On the Relationship between π-calculus and Finite Place/Transition Petri Nets

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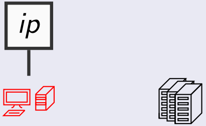
CONCUR Conference, 2009

A Client-Server System in π-calculus

Client sends on public channel *url* his private address *ip* to server

Graphically



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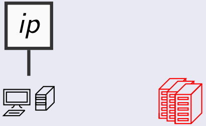

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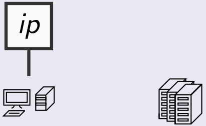

In π-calculus

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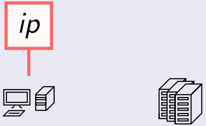

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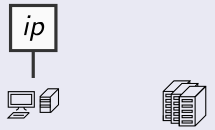
A Client-Server System in π-calculus

In response server spawns a new thread

Graphically



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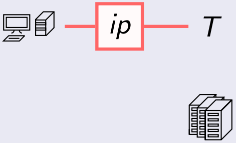
A Client-Server System in π-calculus

Thread sends on the private channel *ip* data *dat* to the client

Graphically



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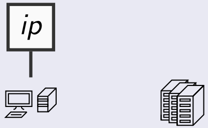
A Client-Server System in π-calculus

Thread terminates, client is ready to contact server again

Graphically



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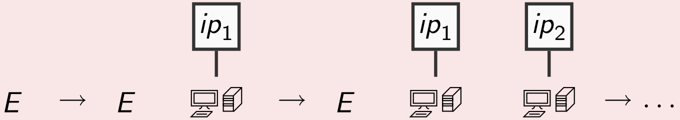
A Client-Server System in π-calculus

Assumption

Environment E generates clients



Contribution

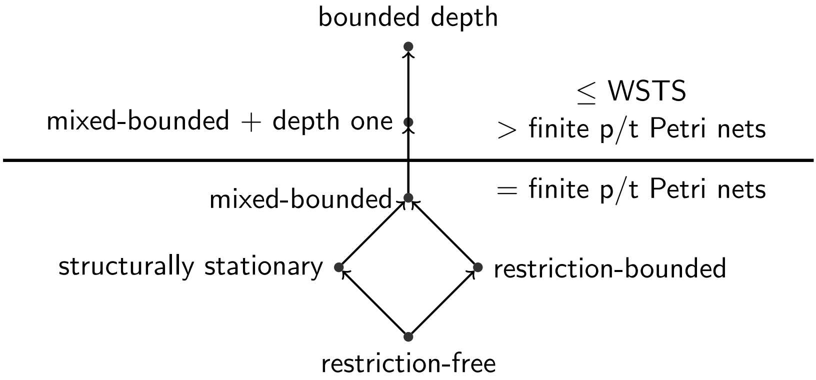
Problem under Study

- Goal: Automatically verify mobile systems
- Approach: Translate system to automata-theoretic model
- Question: When are finite p/t nets sufficient?

Quality Criteria

- Bisimilarity: $\mathcal{T}(P) \approx \mathcal{T}(\mathcal{N}[\![P]\!])$
- Finiteness: $\mathcal{N}[\![P]\!]$ finite iff ...
- Expressiveness: Unbounded concurrency and restrictions

A Hierarchy of Process Classes



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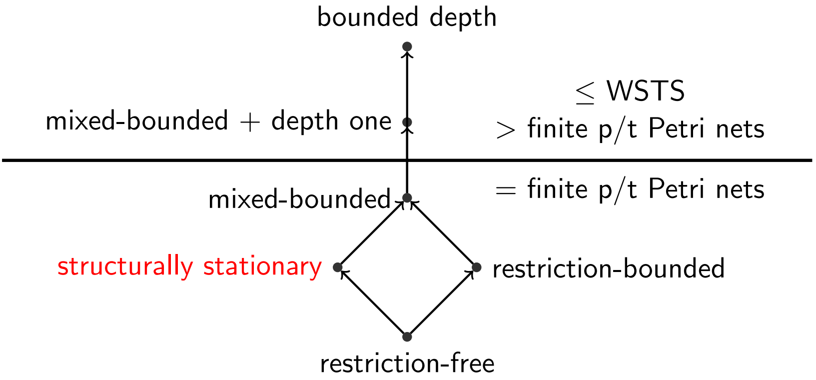
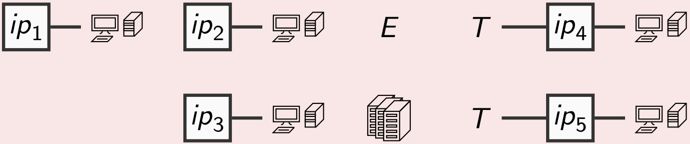


