

PLACEHOLDER

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Introduction

This is an interesting introduction to an interesting subject.

- state of the art?
- what we want: have terms wear the proof of a working reduction, which is proof they're well built.
- how we do it: introducing an annotated calculus, which annotations will allow us to easily type it by allowing interactions between two terms over one variable only. Defining the system well allows us to project to usual π -calculus, and maybe to compare with existing type systems for it.
- we would like the reduction to be confluent, the typing system to be without cut or with a cut elimination property (the latter holds), and the reduction with the typing system to preserve typing (it does).

1 Definitions

We first need to define the language of terms of our annotated π -calculus.

Definition 1

Take two countable sets, $N := \{t, u, v, \dots\}$ the set of names and $V := \{x, y, z, \dots\}$ the set of variables. The annotated terms are defined by the following grammar:

$P, Q ::= x \leftrightarrow y$; 0_x ;	$x, y \in V$ base terms
$\epsilon_x.P$;	$x \notin fv(P)$ variable introduction scheduling prefix
$\lambda_x y.P$;	$x, y \in fv(P)$ variables binding scheduling prefix
$u_x(t).P$; $\bar{u}_x\langle v \rangle.P$;	$t, u, v \in N, x \in fv(P)$ action prefixes
$P _x Q$; $P _x Q$;	$x \in fv(P) \cap fv(Q)$ parallel and synchronization
$(\nu u)P$	$u \in N$ name binding prefix

where construction $x \leftrightarrow y$ is commutative, and $fv(P)$ and $fn(P)$ are defined by induction on terms as follows:

$fv(x \leftrightarrow y) = \{x, y\}$	$fn(x \leftrightarrow y) = \emptyset$
$fv(0_x) = \{x\}$	$fn(0_x) = \emptyset$
$fv(\epsilon_x.P) = fv(P) \cup \{x\}$	$fn(\epsilon_x.P) = fn(P)$
$fv(\lambda_x y.P) = fv(P) \setminus \{y\}$	$fn(\lambda_x y.P) = fn(P)$
$fv(u_x(t).P) = fv(P)$	$fn(u_x(t).P) = (fn(P) \setminus \{t\}) \cup \{u\}$
$fv(\bar{u}_x\langle v \rangle.P) = fv(P)$	$fn(\bar{u}_x\langle v \rangle.P) = fn(P) \cup \{u, v\}$
$fv((\nu u)P) = fv(P)$	$fn((\nu u)P) = fn(P) \setminus \{u\}$
$fv(P _x Q) = fv(P) \cup fv(Q)$	$fn(P _x Q) = fn(P) \cup fn(Q)$
$fv(P _x Q) = (fv(P) \cup fv(Q)) \setminus \{x\}$	$fn(P _x Q) = fn(P) \cup fn(Q)$

Remark: the parallel and synchronization constructions behave differently on their variable. The parallel rule gives a term that puts together the two instances of the variable observed, and keeps it available for further use, while the synchronization rule uses both instances of the variable observed and thus has it unavailable for further use in the created term. The synchronization is a binding operator.

Remark: the lambda is also binding for its second variable (y here), keeping availability for its first variable only. The ϵ , on the opposite, creates its variable, that does not exist in the base term.

Remark: we also define substitution of names and variables by induction on the terms the exact same way as usual. Though, it is important to note that, because names and variables are two distinct and independent sets, substituting a variable for a name (or the opposite) is not possible. The distinction between those two sets is important for the reduction to pose no problem of variable capture, and allows for something akin to α -conversion from λ -calculi: one can rename freely all instances of a free variable or name in a term for a fresh one, or all instances of a bound variable or name (including the binding operator) for a fresh one as well in the scope of the binding operator, and the term is still considered the same.

