On Boundedness in Depth in the π-Calculus

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A Client/Server System in the π-Calculus

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

Graphically

C — $\boxed{ip}$

S — $\boxed{l}$

In π-Calculus

$$\nu ip.\overline{url}\langle ip\rangle.ip(s).s(x).C\lfloor url, ip\rfloor \mid$$
$$\nu l.url(y).(\nu sn.\overline{y}\langle sn\rangle.T\lfloor sn, l\rfloor \mid S\lfloor url, l\rfloor)$$

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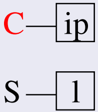

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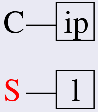

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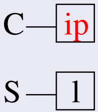

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A Client/Server System in the π-Calculus

Server spawns a new thread that handles the session with the client

Graphically

$\mathrm{C} - \boxed{\mathrm{ip}}$

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A Client/Server System in the π-Calculus

Thread sends back a private session *sn* on the private channel *ip*

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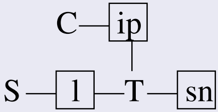

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Thread sends back a private session sn on the private channel ip

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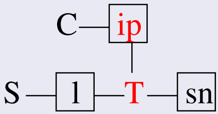

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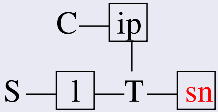

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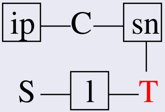
A Client/Server System in the π-Calculus

The thread switches its mode

Graphically



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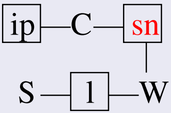
$$\nu sn.(\nu ip.sn(x).C\lfloor url, ip\rfloor \mid \nu l.(T\lfloor sn, l\rfloor \mid S\lfloor url, l\rfloor))$$

A Client/Server System in the π-Calculus

To terminate the session, the thread sends the private session object *sn* on the channel *sn* itself

Graphically



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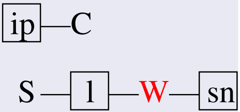
A Client/Server System in the π-Calculus

The thread writes back information to the server and terminates, the client is ready to contact the server again

Graphically



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$$\nu ip.C\lfloor url, ip\rfloor \mid$$
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A Client/Server System in the π-Calculus

This yields the initial state

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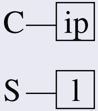

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$$\nu ip.C\lfloor url, ip\rfloor \mid$$
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Motivation and Contribution

Motivation: Verification of dynamically reconfigurable systems

- Does the client/server system terminate?
- Is it finite state?

Contribution: This can be done automatically

- For systems of bounded depth

Overview

1. A client/server system in the π-Calculus ✓
2. Systems of bounded depth
3. From bounded depth to well-structured transition systems
4. Decidability results

A normal form for processes

- Normalise the process
  - Minimise the scopes of restrictions
  - Yields parallel composition of fragments F, G

Example

$$\nu l.\nu sn.\nu sn'.(S\lfloor url, l\rfloor \mid W\lfloor l, sn\rfloor \mid W\lfloor l, sn'\rfloor)$$

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The latter process is a fragment

The nesting of restrictions

- Count the nesting of restrictions in the fragment

Example

$$nest_\nu\left(\nu l.(S\lfloor url, l\rfloor \mid \nu sn.W\lfloor l, sn\rfloor \mid \nu sn'.W\lfloor l, sn'\rfloor)\right)$$

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The nesting of restrictions

- Count the nesting of restrictions in the fragment
- Problem: The fragment representation is not unique

Example

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\begin{aligned}
& \nu l.(S\lfloor url, l\rfloor \mid \nu sn.W\lfloor l, sn\rfloor \mid \nu sn'.W\lfloor l, sn'\rfloor) =: F \\
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Then $nest_\nu(F) = 2$ but $nest_\nu(G) = 3$

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Boundedness in depth

- Solution: Define the depth of a fragment as the nesting of restrictions in the flattest representation

Depth

$$depth(F) = min\,\{nest_\nu(G) \mid G \equiv F\}$$

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Depth

$$depth(F) = min\{nest_{\nu}(G) \mid G \equiv F\}$$

- A process is bounded in depth if the depth of all reachable fragments is bounded

A Characterisation of Boundedness in Depth

- Problem: No good intuition to processes of bounded depth
- How to find the flat representation?

