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Preface

Web services are fundamental to cloud computing and other computing paradigms based on service-oriented architectures and applications. They make functional and autonomous building blocks available over the Internet, independent of platforms and programming languages, and both within and across organizational boundaries. These can then be described, located, orchestrated, and invoked. Virtualization technology has moreover led to the Software as a Service, Platform as a Service, and Infrastructure as a Service notions.

Formal methods can play a fundamental role in research on these concepts. They can help define unambiguous semantics for the languages and protocols that underpin web service infrastructures, and provide a basis for checking the conformance and compliance of bundled services. They can also empower dynamic discovery and binding with compatibility checks against behavioral properties, quality of service requirements, and service-level agreements. The resulting possibility of formal verification and analysis of (security) properties and performance (dependability and trustworthiness) is essential to cloud computing and to application areas like e-commerce, e-government, e-health, workflow, business process management, etc. Moreover, the challenges raised by research on these concepts can extend the state of the art in formal methods.

The aim of the WS-FM workshop series is to bring together researchers working on Web Services and Formal Methods in order to catalyze fruitful collaboration. Its scope is not limited to technological aspects. In fact, there is a strong tradition of attracting submissions on formal approaches to enterprise systems modeling in general, and business process modeling in particular. Potentially, this may have a significant and lasting impact on the ongoing standardization efforts in cloud computing technologies. Previous editions took place in Pisa (2004), Versailles (2005), Vienna (2006), Brisbane (2007), Milan (2008), Bologna (2009), Hoboken (2010), and Clermont-Ferrand (2011).

Following the success of the previous workshops, the 9th International Workshop on Web Services and Formal Methods (WS-FM 2012) took place on 6 and 7 September 2012 in Tallinn, Estonia, co-located with the 10th International Conference on Business Process Management (BPM 2012).

The contributions in this volume cover aspects such as the modeling and analysis of web services, service discovery, and service coordination, with formal methods like BPEL, CSP, Maude, and Petri nets.

The workshop program includes keynotes by Farouk Toumani from the Blaise Pascale University Aubière and Emilio Tuosto from the University of Leicester, and papers from researchers across the globe — including Canada, China, Estonia, Germany, Italy, The Netherlands, and Portugal. The workshop initially received a total of 19 submissions, which were each reviewed by at least 3 researchers from a strong program committee of international reputation. After lively discussions,

the committee eventually decided to accept 8 papers. These proceedings include all accepted submissions, appropriately updated in light of the reviews.

We wish to thank the program committee and the external reviewers for their timely reviewing. We acknowledge the unbeatable support of EasyChair for managing the reviewing process. Finally, we wish to thank Marlon Dumas for his excellent organization of both BPM and WS-FM.

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Regular Papers

Formal approaches for automatic synthesis of web service business protocols

Farouk Toumani

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Abstract. One of the ultimate goals of the web service technology is to enable rapid low-cost development and easy composition of distributed applications, a goal that has a long history strewn with only partial successes. The research problems underlying service composition are varied in nature and depend on several parameters such as the model used to describe the services, the communication model or the composition language. A line of demarcation between existing works in this area lies in the nature of the composition process: manual v.s. automatic. The first category of work deals generally with high-level composition design and programming details related to implementation issues while automatic service composition focuses on different issues such as composition verification, planning or synthesis.
In this talk, we consider more particularly the composition synthesis problem, i.e., the automated construction of a new target service by reusing some existing ones. We will review recent research works and challenges related to automatic synthesis of service composition and discuss the associated computational problems both in bounded and unbounded settings.

"I have read and agree with the terms and conditions"...so what?

Taking contracts for services seriously

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The customary practice to regulate the functioning of services is to set *terms & conditions*. These are legal documents constraining the way services should be used and (sometimes) specifying what providers offer. In such documents it is not rare to find statements like

> "We do our best to keep Facebook safe, but we cannot guarantee it"

(notably, *safety* is not defined in [1]!)

I argue that —despite being a practical way out— this is far from being ideal. For instance, the lack of precise guarantees is a main deterrent for industries wishing to move their applications and business to the cloud. Quoting from [2],

> "Absent radical improvements in security technology, we expect that users will use contracts and courts, rather than clever security engineering, to guard against provider malfeasance."

The key point is that terms & conditions should not be left to lawyers and courts only; rather computer scientists and IT practitioners should strive for robust techniques and methodologies capable of specifying formal contracts amenable of verification.

To support my contention I will overview some research recently carried out to address those issues.

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Service discovery with cost thresholds

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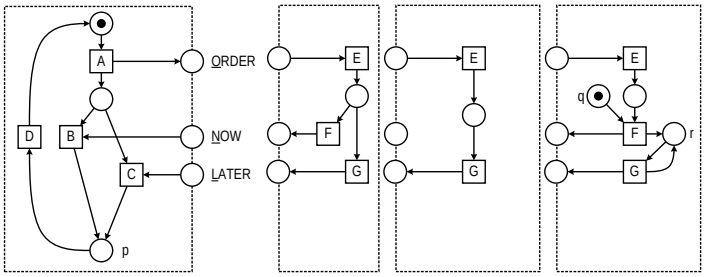
Abstract There exist several approaches to analyze a *behavioral model* of a stateful service N. Such techniques frequently consider the concept of a *partner*. Intuitively, service Q is a partner of N, if N and Q properly interact. So far, existing techniques do not consider non-functional properties, such as *cost thresholds*. Likewise, existing techniques to analyze non-functional properties neglect the behavior.
In this paper, we introduce a compact formal framework to *enhance* behavioral models with *costs*. Thereby, we introduce the concept of a *cost bounded partner*. Intuitively, a partner Q of N is cost bounded, if costs stay below a given threshold. For a class of enhanced models, we present a transformation procedure from an enhanced model N to an equivalent behavioral model N'. Thereby we guarantee that analysis results of N' are also valid for N.

1 Introduction

In a *service-oriented architecture* [8] (SOA), processes are composed from services. We understand a *service* as a stateful component, interacting with other services by means of asynchronous message exchange. *Service discovery* is the task to find a matching partner service Q for a given service N. The SOA-triangle describes an instance of this problem: A *service requester* N queries a *service broker* B for matching *service provider* Q. Thereby, we assume that Q published a service description in a repository accessed by B.

Service broker B ensures the *compatibility* of requester N and provider Q. If N and Q are compatible, we call them *partners*. In our setting, we assume that service descriptions are *formal models*. Here, B applies analysis and verification techniques to check compatibility between N and a candidate Q. If N and Q are indeed partners, B returns Q. Otherwise, it continues the search for a partner. Compatibility, and thus the concept of partner, may be defined on different levels [7]. For example, two services may be partners from a behavioral point of view; that is, they interact and terminate properly. However, this does not imply compatibility on other levels, for example for non-functional properties like costs, and time.

Running example. Consider a requester N, and three providers $\mathsf{Q}_1, \ldots, \mathsf{Q}_3$, depicted in Fig. 1. The four services are modeled as *open nets*, Petri nets extended



(a) N (b) Q_1 (c) Q_2 (d) Q_3

Figure 1: (*Running example*) Requester N and providers Q_1, Q_2, and Q_3, with respective sets of final markings $M^f_{\mathsf{N}} = \{[\mathsf{p}]\}$, $M^f_{Q_1} = M^f_{Q_2} = \{[]\}$, $M^f_{Q_3} = \{[\mathsf{q}], [\mathsf{r}]\}$.

by interfaces and sets of final markings. Transitions are depicted as rectangles, whereas places are depicted as circles. A dot or number on a place represents a token or a respective number of tokens on this place in the initial marking. Places drawn on the dashed line indicate the interface for asynchronous message exchange. Intuitively, composition is realized by glueing the services at respective interface places. The sets of final markings are not directly depicted but may be found in the figure caption. We describe the behavior of each depicted open net. *Requester* N initiates communication by firing transition A, thereby sending an ORDER to its partner. Afterwards, it waits for an incoming payment option: Either a message NOW, enabling transition B, or a message LATER, enabling transition C. Firing one of the transitions B and C results in the single final marking [p] of N. In the final marking, transition D is enabled. Firing D resets N into its initial state. *Provider* Q_1 initially waits for an ORDER to arrive, enabling transition E. Once E fires, Q_1 nondeterministically chooses between sending NOW and sending LATER, firing transitions F or G respectively. The empty marking [] is the single final marking of Q_1. *Provider* Q_2 has a similar structure. However, Q_2 does not make the choice between NOW and LATER. Instead, Q_2 always replies with LATER. *Provider* Q_3 shows more complex behavior than Q_1 and Q_2. Intuitively, Q_3 behaves differently depending on the "round": In the first round, Q_3 replies with NOW. Starting with the second round, it always replies with LATER.

Studying our running example, we observe that N properly interacts with each of the providers $Q_1, \ldots, Q_3$: From any reachable state, a common final state may be reached. We study an example for a nonfunctional property. Consider that paying immediately forces N to use a payment service requiring a fixed fee for each transaction. In contrast to that, paying later is free. Then, we observe that interaction with (1) Q_1 may result in arbitrarily high costs, (2) Q_2 is free, and (3) Q_3 always results in the same amount, namely the fixed fee for one transaction. Set the fixed fee to 10 units per transaction. Assume that N fixes an acceptable

cost threshold of 19 units. Then, (1) Q_1 is inacceptable, (2) Q_2 is acceptable, and (3) Q_3 is acceptable as well.

Problem and contributions. There exist analysis and verification techniques in literature for behavioral compatibility criteria, for instance *deadlock freedom*, or *weak termination*. However, these techniques consider purely behavioral models, completely abstracting from non-functional properties.

In this paper, we present a formal framework to enhance the purely behavioral models with costs. Thereby, we introduce *cost specifications*, consisting of a *cost function* to annotate transitions with costs, a *cost model* to specify how costs are aggregated, and a *cost threshold*, defining an acceptable upper bound for costs. However, a framework to specify costs is not very useful without proper analysis techniques. Thus, we study how existing techniques may be reused for a restricted class of cost specifications. Intuitively, we combine a purely behavioral model N with a cost specification S in a new behavioral model N_S. As a result, one may analyze N_S instead of N.

Outline. We structure our paper as follows: We repeat mathematical preliminaries, and the notion of open nets to formally model services in Sect. 2. We study properties of Petri nets in Sect. 3. We introduce our formal framework for enhancing behavioral models with costs in Sect. 4. We elaborate our approach for the class of worst case total cost specifications in Sect. 5. We discuss related work in Sect. 6, and conclude our paper in Sect. 7.

2 Preliminaries

We write $\mathbb{N}_0$ for the set of all *natural numbers*, starting with 0. Occasionally, we extend the natural numbers by the symbol $\infty \notin \mathbb{N}_0$, denoted by $\mathbb{N}_{0,\infty} := \mathbb{N}_0 \cup \{\infty\}$. In that case, we extend the order $\leq$ on $\mathbb{N}_0$ canonically: For all $x \in \mathbb{N}_{0,\infty}$: $x \leq \infty$.

We define the power set $\mathcal{P}(A)$ of some set A by the set of all its subsets; that is, $\mathcal{P}(A) := \{B \mid B \subseteq A\}$.

Let A be an alphabet. We write A^* for the set of all finite sequences over A. Let $B \subseteq A$ and $\sigma \in A^*$. We define the *restriction* $\sigma|_B$ of σ to B recursively: $\epsilon|_B = \epsilon$, for $b \in B$, $(\sigma b)|_B := \sigma|_B b$, and for $a \in A \setminus B$, $(\sigma a)|_B := \sigma|_B$.

Let R be a binary relation. We define $R^{-1} := \{[b, a] \mid [a, b] \in R\}$. We define $R(a) := \{b \mid [a, b] \in R\}$ for $a \in A$.

A *bag* (or: multiset) generalizes a set by assigning a multiplicity to each element. Formally, a function $m \colon A \to \mathbb{N}_0$ from some set A into $\mathbb{N}_0$ is a *bag over* A. We write $\mathrm{Bags}(A)$ for the set of all bags over A. If $k \in \mathbb{N}_0$ and $m \in \mathrm{Bags}(A)$, we write $m_{>k}$ for the set of all elements which occurr at least $k+1$ times. That is, $m_{>k} := \{a \mid a \in A, m(a) > k\}$. Given a set B, we define the *canonical B-transformation* m_B of m as the bag mapping each element a from the intersection of A and B to $m(a)$, and all other arguments to zero. Formally, $m_B \in \mathrm{Bags}(B)$ is defined by $x \mapsto m(x)$ if $x \in A$, and $x \mapsto 0$, otherwise. We omit the index B if it is clear from the context. Given a bag $m' \in \mathrm{Bags}(B)$, we define $m + m'$

by component-wise addition, treating missing values as zero. Formally, the bag $(m + m') \in \text{Bags}(A \cup B)$ is defined by $x \mapsto m_B(x) + m'_A(x)$. Bag $m \in \text{Bags}(A)$ *covers* bag $m' \in \text{Bags}(A)$, written $m \geq m'$ iff for all $a \in A$, $m(a) \geq m'(a)$. If $m \geq m'$, we define $(m - m') \in \text{Bags}(A)$ by $a \mapsto m(a) - m'(a)$. For two sets $F, G \subseteq \text{Bags}(A)$ of bags over A, we define $(F+G) := \{(m+m') \mid m \in F, m' \in G\}$.

Let $\mathcal{A}$ be a set, and $\leq$ be a partial order on $\mathcal{A}$. Let $A \subseteq \mathcal{A}$ and $b \in A$. We write $b \preceq A$ iff (1) for all $a \in A$, it holds that $a \not< b$, and (2) there exists $a \in A$ with $b \leq A$. Similarly, we write $b \succeq A$ iff (1) for all $a \in A$, it holds that $a \not> b$, and (2) there exists $a \in A$ with $b \geq A$.

2.1 Petri nets and Open nets

We model services as *open nets* [5], a special class of *Petri nets* [9]. We quickly recall the syntax and semantics of Petri nets. Let P and T be finite, disjoint sets, and $V\colon (P \times T) \cup (T \times P) \to \mathbb{N}_0$. Then, $N = [P, T, V]$ is a *Petri net structure*. We call P the *places*, and T the *transitions* of N. We call V the *flow function* of N. A place models a store, buffer, or condition, a transition represents an action. A Petri net has a visual representation, where places are drawn as circles, transitions are drawn as rectangles, and V is realized by inscripted arcs: If $[x, y] \in (P \times T) \cup (T \times P)$, and $V(x, y) > 0$, then we draw an arc inscripted with $V(x, y)$ from x to y. If $V(x, y) = 1$, we usually omit the inscription.

Places of a Petri net structure can be marked by *tokens*. A token represents an arbitrary object, ressource, or value. A function assigning a natural number of tokens to each place $p \in P$ is a *marking of* P. Hence, a marking m is a bag over P, and we frequently use the bag notation. Transitions consume and produce markings as given by the flow function V, thus changing the marking of the Petri net. A transition $t \in T$ is *enabled* in a marking m in Petri net structure N iff for each place $[p, t] \in P \times \{t\}$, we find $m(p) \geq V(p, t)$. Hence, a transition is enabled iff the current marking constitutes the necessary number of tokens on each place connected with t. An enabled transition may *fire*, resulting in a new marking: If t is enabled in m in N, then the resulting marking is m' defined by $p \mapsto m(p) - V(p, t) + V(t, p)$. We call the triple $[m, t, m']$ a *step* of N, often written as $m \xrightarrow{t}_N m'$. Consecutive steps $m_1 \xrightarrow{t_1}_N m_2 \xrightarrow{t_2} \ldots \xrightarrow{t_n}_N m_{n+1}$ are frequently written in the abbreviated form $m_1 \xrightarrow{t_1 \ldots t_n} m_{n+1}$. We further define $m \xrightarrow{\epsilon} m'$ for all markings m of N.

A *Petri net* $N = [P, T, V, m^0]$ consists of a Petri net structure $[P, T, V]$, and a marking m^0 of $[P, T, V]$, called *initial marking* of N. Consecutive steps starting in m^0 induce a *run* of N: An executable transition sequence of N. We define $\text{Runs}(N) = \{\sigma \mid m^0 \xrightarrow{\sigma}_N m\}$.

An *open net* is a Petri net with an *interface*, and a set of *final markings*. The interface consists of *input places*, and *output places*, modeling receiving and sending of messages, respectively. A final marking represents a state where termination is acceptable.

Definition 1 (Open net). *An* open net $N = [P, T, V, m^0, M^f, I, O]$ *extends a Petri net* $[P, T, V, m^0]$ *by a set of* final markings M^f*, a set of* input places $I \subseteq P$*,*

a set of output places $O \subseteq P$*, with* $I \cap O = \emptyset$*, for all* $t \in T$*,* $i \in I$*, and* $o \in O$*:* $V(t,i) = V(o,t) = 0$.

Open net N *is called* closed *iff* $I = O = \emptyset$*. We call two open nets* N_1, N_2 disjoint *iff they share at most interface places; that is,* $(P_1 \cup T_1) \cap (P_2 \cup T_2) \subseteq I_1 \cup O_1 \cup I_2 \cup O_2$.

A run σ *of* $[P,T,V,m^0]$ *is a* run *of open net* N*. If* $m^0 \xrightarrow{\sigma}_N m^f$ *and* $m^f \in M^f$*, then we call* σ terminating*. We write* $\mathrm{TRuns}(N)$ *for the set of all terminating runs of* N*. Open net* N *is* weakly terminating *iff for each* $\sigma \in \mathrm{Runs}(N)$*, there exists* $\sigma' \in T^*$*, such that* $\sigma\sigma' \in \mathrm{TRuns}(N)$.

We define the inner of N *as the Petri net* $\mathrm{inner}(N) := [P \setminus (I \cup O), T, V', m^0]$ *where* $V' = V_{((P \setminus (I \cup O)) \times T) \cup (T \times (P \setminus (I \cup O)))}$.

A central concept in service-orientation is *composition* of services. We compose open nets by gluing the models at the interfaces.

Definition 2 (Composition). *Let* N_1, N_2 *be disjoint open nets with* $I_1 = O_2$ *and* $I_2 = O_1$*. The* composition $N_1 \oplus N_2 = [P,T,V,m^0,M^f,I,O]$ *of* N_1, N_2 *is the open net defined by* $P := P_1 \cup P_2$*,* $T := T_1 \cup T_2$*,* $V := V_1 + V_2$*,* $m^0 := m_1^0 + m_2^0$*,* $m^f := M_1^f + M_2^f$*,* $I := \emptyset$*,* $O = \emptyset$.

Two open nets N and Q are partners [11], if their composition is *closed*, and *weakly terminating*.

Definition 3 (Partner relation). *Let* N, Q *be disjoint open nets such that* $N \oplus Q$ *is defined. We call* N *and* Q partners*, written* $[N,Q] \in \mathrm{Partners}$*, iff* $N \oplus Q$ *is closed and weakly terminating.*

3 Properties of Petri nets

As for any system, we may formulate properties for Petri nets. The following definitions assume a given Petri net $N = [P,T,V,m^0]$.

In this paper, we distinguish between *state predicates*, and *run predicates*. Intuitively, a *state predicate* is a predicate over markings, whereas a *run predicate* is a predicate over transition sequences.

Definition 4. *A* state predicate *of* N *maps each* $m \in \mathrm{Bags}(P)$ *to a truth value. A* run predicate *of* N *maps each* $\sigma \in T^*$ *to a truth value.*

In the sections below, we study properties equivalent to run predicates. The set of all runs of N is infinite in general, even if N has only finitely many reachable markings. Hence, it is desirable to abstract a run predicate ψ to a state predicate. Such an abstraction is valid if it is necessary and sufficient to know the result marking of a run σ to decide $\psi(\sigma)$.

Definition 5 (Valid abstraction of run predicates). *A state predicate* ϕ *of* N *is a* valid abstraction of ψ w.r.t. N*, iff for all* σ *with* $m^0 \xrightarrow{\sigma}_N m$*, it holds* $\psi(\sigma) \Leftrightarrow \phi(m)$.

A valid abstraction of ψ w.r.t. N does not necessarily exist: Consider two runs σ, σ' yielding the same result marking m, and $\psi(\sigma) \neq \psi(\sigma')$. Then, it is impossible to find a valid abstraction. However, for a given run predicate ψ, there exists a class of Petri nets, such that one can find a valid abstraction. We call such a Petri net *conclusive* w.r.t. ψ.

Formally, we first define *conclusiveness* on markings, and extend this definition to Petri nets. A marking m is conclusive iff for any two runs σ, σ' resulting in m, we find $\psi(\sigma) \Leftrightarrow \psi(\sigma')$. A Petri net is conclusive iff all reachable markings are conclusive.

Definition 6 (Conclusiveness). *A marking m of N is* conclusive w.r.t. ψ*, iff for all σ, σ' with $m^0 \xrightarrow{\sigma}_N m$ and $m^0 \xrightarrow{\sigma'} m$, it holds $\psi(\sigma) \Leftrightarrow \psi(\sigma')$. Petri net N is* conclusive w.r.t. ψ *iff each reachable marking of N is conclusive w.r.t. ψ.*

Given a conclusive Petri net, there exists a canonical valid abstraction $\mathrm{abs}_N(\psi)$ of ψ w.r.t. N. Intuitively, for each marking m we pick an arbitrary run σ resulting in m. In order to avoid a restriction of this definition to conclusive Petri nets, we build the conjunction of all runs resulting in a given marking.

Definition 7 (N-abstraction). *We define the* N-abstraction $\mathrm{abs}_N(\psi)$ *of ψ by*

$$\mathrm{abs}_N(\psi)(m) := \bigwedge_{\sigma : m^0 \xrightarrow{\sigma}_N m} \psi(\sigma).$$

As explained above, the N-abstraction of ψ is a valid abstraction, if N is conclusive w.r.t. ψ.

Lemma 1. *If N is conclusive w.r.t. ψ, then $\mathrm{abs}_N(\psi)$ is a valid abstraction of ψ w.r.t. N.*

Proof. Assume exists σ with $m^0 \xrightarrow{\sigma}_N m$, and $\psi(\sigma) \neq \mathrm{abs}_N(\psi)(m)$. Consider (1) that $\psi(\sigma)$ holds, and (2) that $\psi(\sigma)$ does not hold.

1. By assumption, $\mathrm{abs}_N(\psi)(m)$ does not hold. Hence, there exists σ' with $m^0 \xrightarrow{\sigma'}_N m$ such that $\psi(\sigma')$ does not hold. However, this is a direct contradiction to the assumption that N is conclusive w.r.t. ϕ.
2. By assumption, $\mathrm{abs}_N(\psi)(m)$ holds. Hence, we find that for all σ' with $m^0 \xrightarrow{\sigma'}_N m$, it holds $\psi(\sigma')$. However, this contradicts the assumption that $\psi(\sigma)$ does not hold.

□

We study a certain class of run predicates, namely *safety predicates* [2]. Intuitively, once a run σ does not satisfy a safety predicate, it cannot be repaired; that is, σ may not be continued by σ', such that $\sigma\sigma'$ satisfies ψ.

Definition 8 (Safety predicate). *Run predicate ψ of N is a* safety predicate *iff for each $\sigma, \sigma' \in T^*$, it holds: $\neg\psi(\sigma) \implies \neg\psi(\sigma\sigma')$.*

Safety predicates are easier to handle during analysis than arbitrary run predicates. For instance, each run σ has a *minimal prefix* w.r.t. a safety predicate ψ. Intuitively, the minimal prefix is sufficient to decide if σ satisfies ψ.

Definition 9 (Minimal prefix). *Let N be a Petri net, and ψ a run predicate of N. Let $\sigma \in T^*$. We define the* minimal prefix $\sigma^{\psi}_{\min}$ of σ w.r.t. ψ *by*

$$\sigma^{\psi}_{\min} := \begin{cases} \sigma', & \text{if } \sigma' \text{ is the minimal prefix of } \sigma \text{ with } \neg\psi(\sigma') \\ \sigma, & \text{if no such } \sigma' \text{ exists.} \end{cases}$$

We define $\psi_{\min}$ by $\psi_{\min}(\sigma) = \psi(\sigma^{\psi}_{\min})$.

Lemma 2. *If ψ is a safety predicate, and $\sigma \in T^*$, then it holds $\psi(\sigma) \Leftrightarrow \psi(\sigma^{\psi}_{\min})$.*

Proof. We distinguish three cases.

1. Choose σ, such that $\psi(\sigma)$ does not hold. Then, there exists a minimal prefix σ' of σ, such that $\neg\psi(\sigma')$, and $\sigma' = \sigma^{\psi}_{\min}$. We find that $\psi(\sigma^{\psi}_{\min})$ does not hold.
2. Choose σ, such that $\psi(\sigma)$ holds, and for each prefix σ' of σ, it holds $\psi(\sigma')$. Then, $\sigma = \sigma^{\psi}_{\min}$. We find that $\psi(\sigma^{\psi}_{\min})$ holds.
3. Choose σ, such that $\psi(\sigma)$ holds, and there exists a prefix σ' of σ, with $\neg\psi(\sigma')$. Because σ' is a prefix of σ, and ψ is a safety predicate, we infer $\neg\psi(\sigma)$. This contradicts the assumption. Hence, no instance of this case exists.

□

Corollary 1. *If ψ is a safety predicate, then $\psi \equiv \psi_{\min}$.*

4 A formal framework for costs

We study costs which are directly induced by the execution path, and abstract from any other incurring costs. As a further restriction, we assume that each action has fixed, known execution costs. Thereby, *fixed* means that the costs for executing an action do not depend on other occurred actions, or the current state. However, it does not imply that the costs for executing an action are necessarily a single number. They could also be an interval, or an expectation together with a deviation. The set of possible cost values is fixed by means of a *cost domain*. Formally, a cost domain is simply a partially ordered set. The partial order is useful when studying *thresholds*. A threshold is a set of cost values, such that for any other cost value it can be determined whether it is above or below the threshold. In order to specify costs, we introduce *cost functions*. A cost function of an open net N maps a transition of N to a cost value from a cost domain. Formally, we define a cost function as a partial function to later cope with composition: Then, a cost function of N is also a cost function of $N \oplus Q$ for some Q.

Definition 10 (Cost domain, threshold, cost function). *A* cost domain $[\mathcal{A}, \leq]$ *consists of a set* $\mathcal{A}$ *and a partial order* $\leq$ *on* $\mathcal{A}$*. A set* $\triangle \subseteq \mathcal{A}$ *is a* threshold *w.r.t.* $[\mathcal{A}, \leq]$ *iff for all* $a \in \mathcal{A}$*, it holds* $a \preceq \triangle$ *or* $a \succeq \triangle$*. Let* $[\mathcal{A}, \leq]$ *be a cost domain, and* N *be an open net. A partial function* $f \colon T_N \rightsquigarrow \mathcal{A}$ *is a* cost function *of* N *over* $[\mathcal{A}, \leq]$*.*

Example 1. $\mathbb{N}_{0,\infty}$ together with $\leq$ is a cost domain, $\{19\}$ is a cost threshold of $[\mathbb{N}_{0,\infty}, \leq]$. The partial function $\mathsf{f} \colon T_{\mathsf{N}} \to \mathbb{N}_0$ with domain $\{\mathsf{B}\}$ and $\mathsf{f}(\mathsf{B}) = 10$ is a cost function of N (Fig. 1) over $[\mathbb{N}_{0,\infty}, \leq]$.

Next, we define costs of a *run*, and of *sets of runs*. A *cost model* specifies *aggregation methods* for cost values. Thereby, aggregation means the compression of several cost values into one. In our context, we require two types of aggregation: Sequence aggregation and set aggregation. Sequence aggregation yields a single cost value for a sequence of cost values. Set aggregation yields a single cost value for a set of cost values. Intuitively, sequence aggregation will be used to evaluate the costs of a run, whereas set aggregation will yield the costs for a set of runs.

We write down a cost model as an algebraic structure. We reuse the well-studied algebraic structure of a *semiring*. The carrier set of the semiring corresponds to a cost domain, the operations realize the aggregation. A semiring contains two operations, namely *abstract addition* and *abstract multiplication*. To avoid confusion with concrete addition and multiplication operators, we will use the terms *set aggregator* and *sequence aggregator* instead.

Definition 11 (Semiring, cost model). *A* semiring $M = [\mathcal{A}, \bullet, \circ, z, e]$ *consists of a carrier set* $\mathcal{A}$ *with* $z, e \in \mathcal{A}$*, and two operations* $\bullet$ *and* $\circ$*, such that*

- $\bullet \colon \mathcal{A} \times \mathcal{A} \to \mathcal{A}$ *is an associative, commutative binary operation on* $\mathcal{A}$ *with identity element* z*,*
- $\circ \colon \mathcal{A} \times \mathcal{A} \to \mathcal{A}$ *is an associative binary operation on* $\mathcal{A}$ *with identity element* e*,*
- $\circ$ *distributes over* $\bullet$*, and*
- $a \circ z = z \circ a = z$ *for all* $a \in \mathcal{A}$*.*

If $M = [\mathcal{A}, \bullet, \circ, z, e]$ *is a semiring, and* $[\mathcal{A}, \leq]$ *is a cost domain, then* M *is a* cost model *over* $[\mathcal{A}, \leq]$*. We call* $\bullet$ *the* set aggregator *and* $\circ$ *the* sequence aggregator *of* M*.*

We canonically extend the definition of $\bullet$ *to finite sets: Let* $A = \{a_1, \ldots, a_n\} \subseteq \mathcal{A}$*, then* $\bullet(A) = a_1 \bullet \ldots \bullet a_n$*. If the infinite application of* $\bullet$ *is defined, we also define* $\bullet(A)$ *for infinite sets* $A \subseteq \mathcal{A}$ *in the usual way.*

Example 2. $\mathsf{M} = [\mathbb{N}_{0,\infty}, \max, +, -\infty, 0]$ is a cost model over $[\mathbb{N}_{0,\infty}, \leq]$.

A cost function and a cost model over the same cost domain are sufficient to determine the costs of a run. We define the costs of a run by first applying f, yielding a sequence of cost values. Second, we apply $\circ$ to aggregate the sequence into a single cost value. Similarly, we proceed with a set of runs: We aggregate the costs of the single runs with $\bullet$. We further define the costs of an open net as the costs of its set of terminating runs.

Definition 12 (Costs of runs, sets of runs, and open nets). *Let f be a cost function of open net N over $[\mathcal{A}, \leq]$. Let $M = [\mathcal{A}, \bullet, \circ, z, e]$ be a cost model over $[\mathcal{A}, \leq]$. Let $\sigma = t_1 \dots t_n \in T_N^*$. Let $R \subseteq T_N^*$.*

We define the costs of σ w.r.t. f and M *by* $\langle \sigma \rangle_{f,M} = f_M(t_1) \circ \dots \circ f_M(t_n)$, *where* $f_M \colon T_N \to \mathcal{A}$ *with*

$$t \mapsto \begin{cases} f(t), & \text{iff } t \text{ is in the domain of } f \\ e, & \text{otherwise.} \end{cases}$$

If $X = \bullet(\{\langle \sigma \rangle_{f,M} \mid \sigma \in R\})$ is defined, we define the costs of R w.r.t. f and M *by* $\langle R \rangle_{f,M} = X$. *If $Y = \langle \mathrm{TRuns}(N) \rangle_{f,M}$ is defined, we define the* costs of N w.r.t. f and M *by* $\langle N \rangle_{f,M} = Y$.

Example 3. Consider the composition $\mathsf{N} \oplus \mathsf{Q_1}$ of N and $\mathsf{Q_1}$ from Fig. 1. We find that $\sigma_1 = \mathsf{AFB}$, $\sigma_2 = \mathsf{AGC}$, $\sigma_3 = \sigma_1 \mathsf{D} \sigma_2$, and $\sigma_4 = \sigma_1 \mathsf{D} \sigma_1$ are runs of $\mathsf{N} \oplus \mathsf{Q_1}$. We study their respective costs: $\langle \sigma_1 \rangle_{\mathsf{f},\mathsf{M}} = 0 + 0 + \mathsf{f}(\mathsf{B}) = 0 + 0 + 10 = 10$. $\langle \sigma_2 \rangle_{\mathsf{f},\mathsf{M}} = 0 + 0 + \mathsf{f}(\mathsf{B}) = 0 + 0 + 0 = 0$. $\langle \sigma_3 \rangle_{\mathsf{f},\mathsf{M}} = \langle \sigma_1 \rangle_{\mathsf{f},\mathsf{M}} + 0 + \langle \sigma_2 \rangle_{\mathsf{f},\mathsf{M}} = 10 + 0 + 0 = 10$. $\langle \sigma_4 \rangle_{\mathsf{f},\mathsf{M}} = \langle \sigma_1 \rangle_{\mathsf{f},\mathsf{M}} + 0 + \langle \sigma_1 \rangle_{\mathsf{f},\mathsf{M}} = 10 + 0 + 10 = 20$. Consider now the set $R = \{\sigma_1, \sigma_2, \sigma_3, \sigma_4\}$. We study the costs of R: $\langle R \rangle_{\mathsf{f},\mathsf{M}} = \max(\{\langle \sigma \rangle_{\mathsf{f},\mathsf{M}} \mid \sigma \in R\}) = \max(\{0, 10, 20\}) = 20$.

A *cost specification* consists of an open net N, a cost domain, a threshold, a cost function, and a cost model. A partner Q is cost-bounded, iff the costs for $N \oplus Q$ are defined. A partner Q of N *matches* the cost specification, iff Q is a cost-bounded partner, and the costs of $N \oplus Q$ stay below the threshold.

Definition 13 (Cost specification, matching, cost-bounded). *A* cost specification $S = [N, \mathcal{A}, \leq, \triangle, f, M]$ *consists of an open net N, a cost domain $[\mathcal{A}, \leq]$, a threshold $\triangle \subseteq \mathcal{A}$, a cost function f of N over $[\mathcal{A}, \leq]$, and a cost model M over $[\mathcal{A}, \leq]$.*

Let $\sigma = t_1 \dots t_n \in T_N^*$. Let $R \subseteq T_N^*$. Let Q be a partner of N. Sequence σ matches *S iff $\langle \sigma \rangle_{f,M} \preceq \triangle$. Set R is* cost-bounded *w.r.t. S if $\langle R \rangle_{f,M}$ is defined. Set R* matches *S iff R is cost-bounded w.r.t. S and $\langle R \rangle_{f,M} \preceq \triangle$. Partner Q of N is* cost-bounded *w.r.t. S iff $\langle N \oplus Q \rangle_{f,M}$ is defined. Partner Q of N* matches *S iff Q is cost-bounded w.r.t. S and $\langle N \oplus Q \rangle_{f,M} \preceq \triangle$. We write* $\mathrm{Partners}_S$ *for the set of all partners of N matching S.*

Example 4. Open net N from Fig. 1, and $[\mathbb{N}_{0,\infty}, \leq]$, $\{19\}$, f, M from the previous examples, form a cost specification S_{N}. The open nets $\mathsf{Q_2}$ and $\mathsf{Q_3}$ from Fig. 1 are cost-bounded w.r.t. S_{N}. Furthermore, $\mathsf{Q_2}$ and $\mathsf{Q_3}$ match S_{N}, but $\mathsf{Q_1}$ does not.

Notation 1. *Let $S = [N, \mathcal{A}, \leq, \triangle, f, M]$ be a cost specification. Let $x \in T_N^* \cup \mathcal{P}(T_N^*)$. We sometimes write $\langle x \rangle_S$ instead of $\langle x \rangle_{f,M}$.*

We introduce two classes of cost specifications: Universal and monotone cost specifications. Intuitively, in a universal cost specification, the costs of each terminating run must stay below the threshold. In a monotone cost specification, a run stays below the threshold if each prefix does.

Definition 14 (Universality, monotony). *Let $S = [N, \mathcal{A}, \leq, \triangle, f, M]$ be a cost specification. We call S* universal *iff for all $R \subseteq T_N^*$ it holds: R matches S iff for all $\sigma \in R$: σ matches S. We call S* monotone *iff for all $\sigma \in T_N^*$ and $t \in T_N$ it holds: $\langle \sigma \rangle_S \leq \langle \sigma t \rangle_S$.*

Lemma 3. *Let $S = [N, \mathcal{A}, \leq, \triangle, f, M]$ be a universal, monotone cost specification. Let N be weakly terminating. Then it holds:* $\mathrm{TRuns}(N)$ *matches S iff for all $\sigma \in \mathrm{Runs}(N)$: σ matches S.*

Proof. "⇒": Assume a run $\sigma \in \mathrm{Runs}(N)$ not matching S. Then, $\langle \sigma \rangle_S \not\preceq \triangle$. Because N is weakly terminating, σ may be continued to a terminating run σ'. Because S is universal and $\langle \mathrm{TRuns}(N) \rangle_S \preceq \triangle$, it holds $\langle \sigma' \rangle_S \preceq \triangle$. Because S is monotone and σ is a prefix of σ', it holds $\langle \sigma \rangle_S \leq \langle \sigma' \rangle_S$, which contradicts the assumption $\langle \sigma \rangle_S \not\preceq \triangle$.

"⇐": Assume that $\mathrm{TRuns}(N)$ does not match S. Because S is universal, there exists at least one $\sigma \in \mathrm{TRuns}(N)$, such that σ does not match S, which contradicts the assumption that for all $\sigma \in \mathrm{Runs}(N)$: σ matches S. □

Theorem 1. *Let $S = [N, \mathcal{A}, \leq, \triangle, f, M]$ be a universal, monotone cost specification. Let Q be a partner of N. Then, Q matches S iff for all $\sigma \in \mathrm{Runs}(N \oplus Q)$: σ matches S.*

Proof. Because Q is a partner of N, their composition $N \oplus Q$ is weakly terminating.

"⇒": If Q matches S, then $\mathrm{TRuns}(N \oplus Q)$ matches S. By Lemma 3, for all $\sigma \in \mathrm{Runs}(N \oplus Q)$: σ matches S.

"⇐": By Lemma 3, $\mathrm{TRuns}(N \oplus Q)$ matches S. By Def. 13, Q matches S. □

In this paper, we study a specific subclass of universal and monotonoe cost specifications: The class $\mathbb{W}$ of *worst case total costs*. Intuitively, costs are represented as natural numbers. We use addition and maximum as sequence and set aggregator, respecticely.

Definition 15 (Worst case total costs). *A cost specification $S = [N, \mathcal{A}, \leq, \triangle, f, M]$ is a* worst case total costs (WCTC) specification*, iff $\mathcal{A} = \mathbb{N}_{0,\infty}$, $\leq$ is the order on $\mathbb{N}_{0,\infty}$, $M = [\mathbb{N}_{0,\infty}, \max, +, -\infty, 0]$. We denote the set of all* WCTC *specifications by $\mathbb{W}$.*

Example 5. Example cost specification S_{N} is an element of $\mathbb{W}$.

WCTC specifications are monotone and universal: The addition on natural numbers is monotone. Hence, adding a transition never decreases the costs. The supremum of a set of natural numbers is always greater than or equal to the elements in the set. Hence, the costs of a run never rise above the supremum.

Lemma 4 (Monotony and universality). *If $S \in \mathbb{W}$, then S is monotone and universal.*

Proof. $+$ is monotone, hence, S is monotone. max picks the greatest element from a set, and $\leq$ is a total order. □

5 Computing representatives for worst case total costs

In order to integrate costs into existing analysis techniques for stateful services, we advise to substitute the subject open net N by a *representative* R w.r.t. a cost specification S. A representative w.r.t. a given cost specification S is an open net satisfying two properties: First, N and R have the same set of S-partners. Second, each partner of R is a S-partner of R. Therefore, R is more restrictive than N, and the sets $\text{Partners}_S(N)$ and $\text{Partners}(R)$ are equal.

Definition 16 (Representative). *Open net R is a S-representative of N, iff*

1. $\text{Partners}_S(N) = \text{Partners}_S(R)$, *and*
2. $\text{Partners}_S(R) = \text{Partners}(R)$.

We denote the set of all representatives of N by $\text{Rep}_S(N)$.

As a result, we may analyze R instead of N, yielding the same results.

Corollary 2. *Let N be an open net and $R \in \text{Rep}_S(N)$. Then,* $\text{Partners}_S(N) = \text{Partners}(R)$.

In Sect. 5, we tackle the problem to compute a canonical S-representative. Thereby, we restrict ourselves to a class of cost specifications, which is monotone and universal.

We devote the remainder of this section to the computation of a S-representative of an open net N for some given $S \in \mathbb{W}$. First, we solve the problem for a S-conclusive open net. Second, we explain how an arbitrary open net N may be transformed into a S-conclusive open net.

5.1 Representatives for conclusive open nets

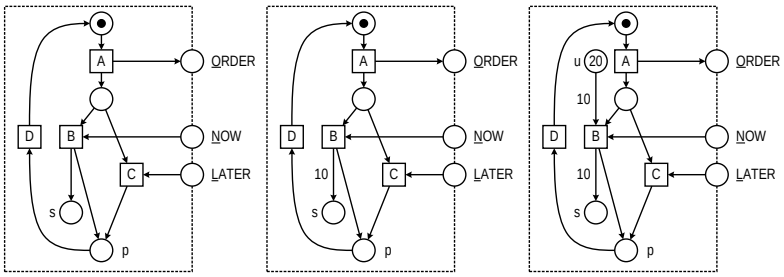
Consider a S-conclusive open net N. Then, we may define a canonical representative N_S based on the N-abstraction $\text{abs}_N(S)$ of S. Intuitively, we modify the final markings by building the intersection with $\text{abs}_N(S)$. The intersection is well defined because $\text{abs}_N(S)$ is a state predicate of N, and thus a set of markings.

Definition 17 (Canonical representative). *The* canonical S-representative *N_S of a conclusive open net N is the open net $N_S := [P, T, V, m^0, M, I, O, \lambda]$ where $M = M^f \cap \text{abs}_N(S)$.*

Example 6. Open net $\mathsf{N_1}$ from Fig. 2 is a S_{N}-conclusive variant of open net N: Place s may be used to decide whether the costs are above or below the threshold $\triangle$. Namely, more than one token proves that the costs rose above the threshold. Adjusting the final markings accordingly yields $\mathsf{N_1}_S$.

Lemma 5. $\text{Partners}_S(N) = \text{Partners}_S(N_S)$.

Proof. We show both directions seperately. In both cases, we choose a partner Q. Then, each run $\sigma \in N \oplus Q$ is a run of $N_S \oplus Q$, and vice versa.



(a) N_1 (b) N_2 (c) N_3

Figure 2: Variants N_1, N_2 and N_3 of N from Figure 1. The respective sets of final markings are $M^f_{\mathsf{N}_1} = M^f_{\mathsf{N}_2} = \{m \mid m(p) = 1, m(s) \geq 0, m(x) = 0, x \in P_{\mathsf{N}_1} \setminus \{\mathsf{s}, \mathsf{p}\}\}$.

1. We show $\text{Partners}_S(N) \subseteq \text{Partners}_S(N_S)$. Choose $Q \in \text{Partners}_S(N)$ arbitrarily. Choose an arbitrary run σ of $N \oplus Q$, and assume that σ may not be continued in $N_S \oplus Q$ to a terminating run, matching S. Because Q is a S-partner of N, there exists σ', such that $\sigma\sigma'$ is a terminating run of $N \oplus Q$ that matches S. We observe that $\sigma\sigma'$ is a run of $N_S \oplus Q$. Let $\sigma\sigma'$ result in m^f. Because S is a safety predicate, $\text{abs}_N(S)$ is a valid abstraction of S w.r.t. N. Hence, it holds $\text{abs}_N(S)(m^f)$. Therefore, m^f is a final marking of N_S. Hence, $\sigma\sigma'$ is a terminating run of $N \oplus N_S$. Additionally, $\sigma\sigma'$ matches S. This contradicts the assumption that σ may not be properly continued.
2. We show $\text{Partners}_S(N) \supseteq \text{Partners}_S(N_S)$. Choose $Q \in \text{Partners}_S(N_S)$ arbitrarily. Choose an arbitrary run σ of $N_S \oplus Q$, and assume that σ may not be continued in $N \oplus Q$ to a terminating run of $N \oplus Q$, matching S. Because Q is a S-partner of N_S, there exists σ', such that $\sigma\sigma'$ is a terminating run of $N_S \oplus Q$ that matches S. We observe that $\sigma\sigma'$ is a run of $N \oplus Q$. Let $\sigma\sigma'$ result in m^f. By definition, $m^f \in M^f$. Therefore, $\sigma\sigma'$ is a terminating run in $N \oplus Q$ matching S. This contradicts the assumption.

