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Private Names in Non-Commutative Logic

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A Model of Concurrent Processes in the Calculus of Structures

Concise Semantics: BV

atomic interaction

$$C\{\, \overline{\alpha} \parallel \alpha \,\} \longrightarrow C\{\, \mathrm{I} \,\}$$

seq

$$C\{\, (P \,;\, Q) \parallel (R \,;\, S) \,\} \longrightarrow C\{\, (P \parallel R) \,;\, (Q \parallel S) \,\}$$

switch

$$C\{\, (P \otimes Q) \parallel R \,\} \longrightarrow C\{\, P \otimes (Q \parallel R) \,\}$$

commutative monoids: $(P, \parallel, \mathrm{I})$ $(P, \otimes, \mathrm{I})$

monoid: $(P, \;;\, , \mathrm{I})$

P is provable ($\vdash P$) whenever $P \longrightarrow \mathrm{I}$.

Applications: multi-party sessions

Client:

$\left(\overline{p\_begin}(Payload) \parallel \overline{l\_begin}(Payload)\right)$;
$c\_commit(Time)$

Leader:

$l\_begin(Payload)$;
$prepare(Time)$;
$\left(\overline{p\_commit}(Time) \parallel \overline{c\_commit}(Time)\right)$

Participant:

$p\_begin(Payload)$;
$\overline{prepare}(Time)$;
$p\_commit(Time)$

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$$\left(\begin{array}{l} \left(\overline{p\_begin}(Payload) \parallel \overline{l\_begin}(Payload)\right) \,; \\ c\_commit(Time) \end{array} \right)$$

$$\parallel$$

$$\left(\begin{array}{l} l\_begin(Payload) \,; \\ prepare(Time) \,; \\ \left(\overline{p\_commit}(Time) \parallel \overline{c\_commit}(Time)\right) \end{array} \right)$$

$$\parallel$$

$$\left(\begin{array}{l} p\_begin(Payload) \,; \\ \overline{prepare}(Time) \,; \\ p\_commit(Time) \end{array} \right)$$

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Applications: multi-party sessions

$$\left(\begin{array}{l} \overline{p\_begin}(Payload) \parallel p\_begin(Payload) \parallel \\ \overline{l\_begin}(Payload) \parallel l\_begin(Payload) \end{array} \right)$$

;

$$(\overline{prepare}(Time) \parallel prepare(Time))$$

;

$$\left(\begin{array}{l} \overline{p\_commit}(Time) \parallel p\_commit(Time) \parallel \\ c\_commit(Time) \parallel \overline{c\_commit}(Time) \end{array} \right)$$

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Applications: multi-party sessions

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An Objective Justification for Processes-as-Propositions

Concise Semantics: BV

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$\mathcal{C}\{\ \overline{\alpha} \parallel \alpha\ \} \longrightarrow \mathcal{C}\{\ \mathrm{I}\ \}$

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$\mathcal{C}\{\ (P\ ;\ Q) \parallel (R\ ;\ S)\ \} \longrightarrow \mathcal{C}\{\ (P \parallel R)\ ;\ (Q \parallel S)\ \}$

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commutative monoids: $(P, \parallel, \mathrm{I})$ $(P, \otimes, \mathrm{I})$

monoid: $(P,\ ;\ , \mathrm{I})$

Linear implication
$P \multimap Q = \overline{P} \parallel Q$

de Morgan dualities
$\overline{P \otimes Q} = \overline{P} \parallel \overline{Q}$ $\overline{P \parallel Q} = \overline{P} \otimes \overline{Q}$
$\overline{P\ ;\ Q} = \overline{P}\ ;\ \overline{Q}$ $\overline{\overline{\alpha}} = \alpha$ $\overline{\mathrm{I}} = \mathrm{I}$

Objectivity

Theorem (Guglielmi 2007)

If $\vdash \mathcal{C}\left\{\ P \otimes \overline{P}\ \right\}$ *then* $\vdash \mathcal{C}\{\ \mathrm{I}\ \}$.

Corollary

Linear implication is a precongruence.

