How to Make Substitution Preserve Strong Bisimilarity

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Abstract

We show that strong bisimilarity of CCS processes without summation and relabelling is preserved by any substition modulo the maintenance of internal channels, if the processes bear *unique input locations*. By this we understand a syntactic means of preventing that substitutions, which are in general not injective, cause synchronisation in one but not in the other of two originally bisimilar processes.

1 Motivation

Substitution is one of the major features of *mobile calculi* such as the π-calculus, where names can be passed and substituted in the receiving process. However, it is a common fact that any of the basic bisimulation equivalences, which are not especially tailored for that purpose, fail to be congruence relations wrt. substitution of names. This can already be observed for less expressive calculi such as CCS. For instance, if we substitute α for β in $\alpha.\bar{\beta}.0 + \bar{\beta}.\alpha.0$ and $\alpha.0 \,|\, \bar{\beta}.0$, which are clearly strongly bisimilar, the result of the latter will be able to perform a synchronisation eating up its two components whereas the former is not. This is due to the expressibility of certain forms of *concurrency* by means of *sequentiality* and *choice* if communication a priori is not possible. In this way, the first process can be understood as a sequentialised implementation of the second one. When the grounds for synchronisation are provided by identifying α and β, the sequential version naturally fails to model the parallel one correctly.

As summation seems to be the main source of such nuisances, we proceed with a discussion on a subset of CCS which does not include the choice operator. For convenience, we also omit relabelling. However, we will see that even in this narrow setting, further restrictions are necessary in order to obtain preservance of strong bisimilarity by substitution.

In the following sections, we examine under which circumstances strong bisimilarity is preserved by substitution of names. This preservation depends strongly on the validity of a *diamond property* which we are going to introduce in the second half of section 4. Intuitively, if a process performs two different transitions, say one on α and another one on β, it will be able to enter exactly

For all $\alpha, \bar{\alpha} \in \mathcal{A}ct$, $\mu \in \mathcal{A}ct_\tau$ let $\xrightarrow{\mu} \subseteq \mathcal{P} \times \mathcal{P}$ be the smallest binary relation containing the following axiom and rules:

$$\text{(pr)}\ \frac{}{\mu.p \xrightarrow{\mu} p}$$

$$\text{(m1)}\ \frac{p \xrightarrow{\mu} p'}{p \,|\, q \xrightarrow{\mu} p' \,|\, q} \qquad \text{(m2)}\ \frac{q \xrightarrow{\mu} q'}{p \,|\, q \xrightarrow{\mu} p \,|\, q'} \qquad \text{(cm)}\ \frac{p \xrightarrow{\alpha} p' \quad q \xrightarrow{\bar{\alpha}} q'}{p \,|\, q \xrightarrow{\tau} p' \,|\, q'}$$

$$\text{(rs)}\ \frac{p \xrightarrow{\mu} p'}{p\backslash A \xrightarrow{\mu} p'\backslash A}\ \mu, \bar{\mu} \notin A \qquad \text{(rc)}\ \frac{p[rec\,x.p/x] \xrightarrow{\mu} p'}{rec\,x.p \xrightarrow{\mu} p'}$$

Table 1: The transition rules for $\mathcal{P}$.

the same state when performing a transition on the name used in the other transition branch. Note that nondeterministic processes may fail to fulfill this property. Take for instance $\alpha.0 + \beta.0$, which is able to perform both an α and a β but not any transition afterwards.
As in the following we wish diamonds to be simulated by diamonds in the bisimulation game, further restrictions have to be made. Section 3 therefore prepares the grounds by providing a syntactical means of restricting oneself to processes fulfilling this diamond requirement. We define a subclass of processes bearing *unique input locations.* For such processes, no input transition, say on α, may yield non-equivalent derivatives p and p'.
Section 5 contains concluding remarks and proposes directions for further work on this topic.