□

Example 7. Example services Q_2 and Q_3 (Fig. 1) are partners of N (Fig. 1), matching S_{N}. Q_2 never sends NOW, and Q_3 (Fig. 1) sends it once. Hence, in any reachable marking m with either partner, $m(\mathsf{p}_S) < 2$. Therefore, we retain the complete behavior. Hence, Q_2, and Q_3 match S_{N}.

Lemma 6. $\text{Partners}_S(N_S) = \text{Partners}(N_S)$.

Proof. The direction $\text{Partners}_S(N_S) \subseteq \text{Partners}(N_S)$ trivially holds. We show $\text{Partners}_S(N_S) \supseteq \text{Partners}(N_S)$. Choose some partner Q of N_S. Then, for each run σ of N_S, there exists σ', such that $\sigma\sigma'$ is a terminating run. Let $\sigma\sigma'$ result in m^f. Because S is a safety predicate, $\text{abs}_N(S)$ is a valid abstraction of S w.r.t. N_S. Hence, $\sigma\sigma'$ matches S, because $\text{abs}_N(S)(m^f)$. □

Example 8. Assume an arbitrary partner Q of N_1 from Fig. 2. It is obvious that any final marking of N_1 is a marking where the costs are below the threshold.

Corollary 3. $N_S \in \mathrm{Rep}(N)$.

Computing N_S therefore boils down to computing $\mathrm{abs}_N(S)$. In the next section, we solve this problem by providing a transformation procedure for arbitrary open nets with the following result: First, the result is a conclusive open net $\mathrm{mod}_S(N)$. As a second result, the procedure yields $\mathrm{abs}_{\mathrm{mod}_S(N)}(S)$.

5.2 Making open nets conclusive

Next, we study arbitrary open nets. Thereby, we exploit the fact that WCTC-specifications correspond to safety predicates: Once the costs of a run rise above the threshold, they stay above the threshold forever. The idea is to construct a new net $\mathrm{mod}_S(N)$, such that $\mathrm{mod}_S(N)$ is conclusive, and $\mathrm{abs}_{\mathrm{mod}_S(N)}(S)$ is obvious. One solution is to add a place p_S to N, *logging* the costs. Here, logging means that the number of tokens on p_S equals the costs of the current run. The resulting net is conclusive: Consider a run σ resulting in marking m. Then, $m(p_S) \leq \triangle$ indicates that the costs of σ are acceptable. If in contrast $m(p_S) > \triangle$, then the costs of σ are above the threshold. This observation also yields $\mathrm{abs}_{\mathrm{mod}_S(N)}(S)$.

Definition 18. *The* S-modification $\mathrm{mod}_S(N)$ of N *is the open net* $\mathrm{mod}_S(N) := [P \cup \{p_S\}, T, V \cup V', m^0, M^f + \mathrm{Bags}(\{p_S\}), I, O, \lambda]$ *where for all* $t \in T$*:* $V'(t, p_S) = f(t)$*, and* $V'(p_S, t) = 0$*. We define the* canonical state predicate $\mathrm{pred}(S)$ *by* $\mathrm{pred}(S)(m) \Leftrightarrow m(p_S) \leq \triangle$.

Example 9. The S_{N}-modification $\mathrm{mod}_S(\mathsf{N})$ is the open net N_2 in Fig. 2: We added a place s, and transition B produces $\mathsf{f}(\mathsf{B}) = 10$ tokens on s. Place s does not constrain any transition of N_2. Hence, adding s does not change the set of runs. Because the final markings of N_2 are indifferent to the number of tokens on s, the set of terminating runs does not differ either.

Lemma 7. $\mathrm{pred}(S) \equiv \mathrm{abs}_{\mathrm{mod}_S(N)}(S)$.

Proof. Assume two runs σ, σ' of $\mathrm{inner}(\mathrm{mod}_S(N))$ resulting in marking m. As a matter of fact, $\langle\sigma\rangle_S = \langle\sigma'\rangle_S = m(p_S)$. Hence, $\mathrm{pred}(S)(\sigma) \Leftrightarrow \mathrm{pred}(S)(\sigma')$. Hence, we find:

$$\bigwedge_{\sigma : m^0 \xrightarrow{\sigma}_{\mathrm{inner}(N)} m} \sigma \Leftrightarrow m(p_S) \leq \triangle.$$

□

Lemma 8. $\mathrm{mod}_S(N)$ *is conclusive.*

Proof. It is sufficient to know the costs of the current run to decide matching of the run. This cost value is immediately represented by the number of tokens on p_S. □

However, this solution has a disadvantage. In general, $\mathrm{inner}(\mathrm{mod}_S(N))$ is unbounded, that is, has infinitely many reachable markings. This even occurs when N is bounded, that is, finite state.

Example 10. The inner of N_2 (Fig. 2) is unbounded, because K may fire arbitrarily often.

We overcome this problem by application of a standard Petri net technique. We introduce a *complementary place* $\overline{p}_S$ for p_S. Intuitively, a transition consuming n tokens from p_S simultaneously produces n tokens on $\overline{p}_S$. Likewise, a transition producing n tokens on p_S simultaneously consumes n tokens from $\overline{p}_S$. The initial marking of $\overline{p}_S$ relies on the threshold $\triangle$, and the costs $f_{\max}$ of the most expensive transition. Initially, there are $\triangle + f_{\max}$ tokens on $\overline{p}_S$. This procedure cuts away behavior: Once the threshold has been breached, no more transitions with costs higher than zero may occur. However, this is acceptable, because S is a safety predicate: It is sufficient to keep the minimal prefix of each run.

Example 11. Figure 2 shows N_3, a variant of N_2 and N_1 (Fig. 2). The idea is that place s in N_3 is bounded by introducing an additional place u with 20 initial tokens. We find that B may only occur twice in inner(N_3) instead of arbitrarily often, as in N or N_2. However, after the second execution of B, the costs have been risen above the threshold. Hence, the minimal prefixes are kept, and no valuable information is lost.

6 Related work

In [1], the authors extend discrete-time Petri nets with a cost model, studying the issue of minimal cost reachability and coverability. We do not study the minimal costs for reaching a certain state, but the maximal costs to terminate. Additionally, we study models of services in contrast to closed systems. Annotating Petri nets with costs is similar to using *Weighted finite automata* (WFA) (see e.g. [4]). We could also approach the topic with a special class of WFA, yielding similar results. Zeng et al. [12] use integer programming to find an optimal composition of atomic tasks each implemented by a web service. The services do not communicate based on its state and therefore do not influence each others costs. De Paoli et al. [6] propose a similar approach for WS-BPEL [3] processes. Both approaches work on well-structured services, whereas we support arbitrary services.

7 Conclusion and future work

In this paper, we introduced a framework to enhance purely behavioral models of services with cost specifiations. Thereby, we seperate the actual annotation with costs from the aggregation of costs along runs and sets of runs. For a class of cost specifications, we explain a transformation procedure, yielding an equivalent, purely behavioral model. For future work, we plan to investigate additional classes of cost specifications. We plan to generalize our result for the class of all universal, monotone cost specifications. Additionally, we believe that other classes are of interest, for example average costs. Our results to find a minimal cost threshold for a given service, yielding cost minimal partners, are preliminary [10]. We

implemented the transformation procedure in a prototype called Tara[1]. However, a comprehensive case study for this approach is still missing.

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[1] Tara is available at http://service-technology.org/tara

Private View Conformance Checking

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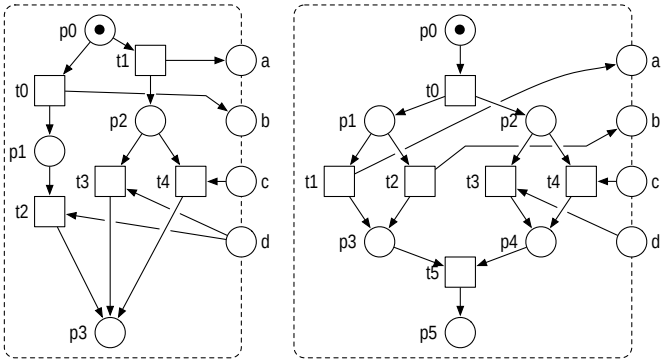
Abstract. Conformance checking techniques can be used to diagnose differences between observed behavior and modeled behavior. Although these techniques can be used to measure the degree of conformance of a running service based on recorded event data (e.g., messages or transaction logs) and its specification, their application may produce "false negatives" because a private view (i.e., an implementation) that accords with its specification may deviate significantly. The implementation may reorder some activities without introducing any problems, yet traditional conformance checking would penalize such changes unjustifiably. To overcome this problem, we present a novel approach that determines a *best matching private view*. We show that among the infinitely many accordant private views, there is a *canonical* best matching private view. Although the current implementation and experiments are limited to acyclic service models, the approach can also be applied to cyclic service models.

1 Introduction

Service-oriented computing (SOC) [17] aims at building complex systems by aggregating less complex, independently-developed building blocks called *services*. A service encapsulates a business functionality and has an interface to interact with its environment—that is, other services—via asynchronous message passing. The service-oriented paradigm enables enterprises to publish their services via the Internet. These services can then be automatically found and used by other enterprises. However, in practice, enterprises usually cooperate only with enterprises they already know. Therefore, a more pragmatic approach is often used instead: The involved parties specify a public version of the overall service, which serves as a *contract* [1,5]. Later on, each party implements (refines) its share of the contract. A party's share of the contract—that is, the *public view*—and the implementation thereof—that is, the *private view*—may differ significantly but the overall implementation has to *conform* to the contract. Correctness of a contract (i.e., the possibility to always terminate) has been formalized by the *accordance relation* [19] between a public view and a private view: if every private view accords with its public view, then the correctness of the contract is preserved and the overall implementation conforms to the contract. Accordance thereby guarantees that any environment that cooperates with the public view can cooperate with the private view.



(a) Open net *Public*. (b) Open net *Private*.

Fig. 1: Private view *Private* accords with its public view *Public*.

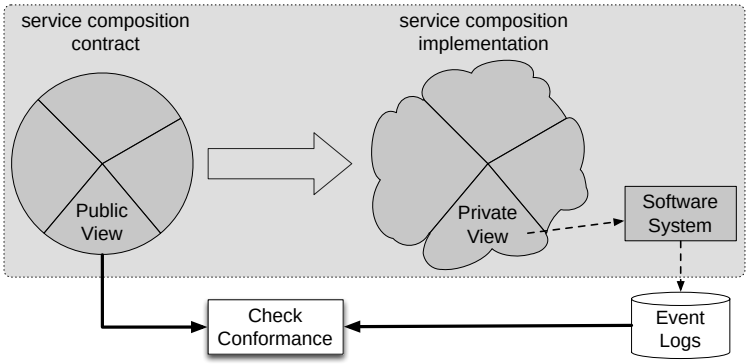
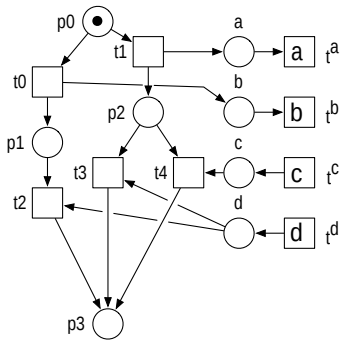


Fig. 2: Illustration of conformance checking in the contract setting.

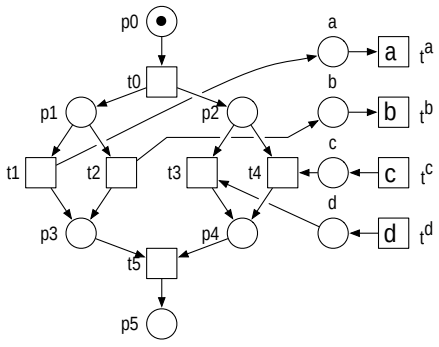
As an example, consider the public view in Fig. 1a, which is modeled as an open net [21,9]—that is, a Petri net extended with interface places[1]. The open net either sends message b and then receives d or sends message a and then receives c or d. A possible private view is shown in Fig. 1b. It is derived from the public view by parallelizing the sending and receiving of messages. In contrast to the public view, the private view can, therefore, receive c after having sent b. Open net *Private* accords with open net *Public*. Intuitively, every cooperating environment of *Public* knows by receiving either a or b whether *Public* is in the left or the right branch. Therefore, no cooperating environment of *Public* will send c after having received b, as otherwise the cooperation may get stuck. *Public* may operate in such an environment. In fact, it even allows for environments that send c after having received b.

Although accordance can be checked efficiently, the approach can hardly be used in practice, because the accordance check assumes that the public and the private view of

[1] Throughout this paper, we assume public views to be given as open nets.



(a) Environment of *Public*.



(b) Environment of *Private*.

#	trace
50	*ad*
40	*bc*
30	*cda*
120	

(c) Log L.

Fig. 3: The environments of the public view *Public* and the private view *Private*. The event log L represents recorded behavior of the implementation of *Public*.

a party are given as formal models that do not change over time. However, it is often *not realistic to assume that all parties will indeed have an up-to-date formal model of their private view.* Even if they have a formal model of the private view, it can differ significantly from the actual implementation: services may have been implemented incorrectly or change over time. Nevertheless, most implementations provide some kind of recorded behavior (also referred to as *event log*, transaction log or audit trail) [3]. Therefore, instead of checking accordance of the public and private view, we check whether event logs of the private view conform to the public view. Figure 2 illustrates our approach for conformance checking in the contract setting.

We illustrate the idea using open net *Public* and the event log L in Fig. 3c, which represents the recorded behavior of the implementation of *Public*. L contains information of 120 traces, partitioned into three cases. A trace is a sequence of messages sent or received by the implementation. We assume that each event x in a trace of a log corresponds to the sending or receiving of x of the environment. We can model this environment of an open net by adding to each x-labeled input place an x-labeled transition that produces tokens on this place and for each x-labeled output place an x-labeled transition that consumes tokens from this place. All other transitions of this environment are internal and, therefore, labeled by τ. Figure 3a illustrates this construction for the public view *Public*; for convenience, we omit all τ labels of transitions.

To check whether L conforms to the (environment of the) public view *Public*, we need to replay the traces of L on the model in Fig. 3a. More precisely, we align [2] each trace in L to a trace (i.e., a firing sequence) of the model in Fig. 3a. Some example alignments for L and the environment of *Public* are:

$$\gamma_1 = \left|\begin{array}{c|c|c|c} \gg & a & d & \gg \\ \hline \tau & a & d & \tau \\ \hline t_1 & t^a & t^d & t_3 \end{array}\right| \quad \gamma_2 = \left|\begin{array}{c|c|c|c|c} \gg & b & \gg & \gg & c \\ \hline \tau & b & d & \tau & \gg \\ \hline t_0 & t^b & t^d & t_2 & \end{array}\right| \quad \gamma_3 = \left|\begin{array}{c|c|c|c|c} c & d & \gg & a & \gg \\ \hline c & \gg & \tau & a & \tau \\ \hline t^c & & t_1 & t^a & t_4 \end{array}\right|$$

The top row of each alignment corresponds to "moves in the log" and the bottom two rows correspond to "moves in the model". There are two bottom rows because multiple transitions may have the same label; the upper bottom row consists of transition labels, and the lower bottom row consists of transitions. If a move in the log cannot be mimicked by a move in the model, then a "$\gg$" ("no move") appears in the upper bottom row. For example, in γ_2 the model in Fig. 3a cannot do the last c-move, because c is not connected to the locally enabled transition t_2. If a move in the model cannot be mimicked by a move in the log, then a "$\gg$" ("no move") appears in the top row. For example, all "silent moves" (occurrences of τ-labeled transitions) in the model in Fig. 3a cannot be mimicked by L. Moreover, L did not do a d-move in γ_2 whereas the model in Fig. 3a has to make this move to reach the end.

Informally, conformance checking of an event log L and a public view N relies on "how good" each case in L can be replayed in the environment of N. Thereby, the smaller the number of mismatches in an alignment of a case is, the better this case can be replayed. A mismatch is a move in the log which cannot be mimicked by the model, or a non-silent move in the model which cannot be mimicked by the log. Clearly, the more traces we can replay on the model the better the implementation conforms to the public view. However, even an implementation that accords with its public view may allow for traces that cannot be replayed on the public view, because the accordance relation allows parties to reorder activities of their share, for instance. As an illustration, consider again the private view in Fig. 1b. We can replay the event log L on the model of the environment of this open net, which is depicted in Fig. 3b. Some resulting alignments are:

$$\gamma_4 = \begin{array}{|c|c|c|c|c|c|}\hline \gg & \gg & a & d & \gg & \gg \\ \hline \tau & \tau & a & d & \tau & \tau \\ \hline t_0 & t_1 & t^a & t^d & t_3 & t_5 \\ \hline \end{array} \quad \gamma_5 = \begin{array}{|c|c|c|c|c|c|}\hline \gg & \gg & b & c & \gg & \gg \\ \hline \tau & \tau & b & c & \tau & \tau \\ \hline t_0 & t_2 & t^b & t^c & t_4 & t_5 \\ \hline \end{array} \quad \gamma_6 = \begin{array}{|c|c|c|c|c|c|c|}\hline c & d & \gg & \gg & a & \gg & \gg \\ \hline \gg & d & \tau & \tau & a & \tau & \tau \\ \hline & t^d & t_0 & t_1 & t^a & t_3 & t_5 \\ \hline \end{array}$$

The example clearly shows that, in general, it is not sufficient to check conformance of an event log and the model of the public view. Checking conformance on the public view may generate "false negatives", i.e., acceptable behavior may be diagnosed as non-conforming. As there may exist a private view that accords with the public view such that the conformance check with that model gives a better result, we need to check conformance of a log with *all private views* that accord with the public view. The challenge thereby is that there exist infinitely many such private views. In this paper, we investigate this challenge and present an approach to determine a best matching private view for a given event log and a public view.

The remainder is organized as follows. More background information is provided in Sect. 2. Section 3 shows the existence of a canonical best matching private view. Experimental results in Sect. 4 validate our approach. In Sect. 5, we review related work, and Sect. 6 concludes the paper.

2 Background

In this section, we provide the basic notions of Petri nets and open nets for modeling services and formalize private view conformance. Suitability of open nets as service

model has been demonstrated by feature-complete open net semantics for various languages such as BPMN and WS-BPEL [11], and the application of open nets in existing conformance checking techniques [18].

2.1 Petri Nets

As a basic model, we use place/transition Petri nets extended with a set of final markings and transition labels.

Definition 1 (Net). A *net* $N = (P, T, F, m_N, \Omega)$ consists of a finite set P of *places*, a finite set T of *transitions* such that P and T are disjoint, a *flow relation* $F \subseteq (P \times T) \cup (T \times P)$, an *initial marking* m_N, where a marking $m \in \mathcal{B}(P)$ is a multiset over P, and a set Ω of final markings.

A *labeled net* is a net N together with an *alphabet* $\mathcal{A}$ of actions and a *labeling function* $l \in T \to \mathcal{A} \cup \{\tau\}$, where $\tau \notin \mathcal{A}$ represents an invisible, internal action.

Graphically, a circle represents a place, a box represents a transition, and the directed arcs between places and transitions represent the flow relation. A marking is a distribution of tokens over the places. Graphically, a black dot represents a token. We write transition labels beside τ into the respective boxes.

Let $x \in P \cup T$ be a node of a net N. As usual, ${}^\bullet x = \{y \mid (y, x) \in F\}$ denotes the *preset* of x and $x^\bullet = \{y \mid (x, y) \in F\}$ the *postset* of x. We interpret presets and postsets as multisets when used in operations also involving multisets. For markings, we define $+$ and $-$ for the sum and the difference of two markings in the standard way.

The *behavior* of a net N relies on changing the markings of N by firing transitions of N. A transition $t \in T$ is *enabled* at a marking m, denoted by $m \xrightarrow{t}$, if for all $p \in {}^\bullet t$, $m(p) > 0$. If t is enabled at m, it can *fire*, thereby changing the marking m to a marking $m' = m - {}^\bullet t + t^\bullet$. The firing of t is denoted by $m \xrightarrow{t} m'$; that is, t is enabled at m and firing it results in m'.

The behavior of N can be extended to sequences: $m_1 \xrightarrow{t_1} \ldots \xrightarrow{t_{k-1}} m_k$ is a *run* of N if for all $0 < i < k$, $m_i \xrightarrow{t_i} m_{i+1}$. A marking m' is *reachable from* a marking m if there exists a (possibly empty) run $m_1 \xrightarrow{t_1} \ldots \xrightarrow{t_{k-1}} m_k$ with $m = m_1$ and $m' = m_k$; for $w = \langle t_1 \ldots t_{k-1} \rangle$, we also write $m \xrightarrow{w} m'$. Marking m' is *reachable* if it is reachable from m_N. The set $M_N = \{m' \mid \exists w : m_N \xrightarrow{w} m'\}$ represents all reachable markings of N.

In the case of labeled nets, we lift runs to traces: If $m \xrightarrow{w} m'$ and v is obtained from w by replacing each transition by its label and removing all τ-labels, we write $m \overset{v}{\Longrightarrow} m'$. For example, if $w = \langle t_1 t_1 t_2 t_1 t_2 t_3 \rangle$, $l(t_1) = a$, $l(t_2) = \tau$, and $l(t_3) = b$, and $m \xrightarrow{w} m'$, then $m \overset{v}{\Longrightarrow} m'$ with $v = \langle aaab \rangle$.

A net N is *bounded* if there exists a bound $b \in \mathbb{N}$ such that for all reachable markings $m \in M_N$ and all places $p \in P$, $m(p) \leq b$. A reachable marking $m \notin \Omega$ of N is a *deadlock* if no transition $t \in T$ of N is enabled at m. If N has no deadlock, then it is deadlock free. A net is *weakly terminating* if from every reachable marking it is always possible to reach a final marking.

2.2 Open Nets

We model services as *open nets* [21,9], thereby restricting ourselves to the communication protocol of a service. In the model, we abstract from data and identify each message by the label of its message channel. An open net extends a net by an *interface*. An interface consists of two disjoint sets of input and output places corresponding to asynchronous input and output channels. In the initial marking and the final markings, interface places are not marked. An input place has an empty preset, and an output place has an empty postset.

Definition 2 (Open net). An *open net* N is a tuple $(P, T, F, m_N, I, O, \Omega)$ with

- $(P \cup I \cup O, T, F, m_N, \Omega)$ is a net such that P, I, O are pairwise disjoint;
- for all $p \in I \cup O$, $m_N(p) = 0$, and for all $m \in \Omega$ and $p \in I \cup O$, $m(p) = 0$;
- the set I of *input places* satisfies for all $p \in I$, ${}^\bullet p = \emptyset$; and
- the set O of *output places* satisfies for all $p \in O$, $p^\bullet = \emptyset$.

Open net N is *sequentially communicating* if each transition is connected to at most one *interface place*. If $I = O = \emptyset$, then N is a *closed net*. Two open nets are *interface-equivalent* if they have the same sets of input and output places.

Graphically, we represent an open net like a net with a dashed frame around it. The interface places are positioned on the frame.

For the composition of open nets, we assume that the sets of transitions are pairwise disjoint and that no internal place of an open net is a place of any other open net. In contrast, the interfaces overlap intentionally. We require that all communication is *bilateral* and *directed*; that is, every shared place p has only one open net that sends into p and one open net that receives from p. We refer to open nets that fulfill these properties as *composable*. We compose two composable open nets N_1 and N_2 by merging shared interface places and turn these places into internal places. The definition of composable thereby guarantees that an open net composition is again an open net (possibly a closed net).

Definition 3 (Open net composition). Open nets N_1 and N_2 are *composable* if $(P_1 \cup T_1 \cup I_1 \cup O_1) \cap (P_2 \cup T_2 \cup I_2 \cup O_2) = (I_1 \cap O_2) \cup (I_2 \cap O_1)$. The *composition* of two composable open nets N_1 and N_2 is the open net $N_1 \oplus N_2 = (P, T, F, m_N, \Omega, I, O)$ where

- $P = P_1 \cup P_2 \cup (I_1 \cap O_2) \cup (I_2 \cap O_1), \quad T = T_1 \cup T_2, \quad F = F_1 \cup F_2$
- $m_N = m_{N_1} + m_{N_2}, \quad I = (I_1 \cup I_2) \setminus (O_1 \cup O_2), \quad O = (O_1 \cup O_2) \setminus (I_1 \cup I_2),$
- $\Omega = \{m_1 + m_2 \mid m_1 \in \Omega_1, m_2 \in \Omega_2\}$.

We want the composition of a set of services to be *correct*. Correctness refers to boundedness and weak termination. A user that communicates with a service such that the composition is correct can be seen as a *controller* of this service.

Definition 4 (Controller). Let $b \in \mathbb{N}$. An open net C is a *b-controller* of an open net N if the composition $N \oplus C$ is a closed net, b-bounded, and weakly terminating.

In the remainder of the paper, we abstract from the actual bound chosen and, therefore, use the term controller rather than b-controller for convenience.

2.3 Private View Conformance

We see a contract as a closed net N, where every transition is assigned to one of the involved parties $X_1, \ldots, X_k$. We impose only one restriction: if a place is accessed by more than one party, it should act as a directed bilateral communication place. This restriction reflects the fact that a party's public view of the contract is a service again. A contract N can be cut into parts $N_1, \ldots, N_k$, each representing the agreed public view of a single party X_i ($1 \leq i \leq k$). Hence, we define a contract as the composition of the open nets $N_1, \ldots, N_k$. For instance, Fig. 2 illustrates a contract involving four parties.

Definition 5 (Contract). Let $\mathcal{X} = \{X_1, \ldots, X_k\}$ be the set of parties and let $\{N_1, \ldots, N_k\}$ be a set of pairwise interface-compatible open nets such that $N = N_1 \oplus \cdots \oplus N_k$ is a closed net. Then, N is a *contract for* $\mathcal{X}$. For $i = 1, \ldots, k$, open net N_i is the *public view of* X_i *in* N and open net $N_i^{-1} = \bigoplus_{j \neq i} N_j$ is the *environment* of X_i in N.

Each Party X_i can independently substitute its public view N_i by a *private view* N_i' if the environment of X_i cannot distinguish between N_i and N_i' [13], which is formalized by the accordance relation [19].

Definition 6 (Accordance). Let N_i and N_i' be interface-equivalent open nets. Open net N_i' *accords with* open net N_i, denoted by $N_i' \sqsubseteq_{acc} N_i$, if every controller of N_i is also a controller of N_i'.

Sending or receiving a message is an activity. Let $\mathcal{A}$ denote the set of all activities. We define an event log as a multiset of traces over $\mathcal{A}$. Each trace describes the life-cycle of a particular case in terms of the activities executed.

Definition 7 (Event log). An *event log* L_i of the observed behavior of party X_i in contract N is a multiset of traces over $\mathcal{A}$, i.e., $L_i \in \mathcal{B}(\mathcal{A}^*)$.

We use labeled nets to relate event logs to process models. The behavior of a labeled net N is described by the runs of N leading from the initial marking to a final marking.

Definition 8 (Traces of a labeled net). Let $N = (P, T, F, m_N, \Omega, l)$ be a labeled net. The *set of final runs* of N is $R(N) = \{\sigma \in T^* \mid \exists m_f \in \Omega : \ m_N \xrightarrow{\sigma} m_f\}$, and $Tr(N) = \{\sigma \in \mathcal{A}^* \mid \exists m_f \in \Omega : \ m_N \stackrel{\sigma}{\Longrightarrow} m_f\}$ is the set of *final traces*.

For conformance checking of party X_i, we compare the observed behavior (event log L_i) with the modeled behavior (N_i or N_i'). We can take two *viewpoints* depending on what/when events are recorded in L_i. If events are recorded when party X_i consumes a message from N_i^{-1} or produces a message for N_i^{-1}, then we can use the *synchronous environment* $env^s(N_i)$ for conformance checking. Here, we label each transition with the adjacent interface places—if possible—and remove the interface places. To simplify the labeling of transitions connected to interface places, we only consider sequentially communicating nets. That way, each transition is labeled by a single label rather than by a set of labels. This restriction is not significant, as every open net can be transformed into an equivalent sequentially communicating open net [9].

Definition 9 (Synchronous environment). The *synchronous environment* of a sequentially communicating open net $N = (P, T, F, m_N, \Omega, I, O)$ is the labeled net $env^s(N) = (P, T, F \cap ((P \times T) \cup (T \times P)), m_N, \Omega, l)$ with $l(t) = p$ where p is the unique interface place $p \in I \cup O$ adjacent to $t \in T$, or $l(t) = \tau$ if no such adjacent interface place exists.

If events are recorded when the environment N_i^{-1} of party X_i consumes a message from party X_i or produces a message for party X_i, then we can use the *asynchronous environment* $env^a(N_i)$ for conformance checking. The net $env^a(N)$ is a net that can be constructed from N by adding to each interface place $p \in I \cup O$ a p-labeled transition t^p in $env^a(N)$. Intuitively, the construction translates the asynchronous interface of N into a synchronous interface with unbounded buffers described by the transition labels of $env^a(N)$.

Definition 10 (Asynchronous environment). The *asynchronous environment* of an open net $N = (P, T, F, m_N, I, O, \Omega)$ is the labeled net $env^a(N) = (P \cup I \cup O, T \cup T', F \cup F', m_N, \Omega, l)$ where $T' = \{t^x \mid x \in I \cup O\}$, $F' = \{(t^x, x) \mid x \in I\} \cup \{(x, t^x) \mid x \in O\}$, $l(t) = x$ for $t^x \in T'$, and $l(t) = \tau$ for $t \in T$.

Figures 3a and 3b show the asynchronous environments of the open nets *Public* and *Private* from Figs. 1a and 1b. A transition label is depicted inside a transition with bold font to distinguish it from the transition's identity.

Thus, the choice of environment depends on what is actually logged. In the remainder, we will abstract from these subtle differences and simply write $env(N)$.

To check conformance, we need to *align* traces in the event log to traces of the service (environment); that is, we need to relate "moves" in the log to "moves" in the model. However, there may be some moves in the log that cannot be mimicked by the model, and vice versa. For convenience, we introduce the set $A_L = \mathcal{A} \cup \{\gg\}$ where $x \in A_L \setminus \{\gg\}$ refers to "move x in the log" and $\gg \in A_L$ refers to "no move in the log". Similarly, for a labeled net N, we introduce the set $A_N = \{(a, t) \in (\mathcal{A} \cup \{\tau\}) \times T \mid l(t) = a\} \cup \{\gg\}$ where $(a, t) \in A_N$ refers to "move a in the model" and $\gg \in A_N$ refers to "no move in the model". A "move τ in the model" (τ, t) is a silent move, as it is only observable by party X_i.

Definition 11 (Alignment). For an event log L and a labeled net N, one *move* in an alignment is represented by a pair $(x, y) \in A_L \times A_N$ such that

- (x, y) is a *move in the log* if $x \in \mathcal{A}$ and $y = \gg$,
- (x, y) is a *move in the model* if $x = \gg$ and $y \in A_N \setminus \{\gg\}$,
- (x, y) is a *move in both* if $x \in \mathcal{A}$ and $y \in A_N \setminus \{\gg\}$,
- (x, y) is an *illegal move* $x = \gg$ and $y = \gg$.

We refer to a move in the model $(x, (a, t))$ with $a = \tau$ as a *silent move*. $A_{LN} = \{(x, y) \in A_L \times A_N \mid x \neq \gg \ \vee \ y \neq \gg\}$ is the set of all *legal moves*.

An *alignment* of $\sigma \in L$ and $w \in R(N)$ is a sequence $\gamma \in {A_{LN}}^*$ such that the projection on the first element (ignoring $\gg$) yields σ and the projection on the second element (ignoring $\gg$) yields w. The *set of alignments for* σ *in* N is $\Gamma_{\sigma,N} = \{\gamma \in {A_{LN}}^* \mid \exists w \in R(N) : \gamma \text{ is an alignment of } \sigma \text{ and } w\}$.

Given a log trace, there may be many possible alignments. To measure the quality of an alignment, we define a *distance function* on legal moves.

Definition 12 (Distance function). A *distance function* $\delta : A_{LN} \to \mathbb{N}$ associates costs to legal moves in an alignment. We define a *standard distance function* δ_S as $\delta_S(a, \gg) = 1$; $\delta_S(\gg, (b, t)) = 1$, for $b \neq \tau$; $\delta_S(\gg, (\tau, t)) = 0$; $\delta_S(a, (b, t)) = 0$, for $a \neq \gg$ and $a = b$; and $\delta_S(a, (b, t)) = \infty$, for $a \neq \gg$ and $a \neq b$.

We generalize a distance function δ to alignments by taking the sum of the costs of all individual moves: $\delta(\gamma) = \sum_{(x,y)\in\gamma} \delta(x, y)$. In δ_S, only moves where log and model agree on the activity, and silent moves of the model have no associated costs. Moves in only the log or model have cost 1, moves where both log and model make a move but disagree on the activity have high costs; thereby, ∞ should be read as a number large enough to discard the alignment. Note that δ_S is just an example cost function; various cost functions can be defined.

Thus far, we considered a *specific* trace of the model. However, our goal is to identify for each log trace the *best matching* trace of the model. Therefore, we define the notion of an *optimal alignment*.

Definition 13 (Optimal alignment). An alignment $\gamma \in \Gamma_{\sigma,N}$ is *optimal* for a log trace $\sigma \in L$ and a labeled net N if for any $\gamma' \in \Gamma_{\sigma,N}$: $\delta(\gamma') \geq \delta(\gamma)$.

If $R(N)$ is not empty, there is at least one (optimal) alignment for any given log trace σ. However, there may be multiple optimal alignments for σ. Since our goal is to align traces in the event log to traces of the model, we nondeterministically select an arbitrary optimal alignment. Therefore, we can construct a function λ_N that provides an "oracle".

Definition 14 (Oracle). Given a log trace σ and a labeled net N, the *oracle* λ_N produces *one* optimal alignment $\lambda_N(\sigma) \in \Gamma_{\sigma,N}$.

The alignments produced by the "oracle" λ_N can be used to quantify conformance of a log L and a model N. Conformance checking involves the interplay of four orthogonal dimensions: *fitness*, *precision*, *generalization*, and *simplicity* [2]. Fitness indicates how much of the behavior in the event log is captured by the model. Precision indicates whether the model is not too general. To avoid "underfitting" we prefer models with minimal behavior to represent as closely as possible the behavior seen in the event log. Generalization penalizes overly precise models which "overfit" the given log, and simplicity refers to models minimal in structure, which clearly reflect the log's behavior.

In the remainder, we abstract from the dimensions involved in conformance checking: we assume a function *conf* that computes the conformance of an event log L and a labeled net N based on the alignments produced by the oracle λ_N; that is, $conf(L, N)$ yields a number between 0 (poor conformance) and 1 (perfect conformance) [2]. We define *private view conformance* as the maximal conformance of all private views of a given public view.

Definition 15 (Private view conformance). Let $N = N_1 \oplus \cdots \oplus N_k$ be a contract for $\mathcal{X} = \{X_1, \ldots, X_k\}$. Let N_i be the public view of X_i, and let L_i be an event log of X_i. Let $Pr(N_i) = \{M \mid M \sqsubseteq_{acc} N_i\}$ denote the set of all private views that accord with N_i. Then

- $M \in Pr(N_i)$ is a *best matching private view* for N_i and L_i if for any $M' \in Pr(N_i)$: $conf(L_i, env(M)) \geq conf(L_i, env(M'))$; and
- $conf(L_i, env(M))$ is the *private view conformance* for party X_i where $M \in Pr(N_i)$ is a best matching private view for N_i and L_i.

Definition 15 provides a well-defined conformance notion that can be parameterized with different correctness notions (e.g., deadlock freedom, weak termination) and different environments (e.g., $env^s(N)$, $env^a(N)$). However, Def. 15 cannot easily be transformed into an algorithm. There may be many (if not infinitely many) private views that accord with N_i. So far, no algorithm has been implemented to select a best matching private view. In the next section, we show how private view conformance for party X_i can be decided.

3 Deciding Private View Conformance

In the previous section, we introduced a notion of private view conformance that is independent from the conformance checking dimensions involved. In this section, we decide private view conformance w.r.t. the fitness dimension.

A model with good fitness allows for most of the behavior seen in the event log. Therefore, it is natural to define $conf(L, N)$ inversely proportional to the sum of the costs of aligning all traces of L to traces of N; that is, $conf(L, N)$ should be maximal if $\sum_{\sigma \in L} \delta(\lambda_N(\sigma))$ is minimal. If a trace appears multiple times in the event log, the associated costs should be counted multiple times.

Definition 16 (Fitness). Conformance $conf(L, N)$ w.r.t to *fitness* of an event log L and a labeled net N yields a number between 0 (poor fitness) and 1 (perfect fitness) and is maximal if the *alignment-based costs* $\delta(L, N) = \sum_{\sigma \in L} \delta(\lambda_N(\sigma))$ are minimal.

Our approach for deciding private view conformance does not rely on a specific fitness measure; any fitness measure is suitable as long as it meets the criteria in Def. 16. Our approach relies on the existence of two specific controllers of any open net N: a *maximal controller* $maxC(N)$ [14,7] and a *most permissive controller* $mpC(N)$ [22]. A maximal controller is maximal w.r.t. the accordance relation; that is, every controller of N accords with $maxC(N)$. A most permissive controller $mpC(N)$ is maximal w.r.t. behavior; that is, N can visit all the states in composition with $mpC(N)$ that can be visited in composition with any controller of N. For technical details of maximal and most permissive controllers we refer to [14] and [22], resp.; here, we only summarize their properties.

Proposition 1 ([14]). *For any open net N, there exist controllers $maxC(N)$ and $mpC(N)$ such that for any controller C of N, we have $C \sqsubseteq_{acc} maxC(N)$ and $Tr(env(C)) \subseteq Tr(env(mpC(N)))$.*

Given a contract $N = N_1 \oplus \cdots \oplus N_k$, we show that $B_i = mpC(maxC(N_i))$ is a *canonical best matching private view* for N_i and event log L_i. In other words, open net B_i accords with N_i and has minimal costs and, hence, maximal fitness.

Theorem 2 (Main result). *Let $N = N_1 \oplus \cdots \oplus N_k$ be a contract for $\mathcal{X} = \{X_1, \ldots, X_k\}$. Let N_i be the public view of X_i, and let L_i be an event log of X_i. Then $B_i = mpC(maxC(N_i))$ is a best matching private view for N_i and L_i.*

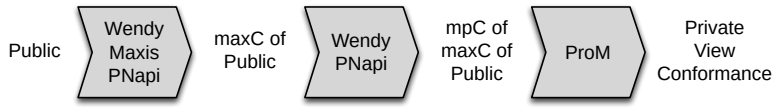


Fig. 4: Toolchain for private view conformance checking.

Proof. Let $N_i' \in \mathcal{P}(N_i)$ be a private view of N_i. We prove $\delta(L_i, N_i') \geq \delta(L_i, B_i)$, which implies $conf(L_i, env(N_i')) \leq conf(L_i, env(B_i))$ for conformance w.r.t. fitness according to Def. 16. By the choice of N_i' and Prop. 1, we conclude $R(env(N_i')) \subseteq R(env(B_i))$. Let $\sigma \in L_i$ be a trace in the event log L_i. Then $\Gamma_{\sigma,env(N_i')} \subseteq \Gamma_{\sigma,env(B_i)}$ by Def. 11 and $\delta(\lambda_{env(N_i')}(\sigma)) \geq \delta(\lambda_{env(B_i)}(\sigma))$ by Def. 12 and 13. Thus, $\delta(L_i, N_i') \geq \delta(L_i, B_i)$ by Def. 16. □

Theorem 2 gives a theoretical solution for deciding private view conformance w.r.t. fitness. The question is, how can we actually calculate B_i for a given open net N_i? Here, we reuse existing theory on maximal controllers [14,7]. Interestingly, the environment (i.e., env^s or env^a) we consider when replaying the log file matters only for the construction of B_i.

In the next section, we show that $B_i = mpC(maxC(N_i))$ can actually be calculated, yet for acyclic open nets only. The reason for this restriction is that for acyclic open nets, the correctness notions weak termination and deadlock freedom coincide. The theory for maximal controllers in case of weak termination exists [7], but has not been implemented so far.

4 Experimental Results

Based on a prototypical implementation, we show first experimental results on computing a canonical best matching private view according to Thm. 2. We assume weak termination as a correctness criterion, use the asynchronous environment env^a, and employ the standard distance function δ_S to find the best matching alignments.

For the running example, γ_1–γ_3 are best matching alignments for L and $env(Public)$ with costs $\delta_S(\gamma_1) = 0$, $\delta_S(\gamma_2) = 2$, and $\delta_S(\gamma_3) = 1$, yielding alignment-based costs $\delta(L, env(Public)) = 3$. Likewise, γ_4–γ_6 are best matching alignments for L and $env(Private)$ with costs $\delta_S(\gamma_4) = \delta_S(\gamma_5) = 0$, and $\delta_S(\gamma_6) = 1$. Thus, $\delta(L, env(Private)) = 1$.

We compute the canonical best matching private view B of *Public* in three steps: (1) compute the maximal controller $maxC(Public)$, (2) compute the most permissive controller $B = mpC(maxC(Public))$, and (3) calculate $\delta(L, env(B))$. Figure 4 shows the three steps and the tools involved. Our toolchain consists of a Bash script for deriving a best matching private view using Wendy [12], Maxis[1], the PNapi [10], and ProM[2]. We illustrate our approach in the following.

[1] `http://svn.gna.org/viewcvs/service-tech/trunk/maxis/`
[2] `http://www.promtools.org/`

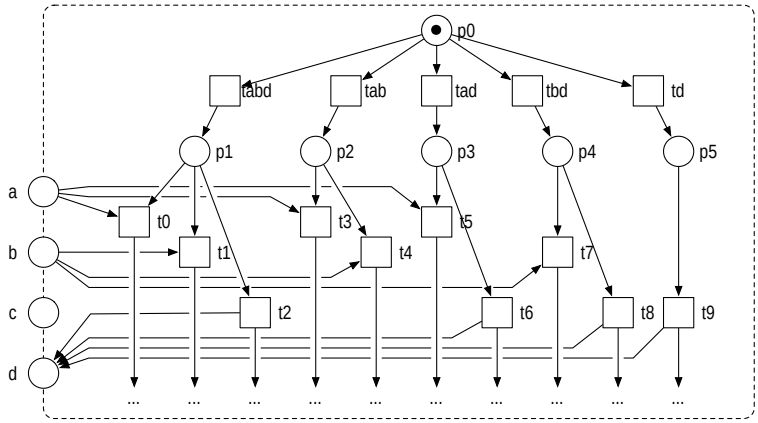


Fig. 5: The maximal controller $maxC(Public)$ of $Public$.

Calculating $maxC(Public)$: Open net $maxC(Public)$ has 34 places and 45 transitions and was constructed following the approach presented in [14]: using the tool Wendy, we constructed an annotated automaton that represents all controllers of $Public$, derived the behavior of $maxC(Public)$ from it using the tool Maxis, and transformed the behavior into an open net using the PNapi. Figure 5 illustrates a part of $maxC(Public)$. As $maxC(Public)$ is a controller of $Public$, it has the same interface as $Public$ with input and output interchanged. Initially, this service fires nondeterministically one of the five transitions $tabd, \ldots, td$. Depending on the state reached, it can perform a number of sending or receiving events. For example, after firing $tabd$, the open net can receive a or b or send d.

