A logical view on scheduling in concurrency

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Plan

Introduction
- Proofs as processes
- Processes as untyped proofs
- Why we should search further

Proofs as schedules
- MLL with actions
- Soundness and completess

Uniform translations
- Asynchronous translation
- Synchronous translation

Discussion

Logic vs computation

- The *formulae as types* approach:

formula	$\leftrightarrow$	type
proof rules	$\leftrightarrow$	primitive instructions
proof	$\leftrightarrow$	program
normalization	$\leftrightarrow$	evaluation

- The *proof search* approach:

formula	$\leftrightarrow$	program
proof rules	$\leftrightarrow$	operational semantics
proof construction	$\leftrightarrow$	execution
proof	$\leftrightarrow$	successful run

(Logic vs computation) vs concurrency

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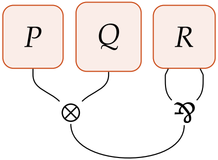
- How can we fit *concurrency* into this framework?
  What is a proper *denotational semantics* for concurrency?

Proofs as processes

- Cut elimination in proof nets is an interactive process:



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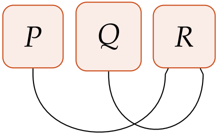

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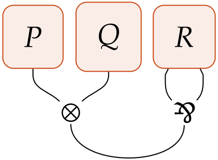

- It is natural to represent it a language for interactive processes:

$$(\nu z)\Big((\nu xy)(\bar{z}\langle xy\rangle \mid P \mid Q) \mid z(xy)R\Big)$$

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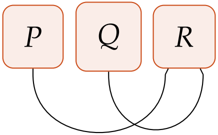

- It is natural to represent it a language for interactive processes:

$$(\nu z)\Big((\nu xy)(\bar{z}\langle xy\rangle \mid P \mid Q) \mid z(xy)R\Big) \to (\nu xy)(P \mid Q \mid R)$$

Proofs as processes

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Good points:

- Adequate representation of proof dynamics
- Study of information flow through proofs

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Good points:

- Adequate representation of proof dynamics
- Study of information flow through proofs

Limitations:

- Requires a lot of coding
- Touches processes of a very restricted form
- Does not provide much insight on the π-calculus

Typing processes in linear logic

Axiom and cut:

$$\frac{}{u \rightarrow v \vdash u : \downarrow A^{\perp}, v : \uparrow A} \qquad \frac{P \vdash \Gamma, \vec{x} : A \quad Q \vdash \vec{x} : A^{\perp}, \Delta}{(\nu \vec{x})(P \mid Q) \vdash \Gamma, \Delta}$$

Multiplicatives:

$$\frac{P \vdash \Gamma, \vec{x} : A \quad Q \vdash \vec{y} : B, \Delta}{P \mid Q \vdash \Gamma, \vec{x}\vec{y} : A \otimes B, \Delta} \qquad \frac{P \vdash \Gamma, \vec{x} : A, \vec{y} : B}{P \vdash \Gamma, \vec{x}\vec{y} : A \parr B}$$

Actions:

$$\frac{P \vdash \Gamma, \vec{x} : A}{u(\vec{x}).P \vdash \Gamma, u : \downarrow A} \qquad \frac{P \vdash \Gamma, \vec{x} : A}{\bar{u}(\vec{x}).P \vdash \Gamma, u : \uparrow A}$$

Exponentials for replication, additives for external choice.

Typing processes in linear logic

The system on the previous slide was introduced in

- EB
  A concurrent model for linear logic
  MFPS 2006

but was found to be strongly related to

- Nobuko Yoshida, Martin Berger, and Kohei Honda
  Strong normalisation in the π-calculus
  LICS 2001

Bellin and Scott's encoding decomposes inside.
Independently developped:

- Luís Caires and Frank Pfenning
  Session types as intuitionistic linear propositions
  Concur 2010

appears as a fragment.

