
Processing Programs: the linear case

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Computational processes

▷ Processes
Outline

*λ*PCF

*lin*Solos

Main Results

Conclusions

In [AbelsonSussman85,Ch1], Harold Abelson and Sussman, Gerald Jay and Julie Sussman state,

“We are about to study the idea of a computational process. Computational processes are abstract beings that inhabit computers. As they evolve, processes manipulate other abstract things called data. The evolution of a process is directed by a pattern of rules called a program. People create programs to direct processes. In effect, we conjure the spirits of the computer with our spells.”

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Our goal is **to formalize** such trivial idea !!!

In literature,

many works touch lightly such idea with more specific goals, as

1. to prove the expressiveness of a mobile calculus, by showing how to represent the λ -calculus evaluation strategies
2. to represent strategies of game semantics for paradigmatic programming languages.

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Outline of the Talk

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- *λ*PCF: a simple linear programming language
- *lin*Solos:
a typed process calculus based on the calculus of solos
- Interpretation of *λ*PCF on *lin*Solos
- Correctness w.r.t the operational semantic of *λ*PCF.
- Parallel evaluation of our *λ*PCF-processes.

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slPCF

linSolos

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Conclusions

- *slPCF*: a simple linear programming language
- *linSolos*:
a typed process calculus based on the calculus of solos
- Interpretation of *slPCF* on *linSolos*
- Correctness w.r.t the operational semantic of *slPCF*.
- Parallel evaluation of our *slPCF*-processes.

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▷ $\mathcal{S}\ell\text{PCF}$

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*λ*PCF is a simple programming language, **fully abstract** modeled by **linear function between coherence spaces**.

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λ PCF is a simple programming language, **fully abstract** modeled by **linear function between coherence spaces**.

λ PCF is not syntactically linear, in fact its programs can contain the same variable more than once.

Linearity can be considered in many respects.

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- Syntactical

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Linearity can be considered in many respects.

- Syntactical
- Denotational

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Linearity can be considered in many respects.

- Syntactical
- Denotational
- Operational

A Semantically Linear Programming Language

Types: $\sigma, \tau ::= \iota \mid (\sigma \multimap \tau)$

0^ι	
$\text{succ}^{\iota \multimap \iota}$	
$\text{pred}^{\iota \multimap \iota}$	

$$\frac{}{\underline{0} \Downarrow \underline{0}} (0) \quad \frac{M \Downarrow \underline{n}}{\text{succ } M \Downarrow \text{succ } \underline{n}} (s) \quad \frac{M \Downarrow \text{succ } \underline{n}}{\text{pred } M \Downarrow \underline{n}} (p_n)$$

A Semantically Linear Programming Language

Types: $\sigma, \tau ::= \iota \mid (\sigma \multimap \tau)$

0^ι	
$\text{succ}^{\iota \multimap \iota}$	
$\text{pred}^{\iota \multimap \iota}$	
x^ι	ground variable (GFV(M))
$x^{\sigma \multimap \tau}$	higher order variable (HFV(M))

A Semantically Linear Programming Language

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$\text{succ}^{\iota \multimap \iota}$	
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x^ι $x^{\sigma \multimap \tau}$	ground variable ($\text{GFV}(M)$) higher order variable ($\text{HFV}(M)$)
$(\lambda x^\iota . M^\tau)^{\iota \multimap \tau}$ $(\lambda x^{\sigma \multimap \tau} . M)$	x can occur zero or many time in M x can occur exactly once

$$\frac{N \Downarrow \underline{m} \quad M[\underline{m}/x]P_1 \cdots P_i \Downarrow \underline{n}}{(\lambda x^\iota . M)NP_1 \cdots P_i \Downarrow \underline{n}} (\lambda^\iota) \quad \frac{M[N/x]P_1 \cdots P_i \Downarrow \underline{n}}{(\lambda x^{\sigma \multimap \tau} . M)NP_1 \cdots P_i \Downarrow \underline{n}} (\lambda^{\multimap})$$

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x^ι $x^{\sigma \multimap \tau}$	ground variable ($\text{GFV}(M)$) higher order variable ($\text{HFV}(M)$)
$(\lambda x^\iota. M^\tau)^{\iota \multimap \sigma}$ $(\lambda x^{\sigma \multimap \tau}. M)$	x can occur zero or many time in M x can occur exactly once
$(\text{lif } M^\iota \text{ L}^\iota \text{ R}^\iota)^\iota$	if $\text{HFV}(\text{L}^\iota) = \text{HFV}(\text{R}^\iota)$, $\text{HFV}(M^\iota) \cap \text{HFV}(\text{R}^\iota) = \emptyset$

$$\frac{M \Downarrow \underline{0} \quad L \Downarrow \underline{m}}{\text{lif } M \text{ L } R \Downarrow \underline{m}} \text{ (if}_l\text{)} \quad \frac{M \Downarrow \text{succ}(\underline{n}) \quad R \Downarrow \underline{m}}{\text{lif } M \text{ L } R \Downarrow \underline{m}} \text{ (if}_r\text{)}$$

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$(\ell \text{if } M^\iota \text{ L}^\iota \text{ R}^\iota)^\iota$	if $\text{HFV}(\text{L}^\iota) = \text{HFV}(\text{R}^\iota)$, $\text{HFV}(M^\iota) \cap \text{HFV}(\text{R}^\iota) = \emptyset$
F^σ $(\mu F^\sigma . M^\sigma)^\sigma$	recursion (stable) variable ($\text{SFV}(M)$) if $F^\sigma \in \text{SFV}(M^\sigma)$ and $\text{HFV}(M^\sigma) = \emptyset$

$$\frac{M[\mu F . M / F] P_1 \cdots P_i \Downarrow \underline{n}}{(\mu F . M) P_1 \cdots P_i \Downarrow \underline{n}} (\mu)$$

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Types: $\sigma, \tau ::= \iota \mid (\sigma \multimap \tau)$

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x^ι $x^{\sigma \multimap \tau}$	ground variable ($\text{GFV}(\mathbb{M})$) higher order variable ($\text{HFV}(\mathbb{M})$)
$(\lambda x^\iota. M^\tau)^{\iota \multimap \tau}$ $(\lambda x^{\sigma \multimap \tau}. M)$	x can occur zero or many time in \mathbb{M} x can occur exactly once
$(\text{lif } M^\iota \ L^\iota \ R^\iota)^\iota$	if $\text{HFV}(L^\iota) = \text{HFV}(R^\iota)$, $\text{HFV}(M^\iota) \cap \text{HFV}(R^\iota) = \emptyset$
F^σ $(\mu F^\sigma. M^\sigma)^\sigma$	recursion (stable) variable ($\text{SFV}(\mathbb{M})$) if $F^\sigma \in \text{SFV}(\mathbb{M}^\sigma)$ and $\text{HFV}(\mathbb{M}^\sigma) = \emptyset$
which?	

