Petri Nets Tutorial, Parametric Verification (session 3)

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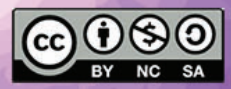
June 20th, 2017

Thanks

Thanks for their support to...

project PACS ANR-14-CE28-0002
IPI-PAN, LS2N, LIPN

and of course...

All the developers of the tools

Outline

- Petri Nets with Parameters
  - Parametric Petri Nets.
  - Parametric Time Petri Nets.
  - Roméo in a nutshell.
- Action synthesis
  - Model.
  - SPATULA in a nutshell.

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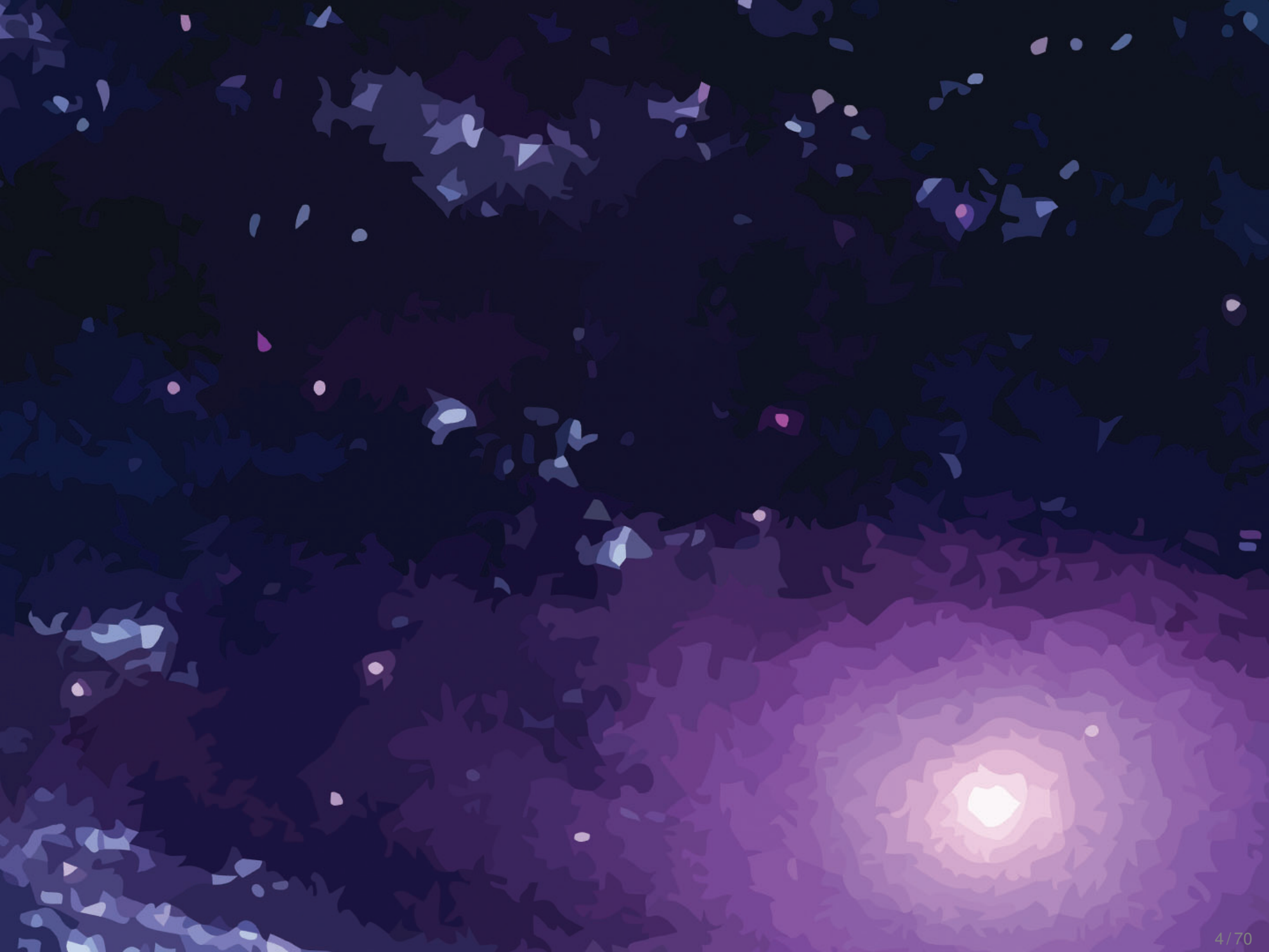

Parametric Petri Nets

First of all. . .

You now know about:

- parametric timed automata
- synthesis of timing parameters
- interval Markov chains with parameters

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First of all. . .

You now know about:

- parametric timed automata
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Let us now see Parametric Petri nets

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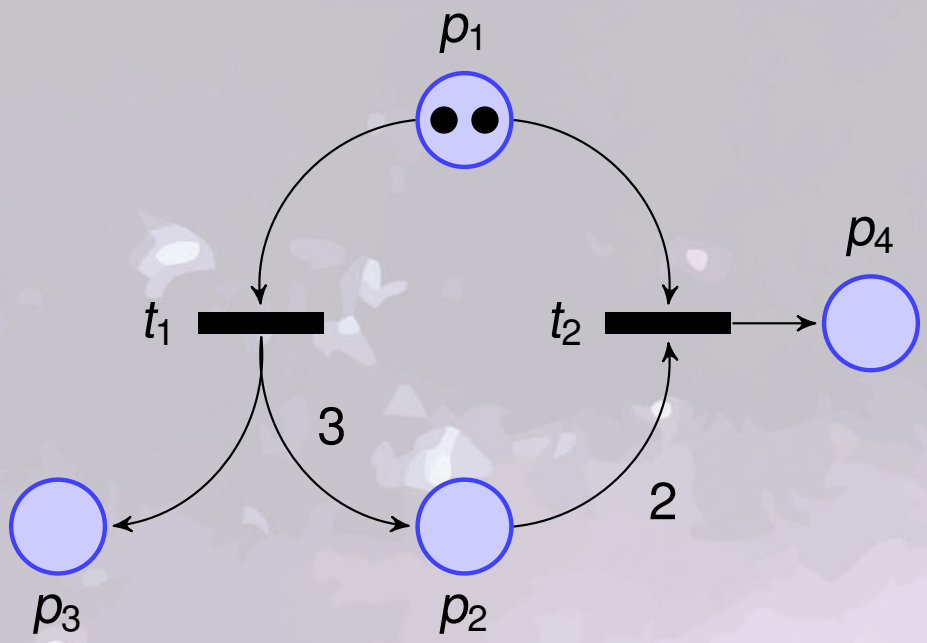
Petri nets



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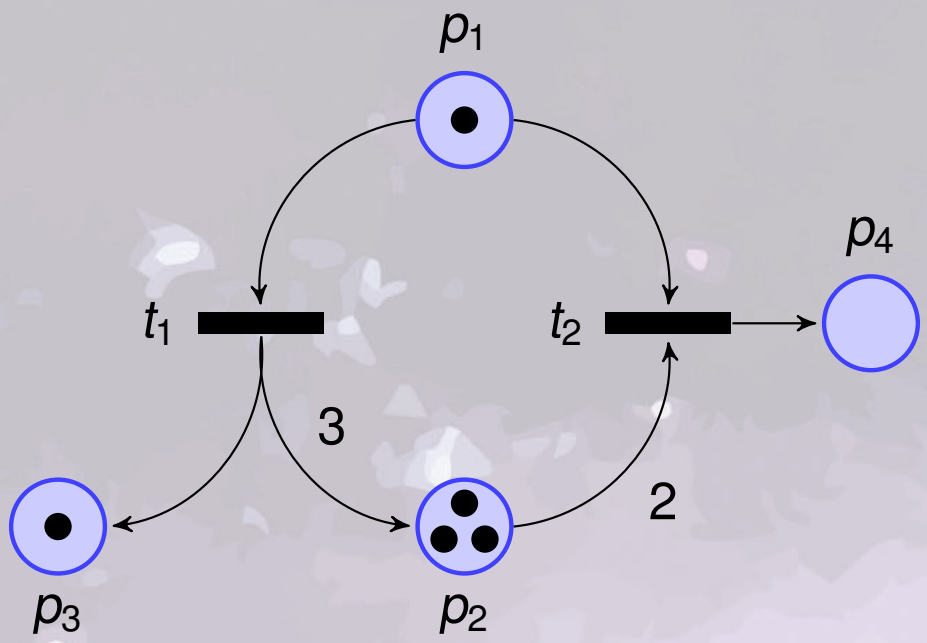
Petri nets



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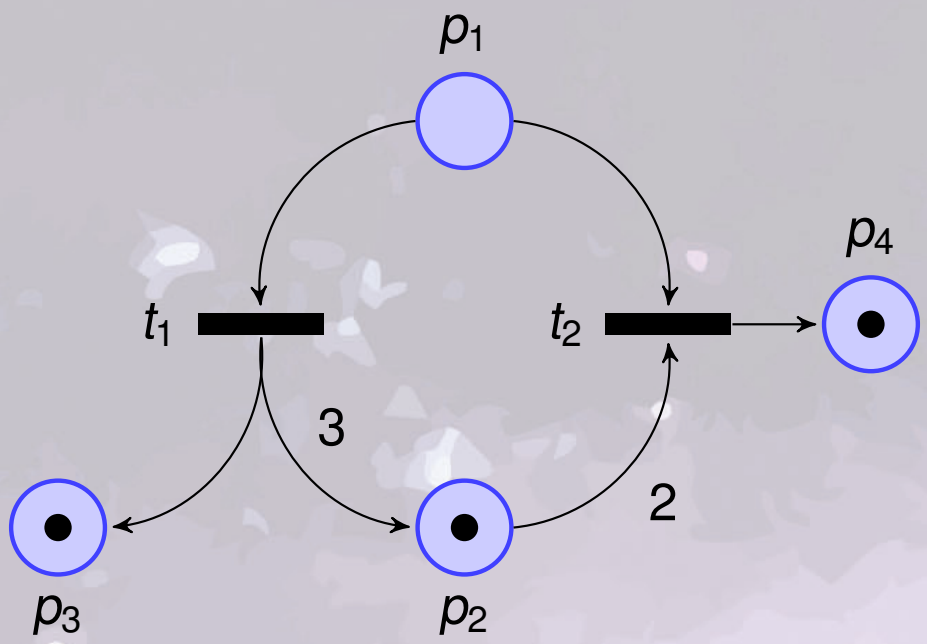
Petri nets



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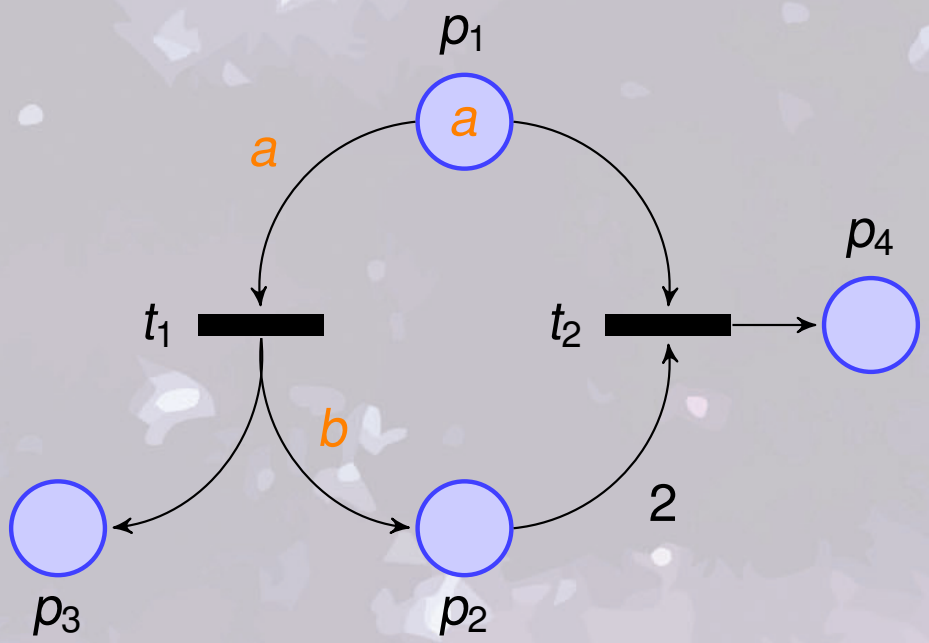
Petri Nets with Parameters David et al. [2015]



- initial marking: number of processes, initial value of a semaphore, etc.
- pre weights: number of processes to synchronise, number of items to take, etc.
- post weights: number of processes to spawn, number of items to give, etc.

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The problem of Coverability

Definition (Coverability)

Given a marking m, does there exist a reachable marking m' such that $m' \geq m$

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The problem of Coverability

Definition (Coverability)

Given a marking m, does there exist a reachable marking m' such that $m' \geq m$

- Coverability is EXPSPACE-complete in Petri nets;
- It is equivalent to knowing if some transition can fire;
- This includes many safety properties.

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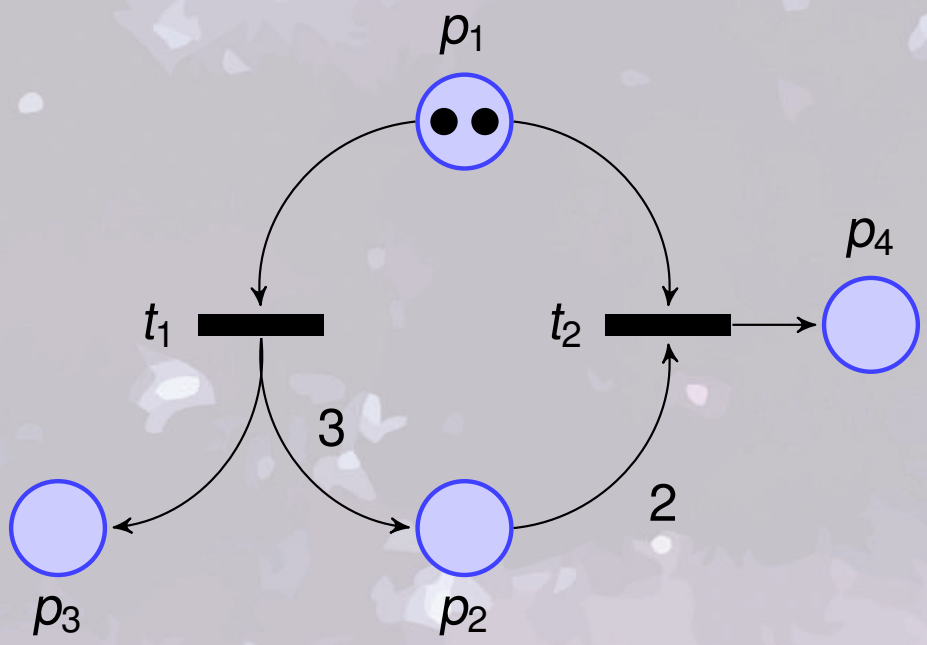
Coverability: Example



Some markings that can be covered:

$(0,0,0,0) - (1,1,1,0) - (0,1,1,1)$

Some markings that cannot be covered:

$(1,0,0,1) - (2,0,1,0) - (0,7,0,0)$

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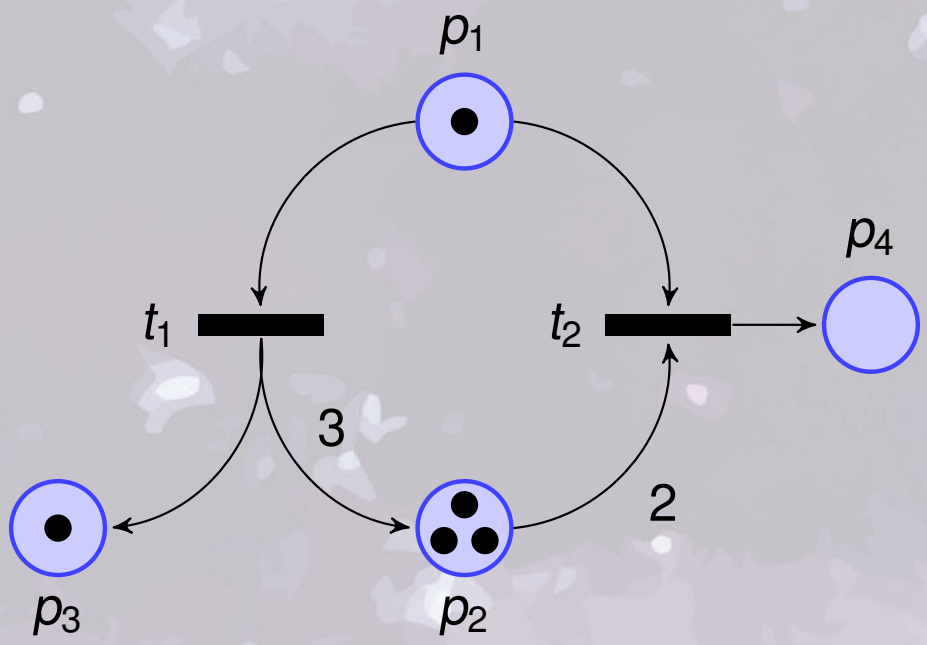
Coverability: Example



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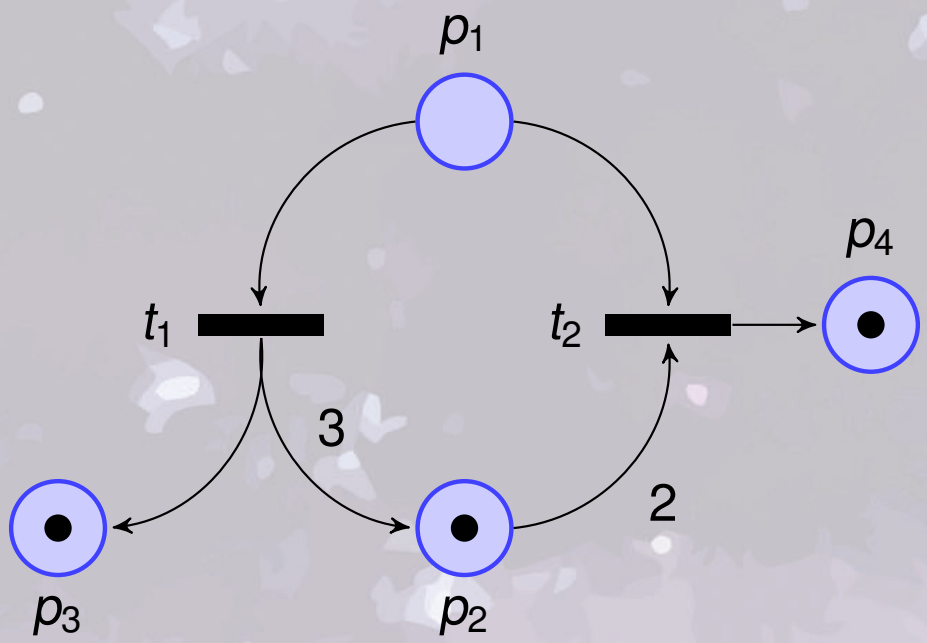

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Coverability in Parametric Petri Nets

Definition (E-cov: Existential Coverability)

Is some given marking coverable for at least one parameter valuation?

Definition (U-cov: Universal Coverability)

Is some given marking coverable for all the parameter valuations?

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Parametric Coverability is Undecidable

Theorem

E-cov and U-cov are undecidable for parametric Petri nets.

