The $C_{\pi}$-calculus: a Model for Confidential Name Passing

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Sharing confidential information in distributed systems is a necessity in many applications, however, it opens the problem of controlling information sharing even among trusted parties. In this paper, we present a formal model in which dissemination of information is disabled at the level of the syntax in a direct way. We introduce a subcaluli of the $\pi$-calculus in which channels are considered as confidential information. The only difference with respect to the $\pi$-calculus is that channels once received cannot be forwarded later on. Another contribution of the model is that some privacy notions already studied in the past, such as group creation and name hiding, are directly representable without any additional language constructs. We also present an encoding of the $\pi$-calculus in our calculus.

1 Introduction

Sharing sensitive information over the internet has become an everyday routine: sending personal data and/or credit card number for online shopping is just one of the examples where the sensitive information can be dispensed to other parties. Such cases open the problem of controlling information sharing even among trusted parties. The problem of privacy can (and must) be perceived both from a legal and technological point of view. One of the first who explored privacy in the information age, a legal scholar, Alan Westin had recognized that “Building privacy controls into emerging technologies will require strong effort…” [14]. On the other hand, new technologies can also provide new ways to deal with privacy problems [12]. According to Solove [11], there are four types of privacy violation: invasions, information collection, information processing, and information dissemination (see also [6]). The focus of this paper will be on presenting the techniques for controlling information dissemination in distributed systems.

Although there is a further taxonomy for information dissemination violation by Solove, all these sub-types roughly speak about harms of revealing the personal data or threats of spreading information. In distributed systems where communication of entities is central, controlling the flow of confidential information poses some obstacles. The forwarding property, that makes it possible to disseminate received information, may be recognized as one problem in controlling such systems. As an example, let us consider the configuration already mentioned: a user sends the credit card number in order to complete the online shopping. In this case, the confidential information, the credit card number, is revealed to another party, but the intention is such that it should not be considered for later usages by the other party. In particular, the receiver should not forward the information.

Another aspect of the example with the credit card is that there is no predefined set of users that may receive the number. Indeed, it is highly unlikely that the owner of the credit card at any point of time knows all possible usages of the card in the future. Therefore, we may conclude that confidential information can also be shared in open-ended systems, where the set of users of the information cannot be statically predefined.

In this paper, we present a formal model in which dissemination of information is disabled at the level of the syntax in a direct way. We build on the $\pi$-calculus [10], a process model tailored for communication-centric systems, by introducing a sub-calculi which we call Confidential $\pi$-calculus, abbreviated $C_{\pi}$. The only information shared in our calculus are names of channels, so channels are the

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confidential information. This is the only difference of our model with respect to the \(\pi\)-calculus, names of channels are confidential and hence once received cannot be forwarded later on. Another contribution of the model is that some privacy notions already studied in the past, such as groups [1] and name hiding [3], are directly representable, without any additional language constructs. The paper presents initial results of the investigation of the model, formalization and verification of most of the results are left for an extended version of the paper.

The paper is organized as follows. In Section 2, we start by presenting the syntax and semantics of \(C_\pi\)-calculus, after which we define a behavioral equivalence relation, called strong bisimilarity. Using the definition of strong bisimilarity we state and prove the non-forwarding property of our calculus: a process that receives a channel cannot, later on, send the same channel. Another consequence of this property is the possibility of creating channels with similar behavior to CCS channels [8]. Section 3 presents some further informal insights on \(C_\pi\) and several interesting scenarios which are naturally represented in our model. Even though non-forwarding property restricts the expressivity of the \(\pi\)-calculus, in Section 4 we show the \(C_\pi\) is expressive enough to model the \(\pi\)-calculus. The base idea of the encoding is to create dedicated processes for each channel that handle sending the respective channels. In Section 5 we conclude and point to the related work.

