Structural Stationarity in the π-Calculus

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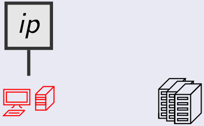
University of Oldenburg

Disputation
2009-02-20

A Client-Server System in the π-Calculus

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

Graphically



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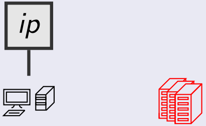

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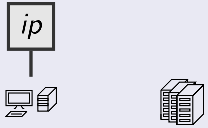

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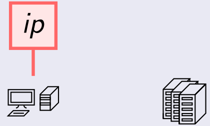

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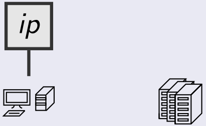
A Client-Server System in the π-Calculus

In response server spawns a new thread

Graphically



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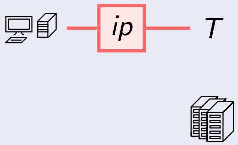
A Client-Server System in the π-Calculus

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

Graphically



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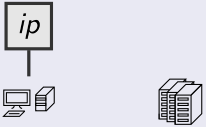
A Client-Server System in the π-Calculus

Thread terminates, client is ready to contact server again

Graphically



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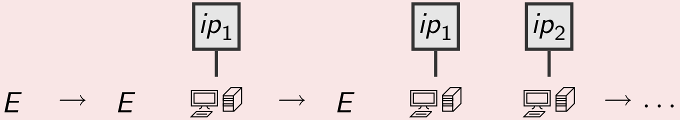
A Client-Server System in the π-Calculus

Assumption

Environment E generates clients



A Semantical Approach to Verification

Goal

Automatic verification of dynamically reconfigurable systems

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Finite representation of infinite state space required

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Approach

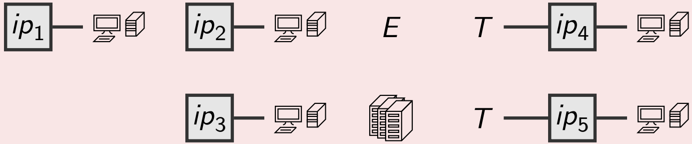
Translate π-Calculus into place/transition Petri nets

Overview

Idea of the Structural Semantics

Problem

Unbounded number of clients and threads



Observation

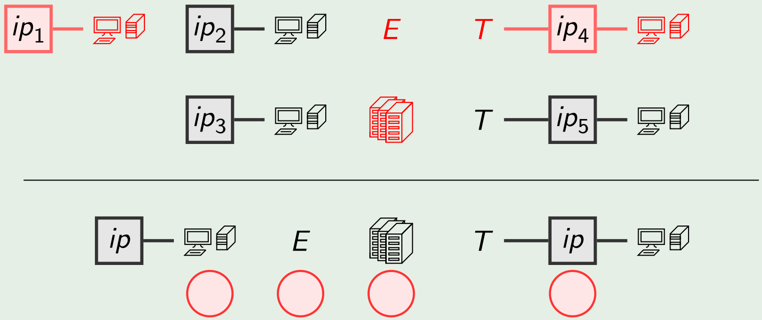
Finite number of connection patterns

Idea of the Structural Semantics

Represent Connections in a Petri net

- Every connection pattern yields a place

Example

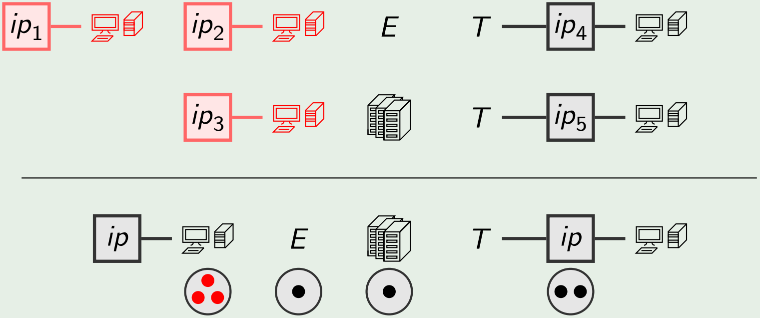


Idea of the Structural Semantics

Represent Connections in a Petri net

- Every connection pattern yields a place
- Every occurence of the pattern yields a token

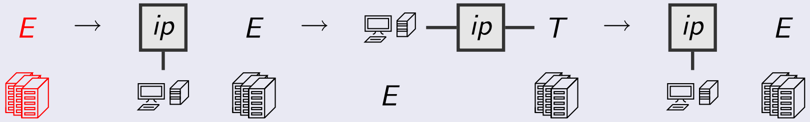
Example



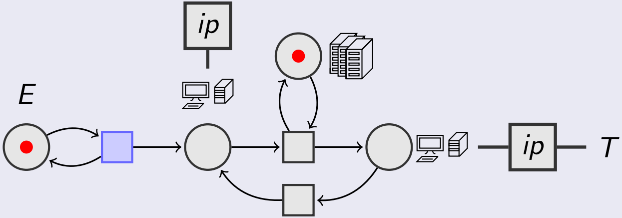
Idea of the Structural Semantics

Transitions model the evolution of patterns

In π-Calculus



The Structural Semantics



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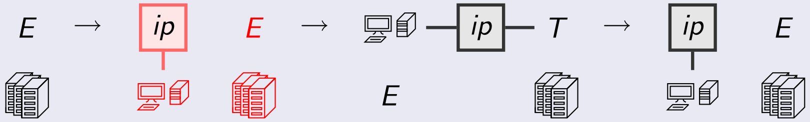

