A Practical Approach to Verification of Mobile Systems Using Net Unfoldings

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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

$$C \xrightarrow{(IP)} S$$

In π-Calculus

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

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Server sends back a private session *ses* on the private channel *ip*

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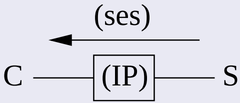

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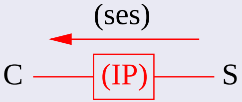

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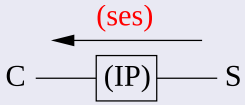

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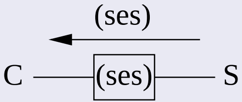
A Client/Server System in the π-Calculus

To terminate the session, the server sends the private session object *ses* on the channel *ses* itself

Graphically



In π-Calculus

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

A Client/Server System in the π-Calculus

The client is ready to contact the server again on the public channel *url*

Graphically

C S

In π-Calculus

$$C\lfloor url\rfloor \mid S\lfloor url\rfloor$$

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Overview

1. A client/server system in the π-Calculus
2. From π-Calculus to Petri nets
3. A Boundedness Result for FCP nets
4. From FCPs to Safe Nets
5. Model Checking with Net Unfoldings

Verficiation of Dynamically Reconfigurable Systems

- Motivation: automatic verification of dynamically reconfigurable systems
- Approach: employ a mapping of π-Calculus processes into Petri nets that preserves the reaction relation
  - The π-Calculus is well suited for modelling dynamically reconfigurable systems
  - Petri nets come with well investigated verification techniques

From π-Calculus to Petri nets

- Observation: a process is represented by several graphs
- Idea: represent this connection structure in a Petri net:
  - Every place represents a possible graph
  - Every token represents an occurence of the graph

From π-Calculus to Petri nets

Example

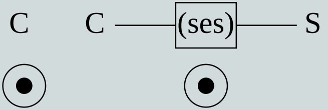
A client and a client who has a session with a server:

In the π-Calculus

C   C —— $\boxed{\text{(ses)}}$ —— S

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

As a Petri net



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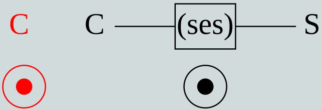

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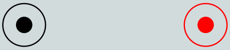


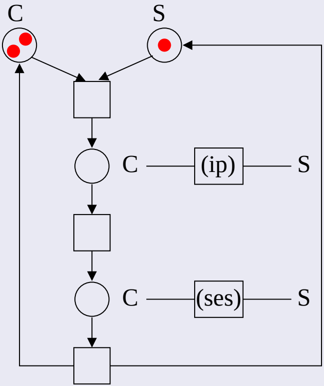
P and $\mathcal{PN}[\![P]\!]$ are isomorphic

In the π-Calculus

↓

C C S

As a Petri net



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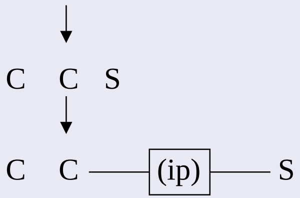
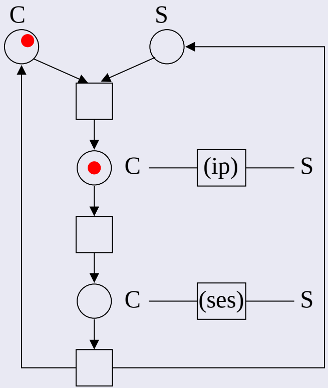


As a Petri net



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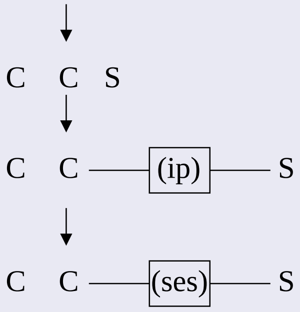

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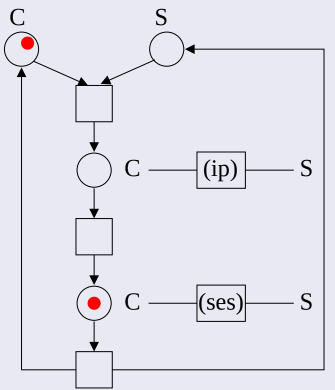

