Formal verification of infinite state systems with unbounded agents

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Prof. S. Sheerazuddin

27/06/2025

Software Development Life Cycle (SDLC) Phases

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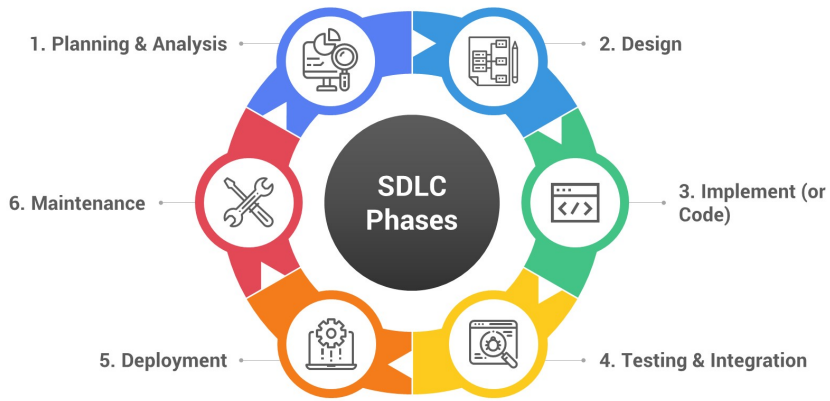
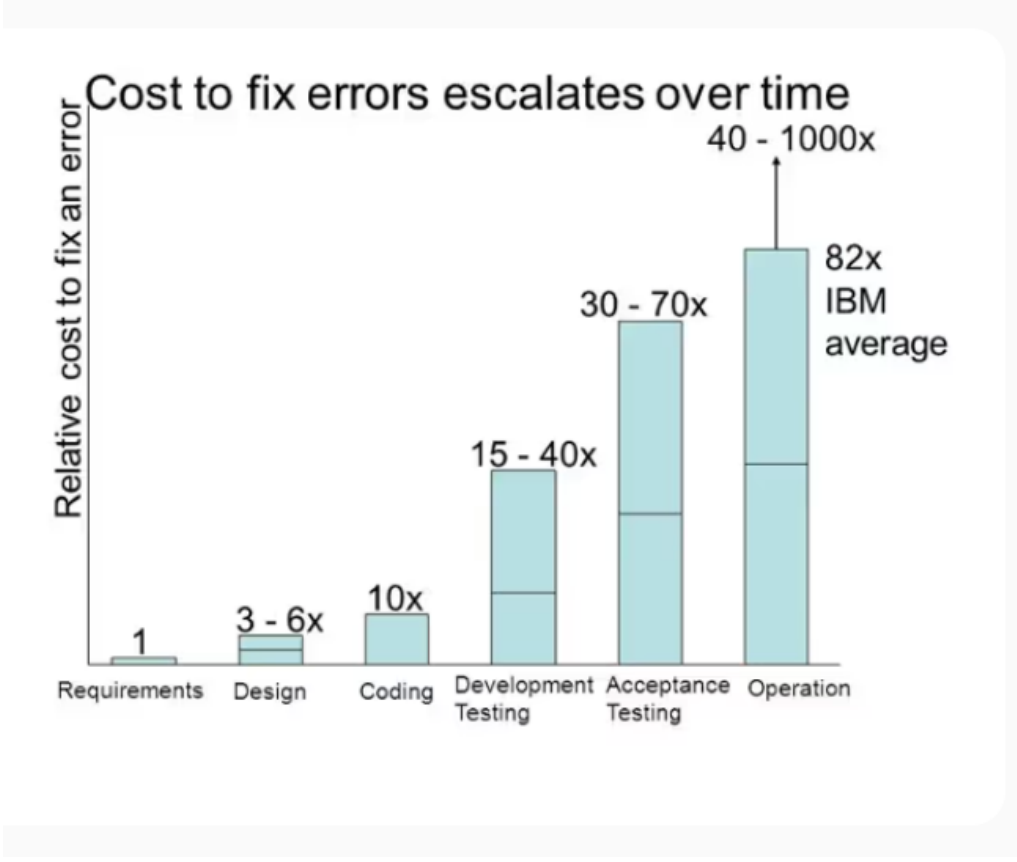


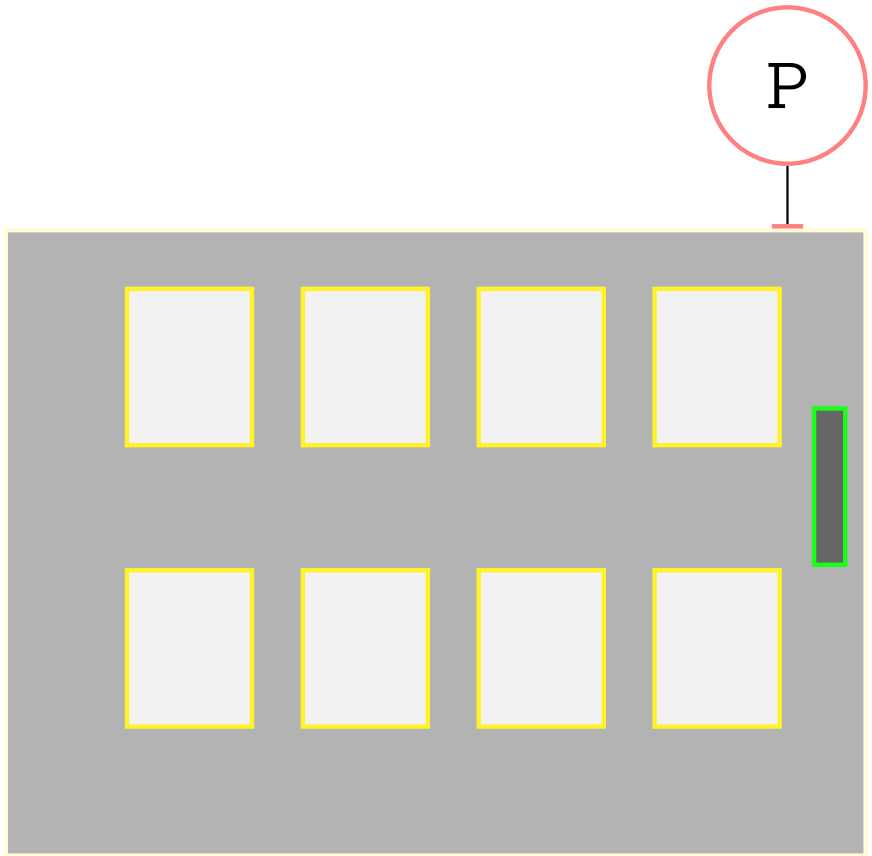
Error Costs



J. Stecklein, "Error cost escalation through the project life cycle, 2010

Running example

An empty Parking Lot waits for vehicles



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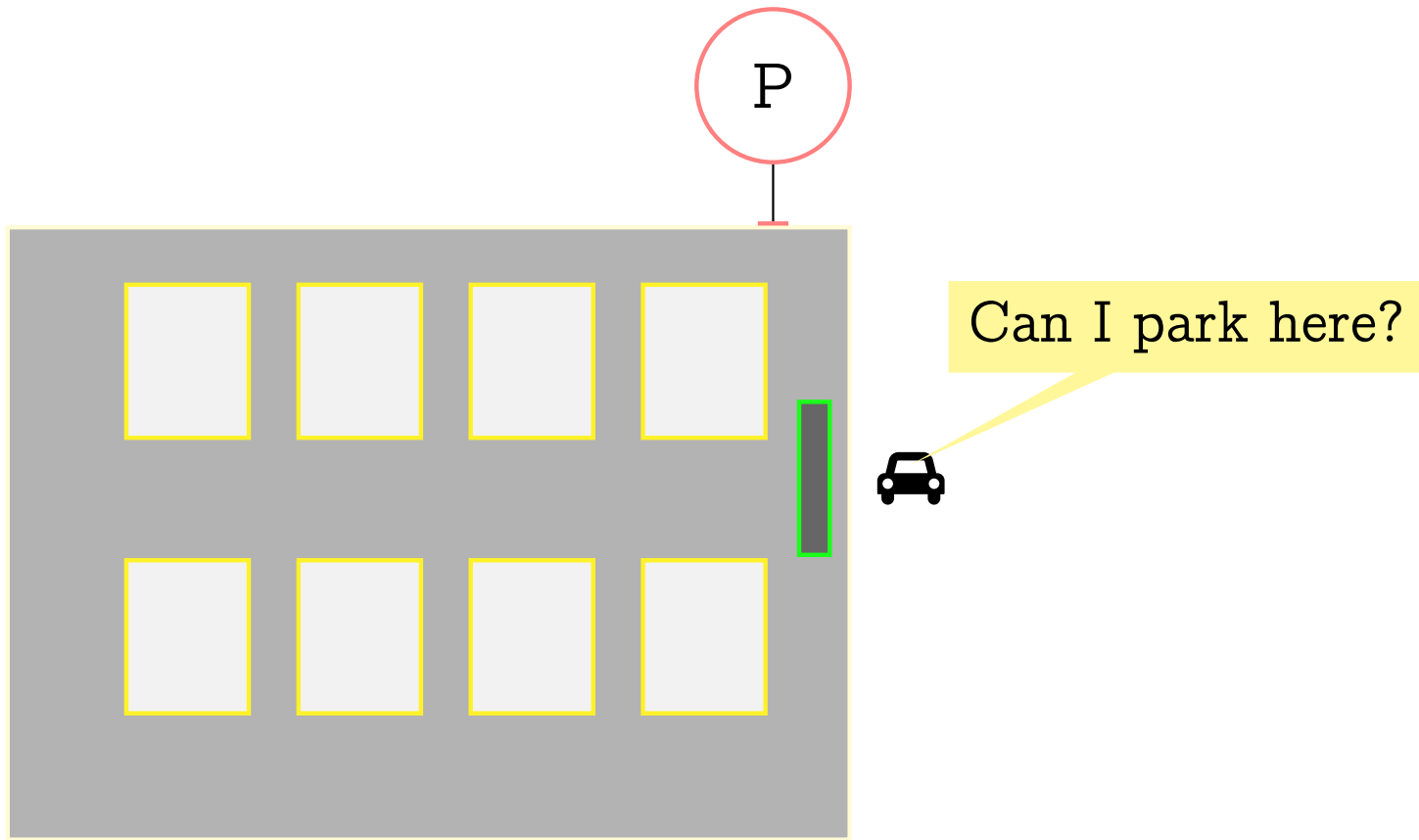