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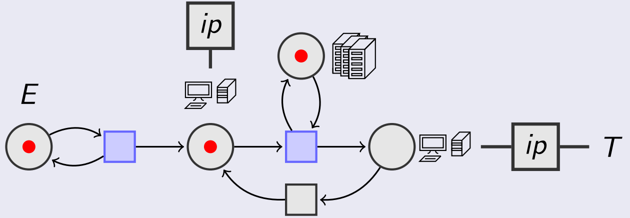

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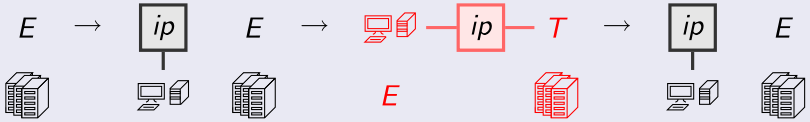

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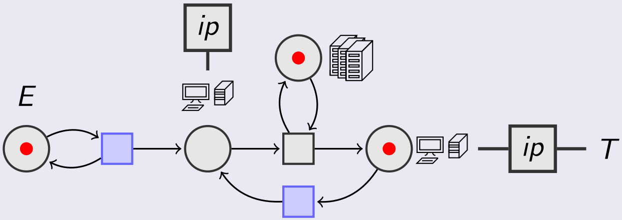

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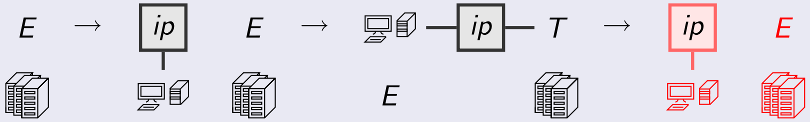

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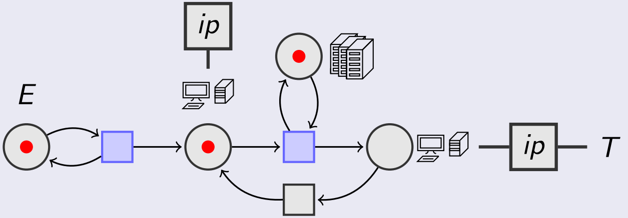

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Purpose

- Formalise the idea of connection patterns
- Define depth and breadth

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Restricted Form of Processes

Fragments

Topmost parallel components are called fragments

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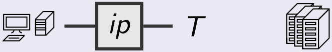
Fragments correspond to connection patterns



Properties of the Semantics

Theorem (Full Retrievability)

Transition systems of P and $\mathcal{N}[\![P]\!]$ are isomorphic. Reachable processes can be computed from markings.

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$$P \equiv Q \text{ iff } \mathcal{N}[\![P]\!] = \mathcal{N}[\![Q]\!]$$

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Lemma

The structural semantics of a closed process is communication-free, i.e., every transition has a single place in its preset.

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Finiteness

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Lemma (Finiteness)

Structural semantics $\mathcal{N}[\![P]\!]$ is finite if and only if process P is structurally stationary.

A First Characterisation of Structural Stationarity

Structural Stationarity is Hard to Prove

Is there a characterisation?

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Theorem (Characterisation via $\|\ \|$)

A process is structurally stationary if and only if the number of sequential processes in every reachable fragment is bounded, i.e.,

$$\exists k \in \mathbb{N} : \forall Q \in Reach(P) : \forall F \in fg\,(rf\,(Q)) : \|F\|_{\mathcal{S}} \leq k.$$

Applications of the Characterisation

Corollary (Restriction-free Processes are Structurally Stationary)

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Corollary (Finitary Processes are Structurally Stationary)

Take k as bound on number of sequential processes in fragments:

$$\|F\|_{\mathcal{S}} \leq \|rf(Q)\|_{\mathcal{S}} = \|Q\|_{\mathcal{S}} \leq k.$$

A Second Characterisation of Structural Stationarity

Understanding Structural Stationarity

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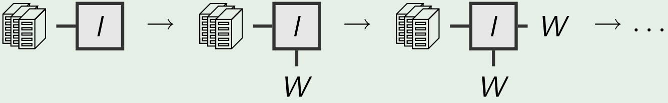
Example

A server with local control channel l is not structurally stationary:



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Maximal number of sequential processes sharing a restricted name

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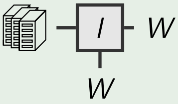
For $F :=$ 

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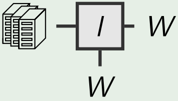
For $F :=$ 

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Problem

Boundedness in breadth does not ensure structural stationarity

Depth of Processes

Example

Lists are bounded in breadth but not structurally stationary:

$$LE \;\rightarrow\; LI - \boxed{id_1} - LE \;\rightarrow\; LI - \boxed{id_1} - LI - \boxed{id_2} - LE \;\rightarrow\; \ldots$$

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Depth

- Minimal nesting of restrictions in the congruence class
- Corresponds to the length of the longest simple path

Example

For $F := LI - \boxed{id_1} - LI - \boxed{id_2} - LE$ we have $\|F\|_{\mathcal{D}} = 2$.

