \rightarrow \\
&\qquad ((\texttt{c\_state}' = s_1) \wedge (\texttt{action}' = req_1))).
\end{aligned}
$$

For a state *s* over *X* and a set of variables $Y \subseteq X$, let *s* [*Y*] denote the valuation over *Y* obtained by restricting *s* to *Y*.

Definition 3 (Execution tree): *Given a set W(X, X^I, X^O, Init, T) of web services and a coordinator c(X_c, X_c^O, X_c^O, $Init_c$, T_c) where $X^I = X_c^O$ and $X^O = X_c^I$, we can define an execution tree, denoted by W||c, which represents the composition of W and c as follows:*

- *Each node in* $W \| c$ *is in* $S \times S_c$.
- *The root node is (s, s_c) such that Init(s) = true and $Init_c(s_c)$ = true.*
- *Each* node (*s*, s_c) *has a set of child nodes*, $\{(s', s_c') \mid T(s, \text{in}, s') = true, in = s_c[X^I], T_c(s_c, in_c, s_c') = true, in_c = s'[X^O]\}$.

In the above, intuitively, the web services *W*, by receiving the input *in* from the current state s_c of the coordinator, collectively proceed from *s* to the next state *s*', and then the coordinator, by receiving the input in_c from the new state *s'* of the web services, proceeds

from s_c to the next state s'. Even though the composition of W and c is defined as synchronous communication, we can easily extend this model for *asynchronous* communication using τ-transition (Pistore et al., 2005b). A `goal` $G \subseteq S$ is a set of states to reach, and specified as a predicate.

Definition 4 (Web service composition problem)*: Given a set W of web* services, a *coordinator c, and a goal G, we define* $W \parallel c \models G$ *if for every path* $(s^0, s_c^0)(s^1, s_c^1)\ldots$ *in the execution tree W||c, there exists i > 0 such that* $s^i \in G$; *namely, every path from the initial node* (s^0, s_c^0) *reaches a goal state eventually.* The *web service composition problem that we focus on in this paper is, given a set W of web services and a goal G, to construct a coordinator web service c such that* $W \parallel c \models G$.

Example 4: In Example 1, we wish to reserve both a flight ticket and a hotel room. This can be represented as $G = (\texttt{flightConfirm} = \textit{reserve}) \wedge (\texttt{hotelConfirm} =$ reserve). Now, given a set $W = \{w_{AR}, w_{hr}\}$ of web services and the goal G above, a WSC problem is to construct a coordinator web service *c* such that $W||c = G$.

To study the computational complexity (i.e. lower bound) for WSC, we define two WSC problems as follows:

- *WSC with full observation:* a special case of WSC problems where $W(X, X^I, X^O, Init, T)$ such that $X = X^O$; i.e. *W* contains no internal variable.
- *WSC with partial observation:* a general WSC problem where there is no restriction for X^O. That is, a coordinator can read only the output variables in X^O.

5 Lower bounds

In this section, we study the computational complexities (lower bounds) for the two decision problems which are defined in Section 4. Our proofs use reductions from an Alternating Turing Machine (ATM) (Papadimitriou, 1994), which show the space complexities for the problems. Finally, based on Theorem 1, we establish the time complexities. While our previous work (Nam et al., 2011) has presented the tight bounds (i.e. lower bounds and upper bounds) of more various problem settings, the paper focuses on presenting an efficient approximation-based algorithm based on the complexity result.

5.1 Definition

An ATM (Papadimitriou, 1994) is a tuple $A = (Q, \Sigma, q_0, \delta, l)$ where

- Q is a finite set of states, Σ is a finite tape alphabet, and $q_0 \in Q$ is *the* initial state.
- $\delta : Q \times \Sigma \rightarrow 2^{Q \times \Sigma \cup \{\#\} \times \{\mathcal{L}, \mathcal{N}, \mathcal{R},\}}$ is a transition *function* where $\{\mathcal{L}, \mathcal{N}, \mathcal{R}\}$ represents the R/W head movement (i.e. it moves left, stays, or right).
- $l : Q \rightarrow \{\forall, \exists, \textit{accept}\}$ *is a labelling function* for states.

A *configuration* of an ATM $A(Q, \Sigma, q_0, \delta, l)$ is a tuple (q, σ, σ') where $q \in Q$ is the current state, $\sigma \in \Sigma^*$ is the tape contents left of the R/W head with the rightmost symbol under the R/W head, and $\sigma' \in \Sigma^*$ is the tape contents strictly right of the R/W head. Given an *ATM A* with an input string σ, the initial configuration is (q_0, a, σ).

Given an *ATM A* and its input string σ, to see if *A* accepts σ (i.e. $\sigma \in L(A)$), we define *n-accepting* for configurations in its computation tree by a bottom-up manner:

- (q, σ, σ') *is* 0*-accepting if* $l(q)$ = *accept.*
- (q, σ, σ') such that $l(q) = \forall$ is *n-accepting* if all the successor nodes are *m*-accepting for some $m < n$ and $max(m) = n-1$.
- (q, σ, σ') such that $l(q) = \exists$ is *n-accepting* if at *least* one of its child nodes is *m*-accepting for some $m < n$ and $min(m) = n-1$.

Finally, *A* accepts σ if the initial configuration is *n*-accepting for some $n > 0$. For the detail of ATMs (see Papadimitriou, 1994).

5.2 Computational complexity

In this paper, we consider the following complexity classes (Papadimitriou, 1994). DTIME(*f*) is a time consumption complexity on deterministic Turing machines, and DSPACE(*f*) is a space consumption complexity on deterministic Turing machines. Similarly, we have ATIME(*f*) and ASPACE(*f*) as time and space consumption complexities on ATMs, respectively.

$$\mathrm{P} = \bigcup_{k \geq 0} \mathrm{DTIME}(n^k)$$

$$\mathrm{EXP} = \bigcup_{k \geq 0} \mathrm{DTIME}(2^{n^k})$$

$$\text{2-EXP} = \bigcup_{k \geq 0} \mathrm{DTIME}(2^{2^{n^k}})$$

$$\mathrm{APSPACE} = \bigcup_{k \geq 0} \mathrm{ASPACE}(n^k)$$

$$\mathrm{AEXPSPACE} = \bigcup_{k \geq 0} \mathrm{ASPACE}(2^{n^k})$$

Then, the class APSPACE (resp. AEXPSPACE) is the set of decision problems that can be solved by an ATM using a polynomial (resp. exponential) amount of memory, respectively. Chandra et al. (1981) have proved interesting connections between time complexities on deterministic Turing machines and space complexities on ATMs:

Theorem 1 (Chandra et al., 1981): *EXP = APSPACE, and 2-EXP = AEXPSPACE*.

