

Local  $\pi$ -Calculus at Work:  
Mobile Objects as Mobile Processes<sup>1</sup>

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## Abstract

*Obliq* is a lexically-scoped, distributed, object-based programming language. In *Obliq*, the *migration* of an object is proposed as creating a clone of the object at the target site, whereafter the original object is turned into an alias for the clone. *Obliq* has only an informal semantics, so there is no proof that this style of migration is safe, i.e., transparent to object clients. In previous work, we introduced *Øjeblik*, an abstraction of *Obliq*, where, by lexical scoping, sites have been abstracted away. We used *Øjeblik* in order to exhibit how the semantics behind *Obliq*'s implementation renders migration unsafe. We also suggested a modified semantics that we conjectured instead to be safe. In this paper, we rewrite our modified semantics of *Øjeblik* in terms of  $\pi$ -calculus, and we use it to formally prove the correctness of *object surrogation*, the abstraction of object migration in *Øjeblik*.

# 1 Introduction

The work presented in this paper is in line with the research activity to use the  $\pi$ -calculus as a

**Aliasing Semantics** In [NHK $\blacksquare$ 00], we gave several proposals of configuration-style semantics for  $\mathcal{O}$ jeblik. One of them fits the *Obliq* implementation [Car94, Car95], but does not guarantee the correctness of object surrogation as of [NHK $\blacksquare$ 00].

<i>Channels:</i>	$c \in \mathbf{C}$	<i>Values</i>	
<i>Keys:</i>	$k \in \mathbf{K}$	$v ::= x$	variable
<i>Names:</i>	$\in \mathbf{N}$	$ \ell_v$	variant
$n ::= c \mid k$		$ \langle v_1..v_n \rangle$	tuple
<i>Auxiliary:</i>	$u \in \mathbf{U}$	<i>Types</i>	
<i>Variables:</i>	$\in \mathbf{X}$	$T ::= \mathbf{C} T)$	channel type
$x ::= n \mid u$		$ \mathbf{K}$	key type
<i>Labels</i>	$\in \mathbf{L}$	$ \ell_1:T_1; \dots; \ell_m:T_m]$	variant type
$\ell, \ell_1, \ell_2, \dots$		$ \langle T_1..T_m \rangle$	tuple type
		$ \mathbf{X}$	type variable
		$ \mu X. T$	recursive type
<i>Processes</i>			
$P ::= \mathbf{0}$			nil process
$ \ c x).P$			single <i>input</i>
$ \ \bar{c}v$			output
$ \ P_1 \mid P_2$			parallel
$ \ \nu n:T) P$			restriction
$ \ !c x).P$			replicated <i>input</i>
$ \ \text{if } [k=k_1] \text{ then } P_1 \text{ elif } [k=k_2] \text{ then } P_2 \text{ else } P_3$			key testing
$ \ \text{case } v \text{ of } \ell_1\text{-}x_1):P_1; \dots; \ell_m\text{-}x_m):P_m$			variant <i>destructor</i>
$ \ \text{let } x_1..x_m) = v \text{ in } P$			tuple <i>destructor</i>
$ \ \text{wrong}$			run time error
The <i>locality constraint</i> requires that in <i>single</i> and <i>replicated</i> ) <i>inputs</i> and in <i>variant</i> and <i>tuple</i> ) <i>destructors</i> the bound names $x, x_1, \dots, x_m$ must not be used in free input position within the respective scope $P, P_1, \dots, P_m$ .			

Table 1: The Calculus  $L\pi^+$

reasoning about, concurrent object-oriented languages. In particular, we can easily guarantee the uniqueness of object identities—a fundamental feature of objects: in object-oriented languages, the name of an object may be transmitted; the recipient may use that name to access the methods of the object, but it cannot create a new object with the same name. When representing objects in the  $\pi$ -calculus, this translates directly into the constraint that the process receiving an object name may only use it in output actions—a guarantee in our setting.

## 2.1 Terms and Types

In Table 1, we introduce the calculus  $L\pi^+$ , a typed version of polyadic  $L\pi$  with: i) labelled values  $\ell_v$ , called *variants* [San98], with case analysis; ii) tuple values  $\langle v_1..v_n \rangle$ , with pattern matching, iii) constants  $k$ , called *keys*, with equality; iv) a *wrong* construct to model run-time typing errors.

We introduce a few syntactic categories: the set  $\mathbf{X}$  of *variables* includes the set  $\mathbf{N}$  of *names* (constants and variables) consisting of the two disjoint sets  $\mathbf{C}$  of *channels* and  $\mathbf{K}$  of *keys*. The auxiliary variables in the set  $\mathbf{U}$  are variables for complex values.  $\mathbf{L}$  is the set of *labels*. In addition to the metavariables mentioned in the grammar, we let  $s, p, q, r, m, t$  range over channels,  $y$  over variables,  $w$  over values,  $Q$  over processes, and  $i, j, d, h, m$  over tuple, variant, or other indices. We abbreviate  $\ell_{-}\langle \rangle$  and  $\ell_{-} )$  as  $\ell$ , as well as  $\bar{q}\langle \rangle$  and  $q ).P$  as  $\bar{q}$  and  $q.P$ , respectively, while  $\tilde{v}$  denotes

a sequence  $v_1 \dots v_m$ .

Restriction, both inputs, and both destructors are *binders* for the names  $x, x_1, \dots, x_m$  in the respective scopes  $P, P_1, \dots, P_m$ . We assume the usual definitions of free and bound occurrences of names, based on these binders; the inductively defined functions  $\text{fn } P$  and  $\text{bn } P$  denote those of process  $P$ . Similarly,  $\text{fc } P$  and  $\text{bc } P$  denote the free and bound channels of process  $P$ . Moreover,  $\text{fn } P = \text{fn } P \cup \text{bn } P$  and  $\text{c } P = \text{fc } P \cup \text{bc } P$ . *Substitutions*, ranged over by  $\sigma$ , are type-preserving functions from variables to values (types are introduced below). For an expression  $e$ ,  $e\sigma$  is the result of applying  $\sigma$  to  $e$ , with the usual renaming to avoid captures. *Relabellings*, ranged over by  $\rho$ , permit replacing a label  $\ell$  with another label  $\ell'$ . We denote such a relabelling with  $[\ell'/\ell]$ . The application of a relabelling to a term is defined thus:

