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On the Representation of References in the π -calculus

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Abstract

The π -calculus has been advocated as a model to interpret, and give semantics to, languages with higher-order features. Often these languages make use of forms of references (and hence viewing a store as set of references). While translations of references in π -calculi (and CCS) have appeared, the precision of such translations has not been fully investigated. In this paper we address this issue.

We focus on the asynchronous π -calculus ($A\pi$), where translations of references are simpler. We first define π^{ref} , an extension of $A\pi$ with references and operators to manipulate them, and illustrate examples of the subtleties of behavioural equivalence in π^{ref} . We then consider a translation of π^{ref} into $A\pi$. References of π^{ref} are mapped onto names of $A\pi$ belonging to a dedicated "reference" type. We show how the presence of reference names affects the definition of barbed congruence. We establish full abstraction of the translation w.r.t. barbed congruence and barbed equivalence in the two calculi. We investigate proof techniques for barbed equivalence in $A\pi$, based on two forms of labelled bisimilarities. For one bisimilarity we derive both soundness and completeness; for another, more efficient and involving an inductive 'game' on reference names, we derive soundness, leaving completeness open. Finally, we discuss examples of uses of the bisimilarities.

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1 Introduction

The π -calculus has been advocated as a model to interpret, and give semantics to, languages with higher-order features. Often these languages make use of forms of references (and hence viewing a store as set of references). This therefore requires representations of references using the names of the π -calculus. There are strong similarities between the names of the π -calculus and the references of imperative languages. This is evident in the denotational semantics of these languages: the mathematical techniques employed in modelling the π -calculus (e.g., [25, 6]) were originally developed for the semantic description of references. Yet names and references behave rather differently: receiving from a name is destructive —it consumes a value —whereas reading from a reference is not; a reference has a unique location, whereas a name may be used by several processes both in input and in output; etc. These differences



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45 make it unclear if and how interesting properties of imperative languages can be proved via
 46 a translation into the π -calculus.

47 A subset of the π -calculus that often appears in the literature, for its expressive power
 48 and elegant theory, is the Asynchronous π -calculus ($A\pi$). $A\pi$ allows one to provide a simpler
 49 representation of references, where a reference ℓ storing a value n is just an output message
 50 $\bar{\ell}\langle n \rangle$ (in $A\pi$ output is not a prefix, hence it has no process continuation). A process that
 51 wishes to access the reference is supposed to make an input at ℓ and then immediately emit
 52 a message at ℓ with the new content of the reference. For instance a process reading on the
 53 reference and binding its content to x in the continuation P is

$$\ell(x).(\bar{\ell}\langle x \rangle \mid P) .$$

54 Another reason that makes this representation of references in $A\pi$ interesting is the bisimilarity
 55 of $A\pi$, called *asynchronous bisimilarity*. It differs from standard bisimilarity in the input
 56 clause, in which a transition $P \xrightarrow{n\langle m \rangle} P'$ (where P is receiving m on n) can be answered by
 57 a bisimilar process Q thus:

$$\bar{n}\langle m \rangle \mid Q \Rightarrow Q' \quad (*)$$

58 (provided P' and Q' are bisimilar), where \Rightarrow stands for zero or several internal communication
 59 steps. Intuitively, Q does not necessarily perform an input on n in response to the transition
 60 done by P . To see why this clause could be interesting with references, consider a process
 61 that performs a *useless read* on a reference ℓ and then continues as P_2 ; in a language with
 62 references this would be equivalent to P_2 itself. When written in $A\pi$, the process with the
 63 useless read becomes $P_1 \stackrel{\text{def}}{=} \ell(x).(\bar{\ell}\langle x \rangle \mid P_2)$ where x does not appear in P_2 . In ordinary
 64 bisimilarity, P_1 is immediately distinguished from P_2 , as the latter cannot answer the input
 65 transition $P_1 \xrightarrow{\ell\langle n \rangle} \bar{\ell}\langle n \rangle \mid P_2$. However, the answer is possible using the clause (*), as we have

$$\bar{\ell}\langle n \rangle \mid P_2 \Rightarrow \bar{\ell}\langle n \rangle \mid P_2 .$$

67 We are not aware of studies that investigate the faithfulness of the above representation
 68 of references in $A\pi$. In this paper we address this issue. For this, we first define π^{ref} , an
 69 extension of $A\pi$ with references and operators to manipulate them. We then consider a
 70 translation of π^{ref} into $A\pi$ and:

71 we study the properties of this translation;

72 we establish proof techniques on $A\pi$ to reason about references.

73 The calculus with references, π^{ref} , has constructs for reading from a reference, writing
 74 on a reference, and a swap operation for atomically reading on a reference and placing a
 75 new value onto it. Modern computer architectures offer hardware instructions similar to
 76 swap, e.g., test-and-set, or control-and-swap constructs to atomically check and modify the
 77 content of a register. These constructs are important to tame the access to shared resources.
 78 In distributed systems, swap can be used to solve the consensus problem with two parallel
 79 processes, whereas simple registers cannot [8].

80 The swap construct is also suggested by the translation of references into $A\pi$. The pattern
 81 for accessing a reference ℓ is $\ell(x).(\bar{\ell}\langle n \rangle \mid P)$. This yields four cases, depending on whether x
 82 is used in P

83 and whether x is equal to n :

| | | |
|---------------------|------------|--------------|
| | $n \neq x$ | $n = x$ |
| x free in P | swap | read |
| x not free in P | write | useless read |

84

85 We define a type system in $A\pi$ to capture the intended pattern of usage of names that
 86 represent references, called *reference names*, in particular the property that there is always
 87 a unique output message available at these names. The type system has linearity features
 88 similar to π -calculus type systems for locks [13] or for receptiveness [22].

89 Imposing a type system has consequences on behavioural equivalences. Since the set
 90 of legal contexts becomes smaller, the behavioural equivalence itself becomes coarser. For
 91 instance, in the case of reference names, a process P is supposed to be tested only in a
 92 context that guarantees that all references mentioned in P are ‘allocated’ (thus, an input
 93 at a reference name ℓ is never ‘stuck’, as an output message at ℓ must always exist). A
 94 consequence of these is a read in which the value read is not used is irrelevant (see formally
 95 law (1)).

96 In both calculi, as behavioural equivalence we use *barbed congruence* and *barbed equivalence*.
 97 These equivalences equate processes which, roughly, in all contexts give rise to ‘matching
 98 reductions’.

99 We establish an operational correspondence between the behaviour of a process in π^{ref} and
 100 its encoding in $A\pi$, and from this we establish full abstraction of the translation of π^{ref}
 101 into $A\pi$ with respect to both barbed equivalence and barbed congruence in the two calculi.
 102 We then investigate proof techniques for barbed equivalence in $A\pi$, based on two forms of
 103 labelled bisimilarities. For one bisimilarity we derive both soundness and completeness. This
 104 bisimilarity is similar to, but not the same as, asynchronous bisimilarity. For instance, it
 105 is defined on ‘reference-closed’ processes (intuitively, processes in which all references are
 106 allocated); therefore inputs on reference names from the tested processes are not visible
 107 (because such inputs are supposed to consume the unique output message at that reference
 108 that is present in the tested processes). The output clause of bisimilarity on reference names
 109 is also different, as we have to make sure that the observer respects the pattern of usage for
 110 reference names; thus the observer consuming the output message on a reference name ℓ
 111 should immediately re-install an output on ℓ .

112 The second bisimilarity is more efficient because it does not require processes to be
 113 ‘reference-closed’. Thus output messages on reference names consumed by the observer need
 114 not be immediately re-installed. However sometimes access to a certain reference is needed
 115 by a process in order to answer the bisimulation challenge from the other process. And
 116 depending on the content of such references, further accesses to other references may be
 117 needed. Since we wish to add only the needed references, this introduces an inductive game, in
 118 which a player requires a reference and the other player specifies the content of such reference,
 119 within the coinductive game of bisimulation. We show that the resulting bisimilarity is sound,
 120 and leave completeness as an open problem. Finally, we discuss examples of uses of the
 121 bisimilarities.

122 **Related Work.** The classic encoding of references in the π -calculus [16] follows their encoding
 123 into CCS [15]: a reference is a stateful recursive process, which may be interrogated using two
 124 names, one for read operations, the other for write operations. Properties of this encoding
 125 have been explored [20], comparing the π -calculus to *Concurrent Idealised Algol* [3], an
 126 extension of Idealised Algol [19] with shared variables concurrency. The encoding has been
 127 shown to be sound but not complete.

128 Many works have studied the effect of type systems on behavioural equivalence, formalised
 129 using both barbed congruence and labelled bisimilarity. (See the references in the books [24,
 130 7]). To our knowledge, no such study has been done regarding the discipline for reference
 131 names which we use in this work. This discipline bears similarities with receptiveness [22],

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132 which is also related to the results in [23, 14]. We can also remark that our notion of complete
 133 processes is reminiscent of the notion of catalysers used by Dezani et al. [5] in session types
 134 to enforce progress.

135 Section 5 discusses further related work.

136 **Paper outline.** In Section 2, we introduce π^{ref} and discuss examples of behavioural equiv-
 137 alences between π^{ref} processes. In Section 3 we present $A\pi$ with reference names, using a
 138 type system that captures the usage of such names. We show the encoding of π^{ref} into such
 139 $A\pi$ and prove its full abstraction for barbed equivalence and congruence. In Section 4 we
 140 introduce the two new labelled bisimilarities for $A\pi$, we establish soundness and completeness
 141 for one and soundness for the other (we conjecture that also completeness holds), and present
 142 a useful ‘up-to’ technique for the second one. Finally we illustrate the benefits of using the
 143 proof techniques based on the labelled bisimilarities of $A\pi$ on some examples.

144 The proofs of most of the results in this work are presented in a full version of this
 145 paper [9].

2 Asynchronous Processes Accessing References: π^{ref}

147 In this section, we introduce π^{ref} , the asynchronous π -calculus extended with primitives to
 148 interact with memory locations.

