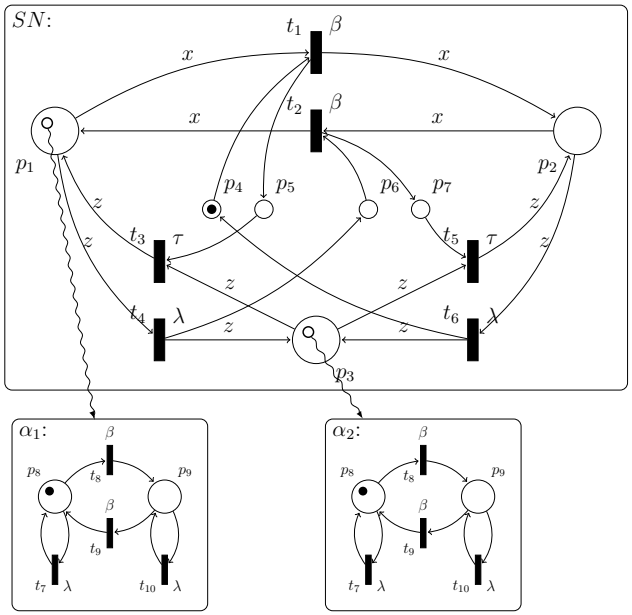
Methods of Analysis for Nested Petri Nets (NP-nets)



Speaker: L. Dworzanski (leo@mathtech.ru)
Sci. Advisor: I. A. Lomazova (ilomazova@hse.ru)
National Research University Higher School of Economics

NP-nets — the first impression

An instance of “nets-within-nets” paradigm (cf. R.Valk 1998)

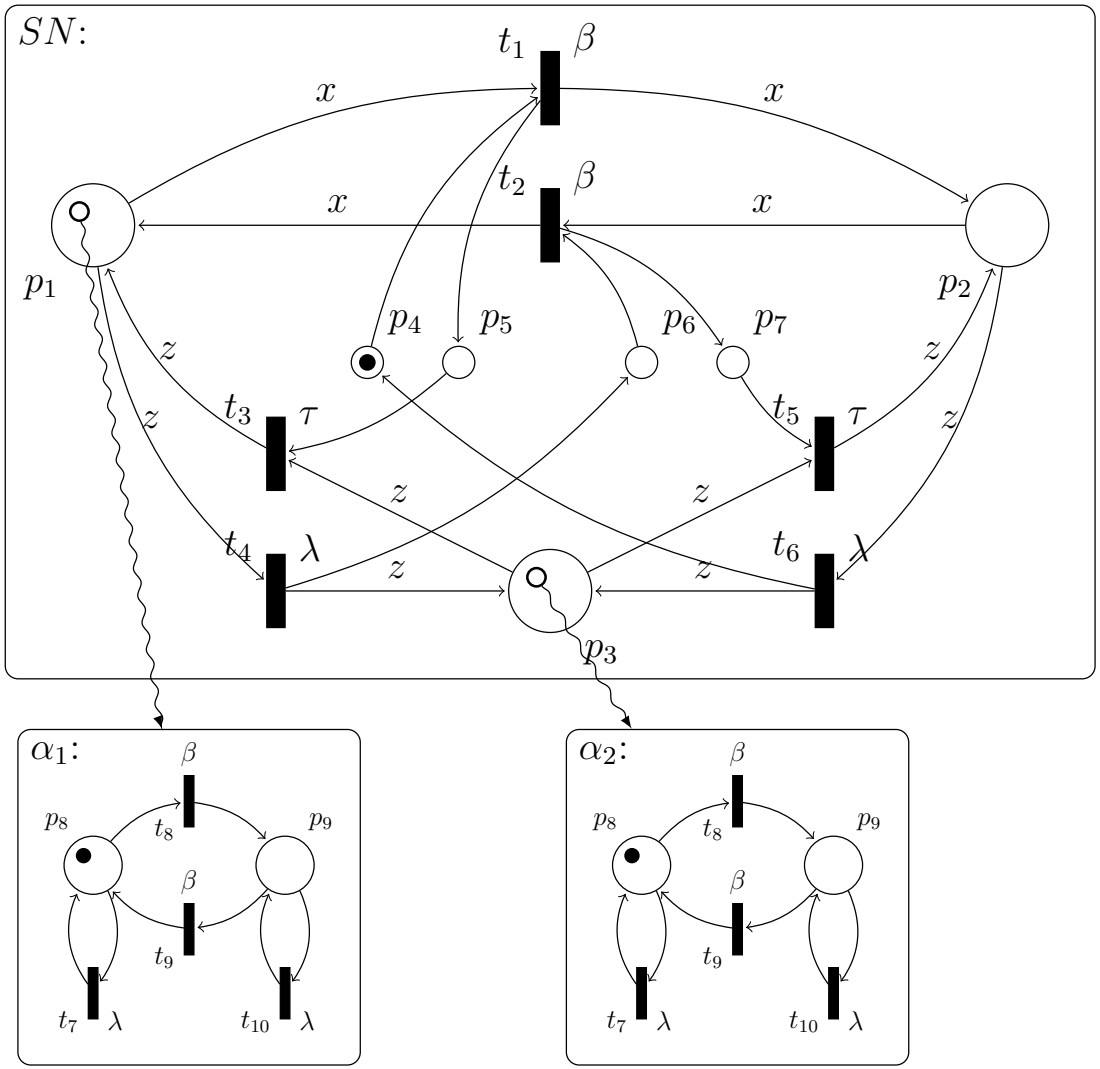
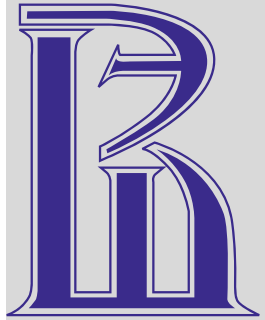


Figure : An NP-net — a caught sample.

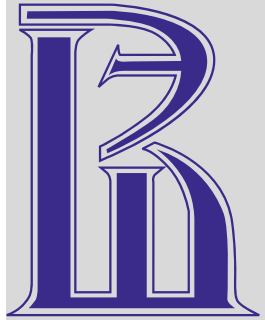
Whats the Plan?

- **Prerequisites of NP-nets**
- Ostensive definition of NP-nets: Simple model of P2P protocol
- Formal definition of NP-nets
- Need for analysis methods
- Compositionality of NP-net properties
- Technical achievements
- Ongoing research
- Conclusions and further directions



Prerequisites of NP-nets

- Via NP-nets we can model/execute adaptive workflow nets and handle exceptions. For details:
  K. M. van Hee, I. A. Lomazova, O. Oanea, A. Serebrenik, N. Sidorova, M. Voorhoeve: *Nested Nets for Adaptive Systems*. ICATPN 2006: 241-260
- "Flat" Petri nets is an inconvenient tool to model systems with distributed agents
  - **P2P protocols**: system net (SN) — orchestration protocol, tokens — peers with protocols implementations (cf. L. Dworzanski, I.A.Lomazova, PSSV'11);
  - **Wireless sensor networks**: SN — physical topology and orchestration protocol, tokens — sensors (cf. N. Buchina paper);
  - **Social systems**: SN — software process, tokens — stuff (developers, testers, project managers et cetera) (A. Phillipov model).
  - **Swarm systems**: SN — orchestration protocol, tokens — attacking drones (D. Frumin model),
  - other applications: unix daemons, mobile code, mobile robot system etc.



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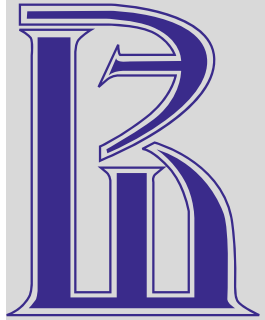
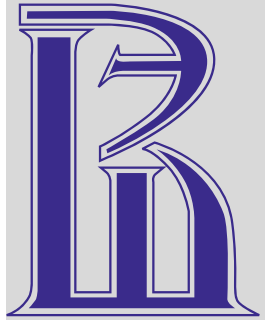


Case study: P2P protocol

P2P protocol (system) consists of the participants of three kinds

- Seeds — sources of datum;
- Peers — consumers of datum;
- Tracking server — coordinator of seeds and peers interaction.



Seed

A **seed** is a source of data. In the initial state it waits for a request from a peer to upload the data to the peer. Then it clears its upload buffer and returns to the initial state.

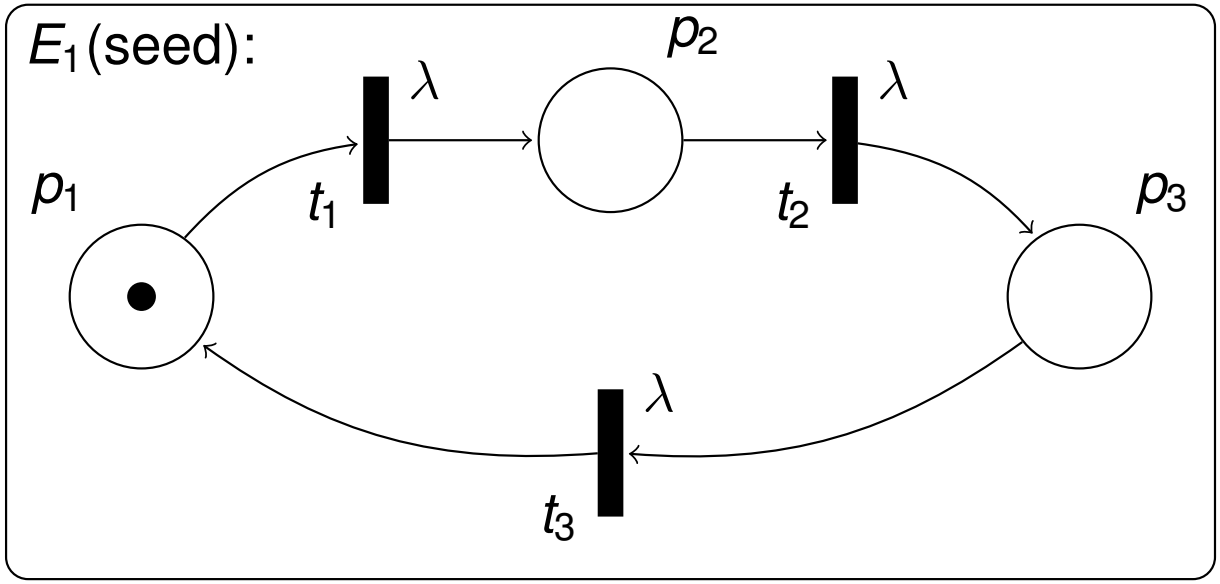
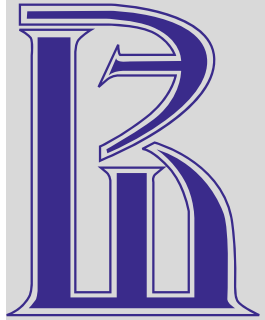


Figure : Seed net.



Peer

A **peer** is just a consumer of data. In the initial state it waits for a seed with a piece of datum. Then it downloads the data and returns to the initial state.

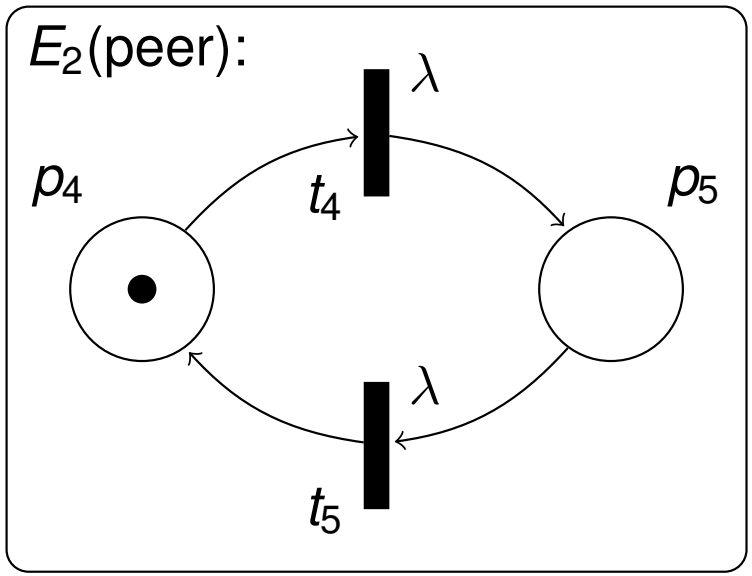


Figure : Peer net.

Tracking server

A **tracking server** is a coordinator of the seeds and peers interaction. It has the pools for ready-to-transmit peers and seeds and the pool for reinitializing seeds.

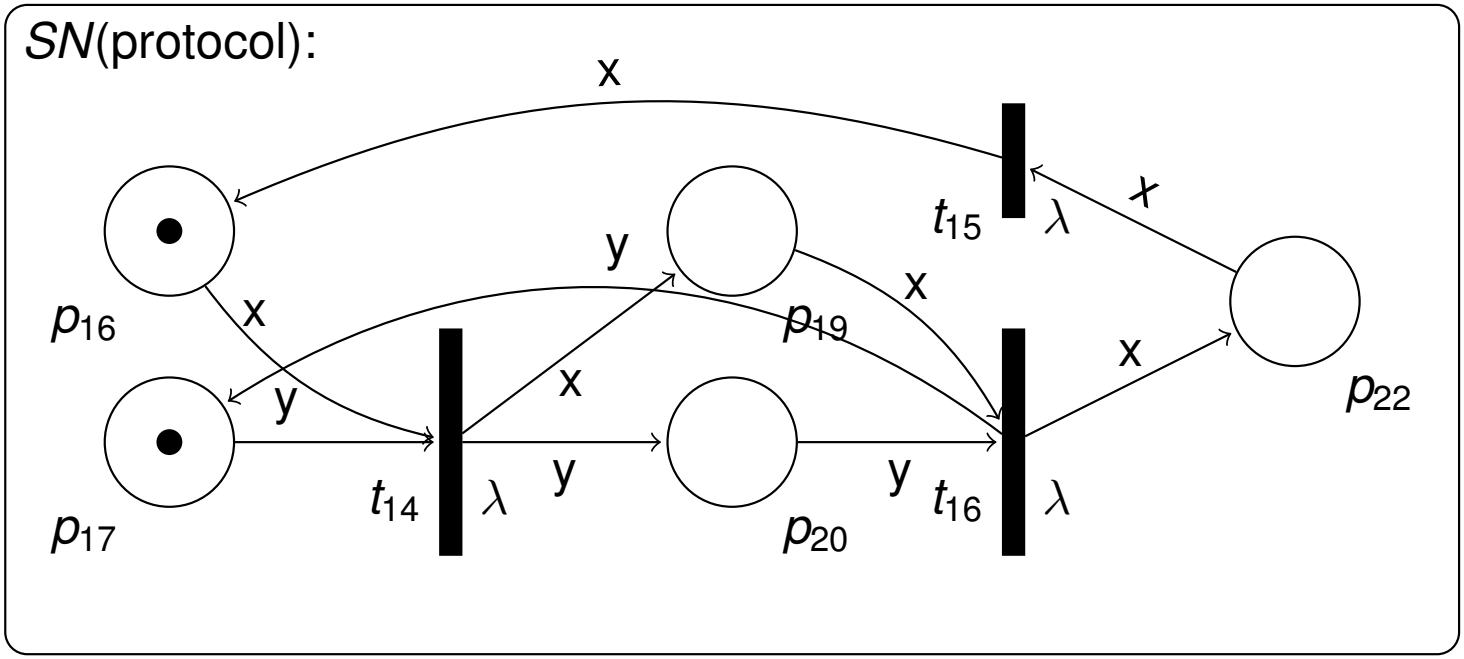


Figure : Tracking server.

Pipe

Tracking server coordinates such interactions by introducing a new entity — **pipe**. In the initial state a pipe waits for a seed and a peer, then it coordinates their interaction. Then the pipe reinitializates its internal buffers and returns to the initial state. A pipe can handle such aspects of a transmition as security, reliability, anonimousity etc.

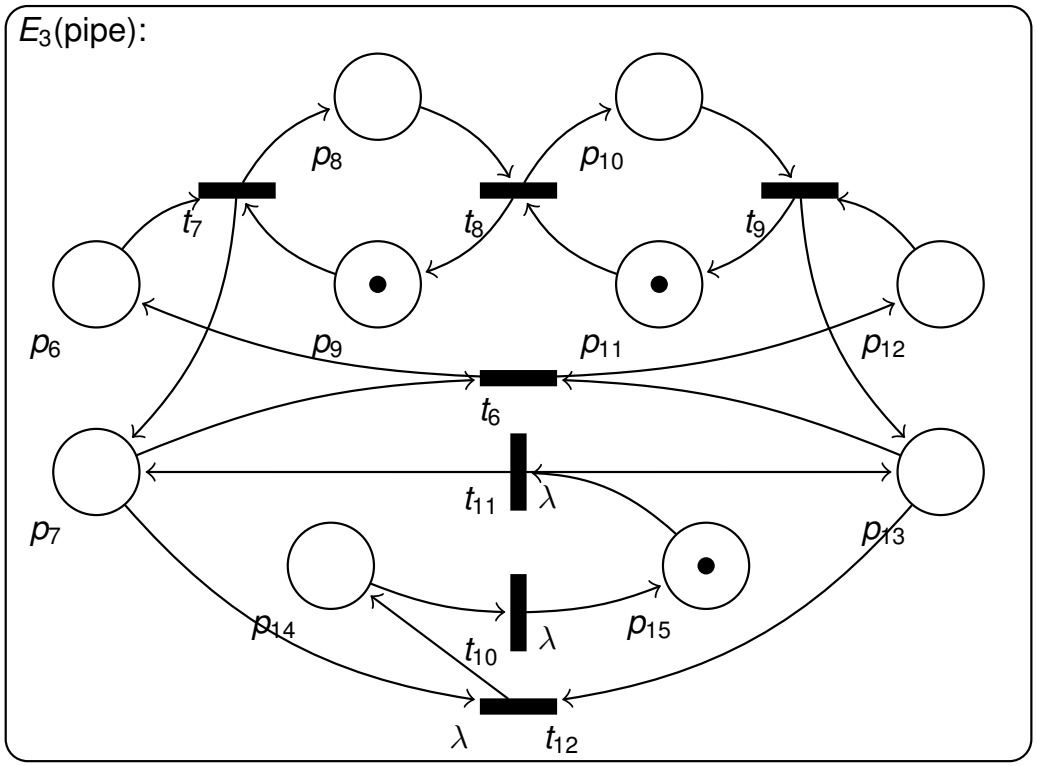
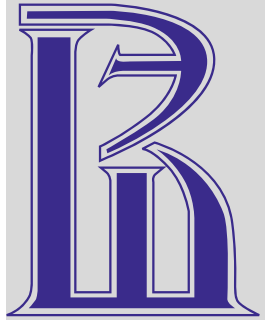


Figure : Pipe net.



Tracking server

Returning to our tracking server. There are no pipes.