Idea of Structural Semantics

Problem

Unbounded number of clients and threads



Observation

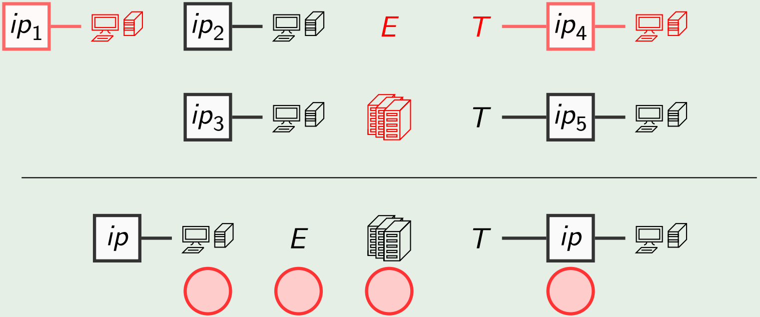
Finite number of connection patterns

Idea of Structural Semantics

Represent Connections in a Petri Net

- Connection patterns yield places

Example



Idea of Structural Semantics

Represent Connections in a Petri Net

- Connection patterns yield places
- Occurence of a pattern yields a token

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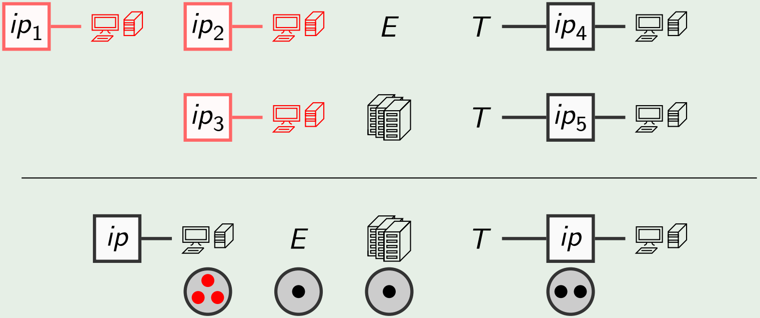
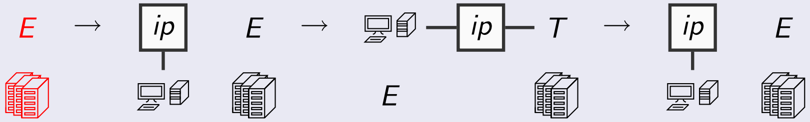


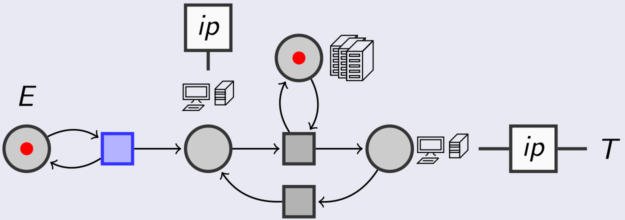
Idea of Structural Semantics

Transitions model evolution of patterns

In π-calculus



Structural Semantics



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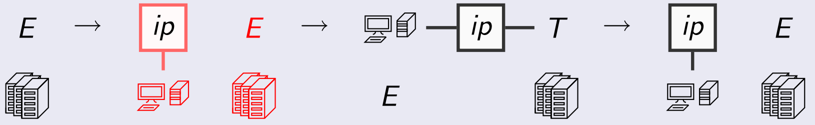

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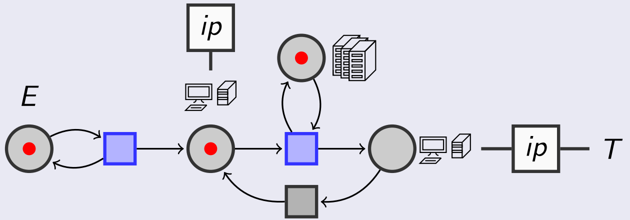

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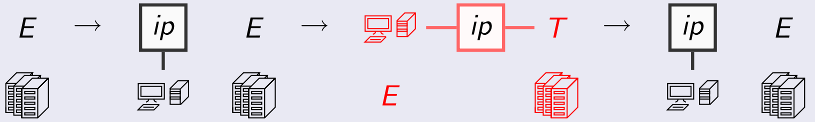

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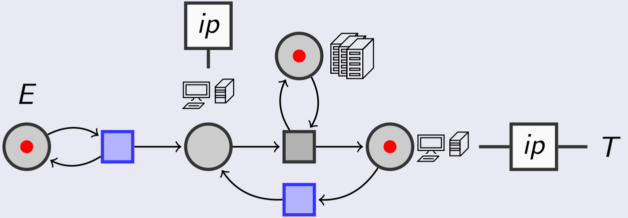

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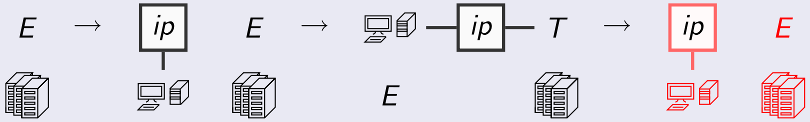

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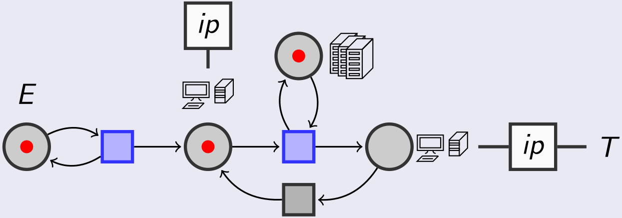