2.1 Syntax and Semantics

150 We assume an infinite set **Names** of *names* and a distinct infinite set **Refs** of *references*.
 151 These sets do not contain the special symbol \star , that stands for the constant “unit”. We use
 152 $a, b, c, \dots, p, q, \dots$ to range over **Names**; ℓ, \dots to range over **Refs**; and n, m, \dots, x, y, \dots to
 153 range over $\text{All} \stackrel{\text{def}}{=} \text{Names} \cup \text{Refs} \cup \{\star\}$. The grammar for the calculus π^{ref} is the following; for
 154 simplicity, we develop our theory on the monadic calculus (one value at a time is handled).

$$155 \quad P ::= \mathbf{0} \mid a(x).P \mid \bar{a}\langle n \rangle \mid !P \mid P_1 \mid P_2 \mid (\nu a)P \mid [n = m]P$$

$$156 \quad \mid (\nu \ell = n)P \mid \ell \triangleleft n.P \mid \ell \triangleright (x).P \mid \ell \bowtie n(x).P$$

158 The operators in the first line are the standard π -calculus constructs for the inactive
 159 process, input, asynchronous output, replication, parallel composition, name restriction, and
 160 matching (however matching here is defined on both names and references). In the second
 161 line, we find the operators to handle references: reference restriction, or allocation (creating
 162 a new reference ℓ with initial value n), write (setting the content of ℓ to n), read (reading in
 163 x the value of ℓ), swap (atomically reading on x and replacing the content of the reference
 164 with n).

165 As usual, we often omit $\mathbf{0}$, and abbreviate $\bar{a}\langle \star \rangle$ as \bar{a} (and similarly for inputs $a.P$). We
 166 use a tilde, $\tilde{\cdot}$, for (possibly empty) finite tuples; then $(\nu \tilde{a})$ is a sequence of restrictions; and
 167 $(\nu \tilde{L})$ a sequence of reference allocations (i.e., a piece of store), using L to represent a single
 168 allocation such as $\ell = n$. Given the binders $(\nu a)P$ and $(\nu \ell = n)P$ (for a and ℓ , respectively),
 169 $a(x).P$, $\ell \triangleright (x).P$ and $\ell \bowtie n(x)$ (for x), we define $\text{bn}(O)$, $\text{fn}(O)$ (resp. $\text{fr}(O)$, $\text{br}(O)$), for the
 170 *bound* and *free names* (resp. *references*) of some object O (process, action, etc.). The set
 171 of *names* of O is defined as the union of its free and bound names; and analogously for
 172 *references*. In $a(x).P$ or $\bar{a}\langle x \rangle$, name a is the *subject* whereas x is the *object*.

173 We assume the calculus is simply-typed. Any basic type system for the π -calculus would
 174 do. In this paper, we assume Milner’s *sorting*: names and references are partitioned into

$$\begin{array}{c}
\text{R-Equiv: } \frac{P \equiv P' \quad P' \longrightarrow Q' \quad Q' \equiv Q}{P \longrightarrow Q} \qquad \text{R-Ctxt: } \frac{P \longrightarrow P'}{E[P] \longrightarrow E[Q]} \\
\\
\text{R-Comm: } \frac{}{a(x).P \mid \bar{a}\langle n \rangle \longrightarrow P\{n/x\}} \\
\\
\text{R-Read: } \frac{\ell, n \notin \text{br}(\nu\tilde{L})}{(\nu\ell = n)(\nu\tilde{L})(\ell \triangleright (x).P \mid Q) \longrightarrow (\nu\ell = n)(\nu\tilde{L})(P\{n/x\} \mid Q)} \\
\\
\text{R-Write: } \frac{\ell, n \notin \text{br}(\nu\tilde{L})}{(\nu\ell = m)(\nu\tilde{L})(\ell \triangleleft n.P \mid Q) \longrightarrow (\nu\ell = n)(\nu\tilde{L})(P \mid Q)} \\
\\
\text{R-Swap: } \frac{\ell, n, m \notin \text{br}(\nu\tilde{L})}{(\nu\ell = m)(\nu\tilde{L})(\ell \bowtie n(x).P \mid Q) \longrightarrow (\nu\ell = n)(\nu\tilde{L})(P\{m/x\} \mid Q)}
\end{array}$$

■ **Figure 1** π^{ref} , reduction relation

175 a collection of *types* (or *sorts*). Name types contain names, and reference types contain
176 references. Then a sorting function maps types onto types. If a name type s is mapped
177 onto a type t , this means that names in s may only carry, or contain, objects in t ; if s is a
178 reference type then only objects of type t may be stored in s . We shall assume that there is a
179 sorting system under which all processes we manipulate are well-typed. For simplicity we use
180 simple types; e.g., the sorting is non-recursive (meaning that the graph that represents the
181 sorting function, in which the nodes are the types, does not contain cycles). In the remainder
182 we assume that all objects (processes, contexts, actions, etc.) respect a given sorting.

183 The definition of structural congruence, \equiv , is the expected one from the π -calculus,
184 treating the $(\nu\ell = n)$ operator like a restriction (see Appendix B).

185 *Contexts*, ranged over by C , are process expressions with a hole $[\]$ in it. We write $C[P]$
186 for the process obtained by replacing the hole in C with P . *Active* (or *evaluation*) *contexts*,
187 ranged over by E , are given by:

$$E ::= [\] \mid E \mid P \mid (\nu a)E \mid (\nu\ell = n)E .$$

188 The reduction relation \longrightarrow is presented in Figure 1. It uses *active contexts* to isolate the
189 subpart of the term that is active in a reduction. We write \Longrightarrow for the ‘multistep’ version of
190 \longrightarrow , whereby $P \Longrightarrow P'$ if P may become P' after a (possibly empty) sequence of reductions.
191 Rules **R-Read**, **R-Write** and **R-Swap** in Figure 1 describe an interaction between the process
192 and a reference ℓ . These rules make use of a store $(\nu\tilde{L})$; this is necessary because there
193 might be references that depend on ℓ , and as such cannot be moved past the restriction
194 on ℓ . An example is $(\nu\ell = a)(\nu\ell' = \ell)\ell \triangleleft b.P$: the write operation is executed by applying
195 rule **R-Write**, with $(\nu\tilde{L}) = (\nu\ell' = \ell)$, as the restriction on ℓ' cannot be brought above the
196 restriction on ℓ . We recall that $\text{br}(\nu\tilde{L})$ are the references bound by the ν .

197 As usual in concurrent calculi, the reference behavioural equivalence will be barbed
198 congruence (in its variant sometimes called *reduction-closed barbed congruence*), a form of
199 bisimulation on reduction that uses closure under contexts and simple observables. In the
200 context closure, however, we make sure that all references mentioned in the tested process

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201 have been allocated. As often in π -calculi, we also consider *barbed equivalence*, that uses only
 202 active contexts.

203 P exhibits a barb at a (so a is in **Names**), written $P \Downarrow_{\bar{a}}$, if $P \equiv (\nu \tilde{b})(\nu \tilde{L})(\bar{a}\langle m \rangle \mid P')$ with
 204 $a \notin \tilde{b}$. We write $P \Downarrow_{\bar{a}}$ if $P \Longrightarrow P_1$ and $P_1 \Downarrow_{\bar{a}}$ for some P_1 .

205 ► **Definition 1.** Given a relation \mathcal{R} on processes, and $P \mathcal{R} Q$, we say that P, Q (in \mathcal{R}) are
 206 – closed under reductions if $P \longrightarrow P'$ implies there is Q' s.t. $Q \Longrightarrow Q'$ and $P' \mathcal{R} Q'$;
 207 – preserved by a set \mathcal{C} of contexts if $C[P] \mathcal{R} C[Q]$ for all $C \in \mathcal{C}$;
 208 – compatible on barbs if $P \Downarrow_{\bar{a}}$ implies $Q \Downarrow_{\bar{a}}$, for all a .

209 A process P is *reference-closed* if $\text{fr}(P) = \emptyset$. A context C is *closing on the references* of
 210 a process P if $C[P]$ is reference-closed; similarly, C is closing on the references of P, Q if it
 211 closing on the references of both P and Q . Since reductions may only decrease the set of
 212 free names of a process, the property of being reference-closed is preserved by reductions.

213 ► **Definition 2** (Barbed congruence and equivalence in π^{ref}). Barbed congruence is the largest
 214 symmetric relation \cong_{ref} in π^{ref} such that whenever $P \mathcal{R} Q$ then P, Q are: closed under
 215 reductions if P, Q are reference-closed; preserved by the contexts that are closing on references
 216 for P, Q ; compatible on barbs if P, Q are reference-closed. Barbed equivalence, \cong_{ref}^e , is
 217 defined in the same way, but using active contexts in place of all contexts.

218 The restriction to closing contexts (as opposed to arbitrary contexts) yields laws such as

$$219 \quad \ell \triangleright (x).P \cong_{\text{ref}} P, \tag{1}$$

220 whenever $x \notin \text{fn}(P)$. Closing contexts ensure that the reading on ℓ is not blocking, and
 221 therefore possible observables in P are visible on both sides.

222 As the quantification on contexts refers to the free references of the tested processes,
 223 transitivity of barbed congruence and equivalence requires some care. As usual in the
 224 π -calculus, barbed equivalence is not preserved by the input construct, and the closure of
 225 barbed equivalence under all (well-typed) substitutions coincides with barbed congruence.

226 2.2 Behavioural Equivalence in π^{ref} : Examples

227 We present a few examples that illustrate some subtleties of behavioural equivalence in
 228 π^{ref} . These examples will be formally treated in Section 4.2 for Examples 3 and 4, and in
 229 Appendix A for Examples 5 and 6.

230 The first example shows that processes may be equivalent even though the store is public
 231 and holds different values. (In the example, the reference ℓ is actually restricted, but the
 232 process P underneath the restriction, representing an observer, is arbitrary).

233 ► **Example 3.** For any P , we have $P_1 \cong_{\text{ref}} P_2$, for

$$P_1 \stackrel{\text{def}}{=} (\nu \ell = a)(P \mid !\ell \triangleleft a \mid !\ell \triangleleft b) \quad P_2 \stackrel{\text{def}}{=} (\nu \ell = b)(P \mid !\ell \triangleleft a \mid !\ell \triangleleft b)$$

234 In the second example, the write on top of P is not blocking, provided that the same writing
 235 is anyhow possible, and provided that the current value of the store can be recorded.