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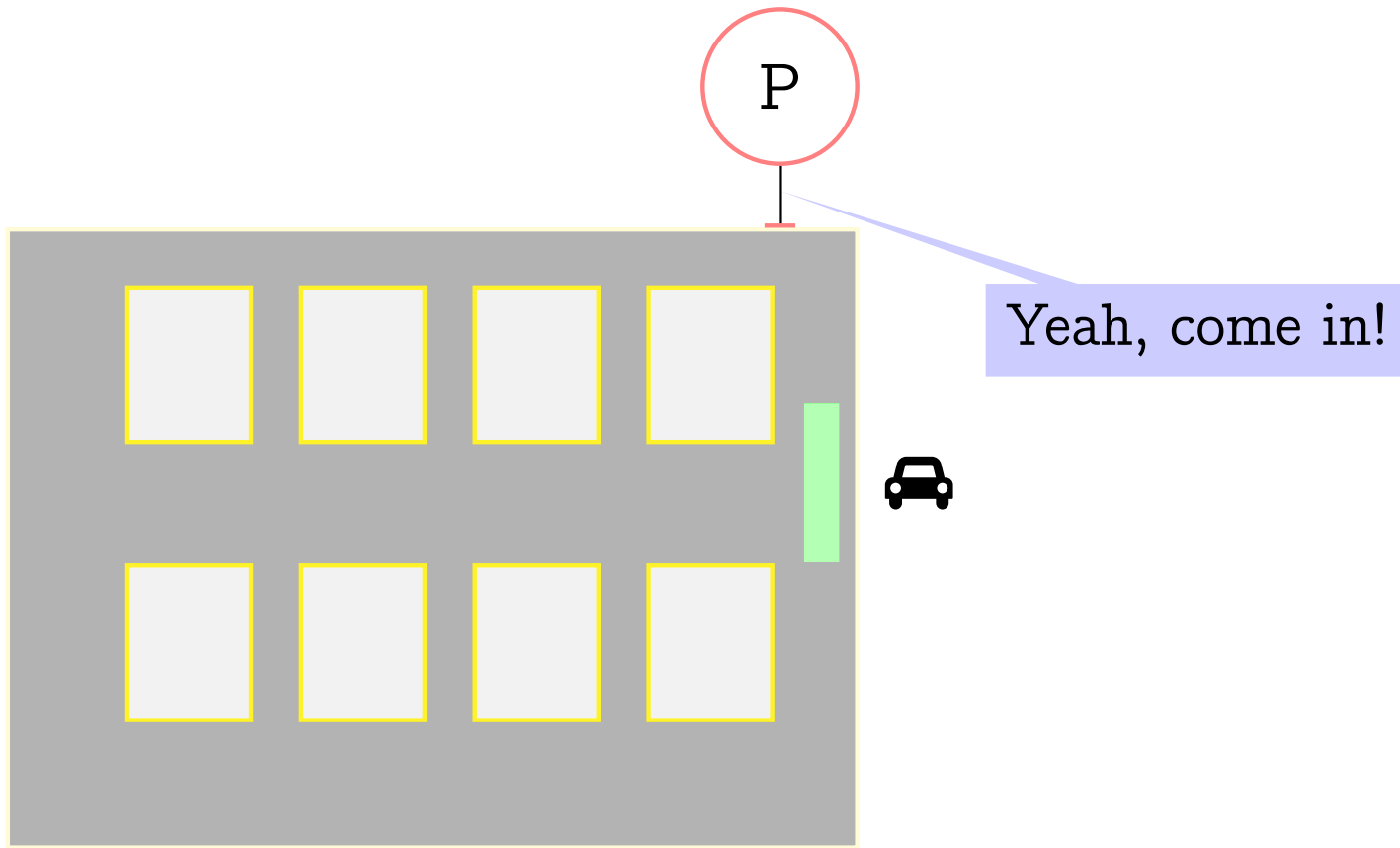

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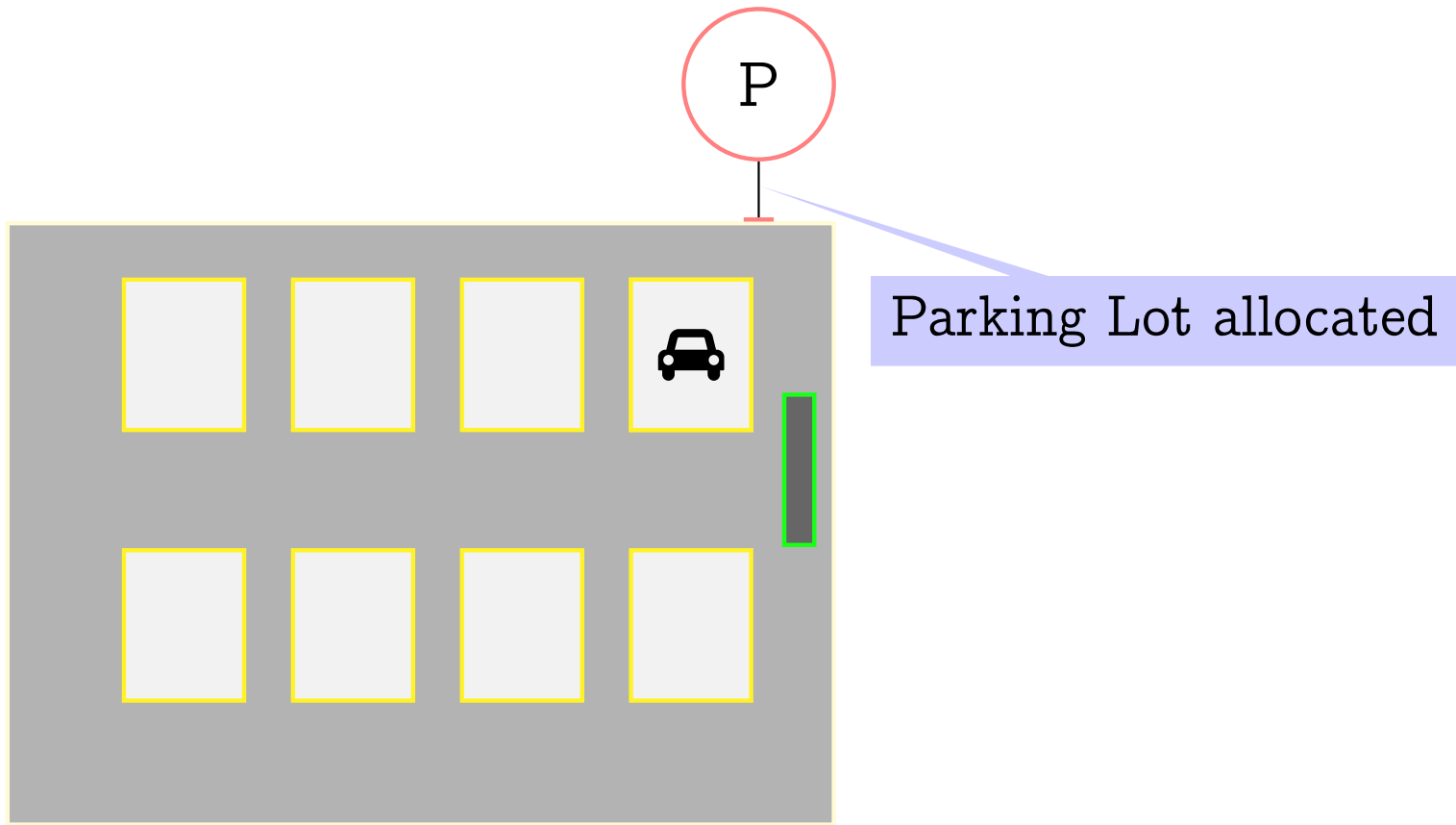
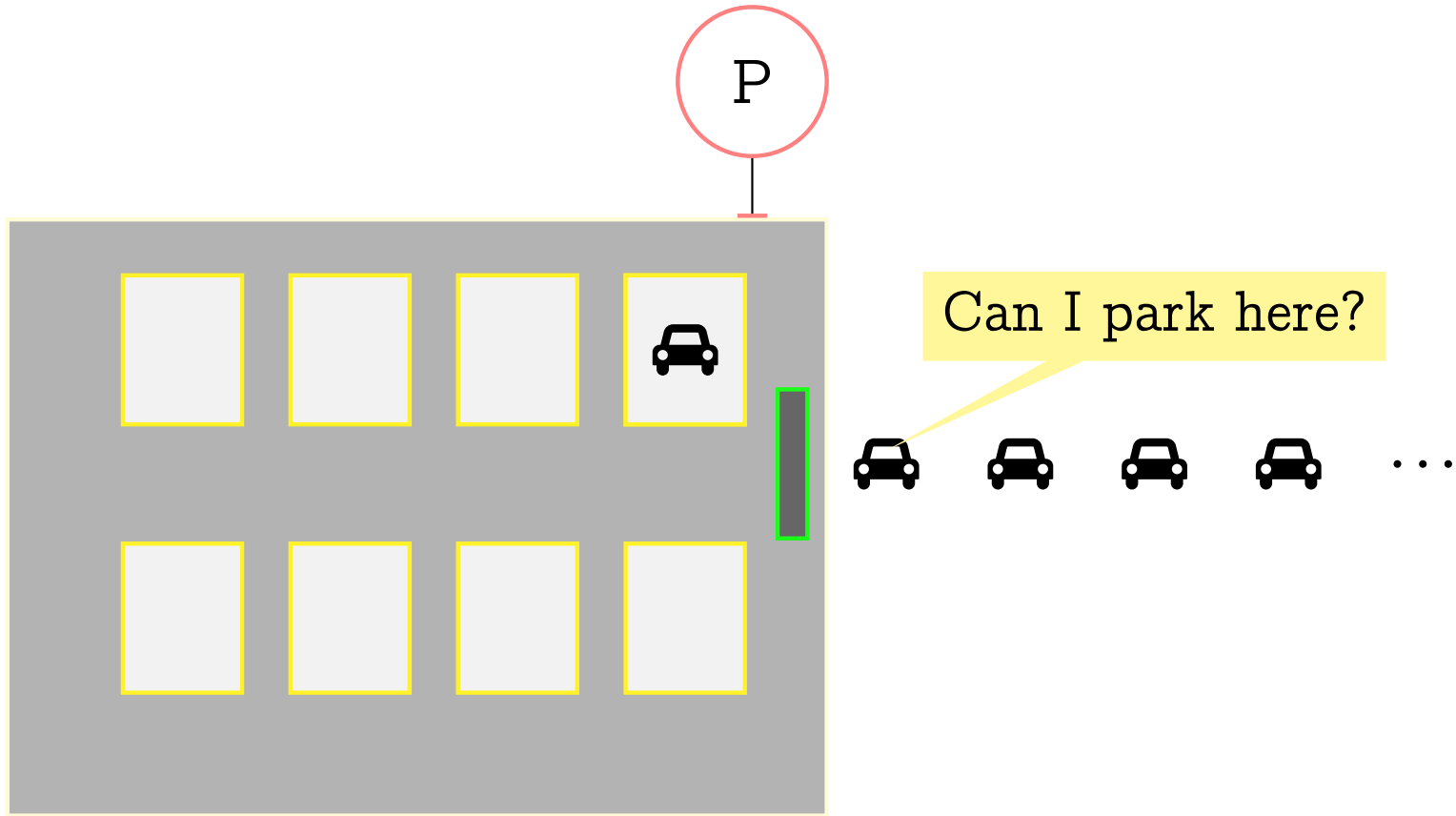