5.3 WSC with full observation

Theorem 2: *The WSC problem with full observation is EXP-hard.*

The proof is to simulate an ATM with a polynomial tape length. That is, for any *ATM A* and an input string σ, we can construct a WSC problem in polynomial time such that *A* accepts σ if and only if there exists a coordinator to satisfy a goal. We prove it using the following lemmas.

Lemma 1: *Given an ATM* $A = (Q, \sum, q_0, \delta, l)$ *with polynomial space bound p(n) and an input string* $\sigma = a_1 \cdots a_n$ *(where n =* $|\sigma|$*), we can construct a WSC problem instance with W and a goal G.*

Proof 1: We can construct a set $W(X, X^I, X^O, Init, T)$ of web services and a goal G which have a polynomial size in the size of the description of A and a as follows. The set X of variables includes the following variables:

- state represents the current state of A; so, it has the domain, $\{q \mid q \in Q\}$.
- For $1 \le i \le p(n)$, each variable cl_i is the contents of the i-th tape cell; its domain is $\Sigma \cup \{\#\}$.
- *hd* describes the R/W head position; its domain is $\{1, \ldots, p(n)+1\}$.
- *label* represents the label of the current state; it has the domain, $\{\forall, \exists,$ accept$\}$.

The set of input variables is $X^I = \{input\}$ where the domain of input is $\{A_{(q,i,a)} \mid q \in Q, l(q) = \forall, 0 \le i \le p(n), a \in \Sigma\} \cup \{E_{(q,i,a,j)} \mid q \in Q, \quad l(q) = \exists, 0 \le i \le p(n), a \in \Sigma, 0 \le j \le |\delta(a, q)|\}$. The set X^O of output variables equals to X since this problem is based on the full observation. As the initial configuration of A, the initial state predicate *Init(X)* is $(state = q_0) \wedge \wedge_{1 \le i \le n}(cl_i = a_i) \wedge \wedge_{n < i \le p(n)}(cl_i = \#) \wedge \quad (hd = 1) \wedge (label = l(q_0))$. Note that the input string is $\sigma = a_1 \ldots a_n$. The transition predicate $T(X, X^I, X')$ *is* $\big((hd = p(n)+1) \rightarrow T_V\big) \wedge ((label = \forall) \rightarrow T_\forall) \wedge \quad ((label = \exists) \quad \rightarrow T_\exists)$ with the following sub-formulae

- $T_V \equiv (state' = state) \wedge (hd' = hd) \wedge (label' = label)$
- $T_\forall \equiv \wedge_{q \in Q, 1 \le p(n), a \in \Sigma}(((state = q) \wedge (hd = i) \wedge (cl_i = a) \wedge (input = A_{(q,i,a)}))$
  $\rightarrow \vee_{1 \le j \le k}((state' = q_j) \wedge (cl_i' = a_j) \wedge \wedge_{m \ne i}(cl_m' = cl_m) \wedge (hd' = hd + \Delta) \wedge$
  $(label' = l(q_j))))$
- $T_\exists = \wedge_{q \in Q, 1 \le i \le p(n), a \in \Sigma, 1 \le j \le k}(((state = q) \wedge ((hd = i) \wedge (cl_i = a)) \wedge$
  $(input = E_{(q,i,a,j)})) \rightarrow ((state' = q_j) \wedge ((cl_i' = a_j) \wedge \wedge_{m \ne i}\big(cl_m' = cl_m\big) \wedge$
  $\big(hd' = hd + \Delta\big) \wedge (label' = (l(q_j))))$

where (q_j, a_j, m_j) is obtained from $\delta(q, a) = \{(q_1, a_1, m_1), \ldots, (q_k, a_k, m_k)\}$, and $\Delta = -1$ if $m_j = L$, $\Delta = 0$ if $m_j = N$ and $\Delta = 1$ if $m_j = R$. Note that the value for the variable input is provided by a coordinator c. Finally, we have a goal, $G = \{s \in S | s\ (label) = accept\}$.

If the *ATM A* violates the space bound, the variable *hd* has the value $p(n)+1$, and after this point we cannot reach goal states since W stays the same state and the same head position forever by T_v.

Lemma 2: *If* $\sigma \in L(A)$*, then there exists a coordinator* $c = (X_c, X_c^I, X_c^O, Init_c, T_c)$ such that $W \parallel c \models G$.

Proof 2: As per Section 5.1, $\sigma \in L(A)$ means that the initial configuration of A with respect to σ is m-accepting $(m \geq 0)$. Now, we show that there exists a coordinator c such that for every path $(s^0, s_c^0)(s^1, s_c^1)\cdots$ in the execution tree W||c, there exists $s^i \in G$. The coordinator to be constructed is $c = (X_c, X_c^I, X_c^O, Init_c, T_c)$ where X_c = {*input*}, $X_c^I = X$, and $X_c^O = \{input\}$. We will provide $Init_c$ and T_c in the later of this proof.

When A accepts σ, we can define an accepting computation tree $ACT_{(A,\sigma)}$ of A with respect to a from its computation tree Υ as follows:

- For each configuration $cf \mid = (q, \sigma_1, \sigma_2) \in \Upsilon$ such that $l(q) = \forall$, all the successor configurations are also included in $ACT_{(A,\sigma)}$. Note that if cf is m-accepting, each successor is at most (m–1)-accepting.
- For each $cf = (q, \sigma_1, \sigma_2) \in \Upsilon$ such that $l(q) = \exists$ and cf is m-accepting, only one successor configuration cf' which is (m–1)-accepting is included in $ACT_{(A,\sigma)}$.

