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# On Abstraction-Based Deadlock-Analysis in Service-Oriented Systems with Recursion

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**Abstract.** We examine deadlock analysis for service-oriented systems with unbound concurrency and unbound recursion. In particular, abstraction-based approaches are considered, i.e., abstract behavior models are derived from service implementations and composed according to the architecture of service-oriented systems. It turns out that there are some limitations of Petri-net-based approaches, e.g., such as workflow nets if deadlocks are analyzed. We show an example that ends in a deadlock if recursion is considered but on a Petri-net-based abstraction, it may regularly end.

**Keywords:** Process Rewrite Systems; Deadlock; Workflow Nets.

## 1 Introduction

To reduce the risk of unintended behavior (e.g., deadlocks or livelocks [14]) of service-oriented systems due to composition, many approaches are proposed, e.g., protocol conformance checking [2], [10], [11] or deadlock analysis [13].

In this paper we focus on an abstraction-based approach for deadlock analysis of service-oriented systems including concurrency and recursion.

Approaches, e.g., van der Aalst's workflow nets [13] are Petri-net-based and used to analyze deadlocks. They do not consider recursion, recursive callbacks and synchronization. These approaches are refinement-based, i.e., the behavior of a service is modeled as a workflow net and then refined to the service implementation. Workflow nets are used to check for the absence of deadlocks. In contrast, we provide an abstraction-based approach, i.e., the behavior is automatically abstracted from the service's implementation using classical compiler technologies [1] covering all kinds of programming concepts (synchronous and asynchronous procedure calls, synchronization, cf. Tab. 1). Motivation for an abstraction-based approach is that there are many services not developed according to a refinement-based approach. Furthermore, even if they have been developed initially by a refinement-based approach, it is unlikely that programmers consistently maintain the implementation and its abstraction.

In [15] it was shown that abstraction from recursion may lead to false positives for protocol conformance checking. In this work, we examine the same question for deadlock analysis. We compare Petri-net-based abstractions with

abstractions including recursion. The behavior of recursive procedures and synchronous procedure calls corresponds to the LIFO principle and requires therefore a stack [8] to trace the calling context. Process rewrite systems (PRSs) are an extension of Petri nets by stacks [9] and therefore PRS allow to model the behavior of (recursive) procedure calls, concurrency (fork), synchronization and exception handling [6].

Furthermore, [6] shows that there is a correspondence between process algebraic expressions defined by an abstraction based on process-algebras and cactus stacks (introduced as tree of stacks by [4]). Therefore, we focus on PRSs which include pushdown systems as well as Petri nets. Checking reachability and deadlocks remains decidable in process rewrite systems [9].

Our main results are:

- Each trace of a process rewrite system based abstraction corresponds step by step to a trace of the corresponding Petri-net-based abstraction.
- A (reachable) deadlock in the process rewrite system based abstraction does not necessarily correspond to a deadlock in the corresponding Petri-net-based abstraction.

This paper is organized as follows: In Section 2 we introduce service-oriented systems, Mayr’s process rewrite systems according to [9] and we show the abstraction and composition process of a service-oriented system including unbound concurrency and unbound recursion. Section 3 discusses the correspondence between Petri net and process rewrite system abstractions. Furthermore, it shows that reachable deadlocks in the process rewrite system based abstraction do not correspond to deadlocks in the corresponding Petri-net-based abstraction. Section 4 discusses the related work and Section 5 concludes with a short overview of the results and gives an outlook.

## 2 Foundations

### 2.1 Services and Service-Oriented Systems

A service-oriented system is composed by two or more services which communicate over a required and provided interface, cf. Fig. 1. We assume that a service  $A$  is an implementation with a provided interfaces  $I_A$ , where an interface is a set of procedure signatures. The required interface  $R_s$  of service  $S$  is the set of procedures of other services called by  $S$ , cf. Fig. 1. It is possible that a service calls a procedure of other services, e.g., service  $S$  calls the required procedure  $a$  of service  $A$  provided by the provided interface  $I_A$ .