The synchronization rule will be used to guide the behavior of terms, thus we define a reduction system over this construction specifically, as follows:

Definition 2

We define a reduction rule for synchronization (that does not hold under action prefixes) as follows:

$\epsilon_x.P _x 0_x \rightarrow P$	symmetric in 1
$P _x x \leftrightarrow y \rightarrow P[y/x]$	symmetric in 2
$(P _x Q) _x \lambda_x y.R \rightarrow P _x (Q[y/x] _y R)$	3a
$\lambda_x y.R _x (P _x Q) \rightarrow (R _x P) _y Q[y/x]$	3b
$\bar{u}_x\langle v \rangle.P _x u_x(t).Q \rightarrow P _x Q[v/t]$	symmetric in 4

We also define rules for commuting the synchronization with other rules, at first not holding under action prefixes:

$(P _x Q) _y R \succ (P _y R) _x Q$	symmetric in $ $, $y \notin fv(Q)$	5a
$(P _x Q) _y R \succ P _x(Q _y R)$	symmetric in $ $, $y \notin fv(P)$	5b
$\epsilon_x.P _y Q \succ \epsilon_x.(P _y Q)$	symmetric in $ $, $x \notin fv(Q)$	6a
$\lambda_x y.P _z Q \succ \lambda_x y.(P _z Q)$	symmetric in $ $, $y \notin fv(Q)$	6b
$(\nu u)P _x Q \succ (\nu u)(P _x Q)$	symmetric in $ $, $u \notin fn(Q)$	6c

Remark: In rules 5 and 6, some parts have strong requirements, such as a variable not being present in one or more subterms. Failure to meet those requirements can lead to terms that do not reduce past a certain point, when no other rule can apply. See an example below of a term annotated to be able to reduce, and the same term with annotations changed that fails to do so.

INCLUDE EXAMPLE HERE (and everywhere really...)

We would like these arrows to have a confluent behavior. First, we remark that \rightarrow is strongly confluent. Then, we will need an equivalence relation to be defined for the confluence of \succ .

Proposition 3

Relation \rightarrow is strongly confluent.

▷ Since a synchronization makes the observed variable unavailable to the term, and because \rightarrow does not allow for an arbitrary term on any side but only explicitly fixed constructions, and not allowing for these constructions to be a synchronization, we can remark that two reductions using \rightarrow in the same term cannot interfere with each other. Thus, a term capable of two reductions using \rightarrow has one of them be either a strict subterm of the other, or distinct parts of a more general term. The reductions then do not interfere with each other, and can be followed in any order. Only exception to that is the interaction of two axiom base terms synchronized on the same variable, but the commutativity of this construction makes it close immediately:

$$\begin{array}{ccc}
 & x \leftrightarrow y ||_x x \leftrightarrow z & \\
 \swarrow & & \searrow \\
 (x \leftrightarrow z)[y/x] & & (x \leftrightarrow y)[z/x] \\
 \Downarrow & & \Downarrow \\
 y \leftrightarrow z & = & z \leftrightarrow y
 \end{array}$$

□

Because of the specificity of the constructions in the \rightarrow , it does not directly interact with \succ rules, except for the $x \leftrightarrow y$ case.

We remind the definitions of a simulation and a bisimulation, as those tools are uncommon enough to justify being introduced here:

Definition 4

- A simulation \mathcal{R} is a binary relation on terms such that, for all terms P, Q , if PRQ then for all $P \rightarrow P'$ there exists a term Q' such that $Q \rightarrow Q'$ and $P'\mathcal{R}Q'$.
- A bisimulation \mathcal{R} is a binary relation on terms such that \mathcal{R} and \mathcal{R}^{-1} are simulations.

Then, because of the lack of direct interaction between \rightarrow and \succ , we have:

Proposition 5

Relation \succ is a simulation for \rightarrow .

▷ The cases to treat are those where $x \leftrightarrow y$ interacts with something. We treat two of them below, and also put the cut variable in exponent of the term where it appears in, in order to apply rule 5 efficiently, where applicable:

$$\begin{array}{ccc}
 (P^y|_x Q)|_y x \leftrightarrow y \rightarrow (P^y|_x Q)[x/y] = P[x/y]|_x Q & \xrightarrow{\Upsilon_{5a}} & \lambda_x y.P|_z z \leftrightarrow x \rightarrow (\lambda_x y.P)[x/z] = P[x/z] \\
 \Upsilon_{5a} \nearrow & & \Upsilon_{6b} \nearrow \\
 (P^y|_y x \leftrightarrow y)|_x Q & & \lambda_x y.(P|_z z \leftrightarrow x)
 \end{array}$$

All other cases act the same way, or are the same as for \rightarrow not interacting with itself because one of the reductions occurs either in a strict subterm of the other, or in a distinct term from the other. □

The \succ relation in itself has a bit more complexity to it being confluent, as two instances can interact with each other. A congruence is needed to make this relation confluent.