When A and σ are clear from the context, we drop the subscript *(A, σ)* and write *ACT*. Let $\sigma[i]$ be the i-th symbol of the string σ. Then, $ACT_{(A,\sigma)}$ is mapped into an execution tree $W \| c$. For this mapping, we have two mapping functions, α and β; α maps a configuration cf in *ACT* to a state s of web services W, and β maps cf to a state s_c of the coordinator c. First, for each $cf = (q, \sigma_1, \sigma_2)$, we have a corresponding state $s = \alpha(cf)$ of W such that

- $s(state) = q$.
- For $1 \leq i \leq |\sigma|$, $s(cl_i) = \sigma[i]$ *where* $\sigma = \sigma_1\sigma_2$, *and for* $|\sigma| < i \leq p(n), s(cl_i) = \#$.
- $s(hd) = |\sigma_1|$.
- $s(label) = l(q)$.

Next, for each configuration $cf = (q,\sigma_1,\sigma_2)$, we have a corresponding state $s_c = \beta(cf)$ of c such that

- If $l(q) = \forall$, then s_c (input) = $A(_{q,i,a})$ where $i = |\sigma_1|$ and $a = \sigma_l[i]$.
- In the case of $l(q) = \exists$, let cf' be the only successor of cf in *ACT*, which is obtained by a transition (q_j,a_j,m_j) among $\delta(q,a) = \{(q_1,a_1,m_1), \ldots, (q_k,a_k,m_k)\}$ where $a = \sigma_1[|\sigma_1|]$. Now, if $l(q) = \exists$, $s_c(input) = E_{(q,i,a,j)}$ *where* $i = |\sigma_1|$ and $a = \sigma_1[i]$.

According to α and β, we have an execution tree of W||c where each node *is* $(\alpha(cf),\beta(cf))$. Now, by induction, we can show that if cf in ACT is m-accepting, every path from the corresponding node $(\alpha(cf),\beta(cf))$ in W||c reaches a goal state eventually. That is, if $\sigma \in L(A)$, there exists a coordinator $c = (X_c, X_c^I, X_c^O, Init_c, T_c)$ such that $W||c = G$. For the detail of the induction, see (Kil et al., 2008).

Lemma 3: *If there exists a coordinator c such that W|| c/= G, then* $\sigma \in L(A)$.

Proof 3: As per Section 4, the fact that there exists a coordinator c such that $W||c| = G$ means that every path $(s^0, s_c^0)(s^1, s_c^1,)\ldots$ from the initial node in the execution tree $W||c$ reaches a goal state eventually. Now, we show that an ACT for A corresponding to $W||c$ can be constructed and the initial configuration is m-accepting.

We denote as *ST*, a finite subtree of *W||c* which includes, for every path $(s^0, s_c^0)(s^1, s_c^1,)\ldots$ of W||c, its prefix ending at a goal state (i.e. $(s^0, s_c^0)\ldots \quad (s^k, s_c^k,)$ such that $s^k \in G$). In what follows, we construct an ACT for the ATM *A* from the subtree *ST*. For the mapping, we have a mapping function γ which maps a state *s* of web services *W* to a configuration *cf* of *A*. For each state *s* such that $s(state) = q$, $s(cl_i) = b_i$ where $1 \le i \le p(n)$, $s(hd) = i$ and $s(label) = l(q)$, we have a corresponding configuration $cf = \gamma(s) = (q, \sigma_1, \sigma_2)$ such that $\sigma_1 = b_1 \ldots b_i$ and $\sigma_2 = b_{i+1} \ldots b_{k-1}$ where *k* is the index of the first appearance of #.

Now, by induction, we can show that if among every path from a node (s, s_c) to a goal in *ST*, the length of the longest one is *m*, the corresponding configuration $\gamma(s)$ is *m*-accepting. That is, if there exists a coordinator *c* such that $W||c\,| = G$, then $\sigma \in L(A)$.

5.4 WSC with partial observation

Theorem 3: *The WSC problem with partial observation is 2-EXP-hard.*

The proof is to simulate an ATM with exponential tape length. As Theorem 2, we prove it by the following lemmas.

Lemma 4: *Given an ATM* $A = (Q, \Sigma, q_0, \delta, l)$ *with exponential space bound* $e(n)$ *and an input string* $\sigma = a_1 \ldots a_n$ *(where* $n = |\sigma|$*), we can construct a WSC problem instance with W and a goal G.*

Proof 4: An important difference with full observation problem is that we are not allowed to have a variable for each tape cell since the number of tape cells is exponential and the reduction could not be polynomial. Instead of including an exponential number of variables cl_i, we have one variable *cl* and its index *idx*. The trick is to establish that if the index matches the current head position, *W* should simulate the ATM *A*, and to force the above to be satisfied universally for every index *idx*. Given an ATM *A* with σ, we construct a set $W(X, X^I, X^O, Init, T)$ of web services and a goal *G* as follows. The set *X* of variables includes the following variables:

- state; its domain is $\{q | q \in Q\}$.
- *idx*; its domain is $\{1, \ldots, e(n)\}$.
- *cl represents the contents of the cell of which index is idx; its domain is* $\Sigma \cup \{\#\}$.
- *hd*; its domain is $\{1, \ldots, e(n)+1\}$. For *idx* and *hd*, we need only $\lceil \log_2(e(n)+1)1 \rceil$ bits.
- *label*; it has a domain, $\{V, \exists, accept\}$.
- *lsb* represents the symbol written by the head in the last step; it has a domain, $\Sigma \cup \{\#\}$.