Characterisation of Structural Stationarity via ν

Theorem

A process is structurally stationary if and only if it is bounded in breadth and bounded in depth.

Decidability in Bounded Depth

Theorem

If a process is bounded in depth, termination and infinity of states are decidable.

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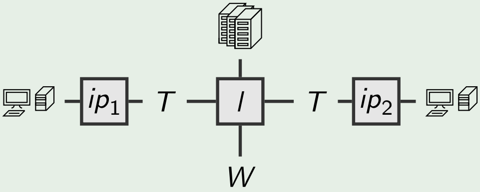
Server with control channel l is bounded in depth by 3



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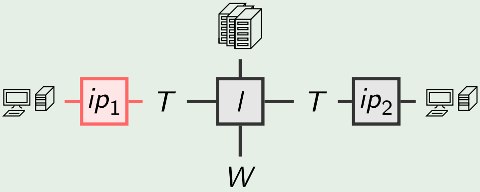

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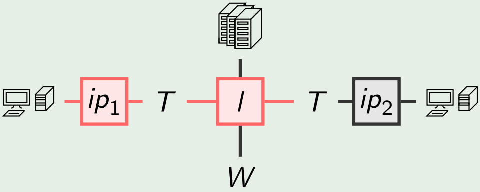

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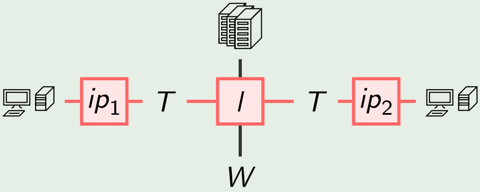

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WSTS [Fin90, FS01, AČJT00]

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$\leq \subseteq S \times S$ is a Well-Quasi-Ordering

Every infinite sequence contains two comparable states

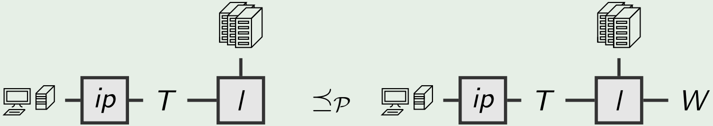
$$s_0 \longrightarrow s_1 \longrightarrow \ldots \longrightarrow \overbrace{s_i \longrightarrow \ldots \longrightarrow s_j}^{\leq} \longrightarrow \ldots$$

Instantiation of the Framework—The Ordering $\preceq_{\mathcal{P}}$

Intuition

Use hypergraph embedding as ordering

Example



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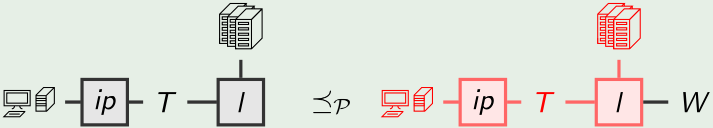

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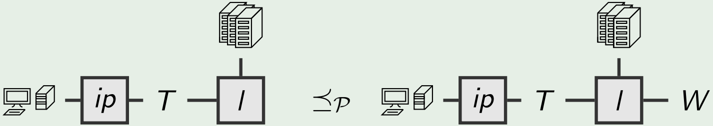

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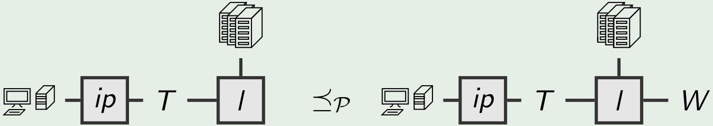

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Instantiation Theorem

Theorem

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

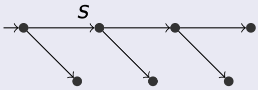
▸ WQO Proof

▸ Undecidability of Reachability

Decidability Results for WSTS [Fin90, FS01, AČJT00]

Finite Reachability Tree

- Build computation tree (finite branching)
- If a new node covers predecessor stop and mark node by $+$



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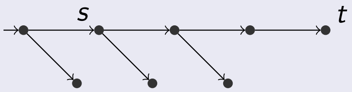

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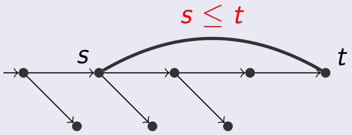

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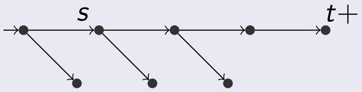

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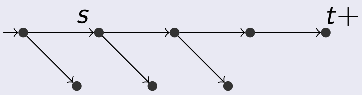

Theorem ([Fin90, FS01, AČJT00])

Non-terminating computation exists iff tree contains $+$ node.