They can simulate 2-counter machines:

- two counters C_1, C_2,
- states $P = \{p_0, ...p_m\}$, a terminal state labelled *halt*
- finite list of instructions $I_1, ..., I_s$ among the following list:
  - increment a counter and go to I_j
  - if the counter is positive decrement it and go to I_j
  - if the counter is null go to I_i else go to I_j

Counters are always non negative.

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An Example of 2-Counter Machine

$$\begin{array}{l} \text{in } p_1: \ C_1 := C_1 + 1; \text{goto } p_2; \\ \text{in } p_2: \ C_2 := C_2 + 1; \text{goto } p_1; \end{array}$$

Successive configurations:

$$(p_1, C_1 = 0, C_2 = 0) \rightarrow (p_2, C_1 = 1, C_2 = 0) \rightarrow (p_1, C_1 = 1, C_2 = 1) \rightarrow (p_2, C_1 = 2, C_2 = 1) \rightarrow ...$$

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Simulation of a 2-Counters Machine

- The halting problem (whether some state `halt` of the machine is reachable) can be reduced to E-cov;
- The counters boundedness problem (whether the counters values stay in a finite set) can be reduced to U-cov;
- Both problems are undecidable for 2-counter machines Minsky [1967].
- From any machine $\mathcal{M}$, we build a parametric Petri net $\mathcal{N}_\mathcal{M}$ encoding it such that:
  - $\mathcal{M}$ halts iff there exists a parameter valuation v such that place $p_{\texttt{halt}}$ is coverable in $v(\mathcal{N}_\mathcal{M})$.
  - a counter of $\mathcal{M}$ is unbounded iff for all parameter valuations v, place p_{error} is coverable in $v(\mathcal{N}_\mathcal{M})$.

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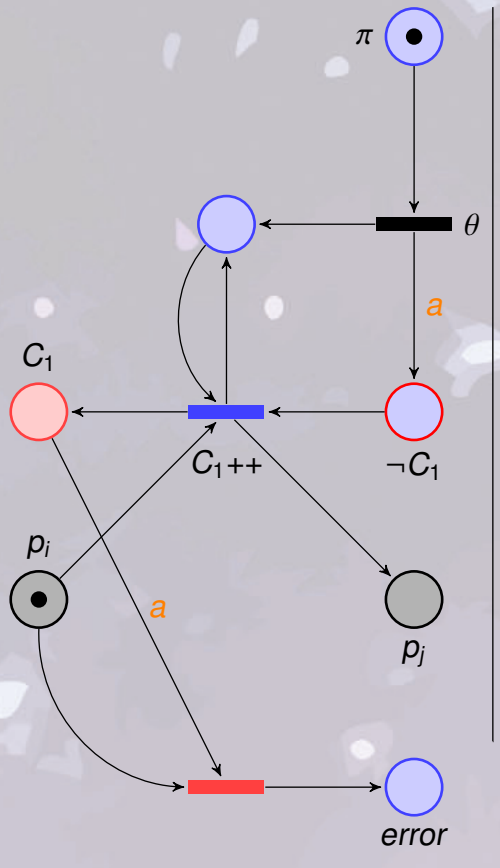
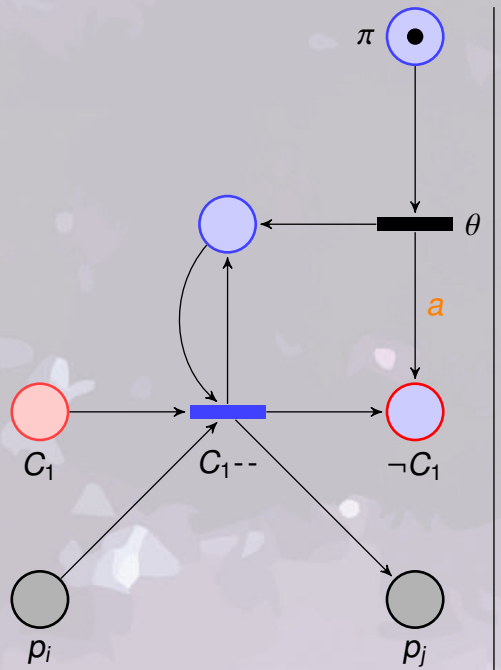
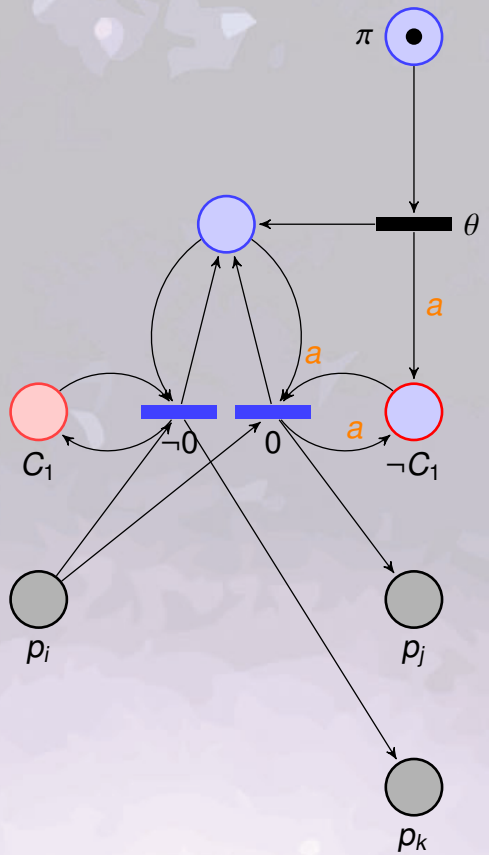
Simulation of Instructions



incrementation
of a counter



decrementation
of a counter



zero test of
a counter

By construction, $m(C_1) + m(\neg C_1) = a$

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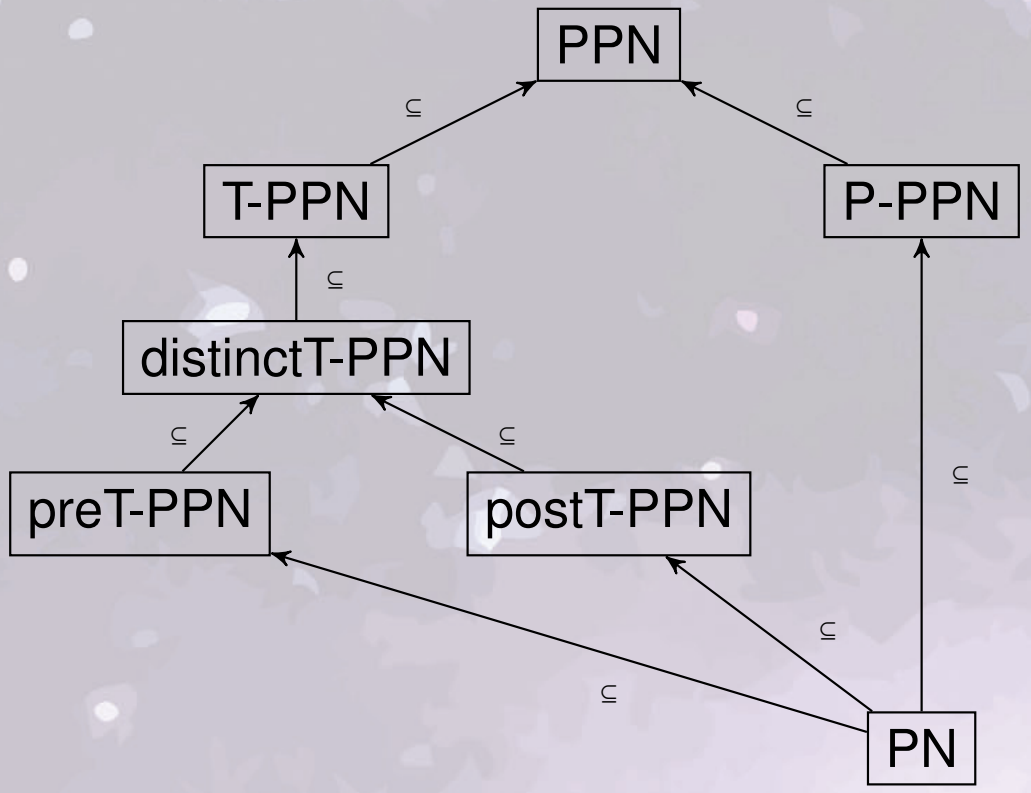
Decidable Subclasses: A Hierarchy of Parametric PNs



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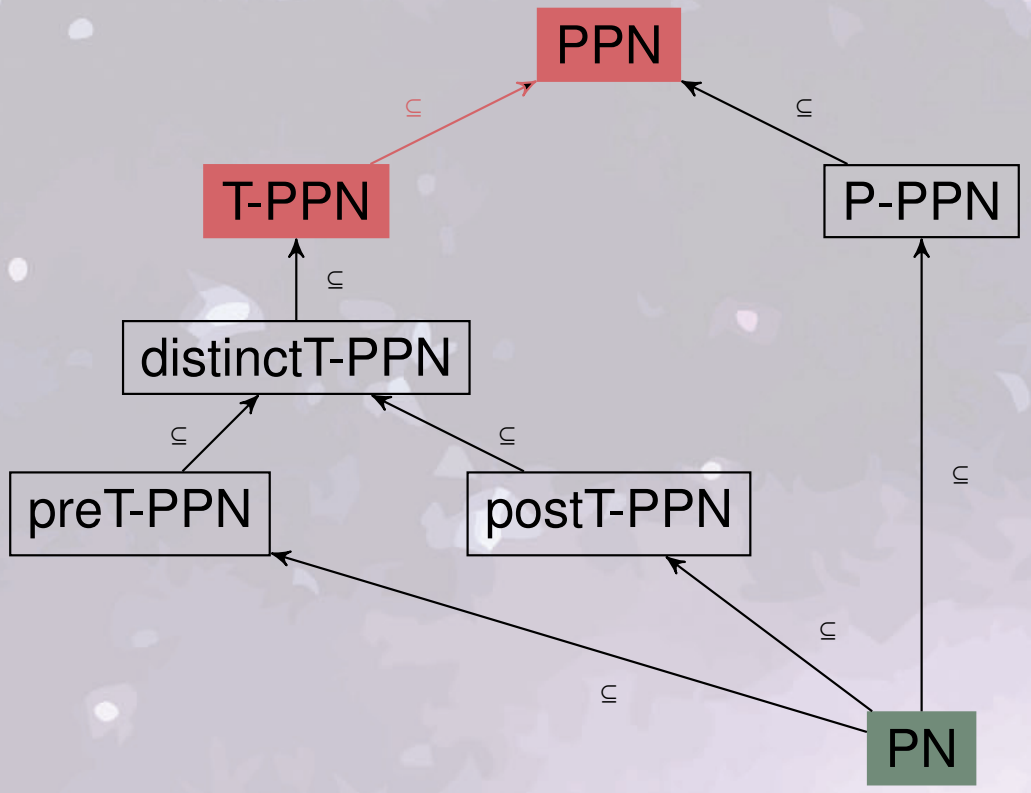

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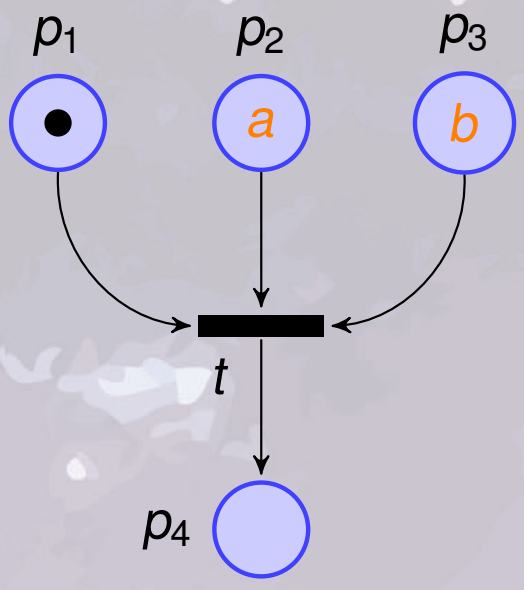
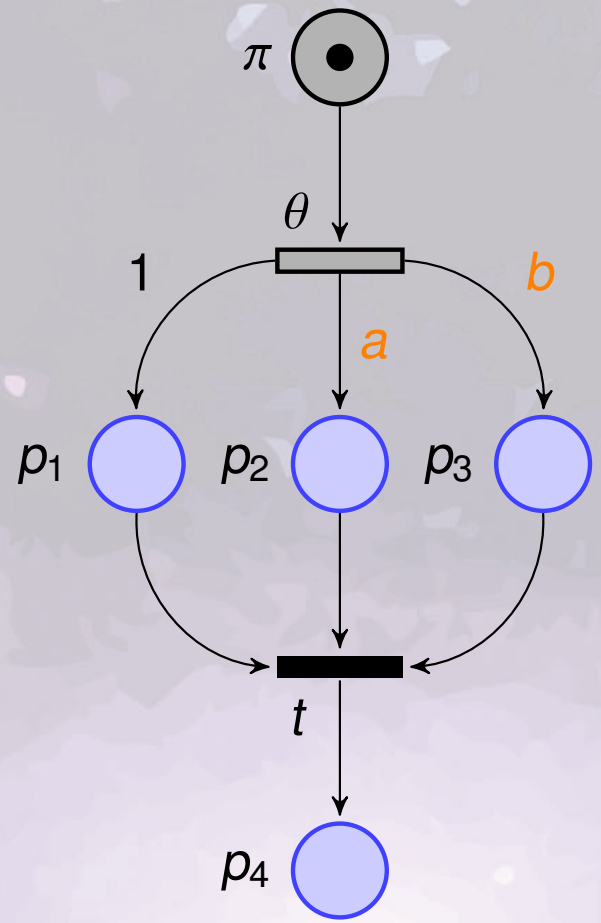
From Markings to Output Weights



replacement of the
P parameters by
postT parameters



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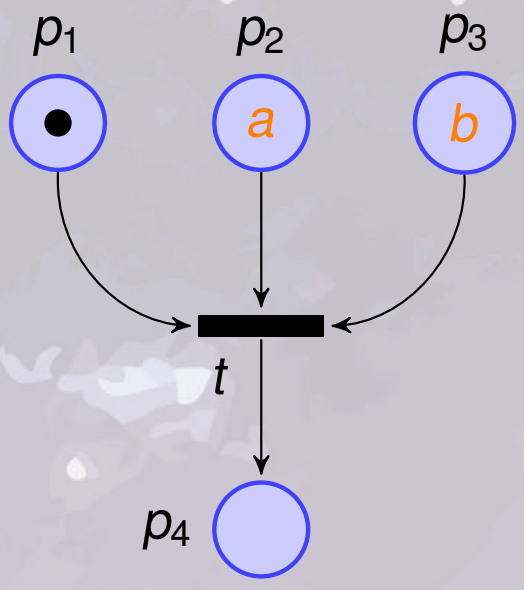

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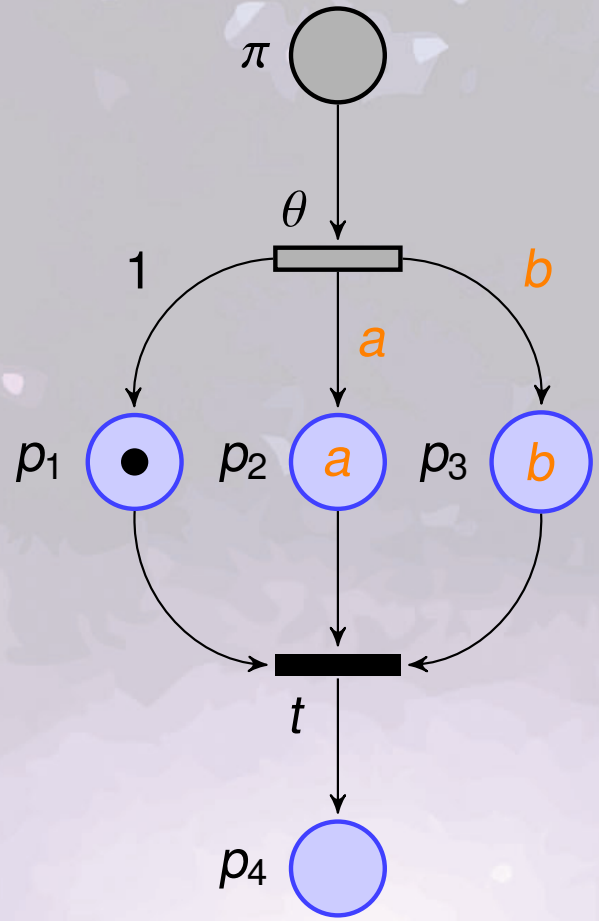

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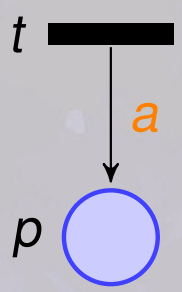
From Output Weights to Markings



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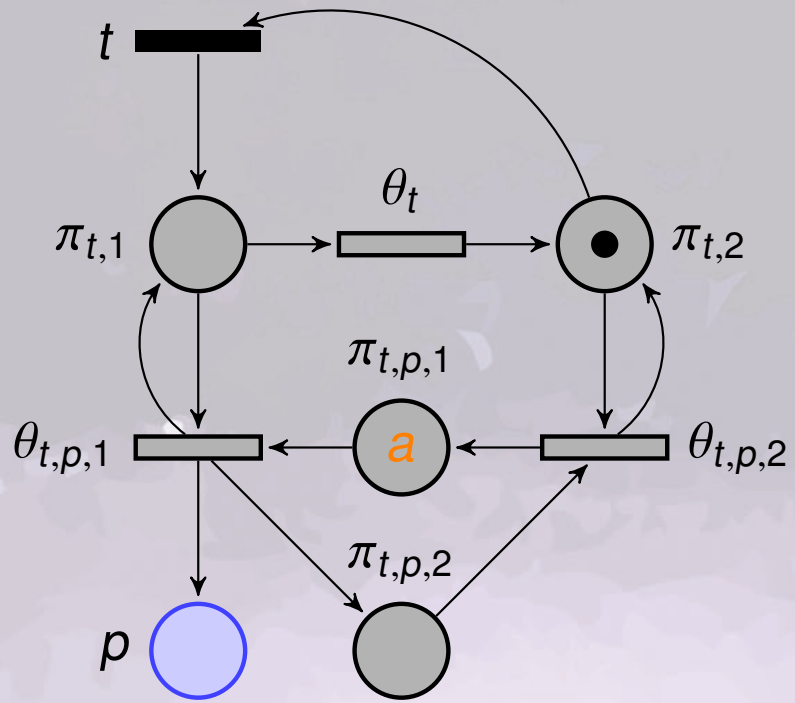
postT parameters
by **P parameters**