The set X^I is {input} where the domain of input is $\{A_{(q,a)} | q \in Q, l(q) = V, a \in \Sigma\} \cup \{E_{(q,a,j)} | q \in Q, l(q) = \exists, a \in \Sigma, 0 \le j \le |\delta(a, q)|\}$. The set X^O is {state, *cl*}. *Init(X)* is $(state = q_0) \wedge ((idx \le |\sigma|) \Leftrightarrow (cl = a_{idx}) \wedge ((idx > \sigma) \quad \Leftrightarrow (cl = \#)) \wedge \Leftrightarrow (hd = 1) \wedge (label$

$= l(q_0))$. The initial predicate allows any value for *idx*, and the value for *cl* is determined, on *idx*. The transition predicate *T(X, X', X') is* $((hd = e(n)+1) \rightarrow T_V) \wedge ((label = \forall) \rightarrow T_\forall) \wedge (label = \exists) \rightarrow T_\exists)$ with the following sub-formulae

- $T_V = (state' = state) \wedge (hd' = hd) \wedge (label' = label)$
- $T_\forall \equiv \wedge_{q \in Q, a \in \Sigma}(((state = q) \wedge (hd = idx) \rightarrow (cl = a) \wedge (input = A_{(q,a)}))$
  $\rightarrow \vee_{1 \le j \le k}((hd = idx) \rightarrow ((state' = q_j) \wedge (cl' = a_j) \wedge (hd' = hd + \Delta) \wedge$
  $(label' = l(q_j) \wedge (isb' = a_j))))$
- $T_\exists = \wedge_{q \in Q, a \in \Sigma, 1 \le j \le k}(((state = q) \wedge ((hd = idx) \rightarrow (cl = a)) \wedge input = E_{(q,i,a,j)})))$
  $\rightarrow (((hd = idx) \rightarrow ((state' = q_j) \wedge ((cl' = a_j) \wedge (hd' = hd + \Delta)$
  $\wedge (label' = (l(q_j)) \wedge (isb' = a_j))))$

where (q_j, a_j, m_j) is obtained from $\delta(q, a) = \{(q_1, a_1, m_1), \ldots, (q_k, a_k, m_k)\}$ and $\Delta = -1$ if $m_j = L$, $\Delta = 0$ if $mj = N$ and $\Delta = 1$ if $mj = R$. Finally, we have a goal, $G = \{s \in S | s(label) = accept\}$.

If the *ATM A* violates the space bound, the variable *hd* has the value $e(n) + 1$, and after this point we cannot reach goal states since *W* stays the same state and the same head position forever by T_v.

Lemma 5: *If* $a \in L(A)$, *then there exists a coordinator c such that* $W \| c = G$.

Proof 5: Given A such that $\sigma \in L(A)$, we can construct a coordinator $c = (X_c, X_c^I, X_c^O,$ $\text{Init}_c, \text{T}_c)$ where $X_c = \{\text{input}\}$, $X_c^I = \{state, lsb\}$, and $X_c^O = \{\text{input}\}$. As the proof of Lemma 2, we can define T_c with a conjunction of two cases: $\forall$-state and $\exists$-state. That is, if $l(q) = \forall$, the transition predicate is $\wedge_{q \in Q, a \in \Sigma}(((state = q) \wedge (cl = a) \rightarrow (input' = A_{(q,a)}))$. Otherwise, $\wedge_{q \in Q, a \in \Sigma}(((state = q) \wedge (cl = a) \rightarrow (input' = E_{(q,a,j)}))$ where *j* is the index of the transition by which the ATM proceeds from the corresponding $\exists$-configuration to the next in $\text{ACT}_{(a,\sigma)}$. Similarly with T_c, *we* can define the initial predicate $Init_c$ as $((l(q_0) = \forall) \rightarrow (input = A_{(q_0,a_1)}) \wedge (l(q_0) = \exists) \rightarrow (input = E_{(q_0,a_1,j)}$ where a_1 is the first symbol of the input string σ and *j* is obtained as the above.

Now, we show that $ACT_{(a,\sigma)}$ is mapped into an execution tree $W \| c$. For this mapping, we have two mapping functions, α and β; α maps a configuration *cf* in ACT to a state s of web services *W*, and β maps *cf* to a state s_c of the coordinator *c*. First, given a configuration $cf = (q, a_1, a_2)$ and a tape index $1 < i < e(n)$, we have a corresponding state $s = a(cf, i)$ of *W* such that

- $s\ (state) = q$.
- $s(cl) = a[i]$ *if* $i < \sigma$ *where* $\sigma = \sigma_1\sigma_2$; *otherwise,* $s(cl) = \#$.
- $s(idx) = i$.
- $s(hd) = |\sigma_l|$.
- $s(label) = l(q)$.

The mapping function β is the same with β in Lemma 2. Now, we claim that if *cf* in ACT is *m*-accepting, then for every $1 < i < e(n)$ every path from the corresponding node $(\alpha(cf,i),\beta(cf))$ reaches a goal state eventually. By using the property that *T* and T_c strictly follow the transition function δ of *A*, we can prove the claim by induction.

Finally, since the initial configuration of ACT is *m*-accepting, every path from the initial node of $W||c$ reaches a goal state; that is, $W||c = G$.

Lemma 6: If there exists a coordinator c such that $W||c = G$, *then* $\sigma \in L(A)$.

Proof 6: For the finite subtree *ST* of $W||c$, we construct $ACT_{(a,\sigma)}$. However, unlike Lemma 3, we are not able to construct a configuration directly from a state of *W* since *W* does not have all the tape contents, but only *cl* and *lsb*. Now, our trick is to construct the computation tree by a top-down manner. Even though the initial state of W has only *cl* and *lsb*, we can construct the initial configuration as $cf = (q_0,a,\sigma')$ where the input string $\sigma = a\sigma'$. Given a predecessor configuration $cf = (q_1,\sigma_1,\sigma_1')$ and a state s of *W* such that $s(state) = q$, $s(cl) = a_1$, $s(idx) = i$, $s(hd) = h$, $s(label) = l(q)$, and $s(lsb) = a_2$, our mapping function γ maps s to a configuration $cf_2 = (q,\sigma_2,\sigma_2')$ where $/\sigma_2/ = h$ and for σ_2 and σ_2', $\sigma_2\sigma_2'$ is copied from $\sigma_1\sigma_1'$ except $(\sigma_2\sigma_2')[|\sigma_1|] = a_2$.

Now, we claim that if among every path from a node (s, s_c) to a goal in *ST*, the length of the longest one is *m*, the corresponding configuration $\gamma(s)$ is *m*-accepting. By using the property that our *T* and T_c strictly follow the transition function δ of *A*, we can prove the claim by induction.

Finally, since the initial node (s, s_c) of *ST* has *m* (for some $m \geq 0$) as the length of the longest path to a goal, the corresponding configuration $\gamma(s)$, namely the initial configuration of *A*, is *m*-accepting.