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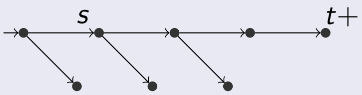
- Build computation tree (finite branching)
- If a new node covers predecessor stop and mark node by $+$

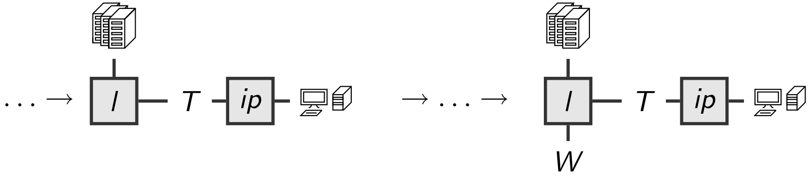


Theorem ([Fin90, FS01, AČJT00])

Non-terminating computation exists iff tree contains + node.
Infinite state iff + node is strictly larger.

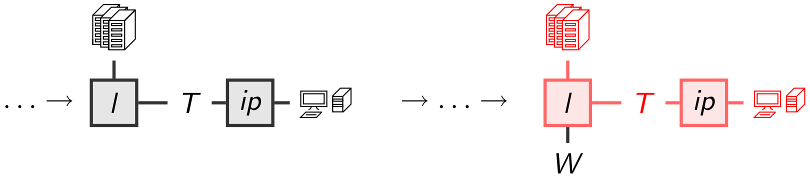
Application to the Client-Server System

Build the computation tree



Application to the Client-Server System

Build the computation tree

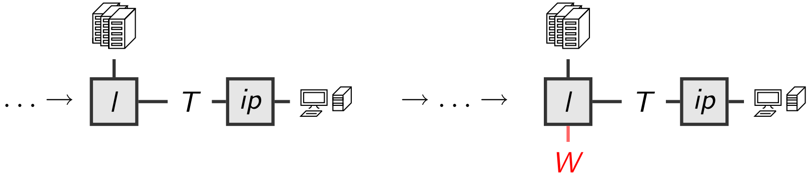


Results

System does not terminate and is infinite state.

Application to the Client-Server System

Build the computation tree



Results

System does not terminate and is infinite state.

Related Work

Processes as Graphs

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

Automata-theoretic Semantics

- Concurrency [Eng96, MP01, AM02, BG08, DKK06]
- Structure [MP95b]

Model Checking Tools

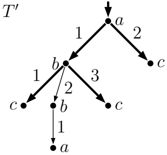
MWB [VM94, Dam96], HAL [FGMP03], SLMC [Cai04]

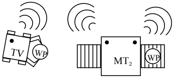
Normal Forms

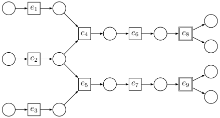
Decidability of structural congruence [EG99, EG04a, EG04b, EG07]

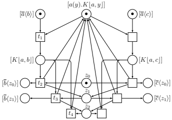
More Related Work

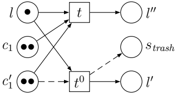
Survey

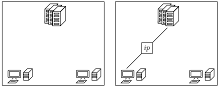

T'
a
1
2
b
c
1
2
3
c
b
c
1
a

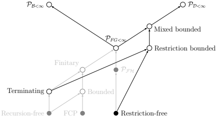

TV
WP
MT_2
WP

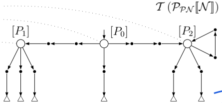

e_1
e_2
e_3
e_4
e_5
e_6
e_7
e_8
e_9


$[a(y).K\lfloor a,y\rfloor]$
$[\overline{a}\langle b\rangle]$
$[\overline{a}\langle c\rangle]$
t_1
$[K\lfloor a,b\rfloor]$
$[K\lfloor a,c\rfloor]$
t_2
t_3
t_4
$[\overline{b}\langle z_0\rangle]$
$[\overline{b}\langle z_1\rangle]$
$[\overline{c}\langle z_0\rangle]$
$[\overline{c}\langle z_1\rangle]$


l
t
l''
c_1
s_{trash}
c_1'
t^0
l'


ip


$\mathcal{P}_{B<\infty}$
$\mathcal{P}_{D<\infty}$
$\mathcal{P}_{FG<\infty}$
Mixed bounded
Restriction bounded
Finitary
$\mathcal{P}_{\mathcal{FH}}$
Terminating
Bounded
Recursion-free
FCP
Restriction-free


$\mathcal{T}(\mathcal{P}_{\mathcal{PN}}[\![\mathcal{N}]\!])$
$[P_1]$
$[P_0]$
$[P_2]$

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More Related Work

WSTS

- Finkel inspired by Petri nets [Fin90, FS01], termination and boundedness problems
- Abdulla inspired by lossy channel systems [AČJT00], temporal and simulation properties

WSTS and Process Algebras

Replication and recursion in CCS [BGZ03, BGZ04, BGZ08]

Termination

Type systems [YBH04, DS06, DHS08]

Return

More Related Work

GRS and Verification

Semi-decision procedures [Bau06, Ren04, KK06]

AVACS

- Spotlight abstraction [WW07, Wes08] + invariants [BTW07]
- Refinement cycle [Tob08]

Extended Petri Nets

- Petri nets with marking dependent arc cardinalities [DFS98]
- Relation to multithreaded JAVA [DRB02]
- Undecidability of LTL [RB04]

Return

Why is $\preceq_{\mathcal{P}}$ a WQO?