Definition 6

We define a congruence rule, that does not act on action prefixes, with the following axioms:

$$\begin{array}{ll}
(P|_x Q)|_y R \equiv (P|_y R)|_x Q & y \notin fv(Q), x \notin fv(R) \quad a_1 \\
P|_x(Q|_y R) \equiv Q|_y(P|_x R) & y \notin fv(P), x \notin fv(Q) \quad a_2 \\
(P|_x Q)|_y R \equiv P|_x(Q|_y R) & y \notin fv(P), x \notin fv(R) \quad b \\
P|_x \alpha_y. Q \equiv \alpha_y.(P|_x Q) & \text{symmetric in } |, \alpha. \in \{\epsilon., \lambda.z\}, y, t \notin fv(P) \quad c \\
\alpha_x.\beta_y.P \equiv \beta_y.\alpha_x.P & \alpha., \beta. \in \{\epsilon., \lambda.z\}, x \neq y \quad d \\
(\nu u)P|_x Q \equiv (\nu u)(P|_x Q) & \text{symmetric in } |, u \notin fn(Q) \quad e \\
(\nu u)\alpha_x.P \equiv \alpha_x.(\nu u)P & \alpha. \in \{\epsilon., \lambda.z\} \quad f
\end{array}$$

This rule is defined as an equivalence (reflexive, symmetric and transitive), and applies inside contexts (except action prefixes).

This equivalence allows for the confluence of \succ :

Proposition 7

Relation \succ is confluent up to \equiv ,
ie. for all $P_1 \prec P \succ P_2$, there exists P'_1, P'_2 such that

$$\begin{array}{ccc}
& P & \\
\prec & & \succ \\
P_1 & & P_2 \\
\Upsilon & & \Upsilon \\
P'_1 & \equiv & P'_2
\end{array}$$

▷ There are 3 possible cases here, for two groups of rules in the \succ relation.

Rule 5 against rule 5: there are 4 cases, depending on where the variable cut against is situated. The variable is noted as an exponent in the terms where it appears, and only 2 cases are treated (as the other two are their complements, and are treated the same):

$$\begin{array}{ccc}
& (P^y|_x Q)|_y (R^y|_z S) & \\
\prec_{5a, left} & & \succ_{5a, right} \\
(P^y|_y (R^y|_z S))|_x Q & & ((P^y|_x Q)|_y R^y)|_z S \\
\Upsilon_{5a} & & \Upsilon_{5a} \\
((P^y|_y R^y)|_z S)|_x Q & \equiv_{a_1} & ((P^y|_y R^y)|_x Q)|_z S
\end{array}$$

$$\begin{array}{ccc}
& (P^y|_x Q)|_y (R|_z S^y) & \\
\prec_{5a, left} & & \succ_{5b, right} \\
(P^y|_y (R|_z S^y))|_x Q & & R|_z ((P^y|_x Q)|_y S^y) \\
\Upsilon_{5b} & & \Upsilon_{5a} \\
(R|_z (P^y|_y S^y))|_x Q & \equiv_b & R|_z ((P^y|_y S^y)|_x Q)
\end{array}$$

Rule 6 against rule 6 works the same, here is an example with ϵ and ν :

$$\begin{array}{ccc}
& \epsilon_x.P|_y(\nu u)Q & \\
\prec_{6a} & & \succ_{6c} \\
\epsilon_x.(P|_y(\nu u)Q) & & (\nu u)(\epsilon_x.P|_y Q) \\
\Upsilon_{6c} & & \Upsilon_{6a} \\
\epsilon_x.(\nu u)(P|_y Q) & \equiv_f & (\nu u)\epsilon_x.(P|_y Q)
\end{array}$$