## 2 Process Model

In this section, we present the syntax and semantics of \(C_\pi\). The main difference with respect to the \(\pi\)-calculus processes is that in \(C_\pi\) names received in an input cannot be later used as an object of an output, hence disallowing forwarding. Apart from this difference, the remainder of this section should come as no surprise to a reader familiar with the \(\pi\)-calculus. To make a clear distinction between names of variables bound in input and names of channels, we introduce two disjoint countable sets \(V\) and \(C\), where \(V\) is the set of variables, ranged over by \(x, y, z, \ldots\), and \(C\) is the set of channel names, ranged over by \(k, l, m, \ldots\). We denote with \(N\) the union of sets \(V\) and \(C\), and we let \(a, b, c, \ldots\) range over \(N\).

### Syntax.

Table 1 presents the syntax of the language. An inactive process is represented with 0. The prefixed process \(\pi . P\) comprehends process \(a!k. P\), which on name \(a\) sends channel \(k\) and then proceeds as \(P\), process \(a?x. P\) which on name \(a\) receives a channel and substitutes the received channel for \(x\) in \(P\), and the last prefix \([a = b] \pi . P\) which exhibits \(\pi . P\) only if \(a\) and \(b\) are the same name. Notice that in our language, unlike in the \(\pi\)-calculus, there is a syntactic distinction between objects of prefixes: only a channel can be sent and only a variable can be used as a placeholder for a channel to be received. Parallel composition \(P \mid P\) stands for two processes simultaneously active, that may interact. Channel restriction \((\nu k) P\) expresses that a new channel \(k\), known only to process \(P\), is created. Replicated process \(! P\) introduces an infinite behavior. Intuitively, consider \(! P\) stands for \(P \mid P \mid \cdots\).

In \((\nu k) P\) and \(a?x. P\), the channel \(k\) and the variable \(x\) are binding with scope \(P\). The set of bound names \(bn(P)\), for any process \(P\), is defined as the union of bound channels and bound variables in \(P\). The set of free names \(fn(P)\) and the set of names \(n(P)\), for any \(P\), are defined analogously.
some specific behavioral identities of our model. To this end, we introduce a behavioral equivalence,

\[
\begin{array}{ccc}
\text{(IN)} & \pi.P \to P' & \text{(MATCH)} & P \to P' & k \notin n(\alpha) \\
\text{(OUT)} & k!P \Rightarrow P & & [a = a]P \Rightarrow P' \\
\text{(PAR-L)} & P \Rightarrow Q & \text{bn(\alpha) \cap fn(R) = \emptyset} & & P \Rightarrow Q' \\
\text{(REP-ACT)} & P \Rightarrow P' & & P \Rightarrow P'' & (\nu l)P \Rightarrow Q \\
\text{(COMM-L)} & P \Rightarrow Q' & \text{\ and} & P \Rightarrow P'' & (\nu l)P \Rightarrow Q \\
\text{(RE-P-COMM)} & P \Rightarrow (P' \mid P'') & l \notin fn(Q) & P \Rightarrow (P' \mid P'') & (\nu l)P \Rightarrow Q \\
\text{(RE-P-CLOSE)} & P \Rightarrow P' & & P \Rightarrow P'' & l \notin fn(P) \\
\end{array}
\]

Table 2: LTS rules.

**Semantics.** We present an operational semantics for our model in terms of the labeled transition system, which build on observable labeled actions \( \alpha \), defined as

\[
\alpha ::= \ k!l \mid k?l \mid (\nu l)k!l \mid \tau
\]

Action \( k!l \) sends the channel \( l \) on the channel \( k \), while \( k?l \) receives the channel \( l \) on channel \( k \). In action \( (\nu l)k!l \) the sent channel \( l \) is bound, and \( \tau \) stands for internal action. Notice that, as in the \( \pi \)-calculus, names bound in input (variables) cannot appear in labels of observable actions. To retain the same notation as for processes, we denote by \( \text{fn}(\alpha) \), \( \text{bn}(\alpha) \) and \( n(\alpha) \), the sets of free, bound and all names of observable \( \alpha \), respectively. As we noted above, these sets contain only channels, and not variables.