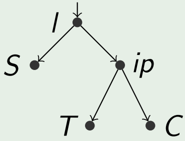
Proof Idea

Understand fragments as (syntax) trees

- Sequential processes are leafs
- Restricted names are nodes

Example

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



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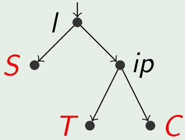
$$\nu l.(\, S\lfloor url, dat, l\rfloor \mid \nu ip.(\, T\lfloor l, ip\rfloor \mid C\lfloor url, ip\rfloor\,))$$



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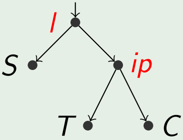


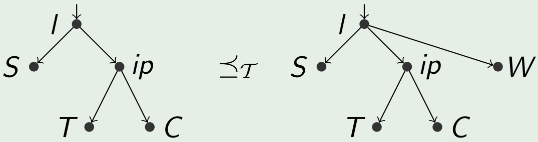
Return

Why is $\preceq_{\mathcal{P}}$ a WQO?

Proof Idea

Use a suitable wqo on trees

Example



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Proof Idea

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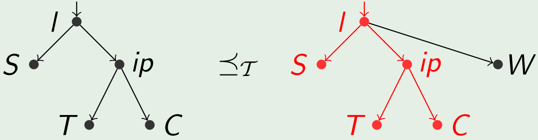
Example



Return

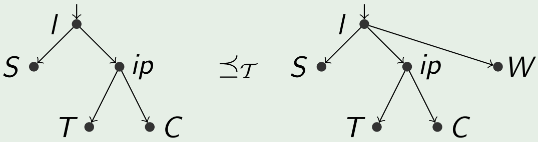
Why is $\preceq_{\mathcal{P}}$ a WQO?

Proof Idea

Use a suitable wqo on trees

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

Example

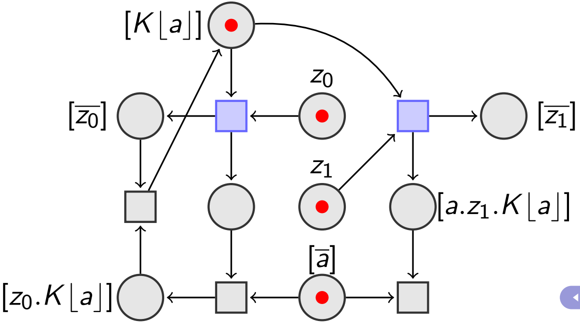


◂ Return

Why Order Name Places?

Counterexample

- Consider $\overline{a} \mid K\lfloor a \rfloor$ with $K(x) := \nu z_0.(\overline{z_0} \mid x.z_0.K\lfloor x \rfloor)$
- Process deadlocks after four steps



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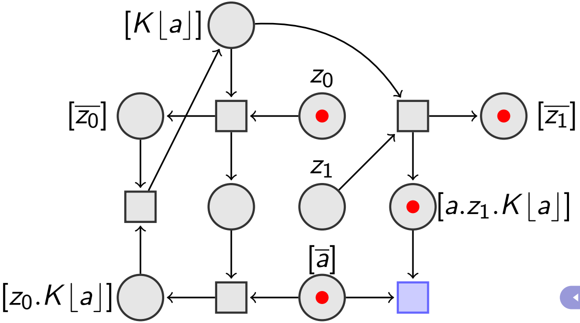

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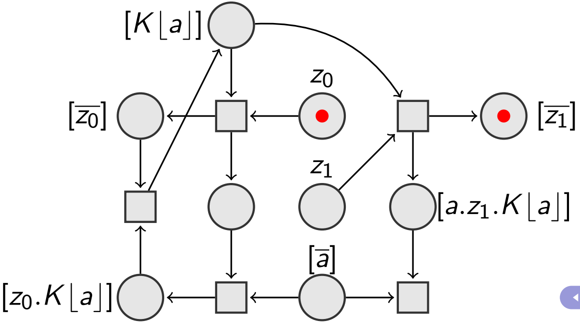

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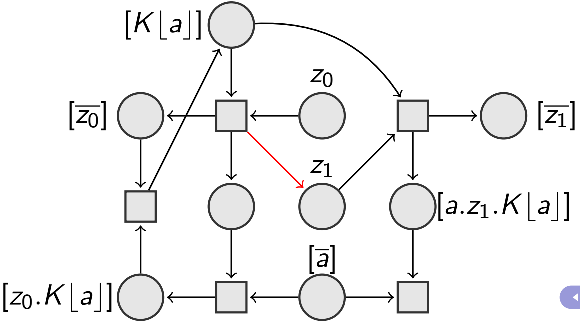
- Insert dependence between z_0 and z_1