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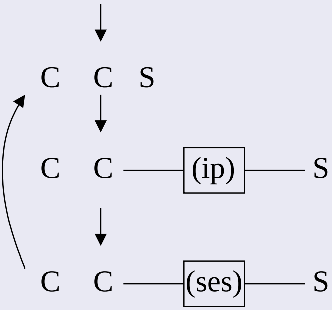

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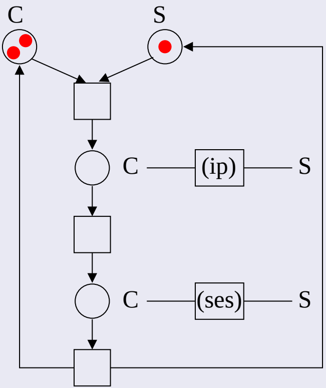


Finite Control Processes

Problem

- Petri net translation may be an infinite or unbounded Petri net
- For model checking we need small bounds $\Rightarrow$ safe nets!

Solution

- Restrict ourselves to an expressive fragment of π-Calculus
- In Finite Control Processes (FCPs) [Dam96], no processes are created, i.e.,

$$P_{\mathcal{FC}} = P_1 \mid \ldots \mid P_n,$$

where the P_i do not use parallel composition $\mid$

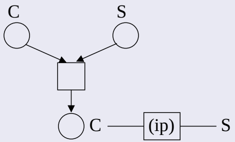
Finite Control Processes

Example (The Client/Server System)

$$C\lfloor url \rfloor \mid C\lfloor url \rfloor \mid S\lfloor url \rfloor$$

Observation

- Initially, each place in the net $\mathcal{PN}[\![P_1 \mid \ldots \mid P_\mathbf{n}]\!]$ carries at most **n** tokens
- Transitions split or join processes



- So, the net $\mathcal{PN}[\![P_1 \mid \ldots \mid P_\mathbf{n}]\!]$ is trivially bounded by **n**
- Better bounds? Where are the safe nets?

Towards the Boundedness Result

Processes use recursive equations to define infinite behaviours

$$K(\tilde{x}) := P.$$

Example

Client and server are defined by:

$$C(url) := \nu ip.\overline{url}\langle ip\rangle.ip(s).s(x).C\lfloor url\rfloor$$
$$S(url) := url(y).\nu ses.\overline{y}\langle ses\rangle.\overline{ses}\langle ses\rangle.S\lfloor url\rfloor.$$

K, C, and S are process identifiers

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Towards the Boundedness Result

Process identifiers cannot be renamed:

Example

The following clients are distinct because $C^1 \neq C^2$:

$$\begin{aligned} & \nu ip.\overline{url}\langle ip\rangle.ip(s).s(x).\boxed{C^1}\lfloor url\rfloor \\ \neq & \nu ip.\overline{url}\langle ip\rangle.ip(s).s(x).\boxed{C^2}\lfloor url\rfloor \end{aligned}$$

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Observation

So **k** tokens on a place in $\mathcal{PN}[\![P_1 \mid \ldots \mid P_n]\!]$ imply

k processes $P_{i_1}, \ldots, P_{i_k}$ have common process identifiers

Orbits

The orbit of a process is the set of process identifiers a process uses

Example

Consider two clients and a server:

$$C\lfloor url \rfloor \mid C\lfloor url \rfloor \mid S\lfloor url \rfloor, \text{ where}$$

$$C(url) := \nu ip.\overline{url}\langle ip \rangle.ip(s).s(x).C\lfloor url \rfloor$$
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The orbits are:

$$orb(C\lfloor url \rfloor) = \{C\}$$

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$$orb(C\lfloor url \rfloor) = \{C\}$$
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$$orb(S\lfloor url \rfloor) = \{S\}.$$

The Boundedness Result

Observation Rephrased

If we have **k** tokens on a place in $\mathcal{PN}[\![P_1 \mid \ldots \mid P_n]\!]$ then there are

k intersecting orbits

$$orb(P_{i_1}) \cap \ldots \cap orb(P_{i_k}) \neq \emptyset$$

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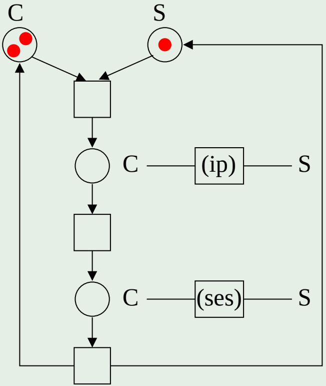
Theorem

The maximal number of intersecting orbits in $P_1 \mid \ldots \mid P_n$ gives a bound for $\mathcal{PN}[\![P_1 \mid \ldots \mid P_n]\!]$.