The transition relation is defined inductively by the rules given in Table 2. The symmetric rules for \( \text{(PAR-L)} \), \( \text{(COMM-L)} \) and \( \text{(CLOSE-L)} \) are elided from the table. Rules \((\text{OUT})\), \((\text{IN})\) and \((\text{MATCH})\) are consistent with the explanations of the corresponding syntactic constructs. Rule \((\text{RES})\) ensures that the action of the process is the action of the process scoped over by name restriction if the name specified in restriction is not mentioned in the action. Rule \((\text{OPEN})\) opens the scope of the restricted channel, enabling the extrusion of its scope while ensuring that subject and the object of the action are different channels. Rule \((\text{PAR-L})\) lifts the action of one of the branches, and the side condition ensures that the channel bound in the action is not specified as free in the other branch. In rule \((\text{COMM-L})\) two processes performing dual actions, one sending and other receiving \( l \) along \( k \), synchronize their actions in the respective parallel composition. In rule \((\text{CLOSE-L})\) the channel sent \( (l) \) by the left process is bound and after the synchronization with the right process (performing the dual action), the scope of \( l \) is closed while avoiding unintended name capture. Rules \((\text{REP-ACT})\), \((\text{REP-COMM})\) and \((\text{REP-CLOSE})\) describe the actions of a replicated process. The first rule lifts the action of a single copy of the replicated process and activates \( !P \) in parallel. The second and the third rules show cases when two copies of replicated process synchronize their actions, either through communicating a free or bound channel, where, again, in both cases a copy of \( !P \) is activated in parallel.

**Behavioral equivalence.** Based on the notion of observable actions, introduced above, we investigate some specific behavioral identities of our model. To this end, we introduce a behavioral equivalence,
called strong bisimulation, which, colloquially speaking, relates two processes if one can play a symmetric game over them: each action of one process can be mimicked by the other (and with the order reversed), leading to two processes that are again related. The relation that we are interested in is the largest such relation, called strong bisimilarity.

**Definition 1 (Strong bisimilarity)** The largest symmetric binary relation over processes $\sim$, satisfying

$$
\text{if } P \sim Q \text{ and } P \xrightarrow{\alpha} P', \text{ where } \text{bn}(\alpha) \cap \text{fn}(Q) = \emptyset, \text{ then } Q \xrightarrow{\alpha} Q' \text{ and } P' \sim Q',
$$

for some process $Q'$, is called strong bisimilarity.

One consequence of the non-forwarding property of our calculus is the possibility of the creation of static channels. A property, resembling the secure channels that cannot be leaked, can be formally stated and verified using the definition of strong bisimilarity.

**Proposition 1** For any process $P$, channel $m$ and prefix $\pi$, the following equality holds

$$(\nu k)((\nu l)k!l.m?y.[y = l]! \pi.0 | k?x.P) \sim (\nu k)((\nu l)k!l.m?y.0 | k?x.P)$$

**Proof.** The proof follows by coinduction on the definition of the strong bisimulation (see Appendix A).

In both processes in Proposition 1 the left thread creates a new channel $l$ and sends it over a (private) channel $k$ to the right thread. The equality states that then the channel $l$ cannot be received afterward in the left thread. This is due to the fact that the right thread cannot forward received channels. The interpretation of this proposition can be twofold. On one hand, the right thread after receiving a fresh channel ($l$) cannot send the received channel, which we call the non-forwarding property. On the other hand, the left thread sends the fresh channel (to the right thread) only once and the channel afterward behaves “statically”, since then it cannot be sent by any process. Further explanation is given in the next section.

### 3 Examples

In this section, we further investigate some interesting scenarios representable in $C_\pi$. Since a process in our calculus can learn new names but cannot gain the capability to send such names, we may distinguish two levels of channel ownership of a process that are invariant to the process evolution:

- **administrator**: the process that can communicate along the channel and can send it;
- **user**: the process that learns the channel name through communication (scope extrusion) and can communicate along the channel but cannot send it.