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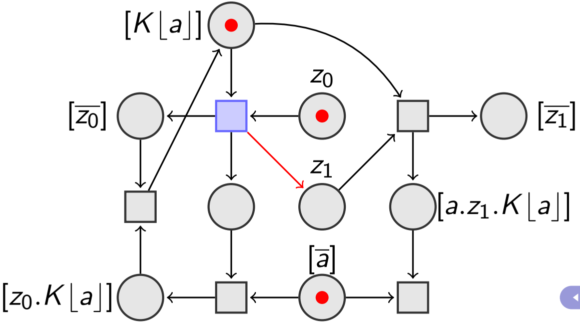

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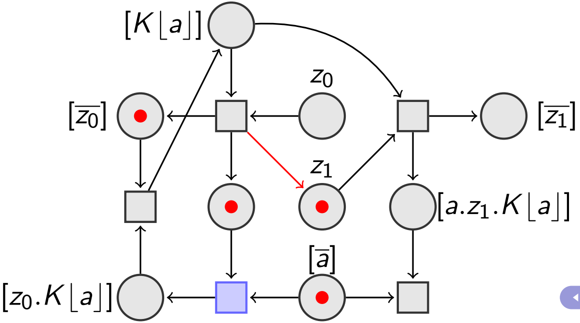

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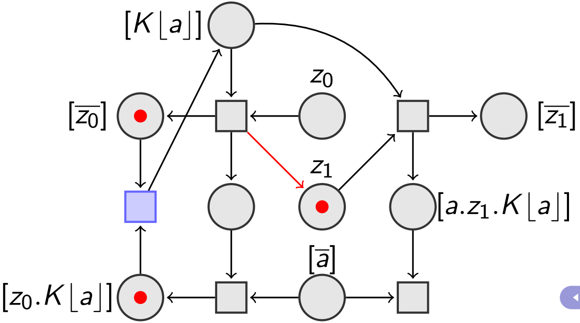

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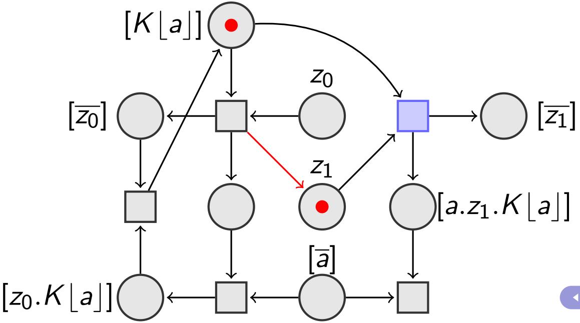

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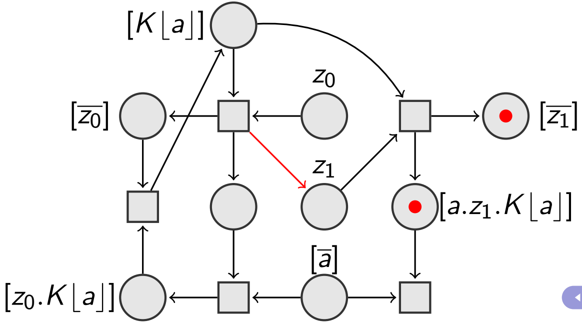


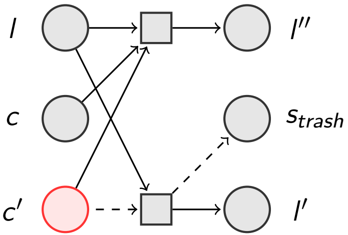
Return

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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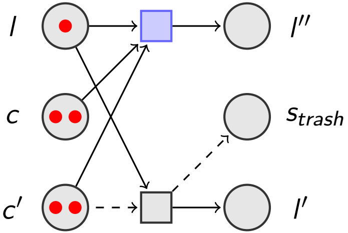

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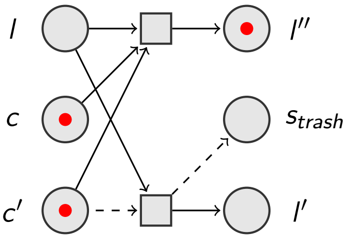

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Undecidability of Reachability in Depth One

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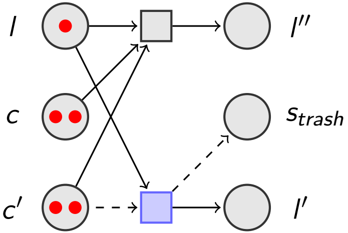
$$l: \ \text{if } c = 0 \text{ then goto } l'; \ \text{else } c := c - 1; \ \text{goto } l'';$$

- Create copy c' of counter c
- Test for zero removes all tokens from c'