A Characterisation of Boundedness in Depth

Theorem

A process is bounded in depth if and only if

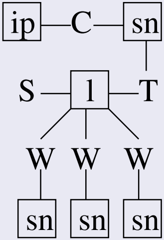
the length of the longest simple paths in the graphs is bounded

- Simple paths do not repeat hyperedges
- Reachable states are star-like
- Anchored fragments are flat representations

Example: The Client/Server System

- In the case study, the depth is bounded by 4

A longest simple path



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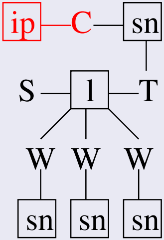

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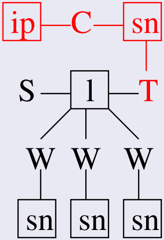

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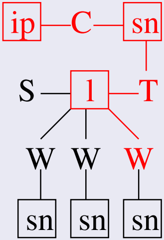

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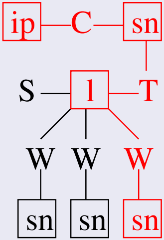

More Examples

All decidable subclasses of π-Calculus are bounded in depth

- Finitary agents [FGMP03], finite control processes [Dam96], bounded processes [Cai04] (finite state systems)
- Structurally stationary processes [Mey08], finite handler processes [Mey08], restriction-free processes [AM02] (Petri nets)
- Bounded input unique receiver systems [AM02] (subclass of transfer nets)
- Finite net processes [BG95, BG08] (subclass of inhibitor nets)

Well-Structured Transition Systems

- Framework for infinite state systems [Fin90, FS01, AČJT00]
- Generalises decidablity results for particular models

Technically

WSTS=$(S, \rightarrow, \leq)$ where

- $(S, \rightarrow)$ is a transition system
- $\leq \subseteq S \times S$ is an ordering on the states with two properties

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Well-Structured Transition Systems

$\leq \subseteq S \times S$ is a well-quasi-ordering

In every infinite sequence of states, there are two comparable ones

$$\leq$$

$$s_0 \longrightarrow s_1 \longrightarrow \dots \longrightarrow s_i \longrightarrow \dots \longrightarrow s_j \longrightarrow \dots$$

Well-Structured Transition Systems

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$\leq \subseteq S \times S$ is a simulation

Larger states can imitate the transition behaviour of smaller ones

$$\begin{tikzcd} s \arrow[r] & s' & & s' \\ t \arrow[u, phantom, "\rotatebox{90}{$\leq$}"] & \Rightarrow & t \arrow[r] & t' \arrow[u, phantom, "\rotatebox{90}{$\leq$}"] \end{tikzcd}$$

Instantiation of the framework—the ordering $\preceq_{\mathcal{P}_{BD}}$

- Intuitively: Hypergraph embedding so that
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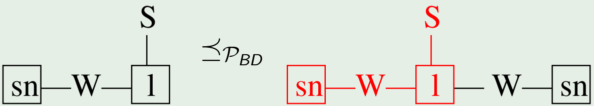

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Why is it a wqo?

- Understand fragments as (syntax) trees
  - Processes are leafs
  - Restricted names are nodes

Example

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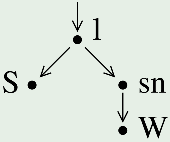

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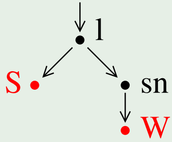

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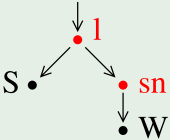

Why is it a wqo?