Other cases in the possible 6 against 6 rules are treated in the exact same manner. The last set of cases is a rule 5 against a rule 6. Those are all treated the same way as well, so we only treat one example:

$$\begin{array}{ccc}
& (P^y|_x Q)|_y(\nu u)R & \\
\prec_{5a} & & \succ_{6c} \\
(P^y|_y(\nu u)R)|_x Q & & (\nu u)((P^y|_x Q)|_y R) \\
\Upsilon_{6c} & & \Upsilon_{5a} \\
(\nu u)(P^y|_y R)|_x Q & \equiv_e & (\nu u)((P^y|_y R)|_x Q)
\end{array}$$

That ends the proof of confluence for \succ up to \equiv . \square

We need \equiv to not alter the behavior of \rightarrow in order for the system to work well. We do not have that kind of property here (*ie.* \equiv is not a simulation for \rightarrow), but we can observe an interesting phenomenon by allowing to do \succ steps where needed:

$$\begin{array}{ccc}
\lambda_x y. \epsilon_z. P \parallel_x (Q \parallel_x R) & \equiv & \epsilon_z. \lambda_x y. P \parallel_x (Q \parallel_x R) \\
\downarrow & & \downarrow \\
(\epsilon_z. P \parallel_x Q) \parallel_y R[y/x] & \equiv & \epsilon_z. (\lambda_x y. P \parallel_x (Q \parallel_x R)) \\
\downarrow & & \downarrow \\
(\epsilon_z. (P \parallel_x Q)) \parallel_y R[y/x] & \succ & \epsilon_z. ((P \parallel_x Q) \parallel_y R[y/x])
\end{array}$$

We have a more general property emanating of that, that gives us something close to a simulation behavior:

Proposition 8

For all $P \equiv Q$ and $P \rightarrow P'$,
there exists $Q \succ^* Q' \rightarrow Q'' \equiv P'' \prec^* P'$

$$\begin{array}{ccc}
P & \equiv & Q \\
\downarrow & & \downarrow \\
P' & & Q' \\
\downarrow & & \downarrow \\
P'' & \equiv & Q''
\end{array}$$

ie.

\triangleright We treat some interesting cases here, to complete from the one above, still where necessary with the cut variable in exponent where it appears:

$$\begin{array}{ccc}
\epsilon_z. \lambda_x y. P \parallel_z 0_z & \equiv & \lambda_x y. \epsilon_z. P \parallel_z 0_z \\
\downarrow & & \downarrow \\
\lambda_x y. P & \longleftarrow & \lambda_x y. (\epsilon_z. P \parallel_z 0_z)
\end{array}$$

$$\begin{array}{ccc}
\epsilon_z. ((P \parallel_x Q) \parallel_y R) \parallel_z 0_z & \equiv & \epsilon_z. (P \parallel_x (Q \parallel_y R)) \parallel_z 0_z \\
\downarrow & & \downarrow \\
(P \parallel_x Q) \parallel_y R & \equiv & P \parallel_x (Q \parallel_y R)
\end{array}$$

$$\begin{array}{ccc}
((P \parallel_x Q^y) \parallel_y R^y) \parallel_y \lambda_y z. S & \equiv & (P \parallel_x (Q^y \parallel_y R^y)) \parallel_y \lambda_y z. S^y \\
\downarrow & & \downarrow \\
(P \parallel_x Q^y) \parallel_y (R[z/y] \parallel_z S) & \prec & P \parallel_x ((Q^y \parallel_y R^y) \parallel_y \lambda_y z. S^y) \\
& & \downarrow \\
& & P \parallel_x (Q^y \parallel_y (R[z/y] \parallel_z S^y))
\end{array}$$

where $P \equiv P'$:

$$\begin{array}{ccc}
u_x(t). P \parallel_x \bar{u}_x \langle v \rangle. Q & \equiv & u_x(t). P' \parallel_x \bar{u}_x \langle v \rangle. Q \\
\downarrow & & \downarrow \\
P[v/t] \parallel_x Q & \equiv & P'[v/t] \parallel_x Q
\end{array}$$