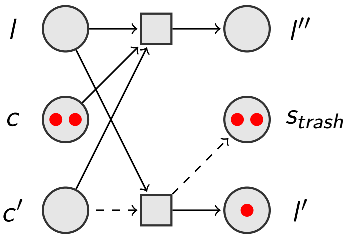
Return

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
- Test for zero removes all tokens from c'



Return

Undecidability of Reachability in Depth One

Process Bunch

Modify an arbitrary number of processes with one communication

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

Example

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

◂ Return

Undecidability of Reachability in Depth One

Process Bunch

Modify an arbitrary number of processes with one communication

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\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

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

Return

Undecidability of Reachability in Depth One

Process Bunch

Modify an arbitrary number of 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

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

Return

Verification Techniques

Algorithms avoid costly state space computations:

- Occurrence number properties
  - Use S-invariants
- Temporal properties
  - Inspect graph structure of the Petri net
- Topological properties
  - Inspect set of places (using regular expressions)

Return

Unfolding-based Verification

Model	[KKN06] unf	[KKN06] sat	MWB dl	HAL π2fc	**Struct** unf	**Struct** sat
ns2	1	< 1	< 1	< 1	< 1	< 1
ns3	7	< 1	1	8	< 1	< 1
ns4	69	1	577	382	< 1	< 1
ns5	532	58	—	—	17	3
ns6	—	—	—	—	1518	84
gsm [OP92]	n/a		—	18	< 1	< 1

Verified car platoon and autonomous transport

Instance	**Struct** $\lvert P\rvert$	**Struct** $\lvert T\rvert$	**Model Checking** unf	**Model Checking** $\lvert B\rvert$	**Model Checking** $\lvert E\rvert$	**Model Checking** sat
1p 6m 4v ref	937	1371	8h	923236	721991	20min

Return

Size of the Translation

Idea

$$\mathcal{N}_1, \quad \mathcal{N}_2, \quad \mathcal{N}_3, \ldots$$

Return

Size of the Translation

Idea

$$\begin{array}{c} \mathcal{N}_1, \quad \mathcal{N}_2, \quad \mathcal{N}_3, \ldots \\ \Big\downarrow \text{linear} \\ \mathcal{P}[\![\mathcal{N}_1]\!], \quad \mathcal{P}[\![\mathcal{N}_2]\!], \quad \mathcal{P}[\![\mathcal{N}_3]\!], \ldots \end{array}$$

Return

Size of the Translation

Idea

$$
\begin{array}{c}
\mathcal{N}_1, \quad \mathcal{N}_2, \quad \mathcal{N}_3, \ldots \\
\Big\downarrow \text{linear} \\
\mathcal{P}[\![\mathcal{N}_1]\!], \quad \mathcal{P}[\![\mathcal{N}_2]\!], \quad \mathcal{P}[\![\mathcal{N}_3]\!], \ldots \\
\Big\downarrow \mathcal{N}_i \text{ state yields } \mathcal{N}[\![\mathcal{P}[\![\mathcal{N}_i]\!]]\!] \text{ place} \\
\mathcal{N}[\![\mathcal{P}[\![\mathcal{N}_1]\!]]\!], \quad \mathcal{N}[\![\mathcal{P}[\![\mathcal{N}_2]\!]]\!], \quad \mathcal{N}[\![\mathcal{P}[\![\mathcal{N}_3]\!]]\!], \ldots
\end{array}
$$

Return

Size of the Translation

Idea

$$
\begin{array}{c}
\mathcal{N}_1, \quad \mathcal{N}_2, \quad \mathcal{N}_3, \ldots \\
\Big\downarrow \text{linear} \\
\mathcal{P}[\![\mathcal{N}_1]\!], \quad \mathcal{P}[\![\mathcal{N}_2]\!], \quad \mathcal{P}[\![\mathcal{N}_3]\!], \ldots \\
\Big\downarrow \mathcal{N}_i \text{ state yields } \mathcal{N}[\![\mathcal{P}[\![\mathcal{N}_i]\!]]\!] \text{ place} \\
\mathcal{N}[\![\mathcal{P}[\![\mathcal{N}_1]\!]]\!], \quad \mathcal{N}[\![\mathcal{P}[\![\mathcal{N}_2]\!]]\!], \quad \mathcal{N}[\![\mathcal{P}[\![\mathcal{N}_3]\!]]\!], \ldots
\end{array}
$$

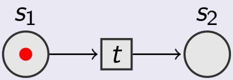
Theorem (Size of the Structural Semantics)

The size of the structural semantics $\mathcal{N}[\![P]\!]$ is not bounded by a primitive recursive function in the size of the process P.