Restricted Form of Processes

Formalise idea of connection patterns

Example (Restricted Form)

Minimise scopes of restricted names

$$\nu ip.(\ ip(x).C\lfloor url, ip\rfloor \mid \overline{ip}\langle dat\rangle \mid S\lfloor url, dat\rfloor\ )$$

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Restricted Form of Processes

Fragments

Topmost parallel components are called fragments

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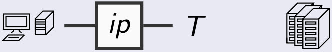

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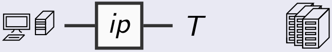

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$\mathcal{N}_{\mathcal{S}}[\![P]\!]$ finite iff there is a finite set of fragments every reachable process consists of

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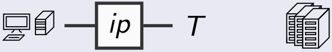

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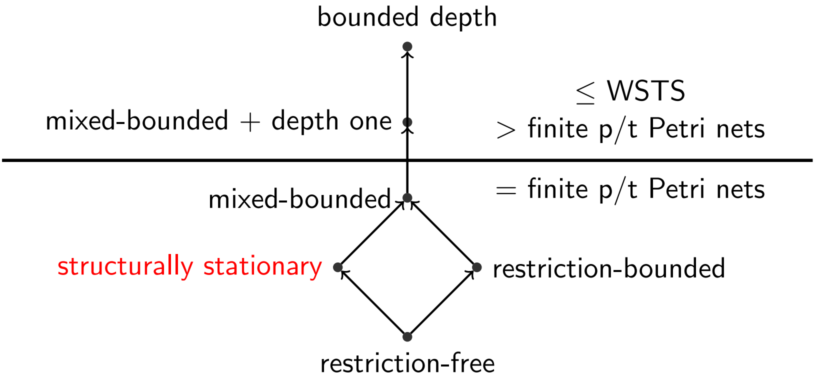

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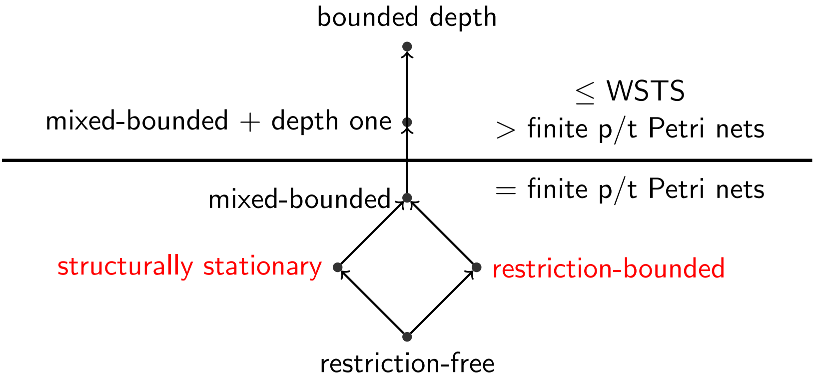
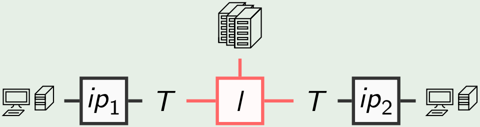


A Modified Server

Server Maintains Control Channel with Threads



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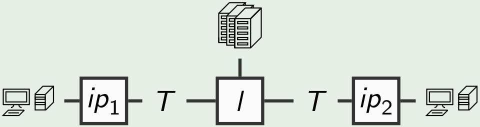
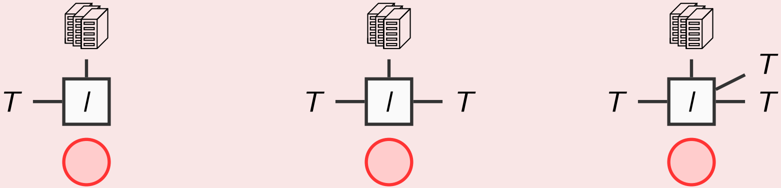


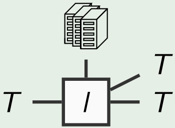
Structural Semantics Infinite



Idea of Concurrency Semantics

- Treat restricted names as free names

Example



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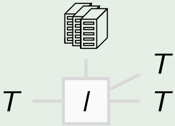

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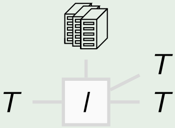

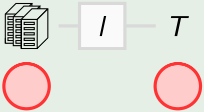

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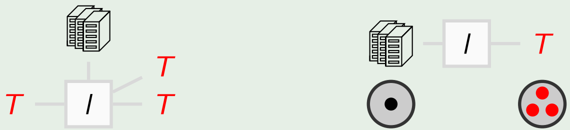

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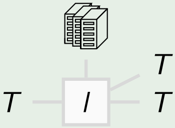

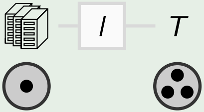

Crucial Technicality

Preserve order in which free names are generated

Name-Aware Processes

Assumption and Preliminaries

- Restricted names have indices

$$\nu z_{\mathbf{0}}.P$$

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- Idea: Store generated restrictions syntactically
- Technically: Pair $(P^{\neq\nu}, \tilde{a})$