$$\frac{\mathbb{M}(\lambda x^\iota. \text{lif}(x \doteq k) \ \underline{k} \ \Omega^\iota) \Downarrow \underline{n}}{\text{which? } \mathbb{M}^{(\iota \multimap \iota) \multimap \iota} \Downarrow [\underline{n}, \underline{k}]} \quad (\text{w}^{\underline{k}})$$

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Causality in process calculi

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- There are two possible ways to express causality in process calculi
 - **Explicit**, by using prefixing
 - ▷ $\alpha.P$
 - **Implicit**, by using the restriction construct
 - ▷ $(\nu v)(\bar{u}\langle v \rangle \parallel v\langle w \rangle)$

Causality in process calculi

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 - **Explicit**, by using prefixing
 - ▷ $\alpha.P$
 - **Implicit**, by using the restriction construct
 - ▷ $(\nu v)(\bar{u}\langle v \rangle \parallel v\langle w \rangle)$

Syntax:

Processes $P ::= \quad | P \parallel Q \quad | (\nu v)P \quad | \mathbf{0}$

Structural congruence: α -rule, abelian monoidal laws for $|$ and

$(\nu v)\mathbf{0} \equiv \mathbf{0}$ $(\nu v)(P \parallel Q) \equiv P \parallel (\nu v)Q$ if $v \notin \text{fn}(P)$	$(\nu v)(\nu w)P \equiv (\nu w)(\nu v)P$
--	--

Reduction rules:

$$\frac{P \longrightarrow P'}{P \parallel Q \longrightarrow P' \parallel Q}$$

$$\frac{P \longrightarrow P'}{(\nu v)P \longrightarrow (\nu v)P'}$$

$$\frac{P \equiv P' \longrightarrow Q' \equiv Q}{P \longrightarrow Q}$$

Syntax:

<i>Solos</i>	$\sigma ::= q\langle\tilde{p}, a\rangle \bar{q}\langle\tilde{p}, a\rangle$
<i>Processes</i>	$P ::= \sigma \quad \quad P\ Q \quad \quad (\nu v)P \quad \quad \mathbf{0}$

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--	--

Reduction rules:

$$\frac{|\tilde{v}_1| = |\tilde{v}_2| \quad \theta \text{ agrees with } \{\tilde{v}_1 = \tilde{v}_2\} \quad \text{ran}(\theta) \cap \tilde{w} = \emptyset \quad \text{Dom}(\theta) = \tilde{w}}{(\nu \tilde{w})(u\langle\tilde{v}_1\rangle \| \bar{u}\langle\tilde{v}_2\rangle \| R) \longrightarrow R\theta}$$

$$\frac{P \longrightarrow P'}{P\|Q \longrightarrow P'\|Q}$$

$$\frac{P \longrightarrow P'}{(\nu v)P \longrightarrow (\nu v)P'}$$

$$\frac{P \equiv P' \longrightarrow Q' \equiv Q}{P \longrightarrow Q}$$

Syntax:

<i>Expressions:</i>	$E ::= n \mid x \mid \text{succ}(E) \mid \text{pred}(E)$
<i>Solos</i>	$\sigma ::= q\langle\tilde{p}, a\rangle \mid \bar{q}\langle\tilde{p}, a\rangle$
<i>Processes</i>	$P ::= \sigma \mid P\parallel Q \mid (\nu v)P \mid \mathbf{0}$

Structural congruence: α -rule, abelian monoidal laws for \mid and

$(\nu v)\mathbf{0} \equiv \mathbf{0}$	$(\nu v)(\nu w)P \equiv (\nu w)(\nu v)P$
$(\nu v)(P\parallel Q) \equiv P\parallel(\nu v)Q$ if $v \notin \text{fn}(P)$	

Reduction rules:

$\overline{n \longrightarrow n}$	$\frac{E \longrightarrow n}{\text{succ}(E) \longrightarrow n + 1}$	$\frac{E \longrightarrow n}{\text{pred}(E) \longrightarrow n - 1}$
$\frac{ \tilde{v}_1 = \tilde{v}_2 \quad \theta \text{ agrees with } \{\tilde{v}_1 = \tilde{v}_2\} \quad \text{ran}(\theta) \cap \tilde{w} = \emptyset \quad \text{Dom}(\theta) = \tilde{w}}{(\nu \tilde{w})(u\langle\tilde{v}_1\rangle \parallel \bar{u}\langle\tilde{v}_2\rangle \parallel R) \longrightarrow R\theta}$		

$$\frac{P \longrightarrow P'}{P\parallel Q \longrightarrow P'\parallel Q}$$

$$\frac{P \longrightarrow P'}{(\nu v)P \longrightarrow (\nu v)P'}$$

$$\frac{P \equiv P' \longrightarrow Q' \equiv Q}{P \longrightarrow Q}$$

Syntax:

Expressions: $E ::= n \mid x \mid \text{succ}(E) \mid \text{pred}(E)$

$\sigma ::= q\langle\tilde{p}, a\rangle \mid \bar{q}\langle\tilde{p}, a\rangle$

Processes $P ::= \sigma \mid a(x)P \mid \bar{a}\langle E \rangle \mid P\parallel Q \mid (\nu v)P \mid [P \oplus E Q] \mid F^q \mid \text{rec}F.P^\dagger \mid \mathbf{0}$

† We impose that P contains exactly one free question-name

Structural congruence: α -rule, abelian monoidal laws for \mid and

$(\nu v)\mathbf{0} \equiv \mathbf{0}$

$(\nu v)(P\parallel Q) \equiv P\parallel(\nu v)Q$ if $v \notin \text{fn}(P)$

$a(x)(P\parallel Q) \equiv P\parallel(a(x)Q)$ if $x \notin \text{FV}(P)$

$\text{rec}F.P \equiv P\{\text{rec}F.P/F\}$

$(\nu v)(\nu w)P \equiv (\nu w)(\nu v)P$

$a(x)b(y)P \equiv b(y)a(x)P$

$a(x)(\nu v)P \equiv (\nu v)(a(x)P)$ if $v \neq a$

Reduction rules:

$\frac{}{n \longrightarrow n} \quad \frac{E \longrightarrow n}{\text{succ}(E) \longrightarrow n + 1} \quad \frac{E \longrightarrow n}{\text{pred}(E) \longrightarrow n - 1}$

$\frac{|\tilde{v}_1| = |\tilde{v}_2| \quad \theta \text{ agrees with } \{\tilde{v}_1 = \tilde{v}_2\} \quad \text{ran}(\theta) \cap \tilde{w} = \emptyset \quad \text{Dom}(\theta) = \tilde{w}}{(\nu \tilde{w})(u\langle\tilde{v}_1\rangle \parallel \bar{u}\langle\tilde{v}_2\rangle \parallel R) \longrightarrow R\theta}$