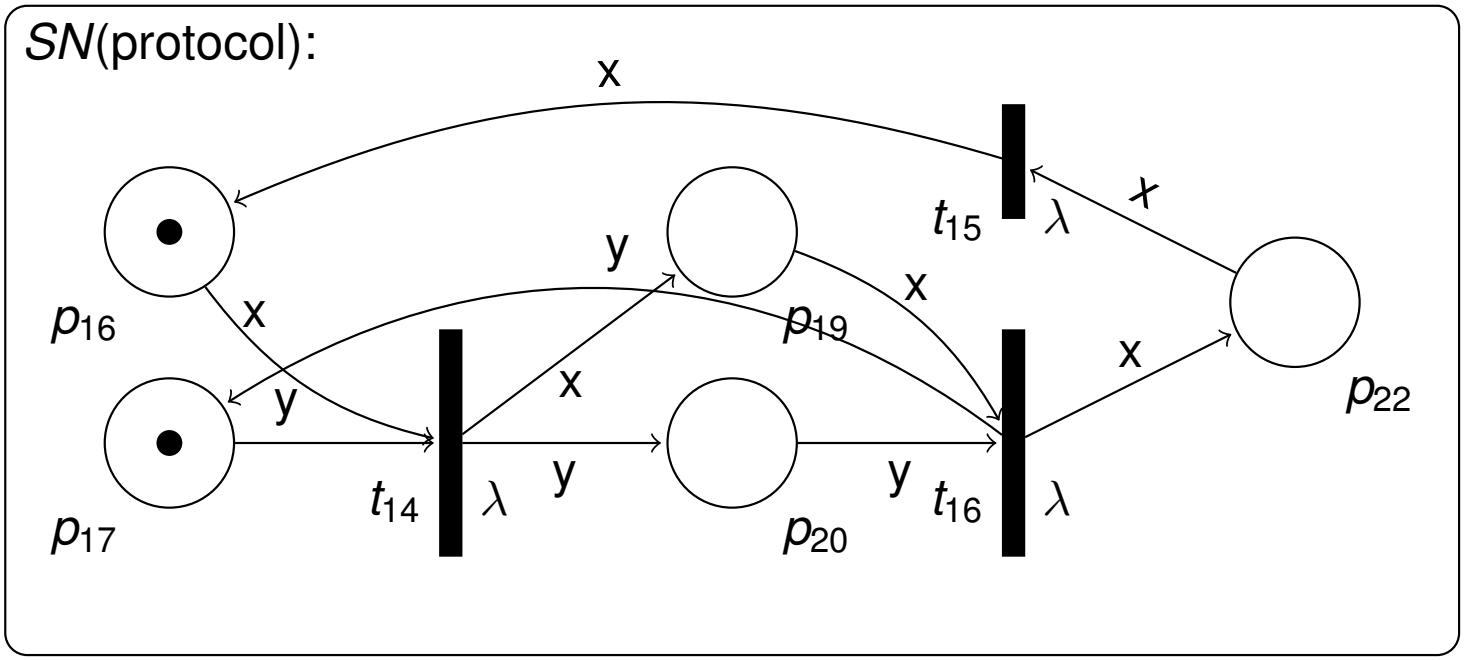


Figure : Tracking server.

Tracking server

But we can add them.

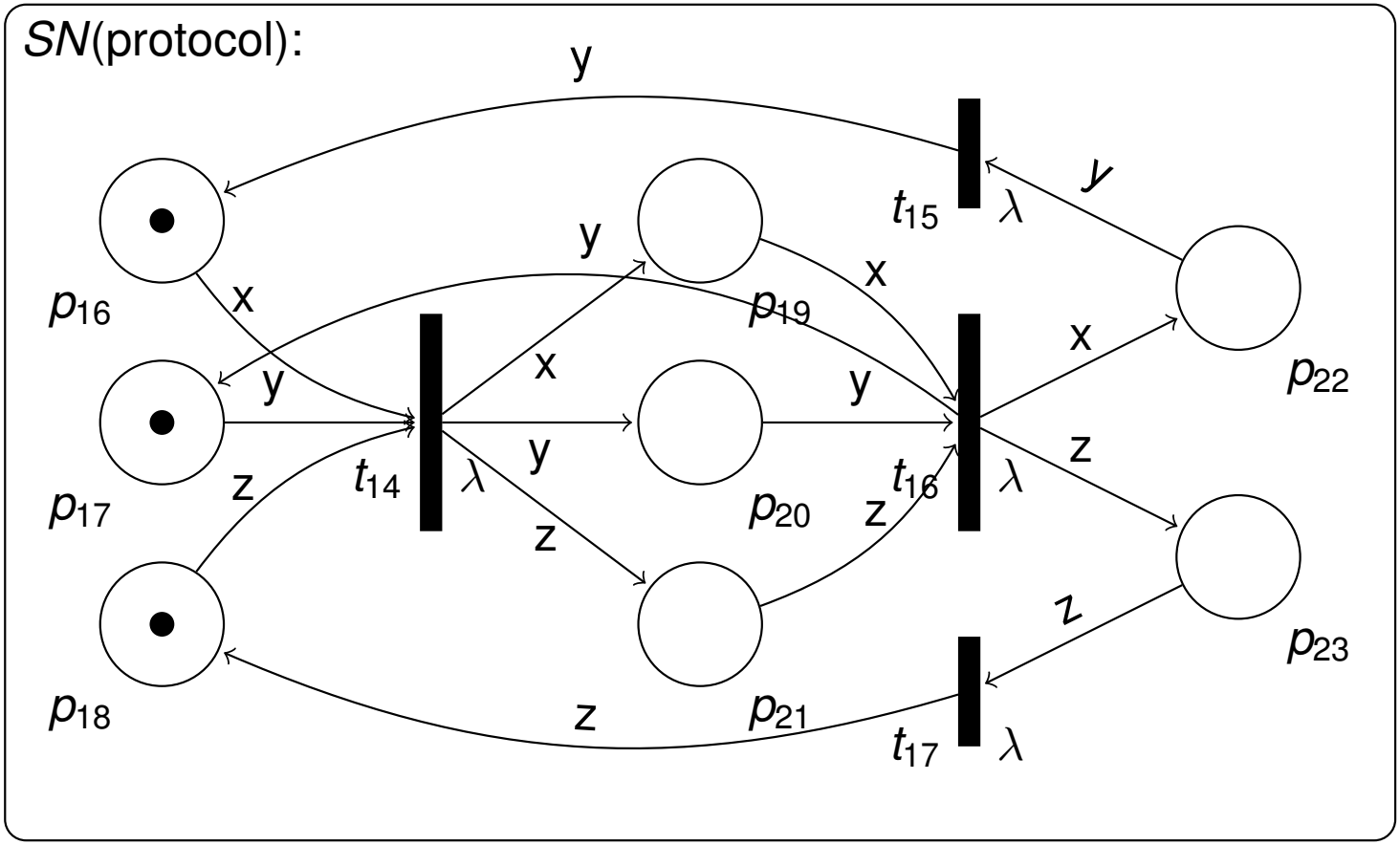
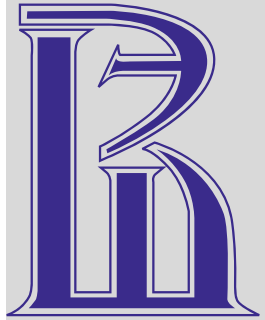
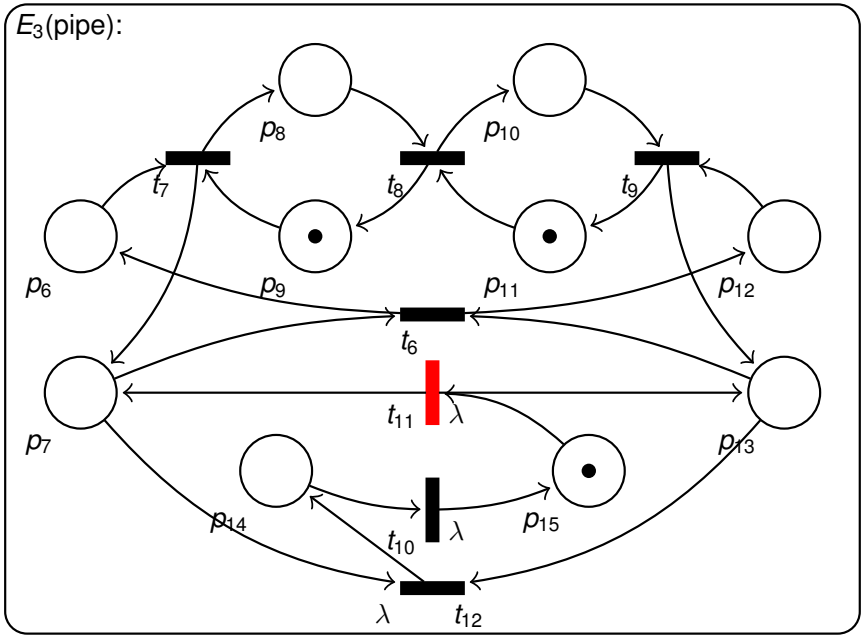
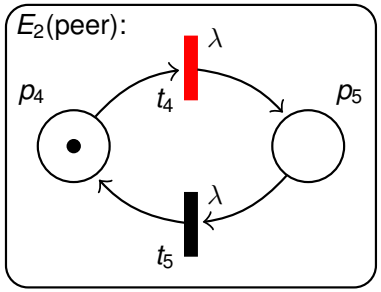


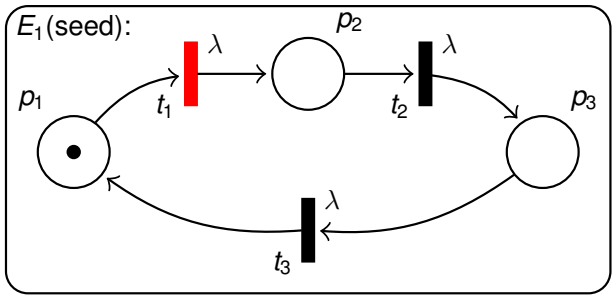
Figure : Tracking server.

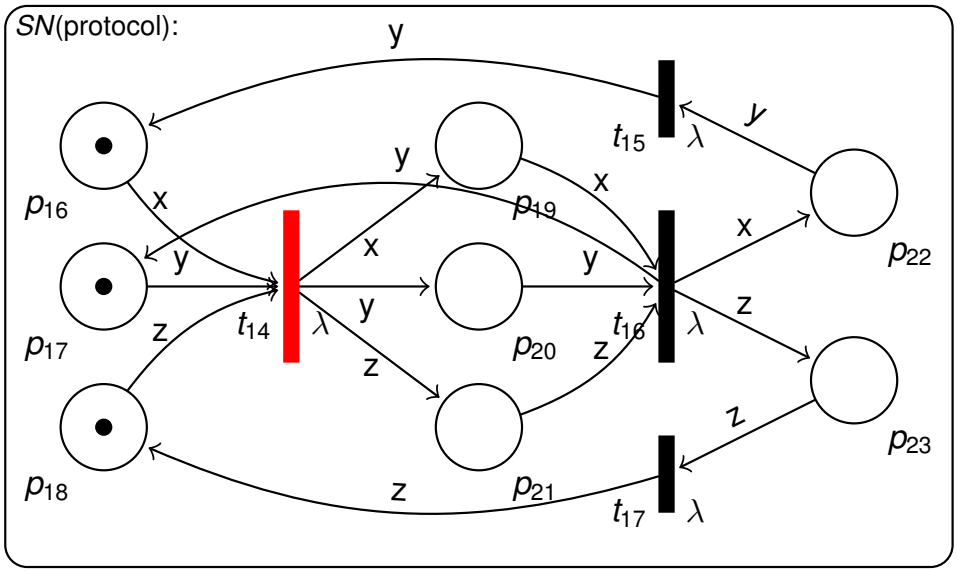


The whole picture

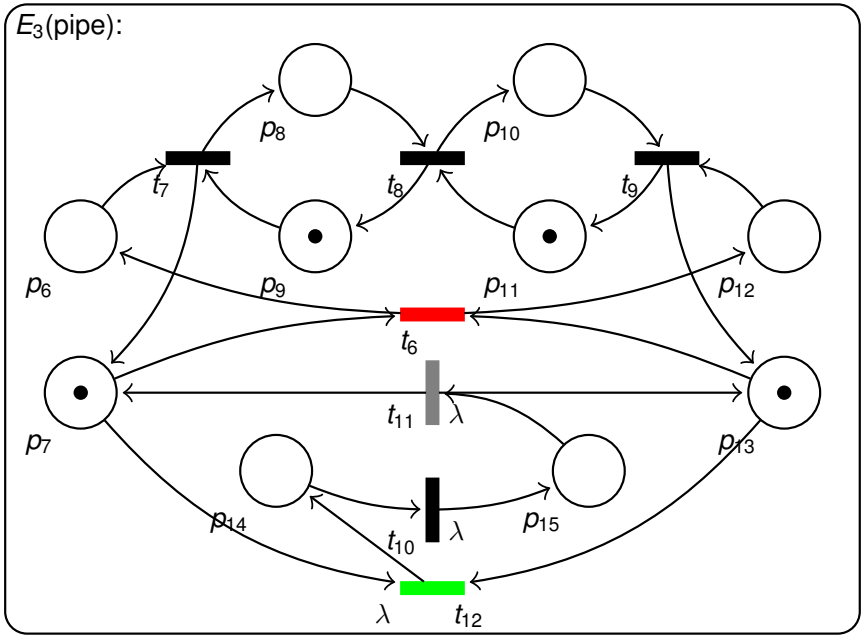


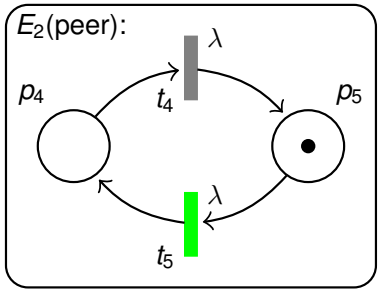


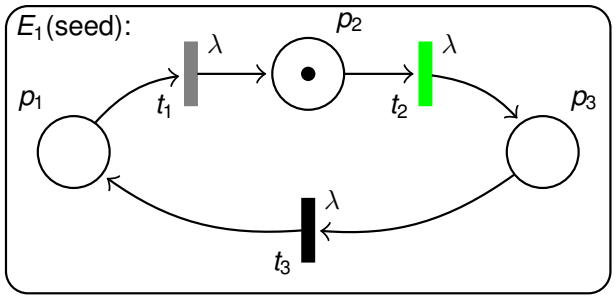


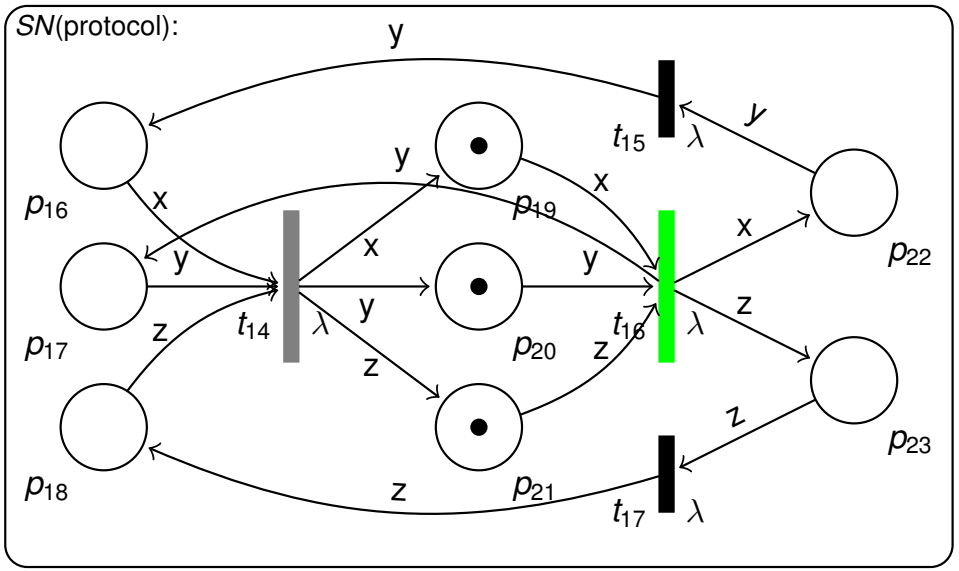


NP-net









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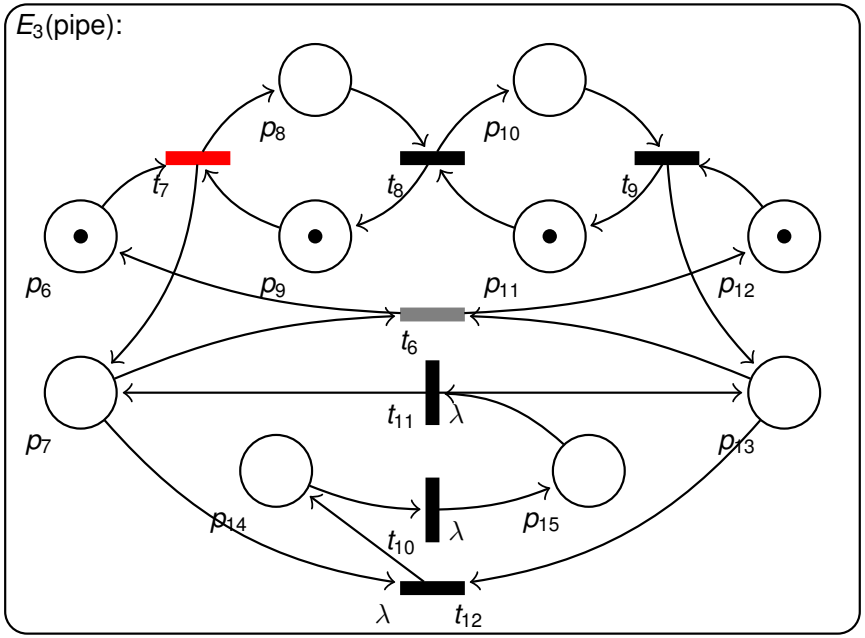

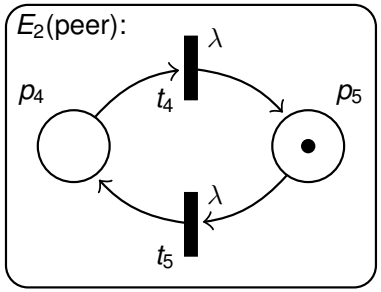

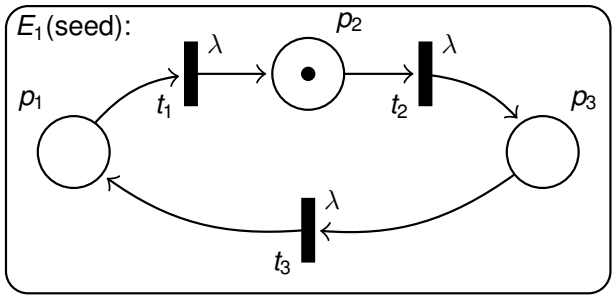

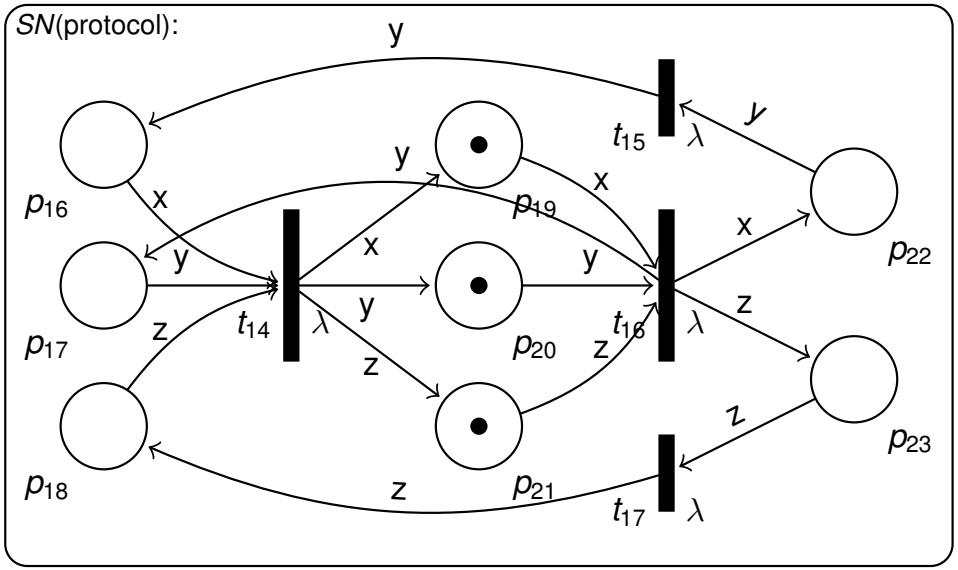

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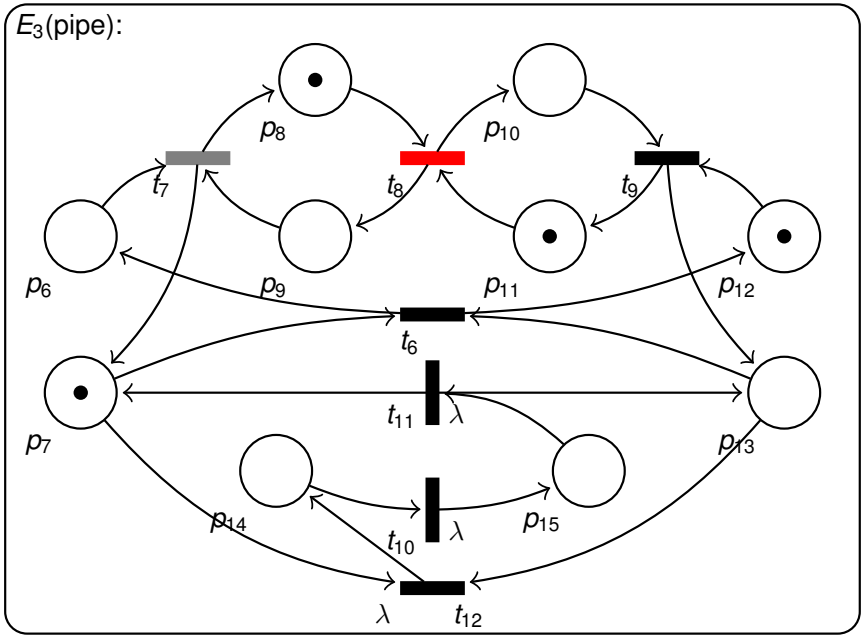