6 Basic algorithm for WSC problem

In this section, we study a basic algorithm for the general WSC problem defined in Section 4. Several researches (Traverso and Pistore, 2004; Pistore et al., 2005b) have successfully applied a planning technique with partial observation (Bertoli et al., 2006) to WSC problems. Thus, we also employ the same method for our baseline algorithm; Algorithm 1 for the WSC problem is based on the automated planning algorithm on partial observation (Bertoli et al., 2006). In a general case of WSC, a coordinator web service is not able to identify the exact state of target web services due to partial observation. Hence, we model this uncertainty by using a *belief state,* which is a set of *possible* states of target web services but *indistinguishable.* For example, given two Boolean variables, *x* and *y,* we assume that *y* is not observed by a coordinator. In this case, although four states may actually exist, the coordinator can distinguish only two states based on *x*, which are called 'belief states'. The underlying idea of Algorithm 1 is to construct an *and-or searching tree* from initial belief states to goal belief states. That is, from any node (a belief state) of the tree, for non-determinism of output values of web services, we extend the tree with a set of child nodes via *and-edges.* In this case, all the child nodes should reach a goal belief state. For the coordinator selecting input values, we construct a set of child nodes via *or-edges.* In this case, at least one child is required to reach a goal belief state.

Algorithm 1 WSC with partial observation

Input: A set *W* of web services and a goal *G*.

Output: A coordinate web service *c*.

```
1  tree:= InitialiseSearchingTree(Init);
2  tree .root .result:= undecided;
3  if (States(Init) ⊆ States(G)) then
4    tree.root.result:= true;
5  end if
6  while (tree.root.result = undecided) do
7     node:= SelectNode(tree);
8     childNodes := ExtendTreeitree, node);
9     if (CheckSuccess(childNodes)) then
10      node .result:= true;
11    end if
12    else if (CheckFailure(childNodes)) then
13      node.result:= false;
14    end if
15    PropagateResult(tree, node);
16  end while
17  if (tree.root.result = true) then
18     return ConstructCoordinator(tree);
19  end if
20  else return null;
```

To initialise the *and-or* searching tree, Algorithm 1 first constructs a root node (a belief state) corresponding to the given initial predicate, *Init,* and assigns '*undecided'* to the result value for the root (lines 1–2). If the states corresponding to *Init* are already included in goal states, we assign *'true'* to the result value for the root (lines 3–5). Next (lines 6–16), until determining the result value for the root, we repeat: (a) select a node which is not determined yet as *'true'* or *'false'* (line 7), (b) extend[2] the tree from the selected node by computing a set of possible successor nodes (line 8), and (c) check if the node can reach a goal state based on the and-or constraint (lines 9–14). Once we identify the result of each node, we propagate the result to its ancestor node (line 15). Finally, if the algorithm identifies the result of root node as *true,* it constructs a coordinator web service from the tree, and returns the coordinator (lines 17–19). Otherwise, it returns *null* (line 20). The complexity of the algorithm is $O\left(2^{2^n}\right)$ where *n* is the number of variables in *W,* since the number of states of *W* is 2^n and thus the number of belief states is 2^{2^n} (recall Theorem 3).

7 Signature-preserving abstraction and refinement

Theorems 2 and 3 imply that the WSC problem is computationally hard. Hence, more efforts to devise efficient approximation solutions to the WSC problem are needed. In addition, the complexity of Algorithm 1 also provides the same implication. Therefore, we propose two approximation-based methods using abstraction and refinement in Sections 7 and 8.

7.1 Signature-preserving abstraction

Given a set *W* of web services, we define *signature-preserving abstract web services* that have the same signature (i.e. the same I/O variables) but fewer variables than *W*.

Definition 5 (Signature-preserving abstract web services): *Given a set of web services* $W(X, X^I, X^O, Init, T)$ *and a set Y of variables such that* $X^{IO} \subseteq Y \subseteq X^A$, *the signature-preserving abstraction of W with respect to Y is* $W_Y = \left(X_Y, X_Y^I, X_Y^O, Init_Y, T_Y\right)$ *where:*

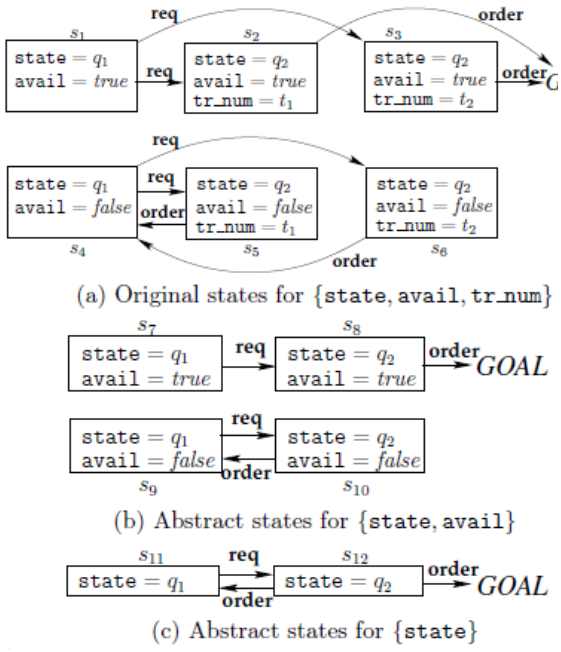
- $X_y = Y / X^1$, $X_Y^I = X^1$, and $= X_Y^O = X^O$.
- *For every* $s_Y \subseteq S_y$, $Init_Y(s_Y) =$ *true iff* $\exists s \in S$. (*Init*(*s*) = *true*) Λ ($s_y = s[X_y]$).
- *For every* $s_Y, s'_Y \in S_Y$, $T_Y\left(s_Y, in, s'_Y\right) = true$ *iff* $\exists s, s' \in S$. ($T(s,\ in,\ s') =$ *true*) Λ $(s_Y = s[X_Y]) \Lambda \left(s'_Y = s'[X_Y]\right)$.

Since W_Y preserves the signature of *W,* once we construct a coordinator *c* which can be composed with W_Y based on Definition 3, *c* also can be composed with *W*. Moreover, since the abstraction W_Y over-approximates the concrete web services *W* (i.e. W_Y contains all the behaviours of *W), W_Y* satisfies the following property.