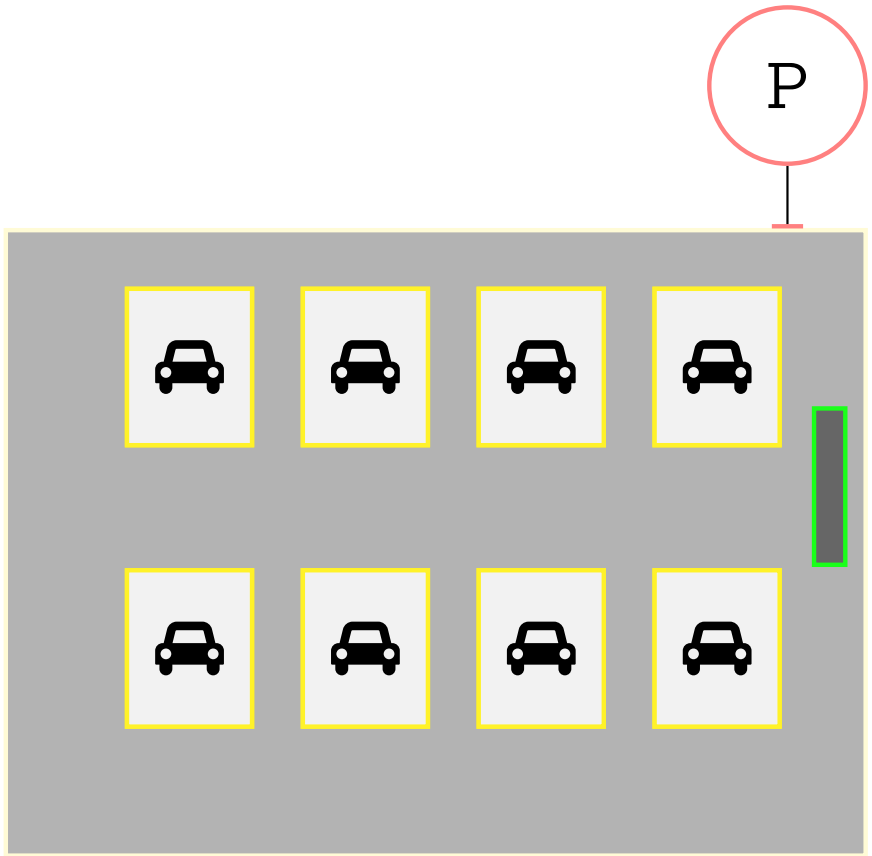
Running example

Unbounded number of parking requests



Running example

No parking space



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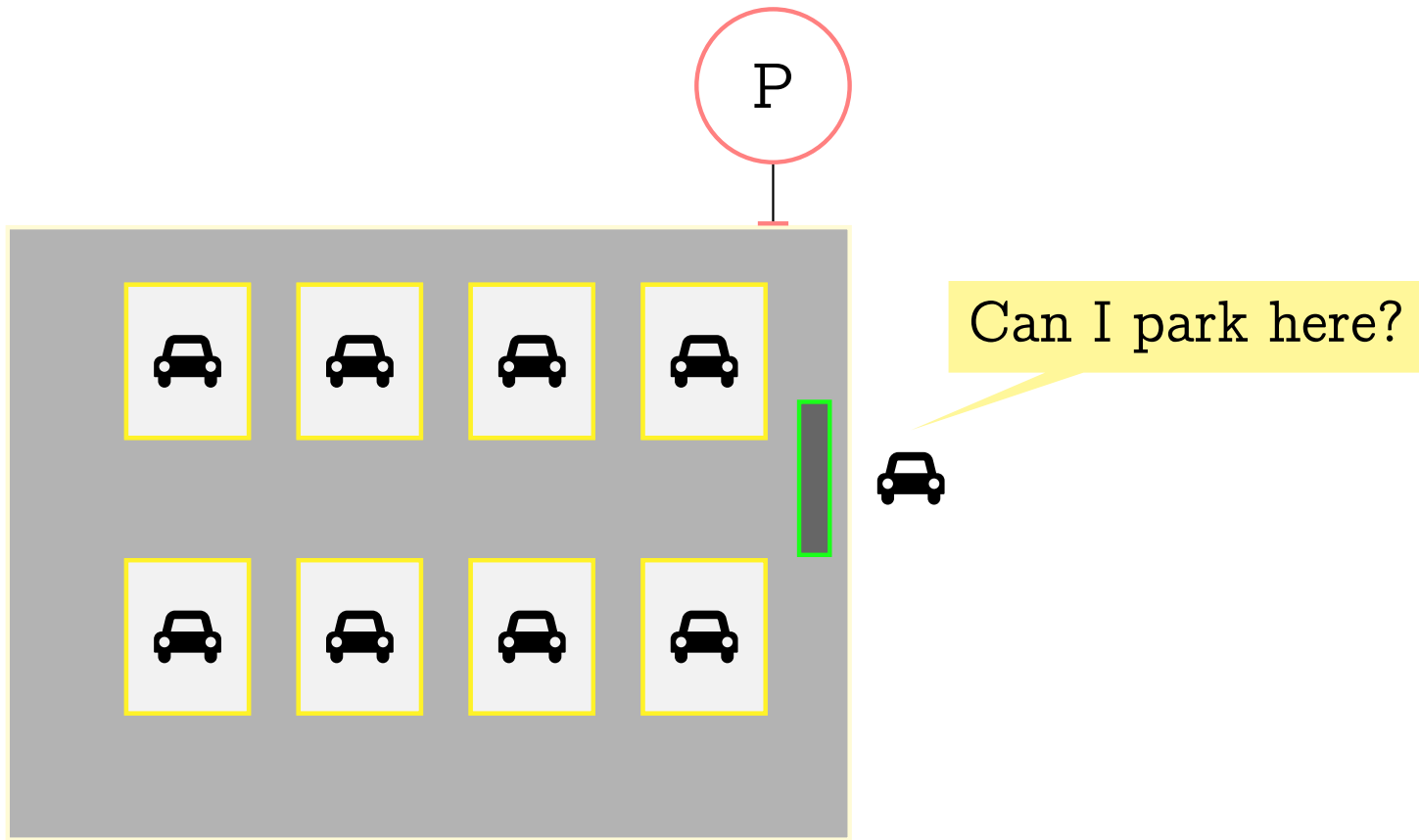