Example



is bounded by 2, since
$orb(C\lfloor url \rfloor) \cap orb(C\lfloor url \rfloor) \neq \emptyset$

Improves the trivial bound of 3

From FCPs to Safe Nets

Definition

An FCP $P_{\mathcal{FC}} = P_1 \mid \ldots \mid P_n$ is called a safe process, if all orbits are disjoint.

- The theorem guarantees that safe processes are mapped to safe Petri nets
- The function *Safe* maps every FCP $P_{\mathcal{FC}}$ to a safe process $\mathit{Safe}(P_{\mathcal{FC}})$

The Function *Safe*

- Idea: Rename all process identifiers used by P_i
- Duplicate the corresponding equations
- Remove the original equations

Example

$$P_{\mathcal{FC}} = C\lfloor url \rfloor \mid C\lfloor url \rfloor \mid S\lfloor url \rfloor$$
$$C(url) := \nu ip.\overline{url}\langle ip \rangle.ip(s).s(x).C\lfloor url \rfloor$$
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The Function *Safe*

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$$Safe(P_{\mathcal{FC}}) = \boxed{C^1}\lfloor url \rfloor \mid C^2\lfloor url \rfloor \mid S^3\lfloor url \rfloor$$

$$\boxed{C^1}(url) := \nu ip.\overline{url}\langle ip\rangle.ip(s).s(x).\boxed{C^1}\lfloor url \rfloor$$

The Function *Safe*

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The Function *Safe*

Example

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\begin{aligned}
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\end{aligned}
$$

$$
\begin{aligned}
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S^3(url) &:= url(y).\nu ses.\overline{y}\langle ses \rangle.\overline{ses}\langle ses \rangle.S^3\lfloor url \rfloor.
\end{aligned}
$$

Bisimilarity

Theorem

$P_{\mathcal{FC}}$ and $Safe(P_{\mathcal{FC}})$ are bisimilar, just remove the superscripts

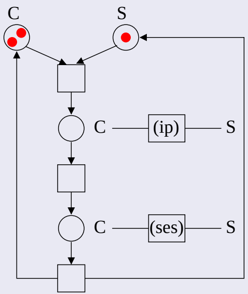
P and $\mathcal{PN}[\![P]\!]$ are isomorphic

Corollary

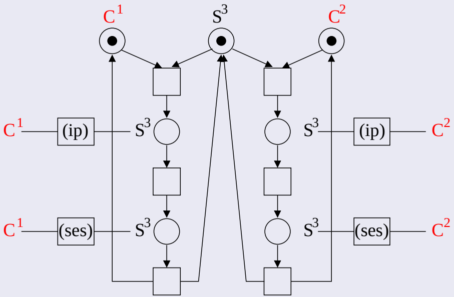
$P_{\mathcal{FC}}$ and $\mathcal{PN}[\![Safe(P_{\mathcal{FC}})]\!]$ are bisimilar. The reachable processes can be reconstructed from the markings.

Bisimilarity

$\mathcal{PN}[\![P_{\mathcal{FC}}]\!]$

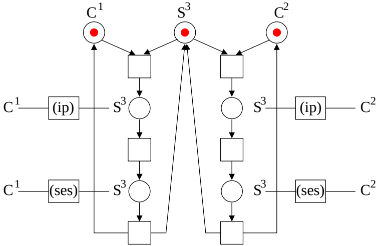


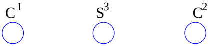
$\mathcal{PN}[\![Safe(P_{\mathcal{FC}})]\!]$



- Unfoldings represent the reachable states of a Petri net implicitly
- Technically: acyclic net that records the causal dependence of transitions
- Intuitively: just fire the transitions and record the places they use

The Finite and Complete Prefix





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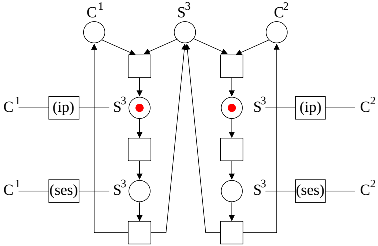