Theorem 4 (Soundness): *Given a set W of web services and a goal G, if a coordinator web service c satisfies* $W' \| c \| = G\ W' \|$ *where W′ is a signature-preserving abstraction of W (e.g.* W_Y *in Definition 5), then c also satisfies* $W \| c \| = G$.

Example 5 (Abstraction): Figure 3a illustrates the concrete state space with six states, where there are three internal variables – `state, avail, tr_num`. Symbols above arrows represent a value of an input variable. In this example, from the state s_1, we have a strategy to guarantee to reach GOAL – invoking *req* and *order*. Figure 3b shows an abstract state space with respect to {`state, avail`}. s_1 and s_4 in the original space are mapped to s_7 and s_9, respectively. Two states, s_2 and s_3 (s_5 and s_6) collapse into s_8 s_{10}, respectively. Although the number of states decreases, every path in the original state space is mapped to one of the paths in the abstract space. Moreover, from the state s_7 corresponding to s_1, we still have a strategy to guarantee to reach GOAL. Figure 3c shows a coarser abstraction. However, from the state s_{11} corresponding to s_1, we no longer have a strategy to guarantee to reach GOAL since we abstract out too much.

Figure 3 Abstraction



7.2 *Abstraction and refinement algorithm*

Algorithm 2 presents a high-level description of our method based on signature-preserving abstraction. In a nutshell, we abstract a given web services W into W' and try to find a solution for the abstraction W'. If we identify such a coordinator, it can indeed control the original web services W to satisfy a given goal. Otherwise, we repeat the search with more accurate abstraction.

First, we abstract W with only input and output variables, i.e. $Y = X^I \cup X^O$ (lines 1–2). We then try to construct a solution coordinator for the abstraction W_Y (line 3). If we find a coordinator c such that $W_Y \| c | = G$, then c also satisfies $W \| c | = G$ by Theorem 4. Otherwise, we refine our current abstraction W_Y by adding more variables, and try to find c for the new abstraction (lines 7–13). How to select additional variables will be elaborated in Section 7.3. We repeat the abstraction/refinement step until we identify a coordinator c satisfying $W_Y \| c | = G$ or the variable set used for abstraction equals to the original variable set. The latter case implies that no solution exists for the given problem. For the procedure *WSCPartialObs* we use in this algorithm, we can employ the algorithm for WSC with partial observation in Algorithm 1, of which the complexity is $O\left(2^{2^n}\right)$. Once we identify a solution by using abstract web services which have fewer variables than the given web services, searching space required is shrunken (double-)exponentially in the number of variables that we save.

Algorithm 2 Signature-preserving Abs/Ref WSC

Input: A set W of web services and a goal G.

Output: A coordinate web service c.

1 $Y := \mathrm{X}^I \cup X^O$;
2 $W_Y := Abstraction(W, Y)$
3 **if** ((c:= $WSCPartialObs(W_Y, G)) \neq null$) **then**
4 **return** c;
5 **end if**
6 *ConstructDependencyGraph* (W, G);
7 **while** (($newVars$:= $SelectNewVars(W, G)) \neq null$) **do**
8 $Y := Y \cup newVars$;
9 W_Y:= $Abstraction(W, Y)$;
10 **if** ((c:= $WSCPartialObs(W_Y, G)) \neq null$) **then**
11 **return** c;
12 **end if**
13 **end while**
14 **return** *null;*

7.3 Automatic refinement

Failure to identify a coordinator for abstract web services (line 3 or 9 in Algorithm 2) is caused either by too coarse abstraction or by the fact that a coordinator for the original web services does not exist. For the latter case, since we check it with the original web services in the worst case, Algorithm 2 will correctly conclude that there is no solution.

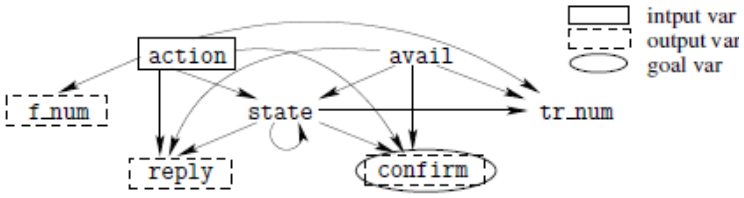
Theorem 5 (Completeness): *Given a set of web services W and a goal G, if there does not exist a coordinator c to satisfy* $W \,||\, c \models G$*, Algorithm 2 eventually returns null.*

However, in the former case, although there exist a coordinator for the original web services W, *WSCFullObs* or *WSCPartialObs* returns *null* for the abstraction W_Y. The reason is that removing too many variables, including ones with significant information to reach a goal, gives too much freedom to the abstraction. It induces some infeasible paths to states not satisfying the goal. For instance, in Figure 3c, since we remove the variable avail, s_1 (s_2 and s_3) is indistinguishable from s_4 (s_5 and s_9, respectively). Thus, an infeasible edge from s_{12} to s_{11} by *order* is introduced, by which we no longer have a strategy to guarantee to reach a goal. Therefore, we have to refine the current abstraction to find a solution by adding more variables. Since the infeasible paths to states not satisfying the goal prevent us from identifying a solution coordinator, it is important to accurately keep track of the values of variables appearing in the given goal predicate. Given this, the most significant criterion for selecting variables to be added is the relevance to variables in the goal predicate. To evaluate each variable's relevance to the goal variables, we construct a variable dependency graph.

Definition 6 (Variable dependency graph): *Given a set of web services W and a goal G, a variable dependency graph is a directed graph G*(V, E) *where a set V of vertexes is* $\{x | x \in X \cup X^I\}$ *and a set E of directed edges is* $\{(x \rhd y) | x, y \in V$*, the value of y depends on the value of x*$\}$.

For instance, the pseudo-codes 'y:= x' and 'if (x = *true*) then y:=0' imply that the value of y depends on x. Figure 4 illustrates a fraction of the variable dependency graph for W and G in Example 4. It shows only variables of w_{AR}. For example, since the values of `state, reply` and `tr_num` depend on the values of `state, action` and `avail` (see the first part of T in Example 2), we have corresponding directed edges (`state ▷ state`), (`action ▷ state`), (`avail ▷ state`), … , and (`action ▷ tr_num`) in Figure 4. In the dependency graph, it is clear that variables with stronger dependency to the variables in the goal predicate have a shorter hop to the goal variables. Thus, in each iteration of Algorithm 2, the procedure *SelectNewVars* returns a set of variables that have the closest hop to the variables in the goal predicate (i.e. 1-hop, 2-hop, and so on). For instance, since `confirm` is a variable in the goal predicate, the set of variables that have 1-hop dependency is {`action, avail, state`}.