2 Basic Definitions

We use $\alpha, \beta, \gamma, \ldots$ to range over the *input channels* Λ, and $\bar{\alpha}, \bar{\beta}, \bar{\gamma}, \ldots$ to range over the *output channels* $\bar{\Lambda}$. $\mathcal{A}ct$ denotes the union of the disjunct sets Λ and $\bar{\Lambda}$, $\mathcal{A}ct_\tau$ also comprises the *silent action* τ. We use μ to range over $\mathcal{A}ct_\tau$. Channels will also be referred to as *atomic actions.* The *name* or *sort* $\alpha \in \Lambda$ denotes both the input channel α and its complement, the output channel $\bar{\alpha}$. $A, B, \ldots \subseteq \Lambda$ denote arbitrary restrictions on names.
The two mappings $sort : \mathcal{P} \longrightarrow \Lambda$ and $action : \mathcal{P} \longrightarrow \mathcal{A}ct$ determine the *visible* names, and the channels respectively, of processes. Both are defined in the usual syntactic way.
Let $\mathcal{P}$ be the set of CCS processes obtained in the usual way from terms of the form

$$p \ ::= \ 0 \ | \ \mu.p \ | \ p|p \ | \ p\backslash A \ | \ rec\,x.p,$$

where $\mu \in \mathcal{A}ct_\tau$ denotes both visible and invisible action prefixes.
We use the common transition system for CCS, only excluding the laws for summation and restriction. Table 1 shows the transition rules applied in this paper.
We use the usual notion of *strong bisimilarity.*

Definition 2.1 (Strong Bisimilarity) *A relation $\mathcal{R}$ on $\mathcal{P}$ is a* strong bisimulation, *if for all $(p, q) \in \mathcal{R}$ and $\mu \in \mathcal{A}ct_\tau$ the following holds:*

$$
\begin{array}{rcll}
p & \equiv_\alpha & p & \\
\mu.p\backslash A & \equiv_\alpha & \mu.(p\backslash A) & \text{if } \mu, \bar{\mu} \notin A \\
(p \,|\, q)\backslash A & \equiv_\alpha & p \,|\, q\backslash A & \text{if } sort(p) \notin A \\
(p \,|\, q)\backslash A & \equiv_\alpha & p\backslash A \,|\, q & \text{if } sort(q) \notin A \\
(p \,|\, q) \,|\, r & \equiv_\alpha & p \,|\, (q \,|\, r) &
\end{array}
$$

Table 2: Structural Congruence up to α-Conversion.

- *if* $p \xrightarrow{\mu} p'$, *then* $\exists\, q'$ *s.t.* $q \xrightarrow{\mu} q'$ *and* $(p', q') \in \mathcal{R}$.
- *if* $q \xrightarrow{\mu} q'$, *then* $\exists\, p'$ *s.t.* $p \xrightarrow{\mu} p'$ *and* $(p', q') \in \mathcal{R}$.

If for processes $p, q \in \mathcal{P}$ *there exists such a bisimulation* $\mathcal{R}$ *including them, we say that* p *and* q *are* strongly bisimilar, *written* $p \sim q$.

We apply substitution on names, strictly mapping input and output channels to such. This means that complementation commutes with substitution, i.e. for all $\alpha \in \mathcal{A}ct$: $\sigma(\bar{\alpha}) = \overline{\sigma(\alpha)}$.
Just like the λ-operator in logics does for variables, the restriction operator $\backslash$ acts as a binder for atomic actions which can be made internal by applying $\backslash A$ for a subset A of Λ to (sub-)processes.
In the following, we will apply a *structural congruence up to* α*-conversion*, $\equiv_\alpha$, which allows us to move around restriction sets more freely. Let $sort(p)$ denote the set of names used in p. Table 2 sums up the congruence equations.
What we need this congruence for, is to extend restriction sets from inner parts of processes to global appearance. For instance, we can write $(p \,|\, q \,|\, r)\backslash(A \cup B)$ instead of $((p \,|\, q)\backslash A \,|\, r)\backslash B$, as α-conversion guarantees for the side condition $sort(r) \notin A$.

3 Unique Input Location

In [BS96], Boreale and Sangiorgi give an example that replication, and thus also recursion, can cause the failure of strong bisimilarity as a congruence wrt. substitution of names. Their example hinges on the possibility of simulating the sequentialisation of certain processes using a combination of recursion and restriction. However, we will show that congruence is gained if we require the processes to yield *unique input locations* in the following sense.
As the transition rule for the recursion operator is not compositional in the sense that the left-hand-side of the conclusion is not made up of the left-hand-side of the premise, we cannot give a syntactical rule but one not allowing for any input locations.