One specific scenario is when the channel administrator creates a channel and evolves to an inactive process. For example, let us consider process

$$(\nu k)((\nu l)k!l.0 | k?x.P)$$

where the left branch creates the channel $l$, sends it to the right branch and then terminates. The right branch receives the name, after which the two actions synchronize and the starting process silently evolves to $(\nu k)(\nu l)(0 | P\{l/x\})$. As we have shown in Proposition 1, process (and any its sub-process) $P\{l/x\}$ cannot perform output with object $l$, since channel $l$ was not originally created by process $P$. For this property we can state that name $l$ will never leak out of the scope of $P$, hence that all communications along channel $l$ are private to process $P$. Also, we may observe that channel $l$ in process $(\nu k)(\nu l)(0 | P\{l/x\})$ has a static behavior, similar to CCS-like channels.
3.1 Authentication

Another consequence of distinguishing two types of processes as channel owners is that we may test a process to check whether the process is an administrator for some channel. As an example consider two processes running in parallel:

\[ k!l.\pi.P \mid k?x.[x = l]k!l.Q \]

where, before activating processes \( \pi.P \) and \( Q \) and their possible interactions, both processes test whether each of them is an administrator for channel \( l \). Namely, after the first synchronization, the left process matches the received channel with \( l \), i.e., we obtain configuration \( k?y.[y = l]\pi.P \mid [l = l]k!l.Q\{l/x\} \). If the channel received is \( l \), then the right process concludes that the left process is an administrator for the name and sends the same channel back to the left process. Then, the left process also matches the received name with \( l \), and continues only if the two names match, leading to \([l = l]\pi.P\{l/x\} \mid Q\{l/x\}\).

3.2 Modelling groups

Going back to the first example of this section, recall we concluded that a channel once sent and having the inactive process as the administrator may be used for secure communications in the process that has received the channel. This constellation resembles the group creation of the \( \pi \)-calculus with groups \([1]\), by Cardelli et al. The similarity is that in the \( \pi \)-calculus with groups, a channel declared as a member of a group cannot be acquired as a result of communication by the process outside the scope of the group. The major difference is that in our example the channel behaves as CCS-like channel, i.e., a channel cannot be acquired as a result of communication by any process. This brings us to our next example, that combines channel declaration and authentication, presented in Section [3.1]. Consider that for a given channel, we want to statically determine a boundary for the possible channel extrusion, the part of the process we shall call a group. In that case, we may conclude that only members of the group should be able to receive the given channel. As a concrete example consider process

\[ (vg_l)((vl)P \mid Q) \]

where by \( g_l \) we denote that the scope of channel \( g_l \) determines the group for channel \( l \). Now, to make sure that channel \( l \), whose administrator is process \( P \), is sent only to processes scoped over with \( g_l \), before each sending of channel \( l \), we must make sure that the receiver is an administrator for channel \( g_l \). Hence, instead of construct \( k!l \) in \( P \), we would use

\[ (vn)k!n.n?x.[x = g_l]n!l \]

where first a private session with the process willing to receive \( l \) is established through channel \( n \), and then the channel received on \( n \) is matched with \( g_l \). Only if the name received on \( n \) is \( g_l \), i.e., after the other process has proved that it is a member of the group, channel \( l \) is sent.

3.3 Open-ended groups

Groups described in the previous example provide an interesting framework to investigate sharing protected resources in distributed environments but has the limitation that a group, once created, always has a fixed scope, which sometimes might be considered too restrictive. Considering examples involving sharing credit card number for online shopping or joining new members to a group in social networks,
one may notice that it is highly unlikely to have a predefined set of potential users of such resources. In \( C_{\pi} \) such scenarios are directly modeled, since sending a resource in \( C_{\pi} \) does not transmit the capability for its further dissemination. For example, in \((v\text{group})!\text{group}.P\) the administrator of \text{group}, that is the process that creates the group, can send the name of the group to other processes, while the receiving process only becomes a user of the group and does not gain the capability to invite new members to the group.

### 4 Encoding Uncontrolled Name Passing

In this section, we show how to model forwarding in \( C_{\pi} \), as in the standard \( \pi \)-calculus. We start by presenting the basic idea, which we later formalize by means of an encoding.

Throughout this section, we use the polyadic version of our calculus. This enables us to formalize our ideas in a more crisp way, but notice that, as in the \( \pi \)-calculus, each polyadic communication \( k!(l_1,\ldots,l_n).0 \mid k?x_1,\ldots,x_n).0 \) can be represented by the monadic

\[
(\nu n)k!n.n!l_1,\ldots,n!l_n.0 \mid k?y.y?x_1,\ldots,y?x_n.0
\]

In the \( \pi \)-calculus, there is no syntactic restriction on names that can appear as objects of output prefixes, a process like \( a?x.c!x.P \mid ab.Q \) is admissible. One way to represent this process in \( C_{\pi} \) is to:

- create a special process dedicated for (repeatedly) sending channel \( b \), called handler of the channel,
- while sending channel \( b \) also send a channel dedicated for communicating with the handler, and
- bypass sending of the received channel to the handler process.