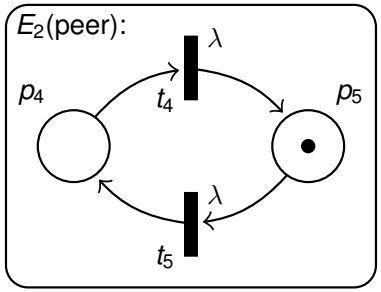

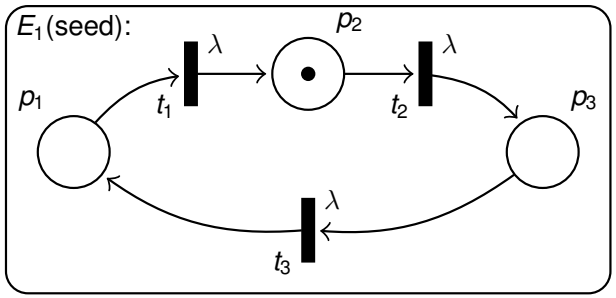

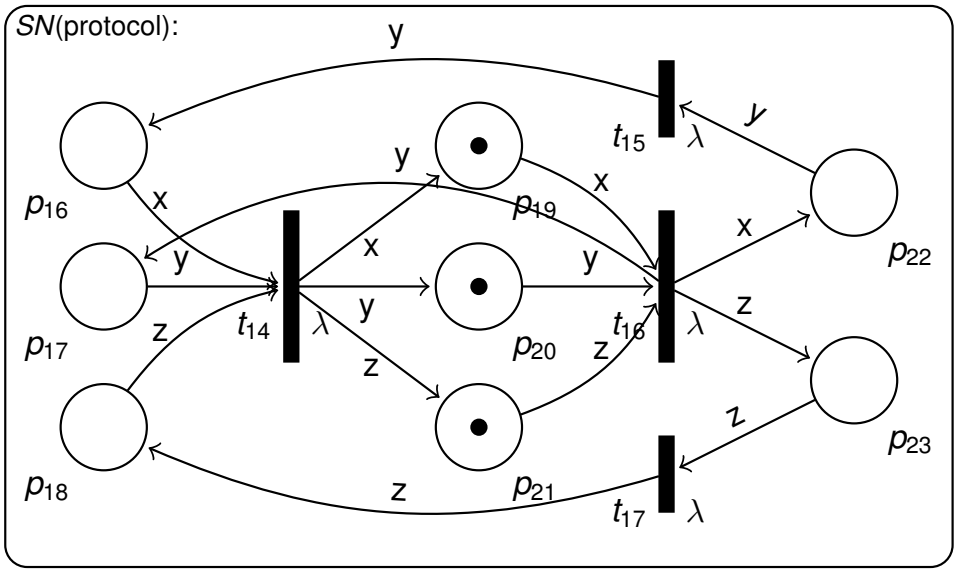

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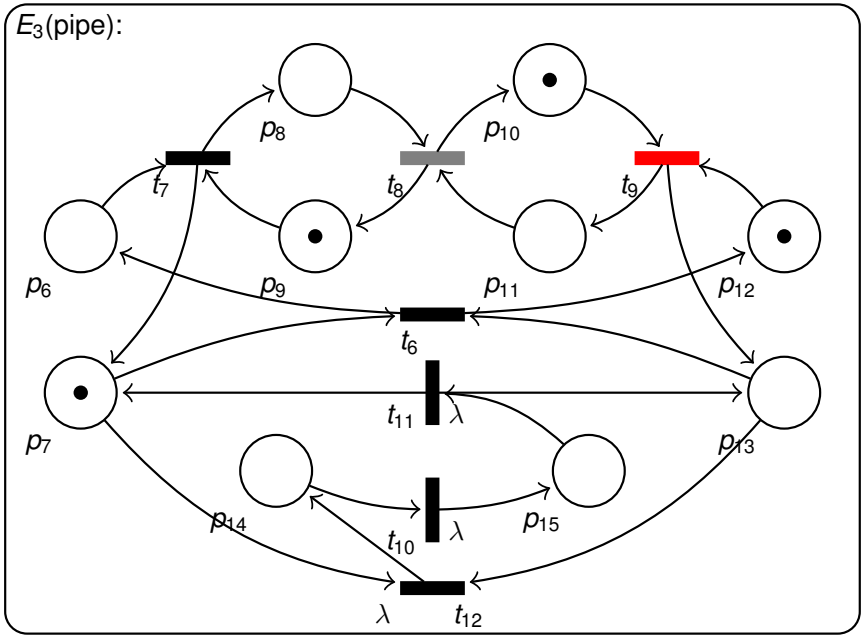

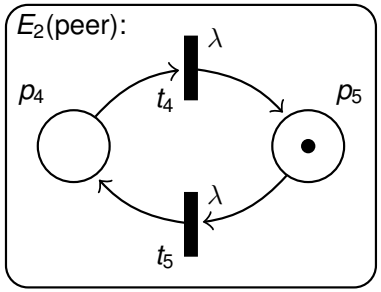

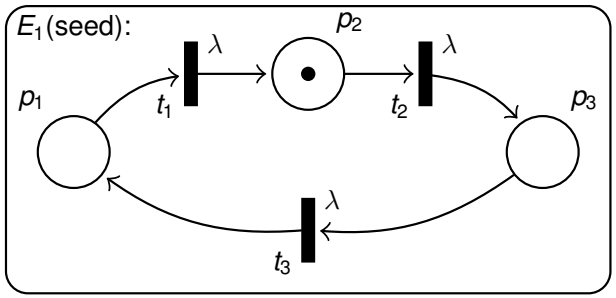

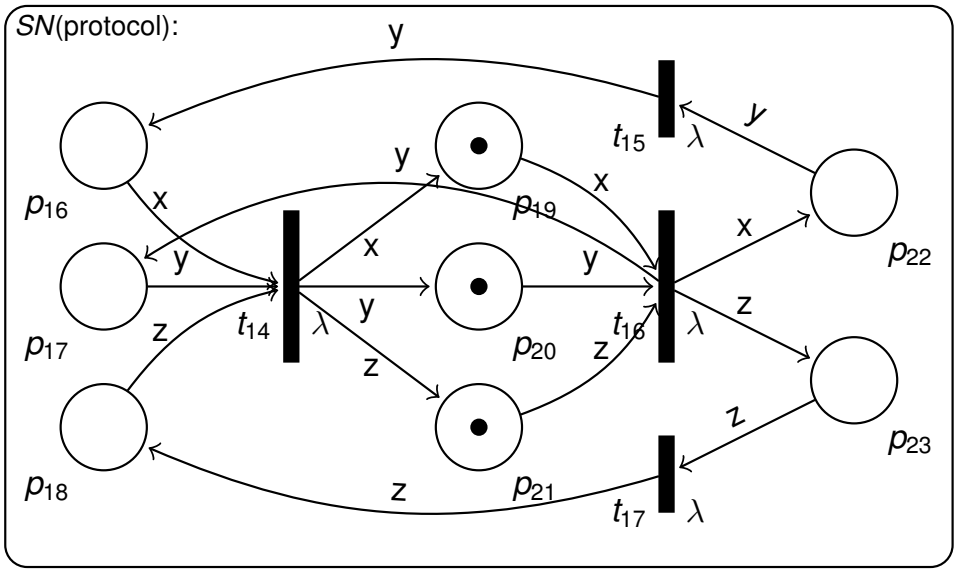

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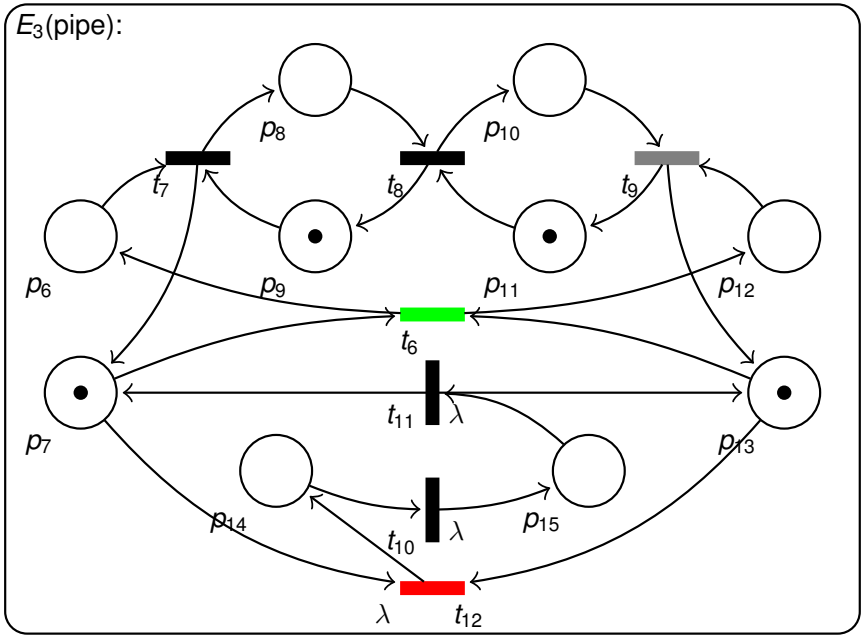

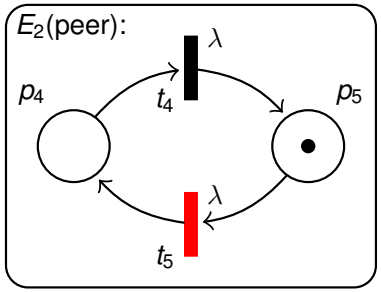

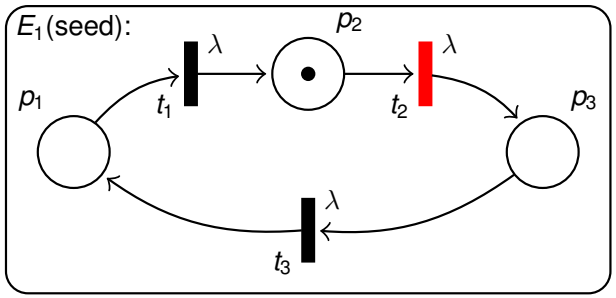

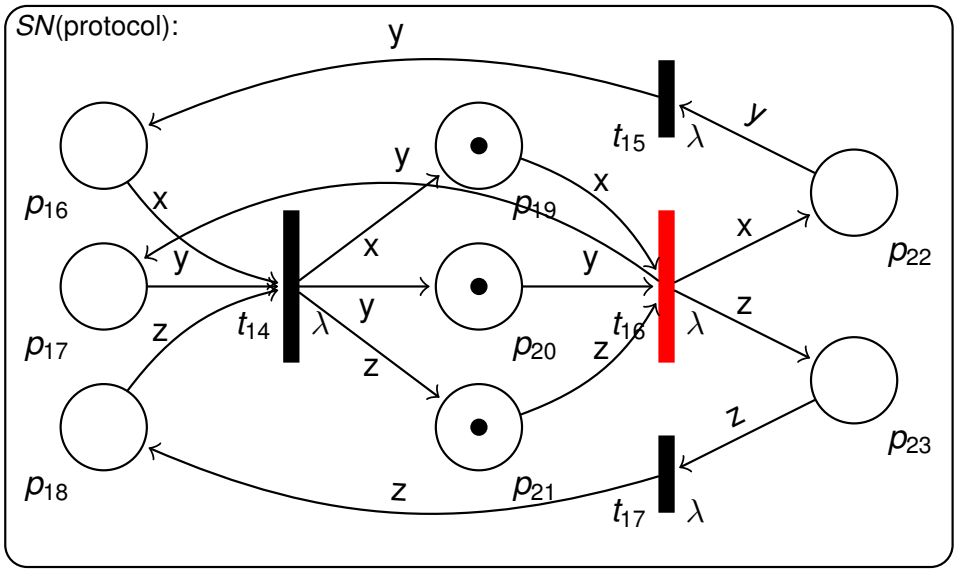

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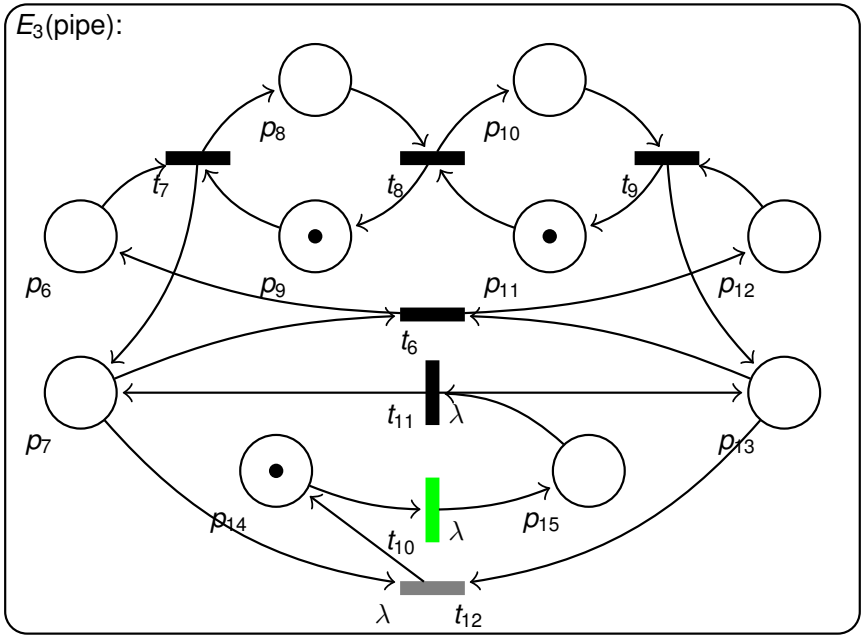

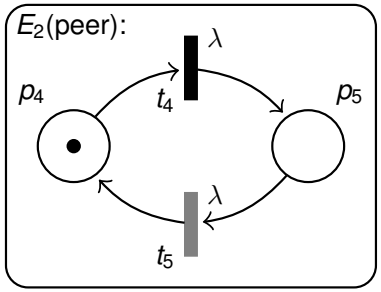

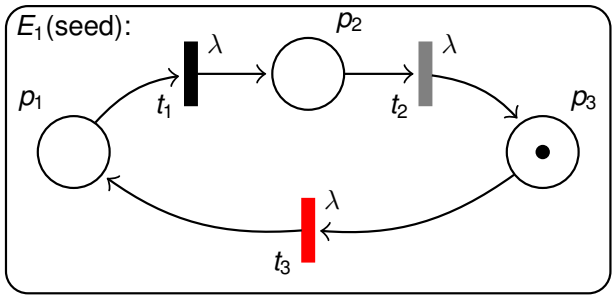

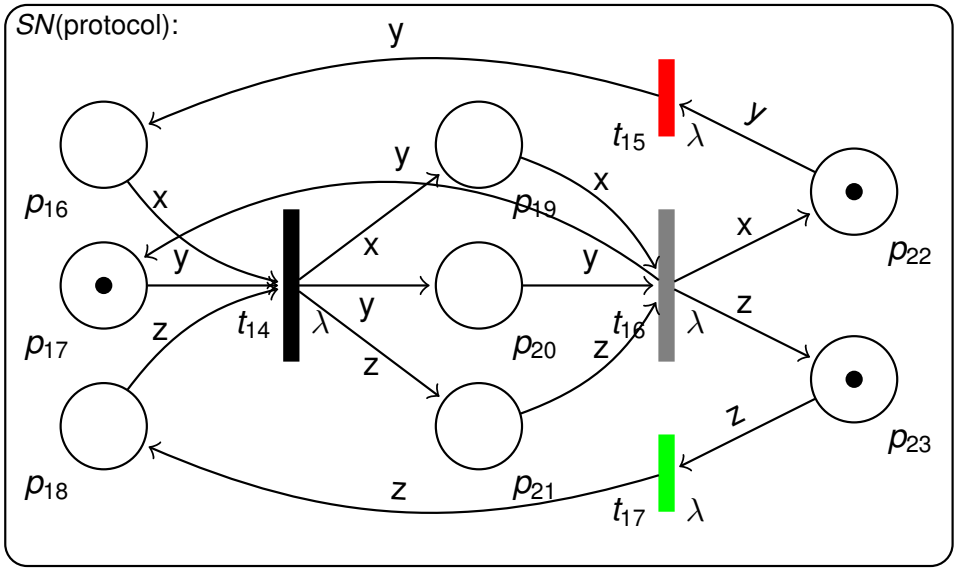

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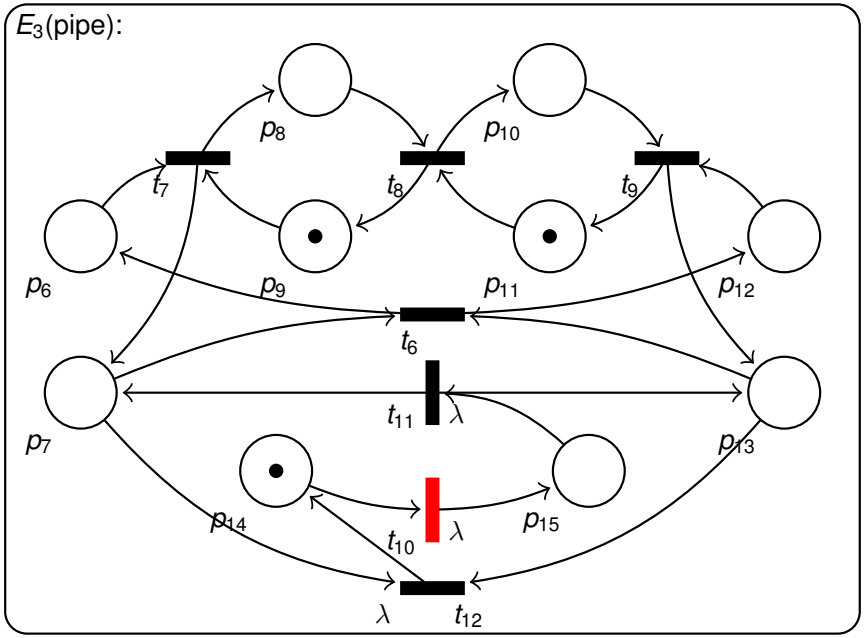