Procedures of an interface can be either called synchronously (procedure  $a$  of interface  $I_A$ ) or asynchronously (procedure  $b$  of interface  $I_B$ ). If a synchronous procedure is called, it blocks the caller until the callee has been completed. If an asynchronous procedure is called then the callee and the caller continue their execution in parallel. They are either synchronized by an explicit statement (**sync**, program point  $q_{a6}$  of service  $A$ ) on the caller site or when both, caller and callee reach their return statement, cf. Fig. 1  $r_a$  of service  $A$ .

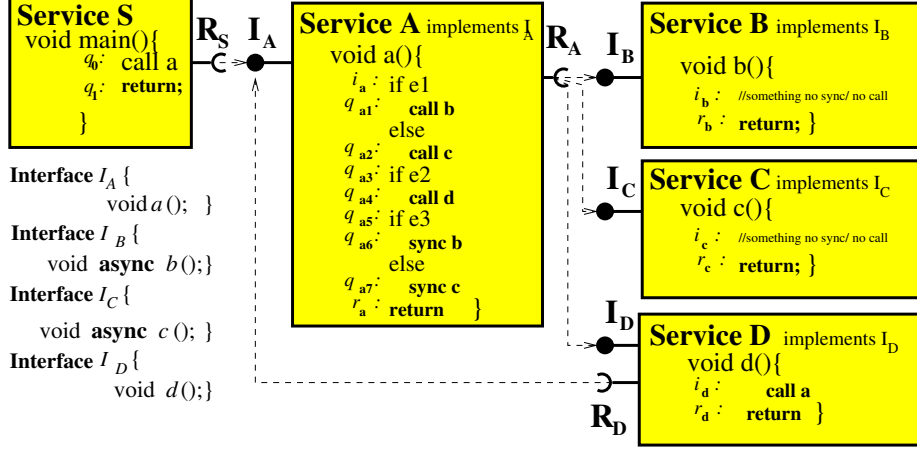


Fig. 1: A Service-Oriented System with Services  $S$ ,  $A$ ,  $B$ ,  $C$  and  $D$ . Service  $S$  acts as a client. Procedure  $b$ ,  $c$  are asynchronous and  $a$ ,  $d$  synchronous procedures.

$$\begin{array}{c}
\frac{e \rightarrow e'}{e \Rightarrow e'} \quad (\text{R}) \qquad \frac{e \Rightarrow e'}{e.s \Rightarrow e'.s} \quad (\text{S}) \qquad \frac{e \Rightarrow e' \quad e' \Rightarrow e''}{e \Rightarrow e''} \quad (\text{T}) \\
\frac{e \Rightarrow e'}{e \parallel s \Rightarrow e' \parallel s} \quad (\text{P1}) \qquad \frac{e \Rightarrow e'}{e \parallel s \Rightarrow e' \parallel s} \quad (\text{P2}) \qquad \frac{}{u \Rightarrow u} \quad (\text{L}) \\
e, e', e'', s \in \text{PEX}(Q)
\end{array}$$

Fig. 2: Inference Rules for the Definition of the Derivation Relation in a PRS

## 2.2 Process Rewrite Systems

Mayr presented a unified view of Petri nets and several simple process algebras by representing them as subclasses of the general rewriting formalism *Process Rewrite Systems* [9]. It is based on rewrite rules on process-algebraic expressions. The set  $\text{PEX}(Q)$  of process-algebraic expressions over a finite set  $Q$  (*atomic processes*) is the smallest set satisfying:

- (i)  $Q \subseteq \text{PEX}(Q)$ ,
- (ii) If  $e, e' \in \text{PEX}(Q)$ , then  $e.e' \in \text{PEX}(Q)$  and  $e \parallel e' \in \text{PEX}(Q)$  (*sequential and parallel composition*, respectively).

The parallel composition is associative and commutative. The sequential composition is associative but not commutative.

**Definition 1 (Process Rewrite Systems)** A process rewrite system (*short: PRS*) is a tuple  $\Pi \triangleq (Q, q_0, \rightarrow, F)$  where

- (i)  $Q$  is a finite set (*atomic processes*),
- (ii)  $q_0 \in Q$  (*the initial state, an atomic process*),
- (iii)  $\rightarrow \subseteq \text{PEX}(Q) \times \text{PEX}(Q)$  is a set of process-rewrite rules,
- (iv)  $F \subseteq Q$  (*the set of final processes*).