- Understand fragments as (syntax) trees
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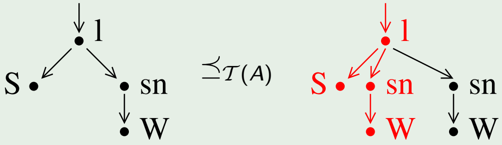
- Use a suitable wqo on trees

Example



- Wqo on trees of bounded depth
- Induction on depth + Higman's result [Hig52]

Main Result

- Simulation is easier to prove

Theorem

If P is a process of bounded depth, then $(\mathit{Reach}(P)/_{\equiv}, \rightarrow, \preceq_{\mathcal{P}_{BD}})$ is a well-structured transition system.

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- Build the computation tree (finite branching)
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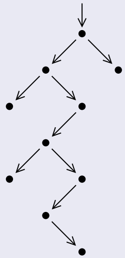

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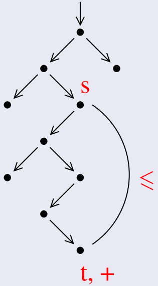

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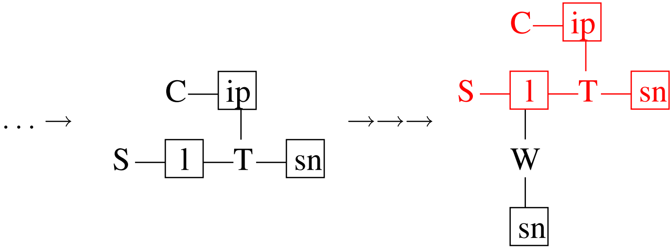
Theorem ([Fin90, FS01, AČJT00])

There is a non-terminating computation if and only if the tree contains a node marked by $+$.
Infinite state if and only if $+$ node is truely bigger

Application to the Client/Server System

- Build the computation tree



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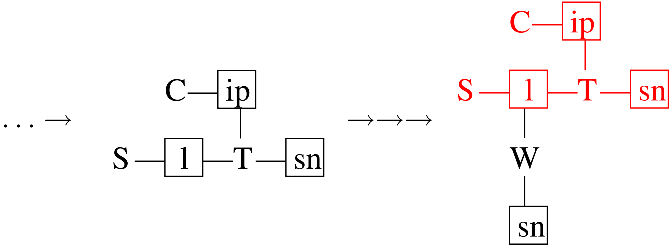

Results

The system does not terminate, the system is infinite state

Related Work

- Interpretation of processes as graphs due to Milner (flow graphs) [Mil79, MM79]
  - For π-Calculus in [MPW92, Mil99, SW01]
  - We relate depth on terms with the longest simple paths in graphs
- Normal forms for π-Calculus by Engelfriet and Gelsema [EG99, EG04] and Milner [Mil99]
  - Similar to minimising scopes
  - Anchored fragments are more stringent

Related Work

- WSTS by Finkel [Fin90, FS01] and Abdulla et. al. [AČJT00]
  - Finkel inspired by Petri nets, termination and boundedness problems
  - Abdulla inspired by lossy channel systems, temporal and simulation properties
  - First instantiation for π-Calculus
  - $\preceq_{\mathcal{P}_{BD}}$ is non-trivial
- Importance of termination for π-Calculus by Yoshida et. al. [YBH04] and Sangiorgi [DS06]
  - Type systems that ensure termination of well-typed processes
  - Instantiate WSTS framework, derive decidability of termination as corollary

Conclusion and Thanks

Processes of bounded depth are graphs where the longest simple path is bounded

- Star-like structures
- Unbounded parallelism/unboundedly many restricted names

They have well-structured transition systems

- Termination is decidable
- Infinity of states is decidable

The class is huge

- Contains all decidable subclasses of π-Calculus known so far [BG95, Dam96, AM02, FGMP03, Cai04, Mey08, BG08]

Conclusion and Thanks

Thanks for your attention

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