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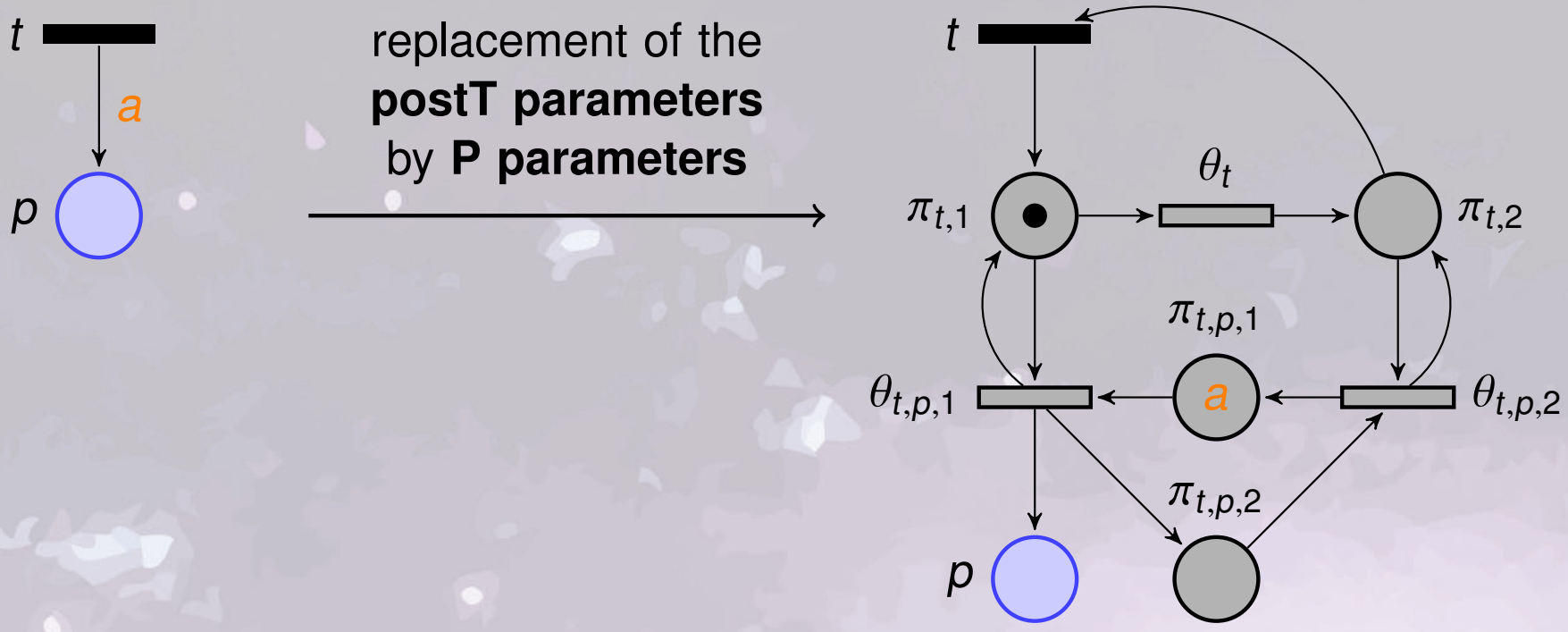

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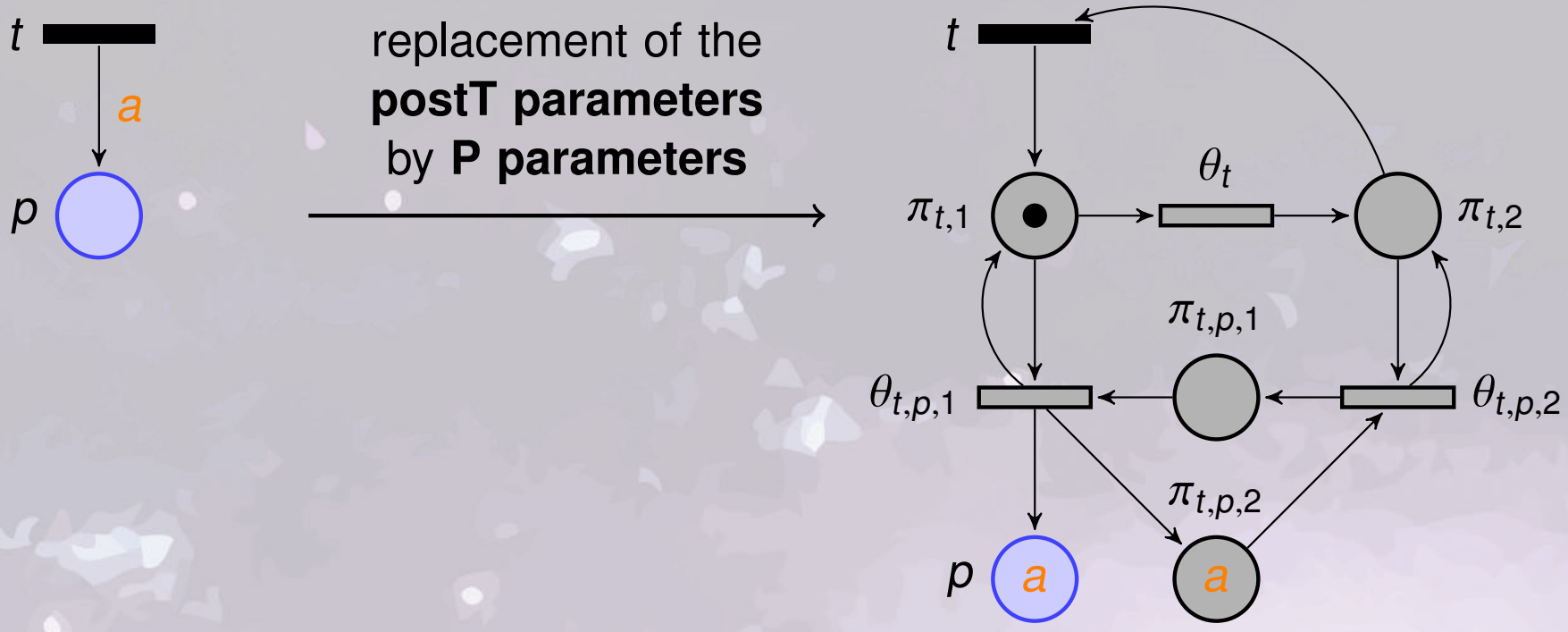

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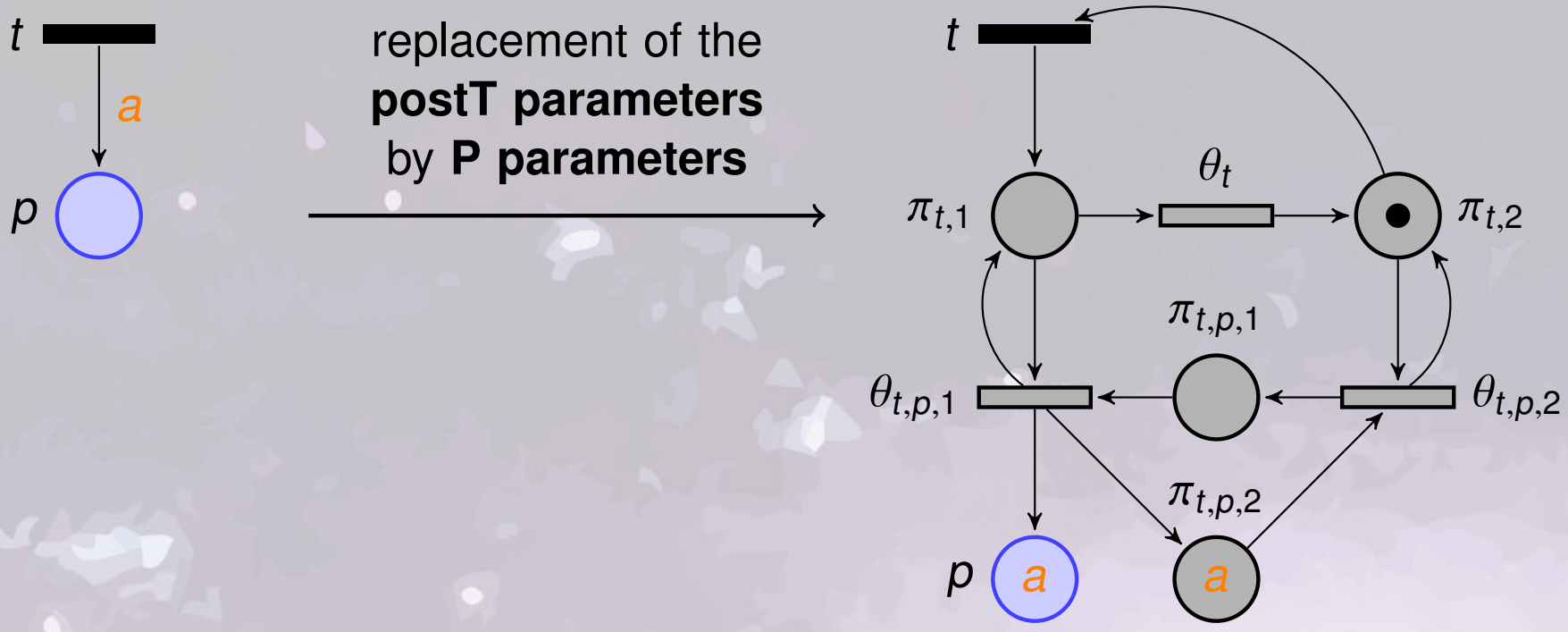

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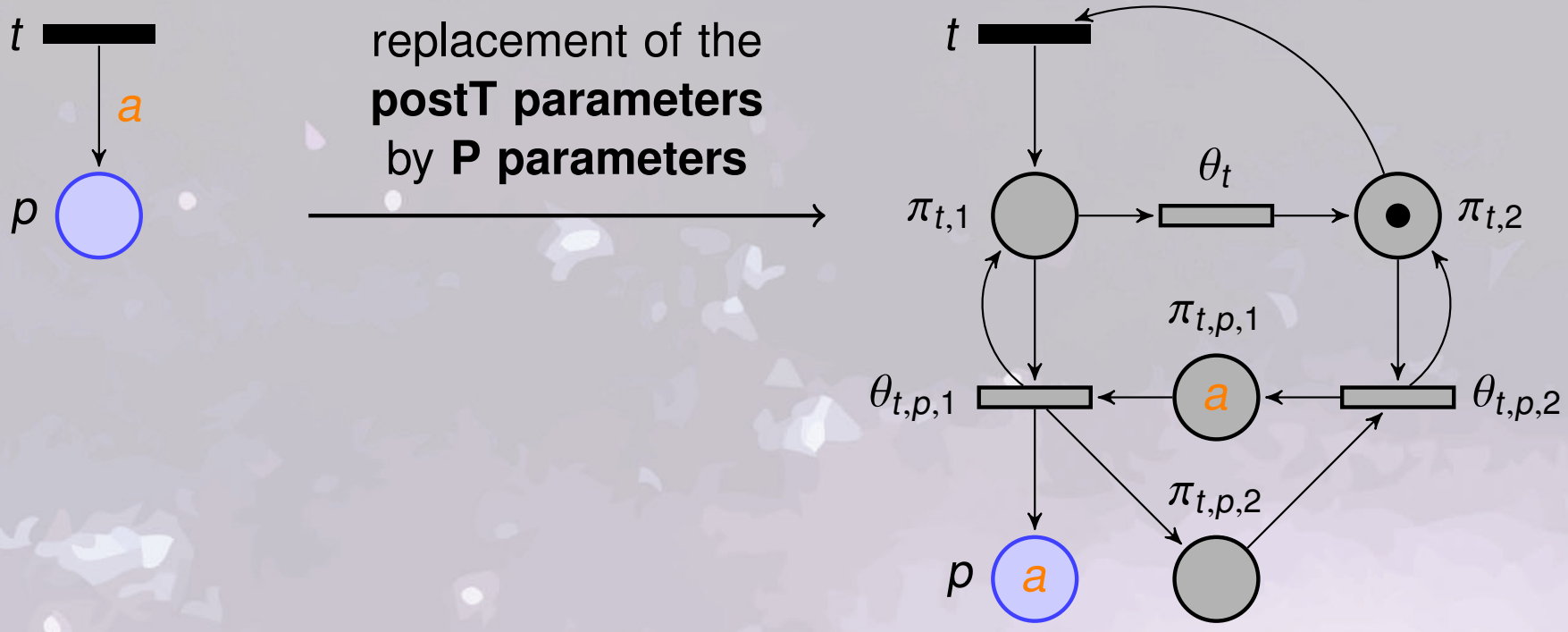

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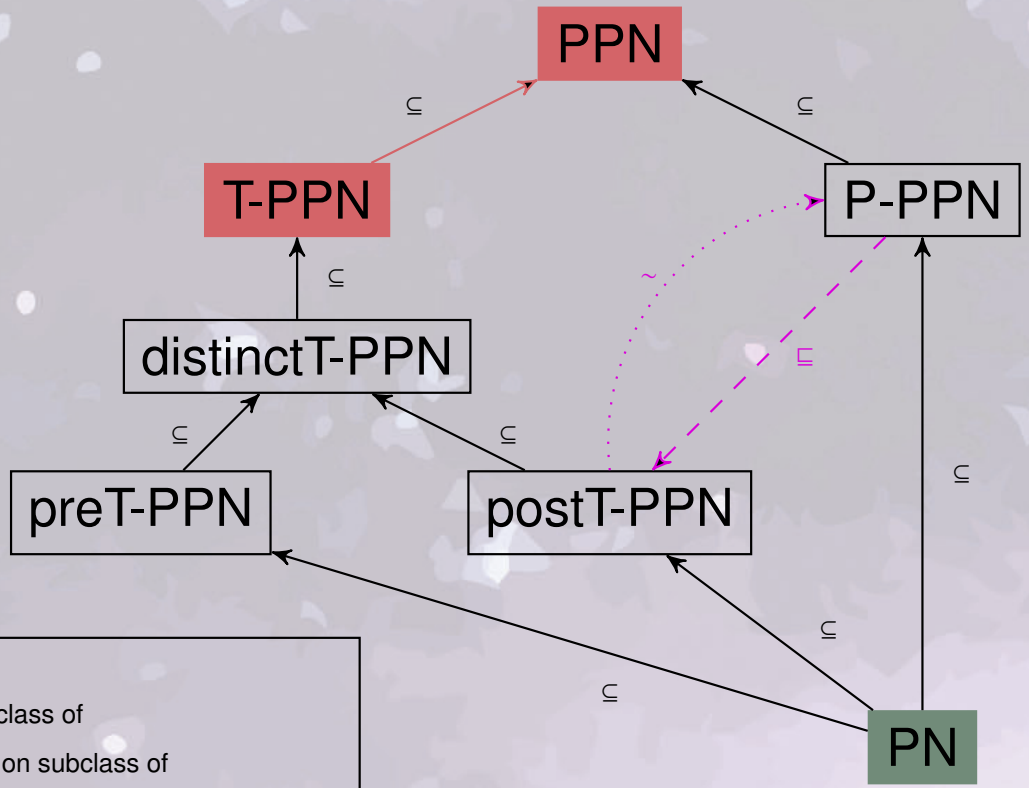
Decidable Subclasses: A Hierarchy of Parametric PNs



Caption:
- ⊆ : is a syntactical subclass of
- ⊑ : is a weak-bisimulation subclass of
- ∼ : is a weak-cosimulation subclass of

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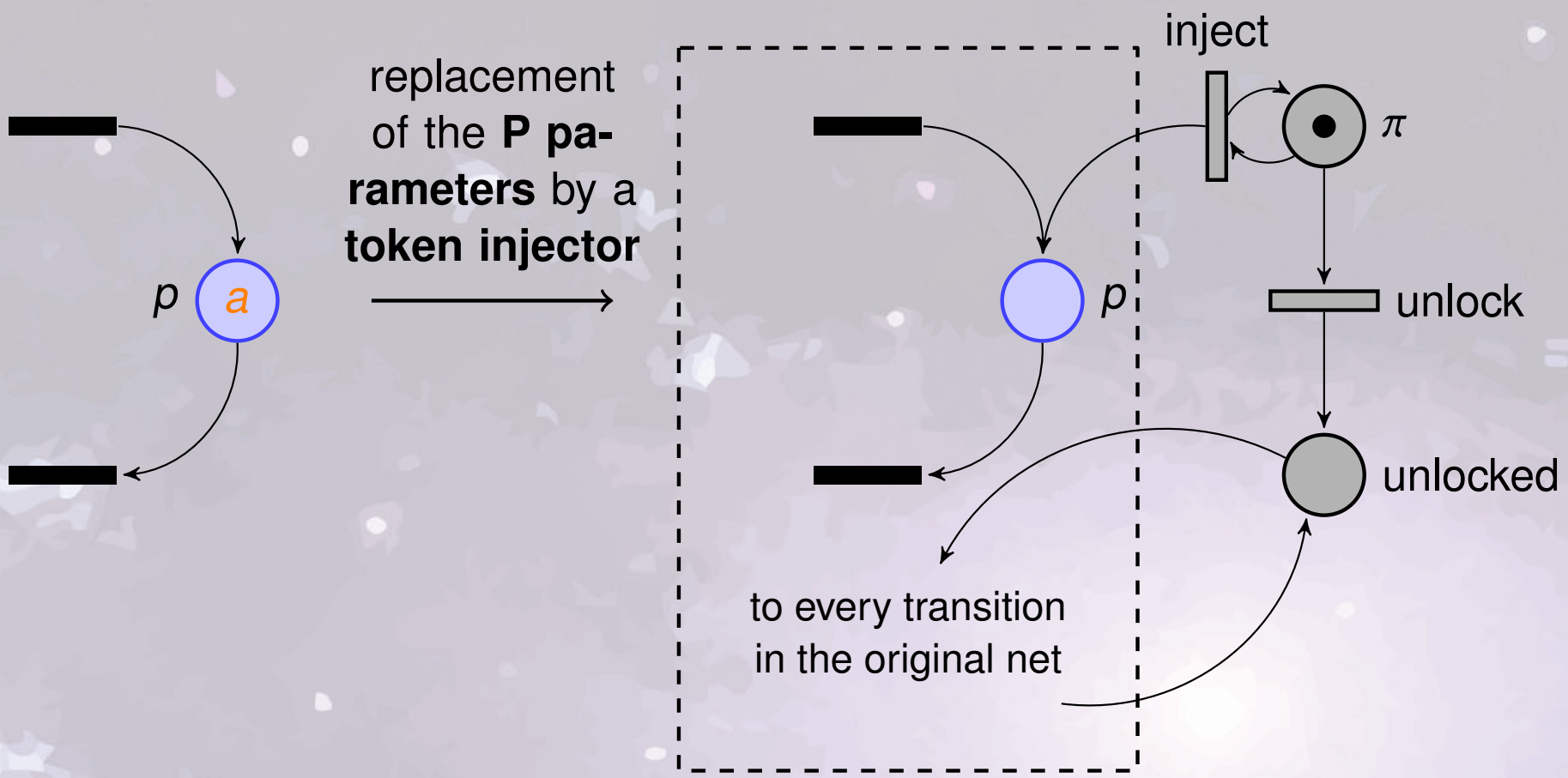
From Parametric Markings to Classic Petri Nets

- for U-cov: all parameters to 0 is the worst case ;
- for E-cov:



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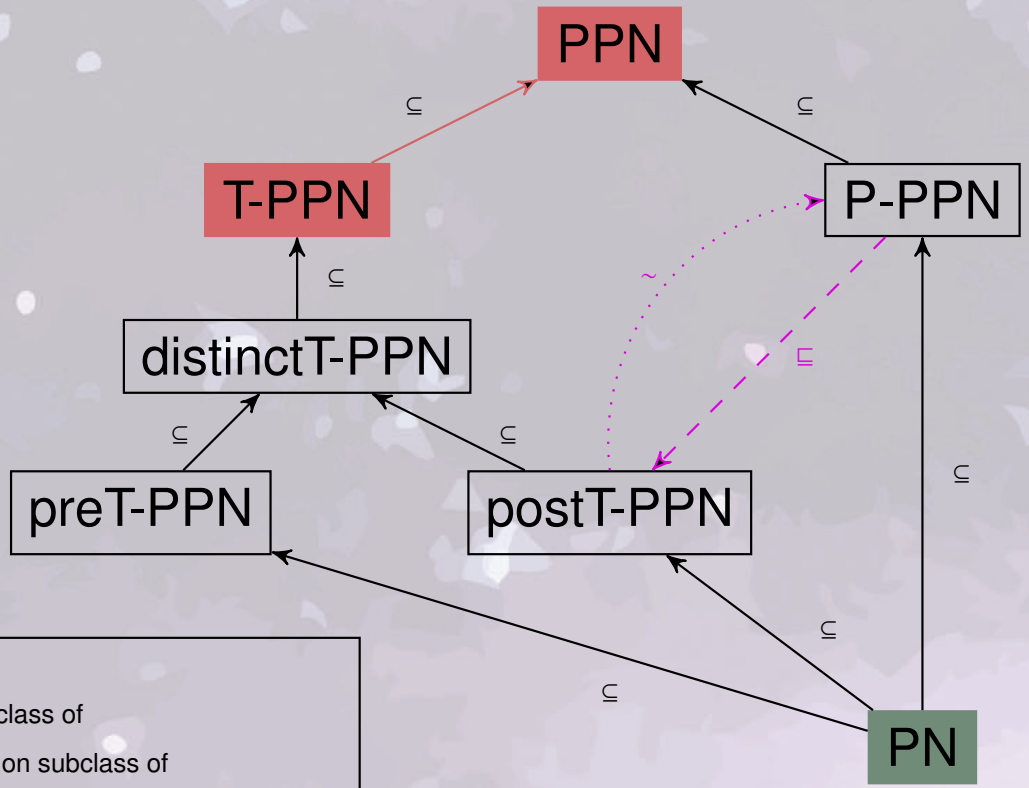

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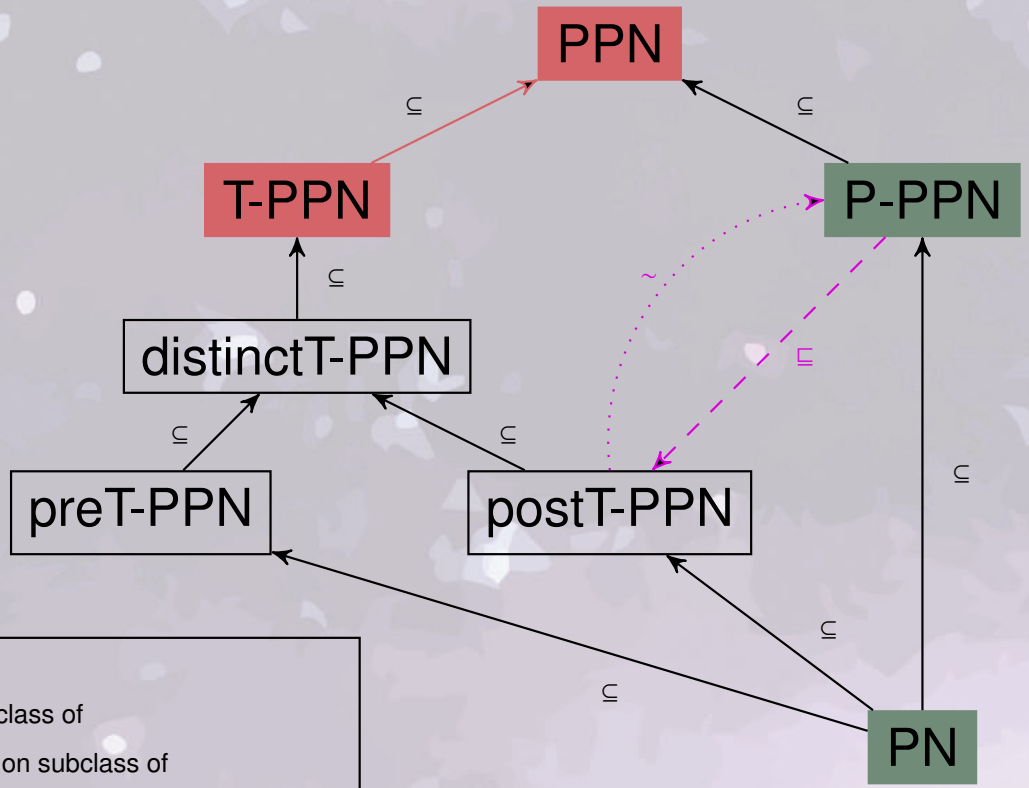

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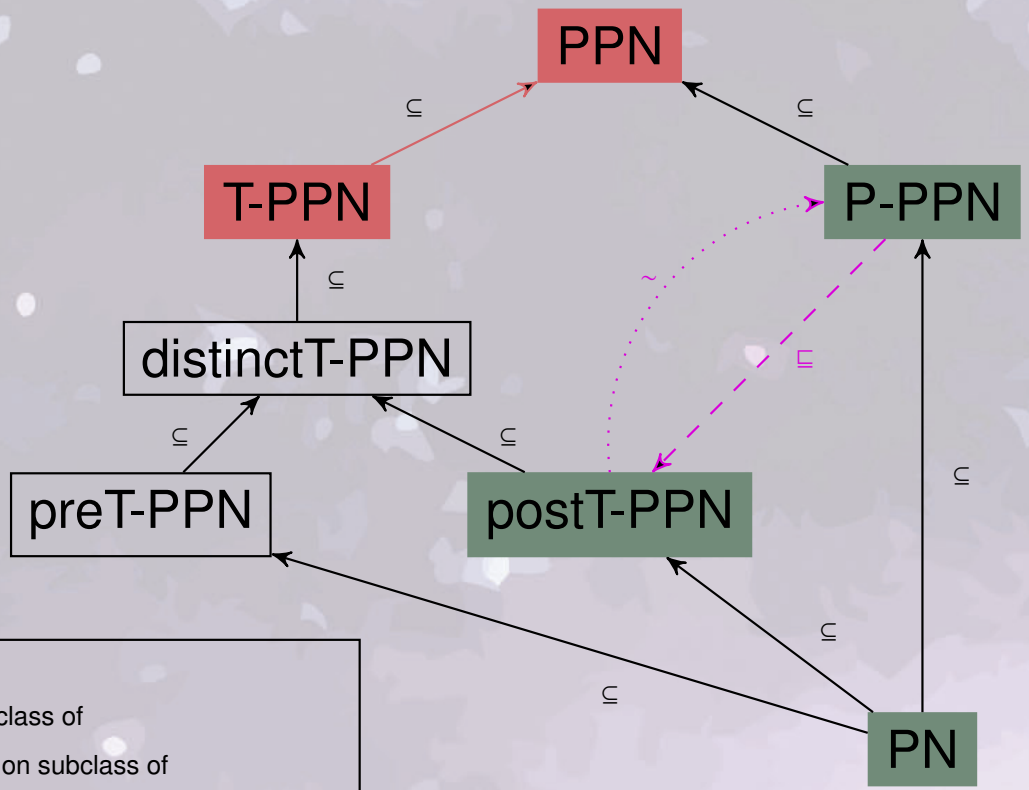

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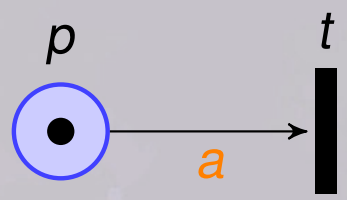
Deciding Coverability with Parametric Input Weights



- for E-cov: all parameters to 0 is the best case;
- for U-cov: reduce to simultaneous unboundedness in Petri Nets Demri [2013];
  - intuitively a transition with parametric arcs can be fired if its corresponding input places are unbounded;
  - guess an order in which to use parametric transitions;
  - verify that the input places to parametric arcs become unbounded in the right order.

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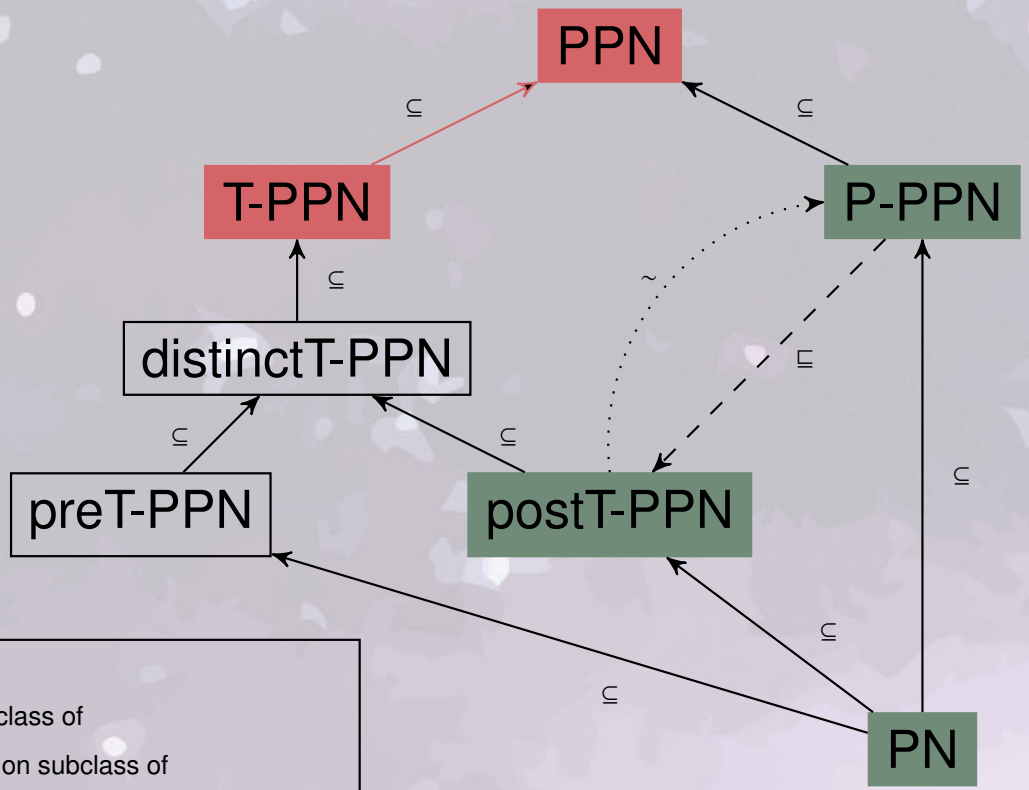

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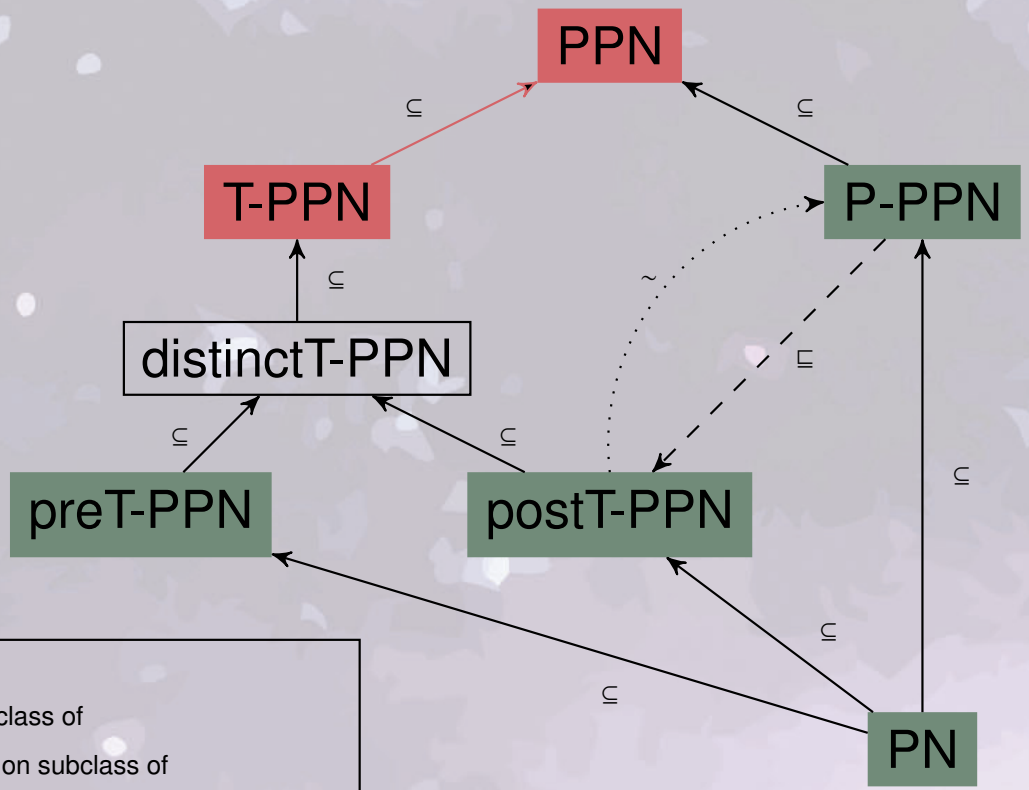

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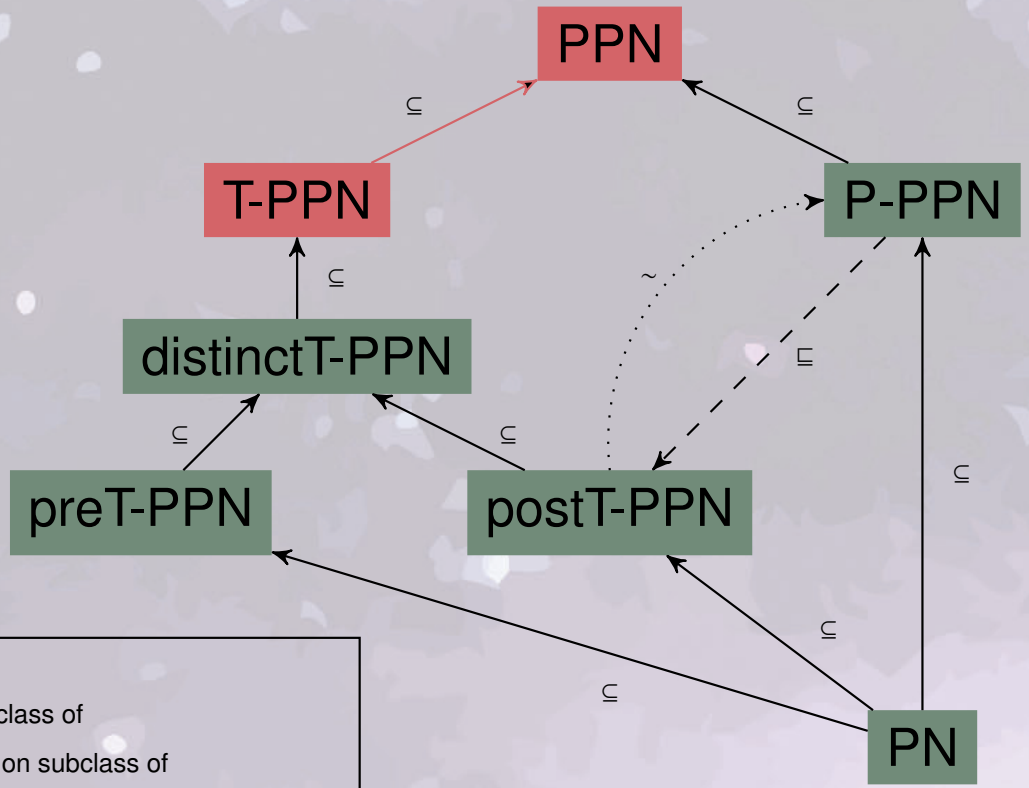

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Synthesis

- Exact synthesis is not feasible in general;
- It can be done for postT-PPNs: the solution set is upward-closed and we can use Valk and Jantzen's algorithm Valk and Jantzen [1985];
- Similarly for preT-PPNs: the solution is downward-closed so its complement is upward-closed;
- Increasing expressiveness to DistinctT-PPNs raises practical issues: we cannot represent the solution set with a formalism for which emptiness of the intersection with equality constraints is decidable:
  1. Take a general PPN
  2. Duplicate parameters p used in both pre and post arcs as p^- used only in pre arcs and p^+ used only in post arcs;
  3. Synthesize the solution set of the obtained DistinctT-PPN;
  4. Intersect with $p^- = p^+$;
  5. Test emptiness.

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Conclusion

- Parametric Petri Nets are an expressive but undecidable model;
- There are interesting and still expressive decidable subclasses;
- For those subclasses, parametric coverability is EXPSPACE-complete;
- We still need efficient (possibly approximate) synthesis algorithms.

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Conclusion

- Parametric Petri Nets are an expressive but undecidable model;
- There are interesting and still expressive decidable subclasses;
- For those subclasses, parametric coverability is EXPSPACE-complete;
- We still need efficient (possibly approximate) synthesis algorithms.

Let us now see how timing parameters can be introduced in (time) Petri Nets

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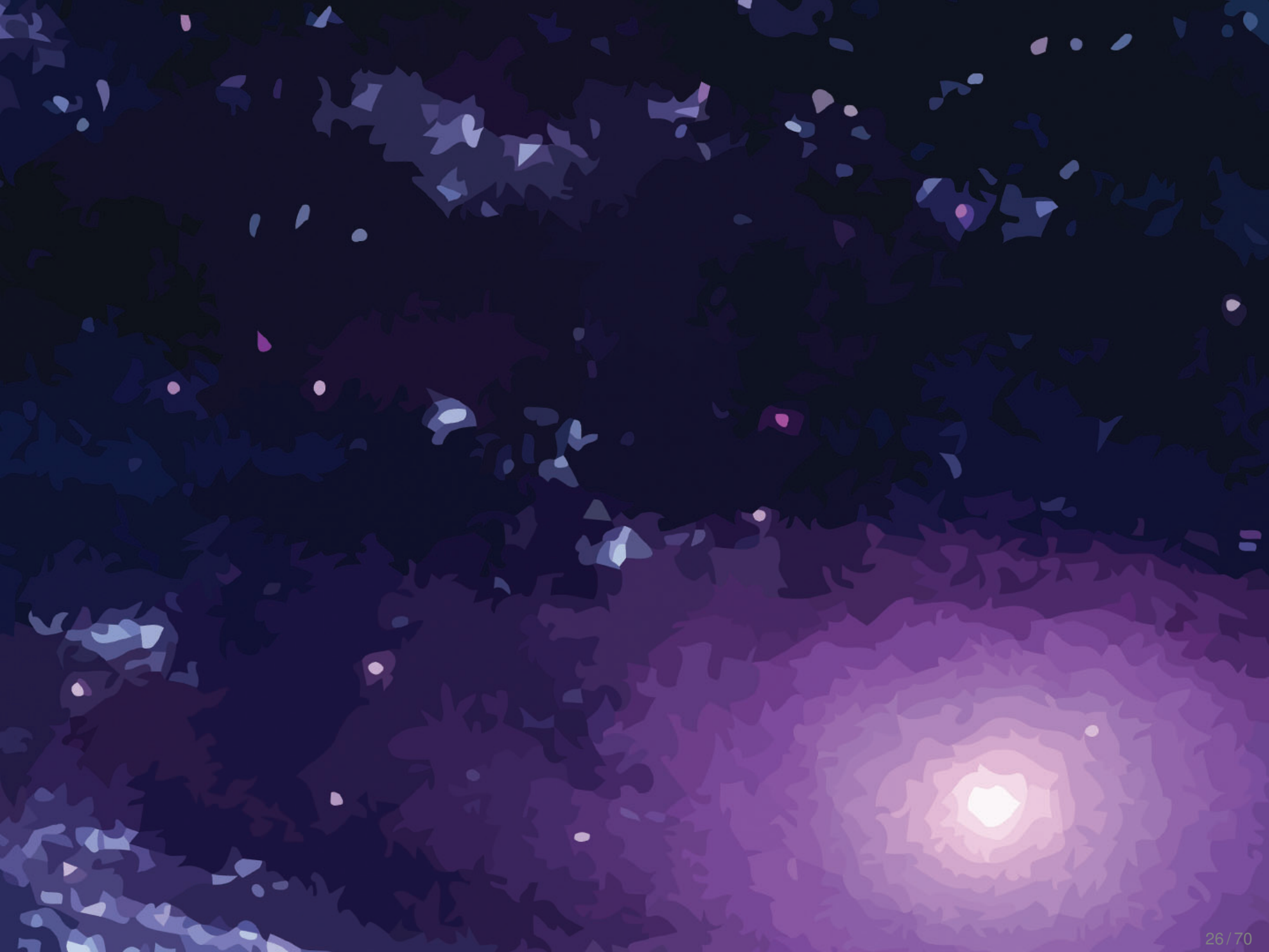

Parametric Time Petri Nets

First of all. . .