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Example

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Name-Aware Reaction Relation

Example

Idea: Generate names by incrementing indices

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Definition (Name-Aware Reaction Relation)

$$(P^{\neq\nu}, \tilde{a}) \rightarrow^{na} (Q^{\neq\nu}, \tilde{a} \uplus \tilde{b}) \quad \text{iff} \quad P^{\neq\nu} \rightarrow \nu\tilde{b}.Q^{\neq\nu} \text{ in sf}$$

Indices in $\tilde{b}$ incremented

Bisimlarity

Lemma (Bisimilarity)

$\mathcal{T}(P) \approx \mathcal{T}_{na}(P^{\neq\nu}, \tilde{a})$ *with* $sf(P) = \nu\tilde{a}.P^{\neq\nu}$

Example $\overline{a} \mid K\lfloor a \rfloor$ **with** $K(a) = \nu z_{\mathbf{0}}.(\overline{z_{\mathbf{0}}} \mid a.z_{\mathbf{0}}.K\lfloor a \rfloor)$

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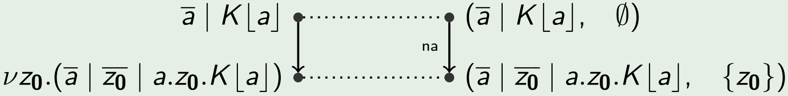

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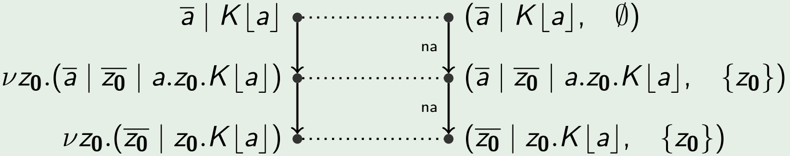

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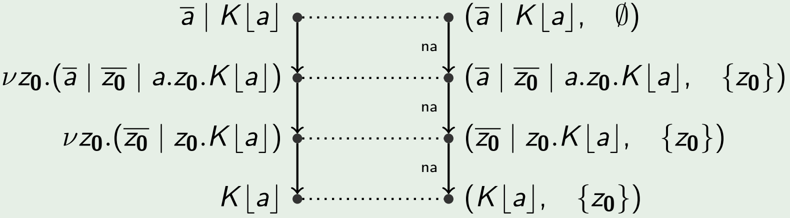

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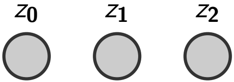
- Reachable names (+1) yield name places



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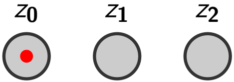

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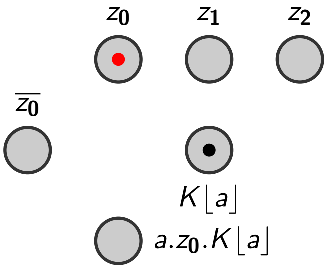
- Reachable processes yield process places



Definition of Concurrency Semantics

- Reachable names (+1) yield name places
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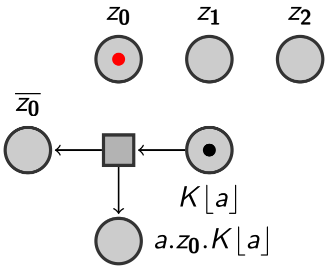

Definition of Concurrency Semantics

- Reachable names (+1) yield name places
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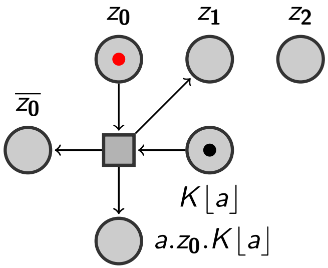
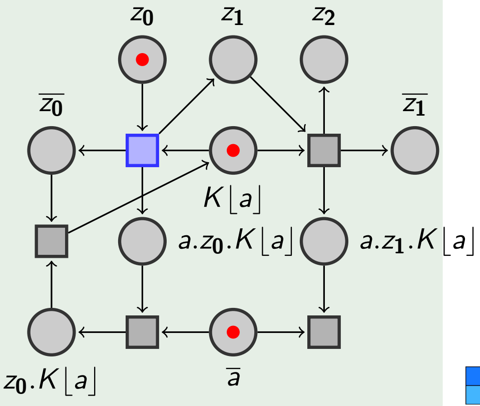


Example $\overline{a} \mid K\lfloor a \rfloor$ with $K(a) = \nu z_0.(\overline{z_0} \mid a.z_0.K\lfloor a \rfloor)$

Name-Aware TS

- $(\overline{a} \mid K\lfloor a \rfloor, \emptyset)$

Concurrency Semantics



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$\downarrow$ na

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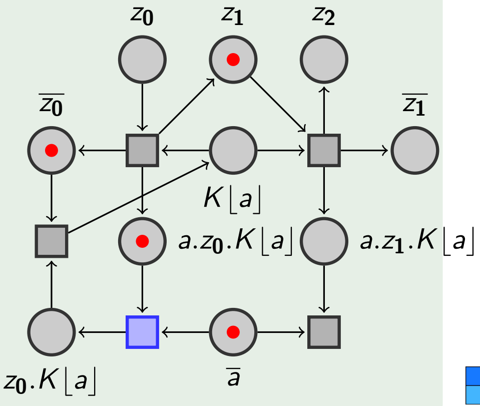