► **Example 4.** We have $P_1 \cong_{\text{ref}} P_2$, for

$$P_1 \stackrel{\text{def}}{=} \ell \triangleleft b.P \mid !\ell \triangleleft b \mid !\ell \triangleright (x). \ell \triangleleft x \quad P_2 \stackrel{\text{def}}{=} P \mid !\ell \triangleleft b \mid !\ell \triangleright (x). \ell \triangleleft x$$

236 On the left, it would seem that P runs under a store in which ℓ contains b ; whereas on the
 237 right, P could also run under the initial store, where ℓ could contain a different value, say a .
 238 However the component $!\ell \triangleright (x). \ell \triangleleft x$ allows us to store a in x and then write it back later,
 239 thus overwriting b .

► **Example 5.** We have $P_s \not\cong_{\text{ref}}^e Q_s$, where

$$P_s \stackrel{\text{def}}{=} (\nu t)\ell \triangleleft b. (\bar{t} \mid !t. \ell \triangleleft a. (\bar{c} \mid \ell \triangleleft b. (\bar{t} \mid c))) \quad Q_s \stackrel{\text{def}}{=} (\nu t)\ell \triangleleft a. (\bar{t} \mid !t. \ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c)))$$

240 The discriminating context being large, the formal discussion is moved in Appendix A.
 241 Intuitively, P_s and Q_s are refinements of the processes in Example 3, in that their initial
 242 writes store different values on the reference ℓ , but both processes maintain the capability
 243 of writing both values in ℓ . The difference with Example 3 are the additional inputs and
 244 outputs on name c , which are generated along the transitions. These allow an observer to
 245 distinguish P_s from Q_s by exploiting the swap construct. We informally explain the reason.
 246 If the two processes have written the same value, say a , in ℓ , then Q_s has generated the
 247 same number of inputs and outputs on c , while P_s must have generated an extra output. An
 248 observer can use swap to read the content of ℓ , so to check that the value is indeed a , and
 249 write back a fresh name, say e . Now the observer can tell that P_s has an extra output on c :
 250 process Q_s cannot add a further output, because this would require overwriting e in ℓ , which
 251 can be tested by the observer at the end.

252 We have seen in Example 3 two equivalent processes whose initial store (a single reference)
 253 is different. The equivalence holds intuitively because the values that the two processes
 254 can store are the same. Using two references, it is possible to complicate the example. In
 255 Example 6, the processes are equivalent and yet the pairs of values that may be simultaneously
 256 stored in the two references are different for the two processes. For each reference separately,
 257 the set of possible values is the same. But setting a reference to a certain value implies first
 258 having set the other reference to some specific values. (The processes could be distinguished
 259 if an observer had the possibility to simultaneously read the two references.)

260 ► **Example 6.** Consider two references ℓ_1, ℓ_2 where booleans (represented as 0,1 below) can
 261 be stored. Then for any P , we have $P_1 \cong_{\text{ref}} P_2$, where

$$262 \quad P_1 \stackrel{\text{def}}{=} (\nu \ell_1 = 0, \ell_2 = 0)(P \mid (\nu t)(\bar{t} \mid !t. \ell_1 \triangleleft 1. \ell_1 \triangleleft 0. \ell_2 \triangleleft 1. \ell_2 \triangleleft 0. \bar{t}))$$

$$263 \quad P_2 \stackrel{\text{def}}{=} (\nu \ell_1 = 0, \ell_2 = 0)(P \mid (\nu t)(\bar{t} \mid !t. \ell_1 \triangleleft 1. \ell_2 \triangleleft 1. \ell_1 \triangleleft 0. \ell_2 \triangleleft 0. \bar{t}))$$

265 P_1 and P_2 can write 0 and 1 in references ℓ_1 and ℓ_2 , but not in the same order. By doing so,
 266 we see that if P_1 loops, the content of ℓ_1 and ℓ_2 will evolve thus: $(0, 0) \rightarrow (1, 0) \rightarrow (0, 0) \rightarrow$
 267 $(0, 1) \rightarrow (0, 0)$, while for P_2 the loop is different: $(0, 0) \rightarrow (1, 0) \rightarrow (1, 1) \rightarrow (0, 1) \rightarrow (0, 0)$.

268 In particular, P_2 can always go through the state $(1, 1)$, independently of the transitions
 269 of P , while P_1 cannot, in general, reach this state.

270 The example above relies on the fact that the domain of possible values for ℓ_1 and ℓ_2 is
 271 finite. A more sophisticated example, without such assumption, is given in the Appendix A.

272 **3 Mapping π^{ref} onto the Asynchronous π -calculus**

273 We present the encoding of π^{ref} into $A\pi$, which follows the folklore encoding of references
 274 into $A\pi$.

275 **3.1 The Asynchronous π -calculus**276 Below is the grammar of the asynchronous π -calculus, $A\pi$; we reuse all notations from π^{ref} .

277
$$P ::= \mathbf{0} \mid n(x).P \mid !P \mid \bar{n}\langle m \rangle \mid P_1 \mid P_2 \mid (\nu n)P \mid [n = m]P$$
278

279 The reduction semantics, as well as barbed equivalence and congruence (written \cong_a^e and
280 \cong_a , respectively), are standard (defined as in π^{ref} , and recalled in Appendix B). We recall
281 the standard definition of asynchronous bisimilarity, \approx_a , from [1]. To define \approx_a , as well as
282 the other forms of bisimilarity we introduce in Section 4, we rely on the early transition
283 system for $A\pi$. In this LTS, which is presented in Appendix B labels are either free inputs of
284 the form $n\langle m \rangle$ (reception of name m on n), output ($\bar{n}\langle m \rangle$), bound output ($(\nu m)\bar{n}\langle m \rangle$) or
285 internal communication (τ).286 **► Definition 7.** *A symmetric relation \mathcal{R} between processes is an asynchronous bisimulation*
287 *if whenever $P \mathcal{R} Q$ and $P \xrightarrow{\mu} P'$, one of these two clauses hold:*

- 288
- there is Q' such that $Q \xrightarrow{\hat{\mu}} Q'$ and $P' \mathcal{R} Q'$;*
-
- 289
- $\mu = n\langle m \rangle$ and there is Q' such that $Q \mid \bar{n}\langle m \rangle \Rightarrow Q'$ and $P' \mathcal{R} Q'$.*

290 *Asynchronous bisimilarity, \approx_a , is the largest asynchronous bisimulation.*291 **► Theorem 8 ([1]).** *Relations \cong_a^e and \approx_a coincide.*292 **3.2 Encoding π^{ref}** 293 In π -calculi such as $A\pi$, there are no references, only names. To make the encoding easier to
294 read, we assume however that the set of names contains the set of references $\{\ell, \dots\}$ of π^{ref} .
295 We call such names *reference names*, and call *plain names* the remaining names. Reference
296 names will be used to represent the references of π^{ref} .The encoding $\mathcal{E}[\cdot]$, from π^{ref} to $A\pi$, is a homomorphism on all operators (thus, e.g.,
 $\mathcal{E}[P_1 \mid P_2] \stackrel{\text{def}}{=} \mathcal{E}[P_1] \mid \mathcal{E}[P_2]$, and $\mathcal{E}[a(m).P] \stackrel{\text{def}}{=} a(m).\mathcal{E}[P]$), except for reference constructs
for which we have:

$$\begin{aligned} \mathcal{E}[(\nu \ell = m).P] &\stackrel{\text{def}}{=} (\nu \ell)(\bar{\ell}\langle m \rangle \mid \mathcal{E}[P]) & \mathcal{E}[\ell \triangleleft v.P] &\stackrel{\text{def}}{=} \ell(_).(\bar{\ell}\langle v \rangle \mid \mathcal{E}[P]) \\ \mathcal{E}[\ell \triangleright (x).P] &\stackrel{\text{def}}{=} \ell(x).(\bar{\ell}\langle x \rangle \mid \mathcal{E}[P]) & \mathcal{E}[\ell \bowtie n(x).P] &\stackrel{\text{def}}{=} \ell(x).(\bar{\ell}\langle n \rangle \mid \mathcal{E}[P]) \end{aligned}$$

297 (We write $\ell(_).Q$ for an input whose bound name does not appear in Q .) In the encoding, an
298 object m stored at reference ℓ is represented as a message $\bar{\ell}\langle m \rangle$. Accordingly, the encoding of
299 a write $\ell \triangleleft v.P$ is $\ell(_).(\bar{\ell}\langle v \rangle \mid \mathcal{E}[P])$, meaning that the process acquires the current message
300 at ℓ (which is thus not available anymore) and replaces it with an output with the new value.
301 The encoding of a read $\ell \triangleright (x).P$ follows a similar pattern, this time however the same value
302 is received and emitted: $\ell(x).(\bar{\ell}\langle x \rangle \mid P)$. The encoding of swap combines the two patterns.303 **3.3 Types and Behavioural Equivalences with Reference Names**304 To prove a full abstraction property for the encoding, we use types to formalise the behavioural
305 difference between reference names and plain names in the asynchronous π -calculus. The
306 typing discipline can be added onto any basic type system for the π -calculus. As for π^{ref} ,
307 we follow Milner's sorting. The types of the sorting impose a partition on the two sets of
308 names (reference names and plain names). Thus we assume such a sorting, under which
309 all processes are well-typed. We separate the base type system (Milner's sorting) from the

$$\begin{array}{c}
\text{TNil} \frac{}{\emptyset \vdash \mathbf{0}} \quad \text{TOut} \frac{}{\emptyset \vdash \bar{a}\langle m \rangle} \quad \text{TInp} \frac{\emptyset \vdash P}{\emptyset \vdash a(x).P} \quad \text{TRep} \frac{\emptyset \vdash P}{\emptyset \vdash !P} \\
\text{TPar} \frac{\Delta_1 \vdash P \quad \Delta_2 \vdash Q}{\Delta_1 \uplus \Delta_2 \vdash P \mid Q} \quad \text{TResN} \frac{\Delta \vdash P}{\Delta \vdash (\nu a)P} \quad \text{TResR} \frac{\Delta, \ell \vdash P}{\Delta \vdash (\nu \ell)P} \\
\text{TRef0} \frac{}{\ell \vdash \bar{\ell}\langle m \rangle} \quad \text{TRefI} \frac{\ell \vdash P}{\emptyset \vdash \ell(x).P}
\end{array}$$

■ **Figure 2** Typing conditions for reference names in $A\pi$ processes

310 typing rules for reference names so as to show the essence of the latter rules. Accordingly,
 311 we only present the additional typing constraints for reference names.