$\frac{E \longrightarrow n}{a(x)P\bar{a}\langle E \rangle \longrightarrow P[n/x]}$

$\frac{E \longrightarrow 0}{[P \oplus E Q] \longrightarrow P}$

$\frac{E \longrightarrow n \quad n \neq 0}{[P \oplus E Q] \longrightarrow Q}$

$\frac{P \longrightarrow P'}{P\parallel Q \longrightarrow P'\parallel Q}$

$\frac{P \longrightarrow P'}{a(\tilde{x})P \longrightarrow a(\tilde{x})P'}$

$\frac{P \longrightarrow P'}{(\nu v)P \longrightarrow (\nu v)P'}$

$\frac{P \equiv P' \longrightarrow Q' \equiv Q}{P \longrightarrow Q}$

Example of Solos-reduction

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Reduction fire requires unification of names.

$$(\nu p_0, p_1, a)(q\langle p, p, a \rangle \parallel \bar{q}\langle p_0, p_1, b \rangle \parallel R) \longrightarrow R[p/p_0, p/p_1, b/a]$$

$$(\nu p_0, p, b)(q\langle p, p, a \rangle \parallel \bar{q}\langle p_0, p_1, b \rangle \parallel R) \longrightarrow R[p_1/p_0, p_1/p, a/b]$$

$$(\nu p)(q\langle p, p, a \rangle \parallel \bar{q}\langle p_0, p_1, b \rangle \parallel R) \not\longrightarrow$$

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- The notion of syntactical linearity used, literally, in a process language become meaningless.

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- The notion of syntactical linearity used, literally, in a process language become meaningless.
- A clever adaptation of such a notion has been has done by Kobayashi, Yoshida, Honda and Berger.

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- The notion of syntactical linearity used, literally, in a process language become meaningless.
- A clever adaptation of such a notion has been has done by Kobayashi, Yoshida, Honda and Berger.
- There is exactly one input and exactly one output on a name, for each possible evolution of the process
 - + output – input \updownarrow consumed.

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- Linear channel types: sorting augmented with a modality

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- Linear channel types: sorting augmented with a modality
- A match operator \odot defined as $S^+ \odot S^- = S^- \odot S^+ = S^\updownarrow$

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□ Linear channel types: sorting augmented with a modality

□ A match operator \odot defined as $S^+ \odot S^- = S^- \odot S^+ = S^\downarrow$

□ The straightforward match operator \odot for environment

$$A \odot B = (A \setminus B) \cup (B \setminus A) \cup \{v : \tau_1 \odot \tau_2 \mid (v : \tau_1) \in A, (v : \tau_2) \in B\}$$

□ Linear channel types: sorting augmented with a modality

□ A match operator \odot defined as $S^+ \odot S^- = S^- \odot S^+ = S^\downarrow$

□ The straightforward match operator \odot for environment

$$A \odot B = (A \setminus B) \cup (B \setminus A) \cup \{v : \tau_1 \odot \tau_2 \mid (v : \tau_1) \in A, (v : \tau_2) \in B\}$$

□ Process variable environments for **Recursion**

Typing rules

Typing judgment in a natural deduction style: $\Gamma \vdash P \triangleright A$

$$\frac{}{\Gamma \vdash \mathbf{0} \triangleright _} \text{ (z)} \quad \frac{\Gamma \vdash P \triangleright A \quad \Gamma \vdash Q \triangleright B \quad A \asymp B}{\Gamma \vdash P \parallel Q \triangleright A \odot B} \text{ (par)} \quad \frac{\Gamma \vdash P \triangleright A^+ \quad \Gamma \vdash Q \triangleright A^+}{\Gamma \vdash [P \oplus Q] \triangleright A^+} \text{ (sum)}$$

Typing rules

Typing judgment in a natural deduction style: $\Gamma \vdash P \triangleright A$

$$\begin{array}{c} \frac{}{\Gamma \vdash \mathbf{0} \triangleright _} \text{(z)} \quad \frac{\Gamma \vdash P \triangleright A \quad \Gamma \vdash Q \triangleright B \quad A \asymp B}{\Gamma \vdash P \parallel Q \triangleright A \odot B} \text{(par)} \quad \frac{\Gamma \vdash P \triangleright A^+ \quad \Gamma \vdash Q \triangleright A^+}{\Gamma \vdash [P \oplus Q] \triangleright A^+} \text{(sum)} \\ \\ \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash q\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^-, \tilde{p} : \tilde{\phi}^-, a : \iota^-} \text{(in)} \quad \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash \bar{q}\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^+, \tilde{p} : \tilde{\phi}^+, a : \iota^+} \text{(out)} \end{array}$$

Typing rules

Typing judgment in a natural deduction style: $\Gamma \vdash P \triangleright A$

$$\begin{array}{c}
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 \\
 \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash q\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^-, \tilde{p} : \tilde{\phi}^-, a : \iota^-} \text{(in)} \qquad \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash \bar{q}\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^+, \tilde{p} : \tilde{\phi}^+, a : \iota^+} \text{(out)} \\
 \\
 \frac{\Gamma \vdash P \triangleright A}{\Gamma \vdash a(x) P \triangleright a : \iota^-, A} \text{(d-in)} \qquad \frac{}{\Gamma \vdash \bar{a}\langle E \rangle \triangleright a : \iota^+} \text{(a-out)} \qquad \frac{\Gamma \vdash P \triangleright A}{\Gamma \vdash P \triangleright A, v : S \updownarrow} \text{(w)}
 \end{array}$$

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Typing judgment in a natural deduction style: $\Gamma \vdash P \triangleright A$

$$\begin{array}{c}
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 \\
 \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash q\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^{-}, \tilde{p} : \tilde{\phi}^{-}, a : \iota^{-}} \text{(in)} \qquad \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash \bar{q}\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^{+}, \tilde{p} : \tilde{\phi}^{+}, a : \iota^{+}} \text{(out)} \\
 \\
 \frac{\Gamma \vdash P \triangleright A}{\Gamma \vdash a(x) P \triangleright a : \iota^{-}, A} \text{(d-in)} \qquad \frac{}{\Gamma \vdash \bar{a}\langle E \rangle \triangleright a : \iota^{+}} \text{(a-out)} \qquad \frac{\Gamma \vdash P \triangleright A}{\Gamma \vdash P \triangleright A, v : S^{\downarrow}} \text{(w)} \\
 \\
 \frac{}{\Gamma, F : \phi \vdash F^{\natural} \triangleright q : \phi^{-}} \text{(p-v)} \qquad \frac{\Gamma, F : \phi \vdash P \triangleright q : \phi^{-}}{\Gamma \vdash \text{rec} F.P \triangleright q : \phi^{-}} \text{(rec)} \qquad \frac{\Gamma \vdash P \triangleright A, v : S^{\downarrow}}{\Gamma \vdash (\nu v) P \triangleright A} \text{(Res)}
 \end{array}$$