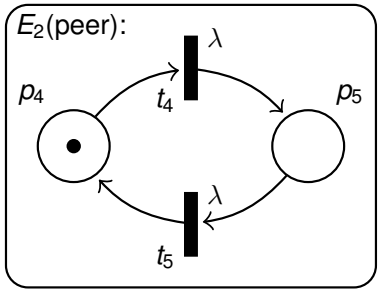

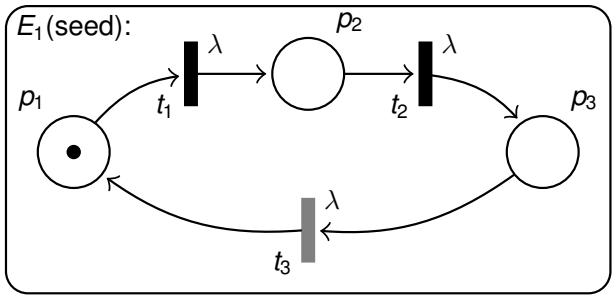

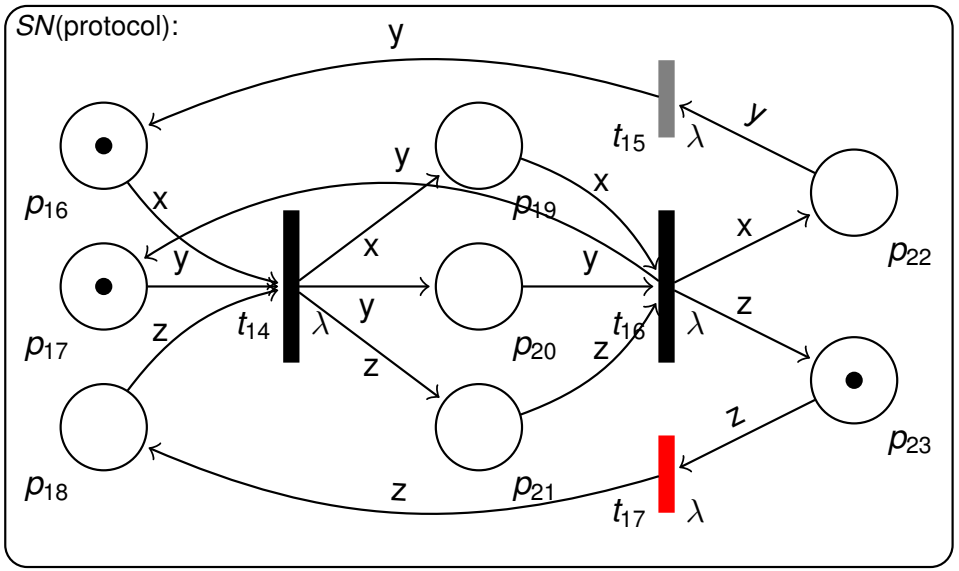

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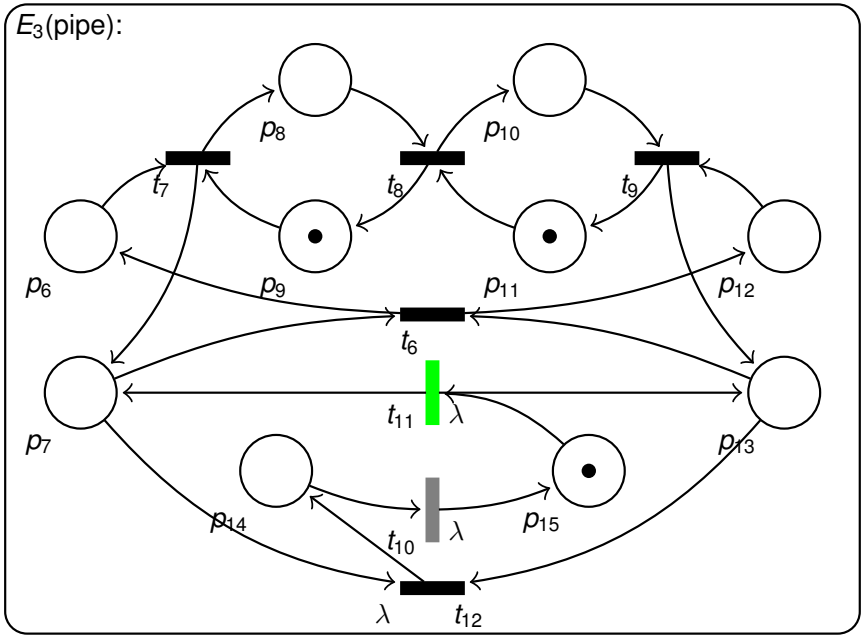
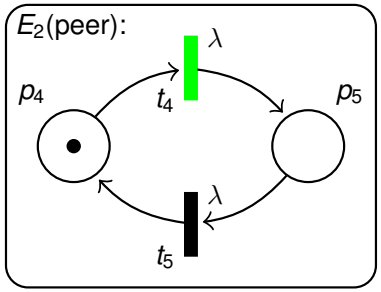
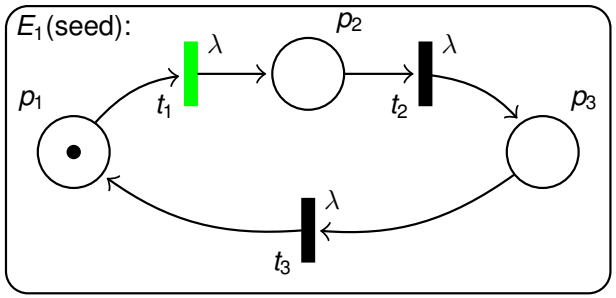
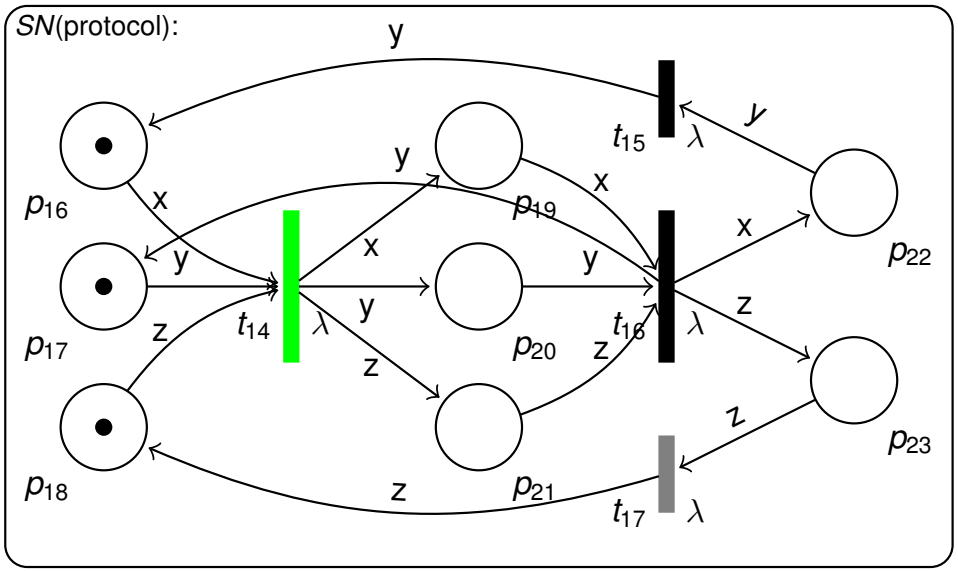
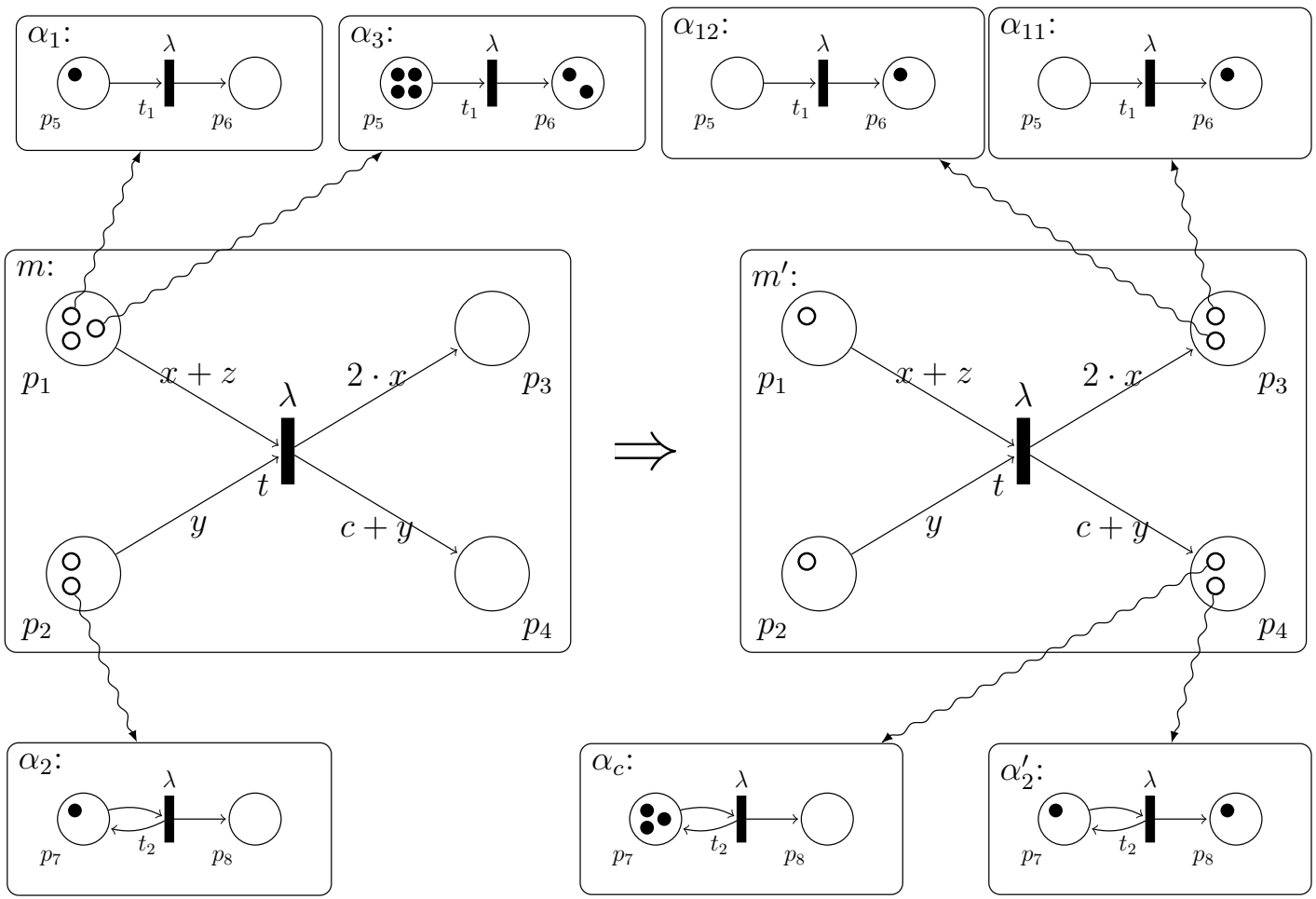








NP-net: net constants, net token elimination



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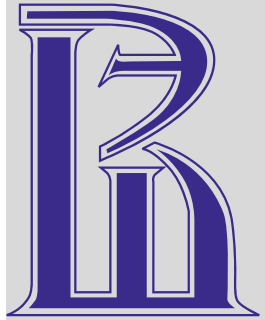
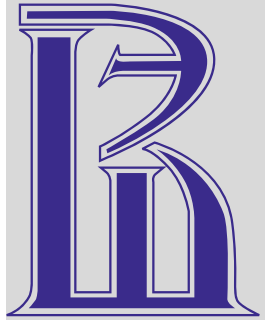


NP-net

Definition

Two-level NP-net is a tuple
$NP = \langle Lab, SN, \mathbb{E} \rangle$ where

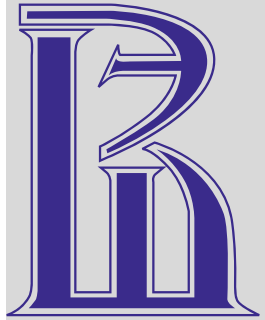
- Lab — set of labels for synchronization of transitions;
- SN — system net of the NP-net;
- $\mathbb{E}$ – finite set of element nets.



Definition

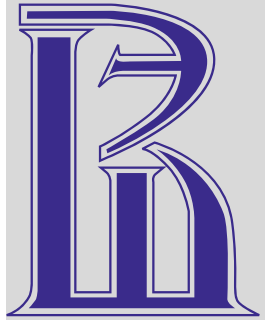
System net is a tuple
$SN = \langle N, \mathcal{L}, \mathcal{U}, W, m_0 \rangle$ where

- $N = \langle P_{SN}, T_{SN}, F_{SN} \rangle$ — high-level PN of System net;
- P_{SN} — set of typed places;
- $\mathcal{L} = Expr$ — arc expression language (sums of constants and variables);
- $\mathcal{U} = \langle A, \mathcal{I} \rangle$ — model of $\mathcal{L}$ with domain $A = A_{net} \cup A_{atom}$;
- A_{net} – set of marked element nets (net tokens);
- A_{atom} — set of plain colored tokens;
- $\mathcal{I} : Con \to A$ — interpretation function;
- $W : F_{SN} \to \mathcal{L}$ — arc expression function;
- $\Lambda : T_{SN} \to Lab$ — transition labeling function.



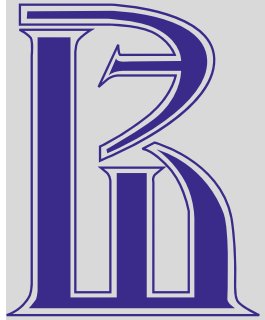
Restrictions

1. constants or multiple instances of the same variable are not allowed in input arc expressions of t;
2. each variable in an output arc expression for t occurs in one of the input arc expressions of t.



Whats the Plan?

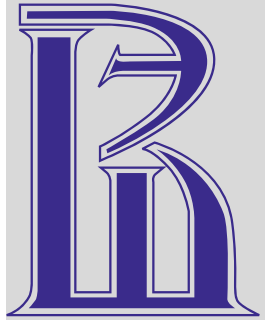
- Prerequisites of NP-nets
- Ostensive definition of NP-nets: Simple model of P2P protocol
- Formal definition of NP-nets
- **Need for analysis methods**
- Compositionality of NP-net properties
- Technical achievements
- Ongoing research
- Conclusions and further directions



Need for analysis methods

Common sense:

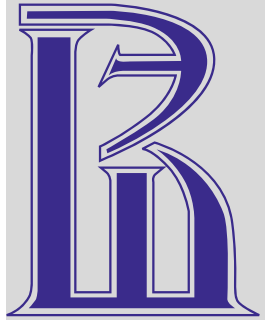
- Vertical synchronization, additional levels, net tokens creation and destruction, net tokens constants;
- Distributed concurrent systems are complex and non-tractable for human understanding;
- Distributed concurrent systems with dynamical hierarchical structure are even more complex;



Need for analysis methods

Theoretical issues:

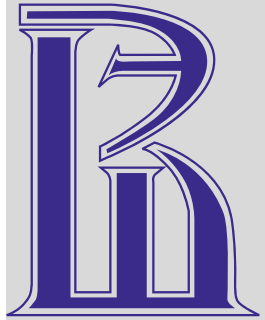
- Covering problem is decidable



Need for analysis methods

Theoretical issues:

- Covering problem is decidable
- NP-nets strictly more expressive than Petri nets
- It is possible to model Petri nets w/ reset arcs via NP-nets so...



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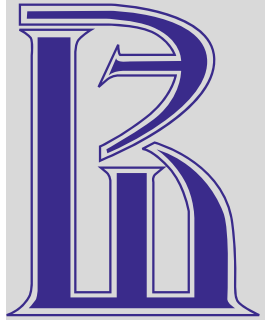
- Reachability is undecidable
- Liveness is undecidable



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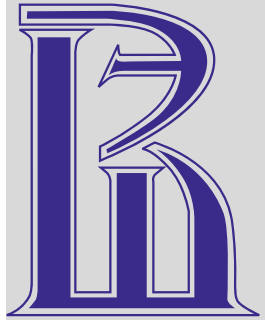
What can we do?



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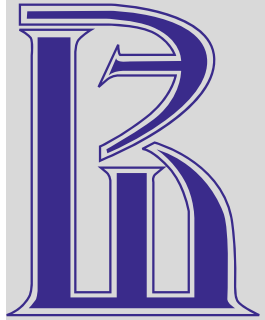


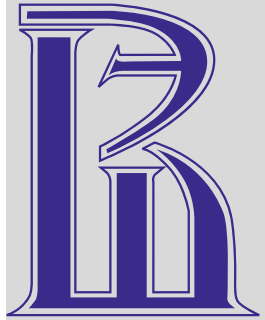
Compositionality and modularity

Modularity allows

- describe system's components independently.

Compositionality enables

- derive system properties from properties of its components;
- reuse components' analysis results for systems with same components (library of verified components);

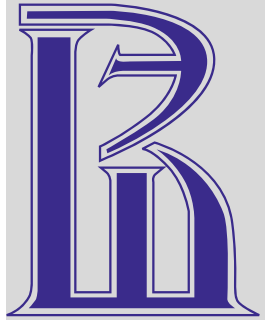


Compositionality and modularity

Prof. Joseph Sifakis, *A Dialogue with Professor Joseph Sifakis about Concurrent Systems Specification and Verification*, Bulletin of the European Association for Theoretical Computer Science, 104, 2011

We need theory, models and tools for cost-effectively building complex systems by assembling heterogeneous components

- *As system synthesis from requirements is intractable for complex systems, we should study principles for building correct systems from components. The aim is to avoid a posteriori monolithic verification as much as possible*;



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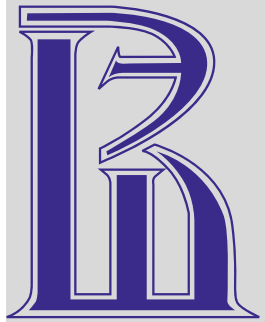

Compositionality and modularity

Prof. Joseph Sifakis, *A Dialogue with Professor Joseph Sifakis about Concurrent Systems Specification and Verification* (contd.),

- *(Complexity problem) As system synthesis from requirements is intractable for complex systems, we should study principles for building correct systems from components. The aim is to avoid a posteriori monolithic verification as much as possible*;
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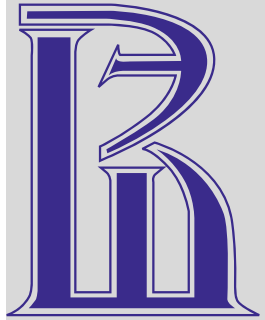

Compositionality and modularity

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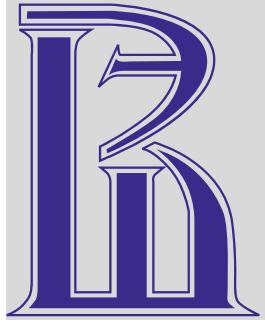
- *Compositionality rules for inferring global properties of composite components from the properties of constituent components e.g. the composition of deadlock-free components is - under some conditions - a deadlock-free component*;



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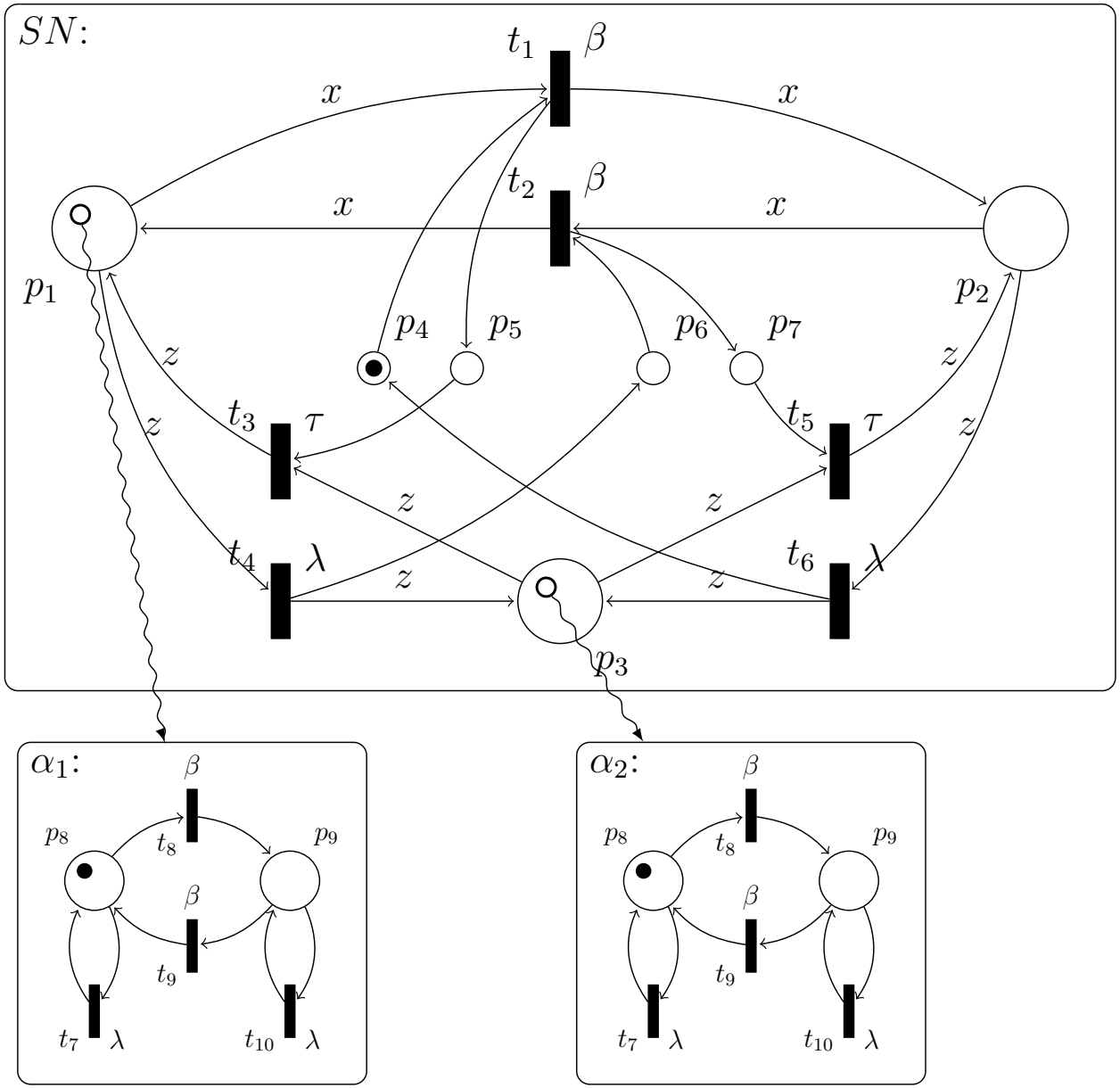

Compositionality and modularity

Compositionality rules for inferring global properties of composite components from the properties of constituent components e.g. the composition of deadlock-free components is - under some conditions - a deadlock-free component.