Hence, we may try to represent the \( \pi \)-calculus process introduced above as

\[
a?x_1,x_2).x_2!c.P \mid a!(b,m_b).Q \mid m_b?y.y!(b,m_b).0
\]

where the process in the middle now sends \( b \) together with channel \( m_b \) dedicated for communicating with the handler process (the rightmost one), and the leftmost process receives both channels and instead of sending \( b \) along \( c \) it sends \( c \) to the handler along \( m_b \). The handler process receives \( c \) and sends \( b \) (again, together with \( m_b \)) along the received channel, in such way mimicking forwarding. Such representation does not work in the case when the leftmost process is not an administrator for channel \( c \), since then it cannot send \( c \) to the handler process. To this end, we must refine our representation of forwarding to support situations when processes are potentially not administrators for any given channel. Thus, we introduce another type of handler processes which are in charge of forwarding channels that are subjects of output actions. For example, the process above would be represented as

\[
a?x_1,x_2).\langle v e \rangle n_e!e.x_2!e.P \mid a!(b,m_b).Q \mid m_b?y.y?z.z!(b,m_b).0 \mid n_e?y.y!c.0
\]

where we added the rightmost thread, which is the handler process of channel \( c \), used to bypass sending of channel \( c \) in the leftmost thread. Now the communication in this process goes as follows: first, the two leftmost threads synchronize on name \( a \) (as in previous examples), leading to

\[
\langle v e \rangle n_e!e.m_b!e.P \mid Q \mid m_b?y.y?z.z!(b,m_b).0 \mid n_e?y.y!c.0
\]

where the name \( x_2 \) is instantiated with handler name \( m_b \) (eliding from substitutions in process \( P \)). Then, instead of sending \( b \) on \( c \), the new channel \( e \) is created and sent to the handlers of \( b \) and \( c \)

\[
\langle v e \rangle(P \mid Q \mid e?z.z!(b,m_b).0 \mid e!c.0)
\]
enabling handler of name \(c\) to send \(c\) to the handler of name \(b\), leading to \((ve)(P | Q | c!(b,m_b)0 | 0)\)
where sending \(b\) (together with the handling name \(m_b\)) on name \(c\) is finally activated.

Notice that (1) since each name can be sent infinitely many times each handling process must be 
repeatedly available for communication and (2) that each name can be used either as a subject or as an 
object of output action, and hence that for each name we need both types of handlers: one as for name \(b\) 
and the other as for name \(c\) in the last example.

An encoding of closed \(\pi\)-calculus processes \([10]\) into \(C_\pi\) processes is presented in Table 3. The 
encoding is parameterized by a partial function \(\sigma\) which maps names to pairs of names. This mapping 
performs an association of a channel with channels dedicated to its handler processes and an association 
of a placeholder variable with placeholders for the respective handler channels. The process scoped 
with channel restriction operator is encoded as a scope specifying the three channels, the original one \(a\) 
and, \(n\) and \(m\) dedicated for communication with the handler processes. We use \((va,n,m)\) to abbreviate 
\((va)(vn)(vm)\). The continuation process \(P\) is encoded, using \(\sigma\) extended with the association of \(a\) with 
\(n\) and \(m\) in parallel with two handler processes: one associated to channel \(n\) to bypass sending channel \(a\) 
when used as a subject of an output action and other associated to channel \(m\) to bypass sending channel 
\(a\) (together with \(n\) and \(m\)) when used as an object of an output action.