Definition 3.1 *Let* $SIL : \Lambda \times \mathcal{P} \longrightarrow I\!N_0$ *be the function counting for input locations* α *at how many* separate input locations *within a process* p α *occurs:*

$$SIL(\alpha, 0) \;=\; 0 \tag{1}$$

$$SIL(\alpha, \mu.p) \;=\; \begin{cases} max\{1, SIL(\alpha, p)\} & \text{if } \mu \equiv \alpha \\ SIL(\alpha, p) & \text{otherwise} \end{cases} \tag{2}$$

$$
\begin{aligned}
SIL(\alpha, p \,|\, q) &= SIL(\alpha, p) + SIL(\alpha, q) && (3)\\
SIL(\alpha, p \backslash A) &= \begin{cases} SIL(\alpha, p) & \text{if } \alpha, \bar{\alpha} \notin A \\ 0 & \text{otherwise} \end{cases} && (4)\\
SIL(\alpha, rec\, x.p) &= \begin{cases} 0 & \text{if } actions(p) \cap \Lambda = \emptyset \\ \infty & \text{otherwise} \end{cases} && (5)
\end{aligned}
$$

Definition 3.2 *A process p bears* unique input locations *if for all input channels α the following holds:*

$$SIL(\alpha, p) \leq 1.$$

In the sequel, we give evidence that this definition of *unique input locations* coincides with the intuitive notion of two input actions never being executable at different locations at the same time.

Lemma 3.3 *For all $p, p' \in \mathcal{P}$, where $p \xrightarrow{\mu} p'$, and all $\alpha \in \Lambda$, $SIL(\alpha, p') \leq SIL(\alpha, p)$.*

Proof: by rule induction, where we make use of the easily deducible fact that $SIL(\alpha, p[rec\, x.p/x]) = SIL(\alpha, rec\, x.p)$. □

The next result may seem a bit technical, but it is as essential for the proof of lemma 3.5 as lemma 3.3.

Lemma 3.4 *For all $p, p' \in \mathcal{P}$, $\alpha \in \Lambda$: $p \xrightarrow{\alpha} p'$ only if $SIL(\alpha, p) > 0$.*

Proof: by rule induction, where $rec\, x.p$ is only capable of performing α if $SIL(\alpha, rec\, x.p) = \infty$. □

The main result of this section consists of two parts. First, unique input locations are preserved by transitions. And second, they guarantee for the unicity of derivatives resulting from arbitrary input transitions.

Lemma 3.5 *If $p \in \mathcal{P}$ is a process with unique input locations, then for every transition $p \xrightarrow{\mu} p'$ the following holds:*

(i) p' is a process with unique input locations and

(ii) if $\mu \in \Lambda$, then there is no $p_1 \not\equiv p'$ s.t. $p \xrightarrow{\mu} p_1$.

Proof:

(i) Follows directly from lemma 3.3.

(ii) By rule induction. Note that $rec\, x.p$ will never be able at all to perform μ if it is to bear unique input locations. □

$$\begin{tikzcd}[column sep=small]
& p \arrow[dl, "\alpha"'] \arrow[dr, "\beta"] & \\
p_1 \arrow[dr, "\beta"'] & & p_2 \arrow[dl, "\alpha"] \\
& p_3 &
\end{tikzcd}$$

(a) Diamond on α and β.

$$\begin{tikzcd}[column sep=small]
& \bar{p} \mid \tilde{p} \arrow[dl, "\alpha"'] \arrow[dr, "\beta"] & \\
\bar{p}' \mid \tilde{p} \arrow[dr, "\beta"'] & & \bar{p} \mid \tilde{p}' \arrow[dl, "\alpha"] \\
& \bar{p}' \mid \tilde{p}' &
\end{tikzcd}$$

(b) Parallel components yielding a diamond.

Figure 1: The diamond property.

4 Congruence Results

In this section, we show that, if we restrict ourselves to processes with unique input locations as introduced above, *strong* bisimilarity is a congruence relation wrt. substitution of names.

Theorem 4.1 *For all $p, q \in \mathcal{P}$ bearing unique input locations and all substitutions σ: If $p \sim q$ then $p\sigma \sim q\sigma$.*

For convention, we assume that domains and ranges of the substitutions are always disjunct from the internal actions of the processes which they are applied to. This is achieved by using α-conversion when necessary. Besides, we assume that $\tau\sigma \equiv \tau$ for any σ. Obeying these two conventions, most of the proofs are straightforward inductions.
The preparatory results fall into two parts. After describing the correspondence between the transitions of processes before and after a substitution, we proceed with establishing the diamond property establishing when visible transition sequences may be subject to a synchronisation.
On the one hand, any transition of the original process can be reflected by a corresponding transition if we apply substitution:

Lemma 4.2 *For $p, p' \in \mathcal{P}$, $\mu \in \mathcal{A}ct_\tau$ and every substitution σ, the following holds: If $p \xrightarrow{\mu} p'$ then $p\sigma \xrightarrow{\mu\sigma} p'\sigma$.*

Proof: by rule induction. $\square$

On the other hand, also the reverse direction holds, where we only have to take into account communication that may not exist in the original process but may well be possible after a non-injective substitution.