- $\ell$



$$\begin{array}{l}
\text{INP)} \frac{-}{c \ x).P \xrightarrow{cv} P\{v/x\}} \quad \text{REP)} \frac{-}{!c \ x).P \xrightarrow{cv} P\{v/x\} \mid !c \ x).P} \\
\text{OUT)} \frac{-}{\bar{c}v \xrightarrow{\bar{c}v} \mathbf{0}} \quad \text{OPEN)} \frac{P \xrightarrow{(\nu\tilde{q}:\tilde{T})\bar{c}v} P' \quad n \in \text{fn } v \setminus \{\tilde{q}, c\}}{\nu n:T) P \xrightarrow{(\nu n:T, \tilde{q}:\tilde{T})\bar{c}v} P'} \\
\text{COM)} \frac{P_1 \xrightarrow{(\nu\tilde{q}:\tilde{T})\bar{c}v} P'_1 \quad P_2 \xrightarrow{cv} P'_2 \quad \tilde{q} \cap \text{fn } P_2 = \emptyset}{P_1 \mid P_2 \xrightarrow{\tau} \nu\tilde{q}:\tilde{T}) P'_1 \mid P'_2)} \\
\text{PAR)} \frac{P_1 \xrightarrow{\mu} P'_1 \quad \text{bn } \mu \cap \text{fn } P_2 = \emptyset}{P_1 \mid P_2 \xrightarrow{\mu} P'_1 \mid P_2} \\
\text{RES)} \frac{P \xrightarrow{\mu} P' \quad n \notin \text{fn } \mu}{\nu n:T) P \xrightarrow{\mu} \nu n:T) P'} \\
\text{TEST-1)} \frac{P_1 \xrightarrow{\mu} P'_1 \quad k_1 = k}{\text{if } [k=k_1] \text{ then } P_1 \text{ elif } [k=k_2] \text{ then } P_2 \text{ else } P_3 \xrightarrow{\mu} P'_1} \\
\text{TEST-2)} \frac{P_2 \xrightarrow{\mu} P'_2 \quad k_1 \neq k = k_2}{\text{if } [k=k_1] \text{ then } P_1 \text{ elif } [k=k_2] \text{ then } P_2 \text{ else } P_3 \xrightarrow{\mu} P'_2} \\
\text{TEST-3)} \frac{P_3 \xrightarrow{\mu} P'_3 \quad k_1 \neq k \neq k_2}{\text{if } [k=k_1] \text{ then } P_1 \text{ elif } [k=k_2] \text{ then } P_2 \text{ else } P_3 \xrightarrow{\mu} P'_3} \\
\text{CASE)} \frac{P_j\{v/x_i\} \xrightarrow{\mu} Q \quad j \in 1..m}{\text{case } \ell_{j-v} \text{ of } \ell_{1-x_1}:P_1; \dots; \ell_{m-x_m}:P_m \xrightarrow{\mu} Q} \\
\text{LET)} \quad P\{v_1..v_m/x_1..x_m\}
\end{array}$$



The proof of the above result is standard see

**Definition 2. (Typed bisimilarity)** Typed bisimilarity, is the largest typed relation  $\mathcal{S}$  such that  $\Delta; P; Q \in \mathcal{S}$  implies:

1. If  $P \xrightarrow{\tau} P'$ , then there exists  $Q'$  s.t.  $Q \Rightarrow Q'$  and  $\Delta; P'; Q' \in \mathcal{S}$ .
2. If  $P \xrightarrow{(\nu \tilde{n}:\tilde{T}) \bar{c}v} P'$ , with  $\tilde{n} \cap \text{fn } Q = \emptyset$ , then there exists  $Q'$  such that  $Q \xrightarrow{(\nu \tilde{n}:\tilde{T}) \bar{c}v} Q'$  and  $\Delta, \tilde{n}:\tilde{T}; P'; Q' \in \mathcal{S}$ .
3. If
  - (i)  $\Gamma$  is a closed extension of  $\Delta$ ,
  - (ii)  $\Gamma \vdash c:\mathbf{C } T$  and  $\Gamma \vdash v:T$ ,
  - (iii)  $P \xrightarrow{cv} P'$ , with  $\text{fc } v \cap \text{fc } P \mid Q = \emptyset$ ,

then there exists  $Q'$  such that:

- (i) either  $Q \xrightarrow{cv}$

- (i)  $\Gamma$  is a closed extension of  $\Delta$ ,
- (ii)

$a, b ::= \mathbb{O}$	object
$a.l\langle a_1 \dots a_n \rangle$	method invocation
$a.l \leftarrow m$	method update
$a.clone$	shallow copy
$a.alias\langle b \rangle$	object aliasing
$a.surrogate$	object surrogation
$a.ping$	object ping
$s, x, y, z$	variables
$let\ x:A = a\ in\ b$	local definition
$fork\langle a \rangle$	thread creation
$join\langle a \rangle$	thread destruction
$\mathbb{O} ::= [l_j = m_j]_{j \in J}$	object record
$m_j ::= \varsigma\ s_j:A, \tilde{x}_j:\tilde{B}_j) b_j$	method
$A, B ::= [l_j:\tilde{B}_j \rightarrow \hat{B}_j]_{j \in J}$	object record type
$Thr\ A$	thread type

Table 4:  $\mathcal{O}$ jeblik Syntax and Types

we show that the relation

$$\mathcal{S} = \{(\bar{p}v \mid R, \nu r:\mathbf{C}\ T) \bar{p}w \mid r \triangleright q \mid R\} \cup \cong$$

is a barbed bisimulation up to  $\equiv$ . The requirements on the barbs are easily satisfied. As for the bisimulation game on silent moves, the only interesting case is when there is a communication along  $p$ , that is, when  $R \xrightarrow{p(x)} R'$ . In this case we get, up to structural equivalence, the pair of processes