The encoding of the output process relies on an association defined in the parameter function since it 
creates a fresh channel \(e\) and sends its one end to the first handler process of name \(a\) (the subject of the 
output) and the other end to the second handler process of name \(b\) (the object of the output). The 
side condition ensures that the only possible actions on channel \(e\) are the actions of the two handling 
processes. The synchronization of these actions leads to sending of name \(b\) (together with channels of 
handlers) along name \(a\) by the second handler of name \(b\) (as explained in the example above). The 
input process is encoded as the input of three channels, and the respective association is added to \(\sigma\) 
in the encoding of the continuation process so that the encoding of process \(P\) can refer to introduced 
variables \(n\) and \(m\). The encoding is a homomorphism elsewhere, e.g., \([P_1 | P_2]_\sigma = [P_1]_\sigma | [P_2]_\sigma\), and 
hence we omit such cases. The only exception is the encoding of the output matched prefixed process 
\([c_1 = d_1] \ldots [c_n = d_n] [a!b.P]_\sigma\) for which the encoding is \((ve) [c_1 = d_1] \ldots [c_n = d_n] [n_1!e.m_2!e.P]_\sigma\), where 
\(\sigma = \sigma_1, \{a \rightarrow (n_1,m_1), b \rightarrow (n_2,m_2)\}\). The restriction operator must be introduced before matching since 
matched prefix is a single language construct (as it is presented for the \(\pi\)-calculus in \([10]\)).

The restriction of encoding only closed \(\pi\)-calculus processes, coming from the fact that in the en-
coding of an output process the handler processes for both names must be already introduced, can be 
overcome by defining an encoding in two layers. The first step for the top level process in which we 
would introduce handlers for all free names of the process, and in the second step consider the encoding 
presented in Table 3. We leave such improvements of the encoding and verifying its correctness (e.g., 
soundness and completeness) for the future work, but our preliminary investigation of soundness allows 
us to be confident about such a result.
The notion of secrecy has been studied intensively in process calculi in the past and the variety of techniques has been proposed. The most related to our work are process models building on the $\pi$-calculus, such as [1, 2, 6, 4, 13].

Cardelli et al. [1] introduce a language construct for group creation and a typing discipline, where a group is the type for a channel. The group creation construct blocks communications of channels that are declared as members of the group outside the initial scope of the group, hence preventing the leakage of protected channels. Kouzapas and Philippou [6] extend the model of $\pi$-calculus with groups by constructs that allow reasoning about the private data in information systems. The work of Giunti et al. [3] introduces an operator called hide which binds a name and has a similar behavior as a name restriction, but in contrast to name restriction it blocks a name extrusion, for which the scope of the hide operator forms a kind of a group that the “hidden” name cannot exit. The paper by Vivas and Yoshida [13] introduces an operator called filter that is statically associated to a process and blocks all actions of the process along names that are not contained in the (polarized) filter. We also mention [4, 2] where the types associate the security levels to channels, where, in the latter work downgrading the security level of a channel is admissible and it is achieved by introducing special, so-called, declassified input and output prefix constructs. All above approaches share the property that, when building on the $\pi$-calculus model, additional language construct and/or a typing discipline is introduced in order to represent some specific aspect of secrecy in a dedicated way. We believe that $C_\pi$-calculus appears to be more suitable as an underlying theory when studying secrecy, and as such that many aspects of secrecy can be represented in a more crisp way. As a first step, we plan to make a precise representation of group creation [11] in the $C_\pi$-calculus, following the intuition provided in Section 3.2.

Several fragments of the $\pi$-calculus have been used in different ways and for different purposes. The asynchronous $\pi$-calculus [5], proposed by Honda and Takoro, constrains the syntax by allowing only an inactive process to be the continuation of the output prefix, in this way modeling asynchronous communications. The Localised $\pi$-calculus [7], proposed by Merro and Sangiorgi, disallows the input capability for the received names and does not consider the matching operator. There, the syntactic restriction is that input placeholder cannot appear as a subject of an input, but, in contrast to our work, the forwarding of names is allowed. The Private $\pi$-calculus [9], proposed by Sangiorgi, makes the restriction that objects of output prefixes are always considered as bound, making the symmetry with the input prefixes. Although in Private $\pi$-calculus the forwarding of names is not possible, it differs significantly from our work in the restriction that one name can be sent only once.