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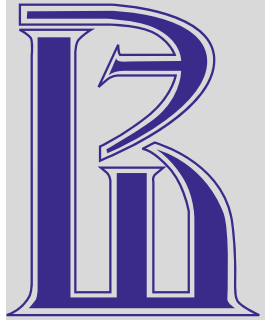

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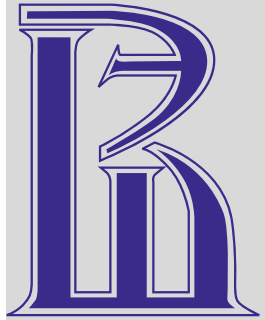

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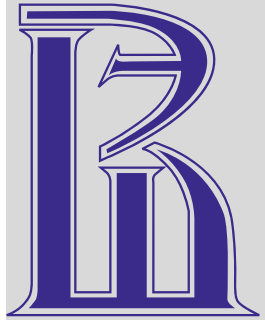

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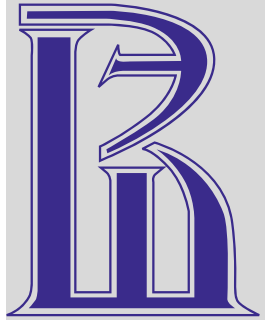

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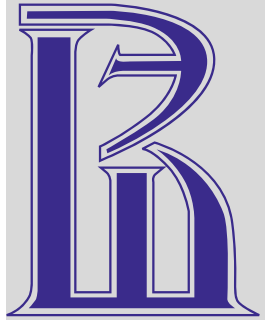

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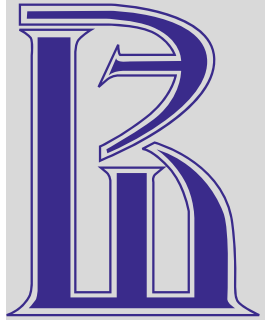
- Some structural/behavioural conditions are satisfied



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- The components of *N* satisfy some property;
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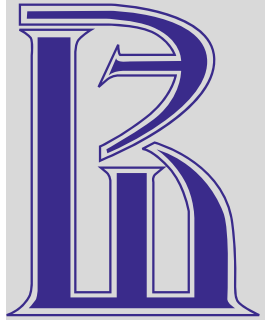
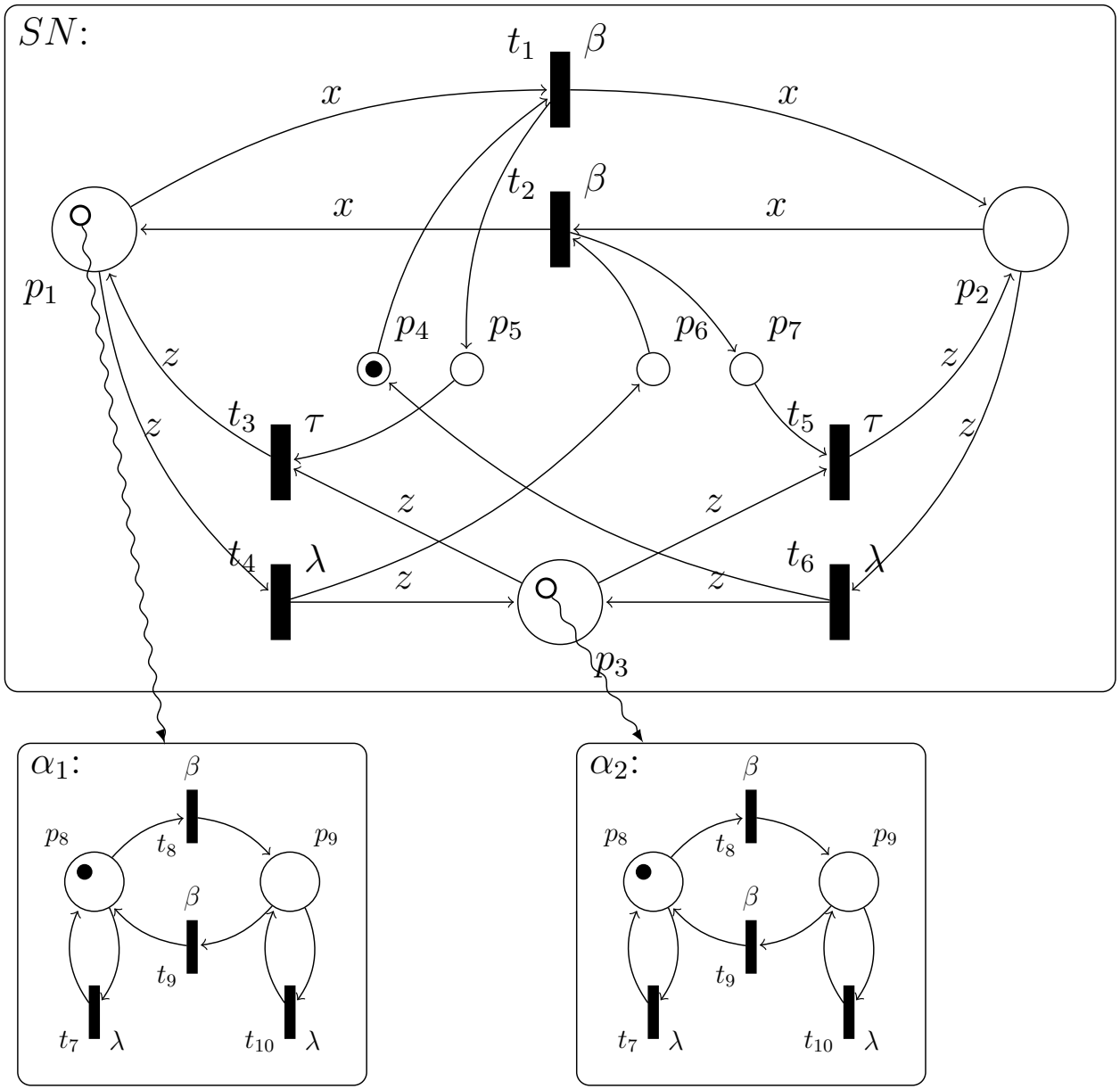
- The whole NP-net *N* satisfies some property.



Compositionality and modularity



Boundedness compositionality

Definition

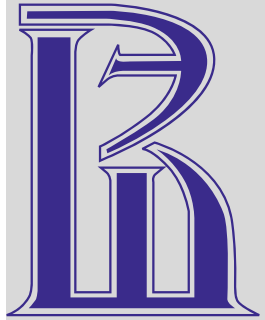
Marked NP-net *NP* is *bounded* iff its reachability set $R_{NP}(m_0)$ is finite.

Theorem

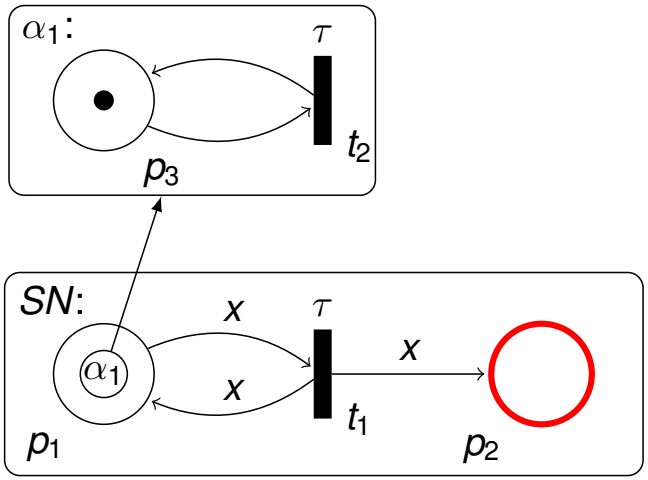
Let NP be a marked NP-net. If

1. *the system net in NP is bounded (as a separate component, i.e. a flat PN)*
2. *all net tokens in the initial marking are bounded (as separate components)*
3. *all net constants in arc expressions in NP are bounded (as separate components)*

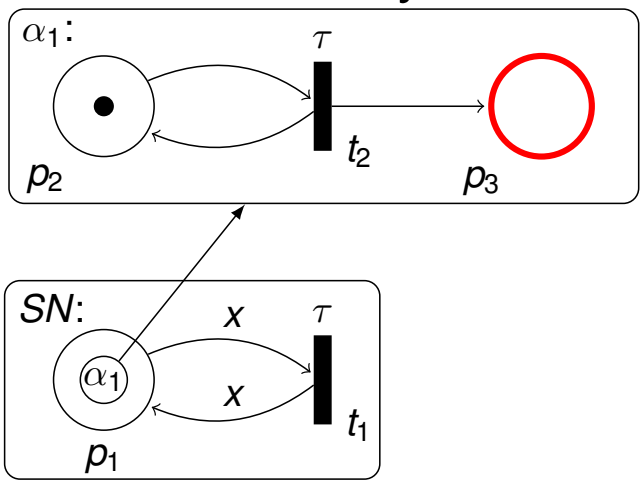
then NP is bounded.



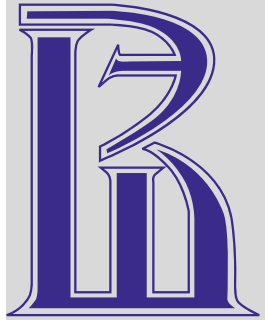
Counterexamples for boundedness (1)



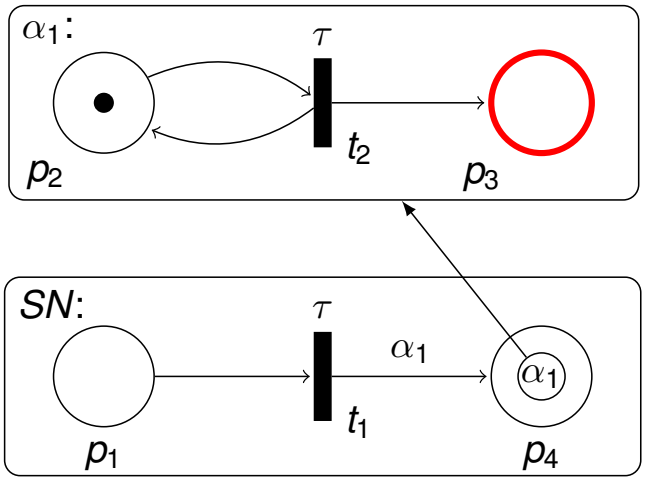
Condition: “the system net in *NP* is bounded”



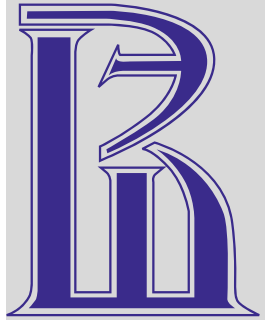
Condition: “all net tokens in the initial marking are bounded”



Counterexamples for boundedness (2)



Condition: all net constants in arc expressions are bounded”



Single label case: Liveness compositionality (0L-live)

Definition

Let *NP* be a marked two-level NP-net. *NP* is called 0L-live iff every transition in its system net is live.

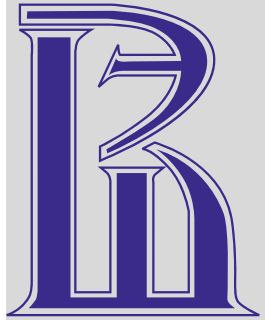
Theorem

Let NP be a marked two-level NP-net. Let also NP satisfy the following conditions:

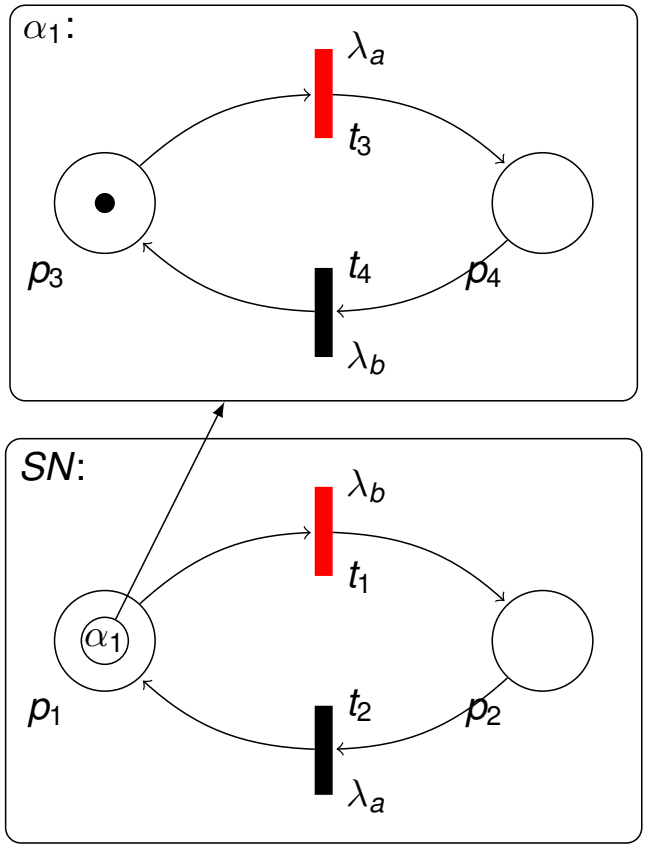
1. *the system net in NP is live (as a separate component, i.e. a flat PN);*
2. *all net tokens in the initial marking and all net constants in every arc expression are live (as separate components);*
3. *NP has only one label of vertical synchronization λ;*
4. *if t is a system net transition in NP labeled with λ, then for any $p \in {}^\bullet t$ the type of p is an element net, containing a transition labeled with λ.*

Then NP is 0L-live.

1,2 — counterexamples are similiar to boundedness property,
3,4 — counterexamples are given below

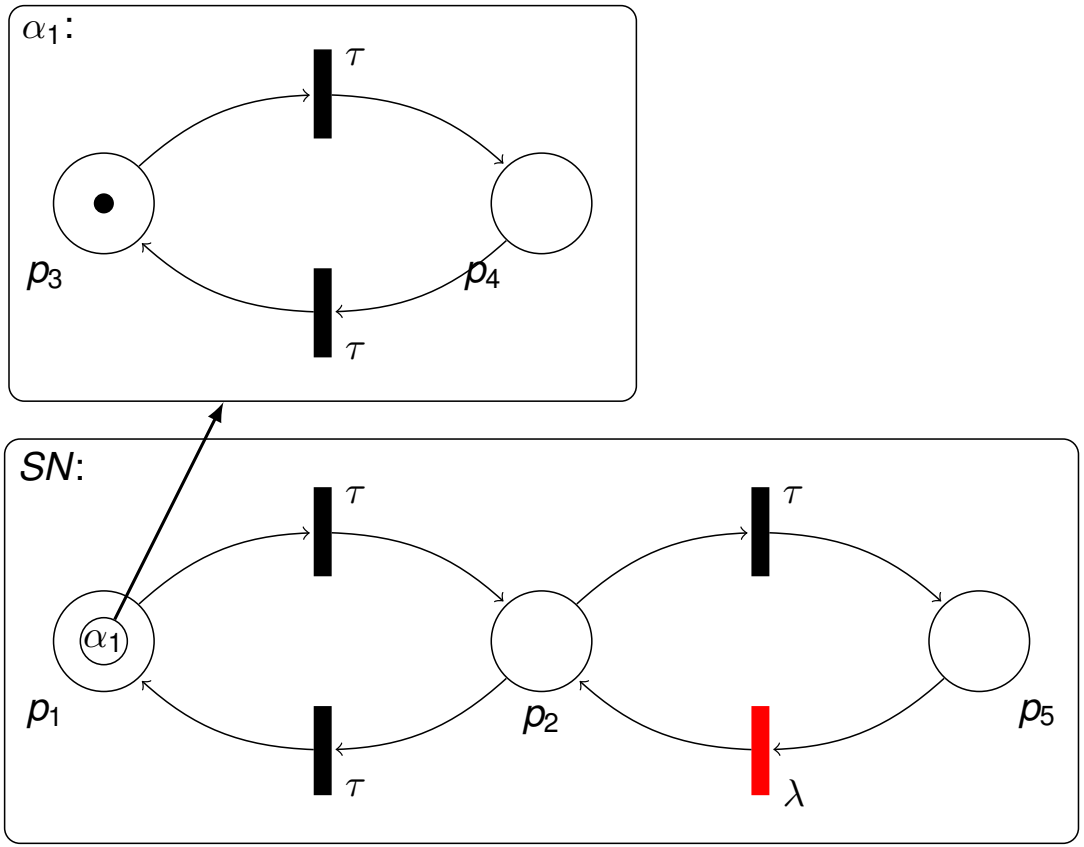


Counterexamples for 0L-liveness (1)



Condition: "*NP* has only one label of vertical synchronization λ".

Counterexamples for 0L-liveness (2)



Condition: “if t is a system net transition labeled with λ, then for any $p \in {}^\bullet t$ the type of p is an element net, containing a transition labeled with λ”.

Single label case: Liveness compositionality (1L-live) (1)

Definition

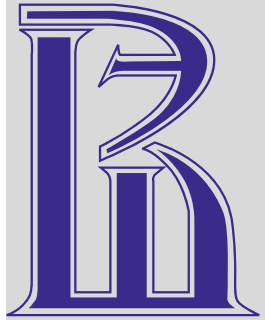
Let *NP* be a marked NP-net. *NP* is said to be 1L-live iff every transition of its system net and every transition in each net token from the initial marking in *NP* are live.

Theorem

Let NP be a marked NP-net.

1. *the system net in NP is live (as a separate component);*
2. *all net tokens in the initial marking and all net constants in every arc expression are live (as separate components);*
3. *NP has only one label for vertical synchronization λ;*
4. *if t is a system net transition in NP labeled by λ, then for any $p \in {}^\bullet t$ an element net corresponding to p contains a transition labeled with λ;*
5. *NP is conservative (on the next slide)*
6. *each SCC of the system net contains at least one transition labeled with λ.*

Then NP is 1L-live.