Typing processes in linear logic

Good things:

- Typed processes cannot diverge or deadlock.
- Typing is preserved by reduction
  up to structural congruence.
- Extends to differential linear logic
  through "algebraic" extensions of process calculi.
- Induces translations of the λ-calculus into the π-calculus.

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Shortcomings:

- Typed processes are essentially functional.
- Only *top-level* cut elimination matches execution.
- Many well-behaved interaction patterns are not typable.

$$a.\bar{b} \mid b.\bar{c} \mid \bar{a}.c.d$$

Processes as proofs

Dual approach: implement processes as proofs in a suitable logic.

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Dual approach: implement processes as proofs in a suitable logic.

- Translating *all* processes requires an untyped proof language.
- Standard linear logic is not an option because of confluence.
- Differential linear logic allows for explicit non-determinism:

$$\frac{P \vdash \Gamma \qquad Q \vdash \Gamma}{P + Q \vdash \Gamma}$$

Its rules allow for an implementation of all processes.

Thomas Ehrhard and Olivier Laurent
Interpreting a finitary π-calculus in differential interaction nets
Concur 2007

Processes as untyped proofs

Good points:

- Does provide insights on concurrent processes
- Relates algebraic proof semantics and process semantics

Processes as untyped proofs

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- Does provide insights on concurrent processes
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Limitations:

- Not clear how to get logic back into the process language
- Prefixing is only described very indirectly:

$$\pi\text{-calculus} \longrightarrow \text{solos calculus} \longrightarrow \text{differential nets}$$

A few observations

Proof normalization, aka *cut elimination*:

- the meaning of a proof is in its normal form,
- normalization is an *explicitation* procedure,
- it really wants to be confluent.

Interpretation of concurrent processes:

- the meaning is the *interaction*, the final (irreducible) state is less relevant,
- a given process may behave very differently depending on scheduling decisions.

Some information is missing.

Proofs as schedules

The principles of our new interpretation:

formula	↔	type of interaction
proof rules	↔	primitives for building schedules
proof	↔	schedule for a program
normalization	↔	evaluation according to a schedule

This is not exactly:

- *Curry-Howard* for processes:
  proofs are not programs, but behaviours of programs
- *Proof search*:
  the dynamics is not in proof construction but in cut-elimination

but a sort of middle ground in between.

Proofs as schedules: step 1

The first step: a logical description of all executions.

EB and Virgile Mogbil
Proofs as executions
IFIP TCS 2012 — Chocola 14/3/2013

How we proceed:

- Back to CCS, for now.
- Slightly change the logic to represent actions explicitly.
- Match each execution with cut elimination of some proof.

Multiplicative CCS

We consider a CCS-style process calculus.

$$
\begin{array}{rl}
P, Q := 1 & \text{inaction} \\
a.P & \text{perform } a \text{ then do } P \\
P \mid Q & \text{interaction of } P \text{ and } Q \\
(\ (\nu a)P & \text{scope restriction}\ )
\end{array}
$$

There is one source of non-determinism:
the pairing of associated events upon synchronization

$$
a.P \mid a.Q \mid \bar{a}.R \ \rightarrow \begin{cases} a.P \mid Q \mid R \\ P \mid a.Q \mid R \end{cases}
$$

MLL with actions

The formulas

Types of schedules:

$A, B := \langle a \rangle A$	do action a and then act as A
$A \otimes B$	two independent parts, one as A, the other as B
$A \parr B$	A and B are both exhibited, but correlated
α	an unspecified behaviour (type variable)
$\alpha^\perp$	something that can interact with α
($\forall \alpha A$, $\exists \alpha A$	quantification over behaviours)

Transforming schedules:

$A_1, \ldots, A_n \vdash B$ — behave as type B in association with processes behaving as each type A_i

Two-sided version.

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Transforming schedules:

$\vdash A_1^\perp, \ldots, A_n^\perp, B$	behave as type B in association with processes behaving as each type A_i

Duality: $(A \otimes B)^\perp = A^\perp \parr B^\perp$, $(\langle a \rangle A)^\perp = \langle \bar{a} \rangle (A^\perp)$.