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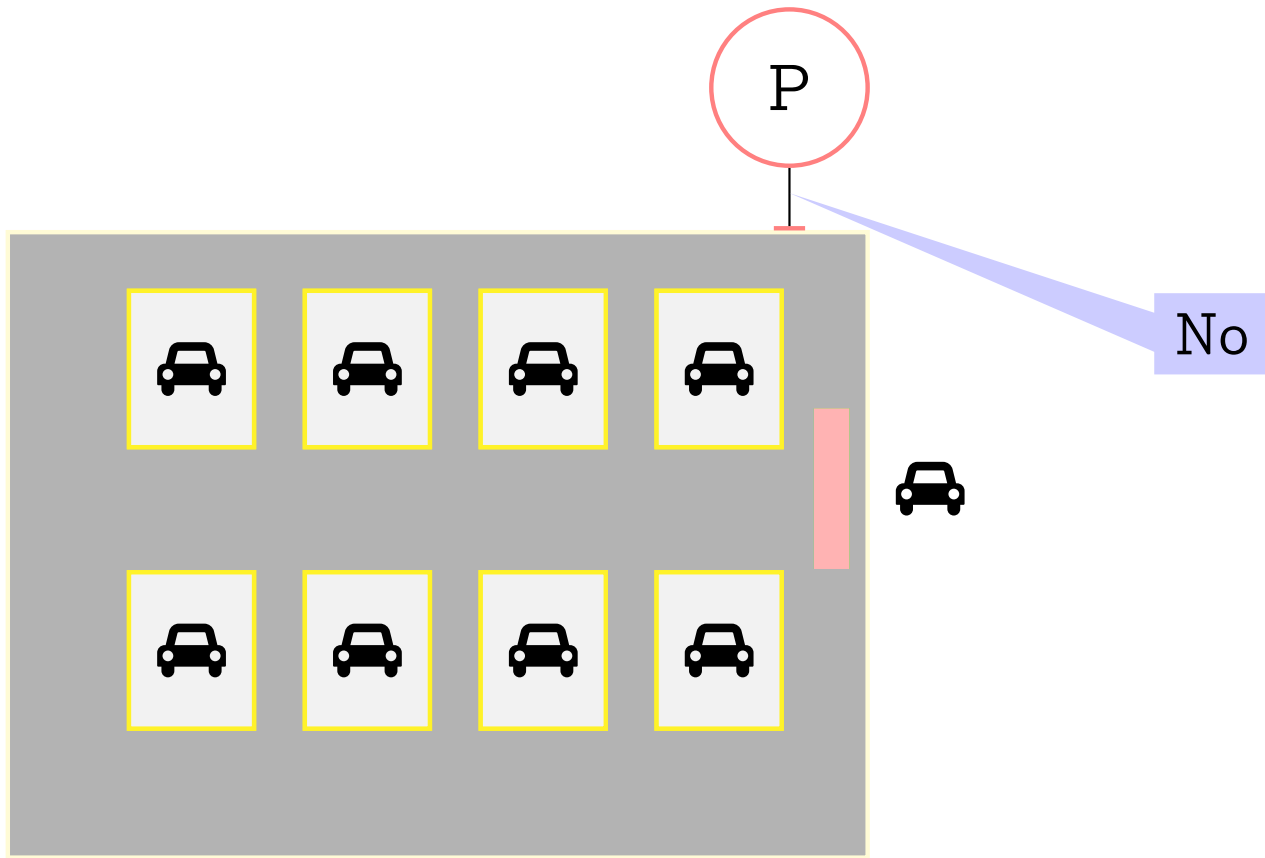

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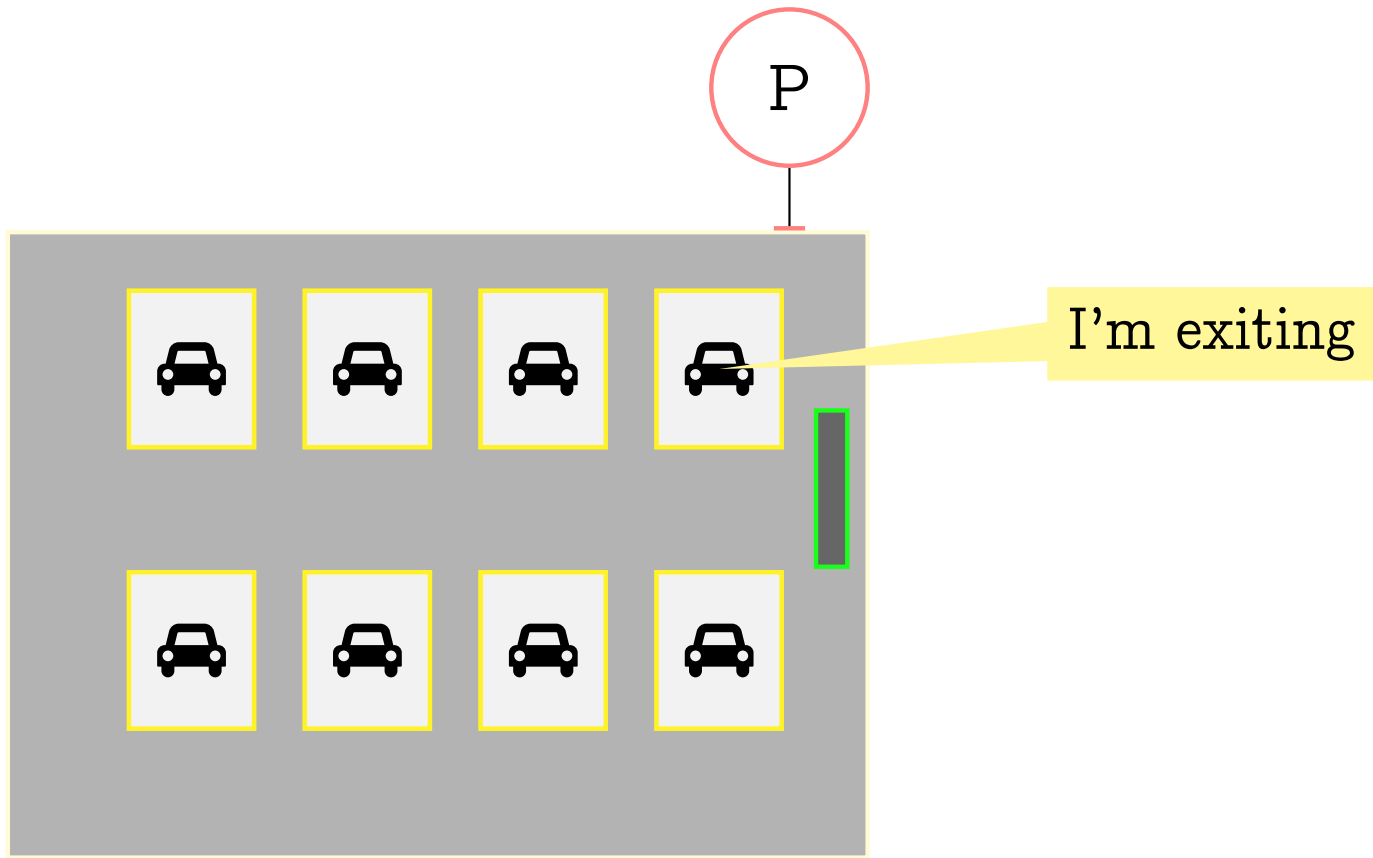