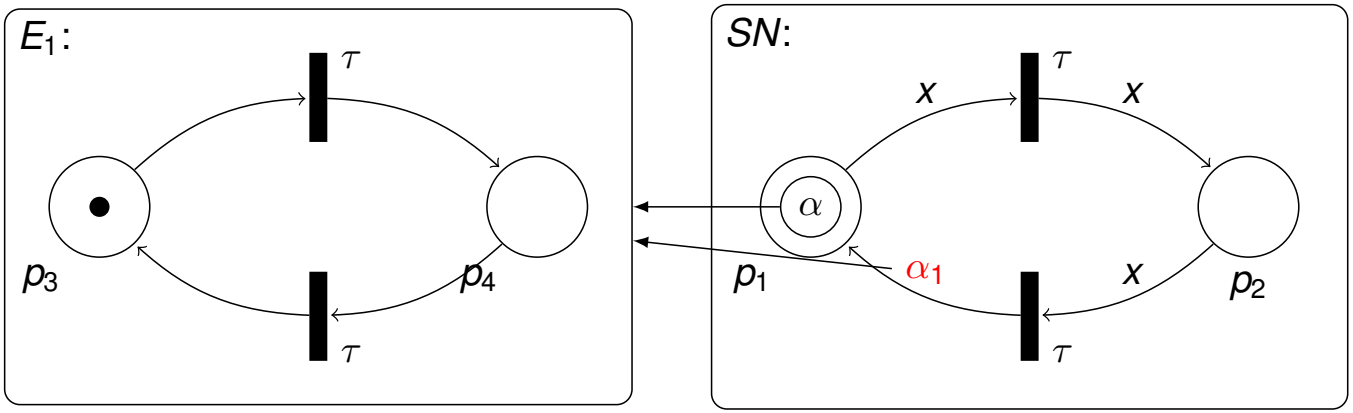


Conservative NP-nets

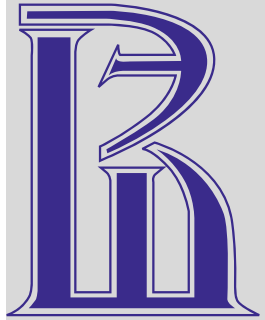
Definition

Let *NP* be an NP-net. *NP* is called conservative iff for each transition *t* in the system net of *NP* the set of all variables in the input arc expressions for *t* is a subset of all variables in its output arc expressions.

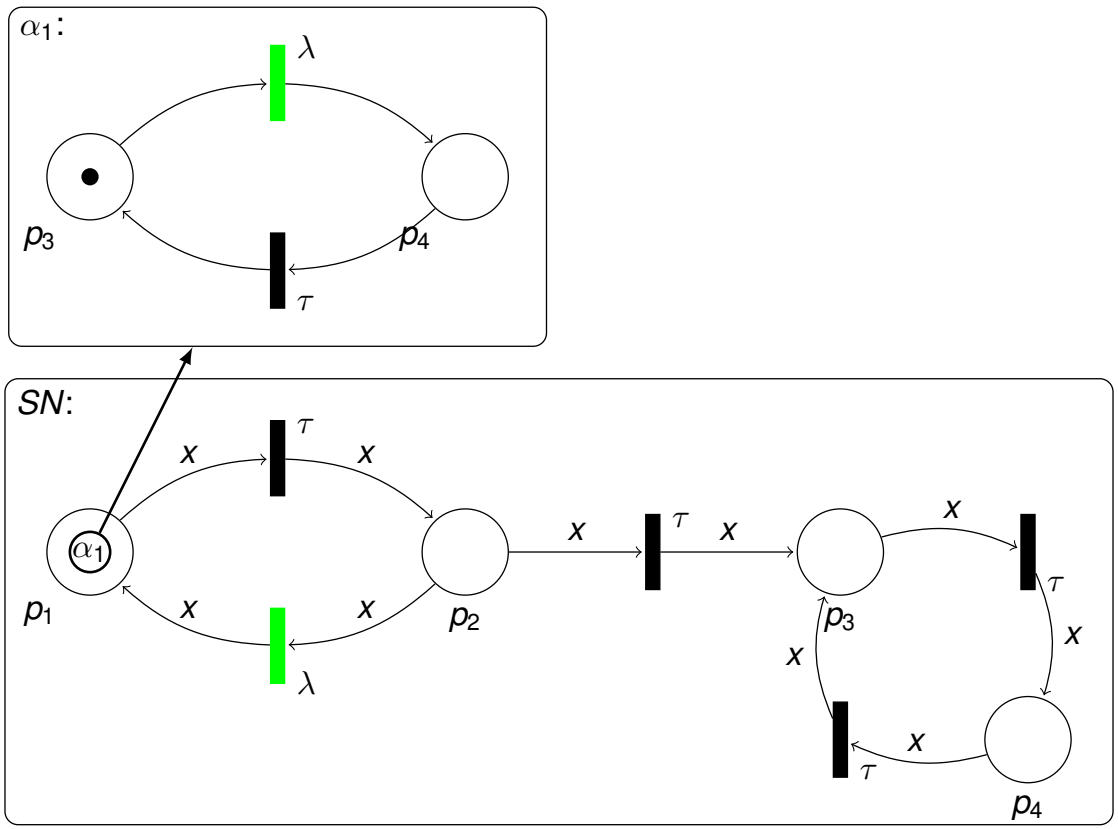
Conservativeness is needed as for 1L-liveness we consider liveness of net-tokens. In exiled net-tokens transitions are "dead":



However, if we don't bother about eliminated net-tokens, we can exclude the condition about convervativeness.

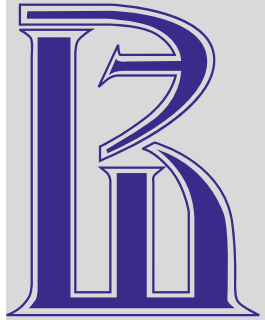


Counterexamples for 1L-liveness (1)



Condition: each SCC of the system net contains at least one transition labeled with λ.
Note: SCCs in SN are cycles in α-trail nets (defined below)

Multiple labels case: Liveness compositionality (1L-live) (1)



Theorem

Let NP be a conservative marked NP-net with a system net SN and initial marking m_0. Let also NP satisfy the following conditions:

1. *the system net in NP is live (as a separate component);*
2. *all net tokens in the initial marking m_0 and all net constants in all arc expression in SN are live (as separate components);*
3. *for each net token α in m_0: α is m-bisimilar to the α-trail net for NP;*
4. *for each arc (t, p) with arc expression e in SN: if e contains a net constant with a value α, then α is m-bisimular to the α-trail net for NP with the initial marking m_α, where $m_\alpha(p) = \alpha$, i.e. α resides in p.*

Then NP is 1L-live.

α-trail net extraction (1)

How to construct α-trail net for the position p_α of the system net *SN* of an NP-net:

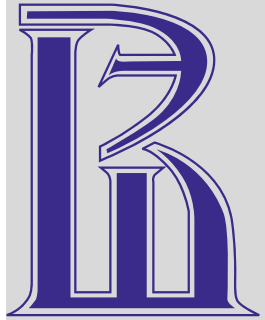
Definition

Step 0. We start building the α-trail net with a new place p', corresponding to p_α, and consider p_α as a current place in *SN*.

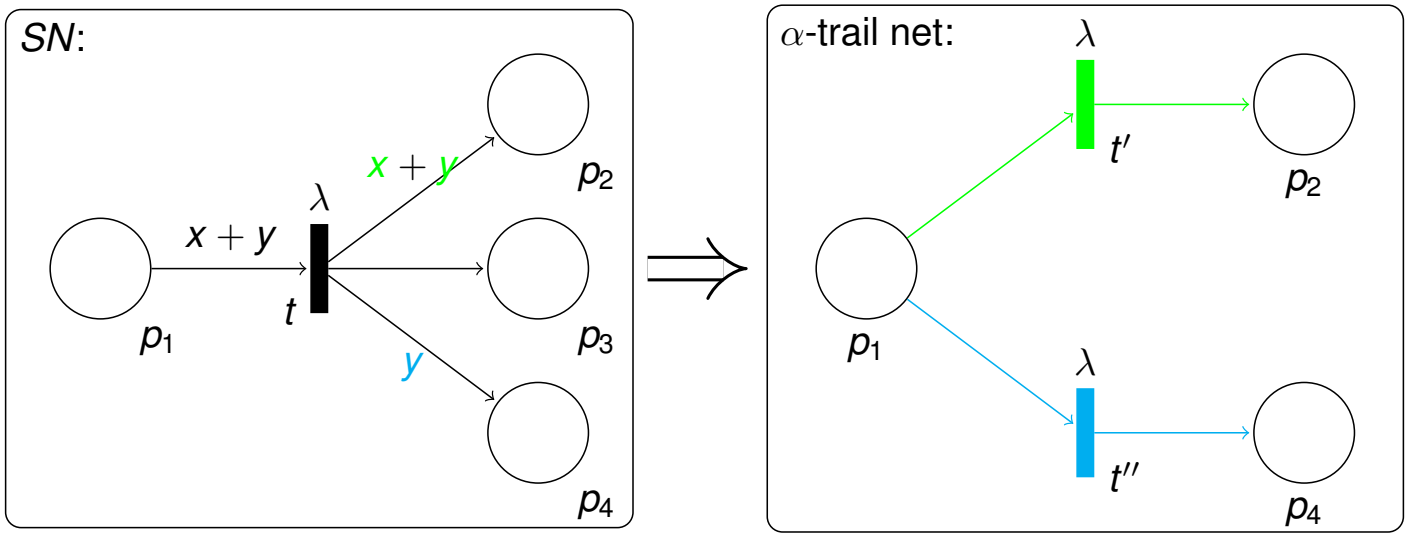
Step 1. Let p be a current place, and let t be a transition in *SN*, for which p is an income place, i.e. there is an arc from p to t with an arc expression *expr*. Let V be the set of variables occurring in *expr*. For each $v \in$ V, s.t. there is an arc from t to some place with an expression containing v, we build a new transition t' and a new place p': ${}^\bullet t' = p$, $t'^\bullet = p'$ and $\lambda(t') = \lambda(t)$.

Step 2. Repeat Step 1 with every new place as a current place.

Illustrations are on the next slide.

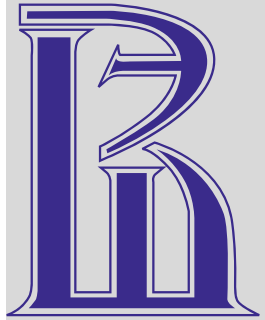


α-trail net extraction (2)

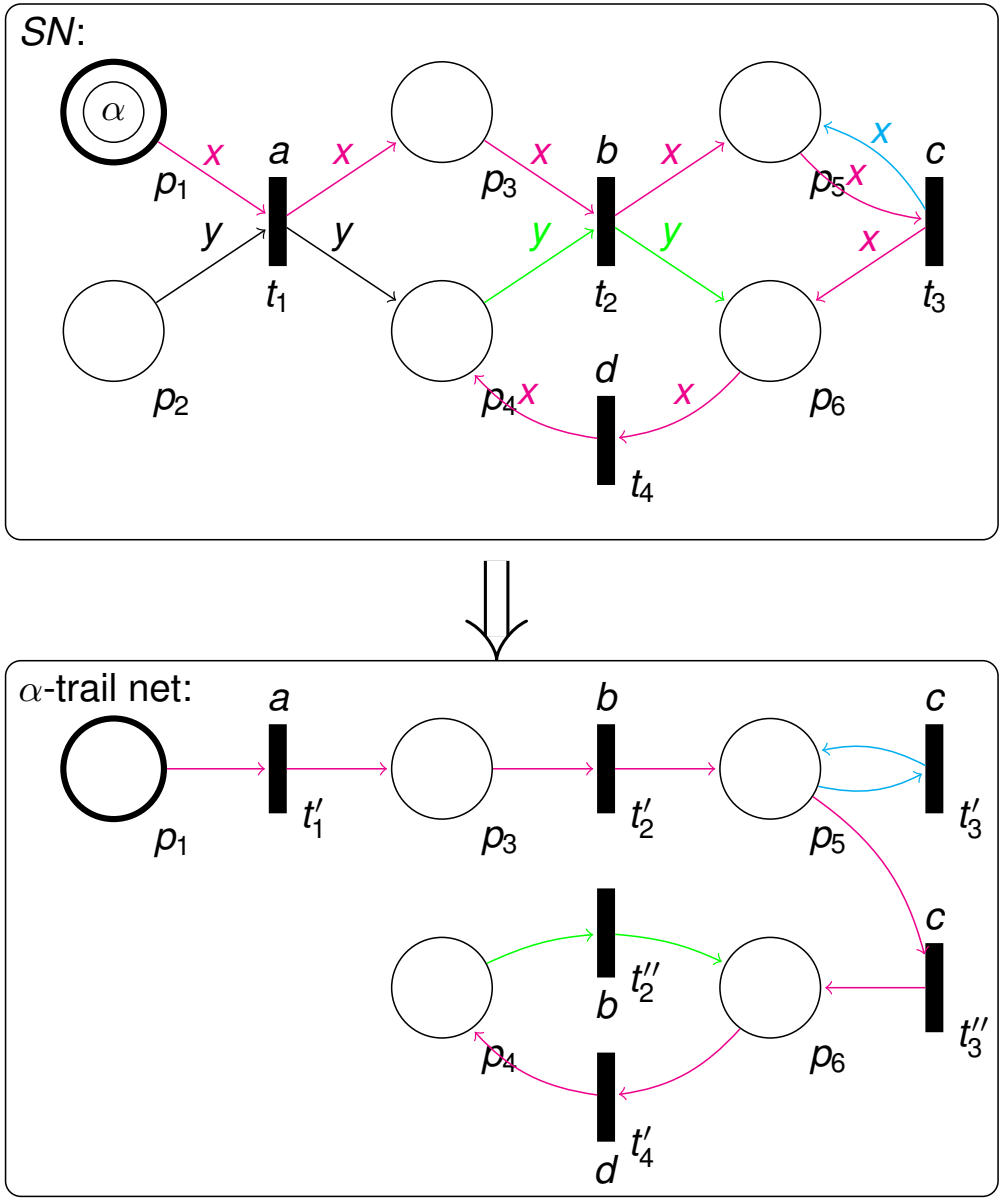


- path $p_1 \to t' \to p_2$ — is a trajectory of a net token under x or y variables from $x + y$ expression on the arc $\langle t, p_2 \rangle$.
- path $p_1 \to t'' \to p_4$ — is a trajectory of a net token under y variable from the arc $\langle t, p_4 \rangle$

No net token can traverse through the t-p_3 arc, so there is no corresponding arc in the constructed α-trail net.



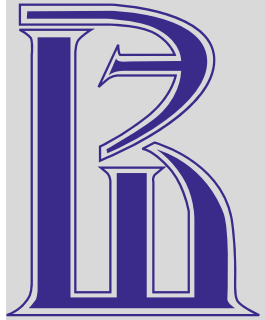
α-trail net extraction (3)



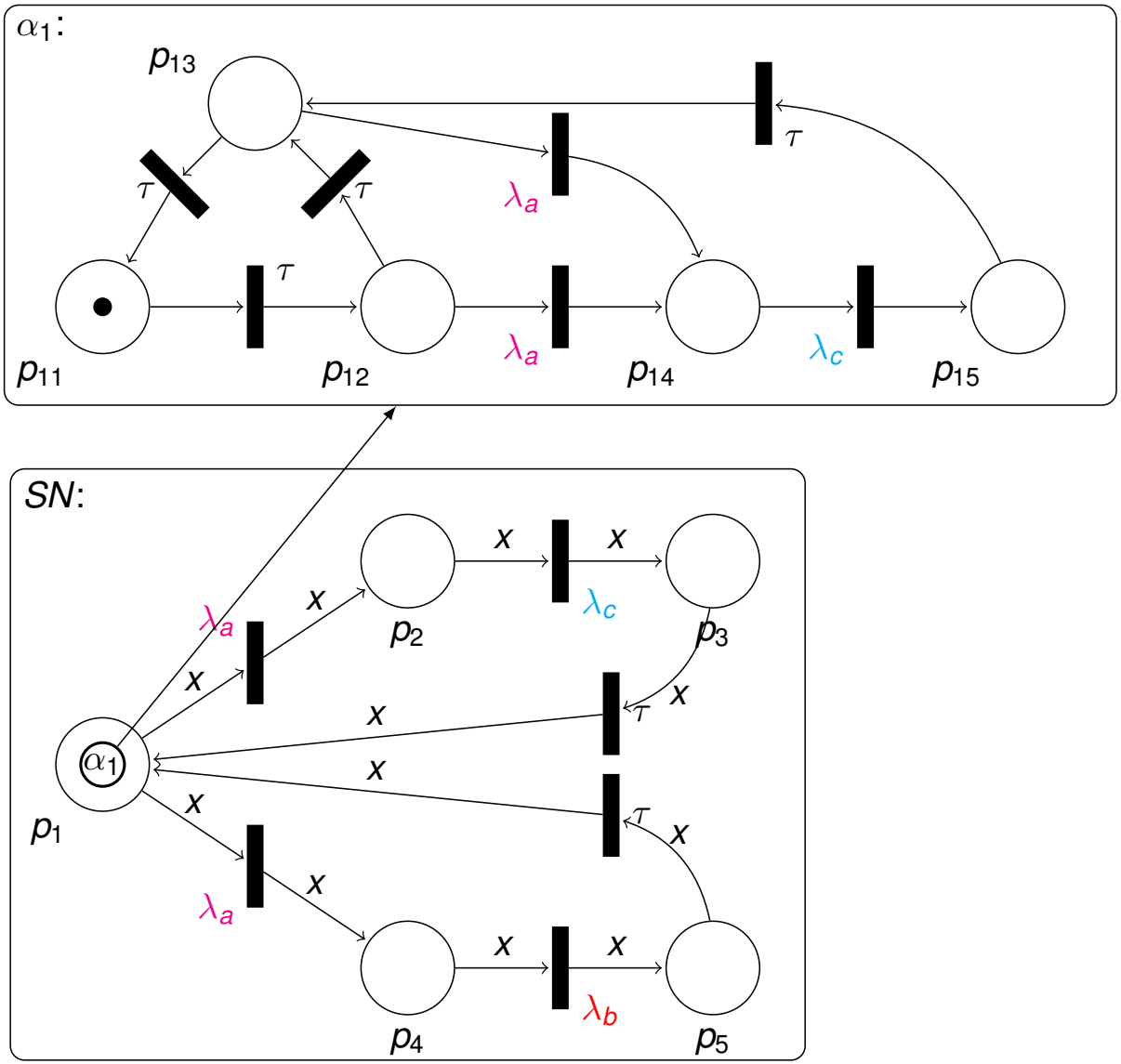
Here is a more complex case of α-trail net extraction.

α-trail net extraction (4)

α-trail net extraction is just a specialization of an extraction of NDA from high level Petri net with transitive inclusion of a token place propagation.



1L-liveness for several labels NP-nets



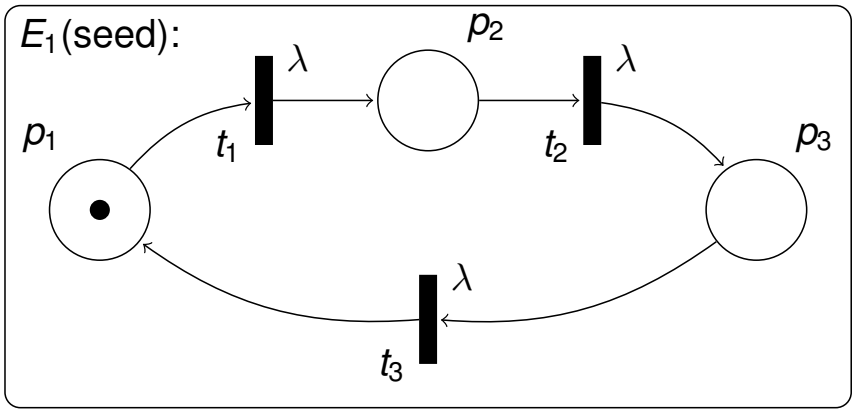
This NP-net has infinite executions, but it's not 1L-live, due to break of m-bisimulation.