Deriving B: In the second step, we calculate the most permissive controller $B = mpC(maxC(Public))$ of $maxC(Public)$. We constructed the behavior of B using the tool Wendy and transformed it into open net B using the PNapi. The resulting open net has 12 places and 22 transitions and is partly depicted in Fig. 6. B and $Public$ are interface-equivalent. Consider the place $empty$. A token on $empty$ corresponds to a marking that is not reachable in the composition of B and any controller of $Public$. As no controller of $Public$ initially sends a message c, transition $t8$ and $t9$ encode such "misbehavior" by producing a token on $empty$. When $empty$ contains a token and hence the composition will not be weakly terminating, every possible sending and receiving of messages is possible; thus, transitions ta, tb, tc, td are connected to the correspondingly labeled interface places (indicated by the respective arcs without source or target). What we can see is that the behavior of $Private$ can be replayed on B. This shows, that it is not wrong to implement a specification such that the resulting implementation has more controllers than the specification. However, the added behavior cannot be used by any controller of the specification. In our example, no controller of $Public$ will initially send message c although there exist implementations such as open net $Private$ that allow such behavior.

Checking conformance with B: By Thm. 2, B is a best matching private view of $Public$. Therefore, in the last step, we calculate the alignment-based cost for L and $env(B)$

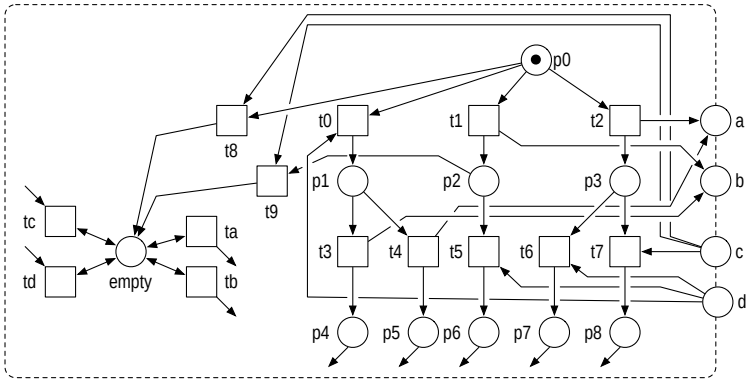


Fig. 6: The best matching private view $B = mpC(maxC(Public))$ of $Public$.

using the latest PNAlignmentAnalysis plug-in from the TU/e SVN repository[3]. We use the A^*-algorithm for cost-based fitness with default options. The best matching alignments for L and $env(B)$ are

$$\gamma_7 = \begin{array}{|c|c|c|c|}\hline \gg & a & d & \gg \\ \hline \tau & a & d & \tau \\ t_2 & t^a & t^d & t_6 \\ \hline \end{array} \quad \gamma_8 = \begin{array}{|c|c|c|c|}\hline \gg & b & c & \gg \\ \hline \tau & b & c & \tau \\ t_1 & t^b & t^c & t_9 \\ \hline \end{array} \quad \gamma_9 = \begin{array}{|c|c|c|c|c|c|}\hline c & \gg & d & \gg & \gg & a \\ \hline c & \tau & d & \tau & \tau & a \\ t^c & t_8 & t^d & td & ta & t^a \\ \hline \end{array}$$

with $\delta(\gamma_7) = \delta(\gamma_8) = \delta(\gamma_9) = 0$ yielding alignment-based costs $\delta(L, env(B)) = 0$. We see that $\delta(L, env(B))$ is indeed lower than $\delta(L, env(Public)) = 3$ and even lower than $\delta(L, env(Private)) = 1$.

We also generated five random public views and event logs using a modified version of the Process Log Generator[4]. This time, we used the synchronous environment env^s for computing the private view conformance with ProM. All experiments were conducted on a MacBook Pro, Intel Core i5 CPU with 2.4 GHz and 8 GB of RAM. The results in Table 1 show that the average cost for each case (using the standard distance function) for conformance checking the log L with the best matching private view B (column 13) is significantly lower than conformance checking L with the public view N (column 11). This detail justifies Thm. 2. However, the lower cost come at a price of an exponentially larger size of B compared to N (columns 1 and 5), which is caused by the construction of B [14]. The net size results in a higher runtime of the A^*-algorithm (last row).

5 Related Work

Research on conformance checking of services follows two lines. One research line assumes a model of the implementation to be given (e.g., [20,5]) or that it is discovered from the event log (e.g., [15]). The former assumption is not always realistic. Furthermore, the result of conformance checking relies on the quality of the (discovered) model.

[3] `https://svn.win.tue.nl/repos/prom/`
[4] `http://www.processmining.it/sw/plg`

Table 1: Fully automatic private view conformance checking of synthetic nets.

public view N				best matching B				event log L		$\delta_S(N,L)$	time	$\delta_S(B,L)$	time
$\|P\|$	$\|I\|$	$\|O\|$	$\|T\|$	$\|P\|$	$\|I\|$	$\|O\|$	$\|T\|$	cases	events	$\delta_S/case$	$ms/case$	$\delta_S/case$	$ms/case$
14	4	2	6	35	4	2	132	100	605	6.21	3.47	0.20	0.34
16	5	3	8	41	5	3	190	100	541	7.53	3.31	0.20	0.88
30	6	3	18	106	6	3	681	100	540	8.26	6.21	0.19	1.41
38	6	4	32	32	6	4	168	100	507	4.89	7.10	0.05	0.17
88	6	5	74	806	6	5	6,060	100	528	7.24	33.93	0.03	45.60

The second research line assumes recorded behavior of the implementation to be given. Here, techniques are adapted from process mining [18,2]. Our contribution follows this research line. Van der Aalst et al. [4] map a contract specified in BPEL onto workflow nets (which can be seen as the synchronous environment) and employ conformance checking techniques from process mining [18]. In contrast, we measure the deviation of an implementation from its specification and all possible private views.

Comuzzi et al. [6] investigate online conformance checking using a weaker refinement notion than accordance. Different conformance relations on a concurrency-enabled model have been studied by De León et al. [8]. As their considered conformance relations differ from accordance, their work is not applicable in our setting (because maximal controllers have not been studied yet).

Motahari-Nezhad et al. [16] investigate event correlation; that is, they try to find relationships between events that belong to the same process execution instance. In contrast to event correlation, we do not vary the service instances, but refine the public view to a private view.

6 Conclusion

We presented an approach to calculate a best matching private view for a given event log and a public view. We proved the existence of a canonical best matching private view and showed that it can be automatically constructed—in the case of acyclic services and weak termination—using existing theory and tools on maximal controllers. Although it is possible to construct maximal controllers for cyclic services and weak termination [7], this has not been implemented yet.

A canonical best matching private view may become exponentially large in net size compared to its public view (see Table 1). It is an open question whether the current cost-based conformance checking techniques can be used for private view conformance checking for industrial service models. Another open question is how our approach can be generalized to deal with other quality dimensions (i.e., precision, generalization, simplicity), as in general there exist many best matching private views for a public view w.r.t. the fitness dimension.

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Event Structures as a Foundation for Process Model Differencing, Part 1: Acyclic processes

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Abstract. This paper considers the problem of comparing process models in terms of their behavior. Given two process models, the problem addressed is that of explaining their differences in terms of simple and intuitive statements. This model differencing operation is needed for example in the context of process consolidation, where analysts need to reconcile differences between process variants in order to produce consolidated process models. The paper presents an approach to acyclic process model differencing based on event structures. First the paper considers the use of prime event structures. It is found that the high level of node duplication inherent to prime event structures hinders on the usefulness of the difference diagnostics that can be extracted thereon. Accordingly, the paper defines a method for producing (asymmetric) event structures with reduced duplication.

1 Introduction

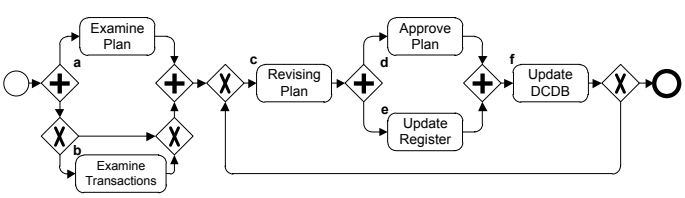
Large companies with mature business process practices often manage multiple versions of the same process. Such variants may stem from distinct products, different types of customers (e.g. corporate vs. private customers), different legislations across countries in which a company operates, or idiosyncratic choices made by multiple business units over time. In some scenarios, analysts need to find ways to consolidate multiple process variants into a single one for the purpose of improving efficiency and creating economies of scale. In this setting, analysts need to accurately understand the differences between multiple variants in order to determine how to reconcile them. In this paper, we define a process model differencing operator that provides intuitive guidance to analysts, allowing them to understand the differences between a pair of process variants.

Behavioral profiles (BPs) [1] are a promising approach to tackle problems pertaining to the management of process variants. The idea behind BPs is to encode a process in terms of behavioral relations between every pair of tasks. In BPs, a pair of tasks is related by one of three types of relations: *strict order*($\mapsto$), *exclusive order*($+$) or *interleaving*($|||$). BPs have been used for defining behavioral similarity metrics [2] and for process comparison and merging [3], among other applications. Nevertheless, BPs suffer from the following issues:

1. *BPs do not correspond to any known notion of equivalence.* Specifically, two processes may have the same BP while not being trace equivalent. Reciprocally, two processes may be trace equivalent, yet have different BPs.

2. *BPs mishandle the following patterns of behavior*: (a) task skipping, (b) behavior inside cycles – which is confused with interleaved parallelism – and (c) duplicate tasks.

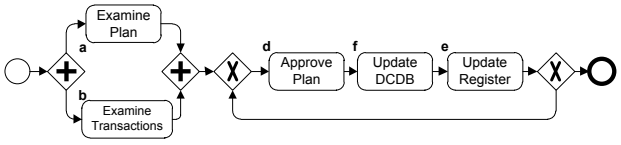
Consider for example the variants of a land development process depicted in Figure 1(a)-(c), and their BPs presented aside. Firstly, even if we abstract away from task "c" both variants are non-trace equivalent, yet their BPs are identical (Issue 1). Secondly, note that task "b" is not always executed in the first variant, meaning that it can be skipped (Figure 1(a)). This fact is not captured in the BPs (Issue 2a). Finally, consider tasks "d","e" and "f" present in both variants. The order in which these tasks are executed is captured in both BPs using the *interleaving* relation. However, the actual order clearly differs between the two variants. This issue stems from the fact that these tasks are contained in a cycle and BPs confuse cycles and interleaved parallelism (Issue 2b).



(a)

	a	b	c	d	e	f
a	+	‖	↦	↦	↦	↦
b	‖	+	↦	↦	↦	↦
c	↤	↤	‖	‖	‖	‖
d	↤	↤	‖	‖	‖	‖
e	↤	↤	‖	‖	‖	‖
f	↤	↤	‖	‖	‖	‖

(b)



(c)

	a	b	d	e	f
a	+	‖	↦	↦	↦
b	‖	+	↦	↦	↦
d	↤	↤	‖	‖	‖
e	↤	↤	‖	‖	‖
f	↤	↤	‖	‖	‖

(d)

Fig. 1. Variants of land development process

The paper makes a step forward by presenting an approach to process model differencing that solves issues 1 and 2a above for acyclic models – although it still suffers from not being able to handle cyclic models nor models with duplicate tasks. The presented approach is based on Event Structures (EVs), which allow us to ensure that two models are treated as equivalent iff they are fully concurrent bisimilar (cf. issue 1). First, the paper considers the use of Prime Event Structures (PES) for process model differencing. However, it is found that PESs inherently involve a significant amount of duplication, which degrades the usefulness of the diagnosis. To address this issue, the use of Asymmetric Event Structures (AES) [4] is considered. It is shown that AES can provide a more compact representation (less duplication), thus leading to a more compact diagnosis of differences.

In the proposed approach, differences between process models are captured by means of a (sparse) matrix wherein each cell represents a difference involving one or two tasks. This matrix can be directly translated into simple and intuitive statements. For instance, the difference between the process models depicted in

Figure 1 can be expressed in terms of statements of the following form:[1] "In model (a), task b **sometimes** precedes $\{d, e, f\}$, whereas in model (b) task b **always** precedes $\{d, e, f\}$", "Task c is present only in model (a)", "In model (a), task d and e are executed in any order, while d always precedes e in model (b)".

The discussion throughout the paper is developed assuming that the input process models are given as Petri nets.

The rest of the paper is organized as follows. Section 2 discusses related work. Section 3 introduces some notions and notation used in the rest of the paper. Section 4 presents the acyclic process model differencing approach based on PES and AES. Finally, Section 5 concludes and discusses directions for future work.

2 Related work

Approaches for process model comparison may be divided into those based on node label similarity, process structure similarity and behavior similarity [5, 6]. In this paper we focus on behavior similarity. Nevertheless, we acknowledge that node label similarity plays an important in the alignment of nodes (e.g., tasks) across the process models being compared. Here, we assume that such an alignment is given, i.e. for each node label in one model we are given the corresponding ("equivalent") node label in the other model. This is equivalent to assuming that the same node labels are used across both models being compared.

There exists a number of equivalence notions for concurrent systems [7]. Several methods for testing the equivalence of two systems according to these notions have been developed. However, most of these methods focus on determining whether or not two systems are equivalent. Relatively few previous research delves into the question of diagnosing all differences between two systems.

Perhaps one of the earliest work on diagnosing concurrent system differences is [8], which presents a technique to derive equations in a process algebra characterizing the differences between two *Labeled Transition Systems* (LTSs). This technique iteratively traverses the data structures used for testing bisimulation equivalence and generates a minimal equation characterizing differences for pairs of states in the input LTSs. However, the use of a process algebra makes the feedback difficult to grasp for end users (process analysts in our context). In [9], a method for assessing the dissimilarity of LTSs in terms of "edit" operations is presented. However, we contend that providing feedback in the form of a series of elementary edit operations (add or remove events) is not simple and intuitive, since it does not directly tell the analyst what relations exist in one model that do not exist in the other. [10] presents a method for diagnosing differences between pairs of process models using standard automata theory. Differences between a pair of models are captured by means of templates of the form "a node in a model has more dependencies than in the other one" or "a node in a model may be executed multiple times in one model but at most once in the other". The method of [10] suffers from two major limitations. First, the set of reported

[1] Note that the cycle is not taken into account in this comparison.

differences is not guaranteed to be complete. Second, the differences are given in a coarse-grained manner. With respect to the example in Figure 1, [10] gives as diagnosis that task "c" has additional dependencies in the first model viz. the second, without explaining the additional dependencies. We note that all three techniques above rely on LTSs and are not able to recognize concurrency relations. Thus, these techniques do not diagnose differences such as "in one model two tasks are done concurrently while in another they are done in sequence."

In this paper, we rely on event structures to capture the behavior of process models. Event structures represent concurrent systems in terms of behavioral relations between events. Other representations of process models in terms of behavioral relations have been proposed in the literature. *Causal footprints* [11] represent behavior as a set of tuples, each comprising a task, its preset, and its postset. These sets of tuples are then mapped to points in a vector space and euclidian distance is used to compute a metric of similarity between a given pair of footprints. This technique however is not intended to provide a diagnosis of differences between pairs of models. Alpha relations are another example of a representation of process models using behavioral relations [12]. Alpha relations include direct causality, conflict and concurrency, and are derived from execution logs for the purpose of process mining. Alpha causality is not transitive. This choice makes alpha relations unsuitable for process model comparison, because causality has a localized scope. Moreover, alpha relations cannot capture so-called "short loops" and hidden tasks (including scenarios where a task may be skipped). The ordering relations graph [13–15] is another representation of (acyclic) process models in terms behavioral relations. However, it too has problems with hidden tasks. The class of asymmetric event structures characterized in the present paper is a refinement of the ordering relations graph.

3 Preliminaries

This section covers basic concepts on Petri nets and partially ordered sets. In particular, the notions of *branching processes*, *behavior relations*, and *fully concurrent bisimulation* are reviewed because they are cornerstones to our approach.

3.1 Petri nets

Definition 1 (Petri net, Net system). *A tuple* (P, T, F) *is a* Petri net*, where* P *is a set of* places*,* T *is a set of* transitions*, with* $P \cap T = \emptyset$*, and* $F \subseteq (P \times T) \cup (T \times P)$ *is a set of arcs. A* marking $M : P \to \mathbb{N}_0$ *is a function that associates each place* $p \in P$ *with a natural number (viz., place tokens). A* net system $N = (P, T, F, M_0)$ *is a Petri net* (P, T, F) *with an* initial marking M_0*.*

Places and transitions are conjointly referred to as *nodes*. We write $\bullet y = \{x \in P \cup T \mid (x, y) \in F\}$ and $y\bullet = \{z \in P \cup T \mid (y, z) \in F\}$ to denote the *preset* and *postset* of node y, respectively. F^+ and F^* denote the irreflexive and reflexive transitive closure of F, respectively.

The semantics of a net system can be defined in terms of markings. A marking M *enables* a transition t if $\forall p \in \bullet t : M(p) > 0$. Moreover, the occurrence of t leads to a new marking M', with $M'(p) = M(p) - 1$ if $p \in \bullet t \setminus t\bullet$, $M'(p) = M(p) + 1$ if $p \in t\bullet \setminus \bullet t$, and $M'(p) = M(p)$ otherwise. We use $M \xrightarrow{t} M'$ to denote the occurrence of t. The marking M_n is said to be reachable from M if there exists a sequence of transitions $\sigma = t_1 t_2 \dots t_n$ such that $M \xrightarrow{t_1} M_1 \xrightarrow{t_2} \dots \xrightarrow{t_n} M_n$. A marking M of a net is *n-safe* if $M(p) \leq n$ for every place p. A net system N is said *n-safe* if all its reachable markings are *n-safe*. In the following we restrict ourselves to *1-safe* net systems. Hence, we identify the marking M with the set $\{p \in P \mid M(p) = 1\}$.

A labeled Petri net $N = (P, T, F, \lambda)$ is a net (P, T, F), where $\lambda : P \cup T \to \Lambda \cup \{\tau\}$ is a function that associates a node with a label. Given a node x, if $\lambda(x) \neq \tau$ then x is said to be *observable*, otherwise x is said to be *silent*. A labeled net system $N = (P, T, F, M_0, \lambda)$ is similarly defined. An example of labeled net system is shown in Figure 2. There, transitions display their corresponding label inside the rectangle. Note that t_2 is a silent transition, hence $\lambda(t_2) = \tau$. Herein, we consider each place to be labeled with its corresponding identifier, e.g., $\lambda(p_0) = p_0$. The labeling of places is introduced for technical reasons and its usage will be clarified later on (cf., Definition 9).

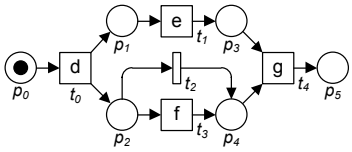


Fig. 2. A labeled net system

3.2 Deterministic and branching processes

The partial order semantics of a net system is commonly formulated in terms of runs or, more precisely, prefixes of runs that are referred to as *deterministic processes* [16]. A process itself can be represented as an acyclic net with no branching nor merging places, i.e., $\forall p \in P : |\bullet p| \leq 1 \wedge |p\bullet| \leq 1$. Alternatively, all runs can be accommodated in a single tree-like structure, called *branching process* [17], that may contain branching places and explicitly represents three behavior relations: *causality*, *concurrency* and *conflict* defined as follows.

Definition 2 (Behavior relations). *Let $N = (P, T, F)$ be a net and $x, y \in P \cup T$ two nodes in N.*

- *x and y are in* causal *relation, denoted as $x <_N y$, iff $(x, y) \in F^+$. The* inverse causality *relation is denoted $>_N$. We use $\leq_N$ to the denote the* reflexive causality *relation.*
- *x and y are in* conflict*, denoted as $x \#_N y$, iff there exist two transitions $t, t' \in T$ such that t and t' are distinct, $\bullet t \cap \bullet t' \neq \emptyset$, and $(t, x), (t', y) \in F^*$. If $x \#_N x$ then x is said to be in* self-conflict*.*
- *x and y are* concurrent*, denoted as $x \|_N y$, iff neither $x <_N y$, nor $y <_N x$, nor $x \#_N y$.*

The tuple $\mathcal{R} = (<_N, \#_N, \|_N)$ denotes the behavior relations of N. We can now provide a formal definition for branching process.

Definition 3 (Branching process). *Let $N = (P, T, F, M_0)$ be a net system. The* branching process $\beta = (B, E, G, \rho)$ *of N is the net (B, E, G) defined by the inductive rules in Figure 3. The rules also define the function $\rho : B \cup E \to P \cup T$ that maps each node in β to a node in N. $\varrho(B)$ is a shorthand for $\bigcup_{b \in B} \rho(b)$.*

$$\frac{p \in M_0}{b = \langle \varnothing, p \rangle \in B \qquad \rho(b) = p}$$

$$\frac{t \in T \quad B' \subseteq B \quad B'^2 \subseteq \|_\beta \quad \varrho(B') = {\bullet t}}{e = \langle B', t \rangle \in E \qquad \rho(e) = t}$$

$$\frac{e = \langle B', t \rangle \in E \qquad t\bullet = \{p_1, \ldots, p_n\}}{b_i = \langle t', p_i \rangle \in B \qquad \rho(b_i) = p_i}$$

Fig. 3. Branching process, inductive rules

For sake of clarity, the elements of B and E in a branching process are called *conditions* and *events*, respectively. $Min(\beta)$ denotes the set of minimal elements of $B \cup E$ with respect to the transitive closure of G. Henceforth, $Min(\beta)$ corresponds to the set of places in the initial marking of N, i.e., $\varrho(Min(\beta)) = M_0$. Figure 4 presents the branching process of the net system from Figure 2. Note that every node in the branching process has multiple labels. The label outside of the node, say "$e_0(t_0)$", indicates that the underlying event is named "e_0" and that it corresponds to transition "t_0" in the net system. The events in the branching process also display the label in the original net system, e.g., "d". This label can be determined by a composition of functions λ and ρ, i.e., $\lambda_\beta =_{def} \lambda_N \circ \rho_\beta$.

One important characteristic of a branching process is that it does not contain merging conditions. To overcome this restriction, some nodes in the net system need to be represented more than once in the branching process. When comparing Figure 2 and Figure 4, we can notice that place p_4 corresponds to both conditions b_4 and b_5, place p_5 corresponds to b_6 and b_7, and that transition t_4 corresponds to events e_4 and e_5.

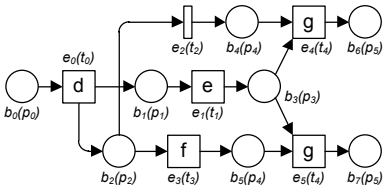


Fig. 4. Branching process of the net system in Figure 2

Engelfriet [16] showed that every Petri net has a unique (possibly infinite) maximal branching process up to isomorphism, a.k.a. *net unfolding*. The branching process of an acyclic net system is finite.

We continue by formally defining *deterministic processes*, which will be used for introducing the notion of equivalence we rely on, namely *fully concurrent bisimulation*. By the same token, we introduce the notion of *configuration*.

Definition 4 (Configuration, deterministic process). *Let $N = (P, T, F, M_0)$ be a net system and $\beta = (B, E, G, \rho)$ its corresponding branching process.*

- *A* configuration *C of β is a set of events, $C \in E$, such that:*
  - *i) C is causally closed, i.e., $e \in C \Rightarrow e' \leq_\beta e : e' \in C$, and*
  - *ii) C is conflict free, i.e., $\forall e, e' \in C : \neg(e \#_\beta e')$.*
- *A* deterministic process *$\pi = (B_\pi, E_\pi, G_\pi, \rho)$ is the net induced by a configuration C, where $B_\pi = {\bullet C} \cup C\bullet$, $E_\pi = C$, and $G_\pi = G \cap (B_\pi \times E_\pi \cup E_\pi \times B_\pi)$.*
- *The* initial deterministic process *of N, denoted $\hat{\pi}$, is the process induced by the empty configuration $C = \varnothing$.*

Let C and C' be configurations of β, such that $C \subset C'$, and π and π' be the processes induced by C and C', respectively. Moreover, if $X = C' \setminus C$, then we write $\pi' = \pi \oplus X$ and we say that π' is an *extension* of π. Given a process π we are interested in extensions to π appending exactly one observable event, whenever such extension exists, i.e., $\pi \oplus X$ such that $|\{x \mid x \in X \wedge \lambda_\beta(x) \neq \tau\}| = 1$. With abuse of notation, we shall write $\pi \oplus_\lambda X$ to denote a process extension with exactly one observable event. In a branching process, each event e can be associated with a unique set of events that causally precede e, denoted $\lceil e \rceil = \{e' \mid e' \leq e\}$, and referred to as the *local configuration* of e.

3.3 Fully Concurrent Bisimulation

The notion of equivalence that we adopt in this work is known as *fully concurrent bisimulation* [18]. This bisimulation can be informally stated as follows: given two net systems, any sequence of observable events (viz., run or process) that might be possibly performed by one net system must also be possibly performed by the other net system and vice-versa, as for other conventional bisimulations, but additionally causal dependencies between observable events must be preserved in the bisimulation. The latter is required to be in-line with the partial order semantics. Below, we provide the corresponding formal definition.

Definition 5 (Fully concurrent bisimulation). *Let $N_1 = (P_1, T_1, F_1, M_0^1, \lambda_1)$ and $N_2 = (P_2, T_2, F_2, M_0^2, \lambda_2)$ be labeled net systems, and $\beta_1 = (B_1, E_1, G_1, \rho_1)$ and $\beta_2 = (B_2, E_2, G_2, \rho_2)$ be their corresponding branching processes. The set of triples $\mathcal{B} \subseteq \Pi_1 \times \Gamma \times \Pi_2$ is a* fully concurrent bisimulation *for N_1 and N_2* iff*:*

- *Π_1 and Π_2 are the set of deterministic processes of N_1 and N_2, respectively, and $\Gamma : E_1 \to E_2$ is a relation from observable events in β_1 to observable events in β_2.*
- *If $\hat{\pi}_1$ and $\hat{\pi}_2$ are the initial deterministic processes of N_1 and N_2, respectively, then $(\hat{\pi}_1, \varnothing, \hat{\pi}_2) \in \mathcal{B}$.*
- *Γ is a bijection w.r.t. labeling, i.e., $\forall e \in Dom(\Gamma) : \lambda_{\beta_1}(e) = \lambda_{\beta_2}(\Gamma(e))$, preserving causality, i.e., $\forall e, e' \in Dom(\Gamma) : e <_{\pi_1} e' \Leftrightarrow \Gamma(e) <_{\pi_2} \Gamma(e')$.*
- *$\forall (\pi_1, \Gamma, \pi_2) \in \mathcal{B}$:*
  - *a) if $\pi_1' = \pi_1 \oplus_{\lambda_1} X_1$ is an extension of π_1 with exactly one observable event, then there exists a tuple $(\pi_1', \Gamma', \pi_2') \in \mathcal{B}$ with $\pi_2' = \pi_2 \oplus_{\lambda_2} X_2$ and $\Gamma \subseteq \Gamma'$.*
  - *b) if $\pi_2' = \pi_2 \oplus_{\lambda_2} X_2$ is an extension of π_2 with exactly one observable event, then there exists a tuple $(\pi_1', \Gamma', \pi_2') \in \mathcal{B}$ with $\pi_1' = \pi_1 \oplus_{\lambda_1} X_1$ and $\Gamma \subseteq \Gamma'$.*

Two net systems N_1 and N_2 are said fully concurrent bisimulation equivalent*, denoted $N^1 \approx_{fcb} N^2$, if there exists a fully concurrent bisimulation for them.*

Note that fully concurrent bisimulation is defined in terms of process extensions with exactly one observable event and, hence, there is implicitly an abstraction of invisible behavior. This abstraction is convenient for our purposes, such that we lift it to the level of behavior relations. Let $N = (P, T, F, M_0, \lambda)$ be a labeled net system and $\beta = (B, E, G, \rho)$ be its branching process. Moreover, let E' be the set of observable events, i.e., $E' = \{e \mid e \in E \wedge \lambda_\beta(e) \neq \tau\}$. Then

$\mathcal{R}|_\lambda = (<_\beta \cap E'^2, \#_\beta \cap E'^2, \|_\beta \cap E'^2)$ defines the *observable behavior relations*, that is the behavior relations of N restricted to observable behavior.

If there exists a mapping of transitions in two net systems such that this mapping preserves their underlying behavior relations, then we say their behavior relations are isomorphic. This is formally defined as follows.

Definition 6 (Isomorphism of observable behavior relations). *Let* $N_1 = (P_1, T_1, F_1, M_0^1, \lambda_1)$ *and* $N_2 = (P_2, T_2, F_2, M_0^2, \lambda_2)$ *be labeled net systems, and* $\beta_1 = (B_1, E_1, G_1, \rho_1)$ *and* $\beta_2 = (B_2, E_2, G_2, \rho_2)$ *be their corresponding branching processes. Moreover, let* $E_1' \subseteq E_1$ *and* $E_2' \subseteq E_2$ *be the set of observable events of the branching processes of* N_1 *and* N_2*, and* $\mathcal{R}|_{\lambda_1}$ *and* $\mathcal{R}|_{\lambda_2}$ *their corresponding observable behavior relations.* $\mathcal{R}|_{\lambda_1}$ *and* $\mathcal{R}|_{\lambda_2}$ *are said* isomorphic*, denoted* $\mathcal{R}|_{\lambda_1} \cong \mathcal{R}|_{\lambda_2}$*,* iff *there exists a bijection* $\varphi : E_1' \to E_2'$ *such that:*

- $\forall e \in E_1' : \lambda_{\beta_1}(e) = \lambda_{\beta_2}(\varphi(e))$*, and*
- $\forall e, e' \in E_1' : (e <_{\beta_1} e' \Leftrightarrow \varphi(e) <_{\beta_2} \varphi(e')) \vee (e \#_{\beta_1} e' \Leftrightarrow \varphi(e) \#_{\beta_2} \varphi(e')) \vee (e \|_{\beta_1} e' \Leftrightarrow \varphi(e) \|_{\beta_2} \varphi(e'))$*.*

The following Theorem establishes the relation between fully concurrent bisimulation equivalence and isomorphism of observable behavior relations for two net systems. The corresponding proof can be found in [13].

Theorem 1 ([13]). *Let* $N_1 = (P_1, T_1, F_1, M_0^1, \lambda_1)$ *and* $N_2 = (P_2, T_2, F_2, M_0^2, \lambda_2)$ *be labeled net systems, and* $\beta_1 = (B_1, E_1, G_1, \rho_1)$ *and* $\beta_2 = (B_2, E_2, G_2, \rho_2)$ *be their corresponding branching processes with distinctive labelings. Moreover, let* $E_1' \subseteq E_1$ *and* $E_2' \subseteq E_2$ *be the set of observable events of* β_1 *and* β_2*, respectively. Assume there exists a bijection* $\psi : E_1' \to E_2'$ *such that* $\forall e \in E_1' : \lambda_{\beta_1}(e) = \lambda_{\beta_2}(\psi(e))$*, then the following holds:*

$$N_1 \approx_{fcb} N_2 \quad \Leftrightarrow \quad \mathcal{R}|_{\lambda_1} \cong \mathcal{R}|_{\lambda_2}$$

3.4 Partial Ordered Sets

We conclude this section by recalling some definitions from the theory of partial ordered sets (posets) [17]. Let $\langle D, \sqsubseteq \rangle$ be a poset. For a subset X of D, an element $y \in D$ is an upper (lower) bound of X, iff $x \sqsubseteq y$ ($x \sqsupseteq y$), for each element $x \in X$. An element $y \in D$ is a greatest (least) element, iff for each element $x \in D$ the property $x \sqsubseteq y$ ($x \sqsupseteq y$) holds. An element $y \in D$ is a maximal (minimal) element, iff there is no element $x \in D$ s.t. $y \sqsubset x$ ($x \sqsubset y$); D_{max} and D_{min} denote the sets of maximal and minimal elements of D, respectively. Two elements $x, y \in D$ are *consistent*, denoted $x \uparrow y$, iff they have a joint upper bound, i.e., $x \uparrow y \Leftrightarrow \exists\ z \in D : x \sqsubseteq z \wedge y \sqsubseteq z$; otherwise, they are said *inconsistent*. A subset X of D is *pairwise consistent*, written $X^{\Uparrow}$, iff every pair of elements in X is consistent in D, i.e., $X^{\Uparrow} \Leftrightarrow \forall x, y \in X : x \uparrow y$. A poset $\langle D, \sqsubseteq \rangle$ is *coherent*, iff each pairwise consistent subset X of D has a least upper bound (lub) $\sqcup X$. An element $x \in D$ is a *complete prime*, iff for each subset X of D, with lub $\sqcup X$, it holds $x \sqsubseteq \sqcup X \Rightarrow \exists\ y \in X : x \sqsubseteq y$. We shall write $\mathbb{P}_P$ to denote the set of complete primes of a poset P. A poset $P = \langle D, \sqsubseteq \rangle$ is *prime algebraic*, iff $\mathbb{P}_P$ is denumerable

and every element in D is lub of the set of complete primes it dominates, i.e., $\forall\ x \in D : x = \sqcup\{y \mid y \in \mathbb{P}_P\ \wedge\ y \sqsubseteq x\}$. A set S is *denumerable*, iff it is empty or there exists an enumeration of S that is a surjective mapping from the set of positive integers onto S.

4 Comparison of acyclic process models

In this section, we explore the use of event structures (EVs) in the process model differencing. The presentation is organized in two parts. Subsection 4.1 introduces the more basic EV, namely *Prime Event Structures* (PESs). By the same token, we define an operator on event structures, that operationalizes the comparison of behavior relations. In spite of their faithful representation of behavior, PESs incur in a great amount of duplication. In Subsection 4.2, we consider *Asymmetric Event Structures* (AESs) as an alternative representation that reduces the amount of duplication observed in PESs.

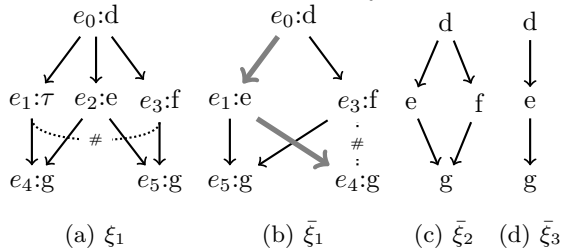
4.1 Prime Event Structures

A *Prime Event Structure* (PES) is a model for computation introduced in [17]. Aligned with the concepts of in the previous section, we formally define PESs.

Definition 7 ((Labeled) Prime Event Structure). *Let $N = (P, T, F, M_0, \lambda)$ be a net system and $\beta = (B, E, G, \rho)$ be its corresponding branching process. The* prime event structure *of β is the tuple $\xi = (E,\ \leq_\xi,\ \#_\xi)$, where $\leq_\xi = \leq_\beta \cap E^2$ and $\#_\xi = \#_\beta \cap E^2$. A* labeled prime event structure *also considers a labeling function $\lambda_\xi = \lambda_N \circ \rho$, that associates each event $e \in E$ with the label of its corresponding transition $t \in T$, i.e., $\lambda_\xi(e) = \lambda_N(t)\ \Rightarrow\ \rho(e) = t$.*

The conflict relation $\#_\xi$ is said *hereditary* w.r.t. $\leq_\xi$, meaning that for all $e, e', e'' \in E$, if $e\ \#_\xi\ e'$ and $e' \leq_\xi e''$ then $e\ \#_\xi\ e''$. The behavior relations of a PES $\xi = (E,\ \leq_\xi,\ \#_\xi)$ are given by the tuple $\mathcal{R}_\xi = (<_\xi,\ \#_\xi,\ E^2 \setminus (<_\xi \cup >_\xi \cup \#_\xi))$ [17]. Clearly, PES behavior relations correspond to the behavior relations of the corresponding branching process as introduced in Definition 2, restricted to the set of events. Armed with Theorem 1, we can restrict our focus to observable behavior. A PES without invisible behavior shall be denoted $\bar{\xi}$.

Figs. 5(a) and 5(b) present the PESs with and without invisible behavior for the net system in Fig. 2, as labeled graphs. There, nodes correspond to events, (solid) directed edges represent causality, e.g., e_0:d $\longrightarrow$ e_1:e in Figure 5(b), whereas (dotted, decorated) undirected edges represent conflict, e.g., e_3:f $\cdot\cdot\#\cdot\cdot$ e_4:g also in Figure 5(b). Both transitive causal and hereditary conflict



(a) ξ_1 (b) $\bar{\xi}_1$ (c) $\bar{\xi}_2$ (d) $\bar{\xi}_3$

Fig. 5. Examples of prime event structures

	e_0:d	e_1:e	e_3:f	e_4:g	e_5:g
e_0:d	∥	<	<	<	<
e_1:e	>	∥	∥	<	<
e_3:f	>	∥	∥	#	<
e_4:g	>	>	#	∥	#
e_5:g	>	>	>	#	∥

(a) $\mathcal{R}_{\bar{\xi}_1}$

	d	e	f	g
d	∥	<	<	<
e	>	∥	∥	<
f	>	∥	∥	<
g	>	>	>	∥

(b) $\mathcal{R}_{\bar{\xi}_2}$

	d	e	g
d	∥	<	<
e	>	∥	<
g	>	>	∥

(c) $\mathcal{R}_{\bar{\xi}_3}$

Fig. 6. Matrix representation

relations are not shown to simplify the graph. When a pair of events is neither direct nor transitively connected, such events are considered to be concurrent. To further simplify the graphs, nodes in a PES will only display event labels and not their identifiers, when it is clear from the context, e.g., Figures 5(c)–(d).

The PES $\bar{\xi}_2$ is a variant of behavior for the net system in Figure 2, where the transition labeled f is not skipped (i.e., the silent transition t_2 is not present). The differences in behavior of $\bar{\xi}_1$ and $\bar{\xi}_2$ are evident. There is one run in $\bar{\xi}_1$ involving events $\{d, e, g\}$, cf., path highlighted with thick gray edges, and that is not present in $\bar{\xi}_2$. Note that the occurrence of event e_4:g precludes that of event e_3:f, because they are "in conflict", which corresponds with the intuition that the transition labeled f may be skipped.

Alternatively, the behavior relations of PESs can be represented with matrices, as illustrated in Figure 6. The subindexes of the relations were omitted for the sake of readability. As usual, we write $\mathcal{R}_\xi[e, e']$ to refer to the cell in the intersection of the row associated to event e and the column of e'. Therefore, $\mathcal{R}_{\bar{\xi}_2}[e, f] = \|$ asserts the fact that events e and f are concurrent in $\bar{\xi}_2$. Note that all behavior relations are represented in the matrix, including the inverse causal relation. Moreover, every event is self-concurrent, that by definition.

In order to characterize the differences on the behavior relations displayed by two PESs, we define a binary operator as follows.

Definition 8 (Symmetric difference of PES behavior relations). *Let $\xi_1 = (E_1, \leq_{\xi_1}, \#_{\xi_1}, \lambda_{\xi_1})$ and $\xi_2 = (E_2, \leq_{\xi_2}, \#_{\xi_2}, \lambda_{\xi_2})$ be labeled prime event structures, and let $\mathcal{R}_{\xi_1} = (<_{\xi_1}, \#_{\xi_1}, \|_{\xi_1})$ and $\mathcal{R}_{\xi_2} = (<_{\xi_2}, \#_{\xi_2}, \|_{\xi_2})$ be their corresponding behavior relations. The matching of events w.r.t. labelings $\mu \subseteq E_1 \times E_2$ and $\breve{\mu} \subseteq E_1 \cup \{\omega\} \times E_2 \cup \{\omega\}$, where ω is a marker for identifying missing events, are defined as follows:*

- $\mu = \{(e_1, e_2) \mid e_1 \in E_1 \ \wedge \ e_2 \in E_2 \ \wedge \ \lambda_{\xi_1}(e_1) = \lambda_{\xi_2}(e_2)\}$, *and*
- $\breve{\mu} = \mu \ \cup \ \{(e_1, \omega) \mid e_1 \in (E_1 \setminus \mathrm{Dom}(\mu))\} \ \cup \ \{(\omega, e_2) \mid e_2 \in (E_2 \setminus \mathrm{Ran}(\mu))\}$.

Let $(e_1, e_2), (e_1', e_2') \in \breve{\mu}$ be event matchings. The symmetric difference *of $\mathcal{R}_{\xi_1}$ and $\mathcal{R}_{\xi_2}$, denoted $\mathcal{R}_{\xi_1} \vartriangle \mathcal{R}_{\xi_2}$, is defined as follows:*
$\mathcal{R}_{\xi_1} \vartriangle \mathcal{R}_{\xi_2}\,[(e_1, e_2), (e_1', e_2')] =$

$$\begin{cases} \cdot & \text{if } \mathcal{R}_{\xi_1}[e_1, e_1'] = \mathcal{R}_{\xi_2}[e_2, e_2'] \\ (\mathcal{R}_{\xi_1}[e_1, e_1'], \mathcal{R}_{\xi_2}[e_2, e_2']) & \text{if } \mathcal{R}_{\xi_1}[e_1, e_1'] \neq \mathcal{R}_{\xi_2}[e_2, e_2'] \\ (\omega, \ \mathcal{R}_{\xi_2}[e_2, e_2']) & \text{if } e_1 = \omega \text{ or } e_1' = \omega \\ (\mathcal{R}_{\xi_1}[e_1, e_1'], \ \omega) & \text{if } e_2 = \omega \text{ or } e_2' = \omega \end{cases}$$

where ω stands for unspecified behavior relation.

	(d,d)	(e,e)	(f,f)	(e_5:g,g)	(e_4:g,g)
(d,d)	·	·	·	·	·
(e,e)	·	·	·	·	·
(f,f)	·	·	·	·	$(\#, <)$
(e_5:g,g)	·	·	·	·	$(\#, \parallel)$
(e_4:g,g)	·	·	$(\#, >)$	$(\#, \parallel)$	·

(a) $\mathcal{R}_{\bar{\xi}_1} \triangle \mathcal{R}_{\bar{\xi}_2}$

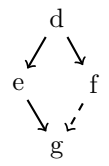
	(d,d)	(e,e)	(f,ω)	(g,g)
(d,d)	·	·	$(<, \omega)$	·
(e,e)	·	·	$(\parallel, \omega)$	·
(f,ω)	$(>, \omega)$	$(\parallel, \omega)$	$(\parallel, \omega)$	$(<, \omega)$
(g,g)	·	·	$(>, \omega)$	·

(b) $\mathcal{R}_{\bar{\xi}_2} \triangle \mathcal{R}_{\bar{\xi}_3}$

Fig. 7. Example symmetric difference of the behavior relations of PESs in Figure 5

Figures 7(a) presents the symmetric difference of the behavior relations of PES $\bar{\xi}_1$, $\bar{\xi}_2$ (cf., Figure 5). Every cell filled up with "·" stands for a perfect match on the behavior of the process models being compared. Interestingly, in this example a large portion of behavior is matched. Let us consider the last column in the matrix. Due to the symmetry of the relations, the analysis of the last row would lead to similar conclusions. On the one hand, $\mathcal{R}_{\bar{\xi}_1} \triangle \mathcal{R}_{\bar{\xi}_2}[(\text{f,f}), (e_4\text{:g,g})] = (\#, <)$ should be read as *"for the first process model, in some cases, task f is in conflict with task g whereas in the other process model task f always precedes task g"*. On the other hand, $\mathcal{R}_{\bar{\xi}_1} \triangle \mathcal{R}_{\bar{\xi}_2}[(e_5\text{:g,g}), (e_4\text{:g,g})] = (\#, \parallel)$ should be read as *"in the first process model task g is involved in two different computations (i.e., runs) that are in conflict"*. It should be recalled that, by definition, task g is self-concurrent. The matrix in Figure 7(b) illustrates the case of missing tasks. The interpretation of this matrix is rather simple: $\mathcal{R}_{\bar{\xi}_2} \triangle \mathcal{R}_{\bar{\xi}_3}[(d,d), (f,\omega)] = (<, \omega)$ should be read as *"task f is only present in the first process model where, additionally, d precedes f"*, and so forth.