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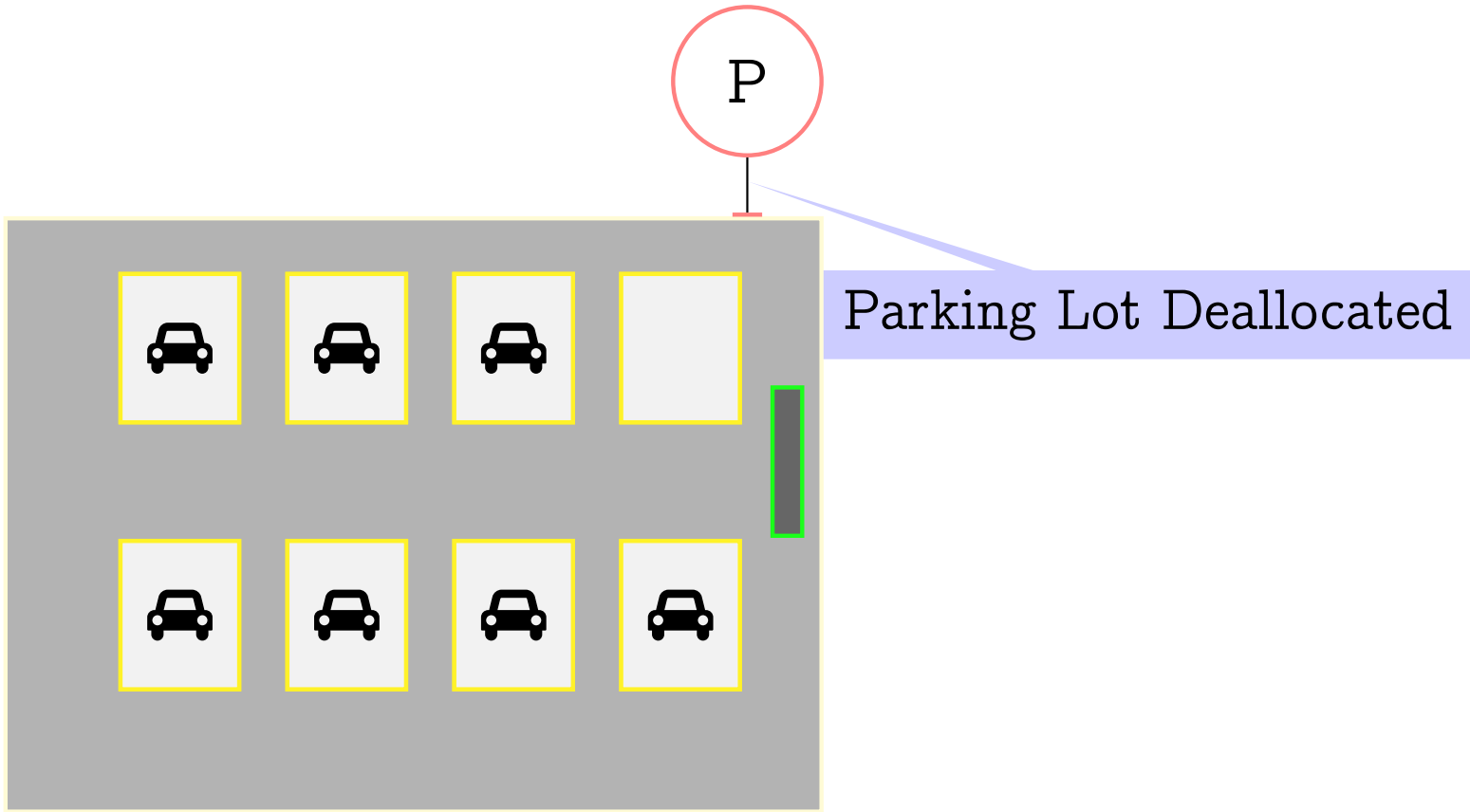
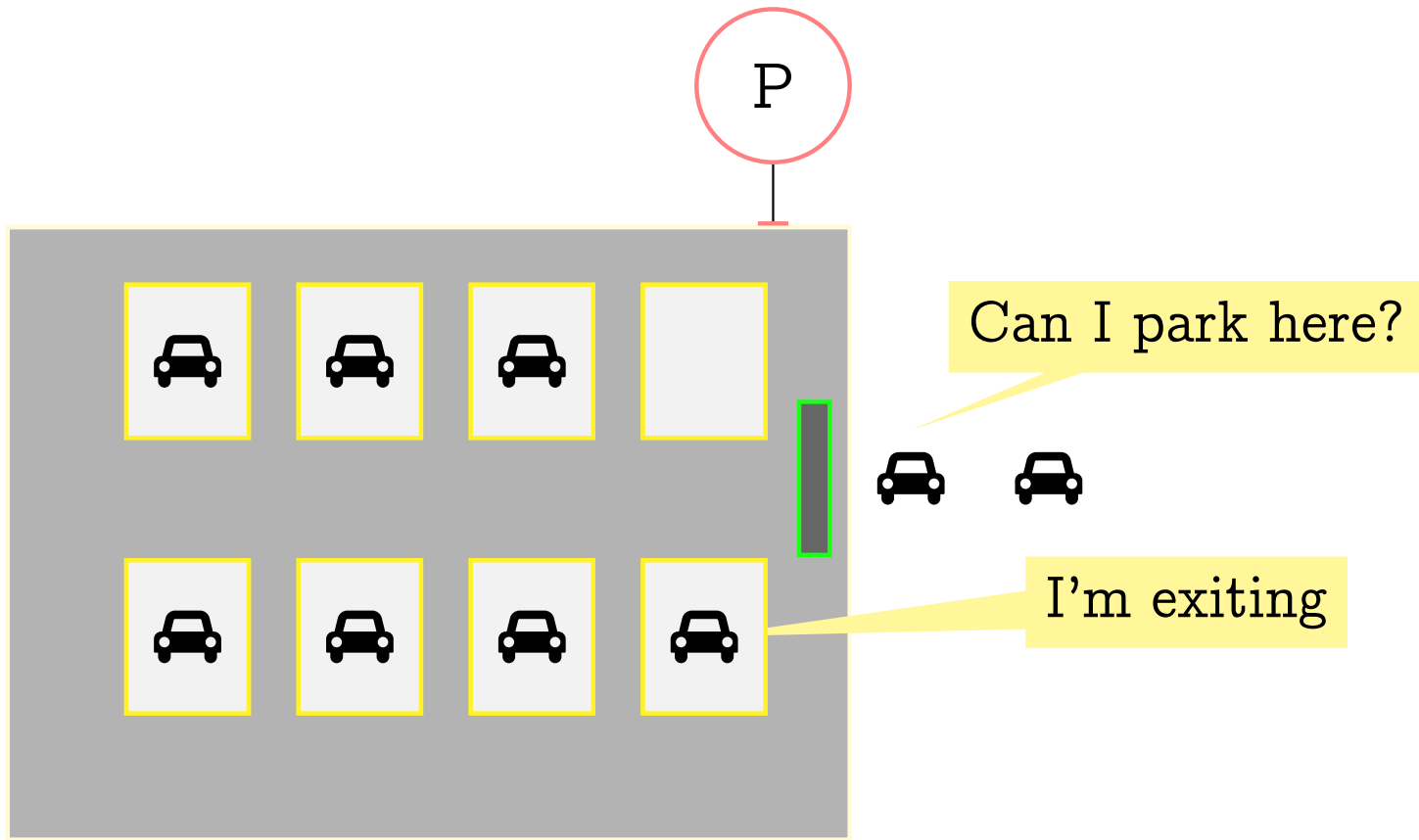
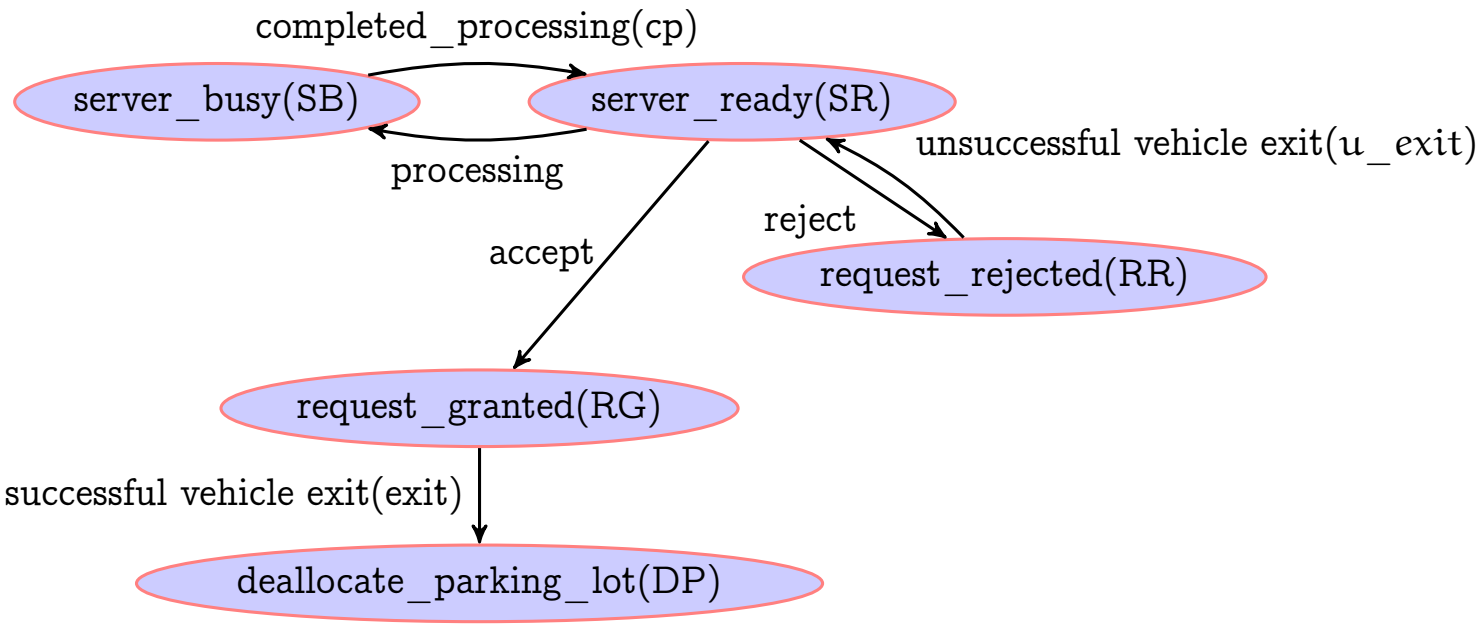