MLL with actions

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MLL with actions

Proof rules

Axiom and cut:

$$\frac{}{1 \vdash A^\perp, A} \qquad \frac{P \vdash \Gamma, A \qquad Q \vdash A^\perp, \Delta}{P \mid Q \vdash \Gamma, \Delta}$$

Multiplicatives:

$$\frac{P \vdash \Gamma, A \qquad Q \vdash B, \Delta}{P \mid Q \vdash \Gamma, A \otimes B, \Delta} \qquad \frac{P \vdash \Gamma, A, B}{P \vdash \Gamma, A \parr B}$$

Actions:

$$\frac{P \vdash \Gamma, A}{a.P \vdash \Gamma, \langle a \rangle A}$$

Quantification:

$$\frac{P \vdash \Gamma, A \qquad \alpha \notin \mathrm{fv}(\Gamma)}{P \vdash \Gamma, \forall\alpha A} \qquad \frac{P \vdash \Gamma, A[B/\alpha]}{P \vdash \Gamma, \exists\alpha A}$$

Ceci n'est pas un système de types.

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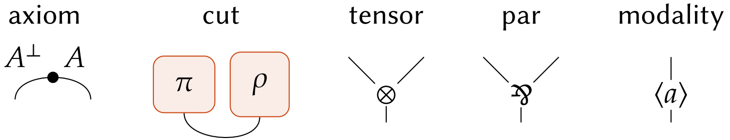
MLL with actions

Proof nets

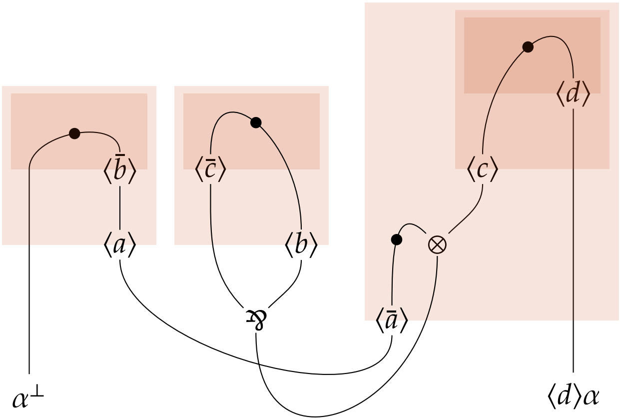
MLLa admits proof nets: those of MLL plus unary links for modalities.



- Modality rules commute with everything, indeed $A \simeq \langle a \rangle A$.
- Correctness criteria: the same as MLL.
- We avoid second-order quantification for simplicity,
  we stick with parametricity in type variables.

The cyclic example

The following proof is an annotation for $a.\bar{b} \mid b.\bar{c} \mid \bar{a}.c.d$:



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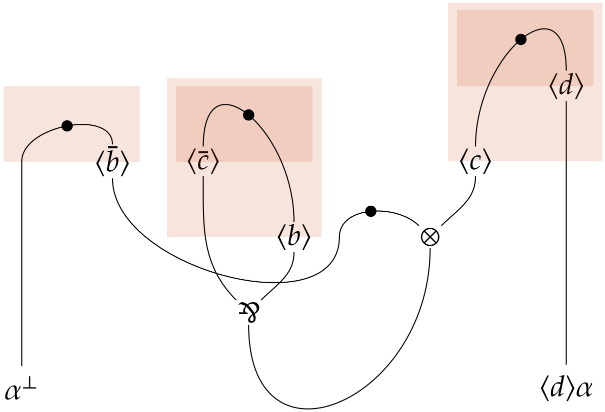