312 We write: **RefTypes** for the the set of reference types (i.e., types that contain reference
 313 names); **Type**(n) is the type of name n ; **ObType**(n) is the type of the objects of n (i.e., the
 314 type of the names that may be carried at n). For example in well-typed processes such as
 315 $\bar{n}\langle m \rangle$ and $n(m).P$, name m will be of type **ObType**(n).

316 **Notations.** We use ℓ, \dots to range over reference names, a, b, \dots over plain names, n, m, \dots
 317 over the set of all names. Δ ranges over finite sets of reference names. We sometimes write
 318 $\Delta - x$ as abbreviation for $\Delta - \{x\}$. Moreover $\Delta_1 \uplus \Delta_2$ is defined only when $\Delta_1 \cap \Delta_2 = \emptyset$, in
 319 which case it is $\Delta_1 \cup \Delta_2$; we write Δ, x for $\Delta \uplus \{x\}$.

320 The type system is presented in Figure 2. Judgements have the form $\Delta \vdash P$, where P is
 321 an $A\pi$ process. Rule **TRef0** along with Rule **TPar** ensures that every reference names in Δ
 322 appears in subject of exactly one unguarded output. Rule **TResR** ensures that new reference
 323 names are always in Δ while Rule **TRefI** ensures that Δ is constant after a communication
 324 between references (by re-emitting an output after one has been consumed).

325 Intuitively, if $\Delta \vdash P$, then P must make available the names in Δ *immediately* and *exactly*
 326 *once* in output subject position. We say that ℓ is *output receptive* in P if there is exactly
 327 one unguarded output at ℓ , and moreover this output is not underneath a replication. Then
 328 $\Delta \vdash P$ holds if

- 329 – any $\ell \in \Delta$ is output receptive in P ;
- 330 – in any subterm of P of the form $(\nu \ell')Q$ or $\ell'(m).Q$, name ℓ' is output receptive in Q .

331 This intuition is formalised in Lemma 9, and in Proposition 10 that relates types and
 332 operational semantics.

333 Typing is important because it allows us to derive the required behavioural equivalences.
 334 For instance, allowing parallel composition with the ill-typed process $\ell(x).\mathbf{0}$ would invalidate
 335 barbed equivalence between the (translations of the) terms in law (1).

336 In the remainder of the paper, it is assumed that all processes are *well typed*, meaning
 337 that each process P obeys the underlying sorting system and that there is Δ s.t. $\Delta \vdash P$
 338 holds. Two processes P, Q are *type-compatible* if both $\Delta \vdash P$ and $\Delta \vdash Q$, for some Δ ; we
 339 write $\Delta \vdash P, Q$ in this case. *In the remainder of the paper, all relations are on pairs of*
 340 *type-compatible processes. Similarly, all compositions (i.e., of a context with processes) and*
 341 *actions are well-typed.*

342 The type system satisfies standard properties, like uniqueness of typing ($\Delta \vdash P$ and
 343 $\Delta' \vdash P$ imply $\Delta = \Delta'$), and preservation by structural congruence ($P \equiv Q$ and $\Delta \vdash P$ imply

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344 $\Delta \vdash Q$). As claimed above, if $\Delta \vdash P$, then names in Δ are output receptive:

345 ► **Lemma 9.** *If $\Delta, \ell \vdash P$ then $P \equiv (\nu \tilde{n})(\bar{\ell}\langle m \rangle \mid Q)$, with $\ell \notin \tilde{n}$, and there is no unguarded*
 346 *output at ℓ in Q .*

347 The following standard property relies on the standard LTS for $A\pi$, which is given in
 348 Appendix B.

349 ► **Proposition 10** (Subject reduction). *If $\Delta \vdash P$ and $P \xrightarrow{\mu} P'$, then*

350 1. *if $\mu = \tau$, $\mu = \bar{a}\langle m \rangle$, $\mu = a\langle m \rangle$ or $\mu = (\nu b)\bar{a}\langle b \rangle$, then $\Delta \vdash P'$.*

351 2. *if $\mu = (\nu \ell)\bar{a}\langle \ell \rangle$ then $\Delta, \ell \vdash P'$.*

352 3. *if $\mu = \ell\langle m \rangle$ and $\ell \notin \Delta$, then $\Delta, \ell \vdash P'$*

353 4. *if $\ell \notin \Delta$, then $\Delta, \ell \vdash P \mid \bar{\ell}\langle m \rangle$.*

354 5. *if $\mu = \bar{\ell}\langle m \rangle$ or $\mu = (\nu b)\bar{\ell}\langle b \rangle$, then $\Delta - \ell \vdash P'$.*

355 6. *if $\mu = (\nu \ell')\bar{\ell}\langle \ell' \rangle$, then $(\Delta - \ell), \ell' \vdash P'$.*

356 We can remark that in case 3, we have $\ell \notin \Delta$, as otherwise the context would not be able
 357 to trigger an input (since, by typing, it could not generate an output on ℓ).

358 **Barbed congruence.** As usual in typed calculi, the definitions of the barbed relations take
 359 typing into account, so that the composition of a context and a process be well-typed. In the
 360 case of reference names, an additional ingredient has to be taken into account, namely the
 361 accessibility of reference names. If a process has the possibility of accessing a reference, then
 362 a context in which the process is tested should guarantee the availability of that reference.
 363 For this, we define the notion of *completing context* and *complete* process. Then, roughly,
 364 barbed congruence becomes “barbed congruence under all completing contexts”.

365 A process P is *complete* if each reference name that appears free in P is ‘allocated’ in P .
 366 We write $\mathbf{frn}(P)$ for the set of free reference names in P .

367 ► **Definition 11** (Open references and complete processes). *The open references of P such*
 368 *that $\Delta \vdash P$ are the names in $\mathbf{frn}(P) \setminus \Delta$; similarly the open references of processes P_1, \dots, P_n*
 369 *is the union of the open references of the P_i ’s. P is complete if it contains no open reference.*
 370 *$\mathbf{frn}(P) \subseteq \Delta$ and $\Delta \vdash P$, for some Δ .*

371 *A context C is completing for P if $C[P]$ is complete.*

372 (Note that an $A\pi$ complete process might have free reference names, if these are not open
 373 references; in contrast, a π^{ref} reference-closed process does not have free references.)

374 ► **Lemma 12.** *P is complete iff $\emptyset \vdash (\nu \tilde{n})P$ where $\tilde{n} \stackrel{\text{def}}{=} \mathbf{frn}(P)$.*

375 Completing contexts are the only contexts in which processes should be tested. We
 376 constrain the definitions of typed barbed congruence and equivalence accordingly. The
 377 grammar for the active contexts in $A\pi$ is as expected:

$$E ::= [] \mid E \mid P \mid (\nu n)E .$$

378 ► **Definition 13** (Barbed congruence and equivalence in $A\pi$ with reference names). *Barbed*
 379 *congruence is the largest symmetric relation \cong_{Arn} in $A\pi$ such that whenever $P \mathcal{R} Q$ then*
 380 *P, Q are: closed under reductions whenever they are complete; closed under the contexts that*
 381 *are completing for P, Q ; compatible on barbs whenever they are complete. Barbed equivalence,*
 382 *\cong_{Arn}^e , is defined analogously except that one uses active contexts in place of all contexts.*

383 This typed barbed equivalence is the behavioural equivalence we are mainly interested in.
 384 The reference name discipline weakens the requirements on names (by limiting the number of
 385 legal contexts), hence the corresponding typed barbed relation is coarser. We are not aware
 386 of existing works in the literature that study the impact of the reference name discipline on
 387 behavioural equivalence.

388 ► **Lemma 14.** *For all compatible P, Q , $P \cong_a^e Q$ (and hence also $P \approx_a Q$) implies $P \cong_{\text{Arn}}^e Q$.*

389 We show in Section 4 that the inclusion is strict.

390 3.4 Validating the Encoding

391 We now show that the two notions of barbed congruence coincide via the encoding.

392 ► **Theorem 15** (Operational correspondence). *If $P \longrightarrow P'$, then $\mathcal{E}[[P]] \longrightarrow \mathcal{E}[[P']]$.
 393 Conversely, if $\mathcal{E}[[P]] \longrightarrow Q$, then $P \longrightarrow P'$, with $\mathcal{E}[[P']] \equiv Q$.*

394 The next lemma shows that, up to asynchronous bisimilarity, we can ‘read back’ well-typed
 395 processes in $A\pi$, via the encoding, as processes in π^{ref} . And similarly for contexts.

396 ► **Lemma 16.** *If $\emptyset \vdash P$, then there exists R in π^{ref} such that $\mathcal{E}[[R]] \approx_a P$.*

397 Theorem 15 and Lemma 16 are the main ingredients to derive the following theorem:

398 ► **Theorem 17** (Full abstraction). *For any P, Q in π^{ref} : $P \cong_{\text{ref}} Q$ iff $\mathcal{E}[[P]] \cong_{\text{Arn}} \mathcal{E}[[Q]]$;
 399 and similarly $P \cong_{\text{ref}}^e Q$ iff $\mathcal{E}[[P]] \cong_{\text{Arn}}^e \mathcal{E}[[Q]]$.*

400 4 Bisimulation with Reference Names

401 4.1 Two Labelled Bisimilarities

402 In this section we present proof techniques for barbed equivalence based on the labelled
 403 transition semantics of $A\pi$. For this we introduce two labelled bisimilarities.