$$(Q\{q/r\}, \nu r:\mathbf{C}\ T) \quad Q \mid r \triangleright q$$

where  $Q = R'\{w/x\}$ . By Lemma 2.14 we can conclude.  $\square$

### 3 $\mathcal{O}$ jeblik: A Concurrent Object Calculus

In this section, we present  $\mathcal{O}$ jeblik [NHK $\blacksquare$ 00], a typed abstraction of Obliq designed to study object migration.  $\mathcal{O}$ jeblik-expressions and  $\mathcal{O}$ jeblik-types are generated by the grammar in Table 4, where  $a$  ranges over  *$\mathcal{O}$ jeblik-terms*,  $l$  over *method labels*,  $m$  over *method bodies*,  $s, x, y, z$  over *variables*,  $\mathbb{O}$  over *object records*, and  $A, B$  over types. The type language extends the one of the imperative object calculus [AC96] by thread types  $Thr\ A$ . Pairs  $\tilde{x}_j:\tilde{B}_j$  denote sequences  $x_{1_j}:B_{1_j} \dots x_{n_j}:B_{n_j}$ . Function types  $A \rightarrow B$  do only occur in object types  $[l_j:\tilde{B}_j \rightarrow \hat{B}_j]_{j \in J}$ , so they are not first-class types. Yet, we sometimes abbreviate such object types by  $[l_j:A_j]_{j \in J}$  to clarify that a type is not a thread type. Typed terms are defined by adding type annotations to all binding occurrences of variables: in let-expressions and in method declarations.

For the sake of simplicity, compared to Obliq, in  $\mathcal{O}$ jeblik we omit ground values (like numbers, booleans, strings, etc.), data operations, and procedures, we restrict field selection to method invocation, we restrict multiple cloning to single cloning, we omit flexibility of object attributes, we replace field aliasing with object aliasing, we omit explicit distribution, and we omit exceptions and advanced synchronisation, so we get a feasible, but still non-trivial language. As in Obliq, computation follows the call-by-value evaluation order. In particular, in the following, whenever we use a term  $a$ , we implicitly assume that we have first evaluated  $a$  to some actual value, i.e. in most cases to an object reference.

## Objects

An object record  $[l_j=m_j]_{j \in J}$  is a finite collection of updatable named methods  $l_j=m_j$ , for pairwise distinct labels  $l_j$ . In a method  $\varsigma s, \tilde{x}$

**Self-Infliction**

The *current method* of a thread is the last method invoked in it that has not yet

$\text{T-VAR)} \frac{\Gamma \ x) = A}{\Gamma \vdash x:A}$	$\text{T-LET)} \frac{\Gamma \vdash a:A \quad \Gamma, x:A \vdash b:B}{\Gamma \vdash \text{let } x:A = a \text{ in } b : B}$
$\text{T-FORK)} \frac{\Gamma \vdash a:A}{\Gamma \vdash \text{fork}\langle a \rangle : \text{Thr } A}$	$\text{T-JOIN)} \frac{\Gamma \vdash a : \text{Thr } A)}{\Gamma \vdash \text{join}\langle a \rangle : A}$
$\text{T-OBJ)} \frac{\forall j \in J \quad \Gamma, s_j:A, \tilde{x}_j:\tilde{B}_j \vdash b_j:\hat{B}_j \quad A = [l_j:\tilde{B}_j \rightarrow \hat{B}_j]_{j \in J}}{\Gamma \vdash [l_j =_{\zeta} s_j:A, \tilde{x}_j:\tilde{B}_j)b_j]_{j \in J} : A}$	
$\text{T-INV)} \frac{\Gamma \vdash a : [l_j:\tilde{B}_j \rightarrow \hat{B}_j]_{j \in J} \quad \Gamma \vdash \tilde{b}_k:\tilde{B}_k \quad k \in J}{\Gamma \vdash a.l_k\langle \tilde{b}_k \rangle : \tilde{B}_k}$	
$\text{T-UPD)} \frac{\Gamma \vdash a:A \quad A = [l_j:\tilde{B}_j \rightarrow \hat{B}_j]_{j \in J} \quad \Gamma, s:A, \tilde{x}:\tilde{B}_k \vdash b:\hat{B}_k \quad k \in J}{\Gamma \vdash a.l_k \Leftarrow_{\zeta} s:A, \tilde{x}:\tilde{B}_k)b : A}$	
$\text{T-PING)} \frac{\Gamma \vdash a:A \quad A = [l_j:A_j]_{j \in J}}{\Gamma \vdash a.\text{ping} : A}$	
$\text{T-CLO)} \frac{\Gamma \vdash a:A \quad A = [l_j:A_j]_{j \in J}}{\Gamma \vdash a.\text{clone} : A}$	
$\text{T-ALI)} \frac{\Gamma \vdash a, b:A \quad A = [l_j:A_j]_{j \in J}}{\Gamma \vdash a.\text{alias}\langle b \rangle : A}$	
$\text{T-SUR)} \frac{\Gamma \vdash a:A \quad A = [l_j:A_j]_{j \in J}}{\Gamma \vdash a.\text{surrogate} : A}$	

Table 5: Typing Rules for  $\mathcal{O}$ jeblik

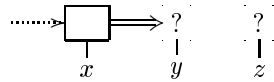
semantics of alias nodes. We address the reader to [NHK $\blacksquare$ 00,  $\blacksquare$ er00] for a full explanation about