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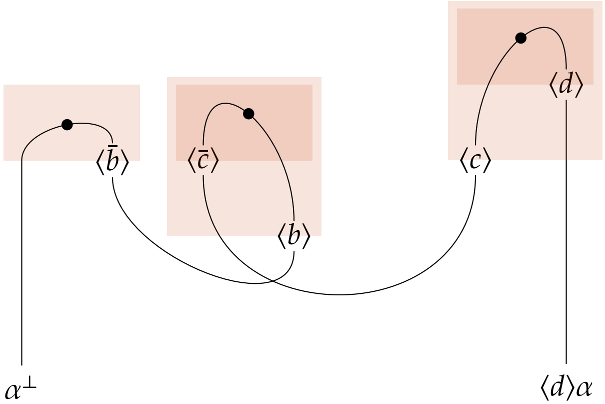

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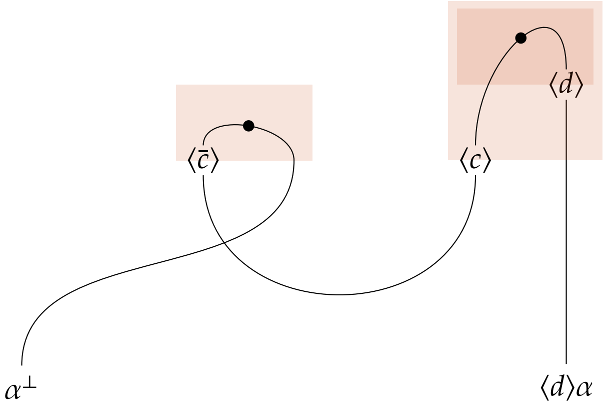

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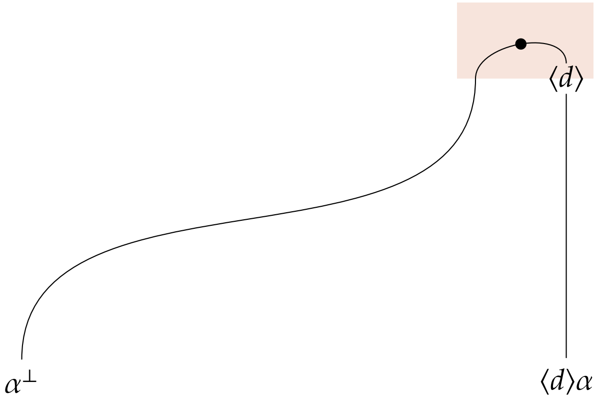

If we use boxes, we have a "head cut elimination" matching execution:

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The results of step 1

Theorem (Soundness)

Typing is preserved by reduction,
head cut-elimination steps correspond to execution steps.

The definition of "head" cut-elimination requires boxes for modality rules, to keep track of prefixing.

Theorem (Completeness)

For every lock-avoiding run $P_1 \to \ldots \to P_n$ *there are annotations such that* $\pi_1 : P_1 \vdash \Gamma \to \ldots \to \pi_n : P_n \vdash \Gamma$ *is a cut elimination sequence.*

Observations

Every execution correspond to some proof:

- the proof provides a schedule (pairing between actions),
- cut elimination provides actual execution.

These proofs have very different types:

- the type is deduced from the execution, it describes control flow according a particular schedule;
- the type decsribes a way for a process interacts with its environment,
- no *most general* type.

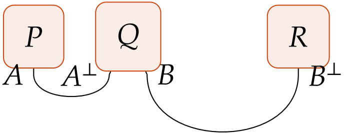
Step 2: make things more uniform.

The trick for actions prefixes

For annotating a process $a.P \mid Q \mid \bar{a}.R$ in an execution step

$$a.P \mid Q \mid \bar{a}.R \quad \to \quad P \mid Q \mid R$$

on may need some plumbing:



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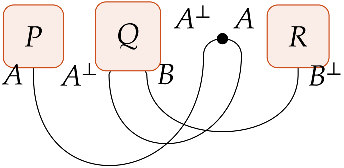

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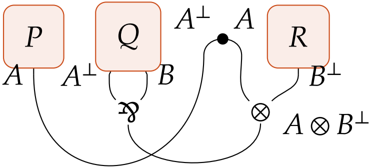