Figure 4 Variable dependency graph



8 Signature-subsuming abstraction

In Section 7, we restricted the target of abstraction to internal variables, namely abstract web services have the same I/O variables as the original ones. However, in many cases, we have observed that some of output variables do not provide any important information for a coordinator to decide its move. For instance, the airline reservation web service in Example 2 simply copies the request value (i.e. req_1 and req_2) to the flight number (i.e. f_1 and f_2), and returns it to clients for reference. In this case, even without this output, the coordinator can successfully control the given web services to satisfy the goal. In this section, we consider, as the target of abstraction, output variables as well as internal variables.

First, we define *signature-subsuming abstract web services* for given web services, which have the same input variables, but less internal variables and output variables.

Definition 7 (Signature-subsuming abstract web services): *Given a set of web services* $W(X, X^I, X^O, Init, T)$, *and a set* Y *of variables such that* $X^I \subseteq Y \subseteq X^A$, *the signature-subsuming abstraction of* W *with respect to* Y *is* W_Y $(X_Y, X_O^I, X_Y^O, Init, T_Y)$ *where* $X_Y = Y \setminus X^I$, $X_Y^I = X^I$, $X_Y^O = Y \cap X^O$ *and* $Init_Y$ *and* T_Y *are defined as the same as Definition 5.*

Since signature-subsuming abstract web services W_Y have less output variables than the original web services W, any coordinator c which can be composed with W_Y is also able to be composed with W by ignoring redundant output variables of W (i.e. ignoring $X^O \setminus X_Y^O$). Moreover, since W_Y contains all the behaviours of W, Theorem 4 is still valid.

For selecting output variables to be used in abstraction, we again employ the variable dependency graph in Section 7.3. In general, output variables which depend on internal variables that in turn depend on variables in a goal predicate tend to provide important information on the state of web services for the coordinator to control the web services. For instance, in Figure 4, `reply` has a dependency on `state` and `avail` that have a dependency on the goal variable `confirm`, and `reply` is an important output by which a coordinator infers whether a flight seat is available. On the other hand, `f_num` that represents a flight number has dependency only on an input variable, action, and it does not provide any information to help a coordinator. Therefore, we find such a set $X^{SO} \subseteq X^{O}$ of *significant output variables* which have a dependency on internal variables with a dependency on variables in a goal predicate, and then use X^{SO} for the initial abstraction. That is, in signature-subsuming abstraction, we start $Y := X^{I} \cup X^{SO}$ as line 1 in Algorithm 2. The rest of output variables (i.e. $X^{O} \backslash X^{SO}$) are used in the last iteration.

9 Empirical validation

We have implemented automatic tools for signature-preserving/signature-subsuming abstraction and refinement, using a state-of-the-art planning tool, MBP (Bertoli et al., 2006). Given a set of web service descriptions in WS-BPEL files, and a goal predicate, our tools automatically construct a coordinator web service which can control the given web services to achieve the goal. To demonstrate that our tools efficiently synthesise coordinators, we compared the basic algorithm (Traverso and Pistore, 2004) and our methods with three sets of realistic examples (8 instances); Travel Agency System (TAS), Producer and Shipper (P&S), and Virtual Online Shop (VOS). Since there are no public benchmark test sets, we have selected web service examples popularly used in *WSC* research. TAS was explained in Example 1. We have three instances, TAS-a, TAS-b and TAS-c, where we have 4, 9 and 16 options, respectively, for input values for flight reservation and hotel reservation each. Producer and Shipper (P&S) (Traverso and Pistore, 2004; Pistore et al., 2005b) includes two web services, Producer and Shipper. Producer produces furniture items, and Shipper delivers an item from an origin to a destination. We have three instances, P&S-a, P&S-b and P&S-c where there are 4, 6 and 8 options, respectively, for furniture order and delivery order each. The VOS example (Barbon et al., 2006) includes Store and Bank web services where Store sells items and Bank transfers money from one account to another account. This example includes two instances, VOS-a and VOS-b where there are 3 and 4 options, respectively, for item orders and money transfer each.

All experiments were performed on a PC using a 2.4 Hz Pentium processor, 2 B memory and a Linux operating system. Table 1 presents the number of total Boolean variables (T var) and input/output variables (I/O var). It also shows the total execution time in seconds for the basic algorithm (Basic) and our methods, i.e. Signature-preserving (Sig-pres) and Signature-subsuming (Sig-subs), and the number of Boolean variables that we saved (Sv var). In the signature-subsuming case, the table presents the number of internal variables/IO variables which we saved. Our experiment shows that our technique outperforms the basic algorithm in terms of execution time. The numbers of iterations in our experiments were around 2–3 since variable dependency graphs were

relatively shallow. In WSC literature, in general, behaviour descriptions in WS-BPEL or OWL-S tend *not* to be complex, which usually yields to shallow variable dependency graphs.

Table 1 Experiment result

Problem	*T var*	*I/O var*	*Basic*	*Sig-pres*	*Sv var*	*Sig-subs*	*Sv var*
TAS-a	38	9	5.8	2.9	6	**0.1**	6/4
TAS-b	42	8	61.4	55.3	2	**13.8**	2/1
TAS-c	69	10	>7200.0	>7200.0	6	**162.0**	6/2
P&S-a	44	9	50.4	49.8	11	**3.2**	11/2
P&S-b	55	10	320.0	364.6	19	**42.3**	19/3
P&S-c	63	10	>7200.0	>7200.0	20	**1214.0**	20/3
VOS-a	61	15	208.3	195.7	14	**18.2**	14/4
VOS-b	74	15	3323.0	2321.3	23	**520.8**	23/4

Although we have employed modest size of examples, our abstraction technique can be useful even for larger size examples since in general, the number of variables which have relevance with goal variables is limited. In such a case, our techniques can eliminate a number of irrelevant variables, improving the convergence speed considerably.