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Typing judgment in a natural deduction style: $\Gamma \vdash P \triangleright A$

$$\begin{array}{c}
 \frac{}{\Gamma \vdash \mathbf{0} \triangleright _} \text{(z)} \qquad \frac{\Gamma \vdash P \triangleright A \quad \Gamma \vdash Q \triangleright B \quad A \asymp B}{\Gamma \vdash P \parallel Q \triangleright A \odot B} \text{(par)} \qquad \frac{\Gamma \vdash P \triangleright A^+ \quad \Gamma \vdash Q \triangleright A^+}{\Gamma \vdash [P \oplus Q] \triangleright A^+} \text{(sum)} \\
 \\
 \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash q\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^{-}, \tilde{p} : \tilde{\phi}^{-}, a : \iota^{-}} \text{(in)} \qquad \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash \bar{q}\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^{+}, \tilde{p} : \tilde{\phi}^{+}, a : \iota^{+}} \text{(out)} \\
 \\
 \frac{\Gamma \vdash P \triangleright A}{\Gamma \vdash a(x) P \triangleright a : \iota^{-}, A} \text{(d-in)} \qquad \frac{}{\Gamma \vdash \bar{a}\langle E \rangle \triangleright a : \iota^{+}} \text{(a-out)} \qquad \frac{\Gamma \vdash P \triangleright A}{\Gamma \vdash P \triangleright A, v : S^{\uparrow\downarrow}} \text{(w)} \\
 \\
 \frac{}{\Gamma, F : \phi \vdash F^{\mathfrak{q}} \triangleright q : \phi^{-}} \text{(p-v)} \qquad \frac{\Gamma, F : \phi \vdash P \triangleright q : \phi^{-}}{\Gamma \vdash \text{rec} F.P \triangleright q : \phi^{-}} \text{(rec)} \qquad \frac{\Gamma \vdash P \triangleright A, v : S^{\uparrow\downarrow}}{\Gamma \vdash (\nu v) P \triangleright A} \text{(Res)}
 \end{array}$$

□ **linearity**

Typing rules

Typing judgment in a natural deduction style: $\Gamma \vdash P \triangleright A$

$$\begin{array}{c}
 \frac{}{\Gamma \vdash \mathbf{0} \triangleright _} \text{ (z)} \qquad \frac{\Gamma \vdash P \triangleright A \quad \Gamma \vdash Q \triangleright B \quad A \asymp B}{\Gamma \vdash P \parallel Q \triangleright A \odot B} \text{ (par)} \qquad \frac{\Gamma \vdash P \triangleright A^+ \quad \Gamma \vdash Q \triangleright A^+}{\Gamma \vdash [P \oplus Q] \triangleright A^+} \text{ (sum)} \\
 \\
 \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash q\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^{-}, \tilde{p} : \tilde{\phi}^{-}, a : \iota^{-}} \text{ (in)} \qquad \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash \bar{q}\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^{+}, \tilde{p} : \tilde{\phi}^{+}, a : \iota^{+}} \text{ (out)} \\
 \\
 \frac{\Gamma \vdash P \triangleright A}{\Gamma \vdash a(x) P \triangleright a : \iota^{-}, A} \text{ (d-in)} \qquad \frac{}{\Gamma \vdash \bar{a}\langle E \rangle \triangleright a : \iota^{+}} \text{ (a-out)} \qquad \frac{\Gamma \vdash P \triangleright A}{\Gamma \vdash P \triangleright A, v : S^{\uparrow\downarrow}} \text{ (w)} \\
 \\
 \frac{}{\Gamma, F : \phi \vdash F^{\natural} \triangleright q : \phi^{-}} \text{ (p-v)} \qquad \frac{\Gamma, F : \phi \vdash P \triangleright q : \phi^{-}}{\Gamma \vdash \text{rec} F.P \triangleright q : \phi^{-}} \text{ (rec)} \qquad \frac{\Gamma \vdash P \triangleright A, v : S^{\uparrow\downarrow}}{\Gamma \vdash (\nu v) P \triangleright A} \text{ (Res)}
 \end{array}$$

- linearity**
- subject reduction**

Typing rules

Typing judgment in a natural deduction style: $\Gamma \vdash P \triangleright A$

$$\begin{array}{c}
 \frac{}{\Gamma \vdash \mathbf{0} \triangleright _} \text{(z)} \qquad \frac{\Gamma \vdash P \triangleright A \quad \Gamma \vdash Q \triangleright B \quad A \asymp B}{\Gamma \vdash P \parallel Q \triangleright A \odot B} \text{(par)} \qquad \frac{\Gamma \vdash P \triangleright A^+ \quad \Gamma \vdash Q \triangleright A^+}{\Gamma \vdash [P \oplus Q] \triangleright A^+} \text{(sum)} \\
 \\
 \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash q\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^{-}, \tilde{p} : \tilde{\phi}^{-}, a : \iota^{-}} \text{(in)} \qquad \frac{\tilde{p}, a \text{ distinct}}{\Gamma \vdash \bar{q}\langle \tilde{p}, a \rangle \triangleright q : [\tilde{\phi}, \iota]^{+}, \tilde{p} : \tilde{\phi}^{+}, a : \iota^{+}} \text{(out)} \\
 \\
 \frac{\Gamma \vdash P \triangleright A}{\Gamma \vdash a(x)P \triangleright a : \iota^{-}, A} \text{(d-in)} \qquad \frac{}{\Gamma \vdash \bar{a}\langle E \rangle \triangleright a : \iota^{+}} \text{(a-out)} \qquad \frac{\Gamma \vdash P \triangleright A}{\Gamma \vdash P \triangleright A, v : S^{\updownarrow}} \text{(w)} \\
 \\
 \frac{}{\Gamma, F : \phi \vdash F^{\natural} \triangleright q : \phi^{-}} \text{(p-v)} \qquad \frac{\Gamma, F : \phi \vdash P \triangleright q : \phi^{-}}{\Gamma \vdash \text{rec}F.P \triangleright q : \phi^{-}} \text{(rec)} \qquad \frac{\Gamma \vdash P \triangleright A, v : S^{\updownarrow}}{\Gamma \vdash (\nu v)P \triangleright A} \text{(Res)}
 \end{array}$$