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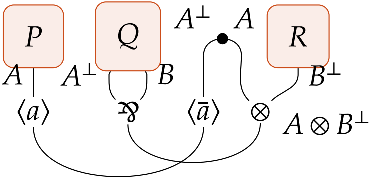

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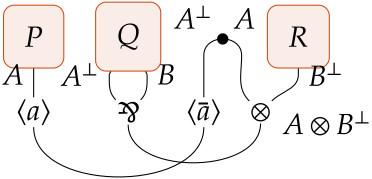

The type of $\bar{a}.R$ depends on that of Q,
even if only Q only interacts with P.

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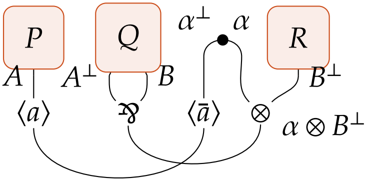


The construction does not depend on the types: *parametricity in α*
one can always proceed the same way.

Type assignment
"Asynchronous" version

Definition

Terms of MCCS are translated into MLLa formulas as follows:

$$\begin{aligned}
\lceil 1 \rceil_A &:= \forall\alpha\ \alpha^\perp \parr \alpha \\
\lceil P \mid Q \rceil_A &:= \lceil P \rceil_A \otimes \lceil Q \rceil_A \\
\lceil a.P \rceil_A &:= \forall\alpha\ \langle a\rangle\alpha^\perp \parr (\lceil P \rceil_A \otimes \alpha) &&= \forall\alpha\ \langle \bar{a}\rangle\alpha \multimap (\lceil P \rceil_A \otimes \alpha) \\
\lceil \bar{a}.P \rceil_A &:= \forall\beta\ (\lceil P \rceil_A \otimes \beta^\perp) \parr \langle \bar{a}\rangle\beta &&= \forall\beta\ (\lceil P \rceil_A \multimap \beta) \multimap \langle a\rangle\beta
\end{aligned}$$

Name hiding is left aside for now.

Proof assignment

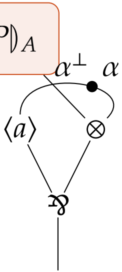
"Asynchronous" version

Fact

For every P, the type $\lceil P \rceil_A$ has one cut-free proof $(\!|P|\!)_A$.

For actions:

$(\!|a.P|\!)_A =$



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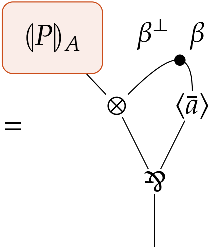

Soundness and completeness

"Asynchronous" version

Theorem

There is an execution $P \to^* 1$ if and only if $\lceil P \rceil_A \multimap \lceil 1 \rceil_A$ is provable in MLL (without modality rules).

Soundness and completeness

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Theorem

There is an execution $P \rightarrow^* 1$ if and only if $\lceil P \rceil_A \multimap \lceil 1 \rceil_A$ is provable in MLL (without modality rules).

From execution to implication:

- each execution step is provable.

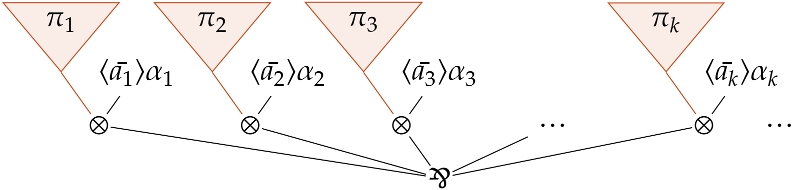
From implication to execution:

- find a first interaction,
  exploiting the correctness criterion for a proof of $\lceil P \rceil_A \multimap \lceil 1 \rceil_A$.