The PRS  $\Pi$  defines a derivation relation  $\Rightarrow \subseteq \text{PEX}(Q) \times \text{PEX}(Q)$  by the inference rules in Fig. 2.

Control Structure	Abstraction	Control Structure	Abstraction
$q_i : \text{assignment};$ $q_j : \dots$	<b>(G,G)</b> $q_i \rightarrow q_j$ <b>(P,P)</b> $q_i \rightarrow q_j$	Synchronization $q_i : \text{sync } b;$ $q_{i+1} : \dots$ $b\{ \dots$ $q_j : \text{return}\}$	<b>(G,G)</b> $q_i \parallel q_j \rightarrow q_{i+1}$ <b>(P,P)</b> $q_i \parallel q_j \rightarrow q_{i+1}$
$q_i : \text{while } e\{$ $q_j : \dots\}$ $q_k : \dots$	<b>(G,G)</b> $q_i \rightarrow q_j$ $q_i \rightarrow q_k$ <b>(P,P)</b> $q_i \rightarrow q_j$ $q_i \rightarrow q_k$	Synchronous procedure $a$ $q_i : \text{call } a;$ $q_{i+1} : \dots$ $a\{q_j : \dots$ $q_k : \text{return}\}$	<b>(G,G)</b> $q_i \rightarrow q_j \cdot q_{i+1}$ $q_k \cdot q_{i+1} \rightarrow q_{i+1}$ <b>(P,P)</b> $q_i \rightarrow q_j$ $q_k \rightarrow q_{i+1}$
$q_i \text{ if } e\{$ $q_j \dots$ $q_k \text{ last}$ $\text{program point}\}$ $\text{else}\{$ $q_l \dots$ $q_m \text{ last}$ $\text{program point}\}$ $q_n \dots$	<b>(G,G)</b> $q_i \rightarrow q_j$ $q_i \rightarrow q_l$ $q_k \rightarrow q_n$ $q_m \rightarrow q_n$ <b>(P,P)</b> $q_i \rightarrow q_j$ $q_i \rightarrow q_l$ $q_k \rightarrow q_n$ $q_m \rightarrow q_n$	Asynchronous procedure $b$ $a\{ \dots$ $q_i \text{ call } b;$ $q_{i+1} \dots$ $q_j \text{ return}$ $\}$ $b\{ \dots$ $q_k : \dots$ $q_l : \text{return}\}$	<b>(G,G)</b> $q_i \rightarrow q_{i+1} \parallel q_k$ $q_j \parallel q_l \rightarrow q_j$ <b>(P,P)</b> $q_i \rightarrow q_{i+1} \parallel q_k$ $q_j \parallel q_l \rightarrow q_j$

Table 1: Control-Flow Abstractions to (G,G)-PRS and (P,P)-PRS

PRSs where no rule contains a sequential composition operator ((P,P)-PRS) are equivalent to Petri nets [9]. Hence, the following definition applies to general process rewrite systems ((G,G)-PRS) as well as to Petri nets.

**Definition 2** Let  $\Pi = (Q, q_0, \rightarrow, F)$  be a PRS. A process algebraic expression  $e \in \text{PEX}(Q)$  is reachable iff  $q_0 \Rightarrow e$ . A reachable  $e \in \text{PEX}(Q)$  is a deadlock iff there exists no  $e' \in \text{PEX}(Q) \setminus F$ ,  $e' \neq e$  such that  $e \Rightarrow e'$ .

### 2.3 Abstraction and Composition Process

Table 1 shows different control structures and their abstraction to (P,P)-PRS and (G,G)-PRS. The main principle is that each statement corresponds to a program point (which refers to a statement). The most important control structures are contained in Table 1, atomic statements, e.g., assignments, conditionals, synchronous and asynchronous procedure calls and synchronizations. Loops and case statements are abstracted similarly to conditionals. For service-oriented abstractions, the control-flow abstraction rules can be applied to every services. The main difference is that entry and exit points are needed for the first program point and the return statement of the procedure of a required interface of a service. These entry and exit points are identified upon composition with the corresponding services implementing the required interface. This combination yields to a PRS modeling an abstract behavior of the service-oriented system, cf. [2]. An analogous idea is used in [13] for combining workflow nets to Petri nets representing the behavior of the composed service-oriented system.