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let z = [l="bar"] in
  let y = [l="foo"] in
    let x = [l=⊔ s, w) s.alias(w)] in x.l⟨y⟩; x.l⟨z⟩

```

after it carried out the invocation  $x.l\langle y \rangle$ , that is, when the object referred to by  $x$  has turned itself into an alias for  $y$  and then terminated its activity. We depict the situation as follows



where, in general, the node  $x$  may itself be referred to by other aliases, while  $y$  and  $z$  may be either an alias or an object record. In fact, the alias  $x \rightarrow y$  is *stable* in the very sense: no re-aliasing operation on  $x$  to another node will ever possibly take place



By calling  $x.l\langle x \rangle$ , the aliasing operation  $x.alias(x)$  is carried out giving rise to the cyclic alias chain  $x \rightarrow x$ . As a consequence, the following external method call  $x.k$  will give rise to a diverging computation.

### 4.3 On forwarding requests within alias nodes

In this section, we describe the behaviour of single alias nodes in Øjeblik by addressing four crucial questions.

1. *What* is the current self of forwarded requests?
2. *Who* is in charge of sending the result of a forwarded external request?
3. *When* does the forwarding take place?
4. *Which* requests are forwarded and which requests fail in an alias node?

Our semantics behaves as follows:

**What?** Let  $a$  be an alias node forwarding requests to  $b$ , that is,  $a \rightarrow b$ . Let  $c$  be a third object invoking a method of  $a$ . Then, when serving the (external) request, the alias  $a$  simply forwards the request to  $b$ , and  *$c$  is still the current self*. Roughly speaking, it is as if  $c$  invokes directly a method of  $b$ . The self-inflicted case is trivial because then  $a = c$ .

**Who?** As above, let  $a \rightarrow b$  and  $c$  be a third object invoking a method of  $a$ . Since alias nodes simply forward requests unchanged, also *the transmission of the result of the request is delegated to  $b$* . As a consequence: should the request in  $a$  have required a mutex, then the mutex can already be released once the request has been forwarded to  $b$ .

**When?** When addressed to stable alias nodes, incoming external requests do not have to wait until previously forwarded requests (there can only be external ones in this case) have successfully signalled termination from their point of action. However, when addressed to unstable alias nodes, incoming external requests must wait for the termination of previous (external and self-inflicted) requests.

**Which?** Protected external requests are supposed to fail only when addressed to non-aliased nodes, thus only in endpoints of alias chains.

- Method invocations (as well as pings and surrogations) are always forwarded (by transitivity to the endpoint of the chain, if it exists).
- Self-inflicted cloning and self-inflicted aliasing are performed at the alias node; external cloning and external aliasing are forwarded because they can possibly reach another node in the alias chain where they are self-inflicted and therefore executable.
- Self-inflicted update requests are forwarded. External update requests are forwarded because they may reach a (non-aliased) object that serves them.

## 5 A translational semantics for Øjeblik

In this section we give a *translational semantics* of Øjeblik into  $L\pi^+$  according to the informal semantics given in Sections 3 and 4. In addition to the syntax of  $L\pi^+$  we use standard abbreviations for:

- *polyadic input*  $a \ x_1 \dots x_n).P \stackrel{\text{def}}{=} (a \ y).\text{let } (x_1 \dots x_n) = y \text{ in } P$  where  $y \notin \text{fn } P$ ). We will also write  $\mathbf{C} \langle T_1 \dots T_n \rangle$  instead of  $\mathbf{C} \langle T_1 \dots T_n \rangle$  denoting the type of a channel carrying a tuple.
- *polyadic case destructor*  $\ell_-. \ x_1 \dots x_n).P \stackrel{\text{def}}{=} (\ell_-. \ y).\text{let } (x_1 \dots x_n) = y \text{ in } P$ , where  $y \notin \text{fn } P$ );

$$\begin{aligned}
\llbracket a.\text{clone} \rrbracket_p^k &\stackrel{\text{def}}{=} (\nu q) \left( \llbracket a \rrbracket_q^k \mid q(y, k') . \bar{y}(\text{cln}_p, k') \right) \\
\llbracket a.\text{alias}(b) \rrbracket_p^k &\stackrel{\text{def}}{=} (\nu q_x q_y) \left( \llbracket a \rrbracket_{q_y}^k \mid q_y(y, k_y) . (\llbracket b \rrbracket_{q_x}^{k_y} \mid q_x(x, k_x) . \bar{y}(\text{ali}_p, k_x)) \right) \\
\llbracket a.l_j \leftarrow \zeta(s, \tilde{x}) b \rrbracket_p^k &\stackrel{\text{def}}{=} (\nu q) \left( \llbracket a \rrbracket_q^k \mid q(y, k') . (\nu t) ( ! t(s, \tilde{x}, r, k) . \llbracket b \rrbracket_r^k \mid \bar{y}(\text{upd}_j, t, p, k') ) \right)
\end{aligned}$$

to become

$\llbracket \mathbb{O} \rrbracket_p^k \stackrel{\text{def}}{=} \nu s \tilde{t} \left( \bar{p} \langle s, k \rangle \mid \text{newO}_{\mathbb{O}} \langle s, \tilde{t} \rangle \mid \prod_{j \in J} ! t_j s_j, \tilde{x}_j, r, k' . \llbracket b_j \rrbracket_r^{k'} \right)$
$\text{newO}_{\mathbb{O}} \langle s, \tilde{t} \rangle \stackrel{\text{def}}{=} \nu m_e m_i k_e k_i \left( \bar{m}_e \mid \text{OM}_{\mathbb{O}} \langle s, m_e, m_i, k_e, k_i, \tilde{t} \rangle \right)$
$\text{newA}_{\mathbb{O}} \langle s, s_a \rangle \stackrel{\text{def}}{=} \nu m_e m_i k_e k_i \left( \bar{m}_e \mid \text{AM}_{\mathbb{O}} \langle s, m_e, m_i, k_e, k_i, s_a \rangle \right)$