404 The first form of bisimulation, *reference bisimilarity*, only relates complete processes;
 405 processes that are not complete have to be made so. Intuitively, in this bisimilarity processes
 406 are made complete by requiring a closure of the relation with respect to the (well-typed)
 407 addition of output messages at reference names (the ‘closure under allocation’ below).
 408 Moreover, when an observer consumes an output at a reference name, say $\bar{\ell}\langle n \rangle$, then,
 409 following the discipline on reference names, he/she has to immediately provide another such
 410 output message, say $\bar{\ell}\langle m \rangle$. This is formalised using transition notations such as $P \xrightarrow{\bar{\ell}\langle n \rangle[m]} P'$,
 411 which makes a swap on ℓ (reading its original content n and replacing it with m). As a
 412 consequence of the appearance of such swap transitions, ordinary outputs at reference names
 413 are not observed in the bisimulation. Similarly for inputs at reference names: an input
 414 $P \xrightarrow{\ell\langle m \rangle} P'$ from a complete process P is not observed, since it is supposed to interact with
 415 unique output at ℓ contained in P (which exists as P is complete). Finally, an observer
 416 should respect the completeness condition by the processes and should not communicate
 417 a fresh reference name — to communicate such a reference, say ℓ , an allocation for ℓ (an
 418 output message at ℓ) has first to be added.

419 A relation \mathcal{R} is *closed under allocation* if $P \mathcal{R} Q$ implies $P \mid \bar{\ell}\langle n \rangle \mathcal{R} Q \mid \bar{\ell}\langle n \rangle$ for any $\bar{\ell}\langle n \rangle$
 420 such that $P \mid \bar{\ell}\langle n \rangle$ and $Q \mid \bar{\ell}\langle n \rangle$ are well-typed. We write $P \xrightarrow{\bar{\ell}\langle n \rangle[m]} P'$ if $P \xrightarrow{\bar{\ell}\langle n \rangle} P''$ and

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421 $P' = \bar{\ell}\langle m \rangle \mid P''$, for some P'' ; similarly for $P \xrightarrow{(\nu n)\bar{\ell}\langle n \rangle[m]} P'$. Then, as usual, $P \xrightarrow{\bar{\ell}\langle n \rangle[m]} P'$
 422 holds if $P \Rightarrow P'' \xrightarrow{\bar{\ell}\langle n \rangle[m]} P''' \Rightarrow P'$ for some P'', P''' , and similarly for $P \xrightarrow{(\nu n)\bar{\ell}\langle n \rangle[m]} P'$.

423 We let α range over the actions μ plus the aforementioned ‘update actions’ $\bar{\ell}\langle n \rangle[m]$ and
 424 $(\nu n)\bar{\ell}\langle n \rangle[m]$.

425 Setting m to be the object of an update actions, we write $\Delta \vdash \alpha$ when: (i) if the object
 426 of α is a free reference name then it is in Δ , and (ii) α is not an input or an output at a
 427 reference name.

428 ► **Definition 18** (Reference bisimilarity). *A symmetric relation \mathcal{R} closed under allocation is a*
 429 *reference bisimulation if whenever $P \mathcal{R} Q$ with P, Q complete, $\Delta \vdash P, Q$ and $P \xrightarrow{\alpha} P'$ with*
 430 *$\Delta \vdash \alpha$, then*

- 431 1. *either there exists Q' such that $Q \xrightarrow{\hat{\alpha}} Q'$ and $P' \mathcal{R} Q'$ for some Q'*
 - 432 2. *or α is an input $a\langle m \rangle$ and $Q \mid \bar{a}\langle m \rangle \Rightarrow Q'$ with $P' \mathcal{R} Q'$ for some Q' .*
- 433 *Reference bisimilarity, written \approx , is the largest reference bisimulation.*

434 We now show that \approx coincides with barbed equivalence. The structure of the proof is
 435 standard, however some care has to be taken to deal with closure under parallel composition.

436 ► **Lemma 19.** *If $P \approx Q$, and $\emptyset \vdash R$, then $P \mid R \approx Q \mid R$.*

437 ► **Proposition 20** (Substitutivity for active contexts). *If $P \approx Q$, then $E[P] \approx E[Q]$ for any*
 438 *active context E .*

439 ► **Theorem 21** (Labelled characterisation). *$P \approx Q$ iff $P \cong_{\text{Arrn}}^c Q$.*

440 In reference bisimilarity, the tested processes are complete: hence all their references
 441 must explicitly appear as allocated, and when a reference is accessed, an extension of the
 442 store is made so to remain with complete processes (and if such an extension introduces
 443 other new references, a further extension is needed). The goal of the bisimilarity \approx_{ip} below
 444 is to allow one to work on processes with open references, and make the extension of the
 445 store only when necessary. The definition of the bisimulation exploits an inductive predicate
 446 to accommodate finite extensions of the store, one step at a time. This predicate can be
 447 thought of as an inductive game, in which the ‘verifier’ can choose rule **Base** and close the
 448 game, or choose rule **Ext** and a reference ℓ ; in the latter case the ‘refuter’ chooses the value
 449 stored in ℓ .

450 ► **Definition 22** (Inductive predicate). *The predicate $\text{ok}(\Delta, \mathcal{R}, P, Q, \mu)$ (where Δ is a set*
 451 *of names, \mathcal{R} a process relation, P, Q processes, and μ an action) holds if it can be proved*
 452 *inductively from the following two rules:*

$$\text{Base} \frac{\left\{ \begin{array}{l} Q \mid \bar{n}\langle m \rangle \Rightarrow Q' \quad \text{for } \mu = n\langle m \rangle \\ Q \xrightarrow{\mu} Q' \quad \text{otherwise} \end{array} \right. \quad P' \mathcal{R} Q'}{\text{ok}(\Delta, \mathcal{R}, P', Q, \mu)}$$

$$\text{Ext} \frac{\ell \notin \Delta \quad \forall m : \text{ok}((\Delta, \ell), \mathcal{R}, P' \mid \bar{\ell}\langle m \rangle, Q \mid \bar{\ell}\langle m \rangle, \mu)}{\text{ok}(\Delta, \mathcal{R}, P', Q, \mu)}$$

453 ► **Definition 23** (Bisimilarity with inductive predicate, \approx_{ip}). *A symmetric relation \mathcal{R} is a*
 454 *\approx_{ip} -bisimulation if whenever $P \mathcal{R} Q$ with $\Delta \vdash P, Q$, and $P \xrightarrow{\mu} P'$ with $\Delta' \vdash P'$, we can*
 455 *derive $\text{ok}(\Delta \cup \Delta', \mathcal{R}, P', Q, \mu)$. We write \approx_{ip} for the largest \approx_{ip} -bisimulation.*

456 The names in $\Delta \cup \Delta'$ are the reference names that appear in output subject position
 457 in P' or Q . Therefore, when using rule **Ext** of the inductive predicate, the condition $\ell \notin \Delta$
 458 ensures us that the message at ℓ can be added without breaking typability.

459 The following up-to technique allows us to erase common messages on reference names
 460 along the bisimulation game.

461 For this, we use the notation M_s , where s is a finite list of pairs (ℓ, m) , to describe parallel
 462 compositions of outputs on reference names (i.e., $M_s \stackrel{\text{def}}{=} \prod_{(\ell, m) \in s} \bar{\ell}\langle m \rangle$), and $\Delta_s \vdash M_s$ where
 463 Δ_s contains all first components of pairs of s . Intuitively, M_s represents a chunk of store.

464 ► **Definition 24** (\approx_{ip} -bisimulation up to store). An \approx_{ip} -bisimulation up to store is defined like
 465 \approx_{ip} -bisimulation (Definition 23), using a predicate $\text{ok}'(\Delta \cup \Delta', \mathcal{R}, P', Q, \mu)$. This predicate is
 466 defined by a modified version of rule **Ext** where ok' is used instead of ok , both in the premise
 467 and in the conclusion, and the following modified version of the **Base** rule:

$$\text{Base-Up} \frac{P' \equiv P'' \mid M_s \quad \begin{cases} Q \mid \bar{n}\langle m \rangle \Rightarrow \equiv Q'' \mid M_s & \text{for } \mu = n\langle m \rangle \\ Q \stackrel{\mu}{\Rightarrow} \equiv Q'' \mid M_s & \text{otherwise} \end{cases} \quad P'' \mathcal{R} Q''}{\text{ok}'(\Delta, \mathcal{R}, P', Q, \mu)}$$

468 Rule **Base-Up** makes it possible to erase common store components before checking that the
 469 processes are related by \mathcal{R} .

470 ► **Proposition 25.** If \mathcal{R} is a \approx_{ip} -bisimulation up to store, then $\mathcal{R} \subseteq \approx_{\text{ip}}$.

471 ► **Proposition 26** (Soundness of \approx_{ip}). $\approx_{\text{ip}} \subseteq \approx$.

472 Intuitively, the inclusion holds because a \approx_{ip} -bisimulation is closed by parallel composition
 473 with M_s processes. We leave the opposite direction, completeness, as an open issue.

474 4.2 Examples

475 We now give examples of uses of the various forms of labelled bisimulation (\approx_a , \approx , \approx_{ip} , \approx_{ip}
 476 up to store) for $A\pi$ to establish equivalences between processes with references. In some
 477 cases, we use the ‘up-to structural congruence’ (\equiv) version of the bisimulations — a standard
 478 ‘up-to’ technique. In the examples we consider barbed equivalence; the results can be lifted
 479 to barbed congruence using closure under substitutions.

480 The first example is about a form of commutativity for the write construct.

481 ► **Example 27.** We wish to establish $! \ell \triangleleft a. \ell \triangleleft b \stackrel{e}{\cong}_{\text{ref}} ! \ell \triangleleft b. \ell \triangleleft a$. For this, we prove the law
 482 $! \ell \triangleleft a. \ell \triangleleft b \stackrel{e}{\cong}_{\text{ref}} ! \ell \triangleleft a \mid ! \ell \triangleleft b$, which will be enough to conclude, by commutativity of parallel
 483 composition. The two given processes are mapped into $A\pi$ as

$$484 \quad P_1 \stackrel{\text{def}}{=} ! \ell(_). (\bar{\ell}\langle a \rangle \mid \ell(_). \bar{\ell}\langle b \rangle) \quad \text{and} \quad P_2 \stackrel{\text{def}}{=} (! \ell(_). \bar{\ell}\langle a \rangle) \mid (! \ell(_). \bar{\ell}\langle b \rangle).$$

485 We can derive $P_1 \approx_a P_2$, using the singleton relation $\mathcal{R} \stackrel{\text{def}}{=} \{(P_1, P_2)\}$, and showing that \mathcal{R}
 486 is an asynchronous bisimilarity up-to context and structural congruence [18] (this known
 487 ‘up-to’ technique allows one to remove additional processes created from the replications
 488 after a transition). We can then conclude by Lemma 14.