You now know about:

- Parametric Petri nets
- Decidability issues

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First of all. . .

You now know about:

- Parametric Petri nets
- Decidability issues

Let us now review Parametric Time Petri nets

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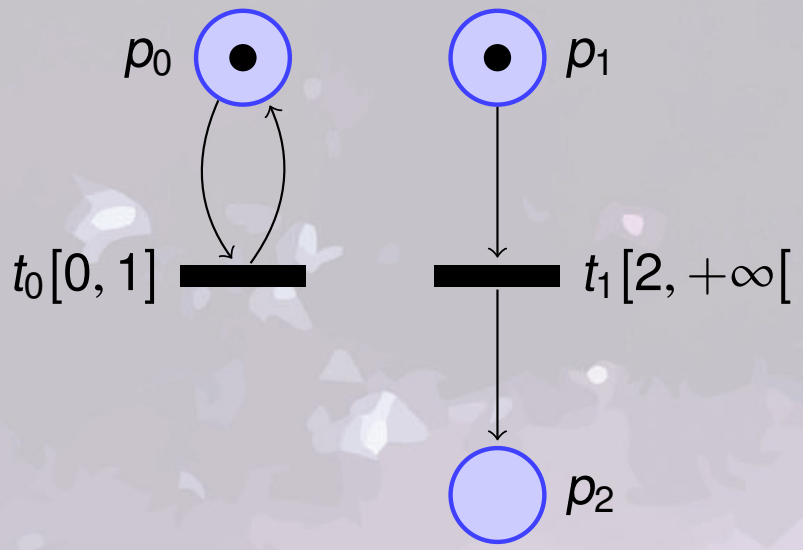
Parametric Time Petri Nets (PTPNs)



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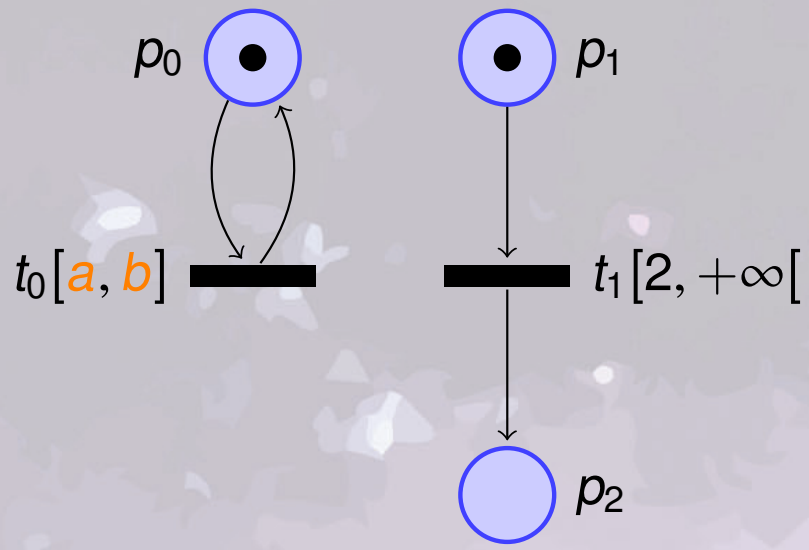
Parametric Time Petri Nets (PTPNs)



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Undecidability Results for Parametric TPNs

- We have a structural translation from timed automata to bounded time Petri nets preserving timed language (implying state reachability) Bérard et al. [2013]
- Has one gadget per simple constraint in guards and timing constants appear explicitly;
- It extends trivially to parameterized guards.

Theorem

The EF-emptiness problem is undecidable for bounded parametric time Petri nets.

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Decidability Results for Parametric TPNs

- We also have structural translations the other way round (preserving almost everything); Bérard et al. [2013]
- All decidability results carry over to parametric Petri nets;
- The symbolic state abstraction presented earlier can also be defined for PTPNs; Gardey et al. [2006]
- EFSynth and similar algorithms can be used as is for PTPNs!
- But TPNs enjoy a “better” symbolic abstraction: Berthomieu & Menasche’s State Classes. Berthomieu and Menasche [1983]; Berthomieu and Diaz [1991]

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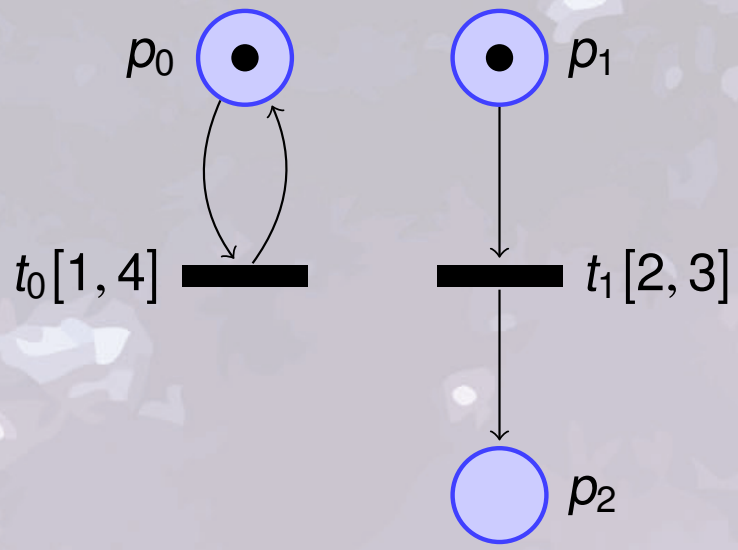
State Classes for Time Petri Nets

- State classes also regroup states obtained with the same discrete transition sequence in a pair (l, Z) where Z is a zone;
- But states record time to firing instead of time elapsed;



Initially:

$$\begin{cases} 1 \le t_0 \le 4 \\ 2 \le t_1 \le 3 \end{cases}$$

Fire t_0:

$$\begin{cases} 1 \le t_0 \le 4 \\ 2 \le t_1 \le 3 \\ t_0 \le t_1 \end{cases}$$

New times to fire:

$$\begin{cases} 1 \le t_0 \le 4 \\ 2 \le t_1' + t_0 \le 3 \\ t_0 \le t_1' + t_0 \end{cases}$$

Disabled (incl. t_0):

$$\begin{cases} 0 \le t_1' \le 2 \end{cases}$$

Newly enabled:

$$\begin{cases} 1 \le t_0 \le 4 \\ 0 \le t_1 \le 2 \end{cases}$$

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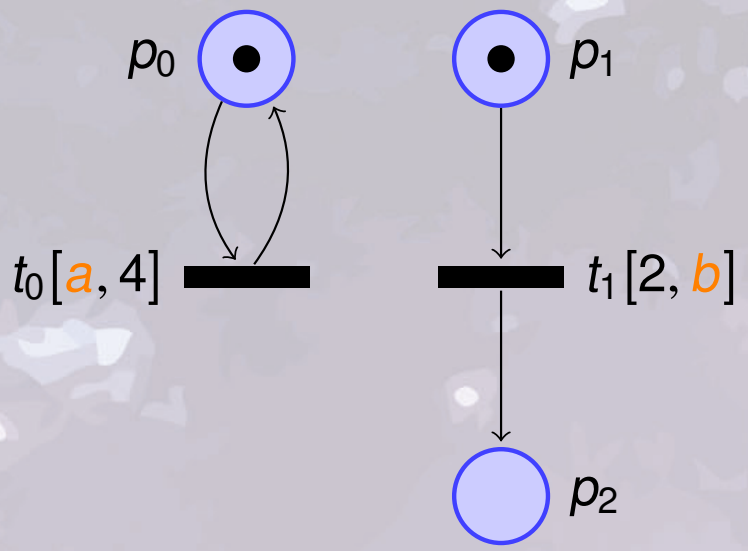
State Classes for Parametric Time Petri Nets

- Successive state classes computations are done with classic polyhedral operations;
- They can be extended to account for timing parameters Traonouez et al. [2009]:



Initially:

$$\begin{cases} a \leq t_0 \leq 4 \\ 2 \leq t_1 \leq b \end{cases}$$

Fire t_0:

$$\begin{cases} a \leq t_0 \leq 4 \\ 2 \leq t_1 \leq b \\ t_0 \leq t_1 \\ (a \leq b) \end{cases}$$

New times to fire:

$$\begin{cases} a \leq t_0 \leq 4 \\ 2 \leq t_1' + t_0 \leq b \\ t_0 \leq t_1' + t_0 \end{cases}$$

Disabled (incl. t_0):

$$\begin{cases} 0 \leq t_1' \leq b - a \end{cases}$$

Newly enabled:

$$\begin{cases} a \leq t_0 \leq 4 \\ 0 \leq t_1 \leq b - a \end{cases}$$

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Synthesis for Parametric TPNs

- EFSynth works the same with parametric state classes;

$$\mathrm{EF}_G(S,M) = \begin{cases} Z{\downarrow_P} & \text{if } l \in G \\ \emptyset & \text{if } S \in M \\ \bigcup\limits_{\substack{t \in T \\ S' = \mathrm{Next}(S,t)}} \mathrm{EF}_G\big(S', M \cup \{S\}\big) & \text{otherwise.} \end{cases}$$

- We can also do synthesis for inevitability Jovanović et al. [2015]:

$$\mathrm{AF}_G(S,M) = \begin{cases} Z{\downarrow_P} & \text{if } l \in G \\ \emptyset & \text{if } S \in M \\ \Big(\bigcap\limits_{\substack{t \in T \\ S' = \mathrm{Next}(S,t)}} \big(\mathrm{AF}_G\big(S', M \cup \{S\}\big) \cup (\mathbb{Q}^P \setminus S'{\downarrow_P})\big)\Big) \setminus \mathrm{dead}(S) & \text{otherwise} \end{cases}$$

- $S = (l, Z)$, G a set of markings to reach;
- M is a list of visited state classes;
- $\mathrm{Next}(S,t)$ computes the state class successor of S by transition t;
- $\mathrm{dead}(S)$ is the set of parameters s.t. S has no successor;
- termination is not guaranteed.

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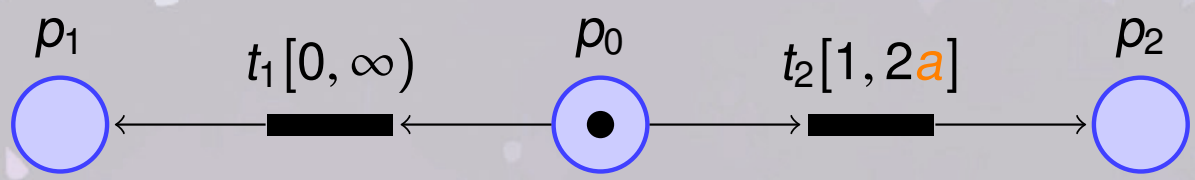
AF: Cutting for More



- Put a token in p_1: no constraint
- Put a token in p_2: $a \geq \frac{1}{2}$
- Ensuring both paths are possible (for AF ($p_1 > 0$ or $p_2 > 0$)): $a \geq \frac{1}{2}$
- Or we can cut t_2 and p_2 off with $a < \frac{1}{2}$ and the property is satisfied with no further constraint
- Finally, AF ($p_1 > 0$ or $p_2 > 0$) is satisfied for all values of a.

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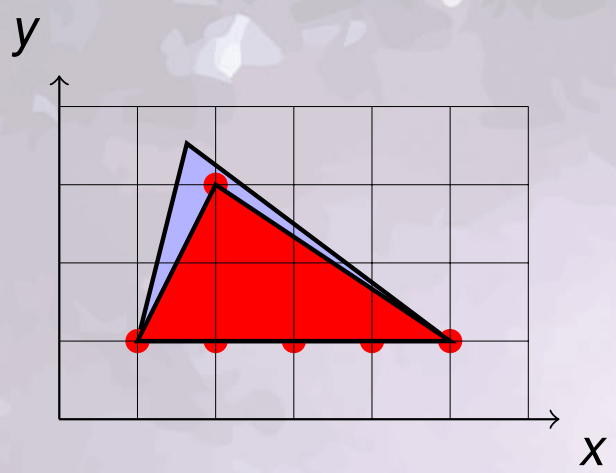
Symbolic Synthesis for Bounded Integers

- EF-emptiness is undecidable for integer parameters Alur et al. [1993];
- It is undecidable for bounded rational parameters Miller [2000];
- It is PSPACE-complete for bounded integer parameters Jovanović et al. [2015].
  - non-deterministically guess a parameter valuation and store it (polynomial storage size);
  - instantiate the PTA or PTPN and solve the problem (PSPACE);
  - PSPACE = NPSPACE (Savitch's theorem).
- Synthesis can be done symbolically, using integer hulls:



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Symbolic Synthesis for Bounded Integer Parameters

- IEF computes polyhedra containing exactly the "good" integer parameter valuations:

$$\mathrm{IEF}_G(S,M) = \begin{cases} Z{\downarrow_P} & \text{if } l \in G \\ \emptyset & \text{if } S \in M \\ \bigcup_{\substack{t \in T \\ S' = \mathrm{IH}(\mathrm{Next}(S,t))}} \mathrm{IEF}_G\big(S', M \cup \{S\}\big) & \text{otherwise.} \end{cases}$$

- It is guaranteed to terminate when the parameters are bounded;
- AF can be modified similarly.

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Density of the Results

- The question:
  - the result of IEF or IAF is a union of convex polyhedra;
  - we know that these sets contain exactly the “good” integer valuations;
  - but what of the non-integer valuations in those polyhedra?
- The short answer:
  - they are all “good” for IEF (but we can do a bit better);
  - they are in general not all “good” for IAF (and we can do a bit better).

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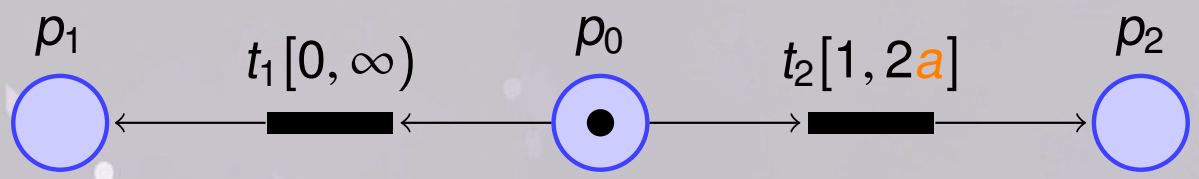
The Result of IAF is not Dense



- To ensure AF ($p_1 > 0$), cut t_2 and p_2, i.e., take $a < \frac{1}{2}$;
- When p_2 is marked, $Z_2 = \{1 \leq x \wedge 1 \leq 2a\}$, so $\mathrm{IH}(C_2) = \{1 \leq x \wedge 1 \leq a\}$
- So, to cut ($p_2 = 1, \mathrm{IH}(Z_2)$), we need $a < 1$.
- $\frac{1}{2} \leq a < 1$ are not "good" valuations.

Integer-preserving Dense Underapproximations

- In IAF, we cut off not enough states because $\mathrm{IH}(Z) \subseteq Z$;
- Solution: use integer hulls only for convergence André et al. [2015]:

$$\mathrm{RIEF}_G(S,M) = \begin{cases} Z{\downarrow_P} & \text{if } l \in G \\ \emptyset & \text{if } \mathrm{IH}(S) \in M \\ \bigcup_{\substack{t \in T \\ S' = \mathrm{Next}(S,t)}} \mathrm{EF}_G\big(S', M \cup \{\mathrm{IH}(S)\}\big) & \text{otherwise.} \end{cases}$$

- Similarly for RIAF;
- Gives a “dense” underapproximation containing at least all integer valuations.

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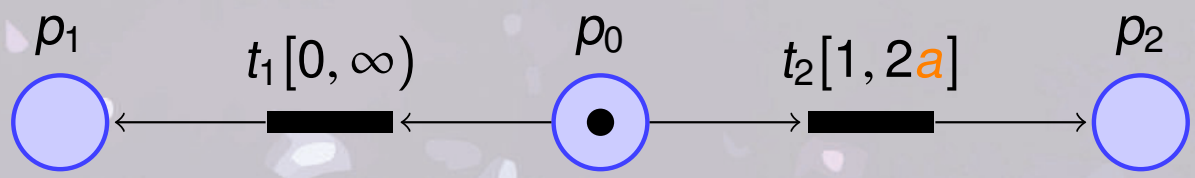
Dense Integer-preserving Underapproxations



- AF l_1: $a < \frac{1}{2}$ instead of (erroneous) $a < 1$ for IAF
- EF l_2: $a \geq \frac{1}{2}$ instead of $a \geq 1$ for IEF

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Conclusion

- Time Petri nets are well-suited to timing parametrization;
- Bounded PTPNs globally have the same decidability results as PTA;
- Synthesis (semi-)algorithms for PTA can be adapted for PTPN (and are sometimes a bit simpler);
- They can use state classes;
- General synthesis is hard and approximate/partial synthesis is a good way to address this problem;

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Roméo is a tool that supports parametric TPNs (next sequence)

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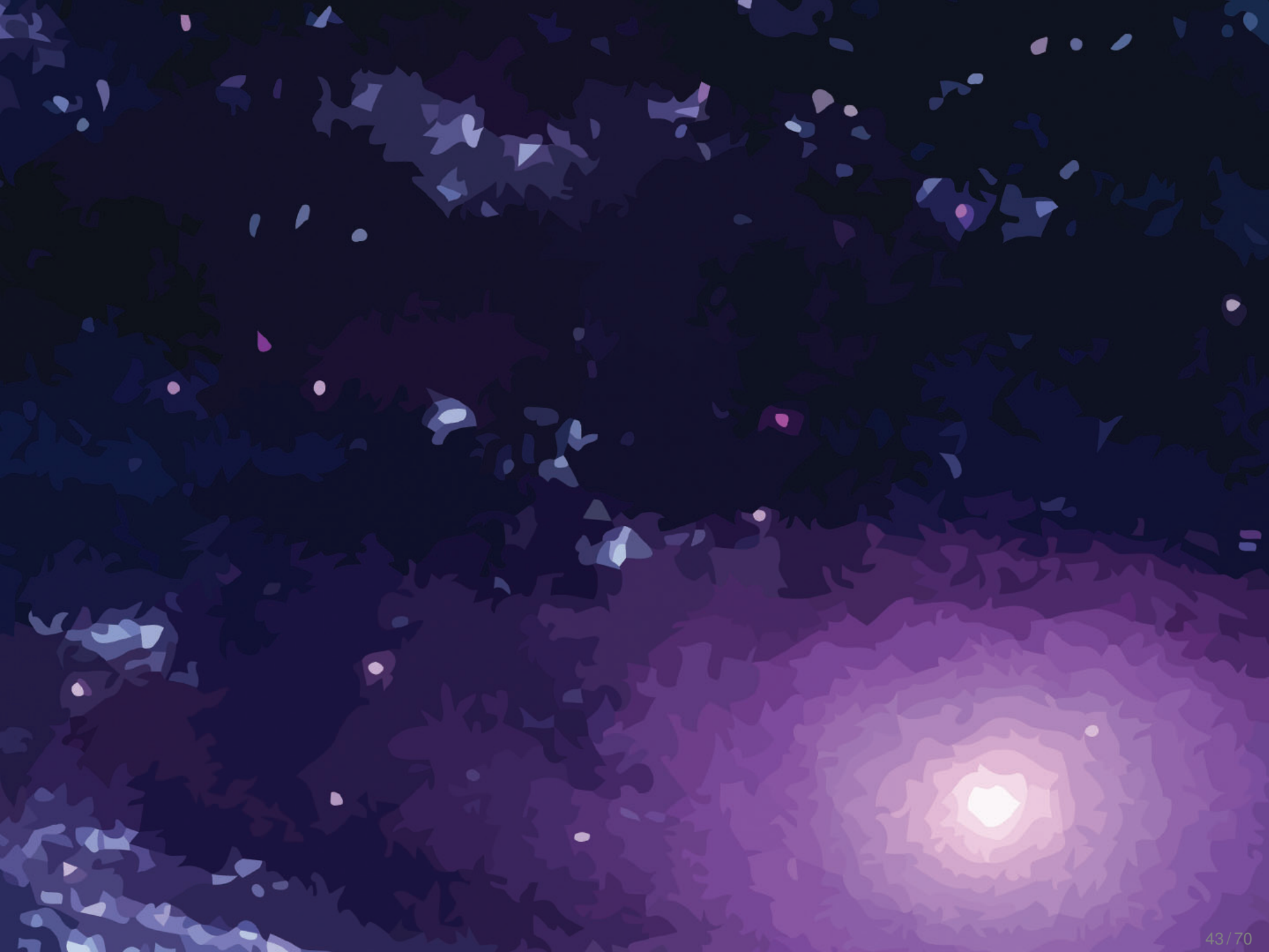

Roméo in a nutshell

First of all . . .