Running example

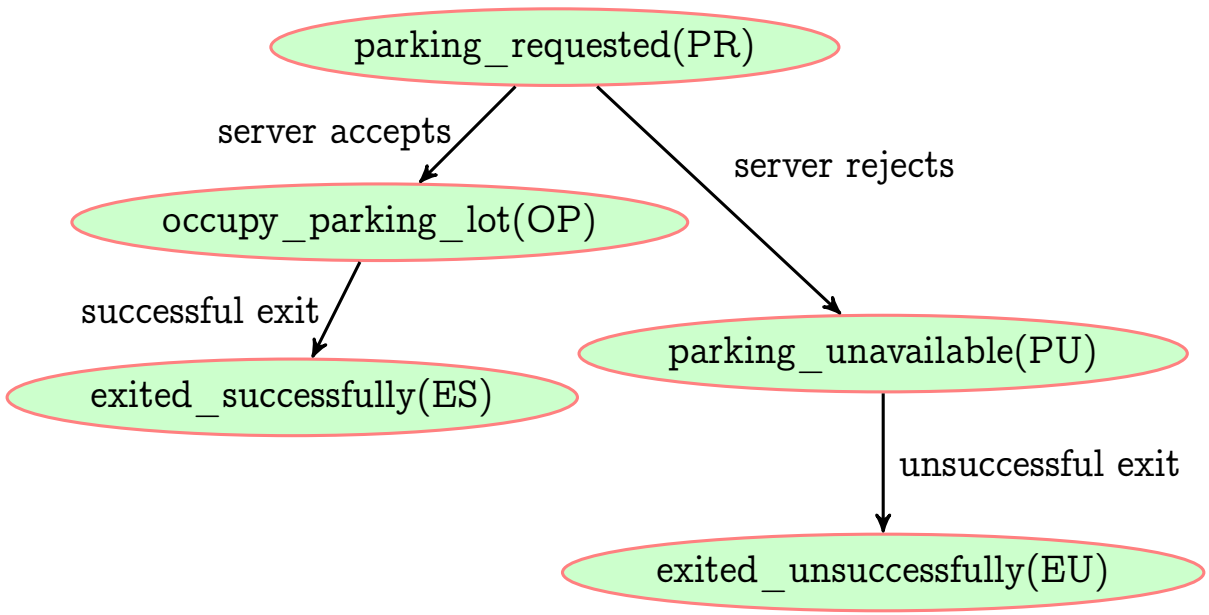
- single server-multiple client system
- unbounded clients of the same type



Case Study Parking System: Server behaviour



Case Study Parking System: Client behaviour



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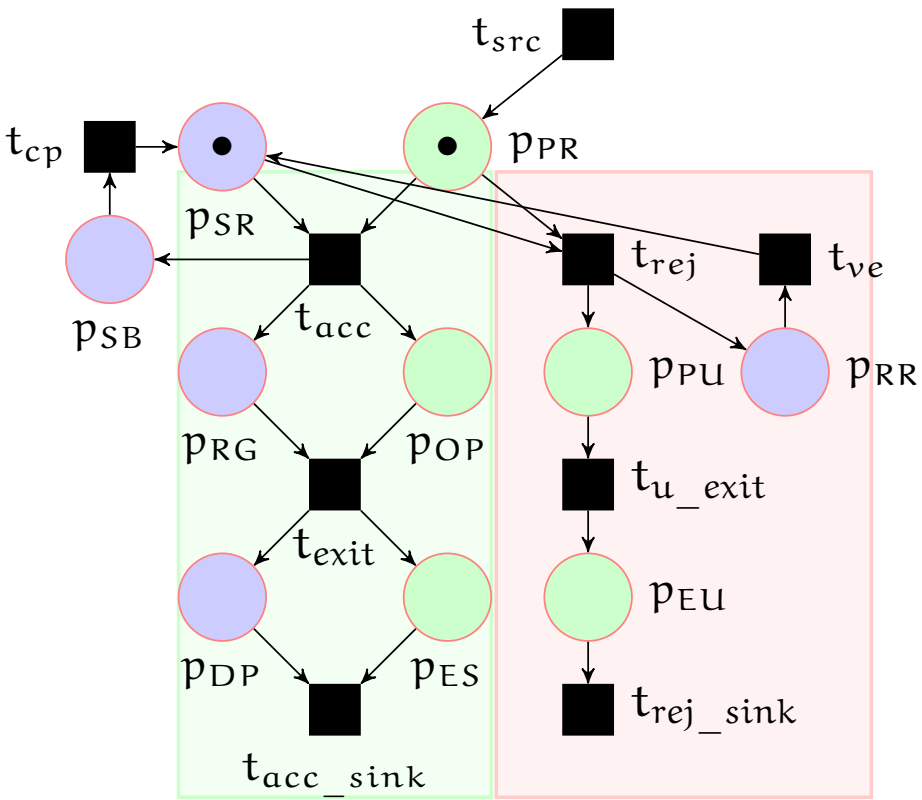
2. How do we express properties of client-server systems naturally?
    1. Do existing logics suffice?
    2. What additional properties are interesting in the context of unbounded client-server systems?
3. Are there formal verification tools for UCS? Can we add to the repertoire?
    1. How are existing tools different, unique? Is another tool necessary?

Part 1: Modelling an Unbounded Client-Server (UCS) using Petri Nets



Finite sets of atomic client propositions P_c and server propositions P_s:

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   $G(\#p_{PR} + \#p_{OP} + \#p_{ES} = 1)$.

3. Is the number of rejected requests greater than the number of accepted requests at some point?

   $F(\#p_{EU} > \#p_{ES})$.

2D-BMC Algorithm

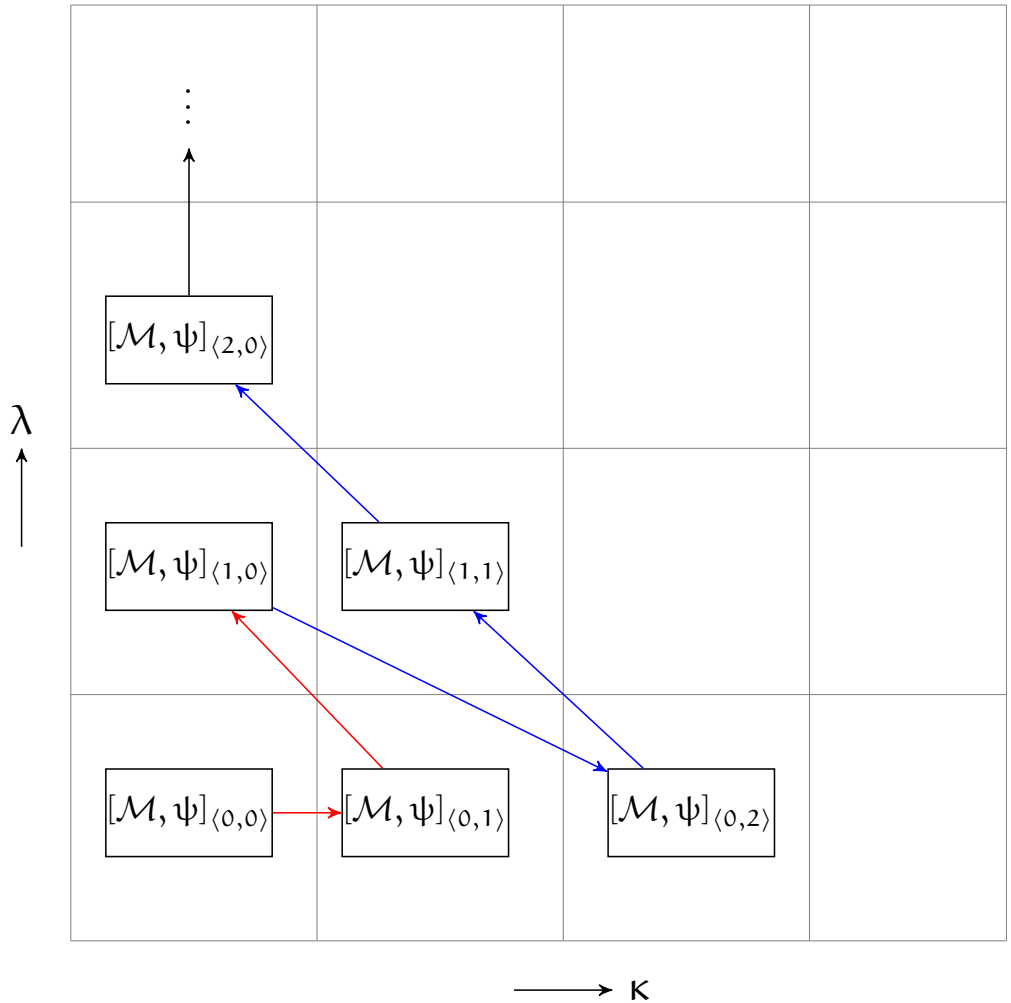

Figure: Unfolding of the encoded formula $[\mathcal{M},\psi]_{(\lambda,\kappa)}$ with respect to λ (execution steps) and κ (number of tokens)