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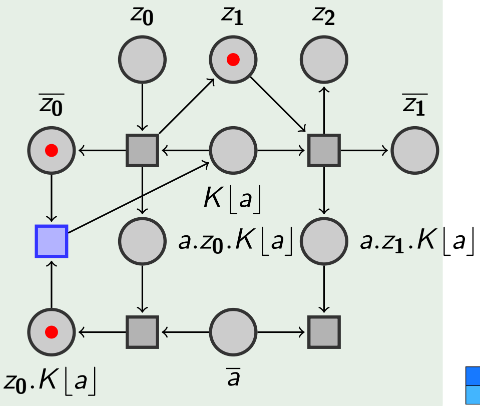

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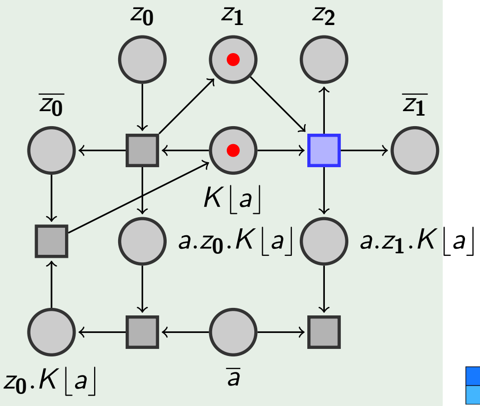

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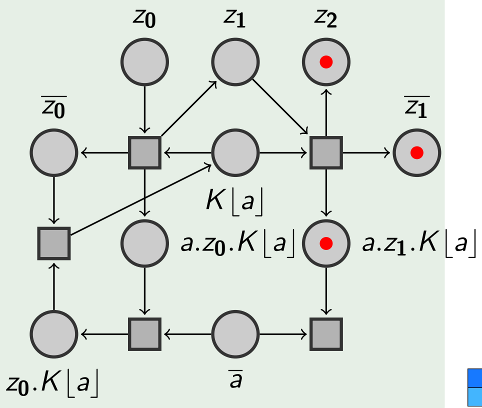
Concurrency Semantics



Properties of Translation

Theorem (Bisimilarity)

$\mathcal{T}(P) \approx \mathcal{T}(\mathcal{N}_{\mathcal{C}}[\![P]\!])$

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Proof Idea $\Leftarrow$: Construct Process Places from Initial Process

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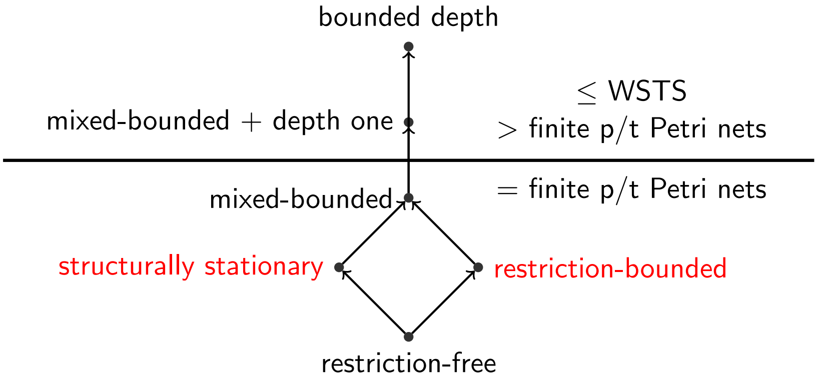
- Reachable sequential processes = derivatives + substitutions

Finite by boundedness assumption

A Hierarchy of Process Classes



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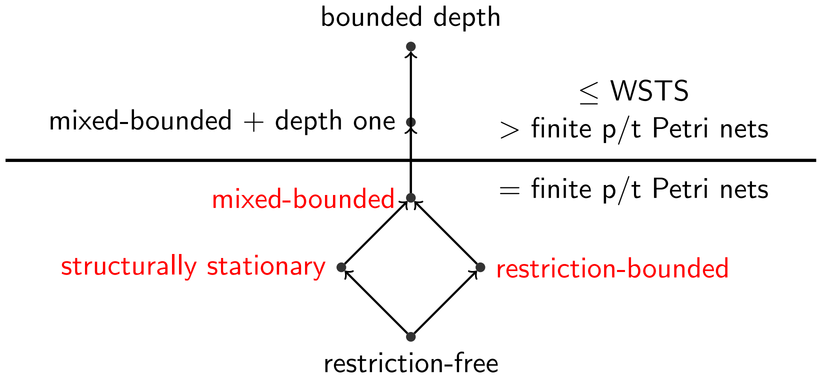
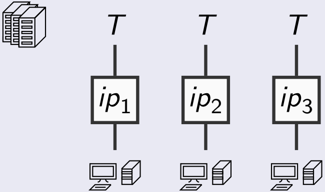