*Example 1 (A Service-Oriented System and its Abstractions).* The example in Fig. 1 was introduced in Subsection 2.1. Figure 3 shows the abstraction of the single services using the entry points  $i_a, i_b, i_c, i_d$  and the exit points  $r_a, r_b, r_c, r_d$  for the initial program points and the program points of the return statements of  $a, b, c, d$ , respectively. The final state of the PRS is  $q_1$ . Figure 3 shows the resulting abstractions for (G,G)-PRS and (P,P)-PRS, respectively.

Source Code of Fig. 1	(G,G)-PRS	(P,P)-PRS
$main\{ q_0 : \text{call } a$ $q_1 : \text{return}; \}$	$q_0 \rightarrow i_a.q_1$	$q_0 \rightarrow i_a$
$a\{ i_a : \text{if } e_1$ $q_{a1} : \text{call } b$ $\text{else}$ $q_{a2} : \text{call } c$ $q_{a3} : \text{if } e_2$ $q_{a4} : \text{call } d$ $q_{a5} : \text{if } e_3$ $q_{a6} : \text{sync } b$ $\text{else}$ $q_{a7} : \text{sync } c$ $r_a : \text{return}; \}$	$i_a \rightarrow q_{a1}, \quad i_a \rightarrow q_{a2}$ $q_{a1} \rightarrow q_{a3} \parallel i_b$ $r_a \parallel r_b \rightarrow r_a$ $q_{a2} \rightarrow q_{a3} \parallel i_c$ $r_a \parallel r_c \rightarrow r_a$ $q_{a3} \rightarrow q_{a4}, \quad q_{a3} \rightarrow q_{a5}$ $q_{a4} \rightarrow i_d.q_{a3}$ $r_d.q_{a5} \rightarrow q_{a7}$ $q_{a5} \rightarrow q_{a6}, \quad q_{a5} \rightarrow q_{a4}$ $q_{a6} \parallel r_b \rightarrow r_a$ $q_{a7} \parallel r_c \rightarrow r_a$ $r_a.q_1 \rightarrow q_1, \quad r_a.r_d \rightarrow r_d$	$i_a \rightarrow q_{a1}, \quad i_a \rightarrow q_{a2}$ $q_{a1} \rightarrow q_{a3} \parallel i_b$ $r_a \parallel r_b \rightarrow r_a$ $q_{a2} \rightarrow q_{a3} \parallel i_c$ $r_a \parallel r_c \rightarrow r_a$ $q_{a3} \rightarrow q_{a4}, \quad q_{a3} \rightarrow q_{a5}$ $q_{a4} \rightarrow i_d$ $r_d \rightarrow q_{a7}$ $q_{a5} \rightarrow q_{a6}, \quad q_{a5} \rightarrow q_{a4}$ $q_{a6} \parallel r_b \rightarrow r_a$ $q_{a7} \parallel r_c \rightarrow r_a$ $r_a \rightarrow q_1, \quad r_a \rightarrow r_d$
$b\{ i_b : \text{calc}(\text{no call}/\text{sync})$ $r_b : \text{return}; \}$	$i_b \rightarrow r_b$	$i_b \rightarrow r_b$
$c\{ i_c : \text{calc}(\text{no call}/\text{sync})$ $r_c : \text{return}; \}$	$i_c \rightarrow r_c$	$i_c \rightarrow r_c$
$d\{ i_d : \text{call } a$ $r_d : \text{return}; \}$	$i_d \rightarrow i_a.r_d$	$i_d \rightarrow r_d$