PESs provide a faithful representation of behavior but at the expense of duplication. This duplication stems from the fact that a new branch in the branching process is started at the point where each conflict place is found. Conversely, concurrency does not induce duplication. Hence, in the worst case scenario the number of events is exponential in size w.r.t. the maximal fan-out of the conflict places, i.e., $O(m^n)$ where n is the number of events and m is the average size of the poset of places. An additional side-effect is that the comparison of PESs requires a combinatorial number of matches among duplicate events.



(a) ϑ_1

	d	e	f	g
d	$\parallel$	<	<	<
e	>	$\parallel$	$\parallel$	<
f	>	$\parallel$	$\parallel$	->
g	>	>	<-	$\parallel$

(b) $\mathcal{R}_{\vartheta_1}$

	(d,d)	(e,e)	(f,f)	(g,g)
(d,d)	·	·	·	·
(e,e)	·	·	·	·
(f,f)	·	·	·	$(<, \rightarrow)$
(g,g)	·	·	$(>, \leftarrow)$	·

(c) $\mathcal{R}_{\bar{\xi}_2} \triangle \mathcal{R}_{\vartheta_1}$

Fig. 8. Comparison with AESs

4.2 Asymmetric Event Structures

To address the problems above, we consider an alternative to PESs known as *Asymmetric Event Structures* (AESs) [4]. In addition to the usual causality relation $\leq$, an AES introduces the *asymmetric conflict* relation $\rightarrow$. Given two events $e, e' \in E$, we say that e is in asymmetric conflict with e', denoted $e \rightarrow e'$, with

two intuitive interpretations: (i) whenever both e and e' occur in a run, e is observed before e', and (ii) the occurrence of e' precludes that of e. We note that in the original definition of AES, duplication of events is not a concern. Henceforth, we develop an approach to identifying the asymmetric conflict relation. We note that in [4] an AES is derived from a PES keeping the same number of events. Therefore, we develop an approach to identifying the asymmetric conflict relation while reducing the number of events.

When comparing the AES ϑ_1 (cf., Figure 8(a)) with the PES $\bar{\xi}_1$ (cf., Figure 5(b)), both of them displaying the observed behavior of the net system in Figure 2, one can immediately note a more compact representation. While in $\bar{\xi}_1$, there are two events with the same label, namely $e4$:g and $e5$:g, in ϑ_1 only one event carries the label g. It turns out that the PES $\bar{\xi}_2$ (cf., Figure 5(c)) is also an AES, such that we can compare the observable behavior relations $\mathcal{R}_{\bar{\xi}_2}$ and $\mathcal{R}_{\vartheta_1}$ directly. The corresponding symmetric difference is presented in Figure 8(c).

In the following, we present a method to compute the asymmetric conflict relation. We start by computing an equivalence relation on the underlying branching process that relies on node labeling and that respects the local environment of events[2]. Such an equivalence, referred to as *future equivalence*, has been introduced in [19] and can be formally stated as follows.

Definition 9 (Future equivalence). *Let $\beta = (B, E, G, \rho, \lambda_\beta)$ be a labeled branching process. The relation $\sim \subseteq B^2 \cup E^2$ on nodes of β is a* future equivalence *iff:*

- $\forall x, x' \in B \cup E : x \sim x' \Rightarrow \lambda_\beta(x) = \lambda_\beta(x') \ \wedge (\ x \ \#_\beta \ x' \vee \ x = x')$*, and*
- $\forall e, e' \in E : e \sim e' \Rightarrow \langle \bullet e \rangle_\sim = \langle \bullet e' \rangle_\sim \ \wedge \ \langle e \bullet \rangle_\sim = \langle e' \bullet \rangle_\sim$.

where $\langle x \rangle_\sim = \{x' \mid x' \sim x\}$ and $\langle X \rangle_\sim = \{\langle x \rangle_\sim \mid x \in X\}$.

Going back to the branching process in Figure 4, its corresponding future equivalence relation is $\{\{e_4{:}\mathrm{g}, e_5{:}\mathrm{g}\}, \{b_4{:}p_4, b_5{:}p_4\}, \{b_6{:}p_5, b_7{:}p_5\}\}$. Interestingly, the future equivalence relation can be used to *fold* a branching process into a Petri net that exhibits the same behavior (see [19, Theorem 8.7] for a formal proof). Indeed, after merging all future equivalent nodes of the branching process in Figure 4, we shall obtain the Petri net in Figure 2. An algorithm to compute future equivalences suitable for our setting is described in [20]. In contrast to previous work, we require future equivalent nodes to be in conflict: merging two concurrent events would eliminate one event from the run, merging two causal events would introduce a loop, both cases are undesirable in our setting.

Intuitively, an equivalence class $\langle e \rangle_\sim$ identifies a set of nodes in a branching process from which runs evolve isomorphically. Conversly, an equivalence class $\langle e \rangle_\sim$ can possibly have multiple different causes, collectively referred to as *history*. Such an intuition is formally defined as $\mathcal{H}(e) = \{\lceil e' \rceil \mid e' \in \langle e \rangle_\sim\}$. Now, let $e \in E$ be an event, then (i) the events in $\bigcap \mathcal{H}(e)$ are the *strict causes* of e, i.e., every event $e' \in \bigcap \mathcal{H}(e)$ is always observed before e, independently of the run, (ii) the events in $\bigcup \mathcal{H}(e) \setminus \bigcap \mathcal{H}(e)$ are the *weak causes* of e, i.e., every event $e' \in \bigcup \mathcal{H}(e) \setminus \bigcap \mathcal{H}(e)$ is observed before e in at least one run, but not in all runs. The notion of weak

[2] The environment of an event is the set of conditions in its preset and postset.

causes of an event is indeed the way we use for identifying the *asymmetric conflict* relation. The following definition formalizes the transformation of an AES.

Definition 10 (Branching process to AES). *Let $\beta = (B, E, G, \rho, \lambda_\beta)$ be a labeled branching process, and let $\sim$ be a future equivalence on β. The tuple $\vartheta = (E_\vartheta, \leq^{\text{full}}_\vartheta, \#_\vartheta, \dashrightarrow_\vartheta, \lambda_\vartheta)$ is the* asymmetric event structure *(AES) of β induced by $\sim$, where*

$$
\begin{array}{lcl}
E_\vartheta & = & \{\langle e\rangle_\sim \mid e \in E\},\\
\leq^{\text{full}}_\vartheta & = & \{(\langle e\rangle_\sim, \langle e'\rangle_\sim) \mid e, e' \in E \ \wedge \ e \leq_\beta e'\},\\
\#_\vartheta & = & \{(\langle e\rangle_\sim, \langle e'\rangle_\sim) \mid e, e' \in E \ \wedge \ (e, e') \in \#_\beta \setminus \sim\},\\
\dashrightarrow_\vartheta & = & \{(\langle e\rangle_\sim, \langle e'\rangle_\sim) \mid e, e' \in E \ \wedge \ e \in \bigcup \mathcal{H}(e') \setminus \bigcap \mathcal{H}(e')\}, \text{ and}\\
\lambda_\vartheta(\langle e\rangle_\sim) & = & \lambda_\beta(e), \text{ for all } e \in E.
\end{array}
$$

Note that the relation $\leq^{\text{full}}_\vartheta$ is a partial order and embeds the asymmetric conflict relation. Henceforth, for AESs we decompose $\leq^{\text{full}}_\vartheta$ into the *strict cause* relation, i.e., $<_\vartheta = <^{\text{full}}_\vartheta \setminus \dashrightarrow_\vartheta$, and the *asymmetric conflict* relation, i.e., $\dashrightarrow_\vartheta$. The relation $\leq^{\text{full}}_\vartheta$ can then be trivially derived from $<_\vartheta$ and $\dashrightarrow_\vartheta$. Technically, $e \#_\vartheta e'$ can also be represented as $e \dashrightarrow_\vartheta e' \ \wedge \ e' \dashrightarrow_\vartheta e$, but we consider that the symmetric conflict is more appropriate as feedback to modelers. As for PES, the concurrency relation on AES is given by $\|_\vartheta = E^2_\vartheta \setminus (<^{\text{full}}_\vartheta \cup >^{\text{full}}_\vartheta \cup \#_\vartheta)$. The behavior relations of ϑ shall be denoted by the tuple $\mathcal{R}_\vartheta = (<_\vartheta, \#_\vartheta, \dashrightarrow_\vartheta, \|_\vartheta)$.

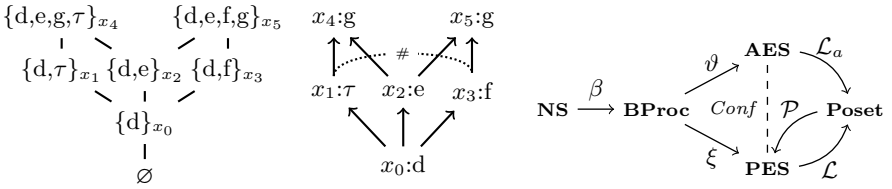
Definition 11 (AES Configuration). *Let $\vartheta = (E_\vartheta, \leq^{\text{full}}_\vartheta, \#_\vartheta, \dashrightarrow_\vartheta, \lambda_\vartheta)$ be an AES. An* AES configuration *of ϑ is a set of events $C \subseteq E_\vartheta$ such that*

- *$<^{\text{full}}_\vartheta \cap C^2$ is* well-founded*,*
- *for all $e \in C$, if $e' <^{\text{full}}_\vartheta e \ \wedge \ e' \notin C$, then there exists $e'' \in C$ s.t. $e' \#_\vartheta e''$.*

As a consequence of the last condition, an AES configuration C is conflict-free, i.e., $\forall e, e' \in C : \neg(e \#_\vartheta e')$. The set of all AES configurations of an AES ϑ shall be denoted $Conf(\vartheta)$. In spite of the differences in their definitions, the set of configurations of a branching process β (cf., Definition 4) is the same as the set of AES configurations (cf., Definition 11) induced by a future equivalence $\sim$ on β. Intuitively, an equivalence class $\langle e\rangle_\sim$ corresponds to a set of events in the branching process from which computation evolves independently, but isomorphically in different branches. When $\langle e\rangle_\sim$ is mapped to a single event into an AES all the branches stemming from events in $\langle e\rangle_\sim$ are merged into a single branch. However, the original set of configurations for $\langle e\rangle_\sim$ can still be rebuilt by appending a copy of the merged branch to each configuration $\lceil e' \rceil$ in $\mathcal{H}(e) = \{\lceil e' \rceil \mid e' \in \langle e\rangle_\sim\}$. This intuition is formally confirmed in [20, Lemma 1]. Now, we define an order $\sqsubseteq$ on AES configurations, referred to as *AES configuration extension*, such that $C \sqsubseteq C'$ stands for "C can evolve into C'".

Definition 12 (AES Configuration Extension). *Let $\vartheta = (E_\vartheta, \leq^{\text{full}}_\vartheta, \#_\vartheta, \dashrightarrow_\vartheta, \lambda_\vartheta)$ be an AES and $X, X' \subseteq E_\vartheta$ sets of events. We say that X'* extends *X, denoted $X \sqsubseteq X'$, iff (i) $X \subseteq X'$, and (ii) $\neg(e' <^{\text{full}}_\vartheta e)$ for all $e \in X, e' \in X' \setminus X$.*

The relation above defines a partial order on the set of configurations of AES ϑ, denoted $\mathcal{L}_a(\vartheta) = \langle Conf(\vartheta), \sqsubseteq\rangle$. Following the approaches in [17] and [21], we now characterize $\mathcal{L}_a(\vartheta)$.



(a) $\mathcal{L}_a(\vartheta_1)$) (b) $\mathcal{P}(\mathcal{L}_a(\vartheta_1))$ (c)

Fig. 9. (a) Poset, and (b) PES induced from AES ϑ_1. (c) Overall transformations.

Theorem 2. *Let* $\vartheta = (E_\vartheta, \leq^{\text{full}}_\vartheta, \#_\vartheta, \dashrightarrow_\vartheta, \lambda_\vartheta)$*. Then,* $\mathcal{L}_a(\vartheta) = \langle Conf(\vartheta), \sqsubseteq \rangle$ *is a prime algebraic coherent partial order. Its complete primes are AES configurations of the form* $[e]_{\mathcal{X}} = \{e' \mid e, e' \in \mathcal{X} \wedge (e', e) \in \leq^{\text{full}}_\vartheta \cap \mathcal{X}^2\}$*, with* $\mathcal{X} \in Conf(\vartheta)$*.*

Proof. Let $\mathcal{X} \subseteq Conf(\vartheta)$ be a set of pairwise consistent AES configurations, i.e., $\mathcal{X}^{\Uparrow}$. If $e, e' \in \cup\{X \mid X \in \mathcal{X}\}$, then there exist $X, Y \in \mathcal{X}$ s.t. $e \in X$ and $e' \in Y$. Since $\mathcal{X}^{\Uparrow}$ there exists an AES configuration Z s.t. $X \sqsubseteq Z$ and $Y \sqsubseteq Z$. Therefore $\neg(e \#_\vartheta e')$ since Z is conflict-free, $\cup\{X \mid X \in \mathcal{X}\} \in Conf(\vartheta)$, and $\sqcup\mathcal{X} = \cup\mathcal{X}$ is lub in $Conf(\vartheta)$. Hence, $\mathcal{L}_a(\vartheta)$ is coherent.

For any AES configuration $X \in Conf(\vartheta)$, we have $X = \sqcup\{[e]_X \mid e \in X\}$. Hence, if X is complete prime, then there exists $e \in X$ s.t. $X = [e]_X$. This shows that the complete primes of $Conf(\vartheta)$ are AES configurations of the form $[e]_X$. Moreover, the formula $X = \sqcup\{[e]_X \mid e \in X\}$ alludes to the fact that any AES configuration is the lub of the complete primes it dominates. $\mathbb{P}_{\mathcal{L}_a(\vartheta)}$ is denumerable since it is a subset of the power set of a finite denumerable set, i.e., the set of events E_ϑ. Hence, $\mathcal{L}_a(\vartheta)$ is prime algebraic. □

Given the poset $\mathcal{L}_a(\vartheta) = \langle Conf(\vartheta), \sqsubseteq \rangle$, we know from [17] that $\mathcal{P}(\mathcal{L}_a(\vartheta)) = (\mathbb{P}_P, \leq, \#)$ is a prime event structure, where $\leq$ is $\sqsubseteq$ restricted to $\mathbb{P}_{\mathcal{L}_a(\vartheta)}$, and for all $\lceil e \rceil, \lceil e' \rceil \in \mathbb{P}_{\mathcal{L}_a(\vartheta)} : \lceil e \rceil \# \lceil e' \rceil$ iff $\lceil e \rceil$ and $\lceil e' \rceil$ are inconsistent in $\mathcal{L}_a(\vartheta)$. Moreover, a labeling function for such PES is given by $\lambda_{\mathcal{P}(\mathcal{L}_a(\vartheta))}(\lceil e \rceil) = \lambda_\vartheta(e)$ for all $\lceil e \rceil \in \mathbb{P}_{\mathcal{L}_a(\vartheta)}$. By applying the notions above, we can derive the poset shown in Figure 9(a) and then the PES in Figure 9(b). The isomorphism of Figures 9(b) and 5(a) is not a surprise, considering that they correspond to isomorphic posets [17, Theorem 9]. All transformations employed in the approach are summarized in Figure 9(c).

An AES built using Definition 10 considers all the equivalence classes in the branching process. However, the comparison of AESs may happen in two phases, first with observable behavior and then with a subset of τ-labeled events. We conjecture that only a subset of τ-labeled events needs to be kept to allow the construction of AES configurations and preserve fully concurrent bisimulation.

5 Conclusion

In this work, we defined an acyclic process model differencing operator based on prime event structures (PESs) and asymmetric event structures (AESs). The

high level of duplication inherent to PES hinders on the usefulness of this representation for the purpose at hand. Hence, AESs were considered as an alternative to reduce duplication. A tailor-made method for computing AESs was described.

We foresee a number of avenues for future research. First, we aim at characterizing the minimal set of τ-labeled events required to preserve fully concurrent bisimulation. Naturally, we target to extend the current approach so as to cover process models with cycles and duplicate tasks. A promising direction for dealing with cyclic process models includes techniques of net unfoldings for finding a finite representation of cyclic behavior. Finally, future research will include experiments to assess the readability of the feedback stemming from this approach and its applicability in real-world settings.

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Formal Modeling and Analysis of the REST Architecture Using CSP

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Abstract. As one of the most promising architectural styles, Representational State Transfer (REST) was first proposed to support the enablement of scalable and reliable design for largescale distributed hypermedia systems such as the World Wide Web (WWW). Rapidly development of the RESTful systems brings the misunderstanding and misapplied of the REST architecture. In this paper, we present a formal model to capture the essential features for the REST architecture, in which components in RESTful systems are modeled as CSP processes. Thus all the REST constraints can be completely described and validated in our framework. Furthermore, many REST constraints are verified using the model checker PAT. The proposed framework for REST architecture is not only confined to HTTP but can also be applied to other REST-compliant protocols. Finally a case study about an application scenario for environment monitoring is illustrated to show the feasibility of our approach. Consequently, better understanding of REST can be achieved and implementations of RESTful systems can benefit from it.

1 Introduction

REST architectural style, which was proposed for distributed hypermedia systems by Fielding in 2000 [6], has been widely used in practice [1, 8]. It is derived from several web-based architectural styles [14, 18] with a number of additional constraints, such as the Client-Server constraint and the Uniform Interface constraint, etc. Nowadays, REST architectural style being more and more widespread in real applications and it has already affected the design of many web-based applications [7, 13], especially for the Mashup [2, 4] and the World Wide Web (WWW) [3]. Unfortunately, the increasing interest of REST also brings the misunderstanding and misapplied of the REST architecture. Therefore, giving a good understanding of REST architectural style has been becoming more and more important for the guidance of the development of web-based applications, which is also the main goal of this paper.

Systems are often referred to as RESTful systems if they cater to the REST constraints. In the literature, as far as we know, there is little on formal modeling and analysis of RESTful system. In [11], Koch has already established a formal model for

hypermedia systems, but the model may cover many unRESTful properties about the WWW instead of the fundamental principles of REST. Zuzak et al. [21] have proposed a framework, which is based on a nondeterministic finite-state machine with epsilon transitions for modeling the RESTful systems and they have also explained how to map some REST principles to the model. They have done well and they hope to add some other principles into their model, including the layered and cacheable sytle constraints which are currently unaddressed in their model. In addition, Autonio et al. [8] have given a precise definition of RESTful semantic web services combining tuple space computing and process calculi, and they focus more on the semantics and application of REST instead of the architecture itself. Moreover, the model in their paper may be limited to standard HTTP methods and the other REST-compliant protocols are not mentioned in their paper. In [10], Uri Klein et al. have formulated two key REST properties and RESTful HTTP within temporal logic. However, the other constraints and the other REST-compliant protocols have not been mentioned in their formalization. Thus, the research for formalizing the RESTful systems is still challenging.

Inspired by Fielding's and Zuzak's works [6, 21], in this paper, we use CSP [9] to model and analyze the REST architecture and map its style constraints to the model. CSP is a well-known process algebra in modeling and reasoning about the web services [20]. We abstract the REST architecture and all of its components, including User Agent, Origin Server, Intermediary Component and Cache, are described as CSP processes, thus the communication between each entity is converted to the communication between CSP processes. We also map the REST constraints to our model, for instance, each component is described as an independent process, so that the Client-Server and the layered structures are obvious. More details about the mapping of the six constraints to our model can be found in our paper. Our framework is not limited to standard HTTP but also can be applied to other REST-compliant protocols such as CoAP (Constrained Application Protocol). Besides, we also use PAT, a model checker tool based on CSP, to verify the Client-Server and the Cacheable constraints in our achieved model to prove that our model caters to the REST architecture. Finally, giving a case study, we use our framework to model and reason about an application scenario used for sensor data retrieval adopting CoAP in order to show the feasibility of our model. The main contributions of this paper are listed as follows:

- **Modeling.** A formalization of the REST architecture (user agent, intermediary components, origin server and cache), based on the process algebra CSP, is presented. An abstract process algebra model for each REST architecture element is given and six constraints characterizing REST are considered.
- **Analysis.** We analyze the constraint features of REST and explain the mapping of the six constraints to the achieved model. Besides, PAT, the model checker, is applied in verifying some constraints in our model to prove that our model caters to the REST architecture.
- **Application.** A case study about environment monitoring is given to show the feasibility of our model. It also illustrate that our framework is not confined to HTTP but also can be applied to other REST-compliant protocols.

The remainder of this paper is organised as follows. We introduce preliminaries about CSP and PAT in Section 2. Section 3 is devoted to the introduction of the REST

architecture including its elements and six constraints. We propose a formalization framework in Section 4 and all the communication components are described as CSP processes. In Section 5, we revisit six REST constraints and show how we map them to the achieved model. In this section, we also use the model checker tool PAT to verify the constraints. Giving a case study, we apply our framework in modeling and reasoning about an application scenario in Section 6. We conclude the paper and present the future directions in Section 7.

2 Preliminaries

2.1 CSP Method

Communicating Sequential Processes (abbreviated as CSP) was proposed by C. A. R. Hoare in 1978 [9]. It has developed and evolved constantly, and it has already become a mature process algebra. It specializes in describing the interaction between concurrent systems using mathematical theories. Due to powerful expressive ability, CSP is widely applied in many fields [15, 16, 19] such as the web service. In CSP, processes are composed of basic processes and actions, and they are connected by operators.

The syntax of CSP is shown below:

$P, Q ::= Skip \mid Stop \mid a \rightarrow P \mid P\ ;\ Q \mid c?x \rightarrow P \mid$
$\quad c!x \rightarrow P \mid P \parallel\ Q \mid P\ [|X|]\ Q \mid P\ \lhd b \rhd\ Q$

Here P and Q represent processes which have alphabets $\alpha(P)$ and $\alpha(Q)$ denoting the actions that the processes can perform respectively. While a and b stand for the atomic actions and c is the name of the channel.

- *Skip* represents a process which does nothing but terminates successfully.
- *Stop* denotes that the process is in the state of deadlock and does nothing.
- $a \rightarrow P$ represents that the process first performs action a, then behaves the same as process P.
- $P; Q$ means performing P and Q sequentially.
- $c?x \rightarrow P$ gets a message through channel c and assigns it to a variable x, then behaves like P.
- $c!x \rightarrow P$ sends a message x using channel c, then behaves like P.
- $P \parallel Q$ describes the concurrent between P and Q.
- $P[|X|]Q$ represents that P and Q perform the concurrent events on set X of channels.
- $P \lhd b \rhd Q$ means if the condition b is true, the behavior is like P, otherwise, like Q.

The above is a brief description of CSP. More details can be found in [9].

2.2 PAT

In this subsection, we give a brief introduction to PAT [17]. PAT (Process Analysis Toolkit) is designed as an extensible and modularized framework based on CSP and it has been used to model and verify a lot of different systems for varieties of properties

such as deadlock-freeness, divergence-freeness, reachability, LTL properties with fairness assumptions, refinement checking and probabilistic model checking. We list some notations in PAT as follows:

1. $\#define\ N\ 0$ defines a global constant N which has the initial value 0.
2. $var\ cache\_user\_list[N]$ defines an array named $cache\_user\_list$ and the size of it is N.
3. $Channel\ c\ 5$ defines a communication channel and the capacity of it is 5.
4. $P = \{x = x + 1\} \rightarrow Skip$ defines an event that can be attached with an assignment, using which we can update the value of a global variable x.
5. $c!a.b \rightarrow P$ and $c?x.y \rightarrow P$ refer to sending message $a.b$ and receiving message from channel c respectively.

Besides, PAT can also describe the control flow structures, such as $if - then - else$ and $while$, etc. More details about this tool can be found in [5, 12].

3 Overview of the REST Architecture

Representational State Transfer (REST) is a software architectural style designed for distributed hypermedia systems. It was first presented by Roy Fielding in his doctoral dissertation in 2000 [6]. World Wide Web (WWW) [3] is the largest implementation conforming to the REST architectural style. REST makes it clear that a web architecture can be obtained by characterizing and constraining the micro-interactions of the components of the architecture.

3.1 The Elements of REST

The REST architectural elements include components, connectors and data elements. Data elements are made up of resources, resource identifiers, representations, representation metadata, resource metadata and control data. Connectors are interfaces which components are used to communicate. They are made up of clients, servers,

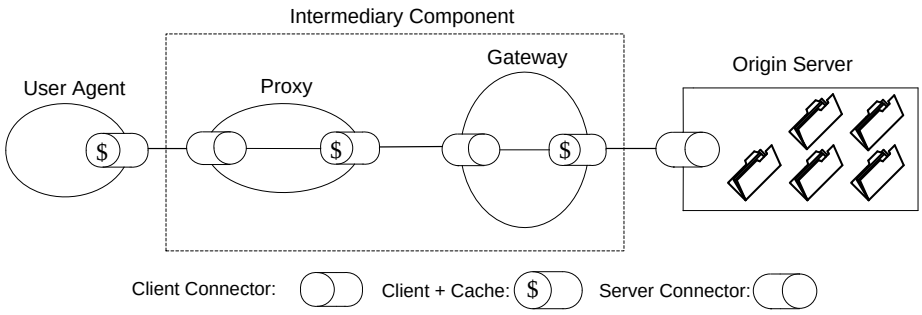

Fig. 1. The framework of the REST architectural style

caches, resolvers and tunnels. Connectors encapsulate the underlying implementation of resources and the communication mechanisms. Components include user agents, origin servers and intermediary components (proxies and gateways). In order to illustrate the architecture of REST clearly, we give a simple framework in Figure 1.

REST identifies the resources involved in the interactions of different components with the use of resource identifiers. Connectors serve as uniform interfaces to access the set of resources. User agents use client connectors to send requests for resources and become the final receiver of corresponding responses. Origin servers use server connectors to manage requested resource namespace. The final receiver of a request to modify the values of resources should be an origin server. The intermediary components include proxies and gateways. Proxies are selected by clients to provide interface encapsulation for data translation or security protection. Gateways are selected by network or an origin server to provide interface encapsulations for other services such as data translation and security enforcement.

3.2 The Constraints of REST

The REST architectural style describes six constraints, including the Client-Server constraint, the Stateless constraint, the Cacheable constraint, the Layered constraint, the Uniform Interface constraint and the Code-On-Demand constraint. A system is usually referred to as a RESTful system if it conforms to these constraints.

1. **Client-Server**: Servers are only responsible for data storage and a uniform interface separates clients from servers. Clients and servers can evolve independently as long as the interfaces between them remaining unchanged.
2. **Stateless**: Servers are stateless and clients store session states. Each request contains all the information that receivers need to process it.
3. **Cacheable**: Clients can determine to or not to store cacheable responses by restricting responses from servers with a property indicating whether they are cacheable or not.
4. **Layered**: Clients originally don't have any knowledge about the components which directly connecting to are end servers or intermediaries in a complicated system. Intermediaries improve the scalability of the system, providing shared cache and load-balance mechanisms. They can also enforce the security of the system.
5. **Uniform Interface**: The uniform interfaces between clients and servers simplify the architecture and enable clients and servers to evolve independently.
6. **Code-On-Demand**: This is an optional constraint. Servers can send executable codes to clients for the expansion of the functions of clients.

REST specifies four principles to standardize the implementation of uniform interfaces. The first one is the identification of resources. Web-based RESTful systems identify resources using URIs. The second one is the manipulation of resources through representations. Clients can modify or delete resources on servers by manipulating the representations of resources. The third one is the self-description of messages. Each message contains enough information describing how to handle the message. The last one is hypermedia as the engine of application state. Clients make state transitions only through actions that are dynamically identified within hypermedia by the server.

4 Formalization

In this section, we apply CSP in modeling the REST architectural style, including the components of the user agent, the cache, the origin server and the intermediary components (proxies and gateways). Firstly, we define the sets and the channels below.

We define the set **User** of user agents, **Server** of origin servers, **Cache** of caches and **Intermediary** of intermediary components (proxies and gateways). The set **Resource** contains the resources which are required by the user agent and **Url** indicates the identification of resources. Besides, we also define the set **Representation** of representations of the resource, **SDInformation** of the self-descriptive messages which can describe the message itself using its own data and metadata, and **HyperMedia** of the hyper media of the resources. In addition, we also define the messages which are delivered among the components as follows:

$$
\begin{aligned}
MSG_{req} =_{df} \{&msg_{req}.info\_cons.sender.receiver| \\
&info\_cons = (url, repr, sdi, hmedia), url \in Url, \\
&repr \in Representation, sdi \in SDInformation, \\
&hmedia \in HyperMedia, sender \in User \cup Intermediary, \\
&receiver \in Cache \cup Intermediary \cup Server\} \\
MSG_{rep} =_{df} \{&msg_{rep}.content.sender.receiver| \\
&content = (url, repr, sdi, hmedia), url \in Url, \\
&repr \in Representation, sdi \in SDInformation, \\
&hmedia \in HyperMedia, sender \in Cache \cup Intermediary \cup Server, \\
&receiver \in User \cup Intermediary, content \in Resource\} \\
MSG =_{df}\ & MSG_{req} \cup MSG_{rep}
\end{aligned}
$$

Here, MSG_{req} represents the set of the request messages which are sent by the user agent and the intermediary component. The user agent can send request to its cache or the intermediary component, and the intermediary component can also send request messages to its own cache or the origin server. MSG_{rep} denotes the reply messages that are sent back to the user agent or the intermediary component. The reply messages may be from the server or caches. Note that $info\_cons$ and $content$ are four-tuples and $content$ is the resource entity returned to the user agent.

We use four channels to model the communication between each component: ComUC, ComCIC, ComUIC, ComICS.

- **ComUC**: it is used to send and receive messages between the user agent and its cache.
- **ComCIC**: it denotes the standard communication between the intermediary component and its cache.
- **ComUIC**: the user agent uses it to send request messages to the intermediary component and also receive the reply messages.
- **ComICS**: the intermediary component communicate with the origin server through this channel.

The declaration of the channels are as follows:
Channel ComUC, ComCIC, ComUIC, ComICS: MSG
Figure 2 illustrates the communications among components using channels.

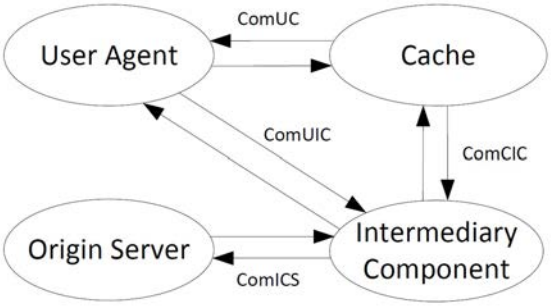

Fig. 2. Communications among components via channels

4.1 User Agent

In the whole process of web service, when the user agent is prepared to send a request message, it checks its local cache for cacheable responses it needs first. That is to say, the user agent makes a request to its cache at first. If there are already cacheable responses in its local cache, the user agent can get the resource directly from the cache. Otherwise, the user agent will make requests to the outer network. The user agent can send the request message to the intermediary component for further processing. We model the behaviors of the user agent as follows:

$$
\begin{aligned}
&UserAgent(info\_cons) =_{df} \\
&\qquad ComUC!request.info\_cons.U.C \rightarrow ComUC?reply.content.C.U \rightarrow \\
&\qquad UserAgent(info\_cons) \lhd (content! = NULL) \rhd \\
&\qquad ComUIC!request.info\_cons.U.IC \rightarrow \\
&\qquad ComUIC?reply.content.IC.U \rightarrow \\
&\qquad UserAgent(info\_cons)
\end{aligned}
$$

Note that, the parameter $info\_cons$ is a four-tuple $(url, repr, sdi, hmedia)$. All of the elements in the tuple are used to describe the resource. url stands for the identification of the resource and $repr$ is the representation. sdi is the self-descriptive message of the resource and $hmedia$ is hypermedia. The parameter $info\_cons$ is a variable, which will change with the changing of these four elements.

4.2 Cache

Here, caches are used to store early received cacheable responses from servers. User agent can quickly access desired data in caches before sending request messages to the origin server, so caches can reduce the number of requests sent to servers and improve the efficiency of the whole system. If there are received cacheable responses, the cache will send the content of the resource back to the user agent. Otherwise, it will send a $NULL$ message to its user. The communication between the intermediary component and its cache is the same as the process between the user agent and its cache. We model

the behaviors of the cache below:

$$Cache(U, info\_cons) =_{df} ComUC?request.info\_cons.U.C \rightarrow ComUC!reply.content.C.U \rightarrow Cache(U, info\_cons)$$

$$Cache(IC, info\_cons) =_{df} ComCIC?request.info\_cons.IC.C \rightarrow ComCIC!reply.content.C.IC \rightarrow Cache(IC, info\_cons)$$

$$Cache(Node, info\_cons) =_{df} Cache(U, info\_cons) \lhd (Node == U) \rhd (IC, info\_cons)$$

Note that, $Cache(Node, info\_cons)$ will perform different processes according to the value of $Node$.

4.3 Intermediary Component

The intermediary component here plays an important role in the REST architectural style. The user agent will send the request message to the intermediary component if it cannot get the resource directly from its cache. The intermediary component also has cache which will be accessed first after the component receives the request message from the user agent. The behaviors of the intermediary component have two types, one is communicating with the user agent and the other one is communicating with the origin server. Here, we use CSP to model the behaviors of the intermediary component as follows:

$$\begin{aligned} &Intermediary(info\_cons) =_{df} \\ &\quad ComUIC?request.info\_cons.U.IC \rightarrow \\ &\quad ComCIC!request.info\_cons.IC.C \rightarrow \\ &\quad ComCIC?reply.content.C.IC \rightarrow \\ &\quad (ComUIC!reply.content.IC.U \rightarrow Intermediary(info\_cons)) \\ &\quad \lhd (content! = NULL) \rhd (ComICS!request.info\_cons.IC.S \rightarrow \\ &\quad ComICS?reply.content.S.IC \rightarrow ComUIC!reply.info\_cons.IC.U \rightarrow \\ &\quad IntermediaryComponent(info\_cons)) \end{aligned}$$

4.4 Origin Server

In the whole process of web service, the resources that the user agent needs are stored in the origin server. If there is no early received cacheable responses from servers stored in the user agent's cache, the user agent will communicate with the server through the intermediary component. Here, the server may receive the request message from the intermediary component and also return the resource to it. We model the behaviors of the origin server below:

$$\begin{aligned} &Server(info\_cons) =_{df} \\ &\quad ComICS?request.info\_cons.IC.S \rightarrow \\ &\quad ComICS!reply.content.S.IC \rightarrow Server(info\_cons) \end{aligned}$$

4.5 System

The whole system can be modeled as a concurrent composition of the user agent, the cache, the intermediary component and the server.

$$USERAGENT =_{df} UserAgent(info\_cons)[|ComUC|]Cache(U, info\_cons)$$
$$INTERMEDIARY =_{df} Intermediary(info\_cons)[|ComCIC|]Cache(IC, info\_cons)$$
$$SERVER =_{df} Server(info\_cons)$$
$$SYSTEM =_{df} USERAGENT[|ComUIC|]INTERMEDIARY[|ComICS|]SERVER$$

5 REST Constraints Revisited

In this section, we mainly give a detailed description about how we map the six REST constraints to our achieved model. Based on the traces analysis, we give the formal definitions of all the constraints, and we use a model checker tool PAT, which we have already introduced in Section 2, to verify some constraints to prove that our achieved model caters to the REST architecture. First we define some functions below:

- $source(event)$ returns the sender of the event $event$ and $source(event) \in$ **Sender**.
- $target(event)$ returns the receiver of the event $event$ and $target(event) \in$ **Receiver**.
- $type(event)$ stands for the type of the event $event$ and $type(event) \in$ **Type**.
- $set(trace)$ returns all the elements of the trace $trace$.
- $trace(system)$ returns the trace of the $system$.
- $channel(event)$ returns the channel name, on which the processes send and receive events. Thus $channel(event) \in$ **Channel**.

Here, we give the definitions of some additional sets. **Sender** is a set containing all the senders that can send an event. The type of all the elements in the set is enumerated, such as $\{client, cache, server, intermediary\}$, the same as the set **Receiver**. The set **Type** stands for the type of an event, elements in which are also enumerated, such as $\{request, reply\}$. The set **Channel** contains all the channels.

5.1 Constraints Descriptions

In this subsection, before we give the formal descriptions of six REST constraints, some notations are defined below.

1. $\bullet$ represents **satisfy**, e.g. $a \bullet A$ means that a satisfies A.
2. $/$ stands for **after**, e.g. $system/tr$ means the process $system$ has done the trace tr. Thus $trace(system/tr)$ represents the trace after the process $system$ has done the trace tr.
3. $\overline{tr}$ is a new trace which is the reversion of trace tr and tr_0 stands for the first event of trace tr. Thus, $\overline{tr}_0$ represents the first event of the reversion of the trace tr. $tr^{'}$ means the remaining of trace tr except the first event.

Client-Server

In our model, we have the process $UserAgent$ to stand for the client connector and the process $OriginServer$ for the server connector. Being as two independent processes, $UserAgent$ and $OriginServer$ are separated through the uniform interface, which is the channel in this paper. Request messages will be sent to the cache or the origin server if the user agent is intended to get resources. Based on the traces analysis, the Client-Server constraint can be formally defined as follows:

Constraint 1:

$$\begin{aligned}&\forall tr \in trace(system), \exists e \in set(trace(system/tr)) \bullet \\ &\qquad (source(\overline{tr}_0) == client \wedge type(\overline{tr}_0) == request) \Longrightarrow \\ &\qquad ((source(e) == cache \vee source(e) == server) \wedge type(e) == reply)\end{aligned}$$

The resource the user agent is intended to get is in its cache or in the origin server. Whenever the user agent sends a request message, it will receive a reply which is from its cache or from the origin server.

Cacheable

In our model, the user agent and the intermediary component have caches, which are abstracted as the CSP process $Cache$. If a response in the reply is cacheable, it will be stored in the cache and reused next time. Note that there is a special mark in the response to show whether the response is cacheable or not. Here, we ignore the responses which can not be cached, that is we only consider the cacheable responses. The formal description is listed below:

Constraint 2:

$$\begin{aligned}&\forall tr \in trace(system), \forall e \in set(\overline{tr}'), \exists e' \in set(trace(system/tr)) \bullet \\ &\qquad (source(\overline{tr}_0) == client \wedge type(\overline{tr}_0) == request \wedge \\ &\qquad source(e) == client \wedge type(e) == request) \Longrightarrow \\ &\qquad (source(e') == cache \wedge type(e') == reply)\end{aligned}$$

If the user agent sends a request message for the first time, which means that its cache does not have the record of the resource, the user agent needs to get the resource from the server. Otherwise, if the response is cacheable, it will be stored in the user agent's cache, and the user agent can get the resource from its cache directly without visiting the server. That is if two requests want to get the same cacheable resource, the second one can visit the cache directly instead of visiting the server.

Stateless

In REST architecture, the communication is stateless, i.e., each request message contains all the information needed to understand the message itself. Context storing in the server cannot be used and all the session states remain in the user agent. In our CSP model, the process $SERVER$ is not modeled as the concurrent composition with the process $Cache$ so that the session cannot be remained in the server. The format of the message sent by the user agent has been defined in the first part of Section 4

and the message contains all the information needed to understand it in the four-tuple $info\_cons$.

Constraint 3:

$$\forall tr \in trace(system) \bullet (system == system/tr \wedge (source(\overline{tr}_0) == server \wedge type(\overline{tr}_0) == reply))$$

Based on the traces analysis, the system will be back to the original state after it performs one session. Here, the process $system$ will be back to itself after it has done the trace tr. The end mark of one session is that the server sends back a reply to the intermediary or the client.

Uniform Interface

In our CSP model, we map the Uniform Interface constraint to the communication channels. The messages transmitted on the channels are unified and the format of the messages has already been defined in the first part of Section 4. In general level, the message can be summarized as $\{msg, resource\_format, sender, receiver\}$. Four constraints of the interface have been described in the four-tuple $resource\_format$.

Constraint 4:

$$\begin{aligned}\forall tr \in trace(system), \forall e \in set(tr), \exists e^{'} \in set(trace(system/tr)) \bullet \\ (type(e) == request \wedge (source(e) == client \vee \\ source(e) == cache \vee source(e) == intermediary)) \Longrightarrow \\ (source(e) == target(e^{'}) \wedge source(e^{'}) == target(e) \wedge \\ channel(e) == channel(e^{'}) \wedge type(e^{'}) == reply)\end{aligned}$$

As mentioned above, for any event in any trace of the process $system$, if there is a request message sent through the channel by client, intermediary or the cache, after the process $system$ has done the trace, there must exist an event $e^{'}$ which contains a reply message sent through the same channel. According to the mapping of the Uniform Interface constraint and the definition of the message, the sender of the request message must be the same as the receiver of the reply message.

Layered and Code-On-Demand

Layered constraint and Code-On-Demand constraint are obvious. We give the descriptions about how we map these two constraints to our model using Constraint 5 as follows:

Constraint 5:

$$System = UserAgent \| Intermediary \| Server$$

- **Layered.** In our model, we have the processes $UserAgent$, $Intermediary$, $Cache$ and $OriginServer$. All the components are modeled as independent processes and can get the knowledge only from its neighbor components, which breaks the architecture into different levels. If a new service is added to the model, we can ab-

stract the service as a new process and combine the new process with the process $OriginServer$ without the effects of the user agent.

- **Code-On-Demand.** It is an optional constraint of REST architecture. We do not discuss more about it. Using concurrent operation, different processes are combined. Our model is easy to add new process in the system to expand the system.

5.2 REST Architecture in PAT

In this subsection, our model of the REST architecture is implemented using PAT. There are four main processes including $UserAgent(info\_cons)$, $Cache(Node)$, $Intermediary()$ and $OriginServer()$. We omit a large number of the PAT codes, only giving the typical relevant codes about the actions of the intermediary component as follows to show how we use PAT to implement our model:

$$
\begin{aligned}
Intermediary() = {} & ComUIC?msgreq.info\_cons.UA.IC- > \\
& ComCIC!msgreq.info\_cons.IC.CA- > \\
& ComCIC?msgrep.content.CA.IC- > \\
& Intermediary\_Check(intermedia, content); \\
Intermediary\_Check(info\_cons, content) = {} & if a(content == 0) \\
& \{ComCS!msgreq.info\_cons.IC.OS- > \\
& \ ComCS?msgrep.content1.OS.IC- > \\
& \ ComUIC!msgrep.content1.IC.UA- > \\
& \{cache\_media\_list[info\_cons][1] = content1\}- > \\
& Intermediary()\} \\
& else \\
& \{ComUIC!msgrep.content.IC.UA- > \\
& \{cache\_media\_list[info\_cons][1] = content\}- > \\
& Intermediary()\};
\end{aligned}
$$

Due to we have already given formal definitions of the six REST constraints in Subsection 5.1 and we also give a detained description about how we map these constraints to our model, here we do not list all the assertions of the REST constraints. We just give two examples about the assertions of Client-Server constraint and Cacheable constraint to show how to express these constraints using the syntax of PAT. Here is the assertions in Table 1. According to the formal descriptions as mentioned above, we verify the constraints using PAT and the results of the verification prove that our model caters to the REST architecture.