Back to Server

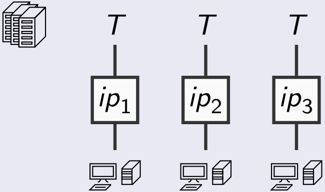
Can Translate



Structural Semantics

Back to Server

Can Translate



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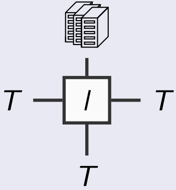
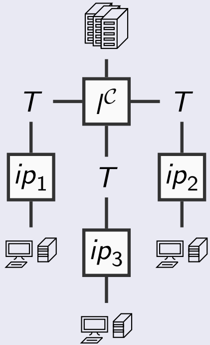


Structural Semantics

Concurrency Semantics

Back to Server

How about



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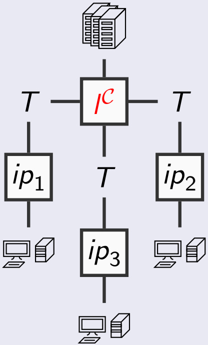
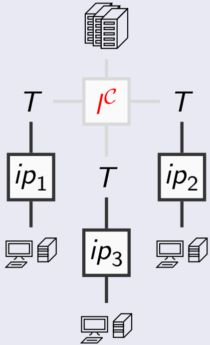


Idea

Tags determine translation of restricted names

Back to Server

How about



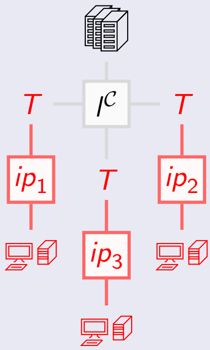
Idea

Tags determine translation of restricted names

- Translate $I^{\mathcal{C}}$ with concurrency semantics

Back to Server

How about



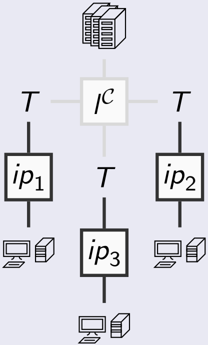
Idea

Tags determine translation of restricted names

- Translate $I^{\mathcal{C}}$ with concurrency semantics
- Translate ip with structural semantics

Back to Server

How about



Idea

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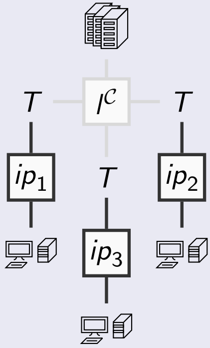
Problems

- Fragments?

Back to Server

How about



Idea

Tags determine translation of restricted names

- Translate $I^{\mathcal{C}}$ with concurrency semantics
- Translate ip with structural semantics

Problems

- Fragments?
- Name-aware transition system?

Mixed Normal Form

Combine Standard and Restricted Form

$$\nu l^{\mathcal{C}}.(\underbrace{S\lfloor url, l^{\mathcal{C}}\rfloor}_{\text{Fragment}} \mid \underbrace{\nu ip.(T\lfloor l^{\mathcal{C}}, ip\rfloor \mid C\lfloor url, ip\rfloor)}_{\text{Fragment}})$$

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Combine Standard and Restricted Form

$$\underbrace{\nu l^{\mathcal{C}}.(\ S\lfloor url, l^{\mathcal{C}}\rfloor \mid \nu ip.(T\lfloor l^{\mathcal{C}}, ip\rfloor \mid C\lfloor url, ip\rfloor)\ )}_{\text{Standard form over fragments}}$$

Mixed Normal Form

Recursive Function $mf(-)$

- Maximise scopes of tagged names
- Minimise scopes of untagged names

$$\nu ip.(\ \nu l^{\mathcal{C}}.(\ S\lfloor url, l^{\mathcal{C}}\rfloor \mid T\lfloor l^{\mathcal{C}}, ip\rfloor\ )\ \mid C\lfloor url, ip\rfloor)$$

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Mixed Semantics

Name-Aware Transition System

Mixed normal form replaces standard form

$$(P^{\neq\nu}, \tilde{a}) \rightarrow^{na} (Q^{\neq\nu}, \tilde{a} \uplus \tilde{b})$$

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$$\rightsquigarrow$$

$$(P^{rf}, \tilde{a}^{\mathcal{C}}) \rightarrow^{na} (Q^{rf}, \tilde{a}^{\mathcal{C}} \uplus \tilde{b}^{\mathcal{C}})$$

Translation of Modified Server

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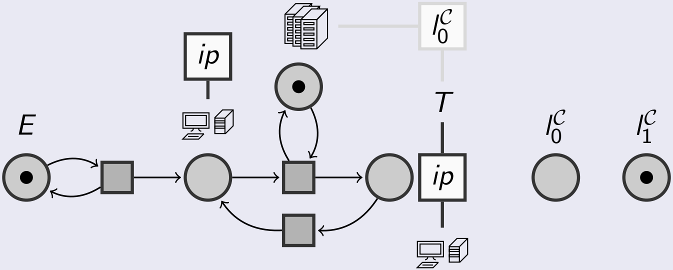