$\text{OM}_{\mathbb{O}} \langle s, \tilde{m}, k_e, k_i, \tilde{t} \rangle \stackrel{\text{def}}{=} s \ l, k) . \nu k^* \left( \right.$ <p>if <math>[k=k_i]</math> then</p> <p>case <math>l</math> of <math>\text{cln}_- r</math> : <math>\text{OM}_{\mathbb{O}} \langle s, \tilde{m}, k_e, k^*, \tilde{t} \rangle \mid \nu s^* \left( \bar{r} \langle s^*, k^* \rangle \mid \text{newO}_{\mathbb{O}} \langle s^*, \tilde{t} \rangle \right) ;</math></p> <p>ali_ <math>s_a, r</math> : <math>\text{AM}_{\mathbb{O}} \langle s, \tilde{m}, k_e, k^*, s_a \rangle \mid \bar{r} \langle s_a, k^* \rangle ;</math></p> <p>upd<math>_j</math></p>



without affecting the state of the manager, so these transitions are completely ignored in Figure 1.

**Serving external requests** [ $k=k_e$ ]



to retrieve the value of a fork'ed term  $a$ , but we used it to send the result channel of the join'ing term, together with its current key—this is precisely represented in the translation of  $\text{Thr } A$ ).

According to the translation of types, we can add type declarations in a straightforward way to all bindings in the translation of terms, as mentioned, although omitted, in Section 5.

Types witness the clean representation of  $\mathcal{O}$ jeblik terms as  $\pi$ -calculus terms.

**Theorem 6.1 (Type Soundness)** *Let  $a \in \mathcal{L}$ , let  $\Gamma$  be a type-environment, and let  $A$  be a type. Then  $\Gamma \vdash a:A$  if and only if  $\llbracket \Gamma \rrbracket, p:\mathbf{R} \llbracket A \rrbracket, k:\mathbf{K} \vdash \llbracket a \rrbracket_p^k$  for names  $p$  and  $k$ .*

PROOF. The implication from left to right is proved using induction in the depth of the derivation of  $\Gamma \vdash a:A$  with a case analysis of the last rule used. The implication from right to left is proved by induction in the structure of  $a$ . Details can be found in Appendix A.2.  $\square$

In addition to the initial correspondence of types in  $\mathcal{O}$ jeblik and their  $\pi$ -calculus counterparts, the preservation of types under reduction in the  $\pi$ -calculus provides us for free with preservation of  $\mathcal{O}$ jeblik types, thus witnessing the subject reduction theorem based on the operational



PROOF. By inspection of the encoding. If a manager is present, it must have been created at some point as described in the encoding, because initially, there is none. Upon creation, its name *ssome*

where the keys mentioned in  $\tilde{v}$  of  $\text{PP}_\circ\langle\dots\rangle$  neither match  $k_e$  nor  $k_i$ . Notice that  $\text{newO}_\circ\langle s, \tilde{t} \rangle \equiv \nu k_i \text{freeO}_\circ\langle s, k_i, \tilde{t}, \emptyset \rangle$ , and analogously for  $\text{newA}_\circ\langle\dots\rangle$ .

*Observation 4:* An

$C[\cdot] ::= [\cdot]$	$  [ l_k = \varsigma \ s, \tilde{x} ) C[\cdot], l_{j \neq k} = m_{j \neq k} ]_{j \in J}$
$  C[\cdot].l(\tilde{a})$	$  a.l(\tilde{a}, C[\cdot], \tilde{a})$
$  C[\cdot].l \leftarrow m$	$  a.l \leftarrow \varsigma \ s, \tilde{x} ) C[\cdot]$
$  C[\cdot].alias(b)$	$  a.alias(C[\cdot])$
$  C[\cdot].clone$	
$  C[\cdot].surrogate$	$  C[\cdot].ping$
$  let \ x = C[\cdot] \ in \ b$	$  let \ x = a \ in \ C[\cdot]$
$  fork(C[\cdot])$	$  join(C[\cdot])$

Table 9: Øjeblik contexts

adds one unconditional step after reducing  $a$ ) and that the notion of equivalence takes all Øjeblik contexts into account, Equation 1 can be reduced to the problem of surrogation on variables:

$$x \doteq x.surrogate \quad 2)$$

However, there is an inherent problem with Equation 2, which is exhibited by

## 7.2 On the absence of self-inflicted surrogation

One of the main observations in [NHK00] was that the safety equation can not hold in full generality for  $\mathcal{O}$ jeblik-contexts, in which the operation  $x.\text{surrogate}$  could occur

$$\llbracket a.\text{surrogate}^* \rrbracket_p^k \stackrel{\text{def}}{=} (\nu q) ( \llbracket a \rrbracket_q^k \mid q(y, i) . \bar{y} \langle \text{sur}^* \_p, i \rangle )$$

$$\llbracket a.\text{ping}^* \rrbracket_p^k \stackrel{\text{def}}{=} (\nu q) ( \llbracket a \rrbracket_q^k \mid q(y, i) . \bar{y} \langle \text{png}^* \_p, i \rangle )$$

$$\text{OM}_{\mathbb{O}}^*(s, \tilde{m}, k_e, k_i, \tilde{t}) \stackrel{\text{def}}{=} s(l, k) . (\nu k^*) ($$

if  $[k=k_i]$  then

case  $l$  of ... :

sur $\_l$ ( $r$ ) :  $\text{OM}_{\mathbb{O}}^*(s, \tilde{m}, k_e, k^*, \tilde{t}) \mid \llbracket s.\text{alias}(s.\text{clone}) \rrbracket_r^{k^*}$  ;

png $\_l$ ( $r$ ) :  $\text{OM}_{\mathbb{O}}^*(s, \tilde{m}, k_e, k^*, \tilde{t}) \mid \llbracket s \rrbracket_r^{k^*}$  ;

sur $\_l^*$ ( $r$ ) :  $\text{OM}_{\mathbb{O}}^*(s, \tilde{m}, k_e, k^*, \tilde{t}) \mid \llbracket s.\text{alias}(s.\text{clone}) \rrbracket_r^{k^*}$  ;

png $\_l^*$ ( $r$ ) :  $\text{OM}_{\mathbb{O}}^*(s, \tilde{m}, k_e, k^*, \tilde{t}) \mid \llbracket s \rrbracket_r^{k^*}$

elif  $[k=k_e]$  {

compares the convergence behaviour of a tagged term and its untagged counterpart with respect to the tagged semantics. By definition, the tagged semantics treats tagged and untagged requests in exactly the same manner.  $\square$

Tagging helps us to detect all “requests arising from the hole”.