Table 1. Assertions of REST Constraints

```
#assert System()|=[]ComUC!msgreq→(<>ComUC!msgrep||<>ComCS!msgrep);

#define goal1 cache_user_list[0][1]!=0;
#define goal2 cache_user_list[1][1]!=0;
#define goal3 cache_user_list[2][1]!=0;
#define goal4 cache_user_list[3][1]!=0;
#assert System()|=[]((ComUC!msgreq && (goal1||goal2||goal3||goal4))→
                    ([](!ComCS!msgrep && ComUC!msgrep)));
```

6 Case Study

In this section, a case study about a scenario for environment monitoring is given to illustrate the feasibility of our framework in modeling and analyzing the RESTful systems. It shows that our proposed framework is not only confined to HTTP but can also be applied to other REST-compliant protocols such as CoAP. More details about the scenario is shown in Figure 3.

The scenario is composed of a wireless sensor network (WSN), an environment supervision unit (ESU) node and an environment monitoring centre (EMC) node. The WSN is made up of numbers of wireless sensor nodes deployed with CoAP and used for the acquisition of values of some physical quantities, for example, the concentration of phosphorus in a river. The ESU is the main computing device which is the border router for the WSN and manages the communication with back-end EMC. EMC acts as a client to access data in those wireless sensor nodes for workers to make correct decisions to control the concentration of phosphorus for environmental protection. Additionally, a telematic device is used for information exchange with the Internet.

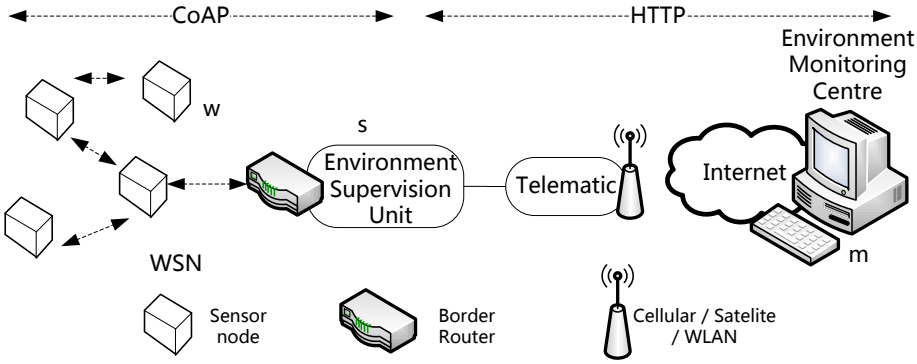

Fig. 3. A Scenario for Environment Monitoring

For simplicity, we only consider about the communications among a WSN node **w**, an ESU node **s** and an EMC node **m** situated on the Internet. According to the model built in section 4, **m** stands for the **user agent**, **s** is an instance of the **intermediary component** and **w** denotes a **server**. In one interaction, the user agent **m** is intended to get a resource, i.e., the value of the concentration of phosphorus, stored in sensor node **w**. Based on the traces analysis, we give the trace of the whole process as follows:

$$\langle m.ComUIC!msg.request.m.s, s.ComUIC?msg.request.m.s,$$
$$s.ComICS!msg.translated\_request.s.w, w.ComICS.translated\_request.s.w,$$
$$w.ComICS!msg.response.w.s, s.ComICS?msg.response.w.s,$$
$$s.ComUIC!msg.response.s.m, m.ComUIC?msg.response.s.m...\rangle$$

At first, the EMC node **m** sends an **HTTP GET** (we use GET_{HTTP} for distinction of the GET method of CoAP, which is expressed as GET_{CoAP}) request to get the concentration of phosphorus of node **w**. ESU node **s** or cache **c** can receive the request.

$$\begin{aligned} request = (&URI:\ coap://node-w.net/phosphorus,\ repr:\ \{\},\\ &sdi:\ \{METHOD:\ GET_{HTTP},\ other-functional-fileds\},\\ &hmedia:\ \{hypermedia\}) \end{aligned}$$

If the resource is cacheable and the response stored in cache **c** is not out of time, then it can be sent to node **m** immediately and node **m** rejects duplicated responses arriving later. If it is neither a cacheable resource nor found in cache **c**, **s** translates this HTTP request into a CoAP request and sends it to the WSN node **w**.

$$\begin{aligned} translated-request = (&URI:\ coap://node-w.net/phosphorus,\ repr:\ \{\},\\ &sdi:\ \{METHOD:\ GET_{CoAP},\ other-functional-fileds\},\\ &hmedia:\ \{translated-hypermedia\}) \end{aligned}$$

After processing the request, **w** returns a CoAP response and after numbers of hops, the response is finally received by node **s**. This response may include some response codes indicating the result of the attempt to understand and satisfy the request. It can be described as follows.

$$\begin{aligned} response = (&uri:\ \{\}, repr:\ \{a\ document\ of\ type\ applicaton/link-format\\ &including\ a\ hyperlink\ coap://node-w.net/calcium\},\\ &sdi:\ \{cacheTag,\ functional-fields\}, hmedia:\ \{hypermedia'\}) \end{aligned}$$

Node **s** receives this response, translates it into an HTTP response and sends it to node **m**. This translation may involve protocol details which are not our concerns. So the translated response is not given. Using our framework, we want to provide a better understanding of REST architecture and its constraints. Here, the REST constraints are listed from the perspective of our model as follows:

- **The Client-Server Constraint.** Node **m** serving as a user agent and **w** as an origin server forms a client/server model.
- **The Stateless Constraint.** Since messages transmitted in the scenario are self-descriptive (see the message format of **request**) and there is no cache to store sessions in the server, this model is stateless.
- **The Cacheable Constraint.** We add a tag **cachTag** in the self-descriptive messages of a response message indicating whether a response is cacheable or not. We also enable node **m** and **s** to have the capacity of the storage of cacheable responses. This scenario satisfies the REST's cacheable constraints.
- **The Layered Constraint.** With the border router **s**, which is regarded as the intermediary component, added, this integrated network is intuitively layered.
- **The Uniform Interface Constraint.** We confine channels in the model to the transmission of several kinds of messages and we consider these channels as uniform interfaces. Since each message contains **URI** for identifications of resources, **representations** and the operation methods for operations of resources by manipulating representations, some meaningful header fields which can serve as the **self-descriptive information** and **hyperlinks** for the transition to next state, we can

conclude that channels, in this point, are mechanisms for the realizations of uniform interfaces. The four interface constraints are listed in Table 2 as follows:

Table 2. Four Interface Constraints of Environment Monitoring

Constraint	Entity
Identification of Resource	URI: coap://node-w.net/phosphorus
Manipulations of Resources through Representations	Type: a document of type application/link-format METHOD: GET
Self-descriptive Messages	Protocol versions, cacheTag
Hypermedia as the Engine of Application State	hlink: coap://node-w.net/calcium

Using our framework, better understanding of the RESTful system in this case study scenario can be achieved and the REST constraints can be illustrated clearly, which demonstrates the feasibility of our model. Moreover, we also use model checker PAT to verify the model of this case study to show that it caters to the REST architecture.

7 Conclusion and Future Work

In this paper, we have proposed a CSP model of the REST architectural style. All of the components in the architecture, including user agent, cache, intermediary component (proxy and gateway) and server, have been specified as processes respectively. Besides, we have discussed the constraints of the REST architecture, including Client-Server, Cacheable, Layered, Uniform Interface, Stateless and Code-on-demand, and mapped these constraints to our achieved model. Moreover, we have used the model checker PAT to verify the constraints to prove that our achieved model is consistent with the REST architecture and detailed descriptions about how to describe these constraints to our framework also have been given. Finally, our model has been applied in modeling and analyzing a web application case study. Our formal framework makes a better understanding of REST from the perspective of formal methods to guide the implementations of the RESTful systems.

For the future, we will continue working on the modeling and analyzing of the REST architecture and the web service. Our model will be applied in reasoning about other web applications in the industry and real world such as the smart home and we also want to use our framework to determine whether a web application caters to REST architecture or not. Further, with formal tools, verifications based on our achieved model for REST architecture are also an interesting topic to be explored.

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SiteHopper: Abstracting Navigation State Machines for the Efficient Verification of Web Applications*

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Abstract. A Navigation State Machine (NSM) is a conceptual map of all possible page sequences in a web application that can be used to statically verify navigation properties. The automated extraction of an NSM from a running application is currently an open problem, as the output of existing web crawlers is not appropriate for model checking. This paper presents SiteHopper, a crawler that computes on-the-fly an abstraction of the NSM based on link and page contents. Experiments show that verification is sped up by many orders of magnitude for applications of real-world scale.

1 Introduction

As web applications form an ever greater part of existing software, their weaknesses account for an increasing part of known vulnerabilities. The knowledge of an application's navigational structure becomes crucial, especially as two of OWASP's 2010 top ten web application security risks [12] are related to navigation handling. It hence becomes desirable to leverage existing formal verification techniques to web applications. In Section 2, we recall how the exhaustive exploration of all links contained in the pages produced by a web application induces a graph called a Navigation State Machine (NSM), which describes the set of all navigation traces expected by the application's code.

We show how the possession of a machine-readable form of the NSM can be put to numerous value-adding uses, from runtime enforcement to static analysis. For example, it has recently been shown how traditional model checking techniques can be applied to this NSM to statically verify navigation properties expressed as temporal logic formulæ [5, 7, 9, 14].

All these works take as given the NSM that models the application to be verified. The generation of the NSM is a step that has been consistently overlooked, on the grounds that so-called *web crawlers* (or *spiders*) can navigate the application and extract the list of links between all pages, from which an NSM

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can easily be built. However, we shall see in Section 4 that the output produced by classical crawlers is far from appropriate for verification purposes, thereby revealing an important missing link in the process.

We present in Section 5 a web crawler called SiteHopper, aimed at producing a formal model of an application's navigational structure suitable for consumption by automated verification tools. In particular, SiteHopper computes on-the-fly, as the application is being explored, an abstraction of its pages and links aimed at reducing state redundancy and model size. Section 5.2 reports our findings on the use of SiteHopper on real-world applications; it presents the potential to greatly simplify the resulting NSM and extend the reach of model checking tools.

Finally, in Section 6, we explain why existing tools such as web crawlers lack some of the features required for the extraction of a precise and meaningful site map. Therefore, to the best of our knowledge, SiteHopper's a symbolic management of URL parameters is original.

2 Navigation Sequences in Dynamic Web Sites

In this section, we shall illustrate how many bugs and vulnerabilities in web applications turn out to be related to an inadequate handling of constraints on navigation paths. To this end, we designed a web site that allows users to browse a list of items from a fictitious company's catalogue called "Hardware Joe".

The site's main page (`index.php`), shown in Figure 1, provides a simple description of the company and a link to a `contact` page. The user must fill a form, providing a login and a password to access the site's catalogue. Provided that proper credentials are given (`user-home.php`) the user can then browse the main list of items (`item-list.php`). The list provides links to a page (`item-info.php`) that gives detailed information on each item, given a specific item `id`. On this page, the user can return back to the list, purchase the item or edit the item's information. Each of these pages also have a clickable "Logout" link that takes the user to a logout confirmation, and then back to the home page.

2.1 Hypotheses on Web Applications

Albeit simple, the site embodies a number of implicit hypotheses about the structure of a web application, which will be used in the method presented in the next section. First, the application exposes its functionality through pages, which are distinct unit of processing that provide a *single*, well-defined functionality. This unit is accessed by sending an HTTP request to a unique base URL. Moreover, the invocation of a URL ends either in the production of HTML content to be displayed by the user's browser, or in the redirection to another resource.

Upon being called, a resource can use additional *context* information to perform its task. In the present case, it is assumed that this context comes from two sources: *parameters* passed along with the HTTP request that invokes the URL, and the *current page* from which the URL is being called. In the Hardware Joe example, the `item-info` page uses an `id` parameter to determine what item

Fig. 1. Start page of "Hardware Joe", the example web site

to show information about. It shall be noted, however, that the context *modulates*, but does not fundamentally changes the page's core functionality.

As a rule, valid navigation paths form a subset of all possible sequences of page calls, and users must therefore follow a set of constraints during their navigation. For example, the front page of Hardware Joe does not show a link to `item-buy`, since a user must first be logged and choose an item id for this action to be meaningful and valid. Similarly, no Logout link is displayed in pages unless the user has previously logged in.

The annotated graph encoding all valid navigation sequences is called a Navigation State Machine (NSM), where each page is a vertex and an edge A→B indicates that page A contains a link to page B. Formally,

Definition 1 *A Navigation State Machine is a tuple* $M = \langle N, P, V, S, s_0, \delta \rangle$, *where* N *is a set of page names,* P *is a set of parameter names,* V *is a set of parameter values.* $S \subseteq N \times (P \to V)$ *is the set of states, where each state is defined by a page name and a mapping from parameters to values. As usual,* $s_0 \in S$ *is the initial state, and* $\delta \subseteq S^2$ *is a transition relation between states.*

We will use the notation $\delta(s)$ to denote the set $S' \subseteq S$ such that $s' \in S'$ if and only if $(s, s') \in \delta$.

2.2 Purpose of NSMs

The NSM shows not only how each page is linked to others, but more importantly what the application *expects* the flow of navigation to be. However, browser functionalities such as the "back" button and the use of multiple windows and bookmarks, allow users to request pages from web applications in unpredictable ways. It was shown in a earlier work [9] that the flaws exposed above can bear consequences that range from the simple inconvenience to a serious security breach. It was argued, however that they share a common cause: the user does

not follow the intended flow of navigation, which in turn causes assumptions about the application's state to fail and produce undesirable behaviour. Hence the possession of the NSM for a given web application opens the way to a variety of uses.

A first possible use is to make sure that the developed application follows a specification that was given beforehand. Moreover, if the NSM is a faithful abstraction of the application's navigation paths, one can perform static analysis on the NSM itself rather than on the actual application's code. One can use *model checking* tools to verify properties of navigation paths expressed in temporal logic [5, 7, 9, 14]. It hence becomes possible to formally demonstrate, for example, that on every valid navigation trace, a user that logs in will always eventually reach the logout page.

A second possible application is to use the NSM in a prescriptive manner, and to enforce at runtime that a user sticks to the paths that the map stipulates. Previous work by Hallé et al. developed a plugin for PHP applications based on the Zend or CodeIgniter frameworks [9]. This plugin acts as an additional layer on top of an existing application that keeps track, upon each page call, of the current state of the NSM. In the event a user veers outside the paths that are stipulated, the plugin prevents the page from being loaded and simply re-displays the last page.

Some of OWASP's Top-10 web application vulnerabilities for 2010 [12] can be prevented in this manner. For example, vulnerability A4, "Insecure Direct Object Access", can happen when a user modifies a parameter in a URL to a value not authorized in the current state of the application. Assuming the application only provides links with authorized parameter values, it is impossible to summon such a page by staying inside the NSM.

We can finally use the NSM to automatically drive test sequences on the actual application. With the knowledge of links between pages, it becomes possible to generate valid navigation sequences that take the user to a given page, for debugging purposes, as was attempted in [16], or tools like ReWeb [13] and TestWeb [15].

3 A Review of Crawler-Generated NSMs

All the aforementioned applications take the state machine model as given. It is therefore sensible to first harvest a navigation map out of existing crawlers such as Googlebot, Microsoft's Bingbot, Heritrix, Nutch or VeriWeb [4].

3.1 Model Checking Crawler-Generated NSMs

Classical crawlers are designed to systematically follow page links in a web site with the purpose of building some form of index. They use a page's URL as the unique identifier for each node. In the case of the Hardware Joe application, a "classical" analysis of page links leads to the NSM shown in Figure 2, where page names and paramter-value pairs are shown in URL style.

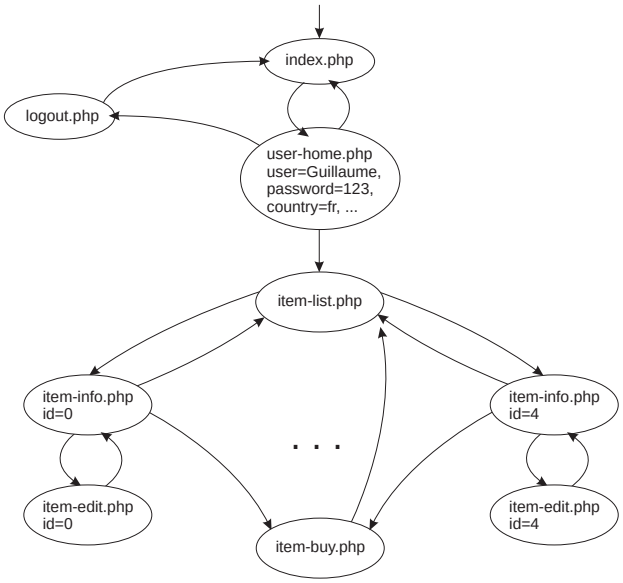

Fig. 2. The navigation state machine for the example web site. Links to `logout` from the various items pages are omitted for clarity.

In our example, since the item list is generated dynamically from the contents of a database, there are as many "Item Info", "Item Buy" and "Item Edit" pages as there are items in the database —and consequently, as many nodes in the resulting NSM that these crawlers produce.

A simple script we designed can convert a Google SiteMap[1] file into a NuSMV state machine. Table 1 shows the time required by NuSMV to validate the CTL property "the user can always return to page p" (**AG EF** p), on our example's NSM with an increasing number of items in the application's database. While the number of nodes in the NSM and the size of NuSMV's input specification grows linearly with the number of items, validation time increases much faster; NuSMV fails to process the NSM when the application's catalogue hosts 10,000 items.

3.2 Issues with Hard-Coded Parameters

The tight coupling of catalogue items and NSM nodes is problematic when one is to use a crawler's output to perform static verification of navigation properties. Apart from rendering the problem intractable for realistic page counts, this characteristic is the source of other problems.

First, if the `item-list.php` page is generated dynamically from the contents of a database, the list of available items can become much larger than the five

[1] `http://www.sitemaps.org/`. The format describes a standardized way of listing a web application's pages.

Nb. of items	Input size (kB)	Time (s)	Nb. of items	Input size (kB)	Time (s)
3	1.940	0.009	300	176.4	0.365
10	6.534	0.018	1,000	587.9	2.688
30	18.16	0.034	3,000	1,777	22.552
100	58.83	0.084	10,000	5,940	—

Table 1. Validation time for increasing database size in a web store application. NuSMV crashes with a segmentation fault at 10,000 items.

`id`'s shown in the figure. This will result in a large number of outgoing links, each of which will need to be explored separately to obtain the complete site map, thereby significantly increasing the time required to exhaust the whole site's contents. In addition, the size of NSMs has a direct impact on the performance of many of the uses of an NSM described in Section 2.2.

Second, providing hard values of the `id` parameters in the state machine amounts to hard-coding the database contents in the site map. This coupling between navigation and data content makes the resulting NSM highly vulnerable to any changes in the store's catalogue. For example, adding a new item in the database will result in one new set of links and pages being available to the user, yet the NSM won't reflect that change unless the application is crawled again. The runtime enforcement or static verification of an application using an outdated NSM may result in false conclusions that undermine their usefulness.

Third, each independent exploration of the site with a different value of `id` will result in the duplication of the same link structure between a small number of pages. Such repetition of what is essentially the same set of pages provides little insight about the site's actual structure, and in particular does not highlight the fact that the trio of pages `item-info`, `item-buy` and `item-edit` always behave in the same way and merely take an `id` as an argument.

It shall be noted upfront that page parameters, such as item IDs or user names, cannot be discarded altogether, as some web crawlers do. Indeed, in our example application, there exists a link between the "View" and the "Edit" page for the same item ID, but no link if the ID is different. Page parameters must be taken into account to retain a faithful navigation map suitable for verification.

4 A Symbolic Management of Request Parameters

These cheerless results are surprising in that the largest NSM in Table 1 is small according to model checking standards (30,000 states). The culprit rather comes from the fact that a very large part of an NSM's size is made of the repetition of patterns of essentially similar pages expressed *in extenso*. Moreover, the information provided by the crawler is not sufficient to assess which pages are similar and could be abstracted; the page's contents also matters. For all these reasons, the simplification of the NSM must be performed upstream of the model checker, at the link harvesting step.

In this section, we expose a technique to automatically discover and handle parameters in application links symbolically. The technique operates on-the-fly as the pages are explored, and can hence be integrated into a web crawler, as we shall see in the next section.

4.1 Abstracting multiple parameter occurrences

Our abstract crawler attempts to generalize the structure of pages in an NSM by replacing multiple nodes (i.e. pages) containing hard-coded parameter values with a single node. At the heart of the abstraction mechanism is the concept of *symbolic parameter*, which acts as a placeholder for actual values, and upon which constraints can be expressed.

The first component of the method consists in detecting sets of links inside a page that appear to be programmatically generated, and hence present high odds of being populated with answers from a database query. A set of such links is likely created by some program loop, and hence the URL structure of each of these links will be similar, except for the values of the "machine-generated" parameters.

When such a pattern is detected in a page's code, we abstract the links that fit the pattern by replacing them with a single node in the NSM, where the repeated parameter is replaced by a symbolic variable and associated with the set of values recorded for that parameter in the explored page.

We extend Definition 1 by adding to V a disjoint set V_s representing symbolic values. Formally, for some parameter $p \in P$ and two nodes $s = (n, f)$ and $s' = (n, f')$ such that $f(x) = f'(x)$ for all parameters $x \in P \setminus \{p\}$, we replace s and s' by $s'' = (n, f'')$, where $f(x) = f'(x) = f''(x)$ for all parameters $x \in P \setminus \{p\}$, and where $f''(p) = v_s$ for some fresh symbolic value in V_s. The new transition relation δ'' is built such that $\delta''(s'') = \delta(s) \cup \delta(s')$, and for all $y \in S$, $\delta''(y) = s''$ whenever either $\delta(y) = s$ or $\delta(y) = s'$.

When visited by the crawler, a page with symbolic parameters needs to be instantiated —that is, hard values must obviously be used in place of symbolic parameters.

The abstraction of all links with different parameters values into a single one with a symbolic variable assumes that all pages resulting from giving a value to this parameter perform essentially the same functionality. We recall that, consistent with the hypotheses laid out in Section 2.1, a parameter passed to a page modulates its functionality, but not in an essential way. This entails, in particular, that exploring the page with some parameter value k will produce links that are similar (up to their own parameter values) to those one would find by exploring the same page with another value k'.

The abstraction scheme also presents the advantage of providing a graceful way of dealing with input forms. All their fields are actually parameters to the POST request that is sent when a user clicks on their Submit button. Many users can type in many values to these fields, and each such form will result in a request URL that only differs from others in its user-supplied values. Therefore,

a form is no different than a list of program-generated links, and its parameters can be marked as free in the same way.

4.2 Context-Based Abstraction

The abstraction of all links with different parameter values into a single one with a symbolic variable assumes that all pages resulting from giving a value to this parameter perform essentially the same functionality. However, for many real-world web applications, the URL alone does not provide enough information to properly discriminate similar links: for example, many web application frameworks use the same page and parameter names for all of their links.

To address this issue, we refine the previous abstraction mechanism by also analyzing the *context* where the links appear. Links leading to similar pages are generally grouped in the same logical section within a page, such as the same top-level container element. For two links that are candidates for abstraction according to the previous rule, the path to their closest common ancestor in the page's DOM tree is computed. Depending on the contents and the length of that path, the decision for performing node abstraction can be vetoed. Moreover, this veto function is user-definable, and can be fine-tuned depending on the application to analyze.

Formally, this is represented by defining a function $d : S \to T$, where T is the set of HTML DOM trees. The function d is built on-the-fly, and each page is associated to its DOM tree once visited by the crawler. The veto described above is a function $v : T^2 \to \{\top, \bot\}$ that takes two DOM trees t and t' and evaluates their DOM similarity. The fusion of the nodes, as per the previous step, is only performed if $v(d(s), d(s')) = \top$.

4.3 Matching input and output parameters

Often times, sequences of pages carry the same parameter in their URLs. This is the case in our example application, where loading the info page for some item ID offers links to the "Buy" and "Edit" page, with the same ID. Hence the inclusion of symbolic parameters reduces the number of nodes in the NSM, but is not sufficient to retain the correct structure of the web application, as a page with a symbolic ID parameter does not say anything about the relationship this ID has with the next page.

A further simplification step addresses that issue. When the crawler loads a page $s_1 = (n_1, f_1)$ where some parameter p is instantiated with value k, and detects that the links to some other page $s_2(n_2, f_2)$ are such that $f_2(p) = k$, then in s_2 we set $f_2(p)$ to the same (symbolic) value as defined by $f_1(p)$. This indicates that, when loading page s_2, the value to give for parameter p should not be arbitrary, but rather propagate the value that was used to load the previous page, s_1. We currently detect parameters with equal values, but the process could be enhanced to discover simple relations such as integer increments, by defining the transition relation between as a set of Boolean conditions expressed on source

and target n and f (the previous example would have $(n = n_1 \wedge n' = n_2) \rightarrow f'(p) = f(p)$).

As a side benefit, a web crawler using such a symbolic management of dependencies between URL parameters is also immune to some forms "spider traps", i.e. potentially infinite sequences of pages being dynamically generated by a script. A simple example of a spider trap is a web calendar providing on each page a link to the previous and next month. A crawler that does not abstract request parameters will not discover the redundancy and treat each page as a distinct one, infinitely looping backward and forward until resources are exhausted. In contrast, the symbolic management of parameter dependencies across pages will result in a single page that only requires to be explored once.

4.4 Domain Reduction

The previous simplification then allows us to perform significant reductions in the size of domains for observed parameters. For example, in our online store application, there is no other constraint on item IDs than the fact that the ID passed to the "Item Buy" and "Item Edit" page must be the same as the ID from the source "Item Info" page. The actual value of the ID is never relevant in the navigation, which entails that the domain for the symbolic parameter ID can be shrunk down to a single constant. For verification purposes, only "hard" values of parameters occurring in pages actually matter, even if the domain for this parameter is larger in practice. We take advantage of this by trimming from the set V all values that do not show up in any node's image for their mapping f.

5 Empirical Evaluation

To test the parameter abstraction scheme described above, we created a web crawler called Site Hopper, which can be used to automatically build and simplify an NSM, and used it in a number of experiments which we describe in this section.

5.1 Crawler Implementation

SiteHopper computes on-the-fly, as the application is being explored, an abstraction of its pages and links aimed at reducing state redundancy and model size by deriving meaningful relationships on link parameters inside and between pages. It operates like a traditional crawler, at the HTTP protocol level, by only sending requests and analyzing the contents of returned pages. In particular, it does not require the application's source code; therefore, SiteHopper is not tied to any particular web programming language, and can be used to explore any web application that a normal browser could access. SiteHopper 1.0 is freely available under an open source license and has been downloaded more than 90 times.

The crawler presents itself to the user in the form of an interactive web application, whose interface is shown in Figure 3. A user first types in the page's

top textbox the starting URL. Site Hopper then loads that page, analyzes its contents and displays in the lower region of the page a partial graph showing the pages and links between them that have been discovered so far. The graph is interactive: by clicking on one of the nodes, the user resumes the exploration from that particular page, and any new pages and links discovered are added to the graph on-the-fly.

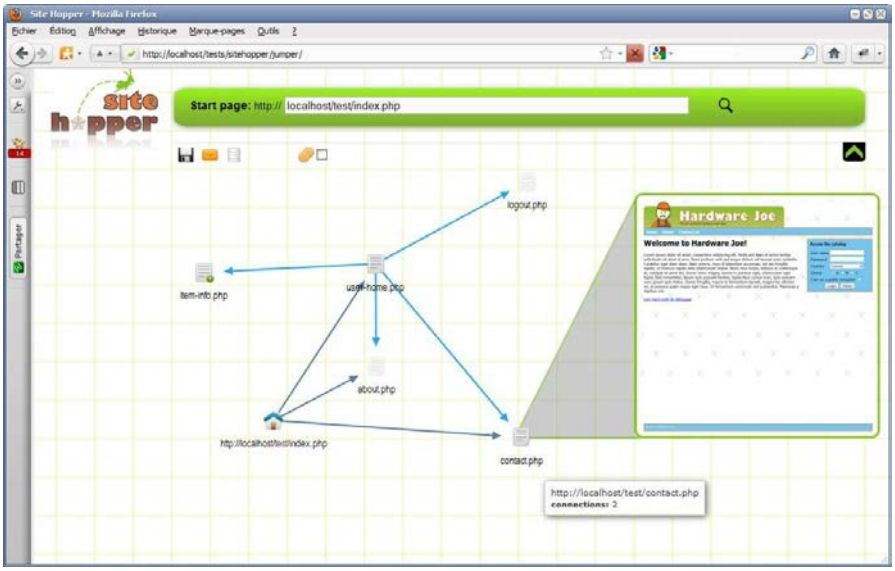

Fig. 3. User interface for Site Hopper, showing a partial exploration of the Hardware Joe website

SiteHopper is made of two components. The first part, invisible to the user, is called the *jumper*: it consists of a web service, hosted on Site Hopper's server, responsible for issuing a particular HTTP request, retrieving the page contents and analyzing the links it contains. The jumper is built to return responses in an XML format extending Google's SiteMap protocol. The second part of Site Hopper is the GUI itself, an Ajax application running in the user's web browser and displaying the progressive construction of an application's NSM. To create a state machine out of the jumper's data, the GUI persists in memory the graph structure created by merging responses to successive requests to the jumper. The resulting structure is again an extended SiteMap XML document that the user can save to a file at any moment.

5.2 Experiments

To assess the effectiveness of our method at generalizing navigation state machines from web applications, we ran Site Hopper on a set of real-world applications.

Besides Hardware Joe, the web site used as an example throughout this paper, we ran Site Hopper on a number of applications:

- Digitalus,[2] an open source content management system
- osCommerce,[3] an open source online catalog management system (8,000 lines of code)
- Phreebooks,[4] an open source inventory management system.

Phreebooks is notable for being hosted online, on a server to which we had no special access outside of the web interface available to anybody to try the application.

NSM extraction We first report the capability of the tool to explore the applications, correctly request their pages and provide meaningful information on symbolic parameters and links between pages.

Phreebooks: Bootstrap Script In the case of Phreebooks, *all* the links in the application point to a single base URL, `index.php`, that acts as a "bootstrap script", which is then responsible of dispatching it to the proper piece of code. No matter what action or what resource is being handled: everything is passed as parameters to this single index file. Hence, editing user account `guillaume` would have a URL `index.php?module=users& page=edit&id=guillaume`. while showing the list of all blog posts on the topic "computers" would have the URL `index.php?module=blog&page=show&cat=computers`. Site Hopper generalizes the site as having a single page of the form `page.php?module=$i&page=$j&cat=$k&id=$l...`, with `$i`, `$j`, `$k` and `$l` free input parameters.

The basic processing unit is therefore not identified by the base URL, but the value of the `module` and `page` parameters. This goes against our assumptions that parameters do not modify the functionality of a page in a fundamental way. Site Hopper can be adapted so that it can take the page name *and* some parameters as the identifier of what constitutes a distinct "page". Once told that `module` and `page` should be handled as part of the page name instead of parameters, Site Hopper had no trouble exploring the application and abstracting the remaining parameters correctly.

Digitalus: Clean URLs Digitalus exposes "clean" URLs to the user using Apache's mod_rewrite module, which allows applications to rewrite URLs on-the-fly upon being invoked. For example, the application can specify a rewriting rule that transforms the URL `edit/users/guillaume` into `index.php?page=edit&id=guillaume` on the server side, and the corresponding script be called.

A configuration file allows Site Hopper to handle such a URL naming scheme. The user provides a predefined list of character strings that define page names,

[2] `http://www.digitaluscms.org`
[3] `http://www.oscommerce.com`
[4] `http://www.phreesoft.com`

such as `edit/users`. When encountering a link, Site Hopper looks in the list for the occurrence of such a string, which makes up the "page" part of the URL. The remaining, slash-separated elements are considered as nameless parameter values. This simple mechanism again turned out to work surprisingly well: Site Hopper correctly interacts with the application and manages parameters symbolically.

These experiments show that the adaptations required to our crawler are not related to our parameter abstraction method, but rather to the capability of distinguishing what constitutes a page vs. its parameters. Once this distinction is made clear, the parameter abstraction mechanism works correctly in all applications we tested.

Empirical Data The combined application of the abstraction steps presented in Section 4 is expected to yield significant reductions in the size of the NSM, while retaining the same navigation sequences. We illustrate the effectiveness of our method at generalizing navigation state machines by running SiteHopper on our example application; the results are shown in Table 2. One can see in the first time column that validation is on average 20 times faster than with an NSM generated by a traditional crawler, due to the fusion of all nodes with different item IDs into a single node. Validation is further improved when adding domain reduction, which, in this case, reduces the NSM into a graph of constant size, regardless of database size. For a database of 3,000 items, this represents a 2,000× speedup with respect to the initial NSM.

Nb. of items	Time 1 (s)	Time 2 (s)
3	0.009	0.011
10	0.010	0.011
30	0.007	0.011
100	0.008	0.011
300	0.018	0.011
1,000	0.158	0.011
3,000	1.427	0.011
10,000	16.14	0.011

Table 2. Validation time for increasing database size in a web store application with SiteHopper, using node fusion (column 1), and adding domain abstraction (column 2).

We repeated the analysis with osCommerce 2.3.1; we populated the application's database with 10,000 elements, and then performed empirical measurements on two aspects of SiteHopper, its running time and the impact of the use of symbolic parameters on an NSM's complexity.

Running Time Running time was defined as the time for the server-side part of SiteHopper to request and process a single page. The analysis step typically takes on average 700 ms per page, with pages containing more links taking a longer time to analyze. We shall mention that this figure includes the time where the web application itself processes the request and generates the page that is then analyzed by SiteHopper. As a rule, each link in a page adds on average 33 ms to the processing time. The total time to generate the whole NSM we used was on average 12.49 s.

Symbolic Parameters To assess the simplification potential of symbolic parameters and the mechanism described in Section 5, we performed a second experiment where we verified CTL properties on the symbolic NSM. The results are shown in Table 3. Validation time averages less than 0.5 s and is independent of database size, while the same validation with the explicit-state NSM crashes NuSMV for all properties, due to its size.

Property	Time (s)
Main page is reachable from all pages	0.480
Product ID can only change through visiting the item list	0.421
Category ID is never constrained	0.415

Table 3. Validation time for a sample set of CTL properties

6 Related Work

Many specialists maintain the idea that crawling the web has been solved a decade ago. This contrasts with a 2009 exhaustive survey of program comprehension through dynamic analysis, which notes that web applications are the least studied of all types of applications on this respect [6]. Indeed, despite the broad range of tools developed over the past decade, we shall see that none of them can produce a site map and deal with symbolic parameters on-the-fly.

6.1 Source Code Analysis

A first approach consists of obtaining the application's source code, and deduce valid navigation paths from the code's control flow. This is the approach taken by Guha et al. [8], who statically analyze an Ajax application on the client side and extract a control-flow graph from its source code. Similarly, Licata and Krishnamurthi present a method for extracting a form of context-free grammar, called WebCFG, from a web application's source code [10]. However, a WebCFG does not have support for symbolic parameters and cannot express dependencies between parameters across multiple pages. This is also true of a reverse-engineering approach called WARE [11].

6.2 Trace Mining

PHP2XMI [1], WAFA [2] and WANDA [3] work on the server side and can be classified as trace mining tools: they record information about page calls made by visitors by instrumenting the application's source code, and process this log *a posteriori*. Some of them try to slice that information into traces corresponding to successive calls made by a single user. However, these tools produce sequence diagrams for individual visits, and do not actively explore an application to

obtain a map of all possible navigation sequences. PHP2XMI does apply some form of "filtering" to simplify the resulting navigation information; however, this filtering still considers as different the same base URL with different request parameters.

6.3 Site Crawlers

The first two approaches do not attempt to extract a model through the exhaustive exploration of the application; both rely on its source code, are tied to one specific implementation language, and assume knowledge of its internals, such as session variables. A natural choice for the extraction of navigation models is therefore the use of spiders or crawlers. Generally, web crawlers such as Googlebot or Microsoft's Bingbot create unordered lists of pages, without keeping information on the way they are connected. While some of them can automatically populate form fields and access pages that require input parameters, they do not use that information to derive relationships between them in the way symbolic parameters in an NSM do.

An exception is a tool called VeriWeb [4], which, while not being labelled a "crawler", explores interactive web sites using a special browser that systematically explores all paths up to a specified depth. However, VeriWeb, like classical crawlers, does not keep track of relationships and constraints in input parameters between multiple pages.

7 Conclusion

In this paper, we developed and exposed a technique to automatically discover and handle parameters in application links symbolically. The technique operates on-the-fly as the pages are explored, and can hence be integrated into a web crawler. The Site Hopper tool we presented in this paper was used to experiment on this method. Tests on real-world applications show that symbolic management of parameters results in a much clearer map of an application where abstract relationships between pages and parameters are explicitly shown. The method drastically reduces the size of the resulting navigation state machineand greatly decreases the adverse impact of database size on the performance of model checking of an NSM. It applies equally well on various URL schemes used by applications, provided that parameters can be distinguished from an URL's base name.

Drawing on this success with server-side applications, the technique is currently being ported inside a web browser plugin, which opens the door to the analysis and abstraction of links generated by JavaScript on the client side. Future work also involves using measurements on the content of destination pages to decide whether to fusion outgoing links, and the study of bisimulation-based methods to identify redundant link structures in an NSM.

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Preference and Similarity-based Behavioral Discovery of Services*

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Abstract. We extend Constraint Automata by replacing boolean constraints with semiring-based soft constraints. The obtained general formal tool can be used to represent preference-based and similarity-based queries, which allow a user more freedom in choosing the behavior of the service to finally use, among all possible choices. A user states his preferences through a "soft" query, and obtains results that satisfy this query with different levels of preference. The soft requirements may involve a parameter data of the service operations, or the (names of the) operations themselves. Moreover, we introduce a first implementation of the search procedure by using declarative (soft) Constraint Programming.

1 Introduction

Service-orientation is a design paradigm to build computer software in the form of services. The term "service" refers to a set of related software functionalities that can be reused for different purposes. In this sense, the service becomes more important than the software. A *Service-Oriented Architecture* (*SOA*) offers some benefits as return on investment, organisational agility and interoperability as well as a better alignment between business and IT. In such loosely-coupled environments, the automatic discovery process becomes more complex, and a user's decision has to be supported taking into account his (often not crisp) preferences, some semantic information on the related knowledge-domain, and the behavior signature of each service, describing the sequence of its operations [17,11]. For instance, a user may need to find an on-line purchase service satisfying the following requirements: *i)* charging activity is before shipping activity, *ii)* to purchase a product, the requester first needs to log into the system and finally log out of the system, and *iii)* filling the electronic basket of the user may consist of a succession of "add-to-basket" actions (a similar scenario is proposed in [17]).

In this paper, we define a formal framework that considers both user's preferences and (stateful) service behavior during the search procedure, in order to

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retrieve multiple results for the same preference-based query; in this way, the end user has the possibility to choose among different results by selecting the service that maximizes his requirements. In the above mentioned purchase scenario, for example, he may prefer to pay with a credit card instead of with a bank transfer. Later in this paper, using the same framework, we also show how it is possible to represent similarity-based search, in order to find the services that perform operations "similar" to those requested. These services can be valid alternatives for the user in case the "best" (i.e., user's most desirable) service is not available at the moment, for example, due to failures or a high number of requests.

In Sec. 2 we report the related work, showing that no general formal framework has been proposed in the literature for such tasks, and this dearth is even more striking if we consider the behavior of the services.

In Sec. 3 we summarize the background on semiring-based soft constraints [6,5], showing the basic operations of this parametric preference-based framework.

As a first result of this paper, in Sec. 4 we extend *Constraint Automata* (*CA*) [2] in order to deal with preferences on data-constraints: instead of (classical) boolean constraints, we adopt semiring-based soft constraints, which can model any preference system as long as it can be cast into a semiring algebraic structure. However, even boolean constraints can be represented with semirings (see Sec. 3), and used in the same framework as well.

In Sec. 5 we show how to model preference-based queries according to the theory presented in Sec. 4. The names of the service operations offered to users correspond to the names on the *CA* transitions (i.e., the synchronization constraints [2]). At the same time, soft data-constraints model preferences on the data exchanged through I/O by each service operation. For example, the data required for the *Charging* operation can involve a bank transfer, a credit card number, or pay-on-delivery with cash. For instance, a user may prefer the second method over the other two. Automata have emerged as a convenient framework to study behavioral issues. In Sec. 5 we also show that the formal results of Sec. 4, such as the join/hide operations on automata, and simulation/bisimulation relationships, can be used to reason on preference-based queries.

In Sec. 6 we focus our attention on similarity-based search. In this scenario, a user is interested in retrieving services with operations "similar" to those in his query; therefore, he uses soft constraints to define a preference for the operation names, and instead of their I/O data as in Sec. 5. For example, instead of the *Charging* operation, an operation named *SendEstimate* can be used by the same user to receive a purchase-estimate (and then buy with a phone call). In this case, the operations *Charging* and *SendEstimate* are "similar" and, then, mutually replaceable up to that user's degree of preference. In Sec. 6.1 we show how to solve this search problem as a *Soft Constraint Satisfaction Problem* (*SCSP*) [6,5].

We suppose the availability of meaning and similarity-scores of names as computed from a proper domain-specific ontology [15] (as proposed by other works in Sec. 2): in this paper we focus on the representation of preference/similarity-based queries, and on the formal framework we propose to resolve them. Finally, in Sec. 7 we draw our conclusions and explain our future work.

2 Related Work

A handful of researchers have investigated the problem of business process reuse based on process similarity, and discovery of processes based on search through repositories. For example, in [3] the discovery queries are abstracted and dependencies among processes are described with the help of ontologies.

In [17] the authors propose a new behavior model for Web Services (WSs) using automata and logic formalisms. Roughly, the model associates messages with activities and adopts the IOPR model (i.e., Input, Output, Precondition, Result) in *OWL-S* [15] to describe activities. The authors use an automaton structure to model service behavior. They develop a new query language to express temporal and semantic properties of service behaviors. As a query evaluation algorithm they show an optimization approach using tree structures and heuristics to improve performance. However, similarity-based search is not mentioned in [17].

The model presented in [18] relies on a simple and extensible keyword-based query language and enables efficient retrieval of approximate results, including approximate service compositions. Since representing all possible compositions and all approximate concept references can result in an exponentially-sized index, the authors investigate clustering methods to provide a scalable mechanism for service indexing. In [10] the problem of behavioral matching is translated to a graph matching problem, and existing algorithms are adapted for this purpose.

In [4], the authors propose a crisp translation from interface description of WSs to classical crisp *Constraint Satisfaction Problems* (*CSPs*). This work does not consider service behavior and, in this framework, it is not possible to quantitatively reason on similarity/preference involving different services: it is not possible to widen the results of a query by obtaining similar services. In [20], a semiring-based framework is used to model and compose QoS features of WSs. However, no notion of similarity relationship is given in in [20].

In [8], the authors propose a novel clustering algorithm that groups names of parameters of web-service operations into semantically meaningful concepts. These concepts are then leveraged to determine similarity of inputs (or outputs) of web-service operations. In [16] the authors propose a framework of fuzzy query languages for fuzzy ontologies, and present query answering algorithms for these query languages over fuzzy *DL-Lite* ontologies.

In [11] the authors propose a metric to measure the similarity of semantic services annotated with an *OWL ontology*. They calculate similarity by defining the intrinsic information value of a service description based on the "inferencibility" of each of *OWL Lite* constructs. The authors of [12] present an approach to hybrid semantic matching of web-services that complements logic-based reasoning with approximate matching based on syntactic Information-Retrieval-based computations. In [19], the authors propose a retrieval method to assess the similarity of available service interfaces with a provided desired-service-description, extended to include semantically similar words according to *wordNet*.