Soundness and completeness

“Asynchronous” version: finding the first action

Suppose there is some proof of $\lceil a_1.P_1 \mid \dots \mid a_n.P_n \rceil_A \multimap \lceil 1 \rceil_A$ but no two a_i can synchronize:



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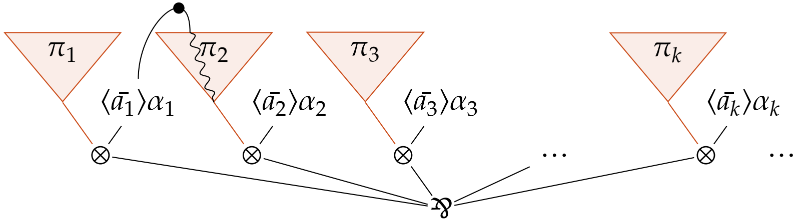

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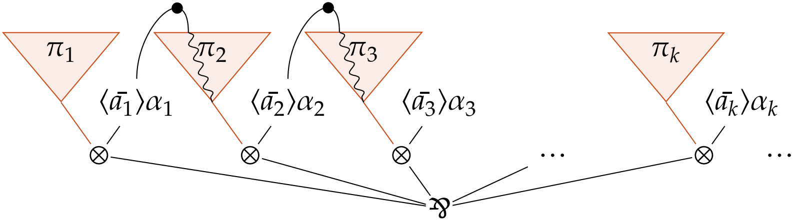

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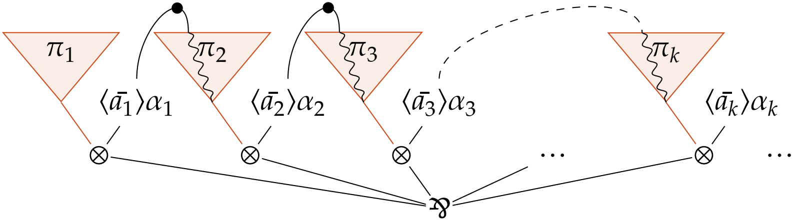
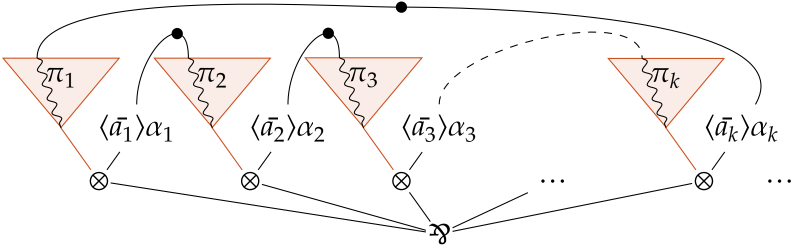


Suppose there is some proof of $\lceil a_1.P_1 \mid \dots \mid a_n.P_n \rceil_A \multimap \lceil 1 \rceil_A$ but no two a_i can synchronize:



Impossible because of acyclicity!

Type assignment

"Synchronous" version

Definition

Terms of MCCS are translated into MLLa formulas as follows:

$$\begin{aligned}
\lceil 1 \rceil_S &:= \forall\alpha\ \alpha^\perp \parr \alpha && = \forall\alpha\ \alpha \multimap \alpha \\
\lceil P \mid Q \rceil_S &:= \lceil P \rceil_S \otimes \lceil Q \rceil_S && \\
\lceil a.P \rceil_S &:= \forall\alpha\ \langle a \rangle (\alpha^\perp \parr (\lceil P \rceil_S \otimes \alpha)) && = \forall\alpha\ \langle a \rangle (\alpha \multimap (\lceil P \rceil_S \otimes \alpha)) \\
\lceil \bar{a}.P \rceil_S &:= \forall\beta\ \langle \bar{a} \rangle (\lceil P \rceil_S \otimes \beta^\perp) \parr \beta && = \forall\beta\ \langle a \rangle (\lceil P \rceil_S \multimap \beta) \multimap \beta
\end{aligned}$$

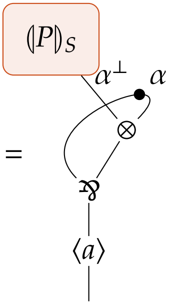
Spot the difference!