**Definition 7.4 (External Contexts)** *Let  $x$  be a variable and  $C[\cdot]$  an untagged  $\emptyset$ jeblik context. Then,  $C[\cdot]$  is called external for  $x.\text{surrogate}$ , if whenever*

$$\llbracket C[x.\text{surrogate}^*] \rrbracket_p^k \Rightarrow \equiv E[ \bar{s} \langle \text{sur}^* \_r, k \rangle \mid \text{OM}_{\emptyset}^* \langle s, \tilde{m}, k_e, k_i, \tilde{t} \rangle ]$$

*it holds that  $k \neq k_i$ .*

We replay the definition using ping instead of surrogate. By definition of the semantics, an  $\emptyset$ jeblik context  $C[\cdot]$  is then external for  $x.\text{surrogate}$  if and only if it is external for  $x.\text{ping}$ . For convenience, by abuse, we simply call  $C[\cdot]$  to be *external for  $x$* .

## 8 On the safety of surrogation

In this section, we prove that that

$$C[x.\text{ping}] \Downarrow \text{ iff } C[x.\text{surrogate}] \Downarrow$$

under the assumption that  $C[\cdot]$  will never lead to self-inflicted

Lemma 8.3 proves that the alias manager

PROOF. By Lemma 7.3 our proof obligation is equivalent to:

$$\llbracket C[x.\text{ping}^*] \rrbracket_p^k \Downarrow_p \text{ iff } \llbracket C[$$



By the tagged counterpart of) Lemma 6.6 it holds that:

$$P_h \equiv \nu_{\tilde{z}_h} ( M_h \mid \text{sur} \mathbf{O}_{\mathbb{O}}^* \langle s_h, q_h, k_h, \tilde{t}_h, \tilde{v}_h \rangle )$$

for some  $\tilde{z}_h$  and  $M_h$ . Now, we simulate the previous reduction sequence, which uses  $\text{sur}^*$ -requests, but now using  $\text{png}^*$ -requests and proceeding up to structural equivalence *and* barbed equivalence.

$$D[\overline{y} \langle \text{png}^* \_q, j \rangle] =$$

$$\begin{array}{cccccccccccc}
 Q_{1,1} & \rightarrow_i & Q_{1,2} & \rightarrow_i & \cdots & \rightarrow_i & Q_{1,n_1} & \rightarrow_s & Q_1 & \simeq_{\Gamma} & \widehat{Q}_1 & \equiv & Q_{2,1} \\
 Q_{2,1} & \rightarrow_i & Q_{2,2} & \rightarrow_i & \cdots & \rightarrow_i & Q_{2,n_2} & \rightarrow_s & Q_2 & \simeq_{\Gamma} & \widehat{Q}_2 & \equiv & Q_{3,1} \\
 \vdots & & \vdots & & & & \vdots & & \vdots & & \vdots & & \vdots \\
 Q_{d,1} & \rightarrow_i & Q_{d,2} & \rightarrow_i & \cdots & \rightarrow_i & Q_{d,n_d} & \rightarrow_s & Q_d & \simeq_{\Gamma} & \widehat{Q}_d & \equiv & Q_{d+1,1} \\
 Q_{d+1,1} & \rightarrow_i & Q_{d+1,2} & \rightarrow_i & \cdots & \rightarrow_i & Q_{d+1,n_{d+1}} & \stackrel{\text{def}}{=} & Q_{\downarrow p} & & & & 
 \end{array}$$

where:

$$Q_{h,g} \stackrel{\text{def}}{=} P_{h,g}[\text{png}^*/\text{sur}^*]$$

The insignificant reduction steps  $\rightarrow_i$  exist because of Lemma 8.8. The significant reduction steps  $Q_{h,n_h} \rightarrow_s Q_h$  are analogous to

$$\text{T-Obj) } \frac{\forall j \in J \quad \Gamma, s_j : A, \tilde{x}_j : \tilde{B}_j \vdash_A b_j : \hat{B}_j \quad A = [\lambda_j : \tilde{B}_j \rightarrow \hat{B}_j]_{j \in J}}{\Gamma \vdash_D [\lambda_j : \varsigma \ s_j : A, \tilde{x}_j : \tilde{B}_j] b_j]_{j \in J} : A}$$

$$\text{T-UPD) } \frac{\Gamma \vdash_D a : A \quad A = [\lambda_j : \tilde{B}_j \rightarrow \hat{B}_j]_{j \in J} \quad \Gamma, s_k : A, \tilde{x}_k : \tilde{B}_k \vdash_A b_k : \hat{B}_k \quad k \in J}{\Gamma \vdash_D a.l_k \Leftarrow \varsigma \ s_k : A, \tilde{x}_k : \tilde{B}_k}$$

semantics for  $\mathcal{O}$ jeblik, the question for some formal correspondence result among the semantics by translation and the direct semantics arises. On the other hand, one may ask to carry out the proofs on the direct semantics instead of employing some other lower-level formalism. However, we found it very natural and useful to develop two semantics at different abstraction levels hand-in-hand. In fact, most of the examples of unsafe surrogation were discovered by means of the  $\pi$ -calculus semantics, and only then “verified” in the direct semantics. Moreover, since we have developed both levels of semantics in lock-step, we have a good basis for formalizing their interrelation. Finally, in contrast to our abstract configuration-style semantics for closed terms only, the  $\pi$ -calculus provides indeed a very rich set of approved reasoning tools that make the life of a theorem prover much easier, as exemplified by Kleist and Sangiorgi [KS98], and also in this paper.

Other strands of future work are twofold. One is to continue to develop and exploit semantics for the  $\mathcal{O}$ bliq-style of object migration, and to use our semantics also to prove other equations on  $\mathcal{O}$ bliq-programs. For example, also equations like  $\text{join}\langle\text{fork}\langle a \rangle\rangle = a$  do only hold under certain conditions inflicted by self-infliction. Another strand is to try to carry over our results to settings that are not based on the notion of serialization via self-infliction, but rather reentrant mutexes, as in Java.

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# A Proofs

## A.1 Proof of Lemma 2.14

PROOF. We show that the relation

$$\mathcal{S} = \{(Q\{p/q\}, \nu q:\mathbf{C} T)) \mid Q \mid q \triangleright p\} : q \text{ in } Q \text{ only in output position}\}$$

is a barbed bisimulation up to structural equivalence.

- Let  $Q\{p/q\} \xrightarrow{\tau} Q'\{p/q\}$ . There are two cases.
  1.  $Q \xrightarrow{\tau} Q'$ . This case can be easily treated.
  2. Otherwise, since  $p$  and  $q$  are channels and they never appear in testing, this means that the  $\tau$ -action is due to a communication along  $p$ . More precisely,  $Q$  must contain an occurrence of  $q$  in output subject position and an occurrence of  $p$  in input position which give rise to the communication. Up to structural equivalence, this implies that