Our solution in this paper appears to be more general and comprehensive compared to the works mentioned above, since it can be adapted to any semiring-like metrics, and comes with several formal tools for reasoning over the queries

(see Sec. 5). Moreover, most of the proposed works do not consider the service behavior at all, but only their interfaces, because no formal standard for web-services covers their behavior yet. We propose an implementation based on (*Soft*) *Constraint Programming*, which proves to be expressive and efficient, and adopts (off-the-shelf) AI-based solving techniques in its underlying machinery.

3 Semirings and Soft Constraint Satisfaction Problems

A c-semiring [6] (simply semiring in the sequel) is a tuple $S = \langle A, +, \times, \mathbf{0}, \mathbf{1}\rangle$, where A is a possibly infinite set with two special elements $\mathbf{0}, \mathbf{1} \in A$ (respectively the bottom and top elements of A) and with two operations $+$ and $\times$ that satisfy certain properties over A: $+$ is commutative, associative, idempotent, closed, with $\mathbf{0}$ as its unit element and $\mathbf{1}$ as its absorbing element; $\times$ is closed, associative, commutative, distributes over $+$, $\mathbf{1}$ is its unit element, and $\mathbf{0}$ is its absorbing element. The $+$ operation defines a partial order $\leq_S$ over A such that $a \leq_S b$ iff $a + b = b$; we say that $a \leq_S b$ if b represents a value *better* than a. Moreover, $+$ and $\times$ are monotone on $\leq_S$, $\mathbf{0}$ is the min of the partial order and $\mathbf{1}$ its max, $\langle A, \leq_S\rangle$ is a complete lattice and $+$ is its *least upper bound* operator (i.e., $a + b = lub(a, b)$) [6].

Some practical instantiations of the generic semiring structure are the *boolean* $\langle\{false, true\}, \vee, \wedge, false, true\rangle$,[3] *fuzzy* $\langle[0..1], \max, \min, 0, 1\rangle$, *probabilistic* $\langle[0..1], \max, \hat{\times}, 0, 1\rangle$ and *weighted* $\langle\mathbb{R}^+ \cup \{+\infty\}, min, \hat{+}, \infty, 0\rangle$ (where $\hat{\times}$ and $\hat{+}$ respectively represent the arithmetic multiplication and addition).

Given a semiring $\langle A, +, \times, \mathbf{0}, \mathbf{1}\rangle$ and $a, b \in A$, we define the residuated negation [7] of a as $\neg a = \max\{b : b \times a = \mathbf{0}\}$, where max is according to the ordering defined by $+$ [7]. Note that over the boolean semiring the negation operator corresponds to the logic negation, since $\neg\mathbf{0} = \max\{b : b \times \mathbf{0} = \mathbf{0}\} = \mathbf{1}$, and $\neg\mathbf{1} = \max\{b : b \times 1 = \mathbf{0}\} = \mathbf{0}$. When the considered semiring has no $\mathbf{0}$ divisors (i.e., when $a \times b = \mathbf{0}$ only if $a = 0$ or $b = 0$), then $\neg a = \mathbf{0}$ for every $a \neq \mathbf{0}$.

A *soft constraint* [6] may be seen as a constraint where each instantiation of its variables has an associated preference. Given $S = \langle A, +, \times, \mathbf{0}, \mathbf{1}\rangle$ and an ordered finite set of variables V over a domain D, a soft constraint is a function that, given an assignment $\eta : V \to D$ of the variables, returns a value of the semiring, i.e., $c : (V \to D) \to A$. Let $\mathcal{C} = \{c \mid c : D^{|I \subseteq V|} \to A\}$ be the set of all possible constraints that can be built starting from S, D and V: any function in $\mathcal{C}$ depends on the assignment of only a (possibly empty) finite subset I of V, called the *support*, or *scope*, of the constraint. For instance, a binary constraint $c_{x,y}$ (i.e., $\{x, y\} = I \subseteq V$) is defined on the support $supp(c) = \{x, y\}$. Note that $c\eta[v = d]$ means $c\eta'$ where η' is η modified with the assignment $v = d$. Note also that $c\eta$ is the application of a constraint function $c : (V \to D) \to A$ to a function $\eta : V \to D$; what we obtain is, thus, a semiring value $c\eta = a$.[4]

[3] The *boolean* semiring can be used to represent classical crisp constraints.

[4] the constraint function $\bar{a}$ always returns the value $a \in A$ for all assignments of domain values, e.g., the $\bar{\mathbf{0}}$ and $\bar{\mathbf{1}}$ functions always return $\mathbf{0}$ and $\mathbf{1}$ respectively.

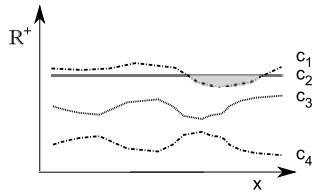

Fig. 1. A graphical representation of four *weighted* constraints, e.g., $c_2 = c_3 \otimes c_4$.

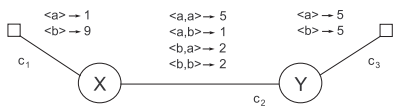

Fig. 2. An SCSP based on a *weighted* semiring.

Given the set $\mathcal{C}$, the combination function $\otimes : \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C}$ is defined as $(c_1 \otimes c_2)\eta = c_1\eta \times c_2\eta$ [6]; $supp(c_1 \otimes c_2) = supp(c_1) \cup supp(c_2)$. Given the set $\mathcal{C}$, the combination function $\oplus : \mathcal{C} \oplus \mathcal{C} \rightarrow \mathcal{C}$ is defined as $(c_1 \oplus c_2)\eta = c_1\eta + c_2\eta$ [5]; $supp(c_1 \oplus c_2) = supp(c_1) \cup supp(c_2)$. Informally, $\otimes/\oplus$ builds a new constraint that associates with each tuple of domain values for such variables a semiring element that is obtained by multiplying/summing the elements associated by the original constraints to the appropriate sub-tuples. Given a constraint $c \in \mathcal{C}$ and a variable $v \in V$, the *projection* [6] of c over $V \backslash \{v\}$, written $c \Downarrow_{(V \backslash \{v\})}$ is the constraint c' such that $c'\eta = \sum_{d \in D} c\eta[v = d]$. Informally, projecting means computing the best possible rating over all values of the remaining variables.

The partial order $\leq_S$ over $\mathcal{C}$ can be easily extended among constraints by defining $c_1 \sqsubseteq_S c_2 \iff \forall \eta, c_1\eta \leq_S c_2\eta$. In order to define constraint equivelance we have $c_1 \equiv_S c_2 \iff \forall \eta, c_1\eta =_S c_2\eta$ and $supp(c_1) = supp(c_2)$.

In Fig. 1 we show a graphical example of four *weighted* constraints (i.e., defined in the *weighted* semiring), where we have $c_3 \otimes c_4 = c_2$, $c_3 \sqsubseteq c_4$, $c_2 \sqsubseteq c_3$, $c_1 \sqsubseteq c_3$, but $c_1 \not\sqsubseteq c_2$ because of the gray region, where $c_2 \sqsubseteq c_1$ instead; moreover, in Fig. 1 we can see that $supp(c_1) = supp(c_2) = supp(c_3) = supp(c_4) = \{x\}$.

An SCSP [6] is defined as a quadruple $P = \langle S, V, D, C \rangle$, where $C \subseteq \mathcal{C}$ is the constraint set of the problem P. The *best level of consistency* notion defined as $blevel(P) = Sol(P) \Downarrow_{\emptyset}$, where $Sol(P) = \bigotimes C$ [6]. A problem P is α-consistent if $blevel(P) = \alpha$ [6]; P is instead simply "consistent" iff $blevel(P) >_S \mathbf{0}$ [6]. P is inconsistent if it is not consistent. Figure 2 shows an SCSP as a graph: S corresponds to the *weighted* semiring, i.e., $\langle \mathbb{R}^+ \cup \{+\infty\}, \min, \hat{+}, \infty, 0 \rangle$. Variables ($V = \{x, y\}$) and constraints ($C = \{c_1, c_2, c_3\}$) are represented respectively by nodes and arcs (unary for c_1 and c_3, and binary for c_2), and semiring values are written to the right of each variable assignment of the constraint, where $D = \{a, b\}$. The solution of P in Fig. 2 associates a preference to every domain value of x and y by combining all the constraints, i.e., $Sol(P) = \bigotimes C$. For instance, for the assignment $\langle a, a \rangle$ (that is, $x = y = a$), we compute the sum of 1 (which is the value assigned to $x = a$ in constraint c_1), 5 (which is the value assigned to $\langle x = a, y = a \rangle$ in c_2) and 5 (which is the value for $y = a$ in c_3). Hence, the resulting preference value for this assignment is 11. The *blevel* for the example in Fig. 2 is 7, corresponding to the assignment $x = a$, $y = b$.

4 Soft Constraint Automata

Constraint Automata were introduced in [2] as a formalism to describe the behavior and possible data flow in coordination models (e.g., the `Reo` language [2]); they can be considered as acceptors of *Timed Data Streams* (*TDS*) [1,2]. In this section we extend some of the definitions given in [2] in order to obtain *Soft Constraint Automata* (*SCA*).

We recall the definition of *TDS* from [1], while extending it using the softness notions described in Sec. 3: we name this result as *Timed Weighted Data Streams* (*TWDS*), which correspond to the languages recognized by *SCA*.[5] For convenience, we consider only infinite behavior and infinite streams that correspond to infinite "runs" of our soft automata, omitting final states, including deadlocks.

Definition 1 (Timed Weighted Data Streams). *Let Data be a data set, and for any set X, let X^ω denote the set of infinite sequences over X; given a semiring $S = \langle A, +, \times, \mathbf{0}, \mathbf{1}\rangle$, a Timed Weighted Data Stream (*TWDS*) is a triplet:*

$$\langle \lambda, l, a\rangle \in \mathit{Data}^\omega \times \mathbb{R}_+^\omega \times A^\omega \textit{ such that, } \forall k \geq 0 : l(k) < l(k+1) \textit{ and } \lim_{k\to+\infty} l(k) = +\infty$$

Thus, a *TWDS* triplet $\langle \lambda, l, a\rangle$ consists of a data stream $\lambda \in \mathit{Data}^w$, a time stream $l \in \mathbb{R}_+^\omega$ and a preference stream $a \in A^\omega$. The time stream l indicates, for each data item $\lambda(k)$, the moment $l(k)$ at which it is exchanged (i.e., being input or output), while the $a(k)$ is a preference score for its related $\lambda(k)$.

CA [2] use a finite set $\mathcal{N}$ of names, e.g., $\mathcal{N} = \{n_1, \ldots, n_p\}$, where n_i ($i \in 1..p$) is the i-th input/output port. The transitions of *SCA* are labeled with pairs consisting of a non-empty subset $N \subseteq \mathcal{N}$ and a soft (instead of crisp as in [2]) data-constraint c. Soft data-constraints can be viewed as an association of data assignments with a preference for that assignment. Formally,

Definition 2 (Soft Data-Constraints). *A soft data-constraint is a function $c : (\{d_n \mid n \in N\} \to \mathit{Data}) \to A$ defined over a semiring $S = \langle A, +, \times, \mathbf{0}, \mathbf{1}\rangle$, where $\{d_n \mid n \in N\} \to \mathit{Data}$ is a function that associates a data item with every variable d_n related to port name $n \in N \subseteq \mathcal{N}$, and* Data *is the domain of data items that pass through ports in $\mathcal{N}$. The grammar of soft data-constraints is:*

$$c_{\{d_n \mid n\in N\}} = \bar{\mathbf{0}} \mid \bar{\mathbf{1}} \mid c_1 \oplus c_2 \mid c_1 \otimes c_2 \mid \neg c$$

where $\{d_n \mid n \in N\}$ is the support of the constraint, i.e., the set of variables (related to port names) that determine its preference (see Sec. 3).

Informally, a soft data-constraint is a function that returns a preference value $a \in A$ given an assignment for the variables $\{d_n \mid n \in N\}$ in its support. In the sequel, we write $SDC(N, \mathit{Data})$, for a non-empty subset N of $\mathcal{N}$, to denote the set of soft data-constraints. We will use *SDC* as an abbreviation for $SDC(\mathcal{N}, \mathit{Data})$.

[5] TWDSs do not imply time constraints, and thus our (soft) CA are not "timed" [2].

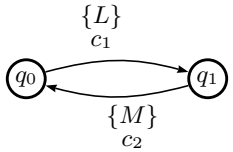

Fig. 3. A Soft Constraint Automaton.

$c_1 : (\{d_L\} \to \mathbb{N}) \to \mathbb{R}^+$ s.t. $c_1(d_L) = d_L + 3$

$c_2 : (\{d_M\} \to \mathbb{N}) \to \mathbb{R}^+$ s.t. $c_2(d_M) = d_M + 5$

Fig. 4. c_1 and c_2 in Fig 3.

Note that in Def. 2 we assume a global data domain *Data* for all names, but, alternatively, we can assign a data domain $Data_n$ for every variable d_n.

We state that an assignment η for the variables $\{d_n \mid n \in N\}$ satisfies c with a preference of $a \in A$, if $c\eta = a$ (see Sec. 3). Equivalence and implication for soft data-constraints are defined in Sec. 3: we respectively write $c_1 \equiv c_2$, and $c_1 \sqsubseteq c_2$.

Note that by using the *boolean* semiring (see Sec. 3), thus within the same semiring-based framework, we can exactly model the "crisp" data-constraints presented in the original definition of *CA* [2]. Therefore, *CA* are subsumed by Def. 3. Note also that weighted automata, with weights taken from a proper semiring, have already been defined in the literature [9]; in *SCA*, weights are determined by a constraint function instead.

Definition 3 (Soft Constraint Automata). *A Soft Constraint Automaton over a domain* Data*, is a tuple* $\mathcal{T}_S = (\mathcal{Q}, \mathcal{N}, \longrightarrow, \mathcal{Q}_0, S)$ *where* i) S *is a semiring* $\langle A, +, \times, \mathbf{0}, \mathbf{1}\rangle$, ii) $\mathcal{Q}$ *is a finite set of states,* iii) $\mathcal{N}$ *is a finite set of names,* iv) $\longrightarrow$ *is a finite subset of* $\mathcal{Q} \times 2^{\mathcal{N}} \times SDC \times \mathcal{Q}$*, called the transition relation of* $\mathcal{T}_S$*, and* v) $\mathcal{Q}_0 \subseteq \mathcal{Q}$ *is the set of initial states. We write* $q \xrightarrow{N,c} p$ *instead of* $(q, N, c, p) \in \longrightarrow$*. We call* N *the name-set and* c *the guard of the transition. For every transition* $q \xrightarrow{N,c} p$ *we require that i)* $N \neq \emptyset$*, and ii)* $c \in SDC(N, Data)$ *(see Def. 2).* $\mathcal{T}_S$ *is called finite iff* $\mathcal{Q}, \longrightarrow$ *and the underlying data-domain Data are finite.*

The intuitive meaning of an *SCA* $\mathcal{T}_S$ as an operational model for service queries is similar to the interpretation of labeled transition systems as formal models for reactive systems. The states represent the configurations of a service. The transitions represent the possible one-step behavior, where the meaning of $q \xrightarrow{N,c} p$ is that, in configuration q, the ports in $n \in N$ have the possibility of performing I/O operations that satisfy the soft guard c and that leads from configuration q to p, while the other ports in $\mathcal{N} \backslash N$ do not perform any I/O operation. Each assignment of variables $\{d_n \mid n \in N\}$ represents the data associated with ports in N, i.e., the data exchanged by the I/O operations through ports in N.

In Fig. 3 we show an example of a (deterministic) *SCA*. In Fig. 4 we define the *weighted* constraints c_1 and c_2 that describe the preference (e.g., a monetary cost) for the two transitions in Fig. 3, e.g., $c_1(d_L = 2) = 5$.

We now define $sdc_{\mathcal{T}_S}(q, N, P)$, which is used in Sec. 5.1 for (bi)simulation:

Definition 4. *For an* SCA $\mathcal{T}_S = (\mathcal{Q}, \mathcal{N}, \longrightarrow, \mathcal{Q}_0, \mathcal{S})$*, a state* $q \in \mathcal{Q}$*,* $N \subseteq \mathcal{N}$*,* $P \subseteq \mathcal{Q}$*, and* $\bigoplus$ *that corresponds to the application of the* $\oplus$ *operator (see Sec. 3)*

to all the constraints of a set ($\oplus$ is commutative and associative), we define:

$$sdc_{\mathcal{T}_S}(q, N, P) = \bigoplus\{c \mid q \xrightarrow{N,c} p \text{ for some } p \in P\}$$

Intuitively, $sdc_{\mathcal{T}_S}(q, N, P)$ is the weakest (i.e., with the best preference) soft data-constraint that ensures the existence of an N-transition from q to a state in P. Note that $sdc_{\mathcal{T}_S}(q, N, P) = \bar{\mathbf{0}}$ if there is no N-transition from q to a P-state.

As introduced before, we define the language accepted by an *SCA* $\mathcal{T}_S$ as

$$\mathcal{L}_{TWDS} = \bigcup_{q \in Q_0} \mathcal{L}_{TWDS}(\mathcal{T}_S, q)$$

where $\mathcal{L}_{TWDS}$ denotes the language accepted by the state q (viewed as the starting state) of $\mathcal{T}_S$. Considering, as an example, a two port automaton $\mathcal{T}_S$, the accepted languages on $\mathcal{N} = \{L, M\}$ are defined as the set of all TWDS pairs $\langle\langle\lambda, l, a\rangle, \langle\mu, m, b\rangle\rangle$ that have an infinite run in $\mathcal{T}_S$ starting in state q. The data streams λ and μ correspond to the data elements that flow through, respectively, L and M; l and m contain the time instants at which these data flow operations take place. $\mathcal{L}_{TWDS}(\mathcal{T}_S, q)$ consists of all pairs $\langle\langle\lambda, l, a\rangle, \langle\mu, m, b\rangle\rangle$ such that there exists a transition $q \xrightarrow{N,c} \bar{q}$ that satisfies the following conditions (where we denote the tail of the stream $\lambda = \lambda(0), \lambda(1), \lambda(2), \ldots$ as $\lambda' = \lambda(1), \lambda(2), \ldots$):

$$l(0) < m(0) \wedge N = \{L\} \wedge c(d_L = \lambda(0)) = a(0) \wedge \langle\langle\lambda', l', a'\rangle, \langle\mu, m, b\rangle\rangle \in \mathcal{L}_{TWDS}(\mathcal{T}_S, \bar{q})$$

$$or \quad m(0) < l(0) \wedge N = \{M\} \wedge c(d_M = \mu(0)) = b(0) \wedge \langle\langle\lambda, l, a\rangle, \langle\mu', m', b'\rangle\rangle \in \mathcal{L}_{TWDS}(\mathcal{T}_S, \bar{q})$$

$$or \quad l(0) = m(0) \wedge N = \{L, M\} \wedge c(d_L = \lambda(0), d_M = \mu(0)) = a(0) = b(0) \wedge$$

$$\langle\langle\lambda', l', a'\rangle, \langle\mu', m', b'\rangle\rangle \in \mathcal{L}_{TWDS}$$

where $a(0), b(0) >_S \mathbf{0}$. Although the above definition is circular in case $q = \bar{q}$, a proper monotone operator can be formally defined [2]. As an example, the language accepted by the automaton in Fig. 3 equals the set $\{\langle\langle\lambda, l, a\rangle, \langle\mu, m, b\rangle\rangle \in TWDS \times TWDS \mid \forall k \geq 0 : \lambda(k), \mu(k) \in \mathbb{N} \wedge l(k) < m(k) < l(k+1) \wedge a(k) = c_1(d_L = \lambda(k)), b(k) = c_2(d_M = \mu(k)), \text{with } a(k), b(k) >_S \mathbf{0}\}$.

We now define the soft-join operator of two *SCA*, performing the (natural) join of two $\mathcal{L}_{TWDS}$. We can use this operator to merge two queries (see Sec. 5).

Definition 5 (Soft-Product Automaton (soft join)). *The soft-product automaton of two* SCA $\mathcal{T}_S^1 = (\mathcal{Q}_1, \mathcal{N}_1, \longrightarrow_1, \mathcal{Q}_{0,1}, \mathcal{S})$ *and* $\mathcal{T}_S^2 = (\mathcal{Q}_2, \mathcal{N}_2, \longrightarrow_2, \mathcal{Q}_{0,2}, \mathcal{S})$ *on the same semiring* S *is defined as* $\mathcal{T}_S^1 \bowtie \mathcal{T}_S^2 = (\mathcal{Q}_1 \times \mathcal{Q}_2, \mathcal{N}_1 \cup \mathcal{N}_2, \longrightarrow, \mathcal{Q}_{0,1} \times \mathcal{Q}_{0,2}, \mathcal{S})$*, where* $\longrightarrow$ *is given by the following two rules (and the symmetric one for (2)):*

$$\frac{q_1 \xrightarrow{N_1,c_1}_1 p_1, q_2 \xrightarrow{N_2,c_2}_2 p_2, N_1 \cap \mathcal{N}_2 = N_2 \cap \mathcal{N}_1}{\langle q_1, q_2\rangle \xrightarrow{N_1 \cup N_2, c_1 \otimes c_2} \langle p_1, p_2\rangle} \quad (1) \qquad \frac{q_1 \xrightarrow{N,c}_1 p_1, N \cap \mathcal{N}_2 = \emptyset}{\langle q_1, q_2\rangle \xrightarrow{N,c} \langle p_1, q_2\rangle} \quad (2)$$

The first rule applies when there are two transitions in the automata that can fire together. This happens only if there is no shared name in the two automata that is present on one of the transitions, but not present on the other one. In this case, the transition in the resulting automaton is labelled with the union of the name sets on both transitions, and the data-constraint is the conjunction of the data-constraints of the two transitions. The second rule applies when a transition in one automaton can fire independently of the other automaton, which happens when the names on each transition are not included in the name set of the automaton of the other transition. The proof for correctness of the soft join derives from the correctness of the crisp join [2].

The hiding operator [2] abstracts the details of the internal communication in an *SCA*, and shows the observable external behaviour of a query. In *SCA*, the hiding operator $\exists O[\mathcal{T}_S]$ (see Def. 6) removes all information about names in $O \subseteq \mathcal{N}$, and removes the influence of the names in O from the *SDC* of $\mathcal{T}_S$: this operator removes O from the support of all soft constraints in $\mathcal{T}_S$.

Definition 6 (Hiding in Soft Constraint Automata). *Let* $\mathcal{T}_S = (\mathcal{Q}, \mathcal{N}, \longrightarrow, \mathcal{Q}_0, S)$ *be an* SCA *and* $N, O \subseteq \mathcal{N}$. *The* SCA $\exists O[T] = (\mathcal{Q}, \mathcal{N} \backslash O, \longrightarrow_O, \mathcal{Q}_{0,O}, S)$ *is defined as follows. Let* $\rightsquigarrow^*$ *be the transition relation such that* $q \rightsquigarrow^* p$ *iff there exists a finite path* $q \xrightarrow{O,c_1} q_1 \xrightarrow{O,c_2} q_2 \xrightarrow{O,c_3} \ldots \xrightarrow{O,c_n} q_n$, *where* $q_n = p$ *and* $c_1, \ldots, c_n$ *are satisfiable (i.e.,* $c_i \not\equiv \bar{\mathbf{0}}$*) and* $\forall c_i.supp(c_i) = O$. *The set* $Q_{0,O}$ *of an initial states is* $Q_0 \cup \{p \in Q : q_0 \rightsquigarrow^* p \text{ for some } q_0 \in Q_0\}$. *The transition relation* $\longrightarrow_O$, *where* $\Downarrow$ *is the soft constraint projection described in Sec. 3, is given by:*

$$\frac{q \rightsquigarrow^* p, p \xrightarrow{N,c} r, N' = N \backslash O \neq \emptyset, c' = c \Downarrow_{\{d_n | n \in N'\}}}{q \xrightarrow{N',c'}_O r}$$

5 Expressing Preference-based Queries

In this section we use *SCA* (see Sec. 4) to model the queries we adopt to describe *i)* the behavior of the services a user is interested in, and *ii)* the preferences of the user with respect to data exchanged through I/O by the operations. The behavioral signature of a service is described via a (crisp) constraint automaton: the operations are described by the names on the transitions of the automaton, as described in Sec. 4; the ordering of the operations is enforced by the ordering of the reached states. Analogously, a query is described via an SCA, where we use *SDC* (see Def. 2) to model user's preferences for the data used by the service operations. Matching these names with the actual names of the services in the database leads to a global preference for that service.

Our model assumes, ignoring details, the existence of a standard vocabulary (i.e., a domain-specific ontology) for messages and activities (e.g., OWL-S [15]). Therefore, we suppose that all names in the following examples are properly obtained from an ontology on services. Ontologies have already been used in the literature to help preference and similarity-based searches (see Sec. 2), and serve as a common dictionary for queries and services.

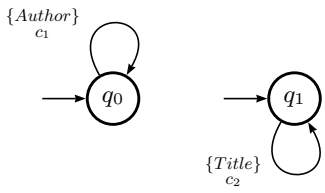

Fig. 5. Two soft Constraint Automata representing two different queries.

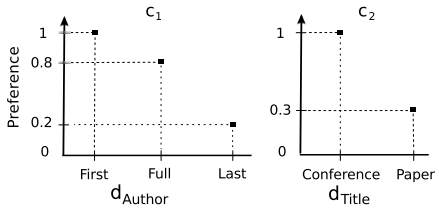

Fig. 6. The definition of c_1 and c_2 in Fig. 5.

In Fig. 5 we show two first examples of soft queries: with q_0 the user looks for a bibliography-search service that is able to search for conference papers by *Author*, while in the case of q_1 the search is by *Title*. The user's preferences on input data that these two services take are summarized by the two soft constraints c_1 and c_2, which are represented in Fig. 6. These examples can be modeled with the *fuzzy* semiring $\langle [0..1], \max, \min, 0, 1 \rangle$: c_1 states that the user prefers to have a search by first name (with a fuzzy score of 1), rather than to have it by full name (i.e., 0.8) or by last name (i.e., 0.2): c_2 states that the user prefers to have a search using the conference title instead of the paper title. The preference is equal to the bottom value of the semiring where not stated (here, $\mathbf{0} = 0$). A possible scenario for this example corresponds to a situation where the user remembers the first name of the author, or the conference where they met, but he has a vague memory of the author's last name, and of the title of the presented paper.

Suppose now that our database contains the four services/operations represented in Fig. 7. According to the preferences expressed by c_1 and c_2 in Fig. 6, queries q_0 and q_1 in Fig. 5 return different preferences for each operation, depending on the instantiation of variables d_{Author} and d_{Title}. Considering q_0, operations a, b, and d have respective preferences of 0.2, 1, and 0.8. If query q_1 is used instead, the possible results are operations c and d, with respective preferences of 1 and 0.3. When more than one service is returned as the result of a search, the end user has the freedom to choose the best one according to his preferences: for the first query q_0, he can opt for service b, which corresponds to a preference of 1 (i.e., the top preference), while for query q_1 he can opt for c (top preference as well). A possible programming-like declaration for opera-

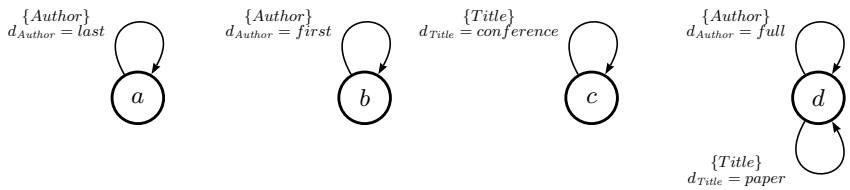

Fig. 7. A database of services for the query in Fig. 5; d perfoms both kinds of search.

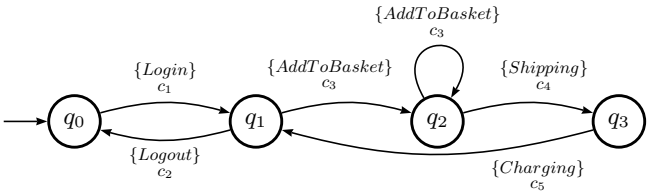

Fig. 8. A more complex soft query for the on-line purchase scenario presented in Sec. 1.

tion a in Fig. 7 is "`void Author(last)`". Note that a fifth possible service in the database may implement a search by name initials, but according to c_1 in Fig. 6, the user's preference for this service would be 0, i.e., $c(d_{Author} = \mathit{Initials}) = 0$.

Note also that we can define n-ary soft constraints for more than one input data at the same time, in order to relate the preference for the values of two or more I/O data. For example, if we want to search by author and title at the same time, we can add a binary constraint c on $\{d_{Author}, d_{Title}\}$, such that $c(d_{Author} = \mathit{First}, d_{Title} = \mathit{Conference}) = a_1$, $c(d_{Author} = \mathit{First}, d_{Title} = \mathit{Paper}) = a_2$, and $a_1 >_S a_2$. This means that, when we know the first name of the author, we prefer to search using the title of the conference, instead of the paper title.

In Fig. 8 we provide a more complex example of a soft query, where we show a classical on-line purchase scenario cited in Sec. 1, considering its behavior. In this case, the requirements of the user are *i)* a login/logout service, *ii)* an electronic basket that can be filled with the user's orders (at least one item has to be added before proceeding further), *iii)* a decision on the shipping method and, finally, *iv)* a payment service. Therefore, this query is expressed with the help of four different states modeling its behavior. The *SDC* expressing the user's preferences are represented in Fig. 9, where we suppose that the user expresses no preference for the data concerning the *Logout* service, i.e., $c_2 = \bar{\mathbf{1}}$. Note that, after the payment, the user can make successive purchases without logging out.

In the following we show that the join and hiding operators presented in Sec. 4 can be used to operate on queries. Note that, by using the same view presented in [14], we can slightly modify the join operator in Sec. 4 in order to be able to compose the two queries in Fig. 10 into the one presented in Fig. 8. Query composition is useful in order to reuse parts of a query in another one, or to split the query into different knowledge domains. For example, in Fig. 10 the first query can be decided by the internal IT department of the company that

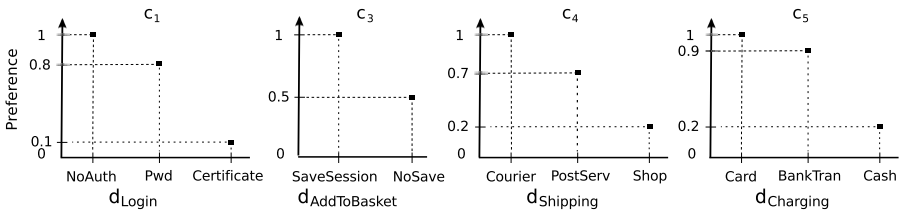

Fig. 9. The definition of c_1, c_3, c_4, c_5 for the query in Fig. 8 (we suppose $c_2 = \bar{\mathbf{1}}$).

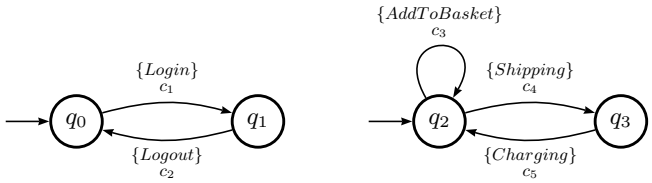

Fig. 10. Two queries that can be composed (i.e., with join [14]) to obtain Fig. 8.

needs to use the service, according to their internal security regulations, whereas the second query can be decided by the purchasing department of the company. For this, the join operator has to be slightly modified, as defined in [14] for the composition of services.

The hiding operator presented in Sec. 4 can be used to hide some over-constraining information from the query, if, for instance, the previous search has led to a "no result" answer for the user. Suppose we ask query q_0 in Fig. 11 having a database as the one represented in Fig. 7. In this case, no result is returned because no service implements a search by *Author* and *Title* at the same time. A user may relax the query by hiding *Title*, and ask again, this time obtaining as possible response services a, b and d in Fig. 7.

5.1 Formally Reasoning on the Similarity of Queries

In the sequel we adapt the notions of bisimulation and simulation on (crisp) constraint automata [2] for SCA by considering soft constraints, instead of crisp ones.

Definition 7 (Soft Bisimulation). *Let $\mathcal{T}_S = (\mathcal{Q}, \mathcal{N}, \longrightarrow, \mathcal{Q}_0, S)$ be an* SCA *and let $\mathcal{R}$ be an equivalence relation on $\mathcal{Q}$. $\mathcal{R}$ is called a soft bisimulation for $\mathcal{T}_S$ if, for all pairs $(q_1, q_2) \in \mathcal{R}$, all $\mathcal{R}$-equivalence classes $P \in \mathcal{Q}/\mathcal{R}$, and every $N \subseteq \mathcal{N}$: $sdc_{\mathcal{T}_S}(q_1, N, P) \equiv sdc_{\mathcal{T}_S}(q_2, N, P)$.*

Recall that $c_1 \equiv c_2$ iff $c_1\eta = c_2\eta = a$ for every assignment η (see Sec. 3). States q_1 and q_2 are called bisimulation-equivalent ($q_1 \sim q_2$) iff there exists a bisimulation $\mathcal{R}$ with $(q_1, q_2) \in \mathcal{R}$. Two automata $\mathcal{T}_S^1$ and $\mathcal{T}_S^2$ are bisimulation-equivalent ($\mathcal{T}_S^1 \sim \mathcal{T}_S^2$) iff their initial states are bisimulation-equivalent [2].

Definition 8 (Soft Simulation). *Let $\mathcal{T}_S = (\mathcal{Q}, \mathcal{N}, \longrightarrow, \mathcal{Q}_0, S)$ be an* SCA *and let $\mathcal{R}$ be a binary relation on $\mathcal{Q}$. $\mathcal{R}$ is called a soft simulation for $\mathcal{T}_S$ if, for all pairs $(q_1, q_2) \in \mathcal{R}$, all $\mathcal{R}$-upward closed sets $P \subseteq \mathcal{Q}$, and every $N \subseteq \mathcal{N}$: $sdc_{\mathcal{T}_S}(q_1, N, P) \sqsubseteq sdc_{\mathcal{T}_S}(q_2, N, P)$.*

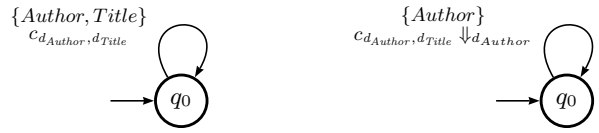

Fig. 11. Hiding information in a soft query.

An automaton $\mathcal{T}_S^2$ simulates another automaton $\mathcal{T}_S^1$ iff every initial state of $\mathcal{T}_S^1$ is simulated by an initial state of $\mathcal{T}_S^2$; this relationship is denoted as $\mathcal{T}_S^1 \preceq \mathcal{T}_S^2$.

Soft bisimulation can be seen as a method to check the equivalence of two $\mathcal{L}_{TWDS}$ languages, while soft simulation concerns language inclusion, as explained in [2] for the crisp version of CA. Moreover, since our timed streams are weighted as explained in Def. 1 we can prove the following proposition:

Proposition 1. *Given two soft constraint automata $\mathcal{T}_S^1$ and $\mathcal{T}_S^2$ able to parse the languages $\mathcal{L}_{TWDS_1}$ and $\mathcal{L}_{TWDS_2}$ respectively, for each stream $\langle \lambda, l, a \rangle \in TWDS_1$ there exists a stream $\langle \mu, m, b \rangle \in TWDS_2$ such that:*

- *If $\mathcal{T}_S^1 \sim \mathcal{T}_S^2$ and $\forall k, \lambda(k) = \mu(k)$, then $a(k) =_S b(k)$.*
- *If $\mathcal{T}_S^1 \preceq \mathcal{T}_S^2$ and $\forall k, \lambda(k) = \mu(k)$, then $a(k) \geq_S b(k)$.*

The proof derives from the fact that, if $\mathcal{T}_S^1 \sim \mathcal{T}_S^2$, then $sdc_{\mathcal{T}_S^1}(q_1, N, P) \equiv sdc_{\mathcal{T}_S^2}(q_2, N, P)$, and, if $\mathcal{T}_S^1 \preceq \mathcal{T}_S^2$, $sdc_{\mathcal{T}_S^1}(q_1, N, P) \sqsubseteq sdc_{\mathcal{T}_S^2}(q_2, N, P)$.

Bisimulation can be used to check if two queries are equivalent, that is if they search the same services with the same preferences expressed by a user. Moreover, a simulation between $\mathcal{T}_S^1 \preceq \mathcal{T}_S^2$ can be used to check if the query expressed through $\mathcal{T}_S^1$ is entailed by $\mathcal{T}_S^2$, and, consequently, the latter's returned services are a subset of the former's. Note that simulation/bisimulation for weighted automata (but not for *SCA*) has already been defined in the literature [9]

6 Similarity-based Queries

In Sec. 5 we adopted the theory presented in Sec. 4 to represent the queries using crisp synchronization constraints (i.e., "crisp names") and soft data-constraints. This way, it is possible to guide the search according to the preferences of the user concerning the data used by the service operations.

In this section, we focus on similarity-based search, instead of preference-based search: transition names are not crisp anymore, allowing for different operations considered somehow similar for the purposes of a user's query. Note that a similar service can be used, e.g., when the "preferred" one is down due to a fault, or when it offers bad performances, e.g., due to the high number of requests. Definition 9 formalizes the notion of soft synchronization-constraint.

Definition 9 (Soft Synchronization-constraint). *A soft synchronization-constraint is a function $c : (V \rightarrow \mathcal{N}) \rightarrow A$ defined over a semiring $S = \langle A, +, \times, \mathbf{0}, \mathbf{1} \rangle$, where V is a finite set of variables for each I/O ports, and $\mathcal{N}$ is the set of I/O port names of the* SCA.

For example, suppose that a user asks only query q_0 in Fig. 5. The possible results are services a, b and d in the database of Fig. 7, since service c performs a search based on the *Title* of the paper only, and not on the *Author*. However, the two services are very similar, and a user may be satisfied also by retrieving (and then, using) service c. This can be accomplished with the query in Fig. 12,

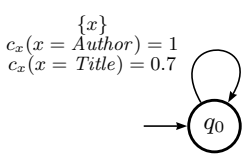

Fig. 12. A similarity-based query for the *Author*/*Title* example.

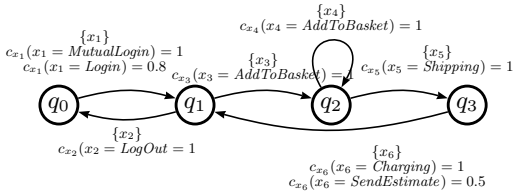

Fig. 13. A similarity-based query for the on-line purchase service.

where $c_x(x = Author) = 1$, and $c_x(x = Title) = 0.7$. In Fig. 13, we show a similarity-based query for our on-line purchase scenario: in this case, we have $V = \{x_1, x_2, x_3, x_4, x_5, x_6\}$, and the domain for each of these variables is $\mathcal{N} = \{MutualLogin, Login, Logout, AddToBasket, Shipping, Charging, SendEstimate\}$. A user can also choose for a mutual login in the first step, and for an estimate of the price instead of a direct charging service.

6.1 A Mapping to Soft Constraint Satisfaction Problems

In this section we map our similarity-based search into an SCSP P (see Sec. 3); by solving P, we find the services in the database closest to the requirements expressed by a user's query. We use this solving method for two fundamental reasons: first, constraint programming is a declarative and very expressive means to quickly define the acceptable results in terms of constraint relationships. Second, SCSPs (and in general, Constraint Programming) come with several AI-based techniques that can be used to cut the search space and improve efficiency. For example, an α-cut on the branch-and-bound search can be used to stop the search as soon as the preference of the partial solution becomes worse than a threshold specified by the user. In this way, we can find only the α-consistent solutions (see Sec. 3), thus sparing computational resources for those solutions with a worse-than-α preference, which would not be selected by the user after all. This is particularly desirable with very large databases of services, containing interfaces with thousands of operations and thousands of behavioral states.

Mapping. We propose a mapping $\mathcal{M}$ such that, given the SCA $\mathcal{T}_S = (\mathcal{Q}, \mathcal{N}, \longrightarrow, \mathcal{Q}_0, S)$ (i.e., our query), and a database of services $DB = \{\mathcal{T}_1, \mathcal{T}_2, \ldots, \mathcal{T}_h\}$ represented by h crisp constraint automata [2], we obtain $\mathcal{M}(\mathcal{T}_S, DB) = P$, where $P = \langle S, V, D, C\rangle$ is an SCSP (defined in Sec. 3). For each transition i in the automaton $\mathcal{T}_S$ modeling the query, we use two variables x_i, y_i representing the source and destination states of the transition. A variable z_i represents the operation names that we associate with transition i. Therefore, $V = \bigcup\{x_i, y_i, z_i\}$, for $i = 1\,..\,\#transitions(\mathcal{T}_S)$. The domain of the state variables in V is $\mathcal{Q}_1 \cup \mathcal{Q}_2 \cup \cdots \cup \mathcal{Q}_h = \mathcal{Q}_{DB}$ (where $\mathcal{Q}_k$ is the set of states in automaton $\mathcal{T}_k$), and the domain of the operation names in V, $\mathcal{N}_{DB}$, is the set of operation names used by all services in DB. We identify two different classes of constraints to build the C component of P:

Automaton-structure constraints. With this set of constraints, we force the solutions (i.e., the crisp automata in DB) to respect the structure of automaton $\mathcal{T}_S$. For each $q_a \xrightarrow{N_l} q_b$ in some $\mathcal{T}_k$ in DB ($q_a, q_b \in \mathcal{Q}_{DB}$), we have $c_{x_i,y_i}(x_i = q_a, y_i = q_b) = \mathbf{1}$, and $\mathbf{0}$ otherwise. In addition, we also need to enforce the sequence of the states/transitions in the solution, according to the one expressed by the query. For example, if we have $q_{x_i} \longrightarrow q_{y_i}$ and $q_{x_j} \longrightarrow q_{y_j}$, and $y_i = x_j$ in $\mathcal{T}_S$, we need to add $c_{x_j,y_i}(x_j = y_i) = \mathbf{1}$, and $\mathbf{0}$ otherwise.

Name-preference constraints. These constraints model the preference for the names on the transitions. For each $q_a \xrightarrow{N_l} q_b \in DB$, $c_{x_i,y_i,z_i}(x_i = q_a, y_i = q_b, z_i = n_l) = a$, where $a \in A$ (the set of preferences in S) represents the preference for the name n_l.

Example 1. Here we list all the *automaton-structure constraints* with a preference better than $\mathbf{0}$, that model the query in Fig 13: $c_{x_1,y_1}(x_1 = q_a, y_1 = q_b) = 1$, $c_{x_2,y_2}(x_2 = q_c, y_2 = q_d) = 1$, $c_{x_1,y_2}(x_1 = y_2) = 1$, $c_{x_2,y_1}(x_2 = y_1) = 1$, $c_{x_3,y_3}(x_3 = q_a, y_3 = q_b) = 1$, $c_{x_3,y_2}(x_3 = y_2) = 1$, $c_{x_4,y_4}(x_4 = q_a, y_4 = q_b) = 1$, $c_{x_4,y_4}(x_4 = y_4) = 1$, $c_{x_4,y_3}(x_4 = y_3) = 1$, $c_{x_5,y_5}(x_5 = q_a, y_5 = q_b) = 1$, $c_{x_5,y_4}(x_5 = y_4) = 1$, $c_{x_6,y_6}(x_6 = q_a, y_6 = q_b) = 1$, $c_{x_6,y_5}(x_6 = y_5) = 1$, $c_{x_3,y_6}(x_3 = y_6) = 1$, for each $q_a \longrightarrow q_b$ in the service database.
In the following we list all *name-preference constraints* with a preference better than $\mathbf{0}$: $c_{x_1,y_1,z_1}(x_1 = q_a, y_1 = q_b, z_1 = \{Login\}) = 0.8$, $c_{x_1,y_1,z_1}(x_1 = q_a, y_1 = q_b, z_1 = \{MutualLogin\}) = 1$, $c_{x_2,y_2,z_2}(x_2 = q_a, y_2 = q_b, z_2 = \{Logout\}) = 1$, $c_{x_3,y_3,z_3}(x_3 = q_a, y_3 = q_b, z_3 = \{AddToBasket\}) = 1$, $c_{x_4,y_4,z_4}(x_4 = q_a, y_4 = q_b, z_4 = \{AddToBasket\}) = 1$, $c_{x_5,y_5,z_5}(x_5 = q_a, y_5 = q_b, z_5 = \{Shipping\}) = 1$, $c_{x_6,y_6,z_6}(x_6 = q_a, y_6 = q_b, z_6 = \{Charging\}) = \mathbf{1}$ and $c_{x_6,y_6,z_6}(x_6 = q_a, y_6 = q_b, z_6 = \{SendEstimate\}) = 0.5$, for each $q_a \xrightarrow{n_l} q_b$ in the service database.