\square

2 Typing decorated terms with MLL

Definition du langage des formules (N + grammaire MLL + quantification premier ordre)

Definition 9

The typing system is given by the following rules:

Rules for neutral elements:

$$\frac{}{0_x \vdash x : 1} \text{NOP}$$

$$\frac{P \vdash \Gamma}{\epsilon_x.P \vdash \Gamma, x : \perp} \text{BOT}$$

$$\frac{}{x \leftrightarrow y \vdash x : E^\perp, y : E} \text{AX}$$

Construction rules:

$$\frac{P \vdash \Gamma, x : E \quad Q \vdash \Delta, x : F}{P|_x Q \vdash \Gamma, \Delta, x : E \otimes F} \text{PARA}$$

$$\frac{P \vdash \Gamma, x : E, y : F}{\lambda_x y.P \vdash \Gamma, x : E \wp F} \text{LAM}$$

$$\frac{P \vdash \Gamma, x : E \quad Q \vdash \Delta, x : E^\perp}{P||_x Q \vdash \Gamma, \Delta} \text{CUT}$$

Action rules:

$$\frac{P \vdash \Gamma, x : A[v/t]^\perp}{\bar{u}_x \langle v \rangle . P \vdash \Gamma, x : \exists_u t . A^\perp} \text{IN}$$

$$\frac{P \vdash \Gamma, x : A \quad t \notin \Gamma}{u_x(t) . P \vdash \Gamma, x : \forall_u t . A} \text{OUT}$$

Nu rule:

$$\frac{P \vdash \Gamma \quad u \notin \Gamma}{(\nu u)P \vdash \Gamma} \text{NU}$$

One important thing to note here, is that for PARA and CUT rules, Γ and Δ are disjoint. The other important thing is that the synchronization construction becomes a CUT operation in the typing system. This rule has elimination transformations, given by the relations \rightarrow and \succ defined in 2. Properties we would like to emerge from such a construction would be that the arrows preserve typing, and that their application for cut elimination terminates and actually eliminates cuts.

Prop 1: Preserv type.

Prop 2: termine.

Observer la non élimination des coupures

Ajouter \rightsquigarrow et \succsim et noter que les deux preuves précédentes ne changent pas

Prop 3: \rightsquigarrow and \succsim élimine les coupures.

TEMPORARY: MOVED THAT FROM DEFINITION IN PART 1 And we extend it into \succsim as follows, allowing for it to act on (and under) action prefixes:

$$u_x(t) . P||_y Q \succsim u_x(t) . (P||_y Q) \quad \text{symmetric in } || \quad 6d$$

$$\bar{u}_x \langle v \rangle . P||_y Q \succsim \bar{u}_x \langle v \rangle . (P||_y Q) \quad \text{symmetric in } || \quad 6e$$

Relation \rightarrow is also extended into \rightsquigarrow by allowing it to act under action prefixes (no specific rule added).

TEMPORARY: MOVED THAT And we also extend it into \cong by allowing α, β to be action prefixes in rules c, d:

$$\alpha, \beta \in \{\epsilon, \lambda, z, u.(t), \bar{u}.\langle v \rangle\};$$

as well as in rule f:

$$\alpha \in \{\epsilon, \lambda, z, v.(t), \bar{v}.\langle w \rangle, u \neq v, u \neq t, u \neq w\}.$$

Remark: With no exponential, it is no surprise that cut elimination terminates.

Remark the other way around: we need commuting action prefixes here, but this hypothesis could be relaxed by proving cut elimination in quantifier-closed context. The proof would then be quite more technical.

Do we need a proper proposition for that last remark, as well as its proof maybe, or at least some elements for the added rules?

Also, insert here the followed example from the other paper that is to be shown in part 1, to show here that it is not only reducing well, but also well-typed. (Question for later: Is there a term, simplest possible if exists, that reduces well without typing, but cannot be well-typed?)