- linearity**
- subject reduction**
- confluence**

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We denote $q(\tilde{v}) = (\nu\tilde{v})q\langle\tilde{v}\rangle$ and $\bar{q}(\tilde{v}) = (\nu\tilde{v})\bar{q}\langle\tilde{v}\rangle$

$$\llbracket 0^l \rrbracket^{q_\epsilon} = q_\epsilon(\mathbf{a}_\epsilon) \bar{\mathbf{a}}_\epsilon \langle 0 \rangle$$

$$\text{(i.e. } \llbracket \underline{\mathbf{n}}^l \rrbracket^{q_\epsilon} = q_\epsilon(\mathbf{a}_\epsilon) \bar{\mathbf{a}}_\epsilon \langle \underline{\mathbf{n}} \rangle)$$

$$\llbracket \text{succ}^{l \rightarrow o_l} \rrbracket^{q_\epsilon} = q_\epsilon(q_1, \mathbf{a}_\epsilon) \bar{q}_1(\mathbf{a}_1) \mathbf{a}_1(x) \bar{\mathbf{a}}_\epsilon \langle \text{succ}(x) \rangle$$

$$\llbracket \text{pred}^{l \rightarrow o_l} \rrbracket^{q_\epsilon} = q_\epsilon(q_1, \mathbf{a}_\epsilon) \bar{q}_1(\mathbf{a}_1) \mathbf{a}_1(x) \bar{\mathbf{a}}_\epsilon \langle \text{pred}(x) \rangle$$

Encoding

We denote $q(\tilde{v}) = (\nu\tilde{v})q\langle\tilde{v}\rangle$ and $\bar{q}(\tilde{v}) = (\nu\tilde{v})\bar{q}\langle\tilde{v}\rangle$

$$\llbracket F^\sigma \rrbracket^{q_\epsilon} = F \smile^{q_\epsilon}$$

$$\llbracket \mu F^\sigma . M^\sigma \rrbracket^{q_\epsilon} = \text{rec} F . \llbracket M^\sigma \rrbracket^{q_\epsilon}$$

Encoding

We denote $q(\tilde{v}) = (\nu\tilde{v})q\langle\tilde{v}\rangle$ and $\bar{q}(\tilde{v}) = (\nu\tilde{v})\bar{q}\langle\tilde{v}\rangle$

$$[[x^\iota]]^{q_\epsilon} = q_\epsilon(\mathbf{a}_\epsilon) \bar{\mathbf{a}}_\epsilon\langle\mathbf{x}\rangle$$

$$[[\lambda x^\iota . M^{\sigma_1 \rightarrow \dots \rightarrow \sigma_n \rightarrow \iota}]]^{q_\epsilon} = q_\epsilon(q_0, q_1, \dots, q_n, \mathbf{a}_\epsilon) \bar{q}_0(\mathbf{a}_0) \mathbf{a}_0\langle\mathbf{x}\rangle \left[\begin{array}{l} (\nu p)(\bar{p}\langle q_1, \dots, q_n, \mathbf{a} \rangle \parallel [[M]]^p) \\ \oplus \mathbf{x} \\ (\nu p)(\bar{p}\langle q_1, \dots, q_n, \mathbf{a} \rangle \parallel [[M]]^p) \end{array} \right]$$

Encoding

We denote $q(\tilde{v}) = (\nu\tilde{v})q\langle\tilde{v}\rangle$ and $\bar{q}(\tilde{v}) = (\nu\tilde{v})\bar{q}\langle\tilde{v}\rangle$

$$\llbracket \mathbf{x}^\iota \rrbracket^{q_\epsilon} = q_\epsilon(\mathbf{a}_\epsilon) \bar{\mathbf{a}}_\epsilon\langle\mathbf{x}\rangle$$

$$\llbracket \lambda \mathbf{x}^\iota . M^{\sigma_1 \rightarrow \dots \rightarrow \sigma_n \rightarrow \iota} \rrbracket^{q_\epsilon} = q_\epsilon(q_0, q_1, \dots, q_n, \mathbf{a}_\epsilon) \bar{q}_0(\mathbf{a}_0) \mathbf{a}_0(\mathbf{x}) \left[\begin{array}{l} (\nu p)(\bar{p}\langle q_1, \dots, q_n, \mathbf{a} \rangle \parallel \llbracket M \rrbracket^p) \\ \oplus \mathbf{x} \\ (\nu p)(\bar{p}\langle q_1, \dots, q_n, \mathbf{a} \rangle \parallel \llbracket M \rrbracket^p) \end{array} \right]$$

$$\llbracket \mathbf{f}^{\sigma_1 \rightarrow \dots \rightarrow \sigma_n \rightarrow \iota} \rrbracket^{q_\epsilon} = q_\epsilon(q_1, \dots, q_n, \mathbf{a}_\epsilon) \bar{\mathbf{f}}\langle q_1, \dots, q_n, \mathbf{a}_\epsilon \rangle \quad \text{where } n \geq 1$$

$$\llbracket \lambda \mathbf{f}^\tau . M^{\sigma_1 \rightarrow \dots \rightarrow \sigma_n \rightarrow \iota} \rrbracket^{q_\epsilon} = q_\epsilon(\mathbf{f}, q_1, \dots, q_n, \mathbf{a}) (\nu p)(\bar{p}\langle q_1, \dots, q_n, \mathbf{a} \rangle \parallel \llbracket M \rrbracket^p)$$

Encoding

We denote $q(\tilde{v}) = (\nu\tilde{v})q\langle\tilde{v}\rangle$ and $\bar{q}(\tilde{v}) = (\nu\tilde{v})\bar{q}\langle\tilde{v}\rangle$

$$\llbracket \mathbf{x}^\iota \rrbracket^{q_\epsilon} = q_\epsilon(\mathbf{a}_\epsilon) \bar{\mathbf{a}}_\epsilon \langle \mathbf{x} \rangle$$

$$\llbracket \lambda \mathbf{x}^\iota . M^{\sigma_1 \multimap \dots \multimap \sigma_n \multimap \iota} \rrbracket^{q_\epsilon} = q_\epsilon(q_0, q_1, \dots, q_n, \mathbf{a}_\epsilon) \bar{q}_0(\mathbf{a}_0) \mathbf{a}_0(\mathbf{x}) \left[\begin{array}{l} (\nu p)(\bar{p}\langle q_1, \dots, q_n, \mathbf{a} \rangle \parallel \llbracket M \rrbracket^p) \\ \oplus \mathbf{x} \\ (\nu p)(\bar{p}\langle q_1, \dots, q_n, \mathbf{a} \rangle \parallel \llbracket M \rrbracket^p) \end{array} \right]$$

$$\llbracket \mathbf{f}^{\sigma_1 \multimap \dots \multimap \sigma_n \multimap \iota} \rrbracket^{q_\epsilon} = q_\epsilon(q_1, \dots, q_n, \mathbf{a}_\epsilon) \bar{\mathbf{f}}\langle q_1, \dots, q_n, \mathbf{a}_\epsilon \rangle \quad \text{where } n \geq 1$$