7 Conclusion

In this paper, we have proposed a general formal framework to express both preference and similarity-based queries for the SOC paradigm. This framework has evolved from Constraint Automata [2] (to model the behavior of services) and semiring-based soft constraints [6,5] (to model preference values). We have merged these two ingredients to obtain *SCA*, which comprise the formalism we use to model these kinds of queries. The resulting framework can parametrically deal with different systems of semiring-based preferences.

In the future, we will automate the search by implementing the mapping proposed in Sec. 6.1 using a real constraint programming environment, such as *CHOCO* [13], and test its performance results. Moreover, we want to unify both preference and similarity-based queries in a single framework, to be able to express similarity-based queries with preferences on I/O data.

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Reconfiguration mechanisms for service coordination*

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Abstract. Models for exogenous coordination provide powerful *glue-code*, in the form of software connectors, to express interaction protocols between services in distributed applications. Connector reconfiguration mechanisms play, in this setting, a major role to deal with change and adaptation of interaction protocols. This paper introduces a model for connector reconfiguration, based on a collection of primitives as well as a language to specify connectors and their reconfigurations.

1 Introduction

The purpose of a service-oriented architecture (SOA)[5,6] is to address requirements of loosely coupled and protocol-independent distributed systems, where software resources are packaged as self-contained *services* providing well-defined functionality through publicly available interfaces. The architecture describes their interaction, ensuring, at the same time, that each of them executes independently of the context or internal state of the others.

Over the years a multitude of technologies and standards [1] have been proposed for describing and orchestrating web services, publish and discover their interfaces and enforce certain levels of security and QoS parameters. Either to respond to sudden and significative changes in context or performance levels, or simply to adapt to evolving requirements, some degree of *adaptability* or *reconfigurability* is typically required from a service-oriented architecture. By a (dynamic) reconfiguration we mean a process of adapting the architectural current configuration, once the system is deployed and without stopping it [9], so that it may evolve according to some (emergent) requirements [7] or change of context.

Reconfigurations applied to a SOA may be regarded from two different point of views. From one of them, they target individual services [16]. In particular, such reconfigurations are concerned with dynamic update of services, substitution of a service by another with compatible interfaces (but not necessarily the

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same behaviour) or even their plain removal. Such reconfigurations are usually triggered by external stimulus [14,8,12,13,18]. Form another point of view, a reconfiguration is entirely decided by the system itself and targets the way components or services interact with each other, as well as the internal QoS levels measured along such interactions. In particular, such reconfigurations deal with substitution, addition or removal of communications channels, moving communication interfaces from a service to another or rearranging a complex interaction structure.

This paper studies reconfiguration mechanisms for the service interaction layer in SOA. Adopting a coordination-based view of interaction [15], the model proposed here represents the 'gluing-code' by a graph of *channels* whose nodes represent interaction points and edges are labelled with channel identifiers and types. A channel abstracts a point-to-point communication device with a unique identifier, a specified behaviour and two ends. It allows for data flow by accepting data on a *source* end and dispensing it from a *sink* end. We call such a graph a *coordination pattern*. A subset of its nodes are intended to be plugged to concrete services, forming the pattern interface.

To keep things concrete, we assume channels in a coordination pattern are described in a specific coordination model, that of Reo [3,2]. Actually, this choice is not essential: the reconfiguration mechanisms are directly defined over the graph and concern only its topology. Only when one intends to reason about the system's behaviour or compare the behavioural effect of a reconfiguration, does the specific semantics of the underlying coordination model become relevant. Such is not addressed, however, in this paper.

Coordination patterns are introduced in Section 4 and instantiated in the context of the Reo coordination model. Section 3 discusses reconfigurations, formally defining a collection of primitives. It is shown how the latter can be combined to yield 'big-step' reconfiguration patterns which manipulate significative parts of a pattern structure. The CooPLa language is introduced in Section 4 as an executable notation for specifying both coordination and reconfiguration patterns. Reconfiguration mechanisms are illustrated through a detailed example in Section 5. Section 6 concludes the paper.

2 Coordination patterns

A pattern is an effective, easy to learn, repeatable and proven method that may be applied recurrently to solve common problems [5]. They are common in several domains of Software Engineering, namely in SOA [17] and business process [20].

Similarly, in this paper, a coordination pattern encodes a reusable solution for an architectural (coordination) problem in the form of a specific sort of *interaction* between the system constituents. A solution for an architectural problem is, therefore, the description of interaction properly designed to meet a set of requirements or constraints. It is reflected in a coordination protocol,

which acts as *glue-code* for the components or services interacting within the system.

Formally, a coordination pattern is presented by a graph of *channels* whose nodes represent interaction points and edges are labelled with channel identifiers and types. As explained in the Introduction, we adopt here the Reo framework [2], in order to give a concrete illustration of our approach.

Let $\mathcal{N}ame$ and $\mathcal{N}ode$ denote, respectively, a set of unique names and a set of nodes associated either with coordination patterns or channels. A node can also be seen as an interaction *port*. It is assumed the following set of primitive types of channels (see Fig. 1) with the usual Reo [3,2]semantics.

$$\mathcal{T}ype \stackrel{\text{def}}{=} \{\mathsf{sync}, \mathsf{lossy}, \mathsf{fifo_f}, \mathsf{fifo_e}, \mathsf{drain}\}$$

Each channel has exactly two ends and are, normally, directed (with a source and a sink end) but Reo also accepts undirected channels (*i.e.,* channels with two ends of the same sort). Channel ends form the nodes of coordination patterns. A node may be of three distinct types: (*i*) source node, if it connects only source channel ends; (*ii*) sink node, if it connects only sink channel ends and (*iii*) mixed node, if it connects both source and sink nodes. Fig. 1 recalls the basic channels used in Reo through the composition of which complex coordination schemes can be defined. The sync channel transmits data from one end to

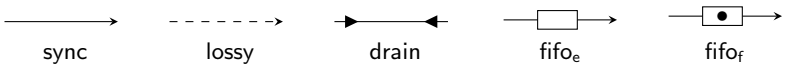


Fig. 1. Primitive Reo channels.

another whenever there is a request at both ends synchronously, otherwise one request shall wait for the other. The lossy channel behaves likewise, but data may be lost whenever a request at the source end is not matched by another one at the sink end. Differently, a fifo channel has a buffering capacity of one memory positions, therefore allowing for asynchronous occurrence of I/O requests. Qualifier e or f refers to the channel internal state (either *empty* or *full*). Finally, the synchronous drain channel accepts data synchronously at both ends and loses it. We use $\mathcal{P}$ to denote the set of all coordination patterns. A *coordination pattern* is defined as follows:

Definition 1 (Coordination pattern). *A coordination pattern is a triple*

$$\rho \stackrel{\text{def}}{=} \langle I, O, R \rangle$$

- $R \subseteq \mathcal{N}ode \times \mathcal{N}ame \times \mathcal{T}ype \times \mathcal{N}ode$ *is a graph on connector ends whose edges are labelled with instances of primitive channels, denoted by a channel identifier (of type* $\mathcal{N}ame$*) and a type (of type* $\mathcal{T}ype$*);*
- $I, O \subseteq \mathcal{N}ode$ *are the sets of source and sink ends in graph* R*, corresponding to the set of input and output ports in the coordination pattern, respectively.*

Clearly, every channel instance gives rise to a coordination pattern. For example pattern

$$\rho_s = \langle \{a\}, \{b\}, \{\langle a, sc, \mathsf{sync}, b\rangle\}\rangle$$

corresponds to a single synchronous channel, identified by sc, linking an input port a to an output port b. Similarly, plugging to its output port two lossy channels yields a lossy broadcaster which replicates data arriving at a, if there exist pending reading requests at d and e:

$$\rho_b = \langle \{a\}, \{d, e\}, \{\langle a, sc, \mathsf{sync}, b\rangle, \langle b, l_1, \mathsf{lossy}, d\rangle, \langle b, l_2, \mathsf{lossy}, e\rangle\}\rangle$$

A drain, on the other hand, has two source, but no sink, ends. Therefore, a pattern formed by an instance of a drain channel resorts to a special end $\perp \in \mathcal{N}ode$ which intuitively represents absence of data flow. Thus, and for example,

$$\rho_d = \langle \{a, b\}, \emptyset, \{\langle a, ds, \mathsf{drain}, \perp\rangle, \langle b, ds, \mathsf{drain}, \perp\rangle\}\rangle$$

As a matter of fact, *well-formadness* invariants of coordination patterns are required. For instance (i) the $\perp$ ports can never be connected to other ports (ii) a name may only be associated to two different ports and a unique channel type (notice the veracity of this also in the drain example) or (iii) only a single channel is allowed to connect two consecutive nodes. We assume the existence of such invariants, and do not address them in this paper.

3 Architectural reconfigurations

This section discusses reconfigurations of coordination patterns. We take a rather broad view of what a reconfiguration is: any transformation obtained through a sequence of elementary operations, described below, is qualified as a reconfiguration. Our aim is to build a framework in which such transformations can be defined and the effect of their application to a specific pattern assessed. Later, one may restrict this set, for example by ruling out transformations which do not preserve the pattern input-output interface or fail to lead to patterns with a behaviour which simulates (or bisimulates) the original one. Such considerations, however, require the assumption of a specific semantics for coordination patterns, easily built from any Reo semantic model, but which lies outside the more 'syntactic' scope of this paper.

Definition 2 (Reconfiguration). *A reconfiguration is a sequence r of operations $\langle o_0, o_1, \ldots, o_n\rangle$, where each o_i belongs to the set*

$$\mathcal{O}p \stackrel{\text{def}}{=} \{\mathsf{par},\ \mathsf{join},\ \mathsf{split},\ \mathsf{remove}\}$$

of elementary reconfigurations, specified below. The application of a reconfiguration r to a pattern ρ yields a new pattern and is denoted by $\rho \bullet r$.

3.1 Primitive reconfigurations

Let us start by defining the set of elementary reconfigurations of a coordination pattern. The simplest reconfiguration is *juxtaposition*. Intuitively, it sets two coordination patterns in parallel without creating any connection between them. Formally,

Definition 3 (The par operation). *Let* $\rho_1 = \langle I_1, O_1, R_1\rangle$ *and* $\rho_2 = \langle I_2, O_2, R_2\rangle$ *be two coordination patterns. Then,*

$$\rho_1 \bullet \ \mathsf{par}(\rho_2) = \langle I_1 \uplus I_2, O_1 \uplus O_2, R_1 \uplus R_2\rangle$$

where $\uplus$ *is set disjoint union.*

The par operation assumes disjunction of nodes and channel identifiers in the patterns to be joined. This is assumed without loss of generality, because formally a disjoint union of all identifiers is previously made.

The second elementary reconfiguration is join. Intuitively, it creates a new node j that superposes all nodes in a given set P. This operation adds fresh node j as a new input or output port if all the nodes in P are, respectively, input or output ports in ρ. Formally,

Definition 4 (The join operation). *Let* $\rho = \langle I, O, R\rangle \in \mathcal{P}$, $P \subseteq \mathcal{N}ode$ *and* $j \in \mathcal{N}ode$. *Then,*

$$\rho \bullet \ \mathsf{join}(P, j) = \langle I', O', R'\rangle$$

- $R' = 2^{jn_{P,j}}(R)$, *with*

$$jn_{P,j}\langle q, id, t, s\rangle = \langle (p \in P \rightarrow j,\, p), id, t, (s \in P \rightarrow j,\, s)\rangle$$

- $I' = (P \subseteq I \rightarrow \{j\}, \emptyset) \cup (I \setminus P)$
- $O' = (P \subseteq O \rightarrow \{j\}, \emptyset) \cup (O \setminus P)$

The notation $(\phi \rightarrow s,\, t)$ corresponds to McCarthy's conditional, returning s or t if predicate ϕ is true or false, respectively. Also note that the power set of a set A is denoted by 2^A and, for a function f from A to B, $2^f(X) = \{f\, x \mid x \in X\}$.

The join operation has two pre-conditions. Clearly, node j must be a fresh name in ρ. Additionally, every node in P shall exist as a node of ρ. Formally, $\forall_{p\in P}.\, \exists_{e\in R}.\, \pi_1(e) = p \vee \pi_4(e) = p$.

The dual to join is the split operation which takes a node p in a pattern and breaks connections, separating all channel ends coincident in p. Technically this is achieved by renaming every occurrence of node p in all $e \in R$ to a fresh name $a.p$ or $p.a$ depending on whether p appears as a sink node in e and a is the corresponding source end, or the other way round. Thus,

Definition 5 (The split operation). *Let* $\rho = \langle I, O, R\rangle \in \mathcal{P}$, *and* $p \in \mathcal{N}ode$. *Then,*

$$\rho \bullet \ \mathsf{split}(p) = \langle I', O', R'\rangle$$

– $R' = 2^{sp_p}(R)$, *with*

$$sp_p\langle q, ch, t, s\rangle = \langle((q = p) \rightarrow p.s,\, q), ch, t, ((s = p) \rightarrow q.p,\, s)\rangle$$

– $I' = (I \setminus \{p\}) \cup \{p.x \mid e \in R' \wedge \pi_1(e) = p.x\}$
– $O' = (O \setminus \{p\}) \cup \{x.p \mid e \in R' \wedge \pi_4(e) = x.p\}$

Finally, the remove operation removes a channel from a coordination pattern, if it exists.

Definition 6 (The remove operation). *Let* $\rho = \langle I, O, R\rangle \in \mathcal{P}$, *and* $ch \in \mathcal{N}ame$. *Then,*

$$\rho \bullet \ \mathsf{remove}(ch) = \langle I', O', R'\rangle$$

where, for $L = \{e \mid e \in R \wedge \pi_2(e) = ch\}$ *and* $L' = \{\pi_1(e), \pi_4(e) \mid e \in L\}$

– $R' = R \setminus L$
– $I' = (I \setminus L') \cup \{y \mid \langle x, ch, t, y\rangle \in L \wedge y \neq \perp \wedge in(y, R')\}$
– $O' = (O \setminus L') \cup \{x \mid \langle x, ch, t, y\rangle \in L \wedge x \neq \perp \wedge out(x, R')\}$
where

$$in(x, S) \stackrel{\text{def}}{=} (\nexists_{e \in S}.\, \pi_4(e) = x) \wedge (\exists_{e \in S}.\, \pi_1(e) = x)$$
$$out(x, S) \stackrel{\text{def}}{=} (\nexists_{e \in S}.\, \pi_1(e) = x) \wedge (\exists_{e \in S}.\, \pi_4(e) = x)$$

Intuitively, removing a channel corresponds to deleting all the ends of that channel from the pattern interface. This may create free nodes that must be added to the coordination pattern interface. The second member of the union in the I' or O' definition, formally encodes these cases.

3.2 Reconfiguration patterns

Practice and experience in software architecture inspire the definition of patterns for reconfiguring architectures. As stated in the Introduction, the focus of traditional reconfiguration is set on the replacement of individual components, rather than on the interaction protocols. Our patterns, on the other hand, focussed on the latter, but still at this lower-level we are interested in defining 'big step' reconfigurations, replacing simultaneously significant parts of a pattern. Fig. 2 sums up the set of such reconfiguration patterns we have found useful in practice. The first one removes from a pattern a whole set of channels, applying the remove primitive systematically,

Definition 7 (The removeP pattern). *Let* $\rho \in \mathcal{P}$ *and* Cs *be a set of channels to remove. Then,*

$$\rho \bullet \mathsf{removeP}(Cs) = rS(\rho, Cs)$$

where

$$rS(\rho, \emptyset) = \rho$$
$$rS(\rho, Cs) = \text{let } \ c \in Cs \ \text{ in } \ rS(\rho \bullet \mathsf{remove}(c), Cs \setminus \{c\})$$

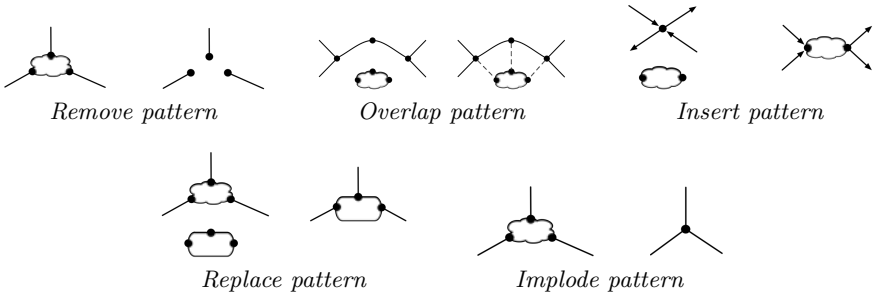


Fig. 2. Reconfiguration patterns

Another common reconfiguration overlaps two patterns by joining nodes from both of them. This is specified by a set of triples indicating which nodes are to be overlapped and a fresh name for the result. Formally,

Definition 8 (The overlapP pattern). *Let $\rho, \rho_r \in \mathcal{P}$ and X be a set of triples of nodes, where the first component is a node of ρ, the second one is a node of ρ_r and the third is a fresh node in both coordination patterns. Then,*

$$\rho \bullet \mathsf{overlapP}(\rho_r, X) = rO(\rho \bullet par(\rho_r), X)$$

where

$$\begin{array}{ll} rO(\rho, \emptyset) = \rho & \\ rO(\rho, X) = & \text{let } e_i \in X, E_i = \{\pi_1(e_i), \pi_2(e_i)\}, \\ & \text{in } rO(\rho \bullet \mathsf{join}(E_i, \pi_3(e_i)), X \setminus \{e_i\}) \end{array}$$

The insertP pattern puts both patterns side by side, uses split to make room for a new pattern to be added, as shown in Fig. 2, and join to re-build connections. Formally,

Definition 9 (The insertP pattern). *Let $\rho, \rho_r \in \mathcal{P}$ and $n, m_i, m_o, j_1, j_2 \in \mathcal{N}ode$, where n is a node of ρ, m_i, m_o are input and output nodes, respectively, of ρ_r and j_1, j_2 are fresh nodes. Then,*

$$\begin{array}{rl} \rho \bullet \mathsf{insertP}(\rho_r, n, m_i, m_o, j_1, j_2) = \text{let } & \rho_1 = \rho \bullet \mathsf{par}(\rho_r) \\ & \rho_2 = \rho_1 \bullet \mathsf{split}(n) \\ & I_{sp} = \pi_1(\rho_2) \setminus \pi_1(\rho_1) \\ & O_{sp} = \pi_2(\rho_2) \setminus \pi_1(\rho_1) \\ & \rho_3 = \rho_2 \bullet \mathsf{join}(O_{sp} \cup \{m_i\}, j_1) \\ \text{in } & \rho_3 \bullet \mathsf{join}(I_{sp} \cup \{m_o\}, j_2) \end{array}$$

Replacing a sub-pattern involves removing the old structure followed by the overlap of the new pattern. A key operation is *remNodes* which computes the nodes to be removed.

Definition 10 (The replaceP pattern). *Let $\rho, \rho_r \in \mathcal{P}$ and X be the set of triples of nodes, where the first component is a node of ρ, the second one is a node of ρ_r and the third is a fresh node in both coordination patterns. Then,*

$$\rho \bullet \mathsf{replaceP}(\rho_r, X) = (\rho \bullet \mathsf{removeP}(\pi_2(remNodes(\rho, 2^{\pi_1}(X)))) \bullet \mathsf{overlapP}(\rho_r, X))$$

Finally, the implodeP pattern collapses a set of nodes taken as the interface of a sub-structure. Formally,

Definition 11 (The implodeP pattern). *Let $\rho = \langle I, O, R\rangle \in \mathcal{P}$, j be a fresh node in ρ and $X \subseteq \mathcal{N}ode$ be a set of nodes of ρ, which represent the border of the structure to implode. Then,*

$$\begin{aligned}\rho \bullet \mathsf{implodeP}(X, j) = \text{let } & (Ch, N) = remNodes(\rho, X)\\ & \rho_1 = \rho \bullet \mathsf{removeP}(Ch)\\ & M = updateNodes(N)\\ \text{in } & \rho_1 \bullet \mathsf{join}(M, j)\end{aligned}$$

where $updateNodes(N) = N \cap \{x | x \neq \bot \wedge (x = \pi_1(e) \vee x = \pi_4(e)) \wedge e \in R\}$

Operation $remNodes$, used above, is defined as follows:

$$\begin{aligned}&remNodes : \mathcal{P} \times 2^{\mathcal{N}ode} \rightarrow 2^{\mathcal{N}ame} \times 2^{\mathcal{N}ode}\\ &remNodes\ (\langle I, O, R\rangle, N) =\\ &\text{let}\ \ N_1 = N \cup \{x \notin N | (\langle x, id, t, \bot\rangle, \langle a, id, t, \bot\rangle \in R)\\ &\qquad\qquad \vee (\langle \bot, id, t, x\rangle, \langle \bot, id, t, a\rangle \in R) \wedge a \in N\}\\ &\qquad N_2 = \textstyle\bigcup_{n \in N_1} \pi_1(collNodes(n, \emptyset, \{n\}, N_1 \setminus \{n\})\\ &\qquad M_{ids} = \textstyle\bigsqcup_{n \in N_2} ms(\{\pi_2(e) | e \in R \wedge (\pi_1(e) = n \vee \pi_4(e) = n)\})\\ &\text{in}\ \ (filter(2, M_{ids}), N_2)\end{aligned}$$

Function $collNodes$ collects all nodes between a given starting one and a set of possible terminal nodes. It aims at identifying the corresponding subgraph. The arguments are a coordination pattern, a starting node, the nodes in path (an empty set at the beginning), the nodes visited and the terminal nodes:

$$\begin{aligned}&collNodes : \mathcal{P} \times \mathcal{N}ode \times 2^{\mathcal{N}ode} \times 2^{\mathcal{N}ode} \times 2^{\mathcal{N}ode} \rightarrow 2^{\mathcal{N}ode} \times 2^{\mathcal{N}ode}\\ &collNodes(\langle I, O, R\rangle, n, a, v, d) =\\ &\text{let}\ A = \{x | x \neq \bot \wedge (n, \_, \_, x) \in R \vee (x, \_, \_, n) \in R\}\\ &\quad (acc, vis) = rC(\langle I, O, R\rangle, n, A, v, d)\\ &\text{in}\ \ (a \cup acc, vis)\end{aligned}$$

where

$$\begin{aligned}&rC : \mathcal{P} \times \mathcal{N}ode \times 2^{\mathcal{N}ode} \times 2^{\mathcal{N}ode} \times 2^{\mathcal{N}ode} \rightarrow 2^{\mathcal{N}ode} \times 2^{\mathcal{N}ode}\\ &rC(\rho, n, \emptyset, v, d) = (\emptyset, v)\\ &rC(\rho, n, (x : xs), v, d) =\\ &\text{if}\ x \in d\ \text{then let}\quad (a, v_1) = rC(\rho, n, xs, v \cup \{x\}, d)\\ &\qquad\qquad\qquad\ \text{in}\quad (\{n\} \cup a, v \cup v_1)\\ &\text{else if}\ x \in v\ \text{then}\ rC(\rho, n, xs, v \cup \{x\}, d)\\ &\qquad\text{else}\quad\ \text{let}\quad (r, v_2) = collNodes(\rho, x, \emptyset, v \cup \{x\}, d)\\ &\qquad\qquad\qquad\ \text{in}\quad \text{if}\ r \neq \emptyset\ \text{then}\ (r \cup \{n\}, v_2)\\ &\qquad\qquad\qquad\qquad\ \text{else}\ rC(\rho, n, xs, v_2, d)\end{aligned}$$

Note that these definitions resort to multi-sets, defined, as usual, as functions from the type of interest to the natural numbers (which encode multiplicities). Typical operations on multisets include *domain* given by $dom(C) = \{a \in A | C(a) \neq 0\}$ and *union*, $(C_1 \sqcup C_2)(a) = C_1(a) + C_2(a)$. Conversion to sets, and back, are also recorded here as $ms : 2^A \to \mathbb{N}^A$, $ms(A) = [a \to 1 | a \in A]$, and $filter : \mathbb{N} \times \mathbb{N}^A \to 2^A$ given by $filter(i, C) = \{x \in dom(C) | C(x) \geq i\}$. The latter converts a multi-set into a set, by filtering the elements that occur at least i times. For a better comprehension of this pattern, the reader may refer to the case study in Section 5.

4 CooPLa: a language for patterns and reconfigurations

Both architectural and reconfiguration patterns can be designed with the help of a domain specific language — CooPLa— and an integrated editor, supplied as a plug-in for Eclipse. It supports syntax colouring and intelligent code-completion and offers during-edition syntax and semantic error checking and error marking for consistent development of patterns. While editing, the tool offers a visualisation of its graph representation, and any change in the code is automatically reflected in this view. Fig. 4 shows a snapshot.

With CooPLa we define communication channels, coordination pattern and reconfigurations.

Channels. Fig. 3 depicts the definition of some of the Reo-like channels introduced above. Note that the lossy channel type extends that of sync (*cf.*, the `extends` keyword). This means the information flow from a to b defined in the latter still applies; only additional behaviour is specified: if there is a request on a but not on b, data will flow through a and lost (*cf.*, `NULL` keyword). Notice the use of $!b$ to explicitly express the absence of requests on b. As another example, consider the drain channel. It has two input ports through which data flows to be lost. The '|' construct means that both flows are performed in parallel. Finally, the FIFO channel has an internal state of type *buffer* specified as a sequence of dimension N and observers E and F on which result depends the channel behaviour.

```
channel sync(a:b){
   a,b -> flow a to b;
}

channel lossy(a:b) extends sync{
   a,!b -> flow a to NULL;
}

channel drain(a,b:) {
   a,b -> flow a to NULL | flow b to NULL;
}
```

```
channel fifo~N(a:b){
   state: buffer;
   observers: E, F;

   // buffer = ELEM*
   // E = buffer.len = 0;
   // F = buffer.len = N;

   a,!F -> flow a to buffer;
   !E,b -> flow buffer to b;
}
```

Fig. 3. The sync, lossy, drain and fifo channels in CooPLa.

Coordination patterns. Coordination patterns are defined by composition of primitive channels and patterns previously defined. Declaration of instances is

preceded by the reserved word `use`. Each instance is declared by indicating (*i*) the entity name with the ports locally renamed and (*ii*) a list of aliases (similar to variables in traditional programming languages) to be used in the subsequent parts of the pattern body definition. In case of instantiating a channel with time or structure, it is defined the inherent dimensions, and in some cases, how such structure is initialised (making use of the observers defined for such structure).

Patterns are composed by interconnecting ports declared in their interfaces. This is achieved by the set of primitive reconfigurations introduced in Definition 2. Fig. 4 shows an example of the Sequencer coordination pattern expressed in the context of the tool developed to support CooPLa.

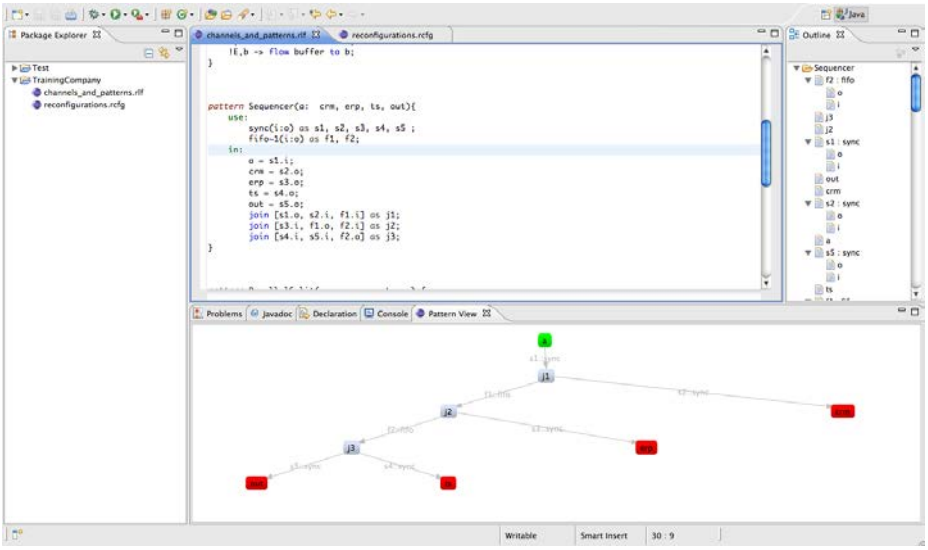


Fig. 4. Tool Support for CooPLa

Reconfigurations. Reconfigurations in CooPLa are also specified compositionally from the primitives given in Definition 2, or from more complex reconfigurations previously defined. Operators over standard data types (*e.g.*, List, Pair and Triple) can also be used: such is the case, in Fig. 5 of the forall structure which iterates over all elements of a list. Application of a reconfiguration r to a pattern ρ is denoted by ρ @ r. Fig. 5 shows an example of two reconfiguration specifications and respective application to instances of coordination patterns. Both Fig. 4 and 5 present parts of the case study addressed next.

5 Example: A fragment of a case-study

This section illustrates the use of architectural and reconfiguration patterns in a typical example of web-service orchestration for system integration. The case-study from where this example was borrowed involved a professional training

channels_and_patterns.rlf reconfigurations.rcfg

```
import "channels_and_patterns.rlf" ;

reconfiguration overlap(Pattern p; List<Triple<Node>> l) {
    @ par (p);
    forall(Triple<Node> e : l) {
        Node e1, e2, e3;
        e1 = fst(e);
        e2 = snd(e);
        e3 = trd(e);
        List<Node> E = [e1, e2];
        @ join(E, e3);
    }
}

reconfiguration implode(List<Node> l; Node j){
    List<Name> ids;
    List<Node> nodes, nodes_up;
    path(l ! ids, nodes);
    @ removeStructure(ids);
    update(nodes ! nodes_up);
    @ join (nodes_up, j);
}


Sequencer @  implode([.j1, .j2, .j3], n)

ParallelSplit @ overlap(Synchroniser<synch>, [T(.o, synch.a, j)])
```

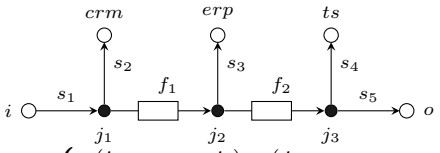
Fig. 5. Reconfigurations in CooPLa

company with facilities in six different locations, which relied on four main software components (all working in complete isolation): an *Enterprise Resource Planner* (ERP), a *Customer Relationship Management* (CRM), a *Training Server* (TS), and a *Document Management System* (DMS). The expansion of this company entailed the need for better integration of the whole system. This lead to changing components into services and adopting a SOA solution.

Several problems, however, were found during service orchestration analysis. A recurrent one was the lack of parallelism in the business workflow, slowing the whole system down. The user's information update activity which involves the user update services provided by ERP, CRM and TS components, was one of the tasks affected by such lack of parallel computation, as these services were invoked in sequence.

Let ρ, in Fig. 6, be the coordination pattern (known as a *Sequencer*) used for sequential service orchestration. Resorting to the reconfiguration patterns introduced in Section 3.2, let us rearrange the coordination policy so that user profiles (in each component) are updated in parallel. A possible solution is obtained by applying the implodeP reconfiguration pattern as $\rho \bullet \mathsf{implodeP}(\{j_1, j_3\}, n)$. The following paragraphs show, step-by-step, how to compute the resulting coordination pattern, depicted in Fig. 7. The actual CooPLa script for this reconfiguration is depicted in Fig. 5.

The first argument of implodeP provides the border nodes of the structure one desires to superpose onto the node in the second argument. From Definition 11 we first identify the complete structure to remove, which is composed of the unique names of the channels and their nodes (the border nodes plus some intermediary ones). Operation $remNodes$, with ρ and $\{j_1, j_3\}$ as arguments, starts by identifying the intermediary nodes and channels to retrieve the relevant



$$\rho = \left\langle \{i\}, \{crm, erp, ts, o\}, \left\{ \begin{array}{lll} (i, s_1, \mathsf{sync}, j_1), & (j_1, s_2, \mathsf{sync}, crm), & (j_1, f_1, \mathsf{fifo_e}, j_2), \\ (j_2, s_3, \mathsf{sync}, erp), & (j_2, f_2, \mathsf{fifo_e}, j_3), & (j_3, s_4, \mathsf{sync}, ts), \\ (j_2, s_5, \mathsf{sync}, o) & & \end{array} \right\} \right\rangle$$

Fig. 6. The *Sequencer* Coordination Pattern

structure:

$$\begin{array}{ll} N_1 & = \{j_1, j_2\} \cup \emptyset = \{j_1, j_2\} \\ N_2 & = \{j_1, j_2\} \cup \{j_3, j_2\} = \{j_1, j_3, j_2\} \\ M_{ids} & = ms(\{s_1, s_2, f_1\}) \sqcup ms(\{f_2, s_4, s_3\}) \sqcup ms(\{f_1, s_3, f_2\}) \\ & = [s_1 \mapsto 1, s_2 \mapsto 1, f_1 \mapsto 2, f_2 \mapsto 2, s_4 \mapsto 1, s_3 \mapsto 1, s_5 \mapsto 1] \\ Ch & = filter(2, M_{ids}) = \{f_1, f_2\} \end{array}$$

Once the intermediary nodes and channels are identified, we proceed by applying the removeP reconfiguration pattern as $\rho \bullet \mathsf{removeP}(Ch)$. This boils down to the recursive application of remove: $(\rho \bullet \mathsf{remove}(f_1)) \bullet \mathsf{remove}(f_2)$. Let ρ' be the result of removing f_1 from ρ:

$$\rho' = \left\langle \{i, j_2\}, \{crm, erp, ts, o\}, \left\{ \begin{array}{ll} (i, s_1, \mathsf{sync}, j_1), & (j_1, s_2, \mathsf{sync}, crm), \\ (j_2, s_3, \mathsf{sync}, erp), & (j_2, f_2, \mathsf{fifo_e}, j_3), \\ (j_3, s_4, \mathsf{sync}, ts), & (j_2, s_5, \mathsf{sync}, o) \end{array} \right\} \right\rangle$$

and ρ'' be the result of removing f_2 from ρ', which is actually the outcome of applying the removeP reconfiguration pattern to ρ:

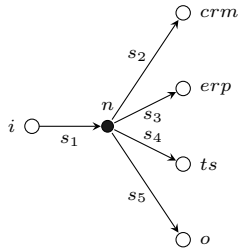
$$\rho'' = \left\langle \{i, j_2, j_3\}, \{crm, erp, ts, o\}, \left\{ \begin{array}{ll} (i, s_1, \mathsf{sync}, j_1), & (j_1, s_2, \mathsf{sync}, crm), \\ (j_2, s_3, \mathsf{sync}, erp), & (j_3, s_4, \mathsf{sync}, ts), \\ (j_2, s_5, \mathsf{sync}, o) & \end{array} \right\} \right\rangle$$

After removing the channels, set N_2 is updated, to delete nodes that have been removed from the initial coordination pattern, ρ. In this case, N_2 remains unchanged, then:

$$M = \{j_1, j_2, j_3\} \cap \{i, j_1, crm, j_2, erp, j_3, ts, j_3, o\} = \{j_1, j_2, j_3\}$$

Finally, we merge the nodes of M with node n, and obtain the desired coordination pattern (Fig. 7) which encodes a parallel workflow policy and consequently allows for the update of user's information in parallel.

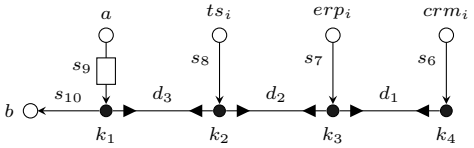
The resulting pattern actually does the job: the three user update services are called simultaneously, and the flow continues to the output port o, which enables contiguous activities. However, it does not cope with another requirement enforcing that no other activity should start before the user's information is updated. The obvious solution is to delay the flow on port o, until the three services



$$\rho_1 = \left\langle \{i, crm, erp, ts\}, \{o\}, \left\{ \begin{array}{lll} (i, s_1, \mathsf{sync}, n), & (n, s_2, \mathsf{sync}, crm), & (n, s_3, \mathsf{sync}, erp) \\ (n, s_4, \mathsf{sync}, ts), & (n, s_5, \mathsf{sync}, o), & \end{array} \right\} \right\rangle$$

Fig. 7. After *imploding* the Sequencer: the Parallel Split coordination pattern

provide a *finish* acknowledgement. A new reconfiguration is, therefore, necessary: we proceed by *overlapping* a *Synchroniser* pattern ρ_s (see Fig. 8). The CooPLa specification of this reconfiguration is shown in Fig. 5. The idea is to connect



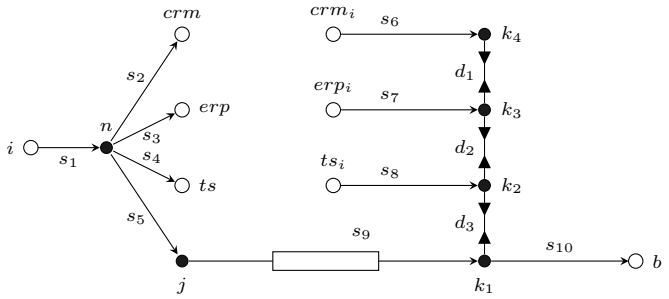
$$\rho_s = \left\langle \{a\}, \{crm_i, erp_i, ts_i, b\}, \left\{ \begin{array}{lll} (a, s_9, \mathsf{fifo_e}, k_1), & (k_1, s_{10}, \mathsf{sync}, b), & (k_1, d_3, \mathsf{drain}, \bot), \\ (k_2, d_3, \mathsf{drain}, \bot), & (ts_i, s_8, \mathsf{drain}, k_2), & (k_2, d_2, \mathsf{drain}, \bot), \\ (k_3, d_2, \mathsf{drain}, \bot) & (erp_i, s_7, \mathsf{sync}, k_3), & (k_3, d_1, \mathsf{drain}, \bot), \\ (k_4, d_1, \mathsf{drain}, \bot), & (crm_i, s_8, \mathsf{sync}, k_4) & \end{array} \right\} \right\rangle$$

Fig. 8. The *Synchroniser* Coordination Pattern

nodes o and a in such a way that all other input ports of ρ_s are free to connect to the feedback service interface of the CRM, ERP and TS components. Fig. 9 depicts the result of performing $\rho_1 \bullet \mathsf{overlapP}(\rho_s, \{(o, a, j)\})$. From Definition 8, we start by computing $\rho_1 \bullet \mathsf{par}(\rho_s)$, which yields the following pattern:

$$\rho''' = \left\langle \begin{array}{c} \{i, a, ts_i, erp_i, crm_i\}, \{o, crm, erp, ts, b\}, \\ \left\{ \begin{array}{llll} (i, s_1, \mathsf{sync}, n), & (n, s_2, \mathsf{sync}, crm), & (n, s_3, \mathsf{sync}, erp) & (n, s_4, \mathsf{sync}, ts), \\ (n, s_5, \mathsf{sync}, o), & (a, s_9, \mathsf{fifo_e}, k_1), & (k_1, s_{10}, \mathsf{sync}, b), & (k_1, d_3, \mathsf{drain}, \bot), \\ (k_2, d_3, \mathsf{drain}, \bot), & (ts_i, s_8, \mathsf{drain}, k_2), & (k_2, d_2, \mathsf{drain}, \bot), & (k_3, d_2, \mathsf{drain}, \bot) \\ (erp_i, s_7, \mathsf{sync}, k_3), & (k_3, d_1, \mathsf{drain}, \bot), & (k_4, d_1, \mathsf{drain}, \bot), & (crm_i, s_8, \mathsf{sync}, k_4) \end{array} \right\} \end{array} \right\rangle$$

Finally, we merge nodes o and a together into a node j, by performing $\rho''' \bullet \mathsf{join}(\{o, a\}, j)$. The result is presented in Fig. 9, which is actually the coordination pattern meeting the requirement of not allowing other activities to start before the user's information update in the CRM, ERP and TS components is completed.



$$\rho_2 = \left\langle \left\{ \begin{array}{cccc} (i, s_1, \mathsf{sync}, n), & (n, s_2, \mathsf{sync}, crm), & (n, s_3, \mathsf{sync}, erp) & (n, s_4, \mathsf{sync}, ts), \\ (n, s_5, \mathsf{sync}, j), & (j, s_9, \mathsf{fifo_e}, k_1), & (k_1, s_{10}, \mathsf{sync}, b), & (k_1, d_3, \mathsf{drain}, \bot), \\ (k_2, d_3, \mathsf{drain}, \bot), & (ts_i, s_8, \mathsf{drain}, k_2), & (k_2, d_2, \mathsf{drain}, \bot), & (k_3, d_2, \mathsf{drain}, \bot) \\ (erp_i, s_7, \mathsf{sync}, k_3), & (k_3, d_1, \mathsf{drain}, \bot), & (k_4, d_1, \mathsf{drain}, \bot), & (crm_i, s_8, \mathsf{sync}, k_4) \end{array} \right\} \right\rangle$$
$$\{i, ts_i, erp_i, crm_i\}, \{crm, erp, ts, b\},$$

Fig. 9. Overlapping Parallel Split with the Synchroniser pattern

6 Conclusions

6.1 Related work

Reconfigurations in SOA are, most of the times, focused on replacing services, or modifying their connections to the coordination layer. Often they neglect structural changes in the actual interaction layer itself [8,12]. In [14,13], however, the authors highlight the role played by software connectors during runtime architectural changes. Although these changes are again focused on the manipulation of components, they recognise that connectors are also amenable to contextual adaptations in order to keep the consistency of the architecture.

Reference [19] resorts to category theory to model software architectures as labelled graphs of components and connectors. Reconfigurations are modelled via algebraic graph rewriting rules. This approach has some points of contact with our strategy. In [11,10], a similar approach is adopted, but in the context of Reo. The authors relay on high-level replacement systems, more precisely on typed hypergraphs, to describe Reo connectors (and architectures, in general). In this perspective, vertices are the nodes and (typed hyper-) edges are communication channels and components. Reconfiguration rules are specified as graph productions for pattern matching. This approach performs atomic complex reconfigurations, rather than a sequence of basic modifications, which is stated as an advantage for maintaining system consistency. Nevertheless, the model may become too complex even when a simple primitive operation needs to be applied.

Differently, in [4] architectures are modelled as Reo connectors, and no information on components is stored in the model. The model is a triple composed of channels with a type and distinct named ports, a set of visible nodes and a

set of hidden nodes. Their model is similar to ours, but for the distinction introduced here between input and output nodes and the need we avoid to be explicit on the hidden nodes of a pattern. Although a number of primitive transformations are proposed, this work, as most of the others, do not consider 'big-step' reconfigurations which seems a severe limitation in practice.