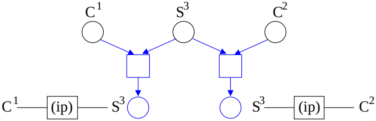

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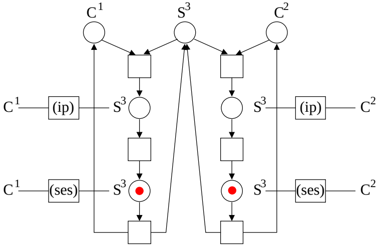

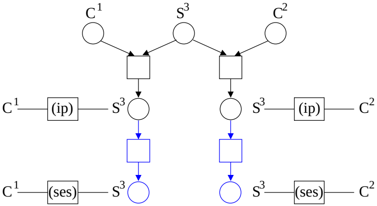

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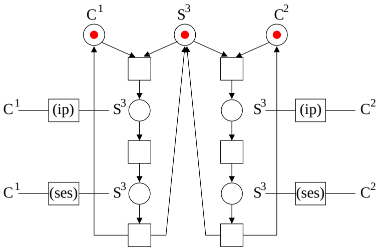
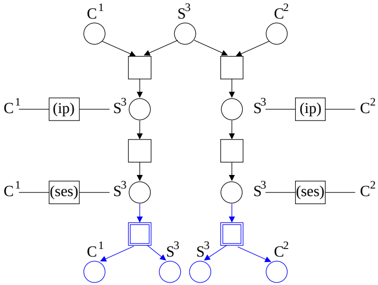
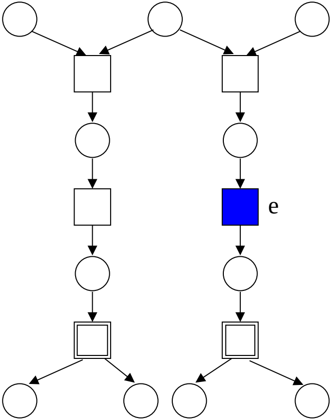




Model Checking Unfoldings with SAT

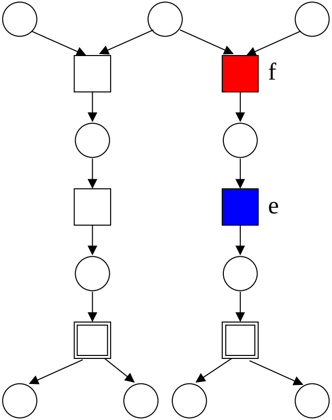
- A Boolean expression φ is built from the prefix so that
  - φ is unsatisfiable iff the property holds
  - Every satisfying assignment gives a violation trace
- φ has the form **Conf** $\wedge$ **Viol**

Conf: Causality



If *e* is executed, then its causal predecessors are executed

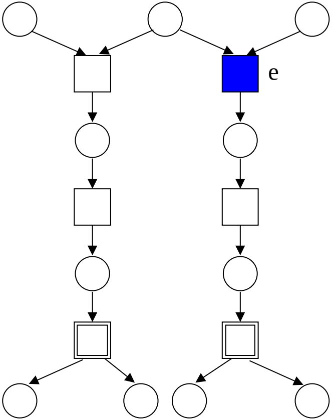
Conf: Causality



If e is executed, then its causal predecessors are executed

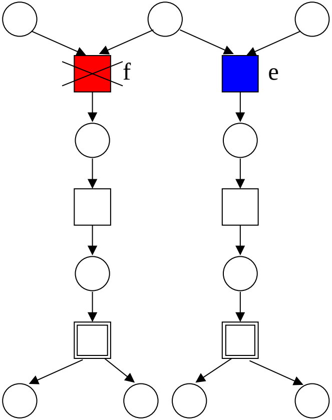
$$\bigwedge_{e \in E \setminus E_{Cut}} \bigwedge_{f \in {}^{\bullet\bullet}e} e \Rightarrow f$$

Conf: Conflicts



If *e* is executed, then events in conflict are not executed

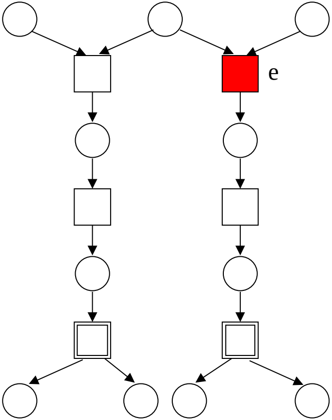
Conf: Conflicts



If e is executed, then events in conflict are not executed

$$\bigwedge_{e \in E \setminus E_{Cut}} \bigwedge_{f \in ({}^{\bullet}e)^{\bullet} \setminus \{e\}} e \Rightarrow \neg f$$