Fig. 3: Abstractions of the Service-Oriented System in Fig. 1

### 3 Correspondence between (G,G)-PRS and (P,P)-PRS Abstractions

A run of process rewrite system  $\Pi = (Q, q_0, \rightarrow, F)$  is a sequence  $e_0, \dots, e_n$  of process-algebraic expressions such that  $e_i \Rightarrow e_{i+1}$ ,  $i = 0, \dots, n-1$  where  $e_i \Rightarrow e_{i+1}$  can be proven without using rules (T) and (L). Intuitively, this means that exactly one PRS-rule is being applied in  $e_i \Rightarrow e_{i+1}$  and the sequence  $e_0, \dots, e_n$  represents a step-wise execution of  $\Pi$ . Let  $S$  be a service-oriented system,  $\Pi_S \triangleq (Q, q_0, \rightarrow_\Pi, F)$  be the (G,G)-PRS abstraction of  $S$  and  $\Pi'_S \triangleq (Q, q_0, \rightarrow_{\Pi'}, F)$  the (P,P)-PRS abstraction of  $S$ , cf. Table 1. Note that the set of atomic processes and the initial state is by construction the same in both (G,G)- and (P,P)-PRS. We show that each run of  $\Pi_S$  corresponds to a run in  $\Pi'_S$ .

For this, we need to define an abstraction function  $\alpha$  for process-algebraic expressions of  $\Pi_S$  and  $\Pi'_S$ . Since the PRS rules  $\rightarrow_{\Pi'}$  do not contain the sequential operator the same holds for all reachable expressions. Therefore, the abstraction function  $\alpha : PEX(Q) \rightarrow PEX(Q)$  forgets the sequential composition, i.e.,  $\alpha$  is inductively defined by

- (i)  $\alpha(q) \triangleq q$  for  $q \in Q \cup \{\varepsilon\}$
- (ii)  $\alpha(e_1 \parallel e_2) \triangleq \alpha(e_1) \parallel \alpha(e_2)$  for  $e_1, e_2 \in PEX(Q)$
- (iii)  $\alpha(e_1.e_2) \triangleq \alpha(e_1)$  for  $e_1, e_2 \in PEX(Q)$

*Example 2 (Runs and Abstractions).* The first two columns of Fig. 4 shows a run of the (G,G)-PRS abstraction  $\Pi_S = (Q, q_0, \rightarrow_\Pi, F)$  and a corresponding run of the (P,P)-PRS abstraction  $\Pi'_S = (Q, q_0, \rightarrow_{\Pi'}, F)$  of the service-oriented system  $S$  in Example 1 (cf. Fig. 1 and Fig. 3). The process algebraic expressions in each row corresponds, i.e.,  $e'_i = \alpha(e_i)$  where  $e_i$  is the first expression (contained in the run in  $\Pi_S$ ) of the  $i$ -th row and  $e'_i$  is second expression (contained in the run in  $\Pi'_S$ ) of the  $i$ -th row. Furthermore, it holds  $\rightarrow_{\Pi'} = \{\alpha(e_1) \rightarrow_{\Pi'}, \alpha(e_2) : e_1 \rightarrow_\Pi e_2\}$

(G,G)-PRS	(P,P)-PRS	applied rules (cf. Fig. 3)	
		(G,G)-PRS	(P,P)-PRS
$q_0$	$q_0$		
$i_a.q_1$	$i_a$	$q_0 \rightarrow i_a.q_1$	$q_0 \rightarrow i_a$
$q_{a1}.q_1$	$q_{a1}$	$i_a \rightarrow q_{a1}$	$i_a \rightarrow q_{a1}$
$(q_{a3} \parallel i_b).q_1$	$q_{a3} \parallel i_b$	$q_{a1} \rightarrow q_{a3} \parallel i_b$	$q_{a1} \rightarrow q_{a3} \parallel i_b$
$(q_{a4} \parallel i_b).q_1$	$q_{a4} \parallel i_b$	$q_{a3} \rightarrow q_{a4}$	$q_{a3} \rightarrow q_{a4}$
$(q_{a4} \parallel r_b).q_1$	$q_{a4} \parallel r_b$	$i_b \rightarrow r_b$	$i_b \rightarrow r_b$
$((i_d.q_{a5}) \parallel q_{12}).q_1$	$i_d \parallel r_b$	$q_{a4} \rightarrow i_d.q_{a5}$	$q_{a4} \rightarrow i_d$
$((i_a.r_d.q_{a5}) \parallel r_b).q_1$	$i_a \parallel r_b$	$i_d \rightarrow i_a.q_{16}$	$i_d \rightarrow i_a$
$((q_{a2}.r_d.q_{a5}) \parallel r_b).q_1$	$q_{a2} \parallel r_b$	$i_a \rightarrow q_{a2}$	$i_a \rightarrow q_{a2}$
$((q_{a3} \parallel i_c).r_d.q_{a5}) \parallel r_b).q_1$	$q_{a3} \parallel i_c \parallel r_b$	$q_{a2} \rightarrow q_{a3} \parallel i_c$	$q_{a2} \rightarrow q_{a3} \parallel i_c$
$((q_{a3} \parallel r_c).r_d.q_{a5}) \parallel r_b).q_1$	$q_{a3} \parallel r_c \parallel r_b$	$i_c \rightarrow r_c$	$i_c \rightarrow r_c$
$((q_{a5} \parallel r_c).r_d.q_{a5}) \parallel r_b).q_1$	$q_{a5} \parallel r_c \parallel r_b$	$q_{a3} \rightarrow q_{a5}$	$q_{a3} \rightarrow q_{a5}$
$((q_{a6} \parallel r_c).r_d.q_{a5}) \parallel r_b).q_1$	$q_{a6} \parallel r_c \parallel r_b$	$q_{a5} \rightarrow q_{a6}$	$q_{a5} \rightarrow q_{a6}$