489 We now consider Examples 3 and 4 from Section 2.

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490 **Proof of Example 3.** Let R_1, R_2 be the encodings of P_1, P_2 in the example:

$$491 \quad R_1 \stackrel{\text{def}}{=} (\nu \ell)(\bar{\ell}\langle a \rangle \mid \mathcal{E}\llbracket P \rrbracket \mid !\ell(_). \bar{\ell}\langle a \rangle \mid !\ell(_). \bar{\ell}\langle b \rangle)$$

$$492 \quad R_2 \stackrel{\text{def}}{=} (\nu \ell)(\bar{\ell}\langle b \rangle \mid \mathcal{E}\llbracket P \rrbracket \mid !\ell(_). \bar{\ell}\langle a \rangle \mid !\ell(_). \bar{\ell}\langle b \rangle)$$

494 We then have $R_1 \Longrightarrow \equiv R_2$ and $R_2 \Longrightarrow \equiv R_1$, which implies $R_1 \approx_a R_2$ (where \approx_a is
495 asynchronous bisimilarity), as $\{(R_1, R_2)\} \cup \mathcal{I}$, where $\mathcal{I} = \{(P, P)\}$ is the identity relation, is
496 an asynchronous bisimulation up to \equiv . We can then conclude by Theorems 8 and 17. \blacktriangleleft

497 **Proof of Example 4.** Let R_1, R_2 be the encodings of P_1, P_2 in the example:

$$498 \quad R_1 \stackrel{\text{def}}{=} \ell(_). (\bar{\ell}\langle b \rangle \mid \mathcal{E}\llbracket P \rrbracket) \mid !\ell(_). \bar{\ell}\langle b \rangle \mid !\ell(x). (\bar{\ell}\langle x \rangle \mid \ell(_). \bar{\ell}\langle x \rangle)$$

$$499 \quad R_2 \stackrel{\text{def}}{=} \mathcal{E}\llbracket P \rrbracket \mid !\ell(_). \bar{\ell}\langle b \rangle \mid !\ell(x). (\bar{\ell}\langle x \rangle \mid \ell(_). \bar{\ell}\langle x \rangle)$$

500
501 Then for all m , processes $\bar{\ell}\langle m \rangle \mid R_1$ and $\bar{\ell}\langle m \rangle \mid R_2$ are complete. We define

$$\mathcal{R} \stackrel{\text{def}}{=} \{(R_1 \mid \bar{\ell}\langle m \rangle \mid B_X, R_2 \mid \bar{\ell}\langle m \rangle \mid B_X)\},$$

502 where $X \stackrel{\text{def}}{=} \{x_1, \dots, x_n\}$ is a possibly empty finite set of names, and

$$B_X \stackrel{\text{def}}{=} \ell(_). \bar{\ell}\langle x_1 \rangle \mid \dots \mid \ell(_). \bar{\ell}\langle x_n \rangle$$

503 Then $\mathcal{R} \cup \mathcal{I}$ is a \approx_{ip} -bisimulation.

504 Reusing the same notations, $\mathcal{R}' \stackrel{\text{def}}{=} \{(R_1 \mid B_X, R_2 \mid B_X)\}$ is an \approx_{ip} -bisimulation up to
505 store: this up-to technique allows us to remove the $\bar{\ell}\langle m \rangle$ particles. \blacktriangleleft

506 The following example shows some benefits of using \approx_{ip} and \approx_{ip} up to store in the proof of
507 a property that generalises (the $\mathcal{A}\pi$ version of) law (1), which involves a ‘useless read’.

508 **► Example 28.** Consider $\emptyset \vdash P_0 \mathcal{R} Q_0$, where \mathcal{R} is an asynchronous bisimulation, $\text{ObType}(\ell) \in$
509 RefTypes , and x is a fresh name. Then $\emptyset \vdash \ell(x). (P_0 \mid \bar{\ell}\langle x \rangle) \approx Q_0$.

510 In general, $\ell(x). (P_0 \mid \bar{\ell}\langle x \rangle)$ and Q_0 are not related by \approx_a (take $P_0 = Q_0 = \bar{a}\langle n \rangle$), thus
511 the inclusion in Lemma 14 is strict.

512 To prove $\ell(x). (P_0 \mid \bar{\ell}\langle x \rangle) \approx Q_0$ using a \approx -bisimulation, we need a relation such as

$$513 \quad \mathcal{R}_1 \stackrel{\text{def}}{=} \{(\ell(x). (P_0 \mid \bar{\ell}\langle x \rangle), Q_0)\}$$

$$514 \quad \cup \{(\ell(x). (P_0 \mid \bar{\ell}\langle x \rangle) \mid \bar{\ell}\langle \ell' \rangle \mid \bar{\ell}'\langle m \rangle, Q_0 \mid \bar{\ell}\langle \ell' \rangle \mid \bar{\ell}'\langle m \rangle) \mid \text{for any } m\}$$

$$515 \quad \cup \{(\ell(x). (P_0 \mid \bar{\ell}\langle x \rangle) \mid \bar{\ell}\langle \ell' \rangle \mid \bar{\ell}'\langle m \rangle \mid M_s, Q_0 \mid \bar{\ell}\langle \ell' \rangle \mid \bar{\ell}'\langle m \rangle \mid M_s) \mid \text{for any } m, M_s\}$$

$$516 \quad \cup \{P \mid \bar{\ell}\langle \ell' \rangle \mid \bar{\ell}'\langle m \rangle \mid M_s, Q \mid \bar{\ell}\langle \ell' \rangle \mid \bar{\ell}'\langle m \rangle \mid M_s) \mid \text{for any } m, M_s, \text{ with } P \mathcal{R} Q\}$$

518 and prove that $\mathcal{R}_1 \cup \mathcal{R}_1^{-1}$ (where \mathcal{R}_1^{-1} is the inverse of \mathcal{R}_1) is a \approx -bisimulation.

519 We can simplify the proof and avoid the several quantifications in \mathcal{R}_1 (in particular on
520 M_s , whose size is arbitrary), and prove that \mathcal{R}_2 is an \approx_{ip} -bisimulation, for

$$521 \quad \mathcal{R}_2 \stackrel{\text{def}}{=} \mathcal{R} \cup \{(P \mid \bar{\ell}\langle m \rangle, Q \mid \bar{\ell}\langle m \rangle), \text{ for any } m, \text{ with } P \mathcal{R} Q\}$$

$$522 \quad \cup \{(\ell(x). (P_0 \mid \bar{\ell}\langle x \rangle), Q_0), (Q_0, \ell(x). (P_0 \mid \bar{\ell}\langle x \rangle))\}.$$

524 The last component of \mathcal{R}_2 is dealt with using rule **Ext** of the inductive predicate (Definition 22),
525 and this brings in the second component (the closure of \mathcal{R} under messages on ℓ).

526 We can simplify the proof further, by removing such second component, and show that
527 \mathcal{R}_3 is an \approx_{ip} -bisimulation up to store, for

$$528 \quad \mathcal{R}_3 \stackrel{\text{def}}{=} \mathcal{R} \cup \{(\ell(x). (P_0 \mid \bar{\ell}\langle x \rangle), Q_0), (Q_0, \ell(x). (P_0 \mid \bar{\ell}\langle x \rangle))\}.$$

5 Future work

In languages with store, which are usually sequential languages, bisimulation is commonly defined on *configurations*. In π^{ref} , a configuration would be written $(\nu \tilde{n})\langle P, s \rangle$, where s is an explicit store and \tilde{n} is a set of private names shared between process P and store s . We could in principle read back \approx onto π^{ref} , and define a behavioural equivalence between π^{ref} configurations. The LTS on configurations would then have specific actions to describe how an observer may act on the visible part of the store. The labelled transition semantics for π^{ref} and π^{ref} configurations would however be more complex than those for $A\pi$; for instance the forms of actions, expressing external observations, would be much broader.

The swap operation arises naturally in the encoding into $A\pi$. We do not know if and how swap increases the discriminating power of external observers. We believe that, without swap, the two processes in Example 5 could not be distinguished. This point deserves further investigation, which we leave for future work. Similarly we leave for future work proving or disproving the completeness of the bisimilarity with an inductive predicate (Definition 23).

It would be interesting to see if the labelled bisimilarities we have considered, whose bisimulation clauses are different from those of ordinary bisimilarity, can be recovered in an abstract setting, e.g., using coalgebras [12, 2, 21]. This would be particularly interesting for \approx_{ip} -bisimulation, whose definition involves a mixture of induction and coinduction.

Equivalences for higher-order languages with state are known to be hard to establish. Various approaches exist, from Kripke logical relations to trace semantics and game semantics [10, 11, 17, 4]. It would be interesting to compare the proof techniques offered by these approaches with those shown in this paper, and developments of them. More generally, more experimentation is needed to test the bisimilarities proposed in this paper and the associated proof techniques, on examples from high-level languages that include higher-order features, mutable state, and concurrency.

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A

 Additional Material for the Examples in Section 2.2

612

613 **Proof of Example 5.** To get a idea of how P_s and Q_s evolve, let us consider first $E \stackrel{\text{def}}{=} (\nu \ell = z)[\]$. Then $E[Q_s]$ can reduce to one of the following:

- 614 1. $(\nu \ell = z)(\nu t)\ell \triangleleft a. (\bar{t} \mid !t. \ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c)))$
- 615 2. $(\nu \ell = a)(\nu t)(\bar{t} \mid !t. \ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c))) \mid c^n \mid \bar{c}^n$
- 616 3. $(\nu \ell = a)(\nu t)(\ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c)) \mid !t. \ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c))) \mid c^n \mid \bar{c}^n$
- 617 4. $(\nu \ell = b)(\nu t)(\ell \triangleleft a. (\bar{t} \mid c) \mid !t. \ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c))) \mid c^n \mid \bar{c}^{n+1}$.