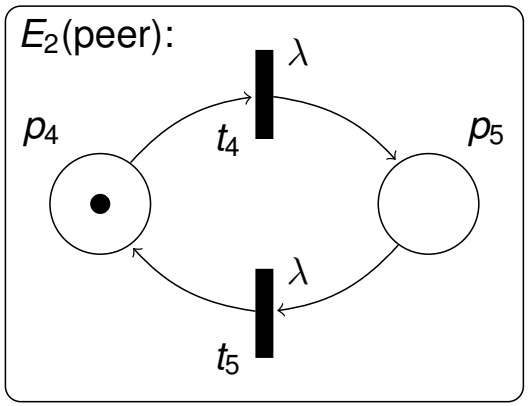
Properties of the components

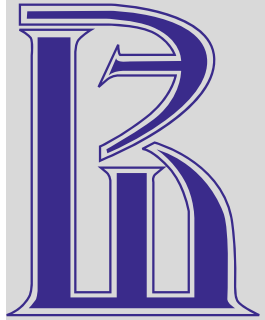
All components are

- free-choice (syntactically)
- bounded
- live

For Seed and Peer nets this is trivial

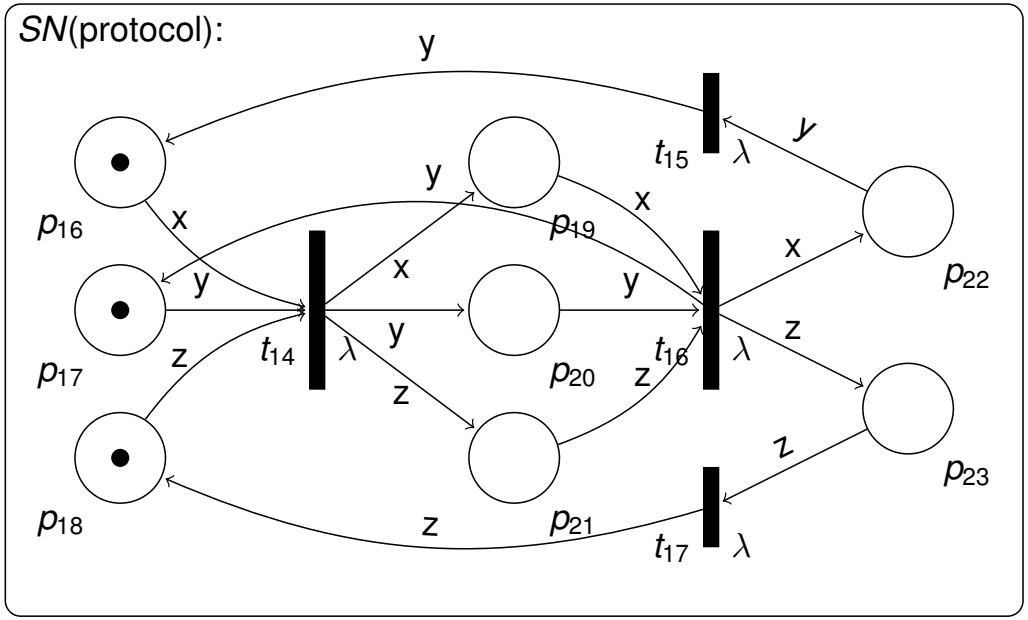




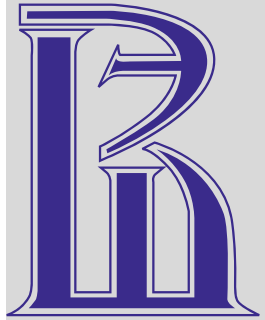


Properties of the components

For protocol net (System Net)

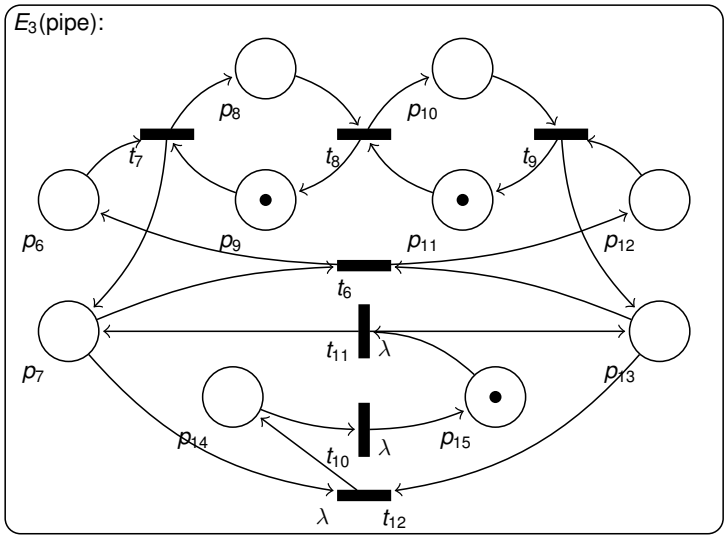


- Free-choiceness — syntactically
- Boundedness — as preset and postset powers are equal for each transition
- Liveness — by simple T-invariant $\langle 1, 1, 1, 1 \rangle$ (transitions are enumerated by their index)



Properties of the components

For Pipe net (E_3)



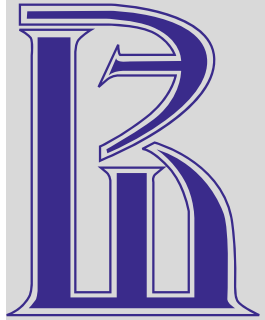
- Free-choice — syntactically
- Boundedness — by simple S-invariant
  $\langle 1, 1, 1, 1, 1, 1, 1, 1, 2, 2 \rangle$
  (places are enumerated by their index)
- Liveness — by simple T-invariant $\langle 1, 1, 1, 1, 1, 1, 1 \rangle$

Invariants are simple as we artificially constructed our example to be simple.

Properties of the system

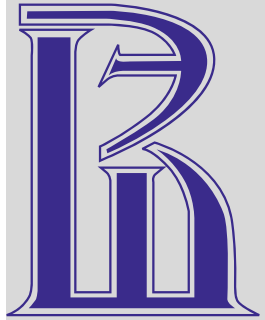
We can conclude the next properties of the whole system

- Boundedness — as “boundedness compositionality” conditions hold;
- “1L-live” property — as “1L-live” conditions hold.



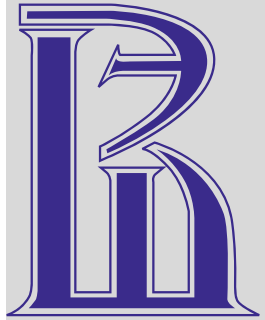
Whats the Plan?

- **Prerequisites of NP-nets**
- Ostensive definition of NP-nets: Simple model of P2P protocol
- Formal definition of NP-nets
- Need for analysis methods
- Compositionality of NP-net properties
- **Technical achievements**
- Conclusions and further directions



Technical achievements: NPN2CPN

- Idea: we don't have any tools at all, so why don't translate NP-nets to models with tool support



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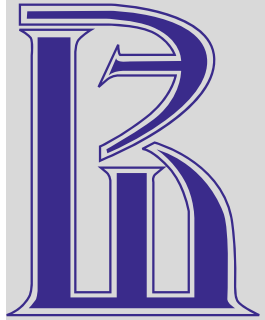
- What tool?



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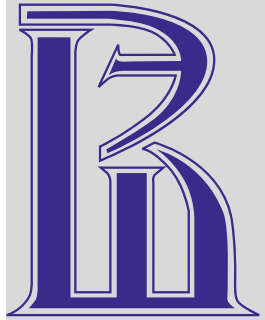
- What tool? - CPNtools



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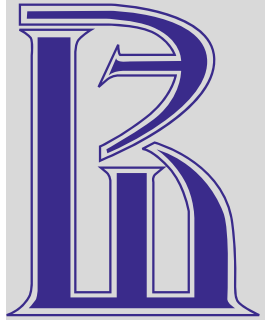
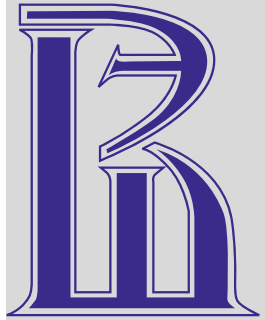
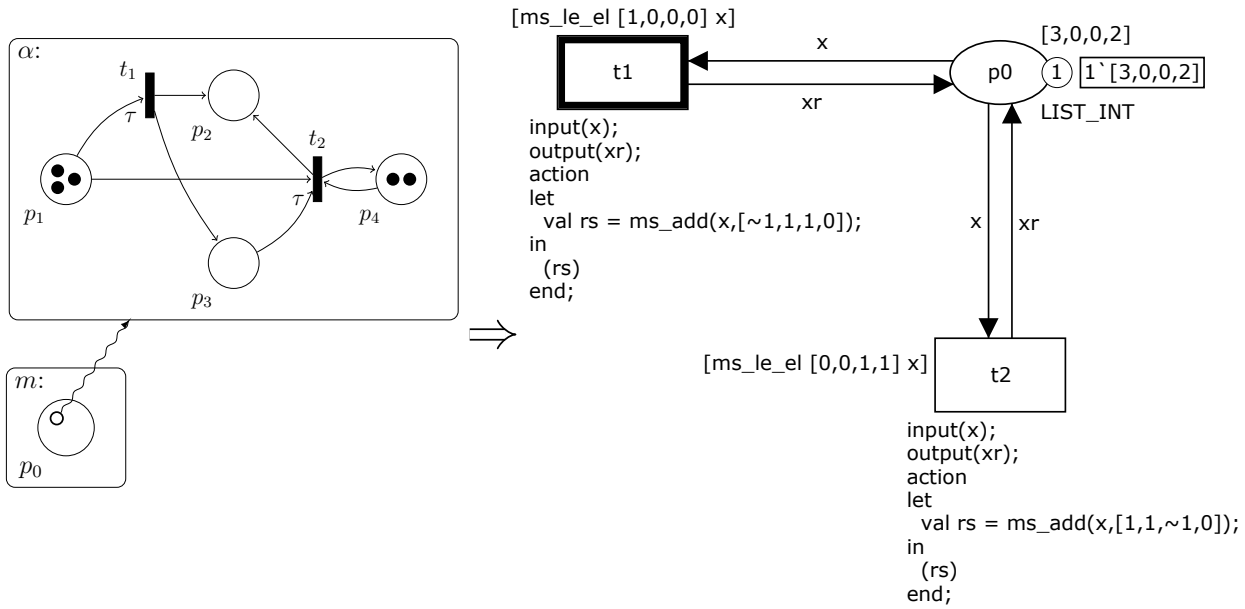


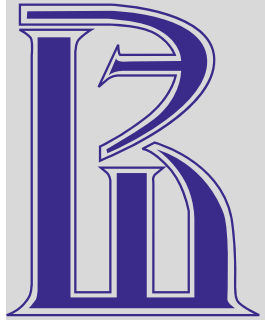
Technical achievements: NPN2CPN

- Idea: we don't have any tools at all, so why don't translate NP-nets to models with tool support
- What tool? - CPNtools
- Why? - Simulation, Performance analysis, Reachability graph, CTL model checking et cetera.
- Implementation of the translation: Hattu Pavel, Sysoev German.