Lemma 4.3 *For every $p, p' \in \mathcal{P}$ and substitution σ, the following holds:*

(i) Whenever $p\sigma \xrightarrow{\beta} p'$, there exist α, p_1 s.t. $p \xrightarrow{\alpha} p_1$, $\beta \equiv \alpha\sigma$ and $p' \equiv p_1\sigma$.

(ii) Whenever $p\sigma \xrightarrow{\tau} p'$,

1. either there exists p_1 s.t. $p \xrightarrow{\tau} p_1$ and $p' \equiv p_1\sigma$.

2. *or there exist* $\alpha, \bar{\beta}, p_1, p_2, p_3$ *s.t.* $p \xrightarrow{\alpha} p_1 \xrightarrow{\bar{\beta}} p_3$, $p \xrightarrow{\bar{\beta}} p_2 \xrightarrow{\alpha} p_3$, $\alpha\sigma \equiv \beta\sigma$ *and* $p' \equiv_\alpha p_3\sigma$.

Proof: by rule induction. □

The next twoo results represent the crucial part of our proof. They guarantee that for bisimilar p and q and some substitution σ, if $p\sigma$ can perform a silent step which is the result of two non-matching visible transitions of p (and hence of q), this also leads to a corresponding synchronisation of $q\sigma$.

Lemma 4.4 (Diamond Property) *For all* $p, p_1, p_2 \in \mathcal{P}$ *and* $\alpha, \beta \in \mathcal{A}ct$ *where* $\alpha \not\equiv \beta$, *the following holds:*

(i) If $p \xrightarrow{\alpha} p_1$ *and* $p \xrightarrow{\beta} p_2$, *then there exists* p_3 *s.t.* $p_1 \xrightarrow{\beta} p_3$ *and* $p_2 \xrightarrow{\alpha} p_3$.

(ii) If $\alpha \equiv \bar{\beta}$ *then* $p \xrightarrow{\tau} p_3$.

Proof: by rule induction. □

Figure 1 (a) illustrates why the term *diamond* was chosen for this property.

Remark: New diamonds arise when both components of a process $\bar{p} \,|\, \tilde{p}$ are able to perform (different) visible transitions, as shown in figure 1 (b).

The diamond lemma is straightforward to establish if we require *unique input locations.*

Lemma 4.5 (Diamond Lemma) *For all* $p, q \in \mathcal{P}$, $\alpha \in \Lambda$ *and* $\bar{\beta} \in \bar{\Lambda}$, *the following holds:*
If $p \sim q$ *and* p *performs a diamond on* α *and* $\bar{\beta}$ *yielding* p_3, *also* q *can perform a diamond on* α *and* $\bar{\beta}$ *yielding some* q_3 *which is bisimilar to* p_3.

Yet, we do not only prove the existence of such a diamond, but show that the diamonds for p and q are bisimilar at every step.

Proof: If there is a diamond for p, then certainly there exists a diamond for q, as $p \xrightarrow{\alpha} p_1$ has to be simulated by some $q \xrightarrow{\alpha} q_1$ and for $p \xrightarrow{\bar{\beta}} p_2$ there has to be a transition $q \xrightarrow{\bar{\beta}} q_2$. By lemma 4.4 there exists some q_3 completing the diamond.
As both p and q bear unique input locations, by lemma 3.5 also p_1, p_2, q_1 and q_2 do. Hence, the only possibility for q to perform an α yields q_1, which therefore has to be bisimilar with p_1. Let q_2 be a $\bar{\beta}$-derivative of q s.t. $p_2 \sim q_2$. As q_2 bears unique input locations (see above), the only possibility for it to perform α is to enter q_3 which, again, has to be bisimilar with p_3. Hence, the only diamond on α and $\bar{\beta}$ existing yields q_3, i.e. by lemma 4.4 also $q_1 \xrightarrow{\bar{\beta}} q_3$. □

With this material, we are now able to prove the main result of this work.