Tool Architecture

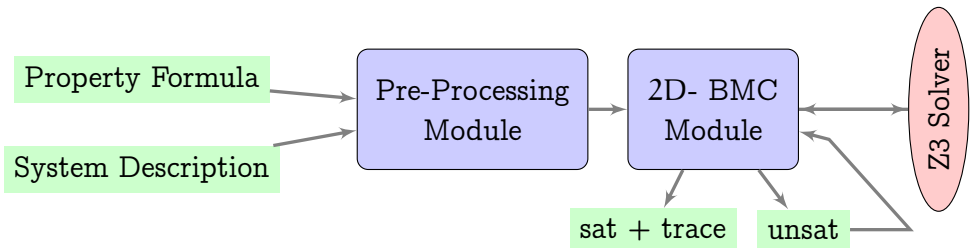

Figure: DCModelChecker architecture

Experimental Results

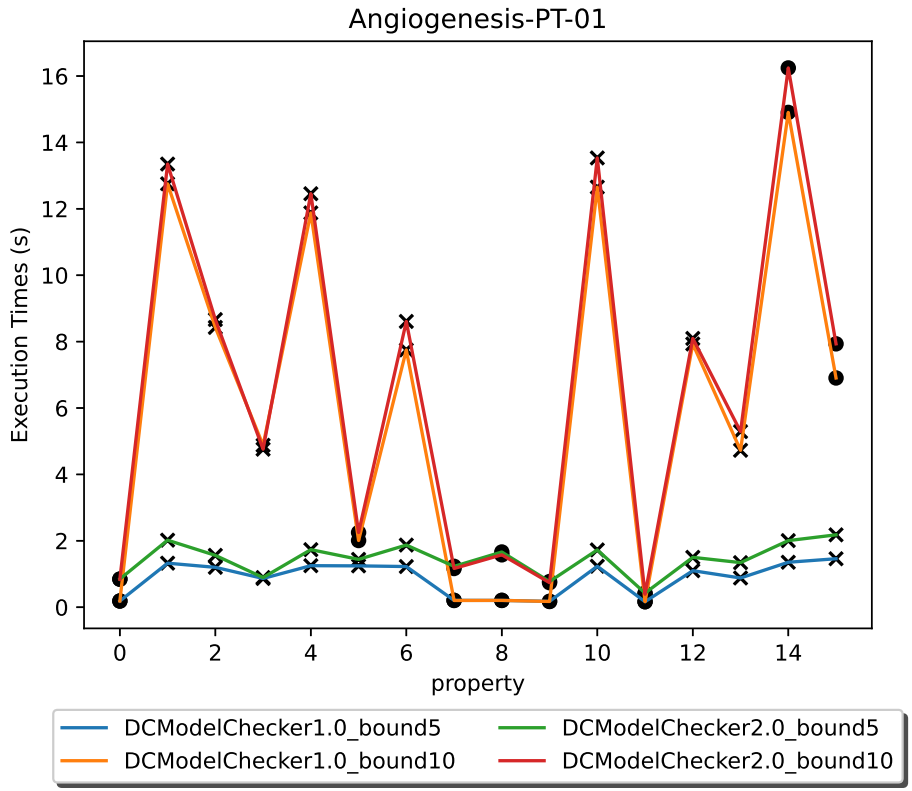

Figure: Verification of FireabilityCardinality Properties with bound 5 and 10

Verified against 16 Benchmarks from Model Checking Contest 2025

Experimental Results

Model	Execution Times(ms)			
	DCModelChecker 1.0	DCModelChecker 2.0	ITS-Tools	Tapaal
Parity	**0.010**	0.40	0.933	0.02
PGCD	**0.019**	0.98	1.487	0.07
Process	0.033	0.85	1.201	**1e-05**
CryptoMiner	0.036	0.64	0.957	**7e-06**
Murphy	0.031	0.83	1.161	**8e-06**

Table: Results of Comparative Experiments on Unbounded PNs

Contributions

- Part 1: Verification of Unbounded Client-Server (UCS) using Petri Nets and Linear Temporal Logic with integer arithmetic using 2D-BMC

What if clients needed to be distinguished?

Running example

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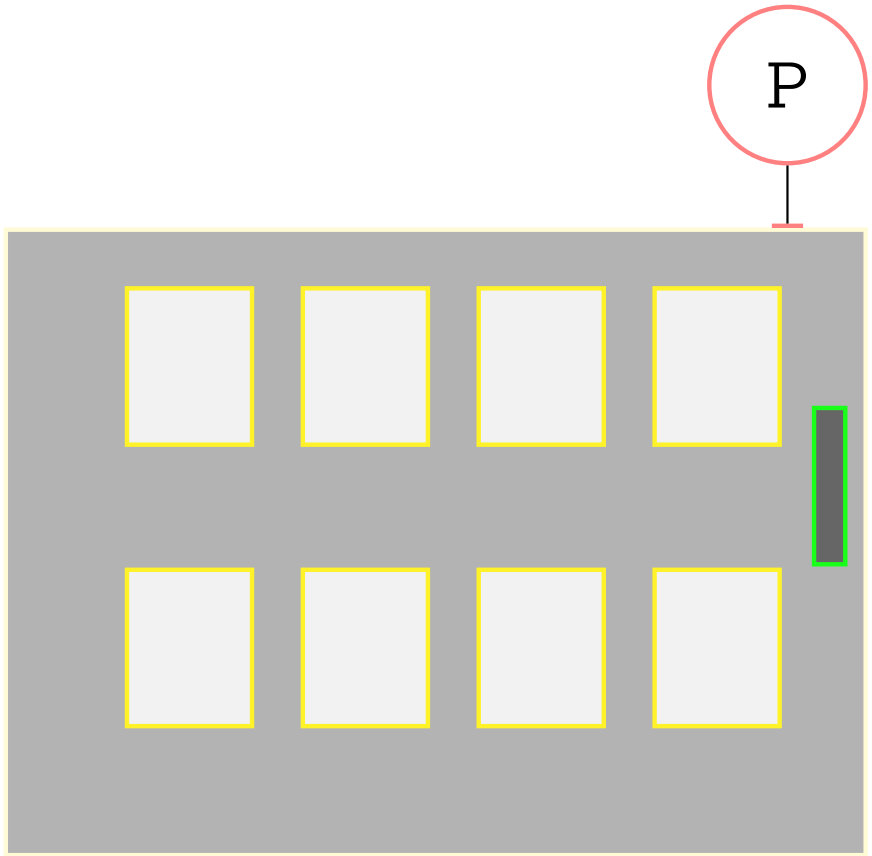

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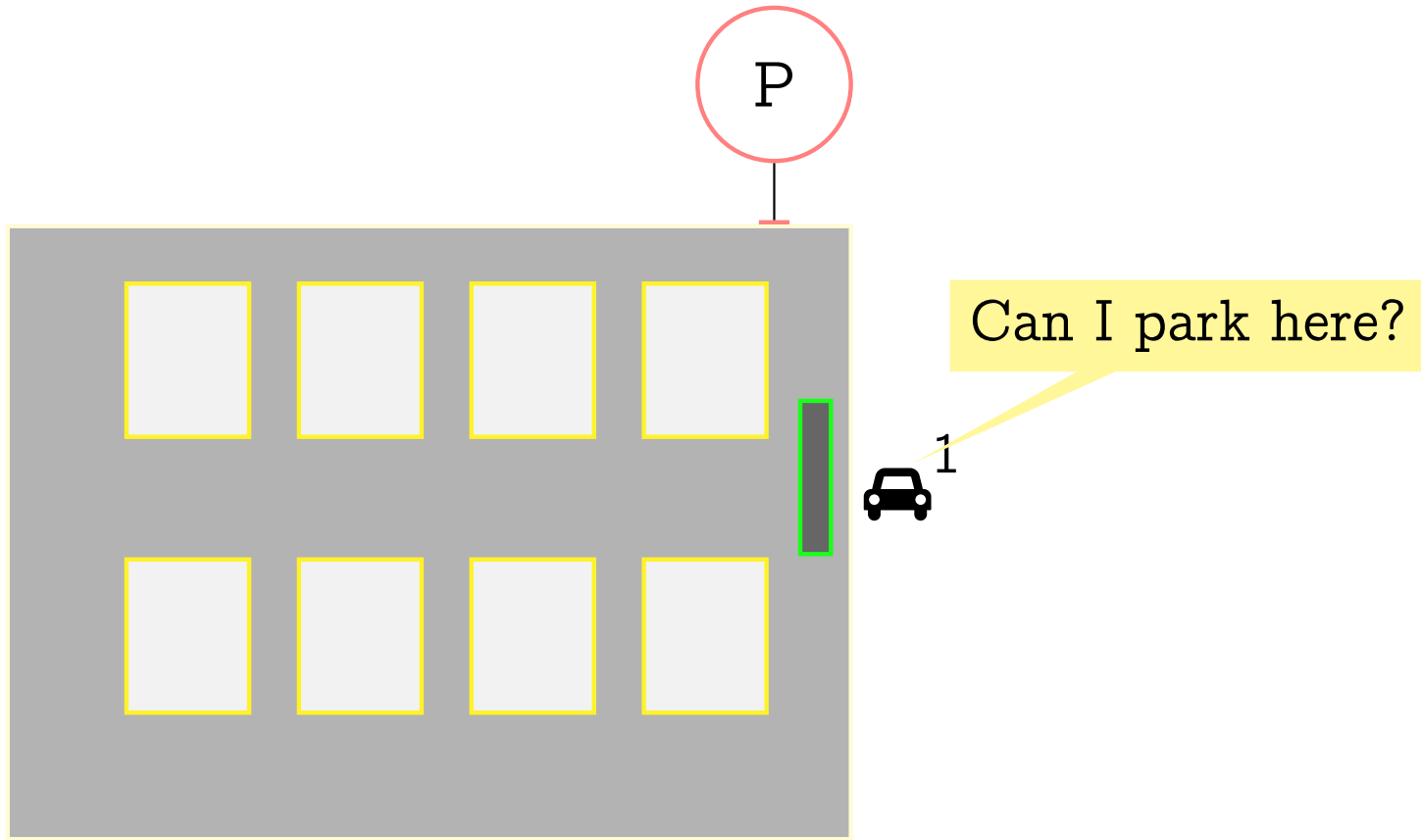