In this paper, we have presented Confidential $\pi$-calculus, a fragment of the $\pi$-calculus [10] in which the forwarding of received names is disabled at the syntax level. To the best of our knowledge, this is the first process model based on the $\pi$-calculus that represents the controlled name passing by constraining and not extending the original syntax. An initial investigation of the behavioral semantics of our model is given and the property that a fresh name received by a process cannot be later on sent by the same process is attested. Examples presented in the paper already give some intuition on scenarios directly representable in $C_\pi$, such as authentication and group modeling, and a complete formalization of these ideas is left for future work. The encoding presented here shows that our model is as expressive as the $\pi$-calculus, while the formal verification of the correctness of the encoding is left for future work.

Acknowledgments. The author would like to thank Hugo Torres Vieira for supervising the work presented here and a great help, to Jovanka Pantović for suggestions and comments on the paper, and to Daniel Hirschkoff for valuable email discussions. This work has been partially supported by the Ministry of Education and Science of the Republic of Serbia, project ON174026.
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A Proof of Proposition 1

Notation: In the proof of Proposition 1 we use fo(P) to denote the set of all free channels appearing as an object of output prefixes in process P.
Proposition[1] For any process $P$, channel $m$ and prefix $\pi$, next equality holds
\[(vk)((vl)k!l.m?y.[y = l]\pi.0 | k?x.P) \sim (vk)((vl)k!l.m?y.0 | k?x.P)\].

Proof. The proof follows by coinduction, by showing that the relation
\[\mathcal{R} = \{( (vk)((vl)k!l.m?y.[y = l]\pi.0 | k?x.P), (vk)((vl)k!l.m?y.0 | k?x.P) \},
\{(vk)(vl)(m?y.[y = l]\pi.0 | Q), (vk)(vl)(m?y.0 | Q) \},
\{(vl)(m?y.[y = l]\pi.0 | Q), (vl)(m?y.0 | Q) \},
\{(vl)(vl)([n = l]\pi.0 | Q), (vl)(vl)(0 | Q) \},
\{(vl)(vl)([n = l]\pi.0 | Q), (vl)(vl)(vn)(0 | Q) \} \}

for all $n, m \in C$, such that $n \neq l$, and all processes $P$ and $Q$, such that $l \notin \text{fo}(Q)$

where $n \neq l$, is contained in the strong bisimilarity, i.e., $\mathcal{R} \subseteq \sim$.

We show that each action of one process can be mimicked by the other process in the pair in $\mathcal{R}$, leading to processes that are again in relation $\mathcal{R}$. Let the process in the first pair
\[(vk)((vl)k!l.m?y.[y = l]\pi.0 | k?x.P) \xrightarrow{\alpha} P'. \]

Then, since actions of the starting process can only be actions of its two branches, we conclude that either $\alpha = (vl)k!l$ or $\alpha = k?n$ or it is the synchronization of these two actions, in which case $\alpha = \tau$. We reject the first two options, since the subject of the action is bound in the starting process and by rule (RES) it cannot be observed outside of the process. Hence, we conclude $\alpha = \tau$ and $P' = (vk)(vl)(m?y.[y = l]\pi.0 | P[l/x])$. Then, by applying (OUT), (OPEN), (IN), (CLOSE-L) and (RES), respectively, we get
\[(vk)((vl)k!l.m?y.0 | k?x.P) \xrightarrow{\tau} (vk)(vl)(m?y.0 | P[l/x]), \]

and since $l \notin \text{fn}(P)$ and $x$ cannot appear as an object in the prefixes in $P$ we conclude $l \notin \text{fo}(P[l/x])$. Hence, we have \((vk)(vl)(m?y.[y = l]\pi.0 | P[l/x]), (vk)(vl)(m?y.0 | P[l/x]) \) \in $\mathcal{R}$. The symmetric case is analogous.

Now let us consider processes in the second pair of $\mathcal{R}$. If
\[(vk)(vl)(m?y.[y = l]\pi.0 | Q) \xrightarrow{\alpha} P', \]

then observable $\alpha$ can originate from both of the branches or from their synchronization.