You know that:

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Roméo is a tool that supports parametric TPNs

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Roméo

- An analysis tool / model-checker for time Petri nets with
  - timing parameters;
  - hybrid extensions;
  - discrete variables;
  - cost optimisation;
- Developed at Nantes since 2000, mostly by Olivier H. Roux and Didier Lime;
- Tool papers Gardey et al. [2005]; Lime et al. [2009]
- Free and open-source (CeCILL license)

Available at `http://romeo.rts-software.org/`

Roméo: Some Success Stories

- Analysis of resilience properties in oscillatory biological systems Andreychenko et al. [2016];
- Environment requirements for an aerial video tracking system (with Thales Research) Parquier et al. [2016];
- Operational scenarios modelling in the DGA OMOTESC project (with Sodius Nantes, Charlotte Seidner's Ph. D.) Seidner [2009].

Conclusion

At this stage, you know about:

- Petri nets with discrete parameters
- time Petri nets with timing parameters

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At this stage, you know about:

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Let us address synthesis of actions (next sequence)

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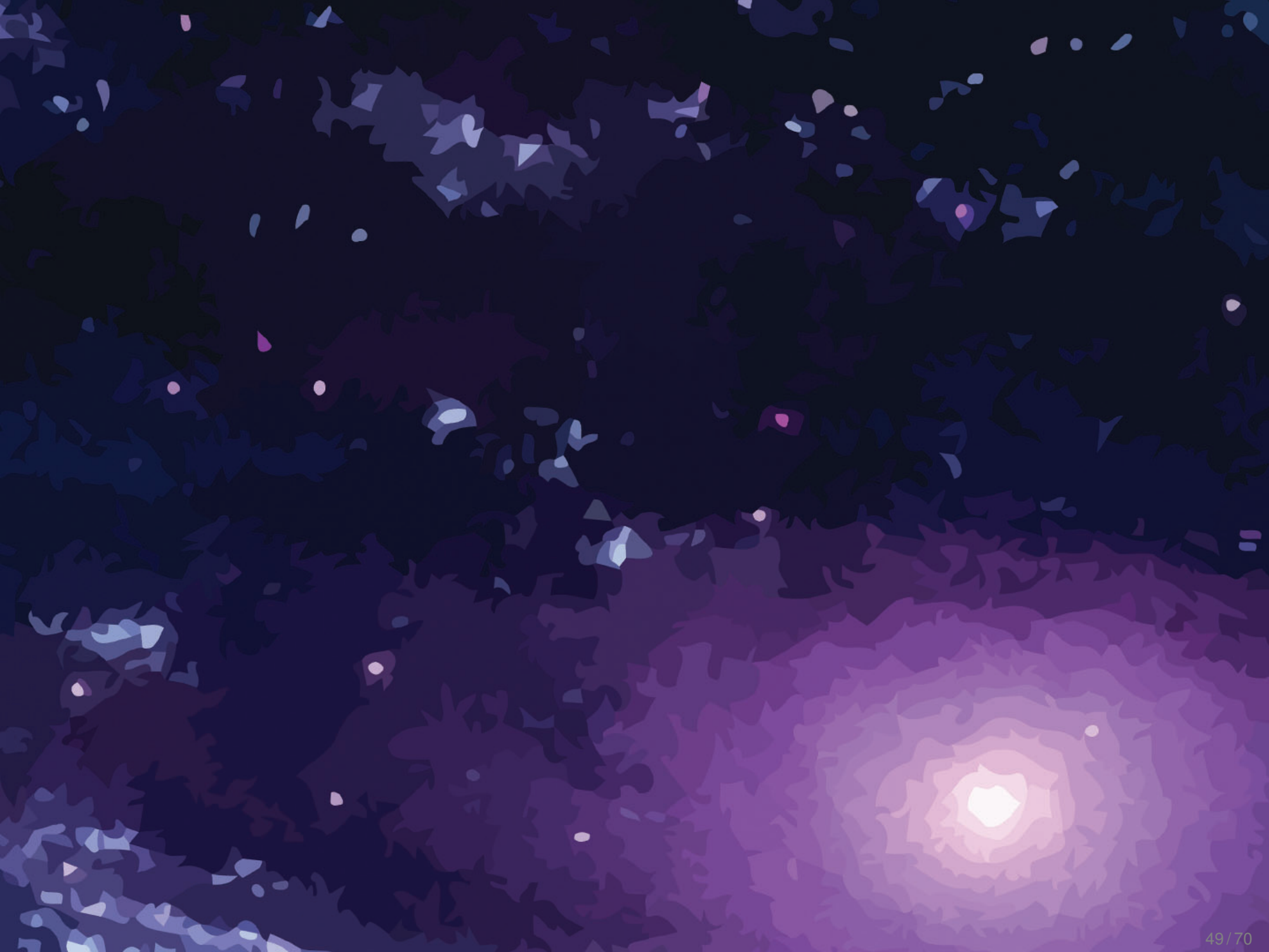

Action Synthesis

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First of all. . .

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Let us now address synthesis of actions

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Mixed Transition Systems (MTS) Pecheur and Raimondi [2006]

MTS: *Kripke structures with action-labelled transitions*

MTS (model) is a 5-tuple $\mathcal{M} = (\mathcal{S}, s^0, \mathcal{A}, \mathcal{T}, \mathcal{L})$, where:

- $\mathcal{S}$ – a set of states,
- $s^0 \in \mathcal{S}$ – the initial state,
- $\mathcal{A}$ – a set of actions,
- $\mathcal{T} \subseteq \mathcal{S} \times \mathcal{A} \times \mathcal{S}$ – a labelled transition relation,
- $\mathcal{PV}$ – a set of the propositional variables,
- $\mathcal{L} : \mathcal{S} \to 2^{\mathcal{PV}}$ – a labelling function.

A path π in $\mathcal{M}$ is a maximal sequence $s_0 a_0 s_1 a_1 \ldots$ of states and actions such that $(s_i, a_i, s_{i+1}) \in \mathcal{T}$.

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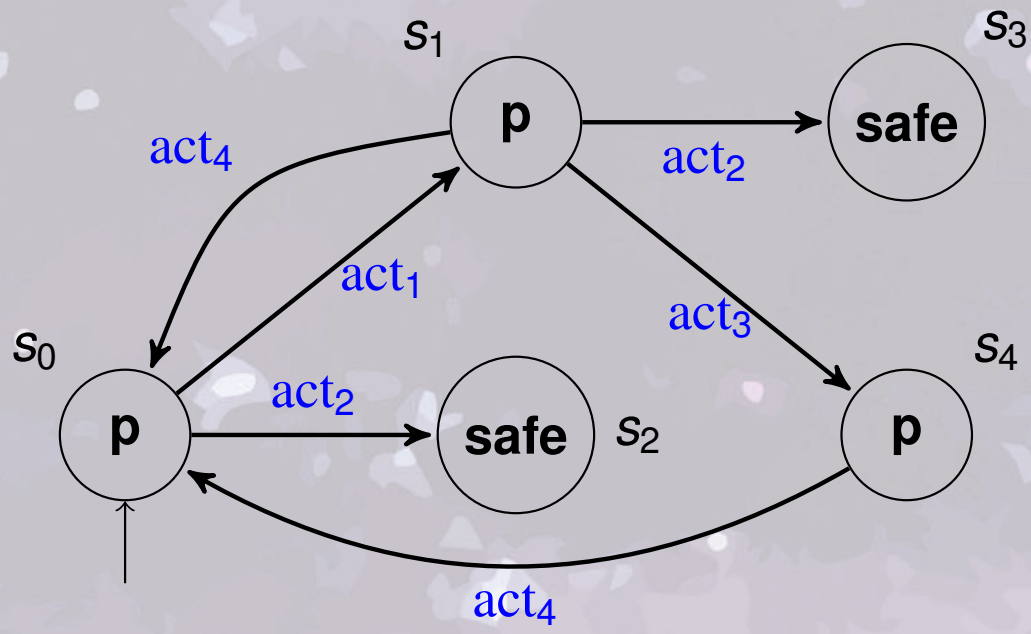
Allowed and disabled actions



$A \subseteq \mathcal{A}$ – a set of allowed actions

- $\Pi(A, s)$ – the maximal paths over A, starting from s

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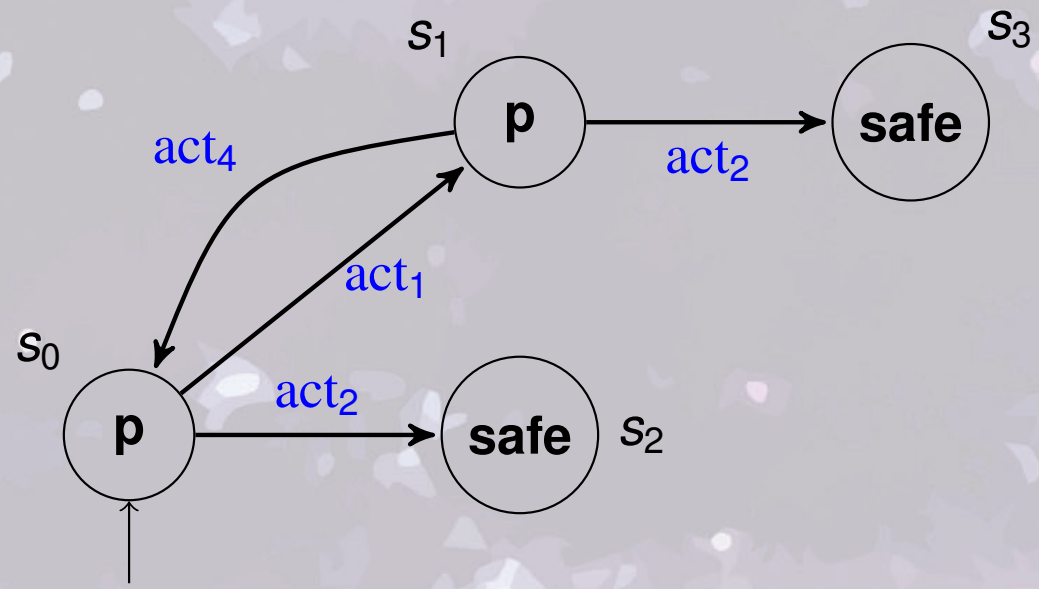

$A \subseteq \mathcal{A}$ – a set of allowed actions

- $\Pi(A, s)$ – the maximal paths over A, starting from s

$$\Pi(\{act_1, act_2, act_4\}, s_0) =$$
$$\{(s_0 act_1 s_1 act_4)^\omega + (s_0 act_1 s_1 act_4)^* s_0 act_1 s_1 act_2 s_3 + (s_0 act_1 s_1 act_4)^* s_0 act_2 s_2\}$$

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Parametric ARCTL

pmARCTL: CTL *with action (variables) subscripts*

ActSets – the non-empty subsets of $\mathcal{A}$
ActVars – the action variables

pmARCTL: the formulae ϕ generated by the BNF grammar:

$$\phi ::= p \mid \neg\phi \mid \phi \vee \phi \mid E_\alpha X\phi \mid E_\alpha G\phi \mid E_\alpha(\phi \; U \; \phi)$$

$p \in \mathcal{PV}$, $\alpha \in \text{ActSets} \cup \text{ActVars}$

- E_α – *"there exists a maximal path over α"*
- X, G, U – *neXt, Globally, Until*

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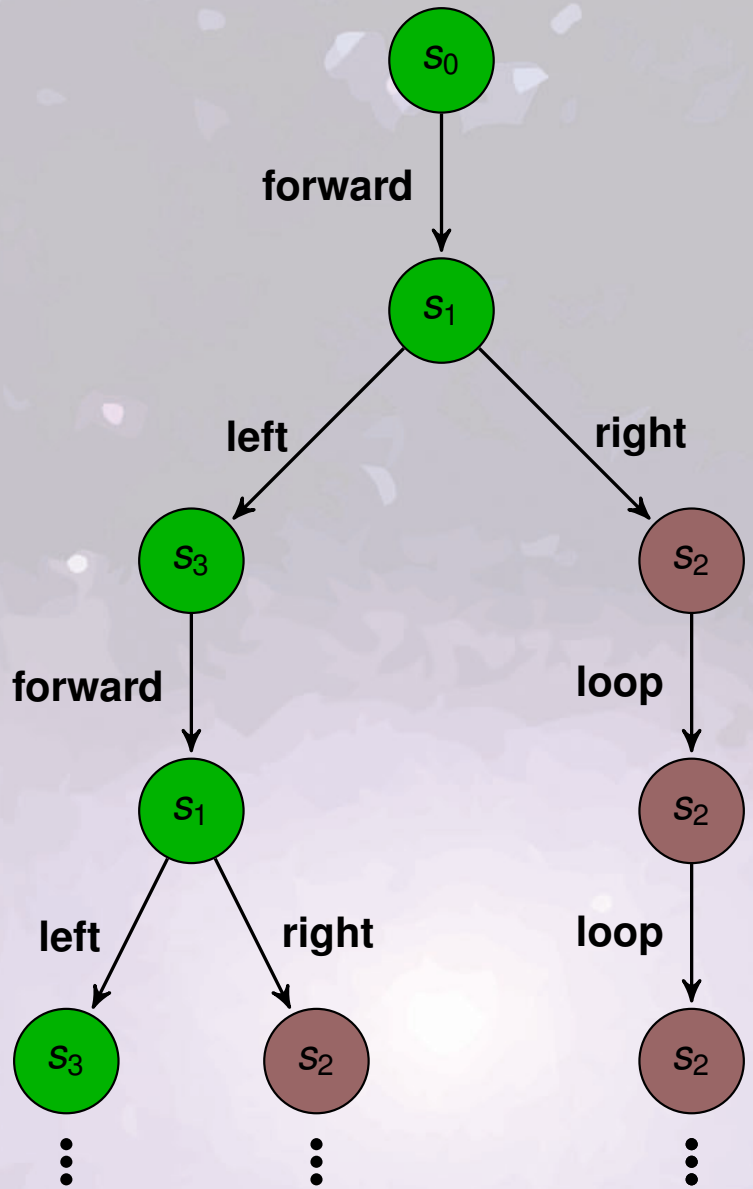
- E_α – *"there exists a maximal path over α"*
- X, G, U – *neXt, Globally, Until*
- (derived) A_α – *"for each maximal path over α"*
- (derived) F – *"in the Future"*

Parametric ARCTL: semantics

States:

- Labelled by p
- Labelled by q

Properties:



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Parametric ARCTL: semantics

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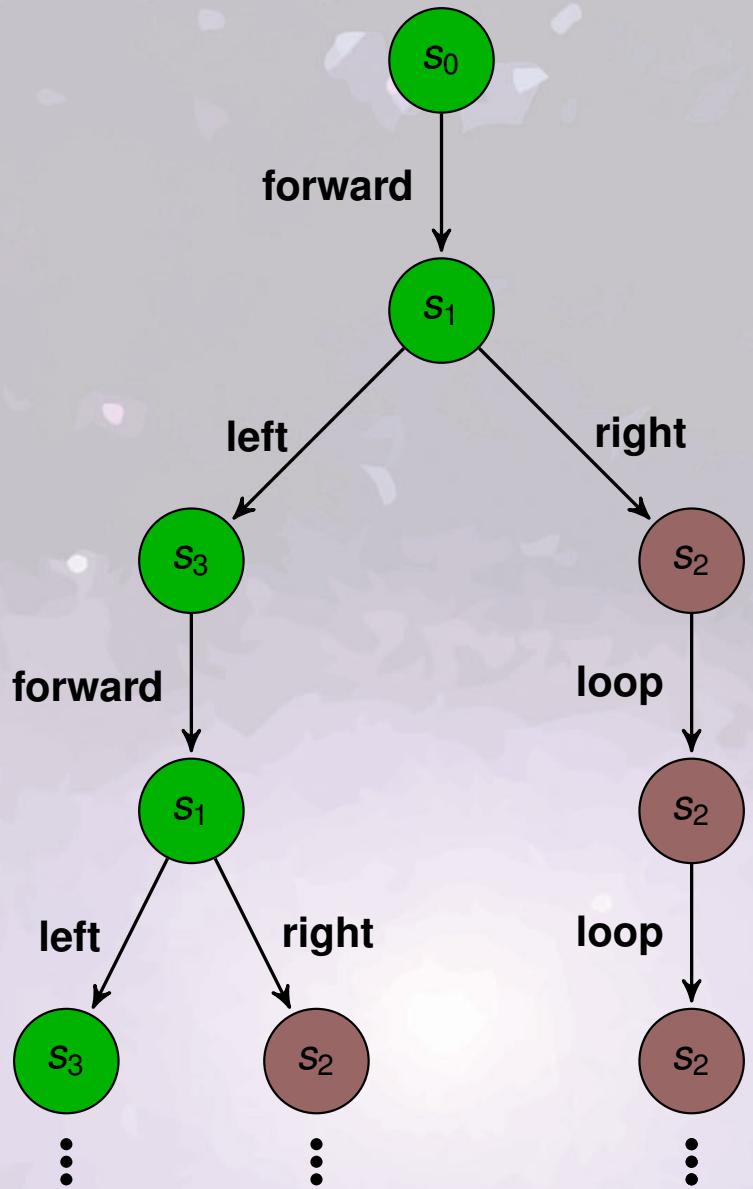
Properties:

- $s_0 \models E_{\{\textbf{forward},\textbf{left}\}} Gp$



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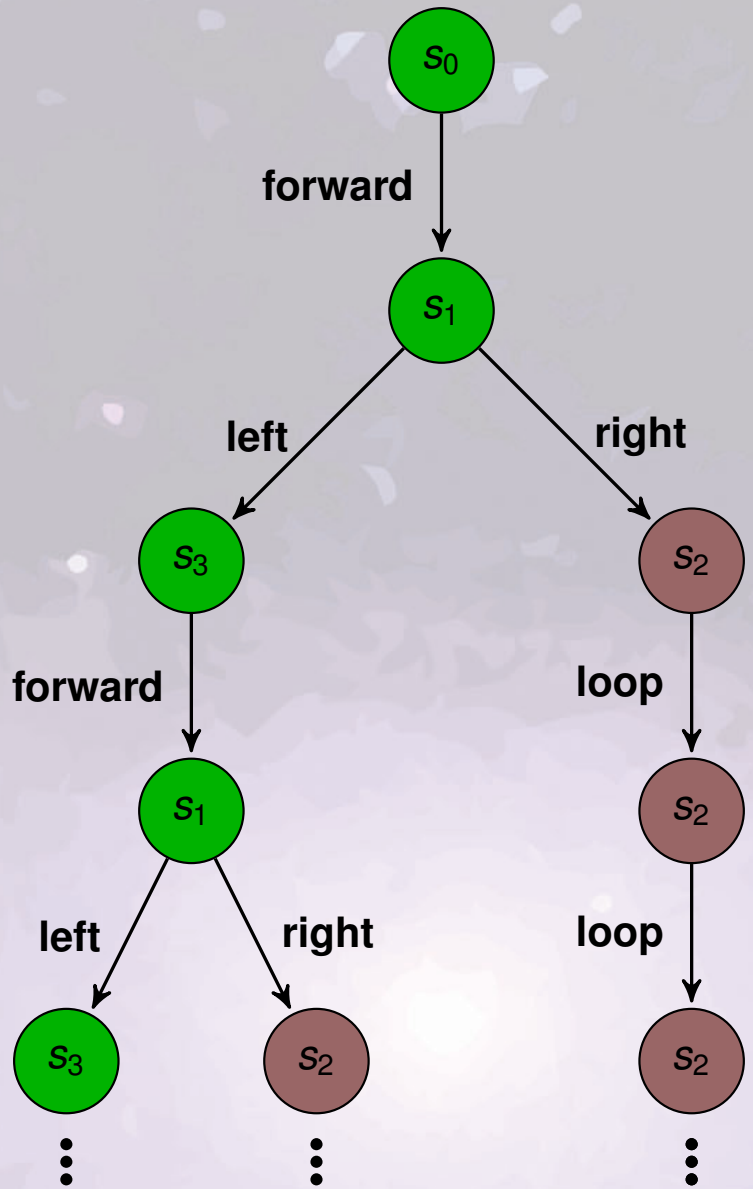

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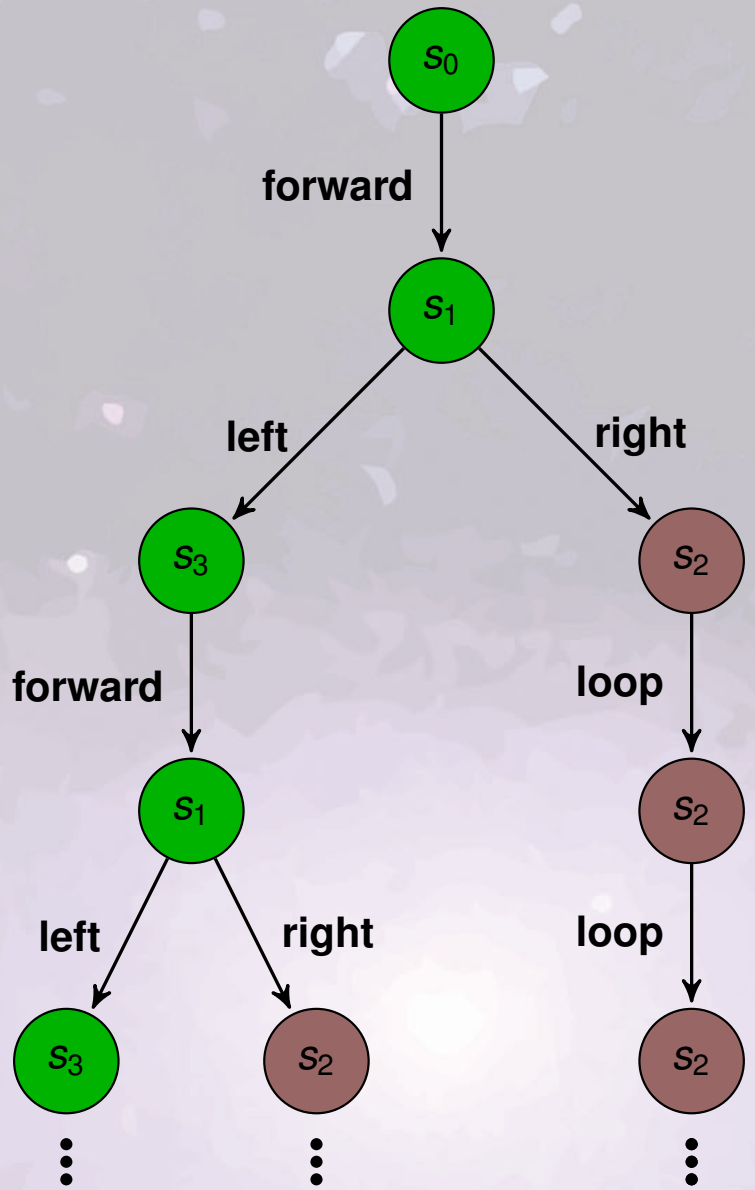
More examples:

- $E_Y G E_Y X \textbf{true}$ – infinite loops detection
- $A_Y G E_Y X \textbf{true}$ – deadlock detection
- $AG_Y(\textbf{p} \wedge EF_Z \textbf{safe})$ – using two action variables Y, Z



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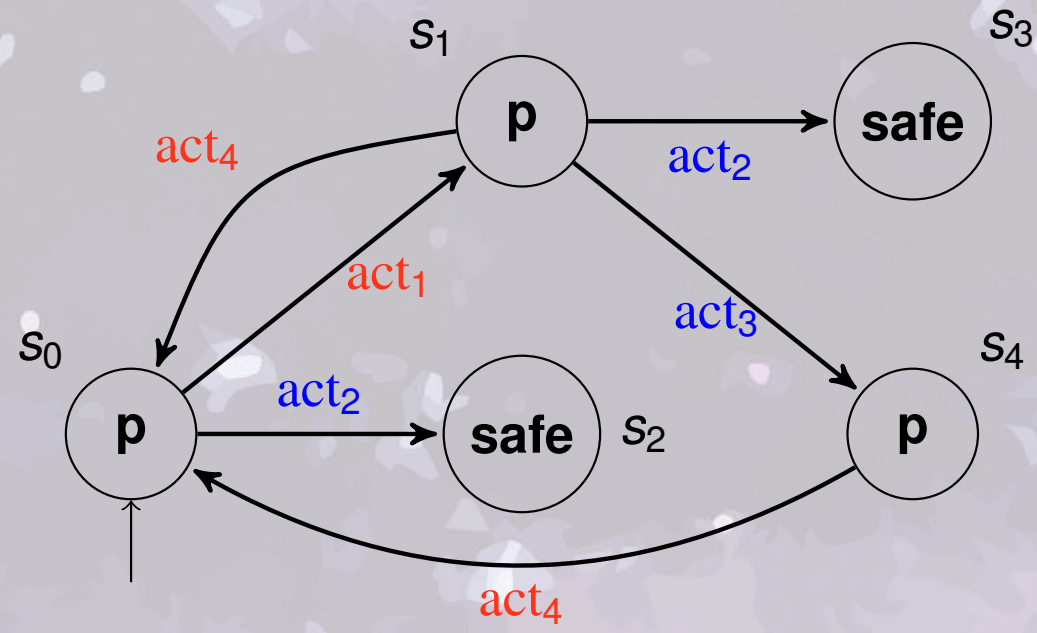
Action synthesis in a nutshell



$A_Y G(\mathbf{p} \wedge E_Z F \mathbf{safe})$: *for each Y-reachable state **p** holds and **safe** is Z-reachable*

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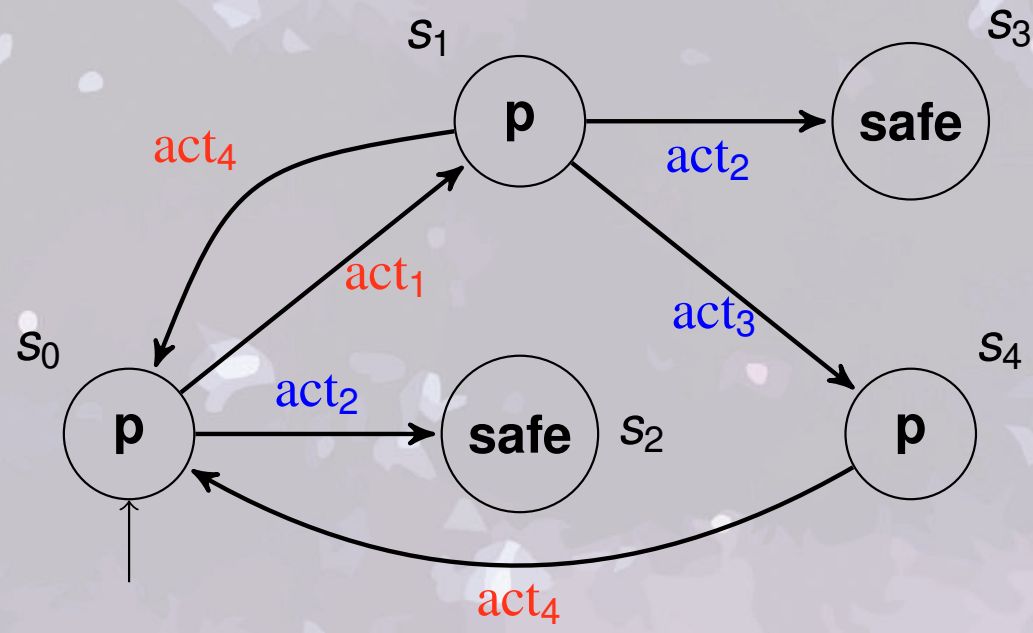
Action synthesis in a nutshell



$A_Y G(\mathbf{p} \wedge E_Z F\mathbf{safe})$: *for each Y-reachable state **p** holds and **safe** is Z-reachable*

$$s_0 \models A_{\{act_1,\, act_4\}} G(\mathbf{p} \wedge E_{\{act_2\}} F\mathbf{safe})$$

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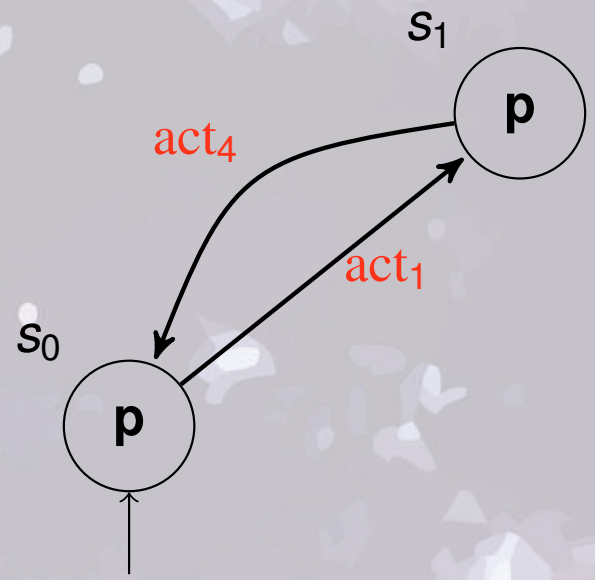

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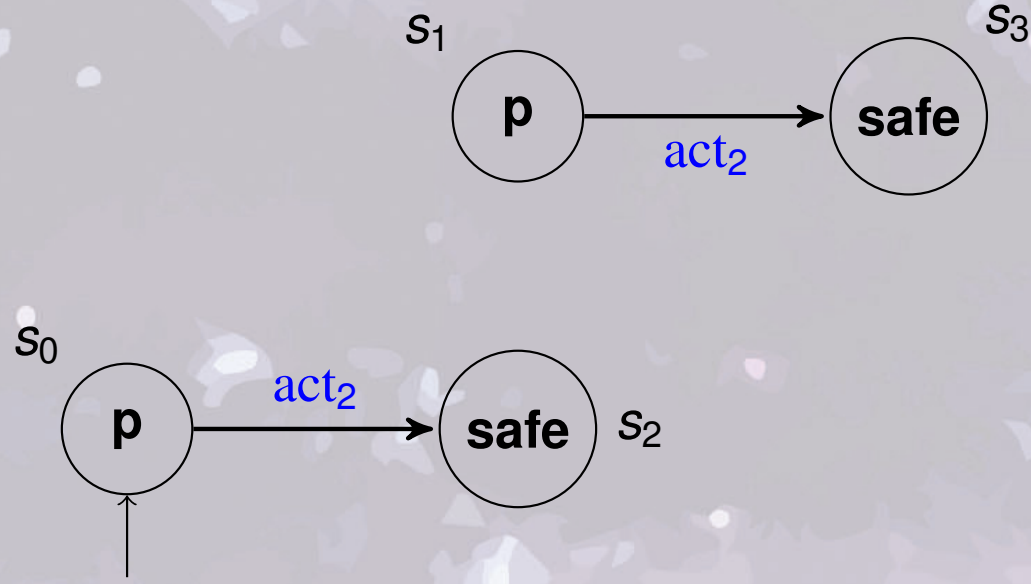

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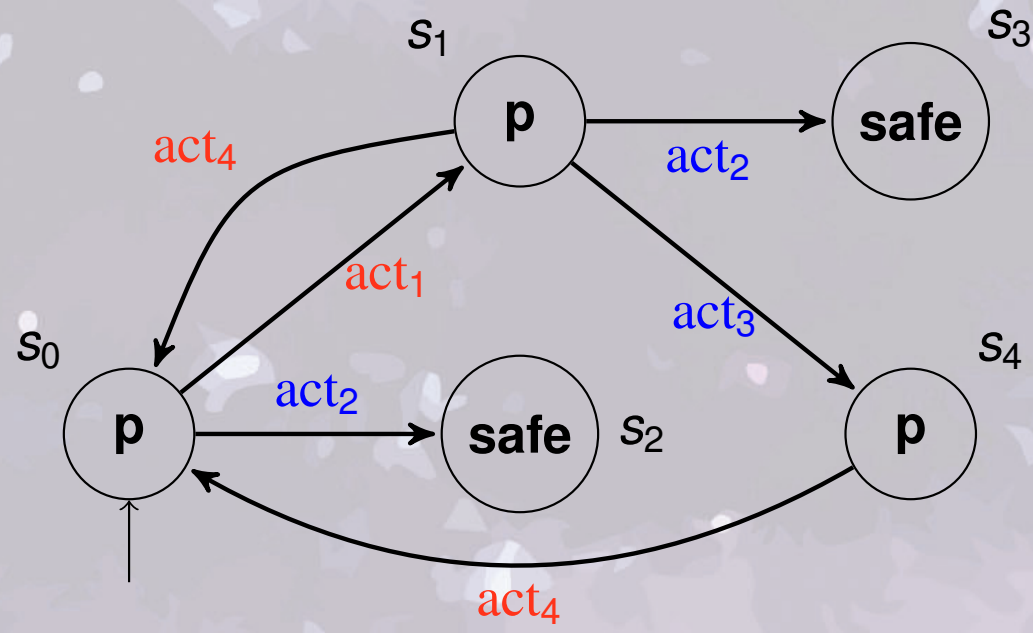

$A_Y G(\mathbf{p} \wedge E_Z F\mathbf{safe})$: *for each Y-reachable state **p** holds and **safe** is Z-reachable*

$$s_0 \not\models A_{\{act_1,\, act_3\}} G(\mathbf{p} \wedge E_{\{act_2\}} F\mathbf{safe})$$

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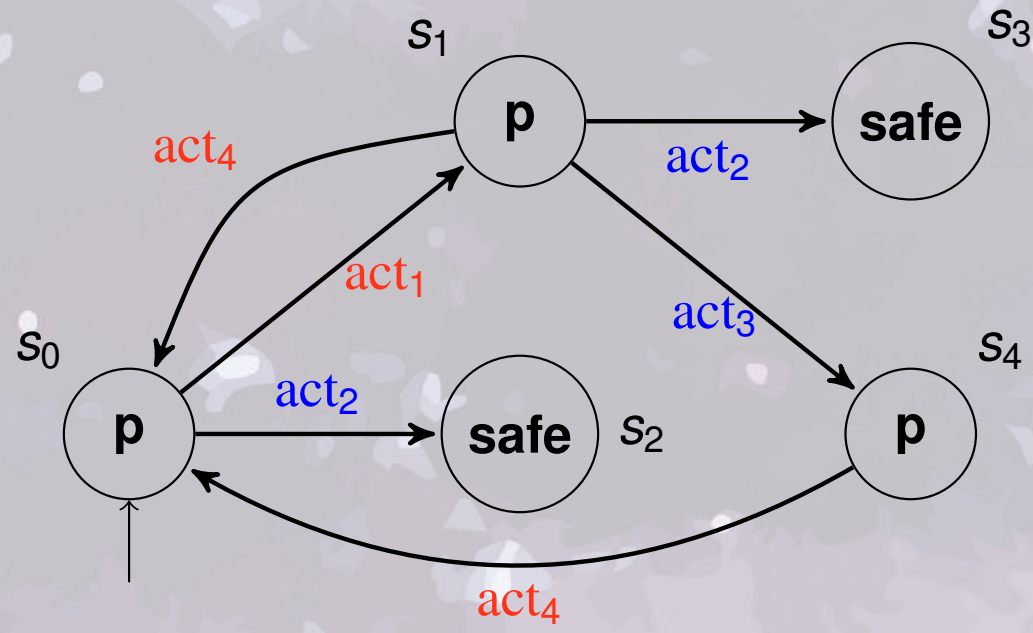

$A_Y G(\mathbf{p} \wedge E_Z F\mathbf{safe})$: *for each Y-reachable state **p** holds and **safe** is Z-reachable*

Goal: describe all Y, Z s.t.: $s_0 \models A_Y G(\mathbf{p} \wedge E_Z F\mathbf{safe})$

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Action synthesis: formal definition

$\mathcal{M} = (\mathcal{S}, s^0, \mathcal{A}, \mathcal{T}, \mathcal{L})$, $\phi \in$ pmARCTL, ActVals $:=$ ActSets$^{\text{ActVars}}$

Goal Knapik et al. [2015]

Build $f_\phi : \mathcal{S} \to 2^{\text{ActVals}}$ s.t. for all $s \in \mathcal{S}$:

$$\upsilon \in f_\phi(s) \iff s \models_\upsilon \phi$$

($f_\phi(s)$ contains all valuations that make ϕ hold in s)

THEOREM Knapik et al. [2015]

The problem of deciding whether $f_\phi(s) \neq \emptyset$ is NP-complete.