10 Discussion

In this section, we discuss our refinement process presented in Section 7.3, comparing it with the *counter-example guided abstraction refinement* (Clarke et al., 2003) in model checking literature.

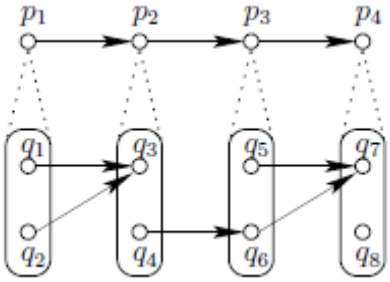
10.1 Refinement in model checking

Model checking is an automatic technique to verify that a system satisfies its specification, where the system is represented as a Kripke structure and the specification is described in a temporal logic, e.g. Linear Temporal Logic (LTL) (Pnueli, 1981) or Computational Tree Logic (CTL) (Emerson, 1990). Model checking has been successfully applied in hardware verification, and is emerging as an industrial standard tool for H/W design. However, one of the main challenges in model checking is the *state explosion problem* which can occur when a system includes many parallel components. A number of approaches have been studied to reduce the number of states in the model. Among them, *abstraction* (Clarke et al., 1994; Clarke et al., 2003) is considered as the most general and flexible method for handling the state explosion problem.

Clarke et al. (2003) proposed a fully automatic technique called *counter-example guided abstraction refinement*. This method starts with a relatively small abstraction of a system to be verified. If this abstraction satisfies a given safety property, we can conclude that the original system also satisfies the property since we use *over-approximation* in this technique. Otherwise, the technique provides a counter-example showing that the abstract model violates the given property. In this case, however, with this counter-example we cannot conclude whether the original system violates the property or not. Therefore, we check if the counter-example is feasible also in the

original system. If so, we can declare that the original system violates the given property. Otherwise, the counter-example path is spurious in the original system, and this path is exploited for refinement step. Figure 5 illustrates a spurious counter-example. Let us assume that we are given a counter-example path $p_1p_2p_3p_4$ for an abstract system, and each state p_1,p_2,p_3, and p_4 corresponds to a set of states of the original system $\{q_1, q_2\}$, $\{q_3, q_4\}$, $\{q_5, q_6\}$, and $\{q_7, q_8\}$, respectively. By traversing the original system, it is easy to see if the counter-example path is spurious. The reason why this infeasible path is introduced is that q_3 and q_4 are mapped into the same abstract state p_2. That is, the concrete state q_3 is reachable from the initial state, but it does not have any outgoing transition to the next state in the counter-example. On the other hand, q_4 is not reachable but it has an outgoing transition which causes the spurious counter-example. Therefore, in the refinement step in model checking, we automatically identify a new abstraction so that these two states do not correspond to the same abstract state. Finally, we repeat the model checking step with the new abstraction.

Figure 5 Spurious counter-example in model checking



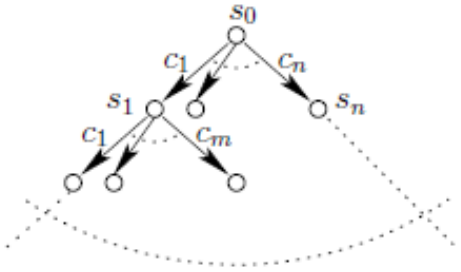
10.2 Refinement in behavioural description based WSC

The behavioural description based WSC presented in the paper has a similar high-level structure. We start with a small abstraction of a given set of web services. If we can identify a coordinator web service that controls the *abstract* web services to reach a given goal state, our algorithm returns the coordinator web service. This coordinator is able to control the *original* web services since we use *over-approximation* (Theorem 4). Otherwise, our tool provides a counter-example which demonstrates that there is no coordinator to control the abstract web services. In this case, as counter-example guided abstraction refinement in model checking, we have to check whether there is indeed no coordinator to control the original web services *or* the counter-example is spurious.

However, the main difference between 'counter-example guided abstraction refinement in model checking' and 'behavioural description based WSC' is the counter-example structure. Since the purpose of the former is to check a safety property of the system, a counter-example is a *path* from the initial state to a state which violates the safety property (see Figure 5). On the other hand, since the purpose of the latter is to construct a coordinator which can control a given set of web services, a counter-example is a *tree* to ensure that for every choice of the coordinator, we cannot enforce the given web services to eventually reach a goal state. Figure 6, for instance, illustrates a counter-example tree for behavioural description based WSC problem. Each node in the counter-

example tree corresponds to a state of a given web services. For each node, we have a set of choices of the coordinator, e.g. $c_1 \ldots c_n$ at the state s_0 in Figure 6. The counter-example tree demonstrates that for any choice there is no path to eventually reach a goal state.

Figure 6 Counter-example for behavioural description based WSC



Now, in order to check whether there is indeed no coordinator to control the original web services *or* the counter-example tree is spurious due to the over-approximation, we have to traverse the abstract web services with the given counter-example tree. The main obstacle for this test is that, in general, the counter-example tree is much larger than the counter-example path in model checking. That is, the number of nodes in the tree is, in the worst case, 2^{2^n} where n is the number of total Boolean variables in a given set of web services since a coordinator has to control them with *partial observation.* Hence, in our technique, we avoid the feasibility checking and add variables with strong dependency on goal variables to the next abstraction. We then try to identify a coordinator for the new abstraction.

11 Conclusion

In this paper, we proposed approximation-based techniques to automatically construct a coordinate web service that controls a given set of web services to reach a goal state, which is a computationally hard problem (i.e. 2-EXP-hard in general). The proposed solutions first reduce the given web services into abstract web services with fewer variables using over-approximation. We then try to find a coordinate web service for the abstract web services. If this trial succeeds, the found coordinator can also control the original web services since we apply over-approximation. Otherwise, we add important variables for the next abstraction. Our experimental results show promising results, validating the effectiveness of our proposals.

Several directions lie ahead for future work. First, we plan to study other abstraction methods and refinement techniques for the early convergence of the conclusion. Second, we will extend our technique for the WSC problem with more expressive goals (e.g. goals specified in temporal logics). Third, we want to study a tight bound for variables required to solve this problem. Finally, it is also an interesting issue to integrate ontological knowledge to constrain the behavioural description-based WSC problem.

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