—Left branch: If the observable originate from the left branch, then $\alpha = m?n$, and by (IN), (PAR-L) and (RES) we get
\[(vk)(vl)(m?y.[y = l]\pi.0 | Q) \xrightarrow{m?n} (vk)(vl)([n = l]\pi.0 | Q), \]

where, by the side condition of (RES) we conclude $n \notin \{k, l\}$. In the same way we get
\[(vk)(vl)(m?y.0 | Q) \xrightarrow{m?n} (vk)(vl)(0 | Q), \]

and $(vk)(vl)([n = l]\pi.0 | Q), (vk)(vl)(0 | Q) \in \mathcal{R}$ holds.

—Right branch: If the action originates from the right branch, i.e., from $Q \xrightarrow{\alpha} Q'$, we distinguish two cases:
(i) if by rules (par-r) and (res) is derived
\[(vl)(m?y.[y = l]π.0 | Q) \xrightarrow{(vk)} (vl)(m?y.[y = l]π.0 | Q'),\]
where we conclude that \(k, l \notin n(α)\), hence \(l \notin fo(Q')\). Then by the same rules we get
\[(vl)(m?y.0 | Q) \xrightarrow{(vk)} (vl)(m?y.0 | Q'),\]
and \(((vl)(m?y.[n = l]π.0 | Q'), (vl)(m?y.0 | Q')) \in \mathcal{R}\) holds.

(ii) if by rules (par-r), (res) and (open) is derived
\[(vk)(vl)(m?y.[y = l]π.0 | Q) \xrightarrow{(vk)} (vl)(m?y.[y = l]π.0 | Q'),\]
then \(l \notin n(α)\). Notice that the scope of channel \(l\) cannot be extruded this way since \(l \notin fo(Q)\).
Hence, process \(Q\) cannot perform output action with object \(l\). Then by the same rules we get
\[(vk)(vl)(m?y.0 | Q) \xrightarrow{(vk)} (vl)(m?y.0 | Q'),\]
and, again, \(((vl)(m?y.[n = l]π.0 | Q'), (vl)(m?y.0 | Q')) \in \mathcal{R}\) holds.

Notice that for any process \(P\), if \(P \xrightarrow{α} P'\) and \(l \notin fo(P)\), we can show that \(l \notin fo(P')\), for any possible action \(α\).

---Synchronization of branches: We again distinguish two cases:

(i) if from
\[m?y.[y = l]π.0 \xrightarrow{m^n} [n = l]π.0 \quad \text{and} \quad Q \xrightarrow{m^n} Q',\]
where we can make the same observation on \(Q\) as before to conclude that \(l \neq n\), by rules (comm-r) and (res) is derived
\[(vk)(vl)(m?y.[y = l]π.0 | Q) \xrightarrow{r} (vk)(vl)([n = l]π.0 | Q').\]
Then, using \(m?y.0 \xrightarrow{m^n} 0\), and the same rules as above we get
\[(vk)(vl)(m?y.0 | Q) \xrightarrow{r} (vk)(vl)(0 | Q'),\]
and we get \(((vk)(vl)([n = l]π.0 | Q'), (vk)(vl)(0 | Q')) \in \mathcal{R}\).

(ii) if from
\[m?y.[y = l]π.0 \xrightarrow{m^n} [n = l]π.0 \quad \text{and} \quad Q \xrightarrow{(vn)m^n} Q',\]
where as before we can assume \(l \neq n\), by rules (close-r) and (res) is derived
\[(vk)(vl)(m?y.[y = l]π.0 | Q) \xrightarrow{r} (vk)(vl)(vn)([n = l]π.0 | Q'),\]
then using \(m?y.0 \xrightarrow{m^n} 0\), we may observe
\[(vk)(vl)(m?y.0 | P) \xrightarrow{r} (vk)(vl)(vn)(0 | Q'),\]
and \(((vk)(vl)(vn)([n = l]π.0 | Q'), (vk)(vl)(vn)(0 | Q')) \in \mathcal{R}\).

The symmetric cases and the rest of the pairs from \(\mathcal{R}\) are analogous. For the rest of the pairs note that in all left branch of the first components we have \([n = l]π.0\), where \(n \neq l\), and hence, its observational power is equivalent to the observational power of inactive process 0 appearing as the left branch in the right components.