Fig. 4: Runs in the (G,G)-PRS and (P,P)-PRS Abstractions of Fig. 3

*Remark 1.* A look at Table 1 shows that in general,  $\rightarrow_{\Pi'} = \{\alpha(e_1) \rightarrow_{\Pi'} \alpha(ee_1 \rightarrow_{\Pi} e_2)\}$ , i.e., the rewrite rules of the (P,P)-PRS can be obtained from the rewrite rules of the (G,G)-PRS by forgetting about the sequential composition.

**Theorem 1 (Correspondence between Abstractions to (G,G)-PRS and (P,P)-PRS).** *Let  $S$  be a service-oriented system,  $\Pi_S = (Q, q_0, \rightarrow_{\Pi}, F)$  be the abstraction of  $S$  to (G,G)-PRS according to Table 1, and  $\Pi'_S = (Q, q_0, \rightarrow_{\Pi'}, F)$  be the abstraction of  $S$  to (P,P)-PRS according to Table 1. If  $e \Rightarrow_{\Pi} e'$  then  $\alpha(e) \Rightarrow_{\Pi'} \alpha(e')$ .*

*Proof.* The proof is by induction on the number of applications of the inference rules. Suppose  $e \Rightarrow_{\Pi} e'$ .

**Case 1:** Rule (R) is being applied. Then  $e \rightarrow_{\Pi} e'$  according to Remark 1 it is  $\alpha(e) \rightarrow_{\Pi'} \alpha(e')$ .

**Case 2:** Rule (S) has been applied. Then,  $e = e''.s$  and  $e' = \bar{e}.s$  for some  $e'', \bar{e}, s \in PEX(Q)$ , and  $e'' \Rightarrow_{\Pi} \bar{e}$ . By induction hypothesis, it holds  $\alpha(e'') \Rightarrow_{\Pi'} \alpha(\bar{e})$ . Now, rule (S) can be applied to obtain  $\alpha(e'').s \Rightarrow_{\Pi'} \alpha(\bar{e}).s$ . Thus  $\alpha(e) \Rightarrow_{\Pi'} \alpha(e')$  using property (iii) of the definition of  $\alpha$ .

The cases where rules (P1), (P2), and (T) are applied are proven analogously to Case 2.

**Corollary 1.** *For each run  $e_0, \dots, e_n$  of  $\Pi_S$ , the sequence  $\alpha(e_0), \dots, \alpha(e_n)$  is a run of  $\Pi'_S$ .*

Hence, each run in the PRS-abstraction corresponds to a run in the (P,P)-PRS abstraction (which is equivalent to the Petri nets). Thus, the workflow nets [13] lead to a coarser abstraction than using general PRS [6].