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(Some) fixed-points for pmARCTL

Recursive equivalences in pmARCTL:

- $q \models_{\upsilon} E_Y G\phi \iff q \models_{\upsilon} \phi \wedge \left(E_Y X E_Y G\phi \vee \neg E_Y X \mathbf{true}\right)$

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  Explanation: ϕ holds along a maximal path starting at q and labelled with a Y–action iff ϕ holds in q and either there is no outgoing Y–action (deadlock) or there is a Y–action s.t. when fired it leads to a state where $E_Y G\phi$ holds

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- $E_Y \phi U \psi \iff \psi \vee (\phi \wedge E_Y X E_Y \phi U \psi)$

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Implementation:

- easy algorithms: implement $E_Y X$ and compute fixpoints (using BDDs)
- similar to CTL, but deal with indicator functions rather than with sets of states see also Jones et al. [2012].

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Conclusion

At this stage, you know about action synthesis

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Conclusion

At this stage, you know about action synthesis

Let us see some tool support (next sequence)

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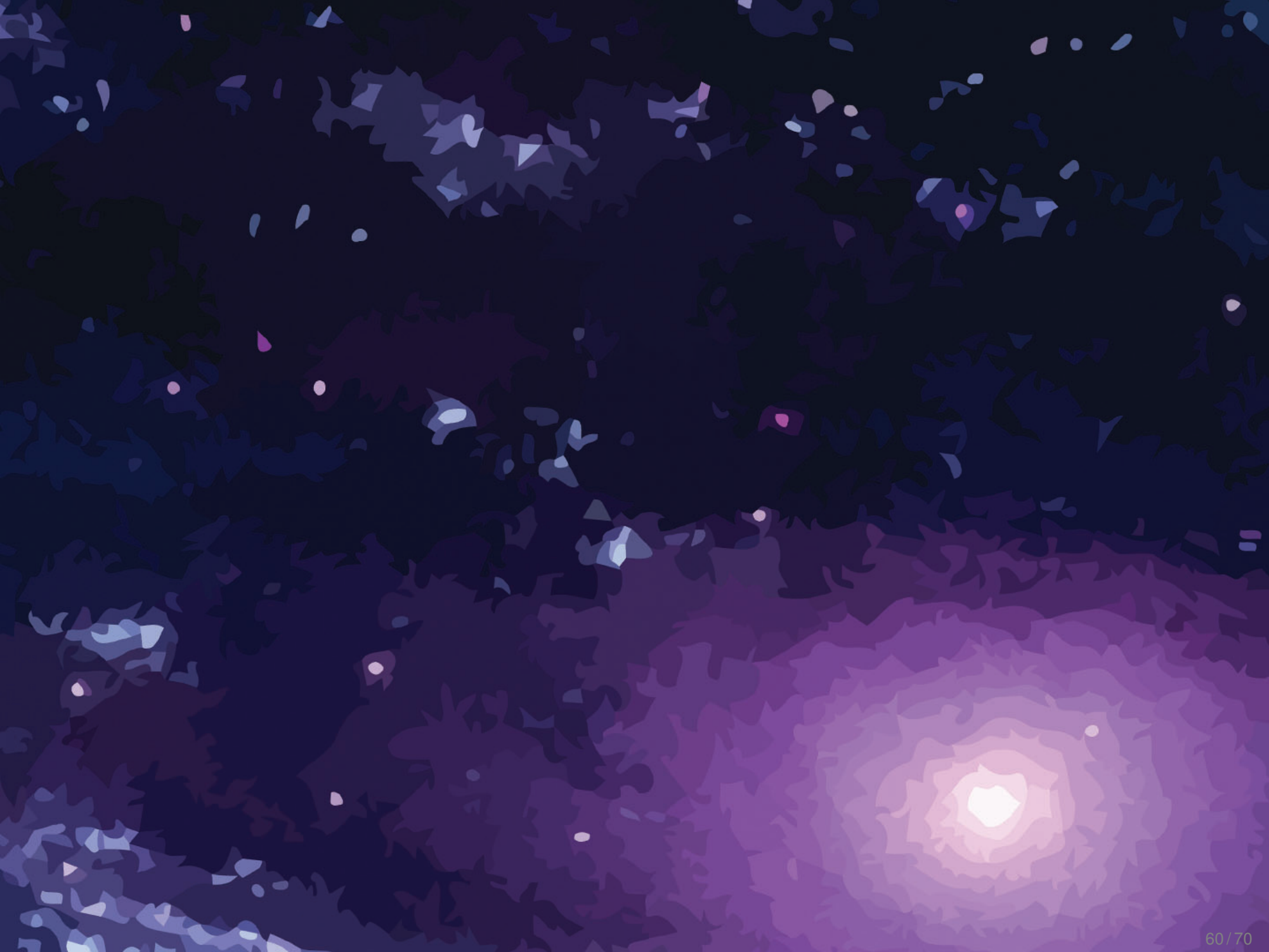

SPATULA in a nutshell

First of all. . .

You now know about action synthesis

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You now know about action synthesis

Let us now see some tool support

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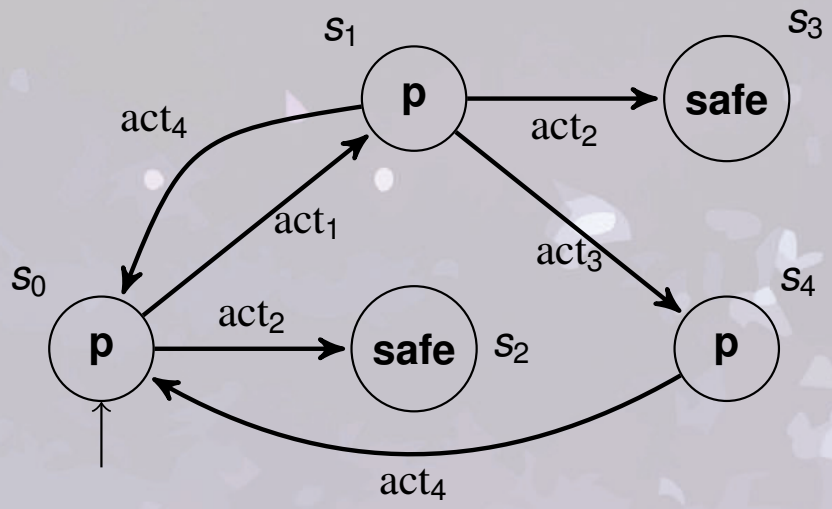
SPATULA: example



$E_Y F$ **safe**

```
module SimpleMTS:

  i = 0;
  for i in (0..5) {
      vert = "s" + i;
      bloom(vert);
    }
  mark_with("s0", "initial");

  mark_with("s0", "p");
  mark_with("s1", "p");
  mark_with("s4", "p");
  mark_with("s2", "safe");
  mark_with("s3", "safe");

  join_with("s0", "s1", "act1");
  join_with("s0", "s2", "act2" );
  join_with("s1", "s0", "act4");
  join_with("s1", "s4", "act3");
  join_with("s1", "s3", "act2");
  join_with("s4", "s0", "act4");

verify:
#EF($Y; (safe));
```

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SPATULA: example

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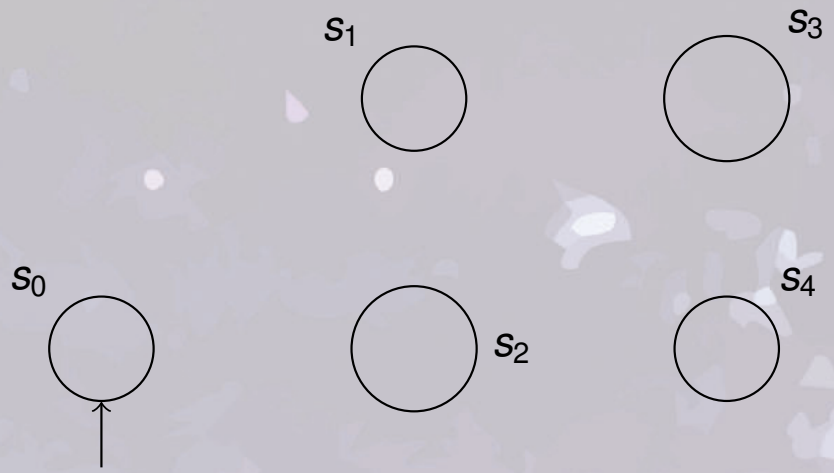
SPATULA: example

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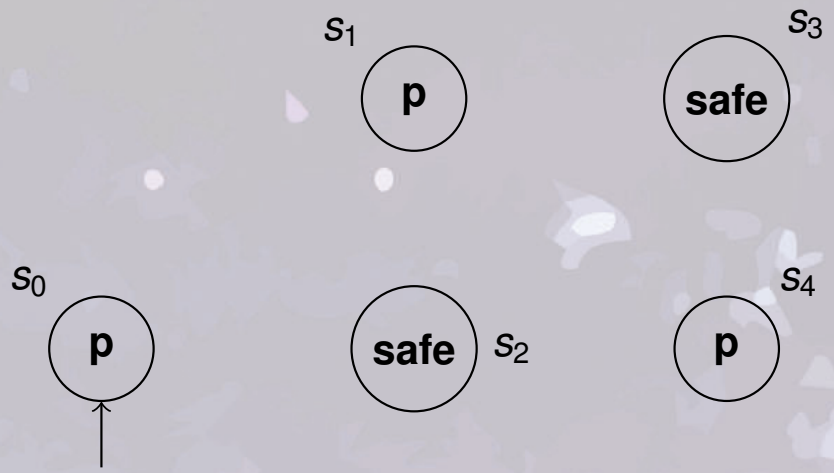


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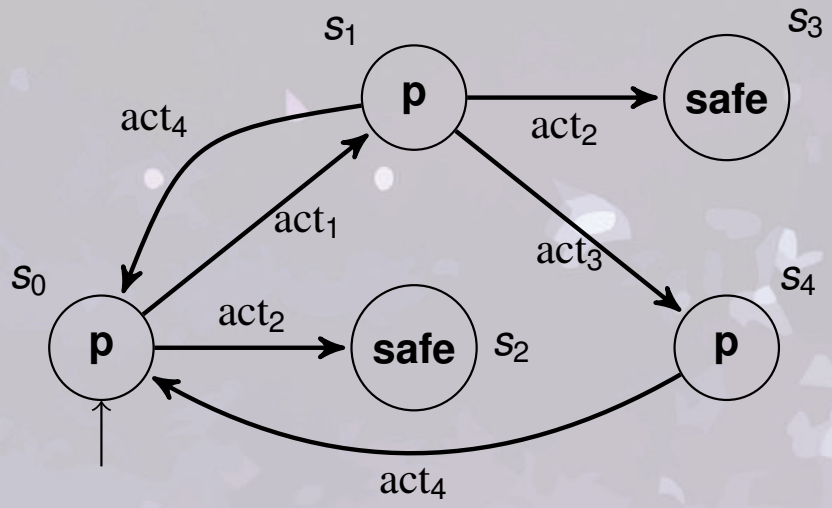


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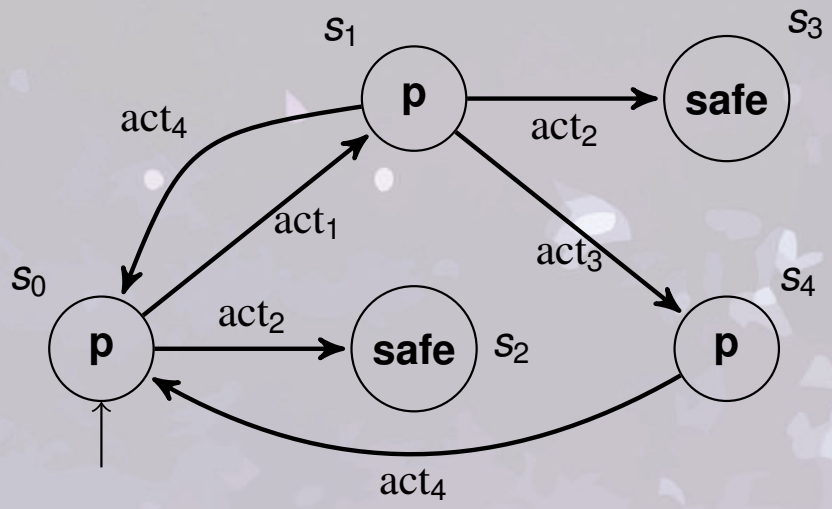

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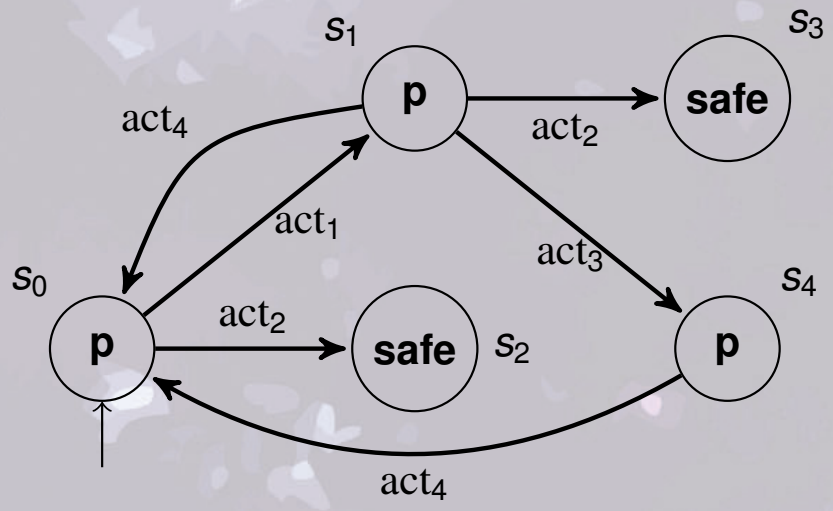
SPATULA: example, ct'd



$E_Y F$**safe**

spatula -f SimpleMTS.txt find all Ys...
spatula -m -f SimpleMTS.txt find minimal covering of Ys...

(Easy) question: what is minimal Y here?

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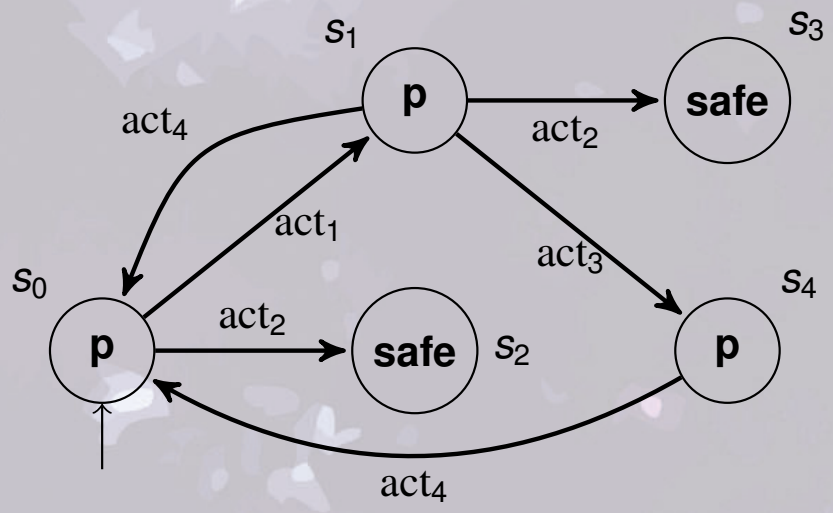
SPATULA: example, ct'd



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(Easy) question: what is minimal Y here?

A: $s_0 \models E_Y F$**safe** $\iff \{act_2\} \subseteq Y$

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Conclusion

At this stage:

- you know basics on Petri nets with two kinds of parameters: discrete parameters and timing parameters
- you know basics of Roméo
- you know what Mixed Transition Systems are
- you understand the problem of action synthesis for Parametric Action-Restricted CTL
- you know basics of modelling and synthesis in SPATULA

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Let us practice with Roméo and SPATULA

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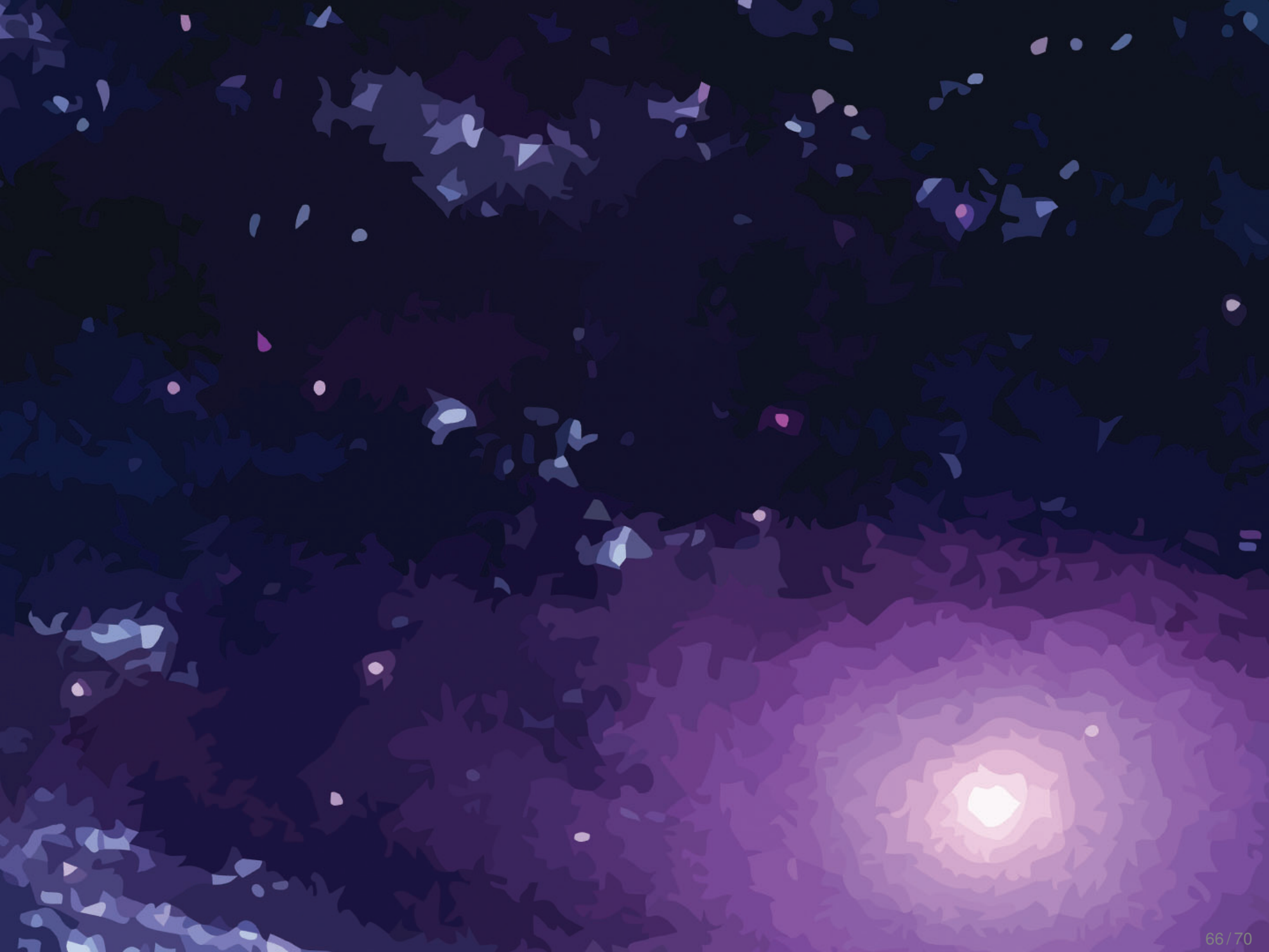

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