Fact

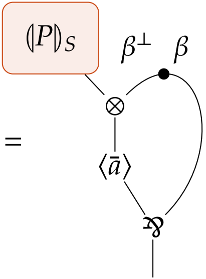
For every P, the type $\lceil P \rceil_S$ has one cut-free proof $(\!| P |\!)_S$.

For actions:

$(\!| a.P |\!)_S =$



$(\!| \bar{a}.P |\!)_S =$



Soundness and completeness

"Synchronous" version

Theorem

There is an execution $P \to^* Q$ if and only if $\lceil P \rceil_S \multimap \lceil Q \rceil_S$ is provable in MLL (without modality rules).

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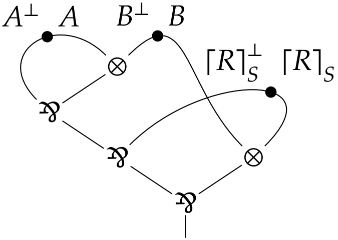
From execution to implication:



with
$$\begin{cases} A = \langle a \rangle (\lceil Q \rceil_S^\perp \parr (\lceil P \rceil_S \otimes \lceil Q \rceil_S)) \\ B = \lceil P \rceil_S \otimes \lceil Q \rceil_S \end{cases}$$

proves $\lceil (a.P \mid \bar{a}.Q) \mid R \rceil_S \multimap \lceil (P \mid Q) \mid R \rceil_S$

Soundness and completeness

"Synchronous" version

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From execution to implication:

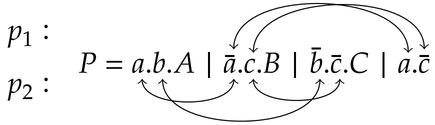
- each execution step is provable.

From implication to execution:

- take a proof of $\lceil P \rceil_S \multimap \lceil Q \rceil_S$
- cut it against $(\!| P |\!)_S$, eliminate the cut
- read back process terms from intermediate steps

Definition

A *pairing* is an association between occurrences of dual actions



Definition

A *determinisation* of P along a pairing p is a renaming $\partial_p(P)$ of actions in P where names are equal only for related actions.

$$\partial_{p_1}(P) = a_1.b_1.\partial(A) \mid \bar{a}_2.c_1.\partial(B) \mid \bar{b}_2.\bar{c}_2.\partial(C) \mid a_2.\bar{c}_1$$

$$\partial_{p_2}(P) = a_1.b_1.\partial(A) \mid \bar{a}_1.c_1.\partial(B) \mid \bar{b}_1.\bar{c}_1.\partial(C) \mid a_2.\bar{c}_2$$

Pairings vs proofs

Facts about pairings:

- each run induces a pairing
- runs are equivalent up to permutation of independent events iff they induce the same pairing
- if p is a *consistent* pairing of P then p is the unique maximal consistent pairing of $\partial_p(P)$

Hence pairings are *execution schedules* and determinized terms represent them inside the process language.

Observation

Pairings are related to placements of axiom links in proofs of $\lceil P \rceil_A \multimap \lceil 1 \rceil_A$.

Discussion

Some points deserve more investigation:

Replication: everything extends smoothly by setting $\lceil !P \rceil_A = ! \lceil P \rceil_A$.

Choice: additives are the natural option

Name hiding: the situation is not obvious

- use quantifiers?
  existential? nabla?
- partial scheduling?
  $(\nu a)P$ is P with some proof that decides what happens on a

Name passing: need to fix hiding first!

Further directions

Current state of affairs:

- A logical description of scheduling in processes
- Explicitation of *control flow* through processes
- Hints for a new study of prefixing in processes

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Ongoing questions:

- Which semantics for the logic of schedules?
  coherence spaces for MLLa, etc
- CPS-like interpretation of processes?
  the translation of actions is a kind of double negation
- A logical account on π-to-solos encoding?
  by relating to other systems

Work in progress...