Now, we examine the deadlock situations. Expression  $e \triangleq (((q_{a6} \parallel r_c).r_d.q_{a5}) \parallel r_b).q_1$  is a deadlock because no PRS rule is applicable, cf. Fig. 4. However, the corresponding (P,P)-PRS expression  $\alpha(e) = q_{a6} \parallel r_c \parallel r_b$  is not a deadlock. Since  $\parallel$  is associative and commutative, it holds

$$q_{a6} \parallel r_c \parallel r_b \xrightarrow{\text{ass. and com.}} q_{a6} \parallel r_b \parallel r_c \xrightarrow{q_{a6} \parallel r_b \rightarrow r_a} r_a \parallel r_c \xrightarrow{r_a \rightarrow r_d} r_d \parallel r_c \xrightarrow{r_d \rightarrow q_{a5}} q_{a5} \parallel r_c \xrightarrow{q_{a5} \rightarrow q_{a7}} q_{a7} \parallel r_c \xrightarrow{q_{a7} \parallel r_c \rightarrow r_a} r_a \xrightarrow{r_a \rightarrow q_1} q_1$$

Thus, the final state  $q_1$  is reached. However, there are alternatives leading to a deadlock. For example the rules  $r_a \rightarrow r_d$  and  $r_d \rightarrow q_{a5}$  could be applied to the derivation  $r_a$ . This can lead to the deadlock  $q_{a7}$ .

## 4 Related Work

Van der Aalst [13] uses Petri-net-based analysis tool to verify business process workflows. Recursion, e.g., recursive callbacks, is not considered.

In [12] recursive Petri nets (rPNs) are used to model the planning of autonomous agents which transport goods from location  $A$  to  $B$ . The model of rPNs is used to model dynamic processes (e.g., agent's request). Recursion in our sense is not considered. Deadlocks can only arise when interactions between agents (e.g., shared attributes) invalidates preconditions. Another refinement based approach is described in [7]. Hicheur models healthcare processes based on algebraic and recursive Petri nets [5]. Recursive Petri nets are used to model by the main process called subprocesses. All these approaches use the ability of rPNs to prune subtrees.

Bouajjani et al. [3] work is the closest to ours. They discuss the abstraction-based analysis of recursive parallel programs based on recursive vector addition systems. They explore decidability of reachability for recursively parallel programs. It seems that their model is slightly more general as there are situations where the reachability problem becomes undecidable.

To our knowledge, abstraction-based deadlock analysis in service-oriented systems including synchronous and asynchronous procedure calls (forking), recursion and recursive callbacks and synchronization in the context of service-oriented systems was not investigated before.

## 5 Conclusion

We examined two different abstractions from service-oriented systems  $S$  to general (G,G)-PRS  $\Pi_S$  and to (P,P)-PRS  $\Pi'$  (which are equivalent to Petri nets). We have shown that  $\Pi'$  is more abstract than  $\Pi$  (Theorem 1). However, there is a reachable deadlock  $e$  in  $\Pi_S$  where the corresponding situation  $e'$  in  $\Pi'_S$  is not necessarily a deadlock although each run  $q_0 \rightarrow_{\Pi_S} e_1 \rightarrow_{\Pi_S} \dots \rightarrow_{\Pi_S} e_n$  in the PRS  $\Pi_S$  has a corresponding run  $q_0 \rightarrow_{\Pi'_S} e'_1 \rightarrow_{\Pi'_S} \dots \rightarrow_{\Pi'_S} e'_n$ . To the best of our knowledge, we are not aware on studies on abstraction-based deadlock analysis of service-oriented systems taking into account unbound recursion and unbound concurrency with synchronization.

The main result shows that the Petri net abstraction is too coarse. Furthermore, the example requires recursion. However, in our example the Petri net abstraction  $\Pi'_S$  the final state as well as a deadlock situation is reachable from  $e'$ . Therefore, the example doesn't provide a false positive (i.e., it erroneously classifies the service-oriented system  $S$  deadlock-free) in the classical sense. Our hypothesis, is that in the context of the paper, if a deadlock situation  $e$  in the PRS abstraction  $\Pi_S$  of a service-oriented system  $S$  is reachable, then a deadlock situation  $e''$  is reachable from the corresponding situation  $e'$  in the Petri net abstraction  $\Pi'_S$ . It is an open question whether this hypothesis is true. However,



even it is true, the trace leading to a deadlock situation  $e''$  cannot be obtained by execution of  $S$ . This may erroneously lead to classify the deadlock  $e''$  as a false alarm.

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