Leader:

$l\_begin(Payload)$;
$prepare(Time)$;
$\left(p\_commit(Time) \parallel \overline{c\_commit}(Time)\right)$

$\multimap$

Refined leader:

$(l\_begin(Payload) \parallel prepare(Time))$;

$\left(\overline{p\_commit}(Time) \parallel \overline{c\_commit}(Time)\right)$

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Corollary

Linear implication is a precongruence.

$$\vdash \left(\begin{array}{l} \overline{l\_begin}(Payload)\ ; \\ \overline{prepare}(Time)\ ; \\ (p\_commit(Time) \otimes c\_commit(Time)) \end{array} \right)$$

$$\parallel$$

$$\left(\begin{array}{l} (l\_begin(Payload) \parallel prepare(Time))\ ; \\ \left(\overline{p\_commit}(Time) \parallel \overline{c\_commit}(Time)\right) \end{array} \right)$$

Extending with Choice: Multiplicative-Additive System MAV

atomic interaction
$$\mathcal{C}\{\, \overline{\alpha} \parallel \alpha \,\} \longrightarrow \mathcal{C}\{\, \mathrm{I} \,\}$$

seq
$$\mathcal{C}\{\, (P \mathbin{;} Q) \parallel (R \mathbin{;} S) \,\} \longrightarrow \mathcal{C}\{\, (P \parallel R) \mathbin{;} (Q \parallel S) \,\}$$

switch
$$\mathcal{C}\{\, (P \otimes Q) \parallel R \,\} \longrightarrow \mathcal{C}\{\, P \otimes (Q \parallel R) \,\}$$

commutative monoids: $(P, \parallel, \mathrm{I})$ $(P, \otimes, \mathrm{I})$

monoid: $(P, \;;\, , \mathrm{I})$

left and right
$$\mathcal{C}\{\, P \oplus Q \,\} \longrightarrow \mathcal{C}\{\, P \,\} \qquad \mathcal{C}\{\, P \oplus Q \,\} \longrightarrow \mathcal{C}\{\, Q \,\}$$

external
$$\mathcal{C}\{\, (P \mathbin{\&} Q) \parallel R \,\} \longrightarrow \mathcal{C}\{\, (P \parallel R) \mathbin{\&} (Q \parallel R) \,\}$$

tidy
$$\mathcal{C}\{\, \mathrm{I} \mathbin{\&} \mathrm{I} \,\} \longrightarrow \mathcal{C}\{\, \mathrm{I} \,\}$$

de Morgan dualities

$$\overline{P \otimes Q} = \overline{P} \parallel \overline{Q} \qquad \overline{P \parallel Q} = \overline{P} \otimes \overline{Q}$$
$$\overline{P \oplus Q} = \overline{P} \mathbin{\&} \overline{Q} \qquad \overline{P \mathbin{\&} Q} = \overline{P} \oplus \overline{Q}$$
$$\overline{P \mathbin{;} Q} = \overline{P} \mathbin{;} \overline{Q} \qquad \overline{\overline{\alpha}} = \alpha \qquad \overline{\mathrm{I}} = \mathrm{I}$$

Theorem (Horne 2015)

If $\vdash \mathcal{C}\left\{\, P \otimes \overline{P} \,\right\}$ *then* $\vdash \mathcal{C}\{\, \mathrm{I} \,\}$.

E.g. **OAuth Server:**

$$\mathit{initiate}(\mathit{app\_ID}, \mathit{scope});$$
$$\overline{\mathit{login\_page}}(\mathit{app\_ID}, \mathit{scope});$$
$$\mathrm{I} \oplus \left(\begin{array}{l} \mathit{authenticate}(\mathit{name}, \mathit{password}); \\ \mathrm{I} \mathbin{\&} \left(\begin{array}{l} \overline{\mathit{authorisation\_code}}(\mathit{code}); \\ \mathit{exchange}(\mathit{app\_ID}, \mathit{secret}, \mathit{code}); \\ \mathrm{I} \mathbin{\&} \overline{\mathit{access\_token}}(\mathit{token}) \end{array} \right) \end{array} \right)$$

Implication in the Spectrum of Preorders over Processes

interleaving

autoconcurrency
$tr(a\,;\,a) = tr(a \parallel a)$

small serialisable systems

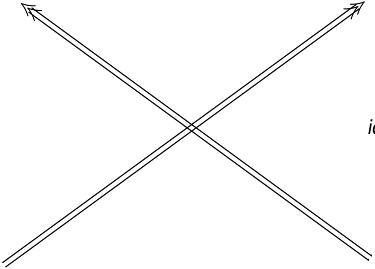
traces

$tr(P) \subseteq tr(Q)$

linear time

$tr(a\,;\,(b \oplus c))$
$= tr((a\,;\,b) \oplus (a\,;\,c))$

static environment



simulation

$P \preceq Q$

pomset traces

$ideals(P) \subseteq ideals(Q)$

causal

no autocurrency
$a \parallel a \not\multimap a\,;\,a$
$a\,;\,a \multimap a \parallel a$

action refinement

scalable systems

history preserving

branching time

$a\,;\,(b \oplus c) \not\multimap (a\,;\,b) \oplus (a\,;\,c)$
$(a\,;\,b) \oplus (a\,;\,c) \multimap a\,;\,(b \oplus c)$

mobile environment

implication

$\vdash P \multimap Q$

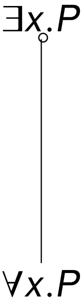
$\forall$ И Э $\exists$

$a(x) \parallel \overline{a}b$ terminates without deadlock.