$$\nu q:\mathbf{C} T)) \mid Q \mid q \triangleright p \xrightarrow{\tau} \xrightarrow{\tau} \equiv \nu q:\mathbf{C} T)) \mid Q' \mid q \triangleright p).$$

As desired.

- Let  $\nu q:\mathbf{C} T)) \mid Q \mid q \triangleright p \xrightarrow{\tau} R$  for some  $R$ . There are two cases.
  1.  $R = \nu q:\mathbf{C} T)) \mid Q' \mid q \triangleright p$  since  $Q \xrightarrow{\tau} Q'$ . This case can be easily treated.
  2. The  $\tau$ -action is due to some communication along  $q$  between  $Q$  and the link  $q \triangleright p$ . More precisely,

Before we start, let

$$A^*(X) \text{ denote } \left[ \begin{array}{l} \text{cln} : \mathbf{R}(X) \\ \text{ali} : \langle X, \mathbf{R}(X) \rangle \\ \text{upd}_j : \langle \mathbf{C}(X, \mathbf{M}(\tilde{B}_j \rightarrow \hat{B}_j), \mathbf{K}), \mathbf{R}(X) \rangle \\ \text{inv}_j : \langle \mathbf{M}(\tilde{B}_j \rightarrow \hat{B}_j) \rangle \\ \text{sur} : \mathbf{R}(X) \\ \text{png} : \mathbf{R}(X) \end{array} \right]_{j \in 1..n},$$

with



and in order to type the object manager we must also have  $K = J$  in order to have the same number of methods in the type and the object manger. The typing of the object manger also yields that we must have the types  $T_j = \mathbf{C} \llbracket A \rrbracket, \llbracket \tilde{B}_j \rrbracket, \mathbf{R} \tilde{B}_j, \mathbf{K}$ . We are now

In state  $\text{OM}^s$ , a png request drives the system into state  $\text{OM}^i$ . In the case of method invocation a reduction along  $t_j$  may occur which allows the evaluation of the method body. At this point a number of self-inflicted requests may be served (external requests are blocked because the external mutex  $m_e$  is no available). This part of the computation will not change the state. Notice that, by hypothesis, since we suppose that  $Z$  contain an object manager and non an alias manager, we exclude self-inflicted aliasing operations. When the last self-inflicted request is served, a reply  $\overline{r^*}\langle o, k \rangle$  will appear unguarded. The confluent reduction along  $r^*$  will drive the computation to state  $\text{OM}^i$ . sur requests are treated similarly.

State  $\text{OM}^i$  can only evolve, by reducing along  $m_i$ , to state  $\text{OM}^f$ .  $\square$

## A.4 Proof of Lemma 8.2

We show that there is a sequence of  $\tau$ -actions such that:

$$\text{surO}_{\circ}\langle s, r, k, \tilde{t}, \tilde{v} \rangle \Rightarrow_{\equiv} \nu s^* ( \nu k_i \text{ freeA}_{\circ}\langle s, k_i, s^*, \tilde{v} \rangle \mid \text{newO}_{\circ}\langle s^*, \tilde{t} \rangle \mid \overline{r}\langle s^*, k \rangle ).$$

We prove that  $\approx_{\Gamma, s}$  is insensitive to these particular  $\tau$ -actions. To this end, we supply the two lemmas A.2 and A.3. We recall that  $\text{M}[\cdot]$  denote the call manager protocol as defined in Table 7.

**Lemma A.2** *Let  $\tilde{n} := m_e, m_i, k_e$ , and  $\tilde{v} := v_1 \dots v_n$  with  $v_j := \langle l_j, k_j \rangle$  for  $j \in 1..n$ , and*

$$\begin{aligned} C_1 &:= \text{M}[ \nu q \ \overline{s}\langle \text{cln}_q, k^* \rangle \mid q \ x, k' . \overline{s}\langle \text{ali}_q, r^* \rangle, k' ) ] \\ C_2 &:= \text{M}[ \nu q \ \overline{q}\langle s^*, k^* \rangle \mid q \ x, k' . \overline{s}\langle \text{ali}_q, r^* \rangle, k' ) ] \\ P\langle \tilde{v} \rangle &:= \nu \tilde{n} k^* ( \overline{m_i} k \mid \text{OM}_{\circ}\langle s, \tilde{n}, k^*, \tilde{t} \rangle \mid \text{PP}_{\circ}\langle s, \tilde{n}, \tilde{v} \rangle \mid C_1 ) \\ &\quad \text{with } k^* \notin \text{fn } \tilde{v} ) \\ Q\langle \tilde{v} \rangle &:= \nu \tilde{n} k^* s^* ( \overline{m_i} k \mid \text{OM}_{\circ}\langle s, \tilde{n}, k^*, \tilde{t} \rangle \mid \text{newO}_{\circ}\langle s^*, \tilde{t} \rangle \mid \text{PP}_{\circ}\langle s, \tilde{n}, \tilde{v} \rangle \mid C_2 ) \\ &\quad \text{with } k^* \notin \text{fn } \tilde{v} ) \\ \Gamma &\vdash P\langle \tilde{v} \rangle, Q\langle \tilde{v} \rangle \text{ for some } \Gamma. \end{aligned}$$

Then,  $P\langle \tilde{v} \rangle \approx_{\Gamma, s} Q\langle \tilde{v} \rangle$ .

**PROOF.** For simplicity, we omit the obligations on types in the coinductive definition of  $\approx_{\Gamma, s}$ . So, we prove that the relation:

$$\mathcal{S} = \{ P\langle \tilde{w} \rangle, Q\langle \tilde{w} \rangle : \tilde{w} = w_1 \dots w_m \text{ with } w_j := \langle l_j, k_j \rangle, j \in 1..n \} \cup \mathcal{I}$$

where  $\mathcal{I}$  is the identity relation, is a  $\approx_{\Gamma, s}$ -bisimulation up to  $\equiv$ .

The only channel which appear free in subject position in  $P\langle \tilde{w} \rangle$  and  $Q\langle \tilde{w} \rangle$  is  $s$ . Since both the external key  $k_e$  and the internal key  $k^*$  are restricted in  $P\langle \tilde{w} \rangle$  and  $Q\langle \tilde{w} \rangle$ , an by well-typedness, the environment can send requests only of the form  $\overline{s}\langle l, k \rangle$  with  $k_e \neq k \neq k^*$ .