$$\llbracket \lambda \mathbf{f}^\tau . M^{\sigma_1 \multimap \dots \multimap \sigma_n \multimap \iota} \rrbracket^{q_\epsilon} = q_\epsilon(\mathbf{f}, q_1, \dots, q_n, \mathbf{a}) (\nu p)(\bar{p}\langle q_1, \dots, q_n, \mathbf{a} \rangle \parallel \llbracket M \rrbracket^p)$$

$$\llbracket M^{\sigma_1 \multimap \dots \multimap \sigma_n \multimap \iota} N^{\sigma_1} \rrbracket^{q_\epsilon} = q_\epsilon(q_2, \dots, q_n, \mathbf{a}) (\nu p, q_1)(\bar{p}\langle q_1, \dots, q_n, \mathbf{a} \rangle \parallel \llbracket M \rrbracket^p \parallel \llbracket N \rrbracket^{q_1})$$

$$\llbracket \text{which? } ((\iota \multimap \iota) \multimap \iota) \multimap \iota \rrbracket^{q_\epsilon} = q_\epsilon(q_1, \mathbf{a}_\epsilon) \bar{q}_1(q_{11}, \mathbf{a}_1) q_{11}(q_{111}, \mathbf{a}_{11}) \bar{q}_{111}(\mathbf{a}_{111}) \\ \mathbf{a}_{111}(\mathbf{x}) \bar{\mathbf{a}}_{11} \langle \mathbf{x} \rangle \mathbf{a}_1(\mathbf{y}) \bar{\mathbf{a}}_\epsilon \langle \mathbf{x}, \mathbf{y} \rangle$$

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$$q_1(q'_{11}, a') \bar{q}'_{11}(a_{11}) a_{11}(x) \bar{a}'\langle x \rangle$$

Identity on natural numbers ($\lambda x^t.x$)

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$$q_1(q'_{11}, a') \bar{q}'_{11}(a_{11}) a_{11}(x) \bar{a}'\langle x \rangle$$

$$q_{11}(a'_{11}) \bar{a}'_{11}\langle 5 \rangle$$

Numeral five ([5](#))

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$$\bar{q}_1 \langle q_{11}, a \rangle$$
$$q(a) (\nu q_1, q_{11}) q_1(q'_{11}, a') \bar{q}'_{11}(a_{11}) a_{11}(x) \bar{a}' \langle x \rangle$$
$$q_{11}(a'_{11}) \bar{a}'_{11} \langle 5 \rangle$$

Identity applied to five $((\lambda x'.x)\underline{5})$

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$$\bar{q}_1 \langle q_{11}, a \rangle$$

 $q(a) (\nu q_1, q_{11}) q_1(q'_{11}, a') \bar{q}'_{11}(a_{11}) a_{11}(x) \bar{a}' \langle x \rangle$

$$q_{11}(a'_{11}) \quad \bar{a}'_{11} \langle 5 \rangle$$

External invocation on q

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$$\bar{q}_1 \langle q_{11}, a \rangle$$

q_{11}, a



$q(a) (\nu q_1, q_{11}) q_1(q'_{11}, a') \bar{q}'_{11}(a_{11}) a_{11}(x) \bar{a}' \langle x \rangle$



$q_{11}(a'_{11}) \bar{a}'_{11} \langle 5 \rangle$

Communication along q_1 of the names q_{11}, a

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$$\bar{q}_1 \langle q_{11}, a \rangle$$
$$q_{11}, a \downarrow$$
$$q(a) (\nu q_1, q_{11}) \quad q_1(q_{11}, a) \quad \bar{q}_{11}(a_{11}) \quad a_{11}(x) \quad \bar{a} \langle x \rangle$$
$$q_{11}(a'_{11}) \quad \bar{a}'_{11} \langle 5 \rangle$$

Unification of the names q'_{11}, a' with q_{11}, a

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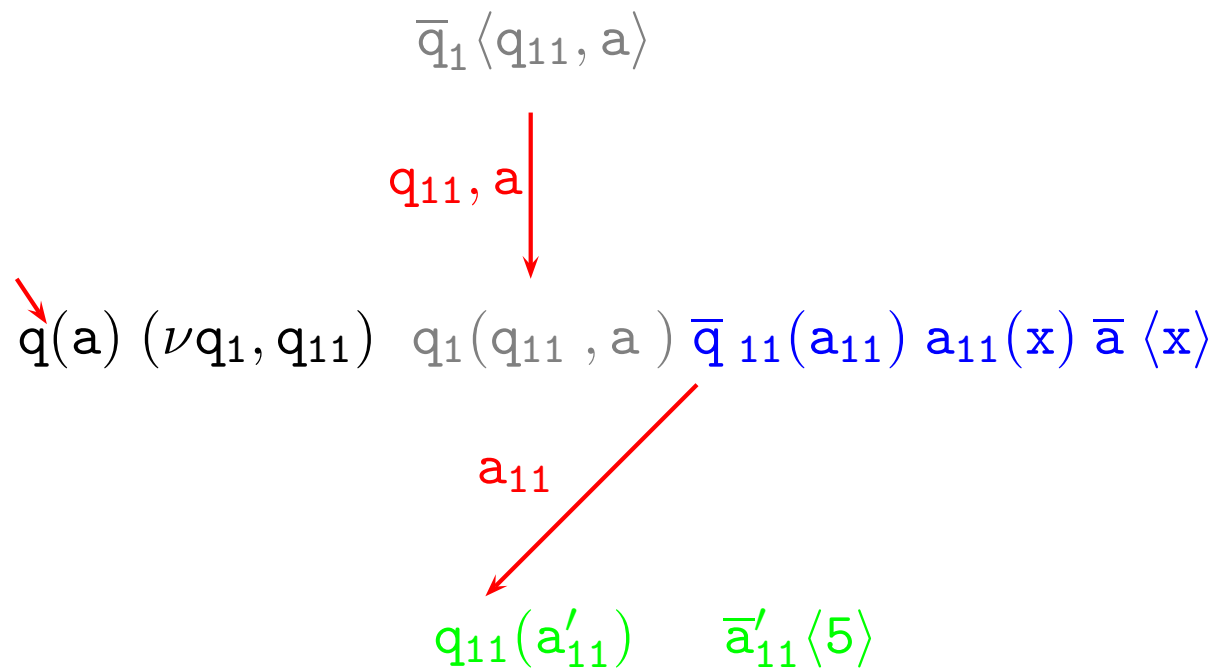
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Communication along q_{11} of the name a_{11}