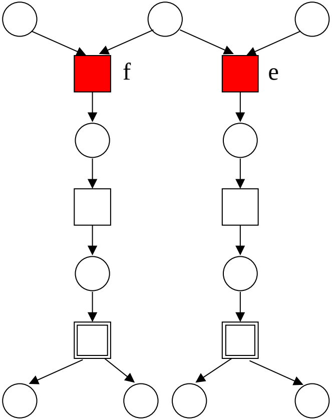
Viol: Deadlock



If *e* cannot be executed,

- either some event in conflict or *e* itself has been executed

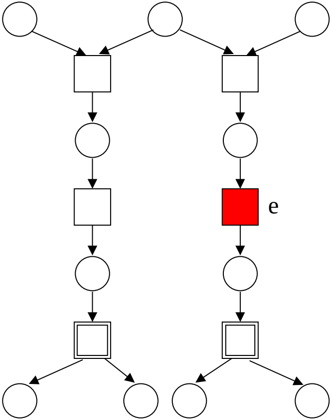
Viol: Deadlock



If *e* cannot be executed,

- either some event in conflict or *e* itself has been executed

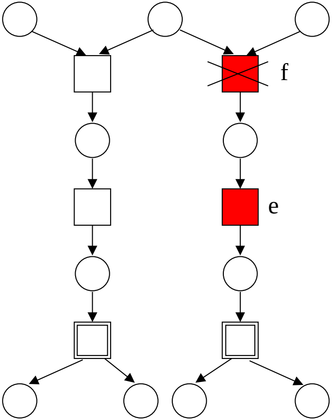
Viol: Deadlock



If *e* cannot be executed,

- either some event in conflict or *e* itself has been executed
- or the predecessor of *e* has not fired

Viol: Deadlock



If e cannot be executed,

- either some event in conflict or e itself has been executed
- or some predecessor of e has not fired

$$\bigwedge_{e \in E} \left(\bigvee_{f \in ({}^{\bullet}e)^{\bullet} \setminus E_{Cut}} f \vee \bigvee_{f \in {}^{\bullet\bullet}e} \neg f \right)$$

Experimental Results

- Comparison with *MWB* [VM94], *HAL* [FGMP03], and [DKK06] translation+Unfolding-based model checking
- Three case studies:
  - Client/Server with scalable number of clients and sessions
  - Education system from [KKN06], high-degree of concurrency, scalable in the number of students
  - Realistic model of GSM network [OP92]
- Property: deadlock-freeness

Experimental Results

- *MWB* and *HAL* do not scale well
- [KKN06]+Unfoldings scales but requires recursion-free processes
- Handled nets of up to 282 places, 1722 transitions
- Building the unfolding took up to 25 minutes, SAT solving 84 seconds
- Others failed when our nets had still 100 places and 300 transitions

Experimental Results

- In absolute numbers:
  - From 4 students (others) to 6 students (our technique)
  - From 2 clients and 2 sessions to 5 sessions and 5 clients
  - Handled the GSM network within < 1 second, *MWB* fails, *HAL* uses 18 seconds

Conclusion and Thanks

Take home message: there is an efficient way of checking FCPs with net unfoldings

Everything is implemeted:
`http://petruchio.informatik.uni-oldenburg.de`

Thanks for your attention

References I

M. Dam.
Model checking mobile processes.
Information and Computation, 129(1):35–51, 1996.

R. Devillers, H. Klaudel, and M. Koutny.
A Petri net semantics of the finite π-Calculus terms.
Fundamenta Informaticae, 70(3):203–226, 2006.

G.-L. Ferrari, S. Gnesi, U. Montanari, and M. Pistore.
A model-checking verification environment for mobile processes.
ACM Transactions on Software Engineering and Methodology, 12(4):440–473, 2003.

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

F. Orava and J. Parrow.
An algebraic verification of a mobile network.
Formal Aspects of Computing, 4(6):497–543, 1992.

References II

B. Victor and F. Moller.
The mobility workbench: A tool for the π-Calculus.
In *Proc. CAV'94*, volume 818 of *Lecture Notes in Computer Science*, pages 428–440. Springer-Verlag, 1994.