Proof:

$$\exists x.ax \parallel \overline{ab} \longrightarrow ab \parallel \overline{ab} \longrightarrow \mathrm{I}$$

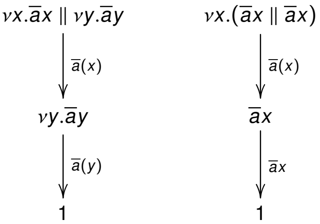
What about ∀ for Private Names?



$$\overline{\forall x.P} = \exists x.\overline{P}$$

$$\overline{\exists x.P} = \forall x.\overline{P}$$

no distributivity over parallel composition



Wrongly:

$$\vdash (\forall x.\overline{ax}) \parallel (\forall y.\overline{ay}) \multimap \forall x.(\overline{ax} \parallel \overline{ax})$$

diagonalisation

Wrongly:

$$\vdash \forall x.\forall y.P(x,y) \multimap \forall x.P(x,x)$$

What about a Self-dual Nominal Quantifier ∇?

$$\exists x.P$$

$$\nabla x.P$$

$$\forall x.P$$

$$\overline{\nabla x.P} \equiv \nabla x.\overline{P}$$

no distributivity over parallel composition

$$\nu x.\overline{a}x \parallel \nu y.\overline{a}y \xrightarrow{\overline{a}(x)} \nu y.\overline{a}y \xrightarrow{\overline{a}(y)} 1$$

$$\nu x.(\overline{a}x \parallel \overline{a}x) \xrightarrow{\overline{a}(x)} \overline{a}x \xrightarrow{\overline{a}x} 1$$

Wrongly:

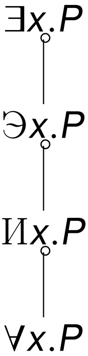
$$\vdash \nabla x.(\overline{ax} \parallel \overline{ax}) \multimap (\nabla x.\overline{ax}) \parallel (\nabla y.\overline{ay})$$

diagonalisation

Correctly (Roversi 2011):

$$\nabla x.\nabla y.P(x,y) \not\multimap \nabla x.P(x,x)$$

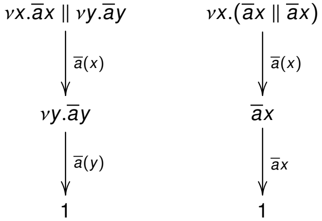
A Pair of De Morgan Dual Nominals Ии and Э!



$$\overline{\text{И} x.P} \equiv \ni x.\overline{P}$$

$$\overline{\ni x.P} \equiv \text{И} x.\overline{P}$$

no distributivity over parallel composition



Correctly:

$$\text{И} x.\,(\overline{ax} \parallel \overline{ax}) \not\multimap (\text{И} x.\overline{ax}) \parallel (\text{И} y.\overline{ay})$$

and

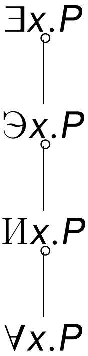
$$(\text{И} x.\overline{ax}) \parallel (\text{И} y.\overline{ay}) \not\multimap \text{И} x.\,(\overline{ax} \parallel \overline{ax})$$

diagonalisation

Correctly:

$$\text{И} x.\text{И} y.P(x,y) \not\multimap \text{И} x.P(x,x)$$

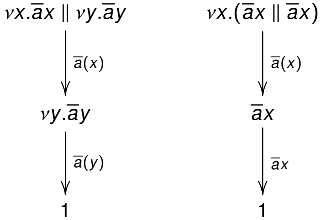
Notice ∋ is Necessary for Implication



$$\overline{\text{И}x.P} \equiv \ni x.\overline{P}$$

$$\overline{\ni x.P} \equiv \text{И}x.\overline{P}$$

no distributivity over parallel composition



Correctly:

$$\nvdash \ni x.\,(ax \otimes ax) \parallel (\text{И}x.\overline{ax}) \parallel (\text{И}y.\overline{ay})$$

and

$$\nvdash (\ni x.ax \otimes \ni y.ay) \parallel \text{И}x.\,(\overline{ax} \parallel \overline{ax})$$

diagonalisation

Correctly:

$$\nvdash \ni x.\ni y.\overline{P(x,y)} \parallel \text{И}x.P(x,x)$$

Semantics of MAV1: Rules determined by Cut Elimination

$\mathcal{C}\{\ \forall x.P \parallel R\ \} \longrightarrow \mathcal{C}\{\ \forall x.(P \parallel R)\ \}$ only if $x \# R$ (extrude1) $\quad \mathcal{C}\{\ \forall x.\mathrm{I}\ \} \longrightarrow \mathcal{C}\{\ \mathrm{I}\ \}$ (tidy1)

$\mathcal{C}\{\ \forall x.(P \,;\, S)\ \} \longrightarrow \mathcal{C}\{\ \forall x.P \,;\, \forall x.S\ \}$ (medial1) $\quad \mathcal{C}\{\ \exists x.P\ \} \longrightarrow \mathcal{C}\{\ P\{^{v}/_{x}\}\ \}$ (select1)

$\mathcal{C}\{\ \text{И}x.P \parallel \text{Э}x.Q\ \} \longrightarrow \mathcal{C}\{\ \text{И}x.(P \parallel Q)\ \}$ (close) $\quad \mathcal{C}\{\ \text{И}x.\mathrm{I}\ \} \longrightarrow \mathcal{C}\{\ \mathrm{I}\ \}$ (tidy name)

$\mathcal{C}\{\ \text{И}x.P \parallel R\ \} \longrightarrow \mathcal{C}\{\ \text{И}x.(P \parallel R)\ \}$ only if $x \# R$ (extrude new)

$\mathcal{C}\{\ \text{Э}x.P\ \} \longrightarrow \mathcal{C}\{\ \text{И}x.P\ \}$ (fresh) $\quad \mathcal{C}\{\ \text{И}x.\text{Э}y.P\ \} \longrightarrow \mathcal{C}\{\ \text{Э}y.\text{И}x.P\ \}$ (new wen)

$\mathcal{C}\{\ \text{И}x.(P \,;\, S)\ \} \longrightarrow \mathcal{C}\{\ \text{И}x.P \,;\, \text{И}x.S\ \}$ (medial new)

$\mathcal{C}\{\ \text{Э}x.P \odot \text{Э}x.S\ \} \longrightarrow \mathcal{C}\{\ \text{Э}x.(P \odot S)\ \}$ where $\odot \in \{\parallel, ;\}$ (medial wen)

$\mathcal{C}\{\ \text{Э}x.P \odot R\ \} \longrightarrow \mathcal{C}\{\ \text{Э}x.(P \odot R)\ \}$ where $\odot \in \{\parallel, ;\}$ only if $x \# R$ (left wen)

$\mathcal{C}\{\ R \odot \text{Э}x.Q\ \} \longrightarrow \mathcal{C}\{\ \text{Э}x.(R \odot Q)\ \}$ where $\odot \in \{\parallel, ;\}$ only if $x \# R$ (right wen)

$\mathcal{C}\{\ \forall x.\mho y.P\ \} \longrightarrow \mathcal{C}\{\ \mho y.\forall x.P\ \}$ for $\mho \in \{\text{И}, \text{Э}\}$ (all name)

$\mathcal{C}\{\ \mho x.P \,\&\, \mho x.S\ \} \longrightarrow \mathcal{C}\{\ \mho x.(P \,\&\, S)\ \}$ for $\mho \in \{\text{И}, \text{Э}\}$ (with name)

$\mathcal{C}\{\ \mho x.P \,\&\, R\ \} \longrightarrow \mathcal{C}\{\ \mho x.(P \,\&\, R)\ \}$ only if $x \# R$ for $\mho \in \{\text{И}, \text{Э}\}$ (left name)

$\mathcal{C}\{\ R \,\&\, \mho x.Q\ \} \longrightarrow \mathcal{C}\{\ \mho x.(R \,\&\, Q)\ \}$ only if $x \# R$ for $\mho \in \{\text{И}, \text{Э}\}$ (right name)