618 Similarly, $E[P_s]$ can reduce to those four processes but with the role of a and b swapped.
619 Notice that when $E[Q_s] \Longrightarrow Q'$, then there is a correspondence between the value stored in
620 ℓ (i.e a or b) and the presence of more \bar{c} processes than c processes (or the same number).
621

622 We now consider the following context:

$$E_0 \stackrel{\text{def}}{=} (\nu \ell = z)([\] \mid \ell \bowtie z(x). [x = b]_{s_0. s_1}. (P_{11} \mid P_{12}) \mid \bar{s}_0 \mid \bar{s}_1)$$

$$P_{11} \stackrel{\text{def}}{=} \ell \triangleright (x). [x = z]_{s_{11}} \mid \bar{s}_{11}$$

$$P_{12} \stackrel{\text{def}}{=} c. \ell \triangleright (x). [x = z]_{s_{12}} \mid \bar{s}_{12}$$

623 with s_0, s_{11}, s_{12} fresh names.

624 At first \bar{s}_0 and \bar{s}_1 are the only observables, meaning $E_0[P_s] \downarrow_{\bar{s}_0}$ and $E_0[P_s] \downarrow_{\bar{s}_1}$, but then
625 $E_0[P_s] \longrightarrow \longrightarrow (\nu \ell = z)((\nu t)(\bar{t} \mid !t. \ell \triangleleft a. (\bar{c} \mid \ell \triangleleft b. (\bar{t} \mid c))) \mid s_1. (P_{11} \mid P_{12}) \mid \bar{s}_1) \stackrel{\text{def}}{=} P'$
626 where the three reductions have been derived using rules **R-Write**, **R-Swap**, and **R-Comm**
627 respectively. Finally, we have $P' \not\Downarrow_{\bar{s}_0}$, whereas $P' \downarrow_{\bar{s}_1}$.

628 Thus, to avoid the observable \bar{s}_0 , process $E_0[Q_s]$ must reduce to a process with b stored
629 in ℓ before doing the swap in E_0 . This implies that the swap is executed in a state that
630 corresponds to case 4 above. So for any Q' with $E[Q_s] \Longrightarrow Q'$ and $Q' \not\Downarrow_{\bar{s}_0}$ and $Q' \downarrow_{\bar{s}_1}$, such
631 process Q' has one of the following forms:

- 632 1. $Q'_1 \stackrel{\text{def}}{=} (\nu \ell = a)((\nu t)(\bar{t} \mid !t. \ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c)) \mid c^n \mid \bar{c}^n) \mid s_1. (P_{11} \mid P_{12}) \mid \bar{s}_1)$
- 633 2. $Q'_2 \stackrel{\text{def}}{=} (\nu \ell = a)((\nu t)(\ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c)) \mid !t. \ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c)) \mid c^n \mid \bar{c}^n) \mid s_1. (P_{11} \mid P_{12}) \mid \bar{s}_1)$
- 634 3. $Q'_3 \stackrel{\text{def}}{=} (\nu \ell = b)((\nu t)(\ell \triangleleft a. (\bar{t} \mid c) \mid !t. \ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c)) \mid c^n \mid \bar{c}^{n+1}) \mid s_1. (P_{11} \mid P_{12}) \mid \bar{s}_1)$
- 635 4. $Q'_4 \stackrel{\text{def}}{=} (\nu \ell = z)((\nu t)(\ell \triangleleft a. (\bar{t} \mid c) \mid !t. \ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c)) \mid c^n \mid \bar{c}^{n+1}) \mid s_1. (P_{11} \mid P_{12}) \mid \bar{s}_1)$

636 Then we use either P_{11} or P_{12} depending on the form of Q' . If Q' is of the first three forms,
637 then we use P_{11} .
638

639 Indeed, $P' \longrightarrow \longrightarrow (\nu \ell = z)((\nu t)(\bar{t} \mid !t. \ell \triangleleft a. (\bar{c} \mid \ell \triangleleft b. (\bar{t} \mid c))) \mid P_{12}) \stackrel{\text{def}}{=} P''$ using rules
640 **R-Read** and **R-Comm** respectively. Notice that $P'' \not\Downarrow_{\bar{s}_{11}}$. On the other hand, z does not appear
641 anywhere else than in a matching in Q' , thus there is no reduction $Q' \Longrightarrow Q''$ with $Q'' \downarrow_{\bar{s}_{11}}$
642 for any Q'' .

643 In the other case, it holds that $Q'_4 \longrightarrow \longrightarrow (\nu \ell = z)((\nu t)(\ell \triangleleft a. (\bar{t} \mid c) \mid !t. \ell \triangleleft b. (\bar{c} \mid \ell \triangleleft a. (\bar{t} \mid c)) \mid c^n \mid \bar{c}^n) \mid P_{11}) \stackrel{\text{def}}{=} Q''$ using rules **R-Comm**, **R-Read**, and **R-Comm** respectively.
644 Then we have $Q'' \not\Downarrow_{\bar{s}_{12}}$. However, the only output \bar{c} is behind a write $\ell \triangleleft a$ in P' . Thus, there
645 is no $P' \Longrightarrow P''$ with $P'' \downarrow_{\bar{s}_{12}}$.
646

647 We can finally conclude $P_s \not\approx_{\text{ref}} Q_s$. ◀

648 **Proof of Example 6.** Recall the definitions of the two processes (we rename the processes
649 that are given in the main text, to ease readability):

$$650 P \stackrel{\text{def}}{=} (\nu \ell_1 = 0, \ell_2 = 0)(R \mid (\nu t)(\bar{t} \mid !t. \ell_1 \triangleleft 1. \ell_1 \triangleleft 0. \ell_2 \triangleleft 1. \ell_2 \triangleleft 0. \bar{t}))$$

$$651 Q \stackrel{\text{def}}{=} (\nu \ell_1 = 0, \ell_2 = 0)(R \mid (\nu t)(\bar{t} \mid !t. \ell_1 \triangleleft 1. \ell_2 \triangleleft 1. \ell_1 \triangleleft 0. \ell_2 \triangleleft 0. \bar{t}))$$

652

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653 To prove their equivalence, we introduce the following processes:

$$654 \quad P' \stackrel{\text{def}}{=} !t. \ell_1(_). (\overline{\ell_1}\langle 1 \rangle \mid \ell_1(_). (\overline{\ell_1}\langle 0 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 1 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 0 \rangle \mid \bar{t}))))$$

$$655 \quad Q' \stackrel{\text{def}}{=} !t. \ell_1(_). (\overline{\ell_1}\langle 1 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 1 \rangle \mid \ell_1(_). (\overline{\ell_1}\langle 0 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 0 \rangle \mid \bar{t}))))$$

657

$$658 \quad P_1 = Q_1 \stackrel{\text{def}}{=} \bar{t}$$

$$659 \quad P_2 \stackrel{\text{def}}{=} \ell_1(_). (\overline{\ell_1}\langle 1 \rangle \mid \ell_1(_). (\overline{\ell_1}\langle 0 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 1 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 0 \rangle \mid \bar{t}))))$$

$$660 \quad Q_2 \stackrel{\text{def}}{=} \ell_1(_). (\overline{\ell_1}\langle 1 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 1 \rangle \mid \ell_1(_). (\overline{\ell_1}\langle 0 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 0 \rangle \mid \bar{t}))))$$

$$661 \quad P_3 \stackrel{\text{def}}{=} \ell_1(_). (\overline{\ell_1}\langle 0 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 1 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 0 \rangle \mid \bar{t})))$$

$$662 \quad Q_3 \stackrel{\text{def}}{=} \ell_2(_). (\overline{\ell_2}\langle 1 \rangle \mid \ell_1(_). (\overline{\ell_1}\langle 0 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 0 \rangle \mid \bar{t})))$$

$$663 \quad P_4 \stackrel{\text{def}}{=} \ell_2(_). (\overline{\ell_2}\langle 1 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 0 \rangle \mid \bar{t}))$$

$$664 \quad Q_4 \stackrel{\text{def}}{=} \ell_1(_). (\overline{\ell_1}\langle 0 \rangle \mid \ell_2(_). (\overline{\ell_2}\langle 0 \rangle \mid \bar{t}))$$

$$665 \quad P_5 = Q_5 \stackrel{\text{def}}{=} \ell_2(_). (\overline{\ell_2}\langle 0 \rangle \mid \bar{t})$$

667 P' and Q' are the encodings of the replicated part of P and Q . Then P_i and Q_i are the
668 processes that can be reached from P' and Q' .

669 We now show that the relation $\mathcal{R} \cup \mathcal{R}^{-1}$ is an \approx_{ip} -bisimulation where we have:

$$670 \quad \mathcal{R} \stackrel{\text{def}}{=} \left\{ \begin{array}{l} (\overline{\ell_1}\langle n_1 \rangle \mid (\nu t)(P' \mid P_i), \overline{\ell_1}\langle n'_1 \rangle \mid (\nu t)(Q' \mid Q_j)) \\ \text{for any } n_1, n'_1 \in \{0, 1\}, i, j \end{array} \right\}$$

$$671 \quad \cup \left\{ \begin{array}{l} (\overline{\ell_2}\langle n_2 \rangle \mid (\nu t)(P' \mid P_i), \overline{\ell_2}\langle n'_2 \rangle \mid (\nu t)(Q' \mid Q_j)) \\ \text{for any } n_2, n'_2 \in \{0, 1\}, i, j \end{array} \right\}$$

$$672 \quad \cup \left\{ \begin{array}{l} (\overline{\ell_1}\langle n_1 \rangle \mid \overline{\ell_2}\langle n_2 \rangle \mid (\nu t)(P' \mid P_i), \overline{\ell_1}\langle n'_1 \rangle \mid \overline{\ell_2}\langle n'_2 \rangle \mid (\nu t)(Q' \mid Q_j)) \\ \text{for any } n_1, n'_1, n_2, n'_2 \in \{0, 1\}, i, j \end{array} \right\}$$

674 First, note that the only free names appearing in those processes are ℓ_1 and ℓ_2 . Thus for any
675 $P \mathcal{R} Q$, the only actions to consider are $\tau, \ell_i\langle n \rangle$ and $\overline{\ell_i}\langle n \rangle$, for $i = 1, 2$.