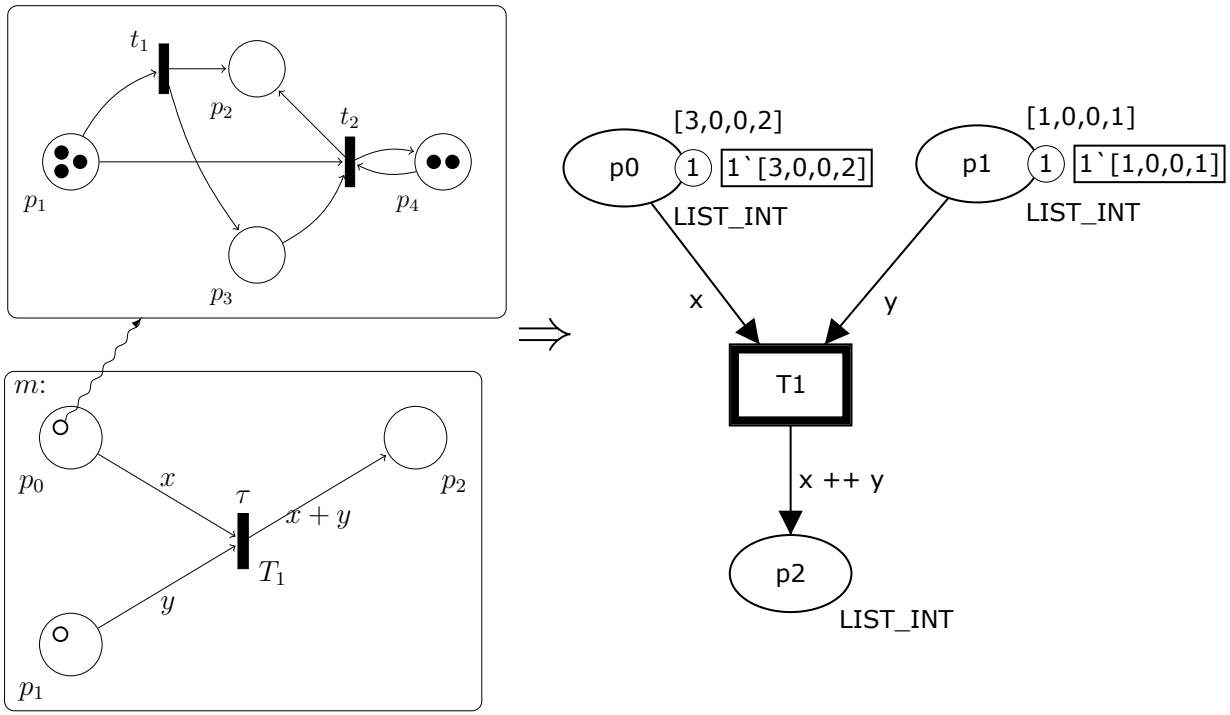


Technical achievements: NPN2CPN

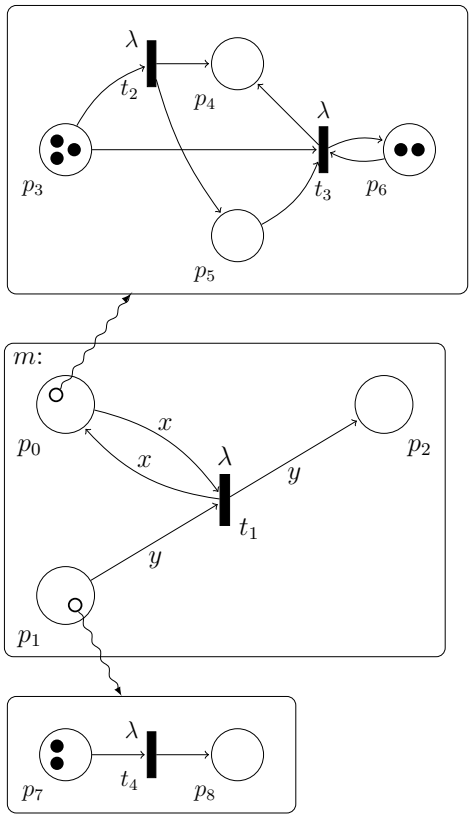


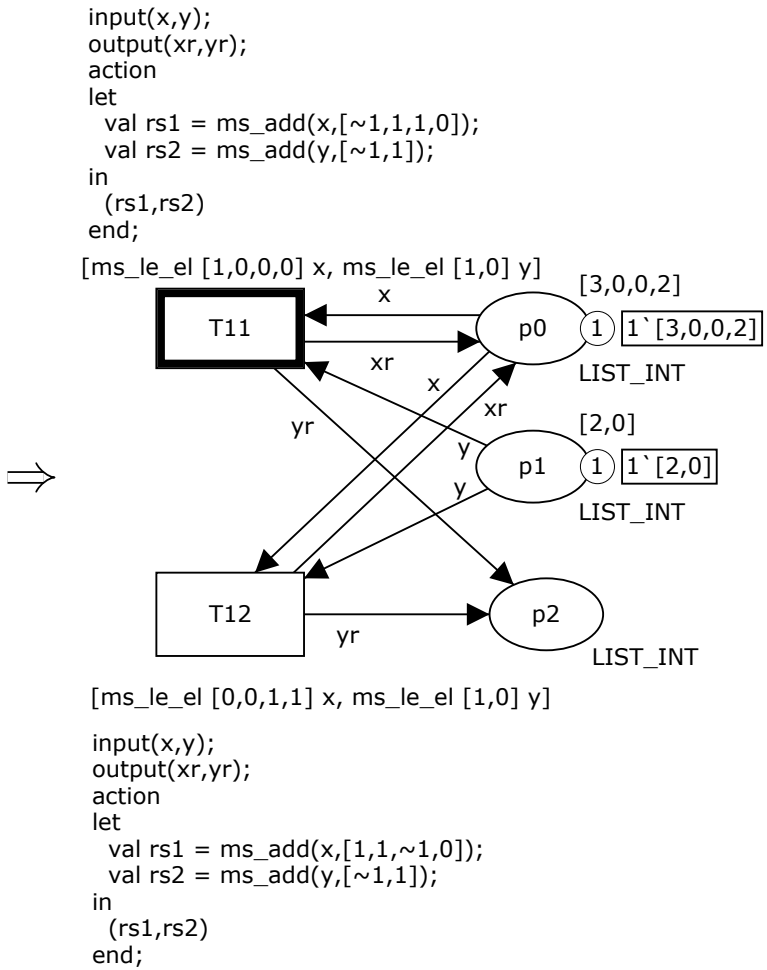


Technical achievements: NPN2CPN



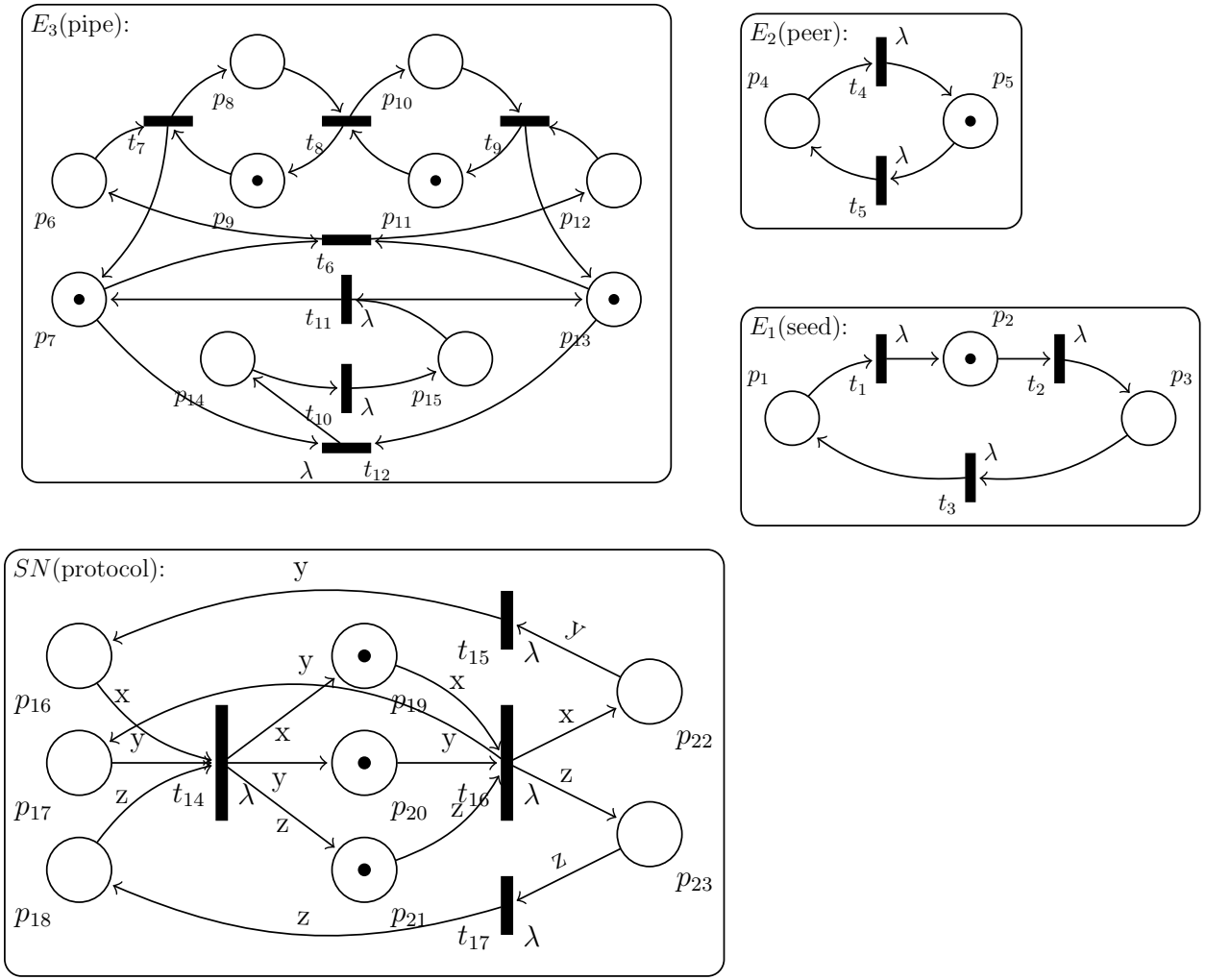
Technical achievements: NPN2CPN

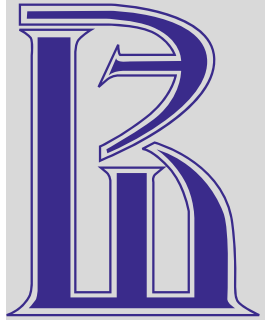




Technical achievements: NPN2CPN

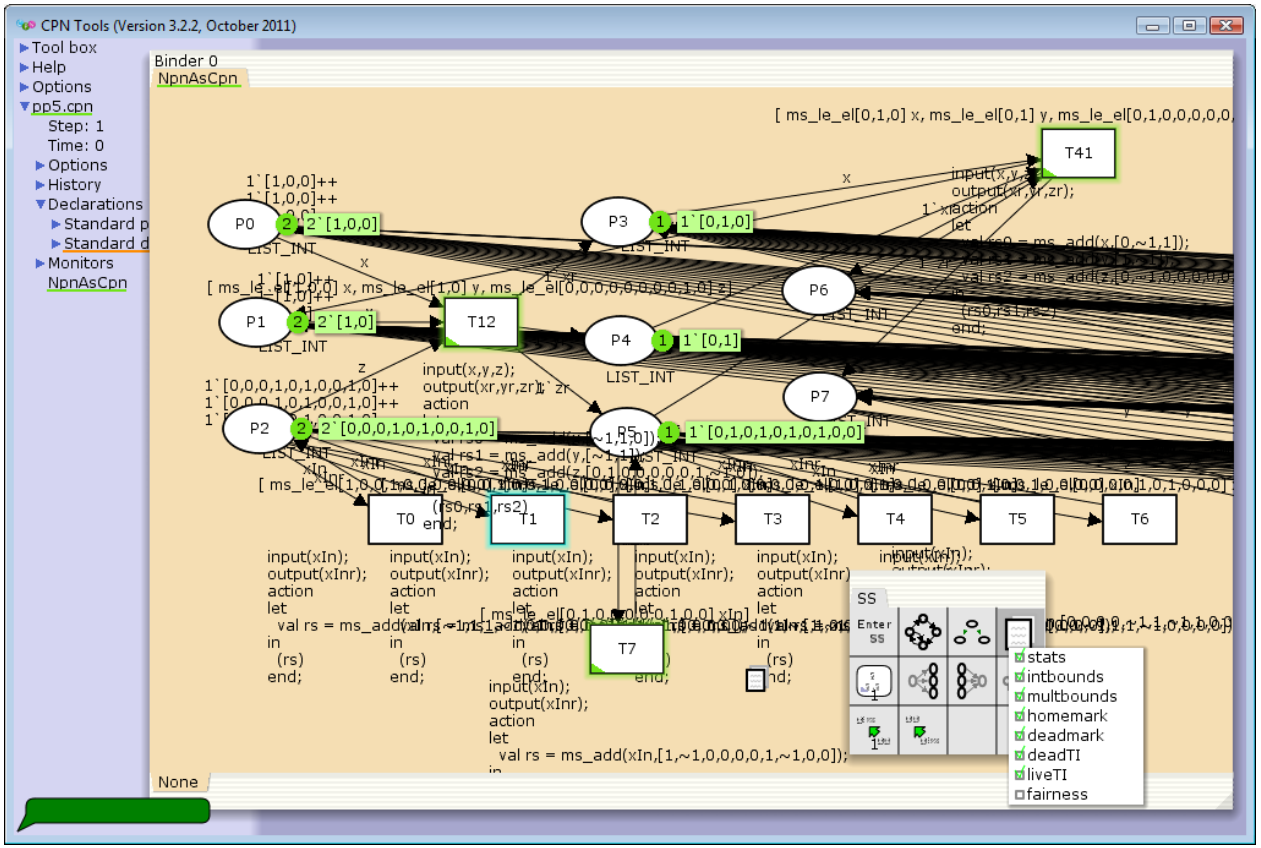
Source NP-net:

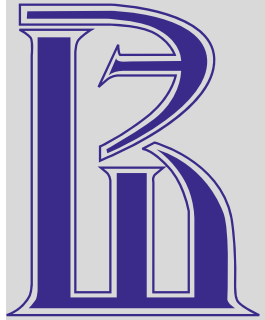




Technical achievements: NPN2CPN

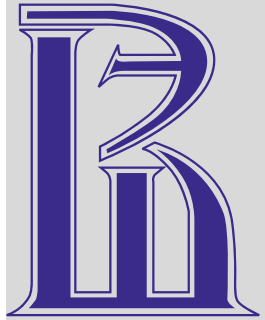
Resultant CP-net:





Technical achievements: EMF model

- It would be better to have our own tool;



Technical achievements: EMF model

- It would be better to have our own tool;
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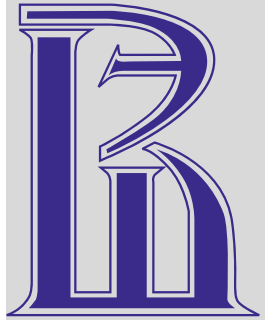
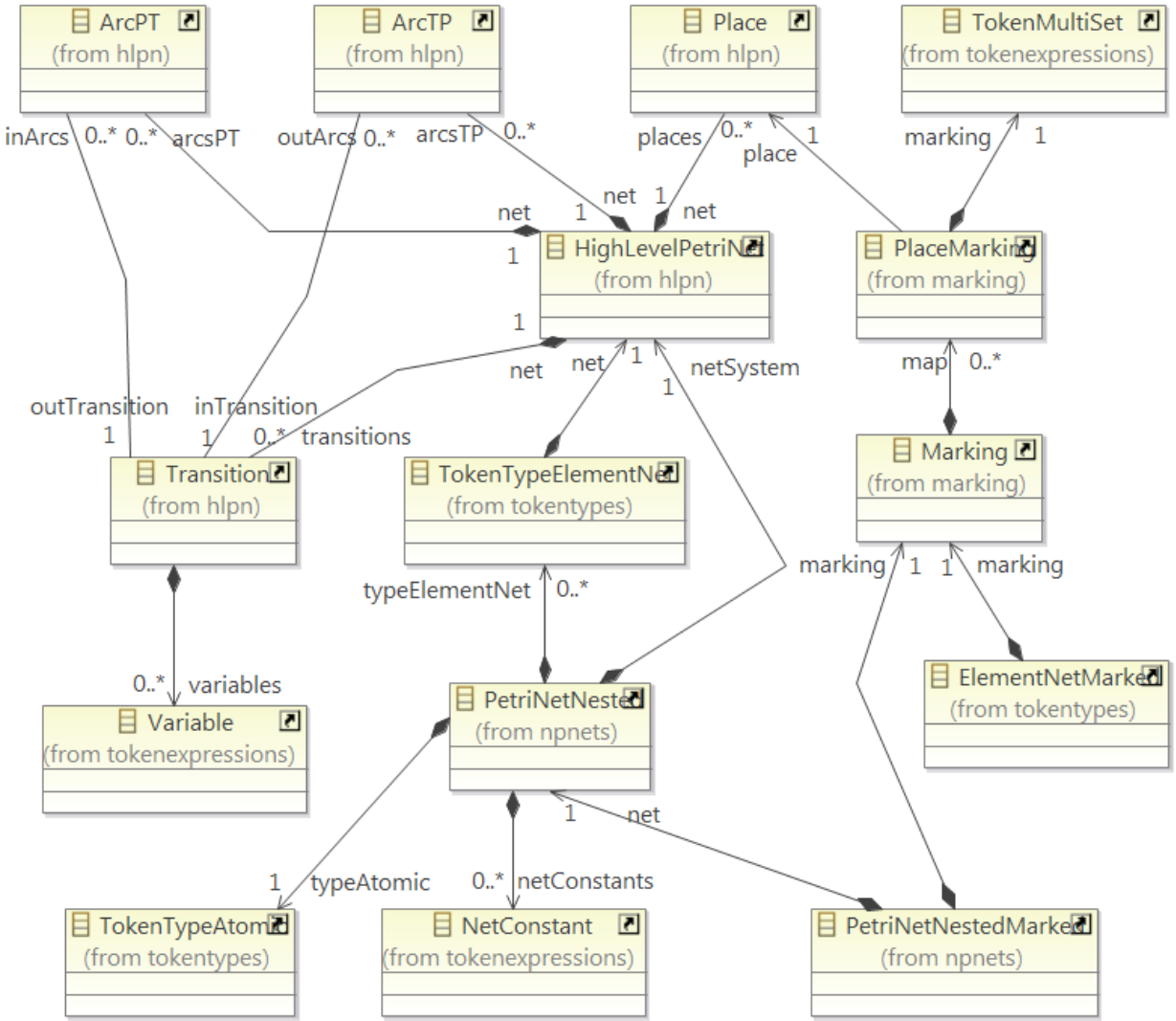
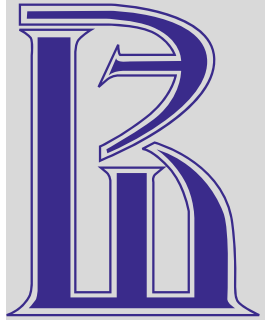


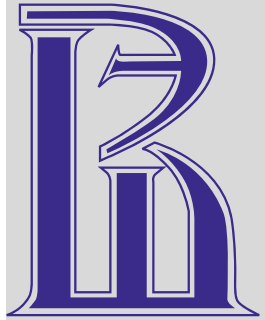
Technical achievements: EMF model





Technical achievements

- It would be better to have our own tool;
- We have to start from a data model;
- Haskell backend (by Daniil Frumin);
  1. Model checking of separate components;
  2. Compositional checking of NP-nets liveness (alpha-trail nets, m-bisimulation algorithm).



Technical achievements

- It would be better to have our own tool;
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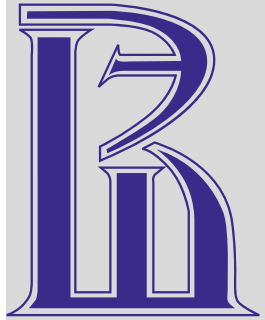
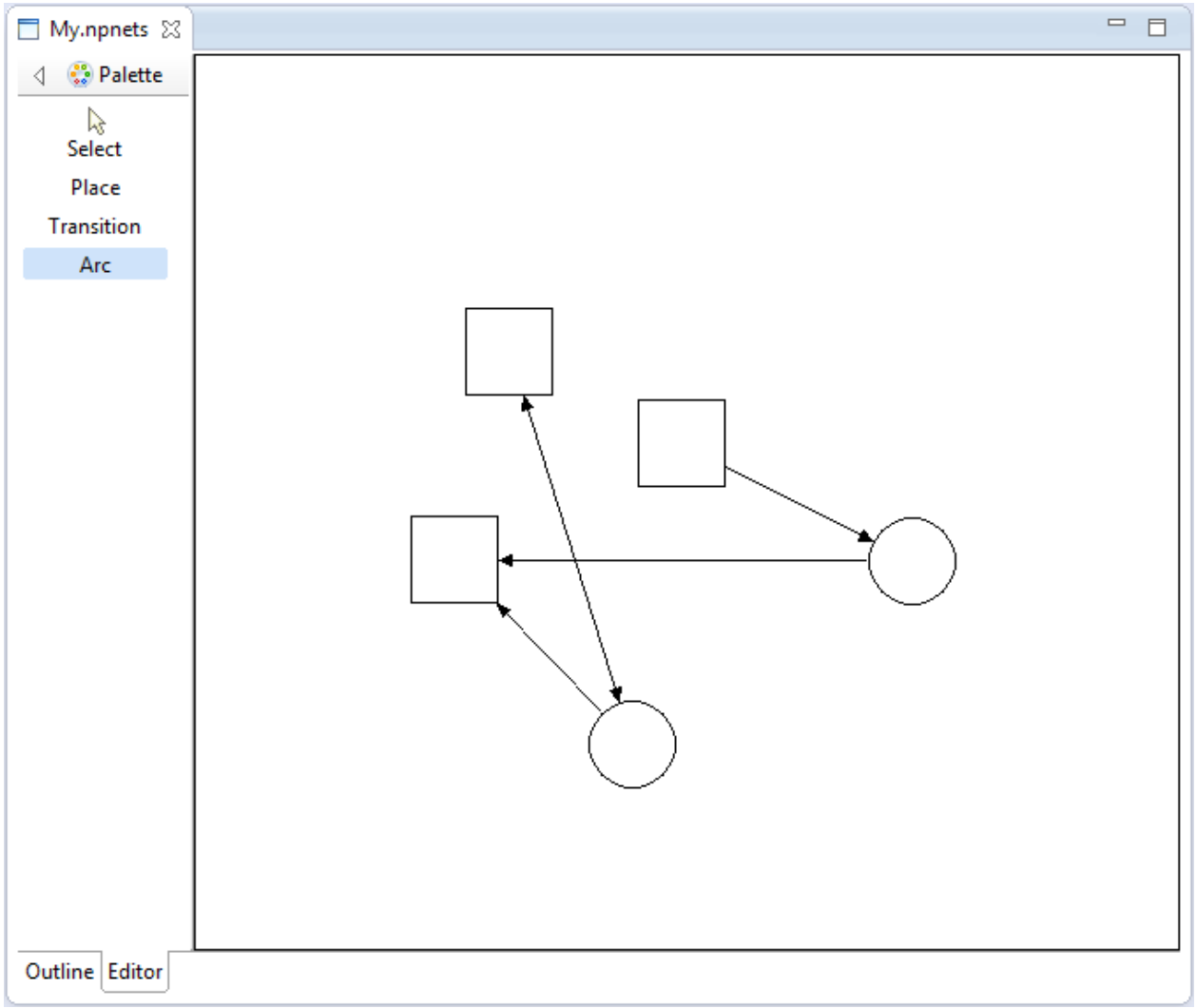
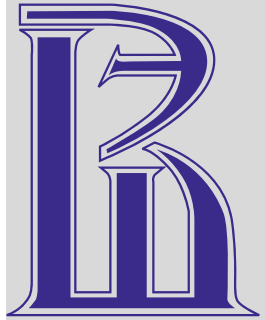
- Graphical editor (by Ilya Zubarev);



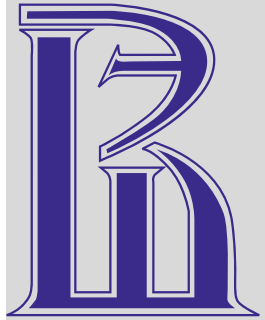
Technical achievements: Eclipse editor



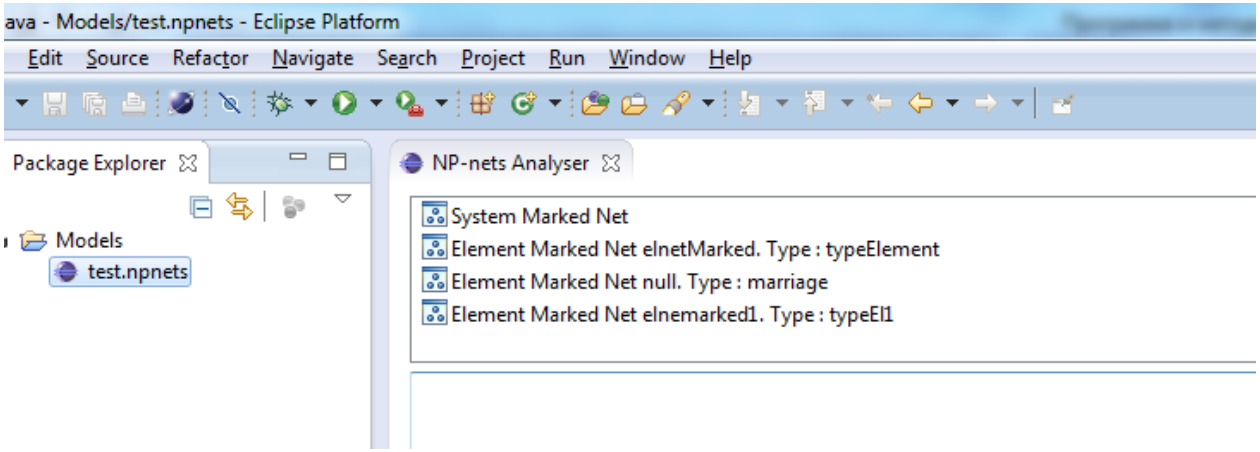


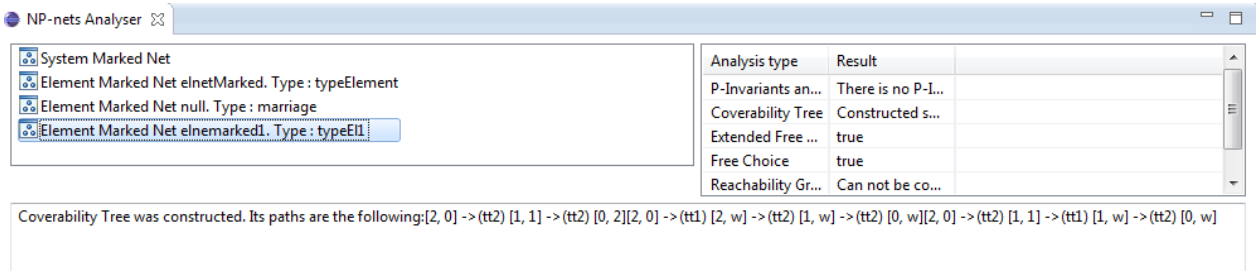
Technical achievements

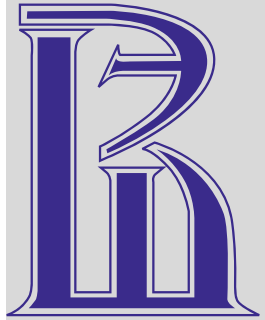
- It would be better to have our own tool;
- We have to start from a data model;
- Haskell backend (by Daniil Frumin);
- Graphical editor (by Ilya Zubarev);
- Analysis of components (by Anton Fillipov);
  - reachability graph, reachability tree, coverability tree, P-invariants, covering P-invariants, (extended) free-choiceness checking.



Technical achievements: EMF model







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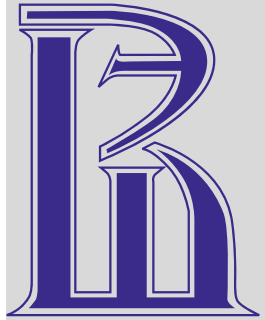
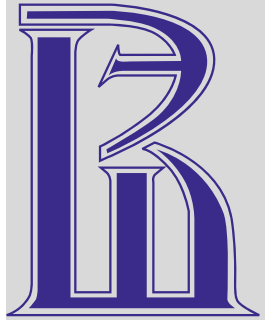
- Haskell backend (by Daniil Frumin);
- Graphical editor (by Ilya Zubarev);
- Analysis of components (by Anton Fillipov);
- Code generation:
  - From NP-nets to Java apps over TCP/IP (by Dmitry Kuznecov)
  - From NP-nets to EJB system (by Nikolenko Artem)



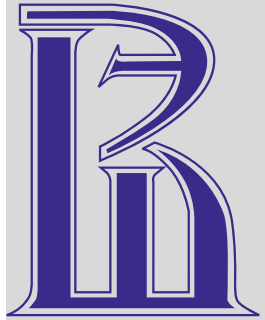
Whats the Plan?

- **Prerequisites of NP-nets**
- Ostensive definition of NP-nets: Simple model of P2P protocol
- Formal definition of NP-nets
- Need for analysis methods
- Compositionality of NP-net properties
- Technical achievements
- Ongoing research
- **Conclusions and further directions**



Ongoing research

1. Compositionality of P-invariants for NP-nets;
2. Compositionality of T-invariants for NP-nets;
3. Time NP-nets;
4. Compositional bounding of unbounded NP-nets by timing;



Conclusions and further directions

1. Nested Petri Nets with well-formed components can be analysed for boundedness and liveness in polynomial time;
2. Boundedness and liveness holds compositionality for NP-nets (under some constraints)
3. Compositionality of:
   - P- and T- invariants;
   - Fairness, impairness, justice.