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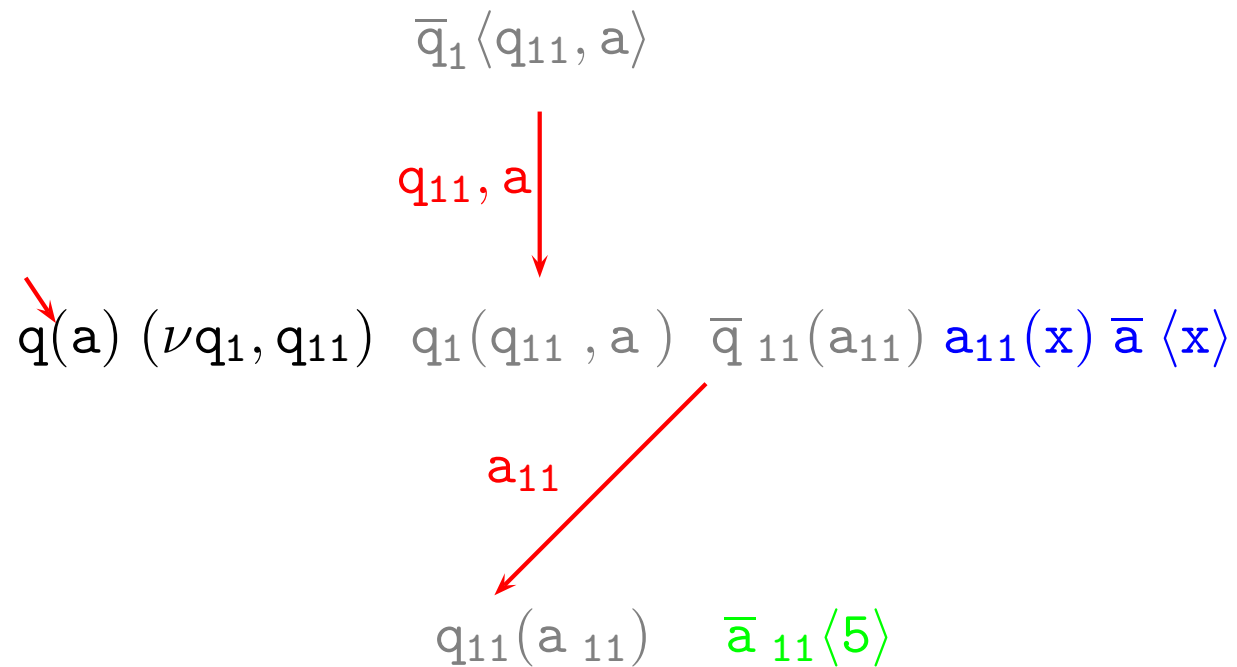
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Unification of the name a'_{11} with a_{11}

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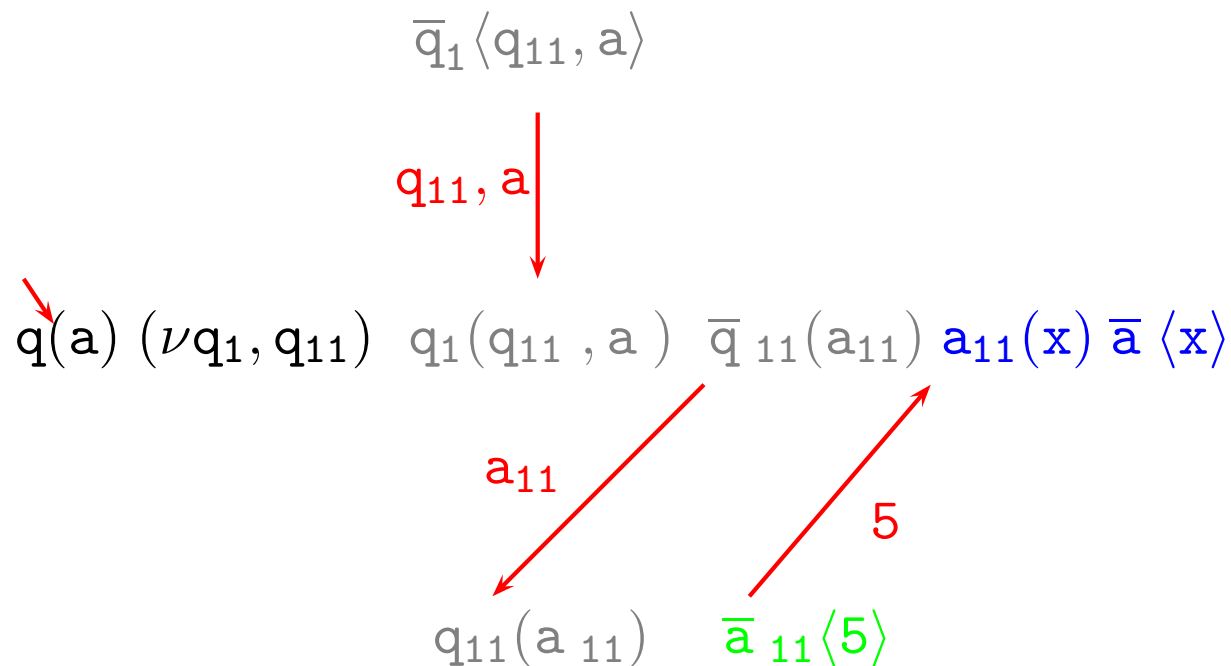
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Communication along a_{11} of the number 5

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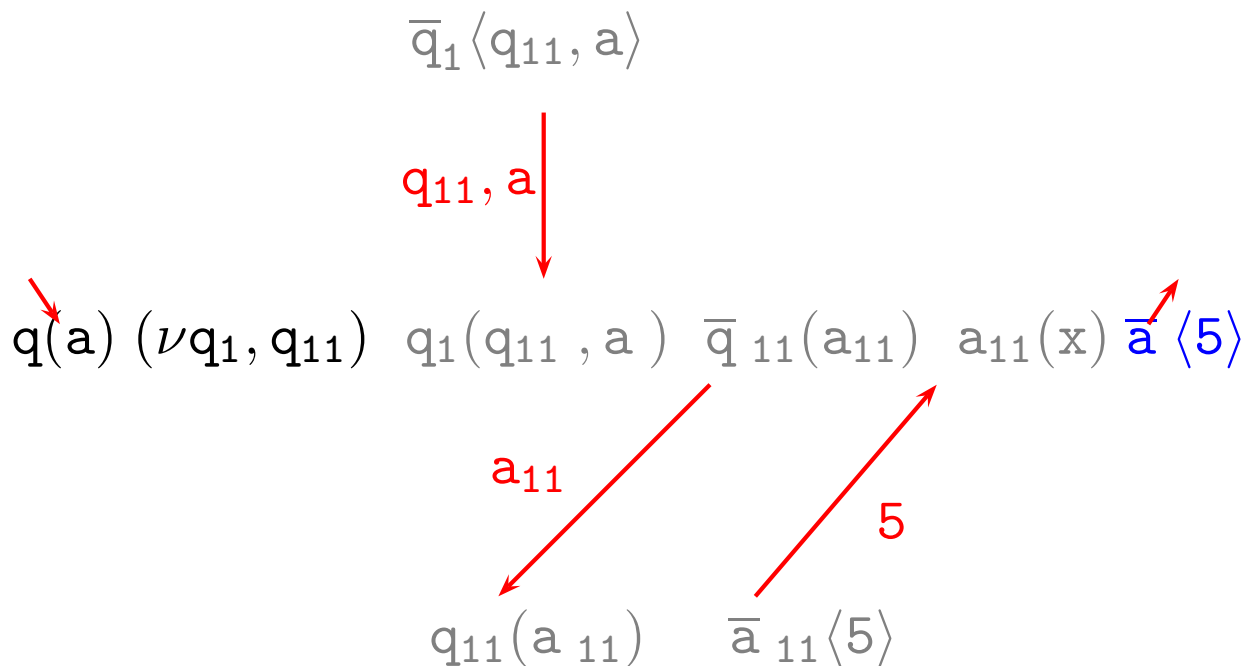
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Output of 5 to the external invocation