Properties of the Translation

Theorem (Bisimilarity)

$\mathcal{T}(P) \approx \mathcal{N}_{\mathcal{M}}[\![P]\!]$

Theorem (Conservative Extension)

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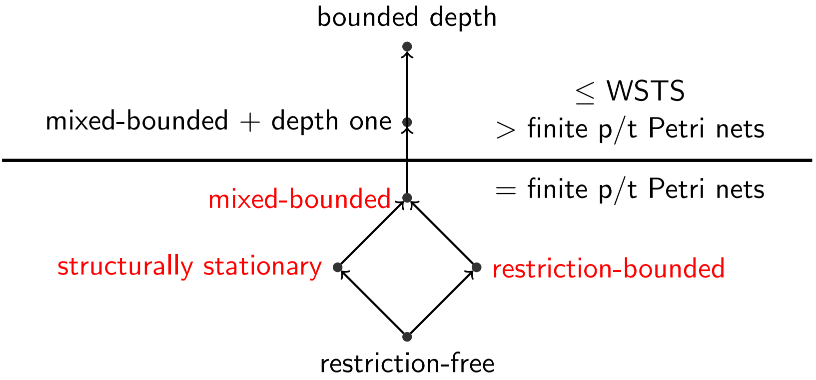
  Reason: no name places

A Hierarchy of Process Classes



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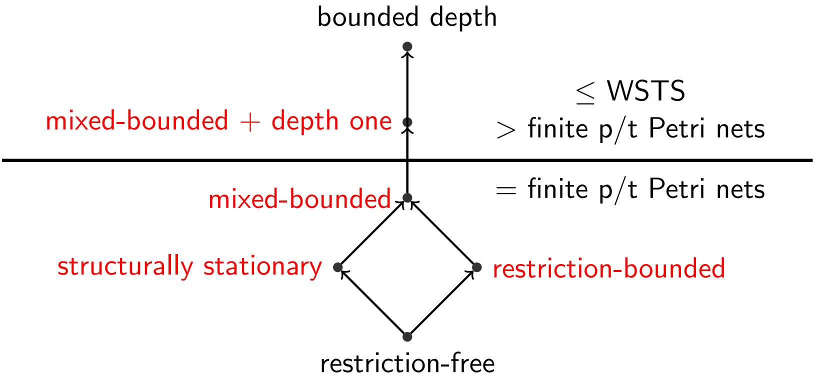
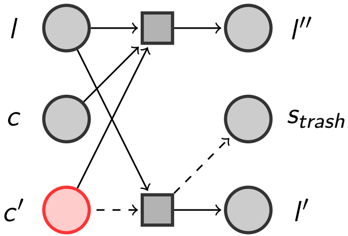


Undecidability of Reachability in Depth One

Test for Zero in Petri Nets with Transfer [DFS98]

$$l: \text{ if } c = 0 \text{ then goto } l'; \text{ else } c := c - 1; \text{ goto } l'';$$

- Create copy c' of counter c



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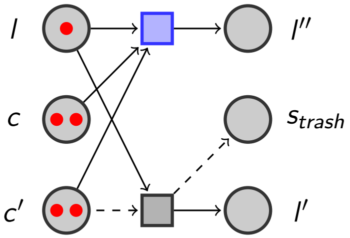

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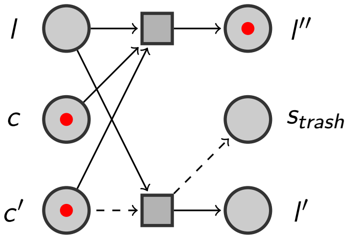

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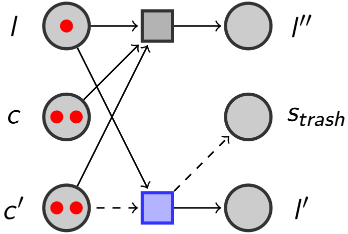

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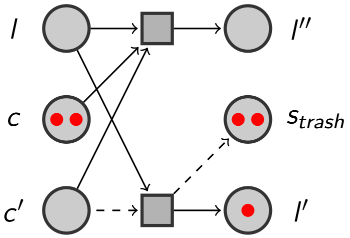

Process Bunch

- Offers increment and decrement operations

$$PB(a, i, d, t) \quad := \quad i.(PB\lfloor a, i, d, t \rfloor \mid \overline{a})$$

Example

$$\nu a.(PB\lfloor a, i, d, t \rfloor \mid \overline{a} \mid \overline{a}) \rightarrow^{*} \nu a.(PB\lfloor a, i, d, t \rfloor \mid \overline{a} \mid \overline{a} \mid \overline{a})$$

Process Bunch

- Offers increment and decrement operations

$$PB(a,i,d,t) := i.(PB\lfloor a,i,d,t\rfloor \mid \overline{a}) + d.a.PB\lfloor a,i,d,t\rfloor$$

Example

$$\nu a.(PB\lfloor a,i,d,t\rfloor \mid \overline{a} \mid \overline{a}) \rightarrow^{*} \nu a.(PB\lfloor a,i,d,t\rfloor \mid \overline{a})$$