Theorem 4.1 *For all* $p, q \in \mathcal{P}$ *bearing unique input locations and all substitutions* σ*: If* $p \sim q$ *then* $p\sigma \sim q\sigma$.

Proof: It suffices to show that, for any substitution σ, the relation $\mathcal{R}^{\sim}_{\sigma} \stackrel{\text{def}}{=} \{(p\sigma, q\sigma) \mid p \sim q\}$ is a strong bisimulation.
Let $p \sim q$. We presume a transition $p\sigma \xrightarrow{\mu} p'$ which has to be simulated by $q\sigma \xrightarrow{\mu} q'$ in such a way that $(p', q') \in \mathcal{R}^{\sim}_{\sigma}$. We proceed by a case study on μ:

- Visible transitions: $\mu \equiv \beta \in \mathcal{A}ct$.
  If $p\sigma \xrightarrow{\beta} p'$ then, by lemma 4.3, there exist α and p_1 s.t. $p \xrightarrow{\alpha} p_1$, $\beta \equiv \alpha\sigma$ and $p' \equiv p_1\sigma$. As $p \sim q$, by definition 2.1 there must exist some q_1 s.t. $q \xrightarrow{\alpha} q_1$ and $p_1 \sim q_1$. By lemma 4.2, $q\sigma \xrightarrow{\beta} q_1\sigma$. Hence, $(p', q') \in \mathcal{R}^{\sim}_{\sigma}$, where $p' \equiv p_1\sigma$ and $q' \stackrel{\text{def}}{=} q_1\sigma$.

- Invisible transitions: $\mu \equiv \tau$.
  Now let $p\sigma \xrightarrow{\tau} p'$. By lemma 4.3,

  - either $\exists p_1$ s.t. $p \xrightarrow{\tau} p_1$ and $p' \equiv p_1\sigma$, which is similar to the case of visible transitions.
  - or $\exists \alpha, \bar{\beta}, p_1, p_2, p_3$ s.t. $p \xrightarrow{\alpha} p_1 \xrightarrow{\bar{\beta}} p_3$, $p \xrightarrow{\bar{\beta}} p_2 \xrightarrow{\alpha} p_3$, $\alpha\sigma \equiv \beta\sigma$ and $p' \equiv_{\alpha} p_3\sigma$. As p and q are bisimilar, q must be able to imitate the α- and $\bar{\beta}$-transitions which p has performed. As $\alpha \not\equiv \bar{\beta}$, we know from lemma 4.5 that there exists an α-β-diamond for q, its tip $\tilde{q}_3$ being bisimilar with $\tilde{p}_3$. Clearly, $(\tilde{p}_3\sigma, \tilde{q}_3\sigma) \in \mathcal{R}^{\sim}_{\sigma}$. Furthermore, this diamond extends to $q\sigma \xrightarrow{\alpha\sigma} q_1\sigma \xrightarrow{\overline{\beta\sigma}} q_3\sigma$ and $q\sigma \xrightarrow{\overline{\beta\sigma}} q_2\sigma \xrightarrow{\alpha\sigma} q_3\sigma$. As $\alpha\sigma \equiv \beta\sigma$, we know from the second part of lemma 4.4 that $q\sigma \xrightarrow{\tau} q_3\sigma$.

- A symmetric argument holds for the transitions initiated by q. $\square$

5 Discussion

In this work, we have shown that for CCS-processes obeying certain restrictions, strong bisimilarity is a congruence wrt. substitution of names. As the exclusion of the summation operator does not yet fully suffice, we proposed unique input locations as a way of further reducing the set of processes. However, we conjecture that for *finite processes*, i.e. if we also omit recursion, this artificial construct would not be necessary.
Another approach would consist of applying equivalence relations which fulfill the diamond property by themselves, as do *local cause* or *global cause equivalence* for large subsets of CCS.
For weak bisimilations the diamond property does not hold. Although the process $\alpha.\beta.0 \mid \bar{\alpha}.0$, for instance, is capable of performing a weak transition both on α and β, the diamond can never be completed. Therefore, one would have to find a new notion of diamond property relying on the use of unique input locations.
As substitutions play a major role in *mobile calculi*, e.g. the π-calculus, it would

also be interesting to study how the results obtained here extend thereupon.

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