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Operational equivalence in \mathcal{SlPCF}

□ Let $M^\sigma, N^\sigma \in \mathcal{SlPCF}$.

1. $M \lesssim_\sigma N$ whenever $\forall C[\sigma]$ s.t. $C[M], C[N] \in \mathcal{P}$, if $C[M] \Downarrow \underline{n}$ then $C[N] \Downarrow \underline{n}$.
2. $M \approx_\sigma N$ if and only if $M \lesssim_\sigma N$ and $N \lesssim_\sigma M$.

Operational equivalence in *SlPCF*

□ Let $M^\sigma, N^\sigma \in \text{SlPCF}$.

1. $M \lesssim_\sigma N$ whenever $\forall C[\sigma]$ s.t. $C[M], C[N] \in \mathcal{P}$, if $C[M] \Downarrow \underline{n}$ then $C[N] \Downarrow \underline{n}$.
2. $M \approx_\sigma N$ if and only if $M \lesssim_\sigma N$ and $N \lesssim_\sigma M$.

Behavioral equivalence in *linSolos*

- Let $\Gamma \vdash P \triangleright a : i^+$. We use $\Gamma \vdash P \Downarrow_{\bar{a}\langle n \rangle}$ to denote that $P \longrightarrow^* P' \equiv (\nu \tilde{\kappa})(\bar{a}\langle E \rangle \| P'')$ where $E \longrightarrow n$.
- \cong_E is the maximum typed congruence on processes such that, $\Gamma \vdash P \cong_E Q$ and $\Gamma \vdash P \Downarrow_{\bar{a}\langle n \rangle}$ imply $\Gamma \vdash Q \Downarrow_{\bar{a}\langle n \rangle}$.

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We can show the following results:

Computational Adequacy: $M^\ell \Downarrow n \iff \llbracket M^\ell \rrbracket^q \longrightarrow^* \llbracket n \rrbracket^q$

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□ \Rightarrow : we can simulate lazy reductions in *lin*Solos.

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Computational Adequacy: $M^l \Downarrow n \iff \llbracket M^l \rrbracket^q \longrightarrow^* \llbracket n \rrbracket^q$

- \Rightarrow : we can simulate lazy reductions in *lin*Solos.
- \Leftarrow : using a computability argument.

We can show the following results:

Computational Adequacy: $M^\ell \Downarrow n \iff \llbracket M^\ell \rrbracket^q \longrightarrow^* \llbracket n \rrbracket^q$

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Correctness $\llbracket M^\sigma \rrbracket^q \cong_E \llbracket N^\sigma \rrbracket^q \Rightarrow M^\sigma \approx_\sigma N^\sigma$

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Correctness $\llbracket M^\sigma \rrbracket^q \cong_E \llbracket N^\sigma \rrbracket^q \Rightarrow M^\sigma \approx_\sigma N^\sigma$

What about **completeness**?

We can show the following results:

Computational Adequacy: $M^\ell \Downarrow n \iff \llbracket M^\ell \rrbracket^q \longrightarrow^* \llbracket n \rrbracket^q$

- \Rightarrow : we can simulate lazy reductions in *lin*Solos.
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Correctness $\llbracket M^\sigma \rrbracket^q \cong_E \llbracket N^\sigma \rrbracket^q \Rightarrow M^\sigma \approx_\sigma N^\sigma$

What about **completeness**?

- **Conjecture:** $M^\sigma \approx_\sigma N^\sigma \Rightarrow \llbracket M^\sigma \rrbracket^q \cong_E \llbracket N^\sigma \rrbracket^q$ holds too.

Work in progress: Study of relevant contexts in *lin*Solos.

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- Parallel β -reduction (without recursion)
 - It requires duplication

$$(\lambda f. \text{lif } x \ f \underline{5} \ f \underline{6}) I \rightarrow_{\beta} \text{lif } x \ I \underline{5} \ I \underline{6}$$

- *lin*Solos-reduction is not able to duplicate terms
- $\llbracket (\lambda f. M) N \rrbracket \longrightarrow^* \llbracket M[N/f] \rrbracket$,
if f does not appear under a *lif*-construct.

Can we code a more parallel evaluation strategy?

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- Parallel β -reduction (without recursion)

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$$(\lambda f. \text{lif } x \ f \underline{5} \ f \underline{6}) I \rightarrow_{\beta} \text{lif } x \ I \underline{5} \ I \underline{6}$$

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if f does not appear under a *lif*-construct.

- Operational linearity

- Reduction does not duplicate terms
- *lin*Solos-reduction: a good point of departure

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Motivations behind this paper are manyfolds.

- From a programming language point of view we provide a tool for study both parallel evaluation and equivalence of programs.

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Motivations behind this paper are manyfolds.

- From a programming language point of view we provide a tool for study both parallel evaluation and equivalence of programs.
- From a process calculi point of view we give representation of a sequential language where redexes can be actually reduced in parallel.

Motivations behind this paper are manyfolds.

- From a programming language point of view we provide a tool for study both parallel evaluation and equivalence of programs.
- From a process calculi point of view we give representation of a sequential language where redexes can be actually reduced in parallel.
- From a game-semantics point of view, we open the road for a parallel description of strategies, since we avoid useless causality.

Work in Progress

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Future works

- Full abstraction
 - Study of the relevant contexts
 - Give a characterization of processes which are interpretation of *λ*PCF-programs
- Correspondence between proof-nets, differential nets and *linSolos*-processes
- Relational model of *linSolos*

Future works

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▷ Future works

- Connection with game semantics
 - What kind of Game Semantics strategies are behind our process calculus?
 - Connections with ludics and true concurrent models (event structures)
- Connection with classical denotational models for PCF
 - Continuous, stable and strongly stable model
 - Possible extensions?
- application to learning theory (problem of Stolzenberg [Barbanera, Berardi])
- parallel compilers of functional languages
- Optimality à la Levy