Process Bunch

- Offers increment and decrement operations
- Modifies arbitrarily many processes with one communication

$$\begin{aligned} PB(a,i,d,t) \quad := \quad & i.(PB\lfloor a,i,d,t\rfloor \mid \overline{a}) \\ & + d.a.PB\lfloor a,i,d,t\rfloor \\ & + t.\,\nu b.PB\lfloor b,i,d,t\rfloor \end{aligned}$$

Example

$$\overline{t} \mid \nu a.(t.\nu b.PB\lfloor b,i,d,t\rfloor + \ldots \mid \overline{a} \mid \overline{a})$$

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\end{aligned}
$$

Example

$$
\begin{aligned}
& \overline{t} \mid \nu a.(t.\nu b.PB\lfloor b,i,d,t\rfloor + \ldots \mid \overline{a} \mid \overline{a}) \\
\rightarrow \quad & \nu b.PB\lfloor b,i,d,t\rfloor \mid \nu a.(\overline{a} \mid \overline{a})
\end{aligned}
$$

Bound is Tight

Undecidability Relies on Combination of Two Features

- Unbounded number of processes $\overline{a}$ per $\nu a.(PB\lfloor a, i, d, t\rfloor \mid \overline{a})$

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Not translatable by structural semantics

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Not translatable by concurrency semantics

Bound is Tight

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- Drop any of the restrictions yields mixed boundedness

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Intuitively

Server where threads gather clients

Related work

Processes as Graphs

Due to Milner [Mil79, MM79, MPW92, Mil99, SW01]

Automata-Theoretic Semantics

- Concurrency
  [Eng96, MP95a, Pis99, AM02, BG95, BG09, DKK08, KKN06]
- Structure [MP95b, Mey09]

Normal Forms

Decidability of structural congruence [EG99, EG04a, EG04b, EG07]

References I

R. Amadio and C. Meyssonnier.
On decidability of the control reachability problem in the asynchronous π-calculus.
Nord. J. Comp., 9(1):70–101, 2002.

N. Busi and R. Gorrieri.
A Petri net semantics for π-calculus.
In *Proc. of CONCUR*, volume 962 of *LNCS*, pages 145–159. Springer, 1995.

N. Busi and R. Gorrieri.
Distributed semantics for the π-calculus based on Petri nets with inhibitor arcs.
J. Log. Alg. Prog., 78(1):138–162, 2009.

C. Dufourd, A. Finkel, and Ph. Schnoebelen.
Reset nets between decidability and undecidability.
In *Proc. of ICALP*, volume 1443 of *LNCS*, pages 103–115. Springer, 1998.

R. Devillers, H. Klaudel, and M. Koutny.
A compositional Petri net translation of general π-calculus terms.
For. Asp. Comp., 20(4–5):429–450, 2008.

J. Engelfriet and T. Gelsema.
Multisets and structural congruence of the pi-calculus with replication.
Theor. Comp. Sci., 211(1-2):311–337, 1999.

References II

J. Engelfriet and T. Gelsema.
The decidability of structural congruence for replication restricted pi-calculus processes.
Technical report, Leiden Institute of Advanced Computer Science, 2004.
Revised 2005.

J. Engelfriet and T. Gelsema.
A new natural structural congruence in the pi-calculus with replication.
Acta Inf., 40(6):385–430, 2004.

J. Engelfriet and T. Gelsema.
An exercise in structural congruence.
Inf. Process. Lett., 101(1):1–5, 2007.

J. Engelfriet.
A multiset semantics for the pi-calculus with replication.
Theor. Comp. Sci., 153(1-2):65–94, 1996.

V. Khomenko, M. Koutny, and A. Niaouris.
Applying Petri net unfoldings for verification of mobile systems.
In *Proc. of MOCA*, Bericht FBI-HH-B-267/06, pages 161–178. University of Hamburg, 2006.

R. Meyer.
A theory of structural stationarity in the π-calculus.
Acta Inf., 46(2):87–137, 2009.

References III

R. Milner.
Flowgraphs and flow algebras.
Journal of the Association for Computing Machinery, 26(4):794–818, 1979.

R. Milner.
Communicating and Mobile Systems: the π-Calculus.
CUP, 1999.

G. Milne and R. Milner.
Concurrent processes and their syntax.
Journal of the Association for Computing Machinery, 26(2):302–321, 1979.

U. Montanari and M. Pistore.
Checking bisimilarity for finitary π-calculus.
In *Proc. of the 6th International Conference on Concurrency Theory, CONCUR 1995*, volume 962 of *LNCS*, pages 42–56. Springer, 1995.

U. Montanari and M. Pistore.
Concurrent semantics for the π-calculus.
Electr. Notes Theor. Comp. Sci., 1:411–429, 1995.

R. Milner, J. Parrow, and D. Walker.
A calculus of mobile processes, part I.
Inf. Comp., 100(1):1–40, 1992.

References IV

M. Pistore.
History Dependent Automata.
PhD thesis, Dipartimento di Informatica, Università di Pisa, 1999.

D. Sangiorgi and D. Walker.
The π-calculus: a Theory of Mobile Processes.
CUP, 2001.