Equivariance is a Design Decision

equivariance for ν

$\nu y.\nu x.P \sim \nu x.\nu y.P$

equivariance in MAV1

$\text{И}y.\text{И}x.P \equiv \text{И}x.\text{И}y.P$

$\text{Э}y.\text{Э}x.P \equiv \text{Э}x.\text{Э}y.P$

Linear implication respects transitions, e.g.:

$$a(x).b(y) \parallel \nu y.\nu x.\overline{a}x.\overline{b}y \xrightarrow{\tau} \nu x.\left(b(y) \parallel \nu y.\overline{b}y\right)$$

$$\vdash \text{И}x.\left(\exists y.by \parallel \text{И}y.\overline{by}\right) \multimap \exists x.(ax \mathbin{;} \exists y.by) \parallel \text{И}y.\text{И}x.\left(\overline{ax} \mathbin{;} \overline{by}\right)$$

Proof:

$$\text{Э}x.\left(\forall y.\overline{by} \otimes \text{Э}y.by\right) \parallel \exists x.(ax \mathbin{;} \exists y.by) \parallel \text{И}y.\text{И}x.\left(\overline{ax} \mathbin{;} \overline{by}\right)$$

$\downarrow$ equivariance and extrude $\text{И}x$

$$\text{Э}x.\left(\forall y.\overline{by} \otimes \text{Э}y.by\right) \parallel \text{И}x.\left(\exists x.(ax \mathbin{;} \exists y.by) \parallel \text{И}y.\left(\overline{ax} \mathbin{;} \overline{by}\right)\right)$$

$\downarrow$ instantiate $\exists x$

$$\text{Э}x.\left(\forall y.\overline{by} \otimes \text{Э}y.by\right) \parallel \text{И}x.\left((ax \mathbin{;} \exists y.by) \parallel \text{И}y.\left(\overline{ax} \mathbin{;} \overline{by}\right)\right)$$

$\downarrow$ push $\text{И}y$ in and sequence

$$\text{Э}x.\left(\forall y.\overline{by} \otimes \text{Э}y.by\right) \parallel \text{И}x.\left(\left(ax \parallel \text{И}y.\overline{ax}\right) \mathbin{;} \left(\exists y.by \parallel \text{И}y.\overline{by}\right)\right)$$

$\downarrow$ extrude $\text{И}y$ and interact

$$\text{И}x.\left(\exists y.by \parallel \text{И}y.\overline{by}\right) \multimap \text{И}x.\left(\exists y.by \parallel \text{И}y.\overline{by}\right)$$

Results: Cut Elimination and it's Consequences

Proposition (decidability)

System MAV1 is analytic.

Lemma (context reduction)

If $\vdash P\sigma \parallel R$ yields $\vdash Q\sigma \parallel R$, for any predicate R and substitution σ, then $\vdash \mathcal{C}\{\ P\ \}$ yields $\vdash \mathcal{C}\{\ Q\ \}$, for any context $\mathcal{C}\{\ \ \}$.

Theorem (cut elimination)

If $\vdash \mathcal{C}\left\{\ P \otimes \overline{P}\ \right\}$ then $\vdash \mathcal{C}\{\ \mathrm{I}\ \}$.

Corollary

Linear implication is a precongruence.

Corollary (completed traces)

If π-calculus (or πI-calculus) process P has completed trace tr then $\vdash [\![tr]\!]_\pi \multimap [\![P]\!]_\pi$.

Corollary (consistency)

If $\vdash \mathcal{C}\{\ a\ \}$ then $\nvdash \overline{\mathcal{C}\{\ a\ \}}$.

Corollary (conservativity)

MAV1 is a conservative extension of both BV and MALL1 with mix.

Corollary (complexity for names)

MAV1 where terms are constants and variables only is PSPACE-complete.

Corollary (complexity)

MAV1 with functions in terms (e.g. spi-calculus) is NEXPTIME-complete.

Corollary (session types)

Coherent protocols are multi-party compatible.

Conclusions on Predicates-as-Processes in MAV1

- Linear implication is a **branching-time** preorder that fully respects **causality**.
- First direct **cut elimination** result in the calculus of structures for $\forall$ and $\exists$.
- First cut elimination result for a **de Morgan dual** pair of **nominal** quantifiers И and Э.
- Can embed the finite π**-calculus** in MAV1.
- Embedding of π-calculus uses half the expressive power of MAV1:

π-calculus process	connective	dual connective	test
prefix / sequential composition	;	;	traces
choice	$\oplus$	&	branching time
parallel composition	$\parallel$	$\otimes$	separation / causality
input of term	$\exists$	$\forall$	symbolic term
fresh private name	И	Э	private input (internal)