676 For any $P \mathcal{R} Q$, we have:

677 ■ If $P \xrightarrow{\tau} P_0$, then $P_0 \mathcal{R} Q$

678 ■ If $P \xrightarrow{\ell_i\langle n \rangle} P_0$, then $P_0 \mathcal{R} Q \mid \overline{\ell_i}\langle n \rangle$

679 ■ If $P \xrightarrow{\overline{\ell_i}\langle n \rangle} P_0$, then either $Q \xrightarrow{\overline{\ell_i}\langle n \rangle} Q_0$ and $P_0 \mathcal{R} Q_0$, or $Q \xrightarrow{\overline{\ell_i}\langle 1-n \rangle} Q_0$. In this case, we
680 use rule **Ext** (from Definition 22) to add the other location if $\Delta \neq \ell_1, \ell_2$. Then after at
681 most 5 internal transitions (by cycling around the P_i or Q_j), we obtain a process Q_0 that
682 can make the required transition $Q_0 \xrightarrow{\overline{\ell_i}\langle n \rangle} Q'_0$ with $P_0 \mathcal{R} Q'_0$.

683 As $\mathcal{R} \cup \mathcal{R}^{-1}$ is an \approx_{ip} -bisimulation, we have $\mathcal{R} \subseteq \approx$. Moreover, $(\nu \ell_1, \ell_2)(\mathcal{E}[[R]] \mid [])$ is
684 an active context, so this implies $\mathcal{E}[[P]] \approx \mathcal{E}[[Q]]$. By Theorems 21 and 17, we can conclude
685 $P \cong_{\text{ref}}^e Q$.

686 To extend this result to barbed congruence, we notice that for all σ ,

687 1. either $P\sigma = (\nu \ell_1 = 0, \ell_2 = 0)(R\sigma \mid (\nu t)(\bar{t} \mid !t. \ell_1 \triangleleft 1. \ell_1 \triangleleft 0. \ell_2 \triangleleft 1. \ell_2 \triangleleft 0. \bar{t}))$

688 2. or $P\sigma = (\nu \ell_1 = 0, \ell_2 = 0)(R\sigma \mid (\nu t)(\bar{t} \mid !t. \ell_1 \triangleleft 0. \ell_1 \triangleleft 0. \ell_2 \triangleleft 0. \ell_2 \triangleleft 0. \bar{t}))$

689 3. or $P\sigma = (\nu \ell_1 = 1, \ell_2 = 1)(R\sigma \mid (\nu t)(\bar{t} \mid !t. \ell_1 \triangleleft 1. \ell_1 \triangleleft 1. \ell_2 \triangleleft 1. \ell_2 \triangleleft 1. \bar{t}))$

690 As $P \cong_{\text{ref}}^e Q$ holds for any R , it also holds for any $R\sigma$, which prove the first case. Moreover,
 691 the proof never uses the fact that 0 and 1 are distinct, so we can prove in the same way that
 692 cases 2 and 3 hold.

693 We conclude $P \cong_{\text{ref}} Q$. ◀

694 We now present an additional example, which corresponds to a generalisation of Example 6.

695 ▶ **Example 29.** Here we remove the assumption that the two references can only hold values
 696 0 and 1. This enables the context to store fresh names in references. If used with the original
 697 processes, these are distinguished by using those fresh values to block transition along the
 698 lines of Example 5. To make these processes equivalent again, we could add in parallel a
 699 buffer as in Example 4. However, by making these additions, we would also enable P_1 to
 700 desynchronise the content in ℓ_1 and ℓ_2 and have (1, 1). The solution is to prevent those
 701 buffers from writing at a different ‘time’ than the ‘time’ they have read. For this we introduce
 702 a more complex buffer B_i^j . Consider the following processes:

$$\begin{aligned}
 703 \quad B_i^j &\stackrel{\text{def}}{=} r(x^j). \mathbf{0} \mid !r(x^j). t_i. \ell^j \bowtie x^j(y^j). (\bar{r}(y^j) \mid \bar{t}_i) \\
 704 \quad S_i^j &\stackrel{\text{def}}{=} !t_i. \ell^j \triangleright (x^j). (\bar{t}_i \mid (\nu r)(\bar{r}(x^j) \mid B_i^j)) \\
 705 \quad P &\stackrel{\text{def}}{=} (\nu t_1, t_2, t_3, t_4) \left(\bar{t}_1 \mid !t_1. \ell^1 \triangleleft 1. \bar{t}_2 \mid S_1^1 \mid S_1^2 \mid !t_2. \ell^1 \triangleleft 0. \bar{t}_3 \mid S_2^1 \mid S_2^2 \right. \\
 706 \quad &\quad \left. \mid !t_3. \ell^2 \triangleleft 1. \bar{t}_4 \mid S_3^1 \mid S_3^2 \mid !t_4. \ell^2 \triangleleft 0. \bar{t}_1 \mid S_4^1 \mid S_4^2 \right) \\
 707 \quad Q &\stackrel{\text{def}}{=} (\nu t_1, t_2, t_3, t_4) \left(\bar{t}_1 \mid !t_1. \ell^1 \triangleleft 1. \bar{t}_2 \mid S_1^1 \mid S_1^2 \mid !t_2. \ell^2 \triangleleft 1. \bar{t}_3 \mid S_2^1 \mid S_2^2 \right. \\
 708 \quad &\quad \left. \mid !t_3. \ell^1 \triangleleft 0. \bar{t}_4 \mid S_3^1 \mid S_3^2 \mid !t_4. \ell^2 \triangleleft 0. \bar{t}_1 \mid S_4^1 \mid S_4^2 \right)
 \end{aligned}$$

712 We have $P \cong_{\text{ref}} Q$. If we take $E \stackrel{\text{def}}{=} (\nu \ell^1 = 0)(\nu \ell^2 = 0)[\]$, we have
 713 $E[Q] \longrightarrow \longrightarrow (\nu \ell^1 = 1)(\nu \ell^2 = 1)Q'$ for some Q' . However, there is no sequence of reductions
 714 such that $E[P] \Longrightarrow (\nu \ell^1 = 1)(\nu \ell^2 = 1)P'$ for any P' .

715 If we forget all S_i^j 's, then these processes are similar to the ‘loop’ used in the previous
 716 example but split into multiple replications. Those S_i^j 's help to equate the two processes
 717 even if the context can write any value in ℓ_1, ℓ_2 .

718 Process S_i^j can only be activated when \bar{t}_i is available. It then reads the content of ℓ_j to
 719 initialise a new buffer B_i^j .

720 Process B_i^j contains value x_i^j that is the object of $\bar{r}(x_i^j)$. Process B_i^j can be stopped by
 721 making the communication with the first input on r , or can be used to swap its content with
 722 the content of ℓ^j . Note that this swap can only be done when \bar{t}_i is available, so it cannot be
 723 used to desynchronise the content in ℓ_1 , and ℓ_2 .

724 B Operational Semantics of $A\pi$: Reduction and Labelled Transitions

725 Reduction

Structural congruence is defined as the smallest congruence that satisfies the following axioms:

$$\begin{aligned}
 P \mid \mathbf{0} &\equiv P & P \mid Q &\equiv Q \mid P & P \mid (Q \mid R) &\equiv (P \mid Q) \mid R & !P &\equiv P \\
 P \mid (\nu n)Q &\equiv (\nu n)P \mid Q \text{ if } n \notin \text{fn}(P) & (\nu n)(\nu m)P &\equiv (\nu m)(\nu n)P & (\nu n)\mathbf{0} &\equiv \mathbf{0} \\
 [x = x]P &\equiv P
 \end{aligned}$$

31:20 On the Representation of References in the pi-calculus

$$\begin{array}{c}
\text{Inp: } \frac{}{n(x).P \xrightarrow{n\langle m \rangle} P\{m/x\}} \qquad \text{Out: } \frac{}{\bar{n}\langle m \rangle \xrightarrow{} \mathbf{0}} \\
\text{Open: } \frac{P \xrightarrow{\bar{n}\langle m \rangle} P'}{(\nu m)P \xrightarrow{(\nu m)\bar{n}\langle m \rangle} P'} \text{ if } m \neq n \qquad \text{Rep: } \frac{P \mid !P \xrightarrow{\mu} P'}{!P \xrightarrow{\mu} P'} \\
\text{Res: } \frac{P \xrightarrow{\mu} P'}{(\nu n)P \xrightarrow{\mu} (\nu n)P'} \text{ if } n \notin \mu \qquad \text{Par: } \frac{P \xrightarrow{\mu} P'}{P \mid Q \xrightarrow{\mu} P' \mid Q} \text{ if } \text{bn}(\mu) \cap \text{fn}(Q) = \emptyset \\
\text{Comm: } \frac{P \xrightarrow{n\langle m \rangle} P' \quad Q \xrightarrow{\bar{n}\langle m \rangle} Q'}{P \mid Q \xrightarrow{\tau} P' \mid Q'} \\
\text{Close: } \frac{P \xrightarrow{n\langle m \rangle} P' \quad Q \xrightarrow{(\nu m)\bar{n}\langle m \rangle} Q'}{P \mid Q \xrightarrow{\tau} (\nu m)(P' \mid Q')} \text{ if } m \notin \text{fn}(P) \qquad \text{Match: } \frac{P \xrightarrow{\mu} P'}{[n = n]P \xrightarrow{\mu} P'}
\end{array}$$

■ **Figure 3** Labelled Transition Semantics for $A\pi$

Active contexts in $A\pi$ are defined by:

$$E ::= [] \mid E \mid P \mid (\nu n)E .$$

Reduction is defined by the following rules:

$$\frac{P \equiv P' \quad P' \longrightarrow Q' \quad Q' \equiv Q}{P \longrightarrow Q} \qquad \frac{P \longrightarrow P'}{E[P] \longrightarrow E[Q]} \qquad \frac{}{n(x).P \mid \bar{n}\langle m \rangle \longrightarrow P\{m/x\}}$$

726 Labelled Transition Semantics

Actions of the LTS are defined as follows:

$$\mu ::= n(m) \mid \bar{n}\langle m \rangle \mid (\nu m)\bar{n}\langle m \rangle \mid \tau .$$

727 Transitions are defined in Figure 3. The symmetric versions of rules PAR, COM and CLOSE
728 are omitted. Weak transitions are defined by $\Rightarrow \stackrel{\text{def}}{=} \tau^*$, $\xRightarrow{\mu} \stackrel{\text{def}}{=} \Rightarrow \xrightarrow{\mu} \Rightarrow$, and $\xRightarrow{\hat{\mu}} \stackrel{\text{def}}{=} \xRightarrow{\mu}$ if $\mu \neq \tau$
729 and \Rightarrow otherwise.