Return

Size of the Translation

Technically



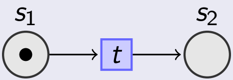
$$\nu act.(\overline{act} \mid act.K_t\lfloor act, s_1, s_2\rfloor \mid \overline{s_1}\langle act\rangle)$$

$$K_t(act, s_1, s_2) := s_1(x).(\overline{act} \mid act.K_t\lfloor act, s_1, s_2\rfloor \mid \overline{s_2}\langle act\rangle)$$

Return

Size of the Translation

Technically

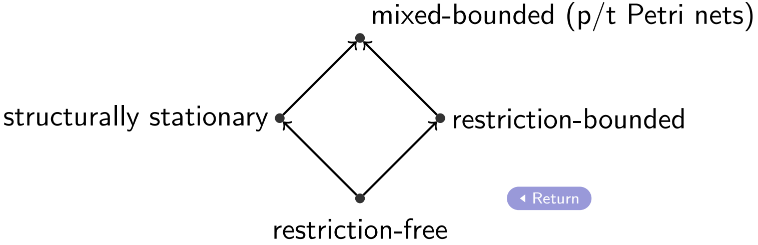


$$\nu act.(\overline{act} \mid act.\,K_t\lfloor act, s_1, s_2\rfloor \mid \overline{s_1}\langle act\rangle)$$

$$K_t(act, s_1, s_2) := s_1(x).(\overline{act} \mid act.K_t\lfloor act, s_1, s_2\rfloor \mid \overline{s_2}\langle act\rangle)$$

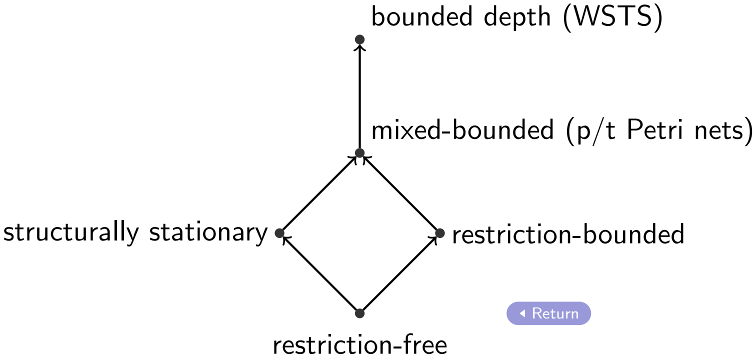
Return

Hierarchy of Processes



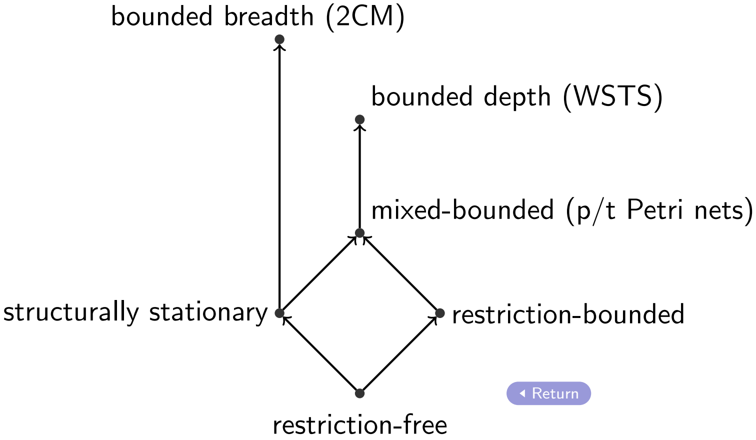
Return

Hierarchy of Processes



Return

Hierarchy of Processes



Return

Finite Handler Processes—Participants

- Register at handler processes via distinguished public channels

Example

- Channel *cfa* is a distinguished name
- A free agent is a participant:

$$\nu id, ca, rq.\, \overline{cfa}\langle id\rangle\, .\overline{id}\langle ca\rangle.\overline{id}\langle rq\rangle \ldots$$

◂ Return

Finite Handler Processes—Participants

- Register at handler processes via distinguished public channels
- Continue to communicate via private names only

Example

- Channel *cfa* is a distinguished name
- A free agent is a participant:

$$\nu id, ca, rq.\overline{cfa}\langle id\rangle.\overline{id}\langle ca\rangle.\overline{id}\langle rq\rangle \ldots$$

Return

Finite Handler Processes—Handler

- Listen on the distinguished channels

Example

The *MRG* process is a handler

$$\boxed{cfa}(id_x).id_x(ca_x)\ldots\boxed{cfa}(id_y)\ldots id_y(rq_y).\overline{ca_x}\langle rq_y\rangle.MRG\lfloor cfa\rfloor$$

Return

Finite Handler Processes—Handler

- Listen on the distinguished channels
- Receive finitely many processes

Example

The *MRG* process is a handler

$$cfa(id_x).id_x(ca_x)\ldots cfa(id_y)\ldots id_y(rq_y).\overline{ca_x}\langle rq_y\rangle.MRG\lfloor cfa\rfloor$$

Return

Finite Handler Processes—Handler

- Listen on the distinguished channels
- Receive finitely many processes
- Communicate with the registered participants only

Example

The *MRG* process is a handler

$$cfa(id_x).id_x(ca_x)\ldots cfa(id_y)\ldots id_y(rq_y).\overline{ca_x}\langle rq_y\rangle.MRG\lfloor cfa\rfloor$$

◂ Return

Fundamental Property of Finite Handler Processes

Theorem

Finite handler processes are structurally stationary.

The car platooning example is a finite handler process

◂ Return