6.2 Summary and future work

The paper introduces a model for reconfiguration of coordination patterns, described as a graphs of primitive channels. It is shown how typical reconfiguration patterns can be expressed in the model by composition of elementary transformations. CooPLa provides a setting to animate and experiment reconfigurations upon typical coordination patterns. We are currently involved in their classification in a suitable ontology. What is still missing, however, is the inclusion in the model of automatic assessing mechanisms to assess reconfigurations semantically and trigger their application. This concern is orthogonal to the work presented in this paper.

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Linking the Semantics of BPEL using Maude

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Abstract. Web services have become more and more important in these years. It is of key importance for enterprise web applications to combine different services available to accomplish complex business process. BPEL4WS (BPEL) is the OASIS standard for web services composition and orchestration. It contains several distinct features, including scope-based compensation and fault handling mechanism. We have already studied the semantics for BPEL, including the operational semantics, algebraic semantics and their linking theory.

This paper considers the mechanical approach to linking the operational semantics and algebraic semantics for BPEL. Our approach is to generate operational semantics from algebraic semantics, and to use equational and rewriting logic system Maude to mechanize the linking between the two semantics. Firstly, we investigate the algebraic laws in the Maude approach. Based on the algebraic semantics, the generation of head normal form is explored. Secondly, we consider the Maude approach to deriving the operational semantics from algebraic semantics, where the derivation strategy is based on the concept of head normal form. Our mechanical approach using Maude can visually show the head normal form of each program, as well as the execution steps of a program based on the derivation strategy. Finally, we also mechanize the derived operational semantics. The results mechanized from the second and third exploration indicate that the transition system of the derived operational semantics is the same as the one based on the derivation strategy.

1 Introduction

Web services and other web-based applications have been becoming more and more important in practice. In this flowering field, various web-based business process languages have been introduced, such as XLANG [30], WSFL [23], BPEL4WS (BPEL) [11] and StAC [4], which are designed for the description of services composed of a set of processes across the Internet. Their goal is to achieve the universal interoperability between applications by using web standards, as well as to specify the technical infrastructure for carrying out business transactions. BPEL4WS (BPEL) is the OASIS standard for web services composition and orchestration. It contains several distinct features, including scope-based compensation and fault handling mechanism.

The most important feature of BPEL is that it supports the long-running

interactions involving two or more parties. Therefore, it provides the ability to define fault and compensation handing in application-specific manner, resulting in a feature called *Long-Running (Business) Transactions (LRTs)*. The concept of *compensation* is due to the use of Sagas [3, 12] and open nested transactions [26]. The fault analysis has been considered in [27, 29] for compensation processes. It addition, BPEL provides two kinds of synchronization techniques for parallel processes. In our model, shared-labels are introduced for the synchronization between a process and its partners within a single service, while channel communications are introduced for message transmission between different services.

We have already studied the various semantics for BPEL [28, 34, 14, 35]. The operational semantics was studied using SOS, and bisimulation is explored for BPEL programs,which is considered in a two-layer form, one is for the equivalence for the compensation lists, the other is for BPEL programs. The denotational semantics was studied using the UTP [19] approach. A set of algebraic laws was explored, and the their correctness is based on the two approaches, operational semantics and denotational semantics respectively. The three semantics should provide the same understanding of the language from different viewpoints and they should be consistent. Therefore, the relating of these three semantics is a challenging task. We have also theoretically investigated some of the linking theories between the three semantics of BPEL [32, 33].

This paper studies the mechanical approach to linking theory of the operational and algebraic semantics for BPEL. Our approach is to generate operational semantics from algebraic semantics. We apply the mechanical method to support the semantic linking by using the equational and rewriting logic system Maude [9, 10]. Firstly, we investigate the algebraic semantics for BPEL. In order to generate the head normal form of each program, four typical forms are introduced. The concept of head normal form supports the linking between algebraic and operational semantics, and its generation is implemented in Maude. Secondly, we investigate the derivation of operational semantics from algebraic semantics. The derivation strategy is defined based on the head normal form and it is encoded in Maude. Finally, based on the derivation strategy, a transition system can be derived (i.e., derived operational semantics). We animate the generated operational semantics in Maude. The results mechanized from the second and third exploration indicate that the transition system of the derived operational semantics is the same as the one based on the derivation strategy.

The remainder of this paper is organized as follows. Section 2 introduces the language BPEL, and we implement its syntax in Maude. Section 3 explores the algebraic semantics for BPEL implemented in Maude. In particular, we study the laws for parallel and scope structure of BPEL. They are the key features of BPEL and deserve a detailed study. Meanwhile, in this section we also study the generation of head normal form mechanically. In section 4 we provide the derivation strategy for deriving operational semantics from algebraic semantics. Our approach is based on the head normal form of each program. An operational semantics can be derived. For the derived operational semantics, we study its

animation in section 5. Section 6 discusses the related work about web services and semantics linking. Section 7 concludes our paper and discuss some future work.

2 The Syntax of BPEL and its Implementation in Maude

2.1 Introduction of BPEL

We have proposed a BPEL-like language, which contains several interesting features, such as scope-based compensation and a fault handler mechanism. The categories of syntactic elements of the language are as follows:

$$BA ::= \texttt{skip} \mid x := e \mid \texttt{rec}\ a\ x \mid \texttt{rep}\ a\ x \mid \texttt{throw}$$

$$A ::= BA \mid g \circ A \mid b \rhd l \mid A;\ A \mid A \lhd b \rhd A \mid b * A \mid A \parallel A \mid A \sqcap A \mid \texttt{undo} \mid \{A\,?\,A,\ A\}$$

where:

- $x := e$ assigns the value of e to local variable x. `skip` behaves the same as $x := x$. Activity `throw` indicates that the program encounters a fault immediately. In order to implement the communications between different services, two statements are introduced; i.e., `rec` $a\ x$ and `rep` $a\ x$. Command `rec` $a\ x$ represents the receiving of a value through channel a, whereas `rep` $a\ x$ represents the output of value of x via channel a.
- Several constructs are similar to those in traditional programming languages. $A; B$ stands for sequential composition. $A \lhd b \rhd B$ is the conditional construct and $b * A$ is the iteration construct. $A \sqcap B$ stands for the nondeterministic choice.
- Shared-labels are introduced to implement the synchronization between a process and its partner. $g \circ A$ awaits the Boolean guard g to be set true, where g is composed of a set of source links; i.e., a set of read only shared-labels. $b \rhd l$ assigns the value of b to label l.
- $\{A\,?\,C,\ F\}$ stands for the scope-based compensation statement, where A, C and F stand for the primary activity, compensation program and fault handler correspondingly. If A terminates successfully, program C is installed in the compensation list for later compensating. On the other hand, if A encounters a fault during its execution, the fault handler F will be activated. Further, the compensation part C does not contain scope activity. On the other hand, statement "`undo`" activates the execution of the programs in the compensation list in reverse order of their installed sequence.
- $A \parallel B$ stands for the parallel composition. Its local variable set is the union of the corresponding sets for the two components. For a shared label, it can be owned by one parallel component; i.e., it can only be written by one parallel component.

For exploring the parallel expansion laws, our language is enriched with the concept of guarded choice, expressed in the form:

$$\{h_1 \to P_1\} [\!] \ldots\ldots [\!] \{h_n \to P_n\}$$

where:

(1) h_i can be a `skip` guard, expressed as b_i&`skip`, where b_i is a Boolean expression and satisfies the condition "$\vee_i b_i = true$".

(2) h_i can also be a communication guard, expressed as `rec` a x and `rep` a x.

(3) h_i can also be a Boolean guard @(g_i); i.e, waiting for g_i to be fired.

2.2 Rewriting Logic and the Maude System

Rewriting logic is a general semantic and logic framework that supports defining semantics of programming languages and models of concurrency. Membership equational logic is included in rewriting logic. Thus rewriting logic supports both static and dynamic specifications. A rewrite theory in rewriting logic is a 4-tuple R = $(\Sigma, E \cup A, \emptyset, R)$, where $(\Sigma, E \cup A)$ is a membership equational logic.

Membership equational logic defines the static part of a theory. Σ, which defines the sorts, subsorts, and operators in the theory, is the fundamental part called the *s*ignature. E is the collection of equations $(t = t')$ and membership $(t : s)$ [1] (possibly conditional) axioms of the theory. It defines simplification rules regarding the signature. A is a set of equational attributes declared for operators, including `assoc` (associative), `comm` (commutative), `id: t` (t as a identity of the operator) and so on. Particularly, the attribute `ctor` (short for constructor) declares the fundamental elements of a sort.

The third component $\emptyset$ of the rewriting theory is the function defining frozen arguments of operators. R is a collection of (possibly conditional) rules specifying the dynamic part of the theory. A rewriting rule $t \rightarrow t'$ represents a transition of a concurrent system, and can naturally depict transitions of operational semantics, which we will describe later in this paper.

Maude is a high-performance implementation of rewriting logic as well as the underlying MEL sublogic. Its syntax is so simple that it is almost identical with mathematical notations. And with rewriting logic as its fundamental logic, it is very expressive, specifying semantics of programming languages and modeling concurrent systems.

Maude supports two levels of declaration, functional modules and system modules. A functional module is declared by the syntax `fmod Module-Name is ... endfm`, where the dots denote the declaration of sorts, subsorts, operations, equations and memberships. Functional modules are implementation of MEL theory. System modules are declared by `mod is Module-Name ... endm`, where rules can be declared in addition to the parts of functional modules. System modules are implementation of rewriting logic.

2.3 Implementation of Syntax of BPEL in Maude

Utilizing the sort oriented system provided by Maude, it is rather convenient to implement the syntax of BPEL. First of all, we use the sort `Assignment` to

[1] where t and t' as terms and s as a sort

define the $x := e$ and *skip*. In order to handle the update of source links, we define a unique sort `UpdateOfLabel` to distinguish it from the assignment of local variables. Communications on channels are defined by the sort `Channel`, including the two basic communication primitives, i.e., *rep* and *rec*. *throw* and *undo* are defined by the sorts `ThrowCommand` and `UndoCommand` respectively. The syntax elements mentioned above constitute the sort `PrimitiveCommand`, by declaring their corresponding sorts as subsorts of `PrimitiveCommand`.

```
sorts Assignment UpdateOfLabel Channel ThrowCommand UndoCommand .
sort PrimitiveCommand .
subsort Assignment AssignmentOfLabel Channel < PrimitiveCommand .
subsort ThrowCommand UndoCommand < PrimitiveCommand .
op _ := _ : Qid Exp -> Assignment [ctor prec 1] .
op _ /> _ : BoolExp Qid -> UpdateOfLabel [ctor prec 1] .
op rec _ _ : Qid Qid -> Channel [ctor prec 1] .
op rep _ _ : Qid Qid -> Channel [ctor prec 1] .
op throw : -> ThrowCommand .
op undo : -> UndoCommand .
```

The structured construction of BPEL programs are defined by the sort `Program`. To be mentioned, three particular states of programs are defined to be basic elements of `Program`. They are `nil`, `special` and `fault`, representing that the program is completed, in the compensating status and confronted a fatal fault. The last two are the essential parts of the scope-based compensation and fault handler mechanism.

$g \circ A$ is represented as `@(g) A` in our code, and `@(g)` is of sort `LabelGuard`. And other syntax constructions are defined as in most programming languages.

```
fmod PROGRAM is ...
subsort PrimitiveCommand < Program .
op nil special fault : -> Program [ctor] .
op _ _ : LabelGuard Program -> Program [ctor prec 5] .
op _ <> _ : Program Program -> Program [ctor prec 10] .
                              ---- Nondeterministic Choice
op _ ; _ : Program Program -> Program [ctor gather (e E) prec 40] .
op if _ then _ else _ : BoolExp Program Program -> Program [ctor prec 20] .
op while _ do _ : BoolExp Program -> Program [ctor prec 20] .
op _ || _ : Program Program -> Program [ctor prec 30] .
op {_ ? _ , _} : Program Program Program -> Program [ctor prec 20] .
endfm
```

3 Algebraic Semantics and Head Normal Form for BPEL

In this section we study the algebraic semantics and head normal forms for BPEL. The concept of head normal form is used to build the link between the operational semantics and algebraic semantics. Firstly, we introduce four

typical forms. Every program can be expressed in one of the four forms or in the summation of a set of initial deterministic processes.

3.1 Typical Forms

In order to explore the head normal form, we introduce four typical forms. We define a sort `NormalForm` declared to represent these four typical forms. Below describes how the four typical forms are represented as elements of `NormalForm.`

The first form stands for the general guarded choice, as mentioned above. For each guarded component, the corresponding guard can be a skip guard, event guard or communication guard.

(form-1) $[\!]_{i\in I}\{b_i \; and \; skip \rightarrow P_i\}[\!][\!]_{j\in J}\{@(g_j) \rightarrow Q_j\}$
$[\!][\!]_{l\in L}\{comm \; a_l \; x_l \rightarrow R_l\}$
where, *comm* can be *rec* or *rep*

```
sorts LabelGuard Guard .
subsort Channel LabelGuard < Guard .
op _&skip : BoolExp -> Guard [ctor].
op @(_) : ParterLink -> LabelGuard [ctor] .
subsort GuardedChoice < NormalForm .
op _ => _ : Guard Program -> GuaredChoice [ctor] .
op $ : -> GuardedChoice [ctor] .
op _[]_:GuardedChoice GuaredChoice -> GuardedChoice[ctor assoc comm id: $]
```

(form-2) $X \rightarrow P$

where X can be of the form $assign(x, e)$, $updatelabel(l, b)$ or $compen(C)$, which we introduce to represent actions of BPEL programs except for the communication actions. $assign(x, e)$ stands for assigning value e to local variable x. $updatelabel(l, b)$ means the update of label l with boolean value b. We use $compen(C)$ to stand for recording program C at the end of the compensation list

```
op assign(_,_) : Qid Exp -> Head [ctor] .
op updatelabel(_,_) : Qid BoolExp -> Head [ctor] .
op compen(_) : Program -> Head [ctor] .
op _ => _ : Head Program -> NormalForm [ctor] .
```

(form-3) *throw*

```
subsort ThrowCommand < NormalForm .
```

(form-4) *undo*

```
subsort UndoCommand < NormalForm .
```

Now we start to consider the algebraic laws.
First we consider the algebraic laws for sequential composition. It is distributive backward through guarded choice and the second typical form. Further, *throw* and *undo* are both a left zero of sequential composition.

```
eq {h => P} ; Q = {h => (P ; Q)} .
```

```
eq ({h => P} [] GC) ; Q = ({h => P} ; Q) [] (GC ; Q) .[2]
eq (X => P) ; Q = X => (P ; Q) .
eq throw ; P = throw .
eq undo ; P = undo .
```

As for function *seq*, it defines that *nil* and *throw* are unit and zero of sequential composition respectively.

```
eq nil ; Q = Q .
eq throw ; Q = throw .
```

In the case of conditional branch and iteration, there are algebraic laws defined as following:

```
eq if b then P else Q = {b &skip => P} [] {!b &skip => Q} .
eq while b do P = {b &skip => (P ; while b do P)} [] {!b &skip => nil} .
```

Scope construct and parallel composition are two main features of BPEL, so we will introduce them in detail in the following two subsections.

3.2 Scope

Scope-based compensation and fault handling mechanism are the core features of BPEL, so we describe them here specially. First we introduce the action called $compen(C)$, installing the program C into the compensation list.

(scope-1) $\{A \ ?\ C, F\} =_{df} (A; compen(C)) \circ F$

When program A terminates successfully, $compen(C)$ will be activated. In this sense, it can be interpreted as a sequential composition. In the mean time, if A encounters a fault, fault handler F will take charge to do protection actions. For the operator $\circ$, it satisfies the following algebraic laws.

```
eq {h => P} ∘ Q = {h => (P ∘ Q)} .
eq ({h => P} [] GC) ∘ Q = ({h => P} ∘ Q) [] (GC ∘ Q) .
eq (X => P) ∘ Q = X => (P ∘ Q) .
eq throw ∘ P = P .
eq undo ∘ P = undo .
```

As for function fau, it defines that *nil* and *throw* are zero and unit of operator $\circ$ respectively, just as the opposite of sequential composition.

```
eq nil ∘ Q = nil .
eq throw ∘ Q = Q .
```

3.3 Parallel Composition

In this subsection, we will explain how the normal forms of two initially deterministic processes are composed together. We consider the four typical forms in

[2] `G1 G2 GC GC1 GC2` are all variables of sort GuardedChoice in this paper.

turn to show the parallel composition. First, we consider the algebraic laws for two parallel programs. *nil* is a unit of parallel composition.

```
eq nil || Q = Q .
```

Then we introduce a fundamental function *par*1 which defines how to combine a guarded choice with a program. It has to distribute the program to every component of the guarded choice.

```
eq ({h => P} [] G1) || Q = {h => P || Q} [] (G1 || Q) .
eq $ || Q = $ .
```

The parallel expansion of normal forms are interpreted by the operator // following.

```
op _ // _ : NormalForm NormalForm -> NormalForm .
```

At first, we consider that the two parallel components are both in the first typical form, i.e., guarded choice. It is implemented by the function `foo`. In order to remember the initial form of the two parallel components, we pass an additional copy of them to the function *foo*.

```
eq G1 // G2 = foo(G1, G2, G1, G2) .
op foo(_,_,_,_) : GuardedChoice GuardedChoice GuardedChoice GuardedChoice ->
GuardedChoice .
```

(para-1) If two processes running in parallel have a common channel and are to communicate through the channel, the message passing can be interpreted as an assignment.

```
eq foo(G1 [] {rep a x => R}, G2 [] {rec a y => T}, GC1, GC2) =
   foo(G1,G2,GC1,GC2) [] {t &skip => (y := x ; (R || T)} .
eq foo(G1 [] {rec a x => R}, G2 [] {rep a y => T}, GC1, GC2) =
   foo(G1,G2,GC1,GC2) [] {t &skip => (x := y ; (R || T)} .
```

(para-2) If both do not have any communication through the same channel right now, they can be composed together by installing one program into another's guarded choice. Here, we will use the initial forms of two components which is passed as additional parameters.

```
eq foo(G1, G2, GC1, GC2) = (G1 || GC2) [] (G2 || GC1) [owise] .
```

(para-3) Next, we consider the case that one belongs to the first kind of typical form and the other one is in the second kind. This situation is of the normal parallel expansion law. Both can have a chance to be scheduled.

```
eq GC // (X => Q) = (GC || (X ; Q))[]{t &skip => (X ; GC || Q)} .
```

(para-4) If one is *throw*, the whole is also *throw*.

```
eq N // throw = throw .
```

(para-5) If both parallel components are of the second typical form, they can be expanded rather easily.

```
eq (X => P) // (Y => Q) = {t &skip => (X ; (P || Y;Q))}
                          [] {t &skip => (Y ; (X;P || Q))} .
```

3.4 Introduction of Summation

The four typical forms can describe most BPEL programs except for the ones containing nondeterministic choices. In order to include nondeterministic choices, we introduce a summation of normal forms. The basic idea is to distribute current possible choices to the front, summing up by the summation operator.

```
sort Summation .
subsort Program < Summation .

op _ (*) _ : Summation Summation -> Summation [assoc comm] .
```

We define it as associative and commutative, to reflect the essence of nondeterministic choice. The laws of summation are defined as:

```
eq (P (*) Q) ; R = P ; R (*) Q ; R .
eq (P (*) S1) ; R = (P ; R) (*) (S1 ; R) [owise] .
eq (P (*) Q) ∘ R = (P ∘ R) (*) (Q ∘ R) .
eq (P (*) S1) ∘ R= (P ∘ R) (*) (S1 ∘ R) [owise] .
```

3.5 Head Normal Form

With `NormalForm` and `Summation`, we are able to translate all BPEL programs to the two kinds of forms. And this is the essence of the head normal form and the algebraic semantics. We combine them together as sort `HeadNormalForm`.Operator `HF` is declared to compute head normal forms of programs.

```
sort HeadNormalForm .
subsort NormalForm Summation < HeadNormalForm .
op HF(_) : Program -> HeadNormalForm .
```

Below we define how head normal forms of each BPEL program can be generated based on the syntax structure.
Assignment $x := e$ is transformed to a single guarded choice with $true\&skip$ as its guard, and $assign(x, e)$ as its subsequent behavior.

```
eq HF(x := e) = {t &skip => assign(x,e)} .
```

Communication action on channels are expressed as a guarded choice with communication guard and *nil* as its subsequent behavior.

```
eq HF(rec a x) = {rec a x => nil} .
eq HF(rep a x) = {rep a x => nil} .
```

throw and *undo* are just as they are, and the update of label $b \rhd l$ is similar to assignment. The transformation of $g \circ A$ is simply to put the guard g in the front and A to the back as a guarded choice component.

```
eq HF(throw) = throw .
eq HF(undo) = undo .
eq HF(b /> l) = {t &skip => assignlabel(l,b)} .
eq HF(@(g) P) = {@(g) => P} .
```

As for sequential composition $P; Q$, if the head normal form of P is a guarded

choice or $X \rightarrow P$, then we can just append Q to the head normal form of P. On the other hand, if the head normal form of P is *throw* or *undo*, then the head normal form of $P;Q$ is also *throw* or *undo* respectively. If the head normal form of P is in the form of summation, the transform is committed on each part of the summation.

```
eq HF(P ; Q) = HF(P) ; Q .
```

For conditional branch and iteration, their head normal form is the guarded choice based on the Boolean condition.

```
eq HF(if b then P else Q) = {b &skip => P} [] {!b &skip => Q} .
eq HF(while b do P) = {b &skip => (P ; while b do P)} [] {!b &skip => nil}.
```

For nondeterministic choice $P \sqcap Q$, we have to take whether P or Q is already a nondeterministic choice into consideration. If the head normal forms of P and Q are both summations of a set of processes, then the head normal form of $P \sqcap Q$ is the sum of their head normal forms. If the head normal form of one of them is a single deterministic process, for example Q, then the result is the sum of $HF(P)$ and Q. Otherwise, the result is the sum of P and Q.

```
ceq HF(P <> Q) = HF(P) (*) HF(Q) if numofsumm(HF(P)) > 1
                                    /\ numofsumm(HF(Q)) > 1 .
ceq HF(P <> Q) = HF(P) (*) Q if numofsumm(HF(P)) > 1
                                /\ numofsumm(HF(Q)) = 1 .
eq HF(P <> Q) = P (*) Q [owise] .
***numofsumm: the number of initial deterministic processes composing the head normal form
***if numofsumm(HF(P)) > 1, then HF(P) is already a summation of a set of processes
```

Parallel is closely related to nondeterministic choice, in the sense that if one of the two processes concurrently executing is nondeterministic, we will put the nondeterministic choice at the front, which is implemented by the function `cross`. If both are deterministic, we apply the parallel expansion law, expressed by the expansion operator // described int subsection 3.3.

```
ceq HF(P || Q) = cross(HF(P),HF(Q))
                        if numofsumm(HF(P)) > 1 /\ numofsumm(HF(Q)) > 1 .
ceq HF(P || Q) = cross(HF(P),Q) if numofsumm(HF(P)) > 1 .
eq HF(P || Q) = HF(P) // HF(Q) [owise] .
op cross(_,_) : Summation Summation -> Summation .
eq cross(P , Q) = par(P,Q) .
eq cross(P , Q(*)S1) = par(P,Q) (*) cross(P,S1)
eq cross(P(*)S1 , S2) = cross(P,S1) (*) cross(S1,S2) .
```

The head normal form of scope $\{A \ ?\ C,\ F\}$ can be expressed as the introduced form in the subsection Scope.

```
eq HF({A ? C,F}) = HF((A ; compen(C)) * F) .
```

For $assign(x, e)$, $updatelabel(l, b)$ and $compen(C)$, their head normal forms are defined as:

```
eq HF(X) = X => nil .
```

3.6 Example

Here, we give an example to show the head normal forms of BPEL programs implemented in Maude. Since parallel and scope structure are the key features, we concentrate on them and explore the results.
First, take this parallel program as an example,

$$(rec\ a\ x\ ;\ if\ x < 0\ then\ \ x := -x\ \ else\ x := x + 1\ ;\ rep\ a\ x)\ \ ||$$
$$(rep\ a\ y\ ;\ rec\ a\ y).$$

Two processes are running in parallel, and will do a receive/reply communication. The first process waits for a reply action on channel a and once it receives a value, it will do the corresponding operations and reply the new value through channel a. In the mean time, the second process will reply a value through channel a and waits for a reply. The head normal form of this program showed in Maude is as:

```
result GuardedChoice:
{t &skip => 'x:='y ; (if 'x<0 then 'x:=(-'x) else 'x:=('x+1) ; rep'a'x) ||
                        rec'a'y)}
```

As we can see from the head normal form, the receive/reply communication is interpreted as an assignment of local variable.
Now we consider the scope structure.

$$\{rec\ a\ x\ ;\ if\ x > 10\ then\ throw\ else\ x := x + 1\ \ ?\ \ x := x - 1,\ \ x := 0\}$$

In this scope structure, the process first receives a value. If it is larger than 10 it will throw a fault otherwise it will increase it by one. The compensating program is to decrease the value, and the fault handler is to assign the value to its initial value zero. The head normal form is:

```
result GuardedChoice:
{rec'a'x => ((if 'x>10 then throw else 'x:=('x+1)) ; compen('x:=('x-1)) * 'x:=0}
```

The initial action is $rec\ a\ x$ which is normal, so the rest of the program under the scope is still protected by the fault handler $x := 0$, which we can see from the operator $*$.

4 Generating Operational Semantics from Algebraic Semantics

4.1 Configuration and Transition Types

With the rewriting rules in Maude, it is natural to implement operational semantics. First, we introduce four transition types of BPEL. They are described using the well-known Structural Operational Semantics (SOS).

$$C \xrightarrow{tau} C' \quad \text{or} \quad C \xrightarrow{c} C' \quad \text{or} \quad C \xrightarrow{v} C' \quad \text{or} \quad C \xrightarrow{a.m} C'$$

The first transition with *tau* action represents the nondeterministic selection. The second with c action represents a transition for local variable assignment while the third with v action represents the update of a shared label. The last is used for communication actions, where a.m is an action *rep* or *rec*. The action is declared by sort `Act`.

```
op tau c v : -> Act [ctor] .
op _@_?_ : Qid Qid Int -> Act [ctor] . ---- rep : Variable Channel Value
op _&_!_ : Qid Qid Int -> Act [ctor] . ---- rec : Variable Channel Value
```

The configuration is composed of four parts, the program, state of local variables, state of shared labels, and compensation list, represented as $\langle P, \sigma, L, Cpens \rangle$.

```
op < _,_,_,_ > : Program Env Labels Cpenslist -> Config [ctor] .
op {_}_ : Act Config -> Config [ctor frozen] .
```

In order to show what kind of transition it is in Maude, we declare two kinds of configurations as shown above. Rewriting rules are a natural way to represent steps of transitions. We use the configuration with an act in the front as the right side of a transition. In this way, we can capture explicitly the type of a transition.

4.2 Derivation Strategy

We have described in detail how to generate the head normal form of a BPEL program in section 3. In this subsection we consider how to derive operational semantics from the head normal form, which we call it as derivation strategy.

First, if the head normal form of a program is a summation of at least two programs, it will do a nondeterministic selection among the programs composing the summation and reach any one of them. It takes a *tau* action as described by rule `[0]`.

If the head normal form is in the form of guarded choice, it can do four kinds of transitions according to the guarded components in the guarded choice. The transitions are as `[a1]-[a4]`.

For the case of the other two typical forms, the update of local variables and shared labels can be done immediately. $compen(C)$ is to install the compensation program C. For a program whose head normal form is *throw*, it has encountered fatal error and has to be terminated. If the head normal form is *undo*, the program will do compensation programs installed in the compensating list in the reverse order, which is the core semantics in the compensating mechanism.

```
crl [0] : < P,sigma,label,cpens > => {tau}< Pi,sigma,label,cpens >
          if Pi(*)S1 := HF(P) .
crl [a1] : < P,sigma,label,cpens > => {c}< Pi,sigma,label,cpens >
           ------------------------------------------------------
              if {b &skip => Pi} [] G := HF(P) /\ b[sigma] .
crl [a2] : < P,sigma,label,cpens > => {c}< R,sigma,label,cpens >
           ------------------------------------------------------
              if {@(g) => R} [] G := HF(P) /\ g(label) .
crl [a3] : < P,sigma,label,cpens >
```

```
        => {x & a ! (sigma).x} < R,sigma,label,cpens >
        ----------------------------------------------
        if {rep a x => R} [] G := HF(P) .
crl [a4] : < P,sigma,label,cpens >
        => {x @ a ? i} < Q,sigma <-(x,i),label,cpens >
        ---------------------------------------------
        if {rec a x => Q} [] G := HF(P) .
crl [b] :
 < P,sigma,label,cpens > => {c} < P',sigma <-(x,e),label,cpens >
-------------------------------------------------------------
             if assign(x,e) => P' := HF(P) .
crl [c] :
 < P,sigma,label,cpens > => {v} < P',sigma,label <-[l,b],cpens >
-------------------------------------------------------------
             if assignlabel(l,b) => P' := HF(P) .
crl [d] :
 < P,sigma,label,cpens > => {c} < P',sigma,label,cpens ^ C >
-------------------------------------------------------------
             if compen(C) => P' := HF(P) .
crl [e] :
 < P,sigma,label,cpens > => {c} < fault,sigma,label,cpens >
-------------------------------------------------------------
             if throw := HF(P) .
crl [f1] :
 < P,sigma,label,Y ^ X > => {c} < X;undo,sigma,label,Y >
-------------------------------------------------------------
             if undo := HF(P) .
crl [f2] :
 < P,sigma,label,cpens > => {c} < special,sigma,label,empty >
-------------------------------------------------------------
             if undo := HF(P) .
```

5 Mechanizing the Generated Operational Semantics from Algebraic Semantics

In the last section, we studied the derivation of operational semantics from algebraic semantics. A derivation strategy was defined and a set of transition rules for each statement can be derived. From the derivation strategy, we can generate operational semantics in traditional style inductively based on the syntax of programs. We also implement them separately in Maude as transition rules. In this section we study the derived operational semantics implemented in Maude.

5.1 Sequential Composition

For sequential composition, the following four rules reflect its semantics. Specially, when a program transits into the *special* or $fault$ state, any program following it will never be executed. As illustrated in `Sequential-3` and `Sequential-4`, program $P;Q$ will transit into *special* or $fault$ in case that P does.

```
crl [Sequential-1] :
  < P;Q,sigma,label,cpens > => {act} < Q,sigma',label',cpens' >
 if ------------------------------------------------------------
  < P,sigma,label,cpens > => {act} < nil,sigma',label',cpens' > .

crl [Sequential-2] :
```

```
    < P;Q,sigma,label,cpens > => {act} < P' ; Q,sigma',label',cpens' >
 if ------------------------------------------------------------------
    < P,sigma,label,cpens > => {act} < P',sigma',label',cpens' > .
      /\ P' =/= nil /\ P' =/= special /\ P' =/= fault .

crl [Sequential-3] :
    < P;Q,sigma,label,cpens > => {act} < special,sigma',label',cpens' >
 if ------------------------------------------------------------------
    < P,sigma,label,cpens > => {act} < special,sigma',label',cpens' > .

crl [Sequential-4] :
    < P;Q,sigma,label,cpens > => {act} < fault,sigma',label',cpens' >
 if ------------------------------------------------------------------
    < P,sigma,label,cpens > => {act} < fault,sigma',label',cpens' > .
```

5.2 Parallel Composition

In this section, we will explain how parallel composition works. First, when any one of the parallel components P and Q is nondeterministic, $P \parallel Q$ first perform a *tau* action as shown by `Parallel-1-1` and `Parallel-1-2`.

```
crl [Parallel-1-1] :
    < P||Q,sigma,label,cpens > => {tau}< par(P',Q'),sigma,label,cpens >
if ------------------------------------------------------------------
    < P,sigma,label,cpens > => {tau}< P',sigma,label,cpens > /\
    < Q,sigma,label,cpens > => {tau}< Q',sigma,label,cpens > .

crl [Parallel-1-2] :
    < P||Q,sigma,label,cpens > => {tau} < par(P',Q),sigma,label,cpens >
if ------------------------------------------------------------------
    < P,sigma,label,cpens > => {tau}< P',sigma,label,cpens > /\
 < Q,sigma,label,cpens > => {act}< Q',sigma,label,cpens > /\ act =/= tau .
```

In the normal case, when there is no communication between the parallel components, we apply the interleaving semantics to the parallel composition as shown by `Parallel-2-1`.

```
crl [Parallel-2-1] :
    < P||Q,sigma,label,cpens > => {c}< par(P',Q),sigma',label',cpens' >
if ------------------------------------------------------------------
    < P,sigma,label,cpens > => {c}< P',sigma',label',cpens' > /\
    < Q,sigma,label,cpens > => {act}< Q',sigma'',label'',cpens'' > /\
    act =/= tau /\ Q' =/= fault .
```

The following rules define transitions when there are communications between processes. When one is to reply and the other is to receive through the same channel, they can do the communication and an assignment is used to represent the value passing. Otherwise, the communication will fail.

```
crl [Parallel-3] :
 < P||Q,sigma,label,cpens > => {c}< x := y ; par(P',Q'),sigma,label,cpens >
if ------------------------------------------------------------------
    < P,sigma,label,cpens > => {x @ a ? m}< P',sigma',label,cpens > /\
    < Q,sigma,label,cpens > => {y & a ! m}< Q',sigma,label,cpens > .

crl [Parallel-4] :
    < P||Q,sigma,label,cpens > => {act}< fault,sigma',label',cpens' >
 if ------------------------------------------------------------------
    < P,sigma,label,cpens > => {act}< fault,sigma',label',cpens' > /\
```

```
< Q,sigma,label,cpens > => {act'}< Q',sigma'',label'',cpens'' > /\ act'=/=tau.
```

5.3 Scope

In this subsection, we concentrate on the scope structure. For program $\{A?C, F\}$, if A has successfully terminated, then it will install the compensating program C into the compensation list by the action $compen(C)$. On the other hand, if A has encountered a fatal error, the fault handler F will take in charge, as shown by `Scope-2`. Otherwise, A will continue to execute. Specially, if A is to do an *undo*, it will start the compensation mechanism until all the actions in the compensation list are executed, as shown in `Scope-3`.

```
crl [Scope-1-1] :
 < {A ? C,F},sigma,label,cpens > => {act}< compen(C),sigma',label',cpens' >
if ------------------------------------------------------------------------
   < A,sigma,label,cpens > => {act} < nil,sigma',label',cpens' > .

rl [Scope-1-2] :
 < compen(C),sigma,label,cpens > => {act} < nil,sigma,label,cpens ^ C > .

crl [Scope-2] :
 < {A ? C,F},sigma,label,cpens > => {act'} < F',sigma'',label'',cpens'' >
if ------------------------------------------------------------------------
 < A,sigma,label,cpens > => {act} < fault,sigma',label',cpens' >

 < F,sigma,label,cpens > => {act'} < F',sigma'',label'',cpens'' > .

crl [Scope-3] :
 < {A ? C,F},sigma,label,cpens > => {act} < speical,sigma',label',cpens' >
if ------------------------------------------------------------------------
 < A,sigma,label,cpens > => {act} < special,sigma',label',cpens' > .

crl [Scope-4] :
< {A ? C,F},sigma,label,cpens > => {act}< {A' ? C,F},sigma',label',cpens' >
if ------------------------------------------------------------------------
 < A,sigma,label,cpens > => {act} < A',sigma',label',cpens' > /\
 A' =/= nil /\ A' =/= fault /\ A' =/= special .
```

As a basic element of compensation mechanism, we explain here the *undo* command.

```
 rl [Undo-1]:< undo,sigma,label,empty > => {c}< special,sigma,label,empty >.
 rl [Undo-2]:< undo,sigma,label,Y ^ X > => {c}< X ; undo,sigma,label,Y > .
```

Until the compensation list is empty, the program will try to do the programs stored in the compensation list in reverse order whenever it encounters an *undo* action. In the end, it will transit to *special* state. These two transitions together with the scope structure compose the compensation mechanism for BPEL.

5.4 Linking between Derivation Strategy and Derived Operational Semantics

In the last section we considered the derivation of operational semantics from algebraic semantics. A derivation strategy was defined and the operational se-

mantics for each statement can be derived. Also in the last subsections we mechanized the derived operational semantics. This subsection studies the linking between the derivation strategy and the derived operational semantics from the mechanical viewpoint. Firstly we use an example to illustrate the equivalence between the derivation strategy and the derived operational semantics. Secondly we discuss the mechanical approach for the proof of the equivalence.

Example. We use the first example described in section 3.6 to show the equivalence of the derivation strategy and the derived operational semantics. The parallel program is shown below:

$$(rec\ a\ x\ ;\ if\ x <= 0\ then\ \ x := -x\ \ else\ x := x + 1\ ;\ rep\ a\ x)\ \ ||$$
$$(rep\ a\ y\ ;\ rec\ a\ y)$$

We show one of the execution paths below. The initial values of x and y are set to 0 and 5. `empty` represents the uninitialized state of `Env, Labels, Cpens` in the configuration.

```
< (rec'a'x ; if 'x<0 then 'x:=(-'x) else 'x:=('x+1) ; rep'a'x)
|| (rep'a'y ; rec'a'y),('x,0)|('y,5),empty,empty >
-------------------------------------------------------------------->
< 'x:='y ;              ****** a first receive/reply sync
(if 'x<0 then 'x:=(-'x) else 'x:=('x+1) ; rep'a'x)
|| rec'a'y,('x,0) | ('y,5), empty, empty >
-------------------------------------------------------------------->
< assign('x,'y) ; (if 'x<0 then 'x:=(-'x) else 'x:=('x+1) ; rep'a'x)
|| rec'a'y,('x,0) | ('y,5), empty, empty >
-------------------------------------------------------------------->
< (if 'x<0 then 'x:=(-'x) else 'x:=('x+1) ; rep'a'x)
|| rec'a'y,('x,5) | ('y,5), empty, empty >
-------------------------------------------------------------------->
< ('x:=('x+1) ; rep'a'x) || rec'a'y, ('x,5) | ('y,5), empty, empty >
-------------------------------------------------------------------->
< rep'a'x || {rec'a'y => nil },('x,6) | ('y,5), empty, empty>
-------------------------------------------------------------------->
< 'y:='x ;              ****** a second receive/reply sync
nil,('x,6) | ('x,5), empty, empty >
```

There are two receive/reply synchronization in the path, which we have marked in the above. At the end, the second program of the parallel process will be blocked at the action *rep*. This path together with others are all searched out in both the derivation strategy and derived operational semantics, and here we only show this particular one shown above as an example, indicating the equivalence of the derivation strategy and derived operational semantics for the example parallel program.

Discussion. Now we study the mechanical proof of the equivalence of the derivation strategy and the derived operation semantics. Theoretically we have two theorems to be proved.

(1) If transition aa exists in the transition system of the derived operational semantics, then it also exists in the derivation strategy.
(2) If transition bb exists in the derivation strategy, then it also exists int the transition system of the the derived operation semantics.

The two theorems have been proved in our previous paper by theoretical analysis. Since we have implemented the derivation strategy and the derived operational

semantics in Maude, we want an proof for the equivalence by machine. The derivation strategy and transition system are implemented in rewriting logic, we have several challenges to prove the above theorems in Maude ITP (i.e., an interactive theorem prover [15]). One of them is how to represent transitions in MEL. Our strategy is to declare two new sorts `Pair` and `Ar` with `Ar` as `Pair`'s subsort. And an operator is declared to represent transitions in the style of membership relations.

```
sort Ar Pair .
subsort Ar < Pair .
op _-->_ : Config Config -> Pair .
```

The sort `pair` contains all the pairs of two configurations, but not all of them are correct transitions. So we can use the membership operator, declaring the correct transitions represented as pairs to be a member of sort `Ar`.
For theorem (1), we can declare all the transitions represented as `Pair`s in the derived strategy to be members of sort `Ar`.

```
fmod DERIVATION-STRATEGY' is
......
   cmb [a1'] : < P,sigma,label,cpens > --> {c}< Pi,sigma,label,cpens > : Ar
if {b &skip => Pi} [] GC := HF(P,null) /\ b[sigma] .
   cmb [a2'] : < P,sigma,label,cpens > --> {c}< R,sigma,label,cpens > : Ar
if {@(g) => R} [] GC := HF(P,null) /\ g(label) .
......
endfm
```

Then all we have to do is to prove the transitions, also represented as `Pair`s, to be members of sort `Ar`.

```
(goal sequential1 : DERIVATION-STRATEGY'
|- AP:Program ; Q:Program ; s:Status ; s':Status
(((< P,s > --> < nil,s' >): Ar) => ((< P ; Q, s > --> < Q,s' >): Ar)) .)
```

For theorem (2), the method is the same. Here, we give a strategy for proving the equivalence of derivation strategy and the derived operational semantics. Many implementation details for interactive proof in Maude ITP are a big challenge.

6 Related Work

Compensation is one typical feature for long-running transactions. Butler *et al.* have explored the compensation feature in the style of process algebra CSP [16], namely *compensating* CSP. The operational semantics and trace semantics have been studied [8, 7]. The compensation was introduced via a construct $P \div Q$, where P is the forward process and Q is its associated compensation behavior. StAC (Structured Activity Compensation) [5] is another business process modeling language, where compensation acts as one of its main features. Its operational semantics has also been studied in [4]. Meanwhile, the combination of StAC and B method [1] has been explored in [6], which provides the precise description of business transactions. Bruni *et al.* have studied the transaction

calculi for Sagas [3]. The long-running transactions were discussed and a process calculi was proposed in the form of Java API, namely Java Transactional Web Services [2].

π-calculus has been applied in describing web services models. Laneve and Zavattaro [21] explored the application of π-calculus in the formalization of the semantics of the transactional construct of BPEL. They also studied a standard pattern of Web Services composition using π-calculus. For verifying the properties of long-running transactions, Lanotte *et al.* have explored their approach in a timed framework [22]. A model of Communicating Hierarchical Timed Automata was developed where time was also taken into account. Model checking techniques have been applied in the verification of properties of long-running transactions.

Unifying Theories of Programming (abbreviated as *UTP*) was developed by Hoare and He in 1998 [19]. *UTP* covers wide areas of fundamental theories of programs in a formalized style and acts as a consistent basis for the principles of programming language. For relating operational and algebraic semantics, Hoare and He have studied the derivation of operational semantics from the algebraic semantics [18, 19]. An operational semantics of CSP [16] was derived, based on CSP's algebraic laws according to a derivation strategy (called the action transition relation). An operational semantics of Dijkstra's Guarded Command Language (abbreviated as GCL) was also derived based on GCL's algebra according to the derivation strategy (called the step relation). The total correctness of the derived GCL's operational semantics was also discussed in [20]. Recently, Hoare proposed the challenging research for the semantic linking between algebra, denotations, transitions and deductions [17].

7 Conclusion

Business process modeling languages are important for the web-based enterprise application. Our method is a new aspect of studying scope-based compensating and fault handling mechanism. In this paper, we studied the linking theory between algebraic semantics and operational semantics for BPEL. The linking was mechanized in rewriting logic system Maude.

First we implemented the syntax of BPEL in an obvious but accurate way thanks to the expressiveness of Maude. Then four typical forms for BPEL program is introduced, and the algebraic laws for sequential, parallel and scope structure are studied. The concept of summation was introduced. All the laws were encoded in Maude. Besides the algebraic laws, the head normal form of each program was defined and encoded in Maude. Based on the concept of head normal form, a strategy for deriving operational semantics from algebraic semantics war provided and a set of transition rules for each program can be generated. The generated operational semantics were implemented in Maude. Finally we used two examples to show the equivalence of the derivation strategy and the derived operational semantics.

For the future, we continue to explore the unifying theories for web services [19, 31], as well as the further web service models, including the probabilistic web service models [25, 13] and web service transaction models [24]. Further, we are also interested in how our mechanical approach can be applied to system verification.

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