3 Links with the usual π -calculus

Definition 10

Given a countable set of names $N := \{t, u, v, \dots\}$, the grammar defining the terms of the multiplicative π -calculus is as follows:

$$\begin{array}{ll} P, Q ::= 0 & ; \quad P|Q & \text{null action and parallel construction} \\ & u(t).P & ; \bar{u}(v).P & \text{sending and receiving names over a channel} \\ & (\nu u)P & \text{name binding prefix} \end{array}$$

We also define a structural congruence on terms as follows:

$$\begin{aligned} P|0 &\equiv P \\ P|Q &\equiv Q|P \\ P|(Q|R) &\equiv (P|Q)|R \\ (\nu u)P &\equiv P \quad \text{if } u \text{ is not a free name in } P \end{aligned}$$

and a reduction rule:

$$u(t).P|\bar{u}(v)Q \rightarrow P[v/t]|Q$$

We remark most of the important constructions we use in the decorated calculus are here as well, especially being able to specify a name being private, running two processes in parallel as well as send or receive names over a channel. In fact, the synchronization construction from our annotated calculus is a form of parallelization as well, and in a world with no variables to describe the behavior of terms it makes sense to not have a separate construction for that. Also, the \leftrightarrow , ϵ and λ constructions in our annotated system don't do much in the calculus part, aside from allowing to eliminate the synchronization/cut, and their content only affects the typing system. Thus, it makes no sense to have such constructions in a calculus-only system where there is no equivalent to the cut rule from logic systems. We then have covered all constructions from both calculi here, so an interesting thing to do would be to project the annotated calculus that has more constructions in the usual π -calculus and see if we can get some interesting properties out of that.

Definition 11

We define a projection operator $\lfloor \cdot \rfloor$ from the annotated calculus to the above defined π -calculus as follows:

$$\begin{aligned} \lfloor 0_x \rfloor &= 0 \\ \lfloor x \leftrightarrow y \rfloor &= 0 \\ \lfloor \lambda_x y.P \rfloor &= \lfloor P \rfloor \\ \lfloor \epsilon_x.P \rfloor &= \lfloor P \rfloor \\ \lfloor u_x(t).P \rfloor &= u(t).\lfloor P \rfloor \\ \lfloor \bar{u}_x(v).P \rfloor &= \bar{u}(v).\lfloor P \rfloor \\ \lfloor P|_x Q \rfloor &= \lfloor P \rfloor|\lfloor Q \rfloor \\ \lfloor P||_x Q \rfloor &= \lfloor P \rfloor|\lfloor Q \rfloor \\ \lfloor (\nu u)P \rfloor &= (\nu u)\lfloor P \rfloor \end{aligned}$$

The important part to verify is that the projection behaves well with the reduction system proposed in part 1:

Proposition 12

If $P \rightarrow P'$ in the annotated calculus, then $\lfloor P \rfloor \rightarrow \lfloor P' \rfloor$ or $\lfloor P \rfloor \equiv \lfloor P' \rfloor$ in usual π -calculus.
If $P \succ P'$ or $P \equiv P'$ in the annotated calculus, then $\lfloor P \rfloor \equiv \lfloor P' \rfloor$ in the usual π -calculus.

▷ Do all meaningful constructions here.

In essence: the reduction of $u_x.P||_x\bar{u}_x.Q$ projects to a reduction, everything else projects to structural congruence. Maybe treating this and a few of the structural congruence projections is good, and say that the rest is treated the same way (many similar cases and not really complicated to see, writing everything feels like trying to occupy space just to increase the page count). \square

Open about \rightsquigarrow here or in the conclusion, because it does not act like a reduction in the projection, but gives some

sort of pre-order on terms.

Conclusion

A nice conclusion and working trails for later here.

- what we did so far: working small part of the calculus, good properties and behavior, reasonable projection
- ideas for the behavior of \equiv as a "bisimulation" in the annotated calculus
- behavior of \rightsquigarrow and \succsim with the projection: in the general case you do not want to have an action prefix be able to commute like that, but there is at least an "order" on the capabilities of terms $u.P|Q$ and $u.(P|Q)$
- next step: work on exponential rules, and additive rules too
- talk about failed attempts here maybe, and/or about misleading intuitions that were explored in the past 2.5 months ?
- more things maybe, if something interesting comes up