The process  $P\langle \tilde{w} \rangle$  can perform only two kinds of actions. Either i) an input action  $s\langle l, k \rangle$  (with  $k_e \neq k \neq k^*$ ), or ii) a silent move along  $s$  involving the self-inflicted cloning request contained in  $C_1$ . In case i), the pre-processing of the request creates the process  $m_e. \overline{s}\langle l, k_e \rangle \mid \overline{m_i} k$  which can be added in  $\text{PP}_{\circ}\langle s, \tilde{n}, \tilde{w} \rangle$  obtaining some  $\text{PP}_{\circ}\langle s, \tilde{n}, \tilde{w}' \rangle$  with  $\tilde{w}' = \tilde{w} \cup \langle l, k \rangle$ . The process  $Q\langle \tilde{w} \rangle$  can perform the same action and the derivatives are again related by  $\mathcal{S}$ . In case ii), the process  $Q\langle \tilde{w} \rangle$  can mimic the  $\tau$ -action by not performing any reduction at all. Up to structural equivalence, we get into the identity relation.

The process  $Q\langle \tilde{w} \rangle$  can only perform two kinds of actions. Either i) a input action  $s\langle l, k \rangle$  (with  $k_e \neq k \neq k^*$ ), and we reason as above, or ii) a silent move along the restricted channel  $q$  in  $C_2$ . In this case  $P\langle \tilde{w} \rangle$  can perform two silent actions, along  $s$  and  $q$ , getting, up to structural equivalence, into the identity relation.  $\square$

**Lemma A.3** *Let  $\tilde{n} := m_e, m_i, k_e$ , and  $\tilde{v} := v_1 \dots v_n$  with  $v_j := \langle l_j, k_j \rangle$  for  $j \in 1..n$ , and*



$$\begin{aligned}
C_3 &:= M[\overline{s}\langle \text{ali}_-\langle s^*, r^* \rangle, k^* \rangle] \\
C_4 &:= M[\overline{r^*}\langle s^*, k^* \rangle] \\
P\langle \tilde{v} \rangle &:= \nu \tilde{n} k^* s^* (\overline{m_i} k \mid \text{OM}_\circ \langle s, \tilde{n}, k^*, \tilde{t} \rangle \mid \text{newO}_\circ \langle s^*, \tilde{t} \rangle \mid \text{PP}_\circ \langle s, \tilde{n}, \tilde{v} \rangle \mid C_3) \\
&\quad \text{with } k^* \notin \text{fn } \tilde{v} \\
Q\langle \tilde{v} \rangle &:= \nu \tilde{n} k^* s^* (\overline{m_i} k \mid \text{AM}_\circ \langle s, \tilde{n}, k^*, s^* \rangle \mid \text{newO}_\circ \langle s^*, \tilde{t} \rangle \mid \text{PP}_\circ \langle s, \tilde{n}, \tilde{v} \rangle \mid C_4) \\
&\quad \text{with } k^* \notin \text{fn } \tilde{v}. \\
\Gamma &\vdash P\langle \tilde{v} \rangle, Q\langle \tilde{v} \rangle \text{ for some } \Gamma.
\end{aligned}$$

Then,  $P\langle \tilde{v} \rangle \approx_{\Gamma; s} Q\langle \tilde{v} \rangle$ .

PROOF. Similar to that of Lemma A.2. □

PROOF OF LEMMA 8.2. As said above there is a sequence of  $\tau$ -actions, such that:

$$\text{surO}_\circ \langle s, r, k, \tilde{t}, \tilde{v} \rangle \Rightarrow_{\equiv} \nu s^* (\nu k_i) \text{freeA}_\circ \langle s, k_i, s^*, \tilde{v} \rangle \mid \text{newO}_\circ \langle s^*, \tilde{t} \rangle \mid \overline{r}\langle s^*, k \rangle.$$

The above sequence consists of 7 silent steps. These  $\tau$ -steps are of two kinds: i) confluent reductions along restricted channels of the form

$$C[\nu q \ \overline{q}\langle \tilde{v} \rangle \mid q \ \tilde{x}.P] \xrightarrow{\tau} C[P\{\tilde{v}/\tilde{x}\}]$$

where  $q \notin \text{fn } P$ , let us call these reductions of kind  $\alpha$ ; ii) reductions involving self-inflicted requests (induced by the surrogation) of the form

$$C[\nu k^* \ \text{OM}_\circ \langle s, \tilde{m}, k_e, k^*, \tilde{t} \rangle \mid \overline{s}\langle \text{op}_-\langle r^*, k^* \rangle \rangle] \xrightarrow{\tau}$$



$$\nu \tilde{m} k_e) (\overline{m_e} \mid !s \ l, k). \text{if } [k=k_e] \text{ then } m_i \ k). \overline{s^* \langle l, k \rangle} \mid \overline{m_e}) \\ \mid \text{else } m_e. \overline{s \langle l, k_e \rangle} \mid \overline{m_i k}) \\ \mid \prod_{j \in 1..n} m_e. (\overline{s \langle l_j, k_e \rangle} \mid \overline{m_i k_j}) )$$

$\approx_{\Gamma, s}$  by exhibiting the appropriate bisimulation)

$$\nu \tilde{m} s_e) (\overline{m_e} \mid !s \ l, k). m_e. \overline{s_e \langle l, k \rangle} \mid \overline{m_i k}) \\ \mid !s_e \ l, k). m_i \ k). \overline{s^* \langle l, k \rangle} \mid \overline{m_e}) \\ \mid \prod_{j \in 1..n} m_e. \overline{s_e \langle l_j, k_j \rangle} \mid \overline{m_i k_j}) )$$

$\approx_{\Gamma}$  reductions on  $m_i$  are confluent)

$$\nu m_e s_e) (\overline{m_e} \mid !s \ l, k). m_e. \overline{s_e \langle l, k \rangle} \\ \mid !s_e \ l, k). \overline{s^* \langle l, k \rangle} \mid \overline{m_e}) \\ \mid \prod_{j \in 1..n} m_e. \overline{s_e \langle l_j, k_j \rangle} )$$

$\approx_{\Gamma}$  by Lemma A.4)

$$\nu m_e s_e) (\overline{m_e} \mid !s \ l, k). m_e. (\overline{s^* \langle l, k \rangle} \mid \overline{m_e}) \\ \mid !s_e \ l, k). \overline{s^* \langle l, k \rangle} \mid \overline{m_e}) \\ \mid \prod_{j \in 1..n} m_e. \overline{s^* \langle l_j, k_j \rangle} \mid \overline{m_e}) )$$

$\approx_{\Gamma}$  by garbage collection on  $s_e$ )

$$\nu m_e) ($$

We recall that  $\approx_{\Gamma, s}$  is ground on channels. This means that we always suppose to receive fresh channels, in particular, we never receive channels  $s$  and  $s^*$ .

As regards the left side, the only interesting transition is the input action along  $s$ . This action can be emulated by the

3. If  $(\nu\tilde{z}) \ A \mid R) \xrightarrow{\tau} (\nu\tilde{y}) \ A' \mid R'$ , where the  $\tau$ -action is due to a communication along  $s$  between  $A$  and  $R$  (recall that  $s$  can only appear in output in  $R$ ), then we reason

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