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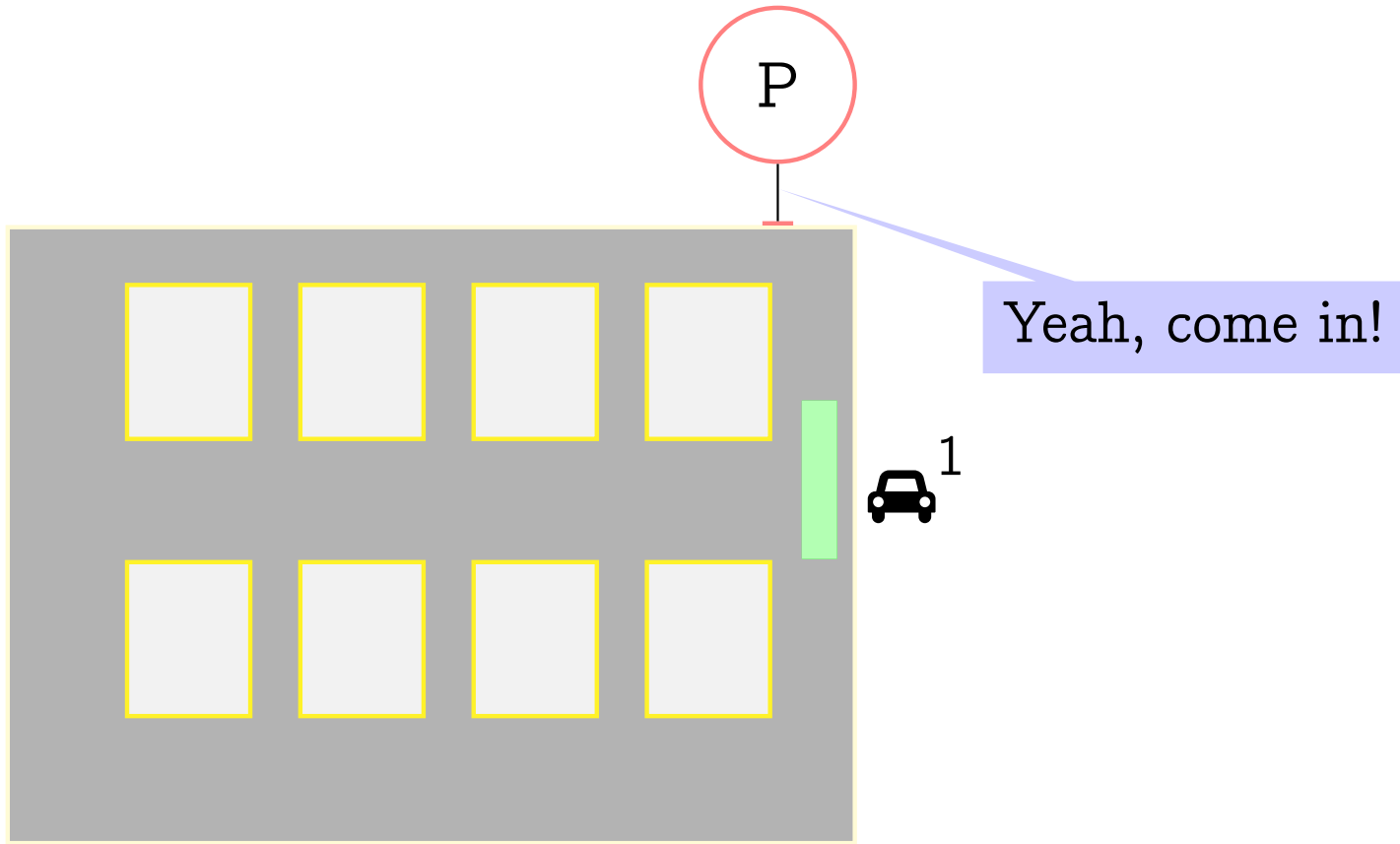

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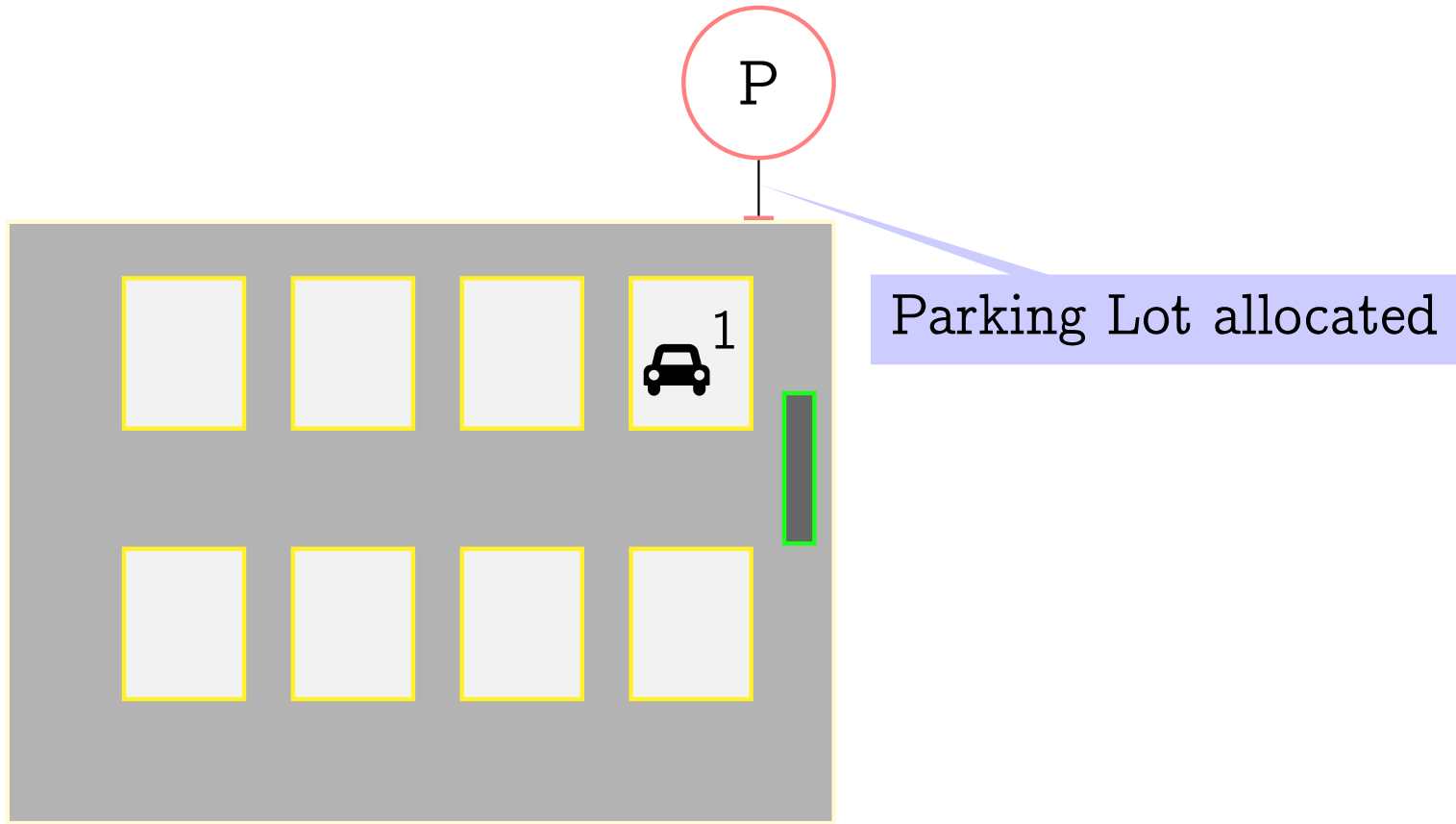

Running example

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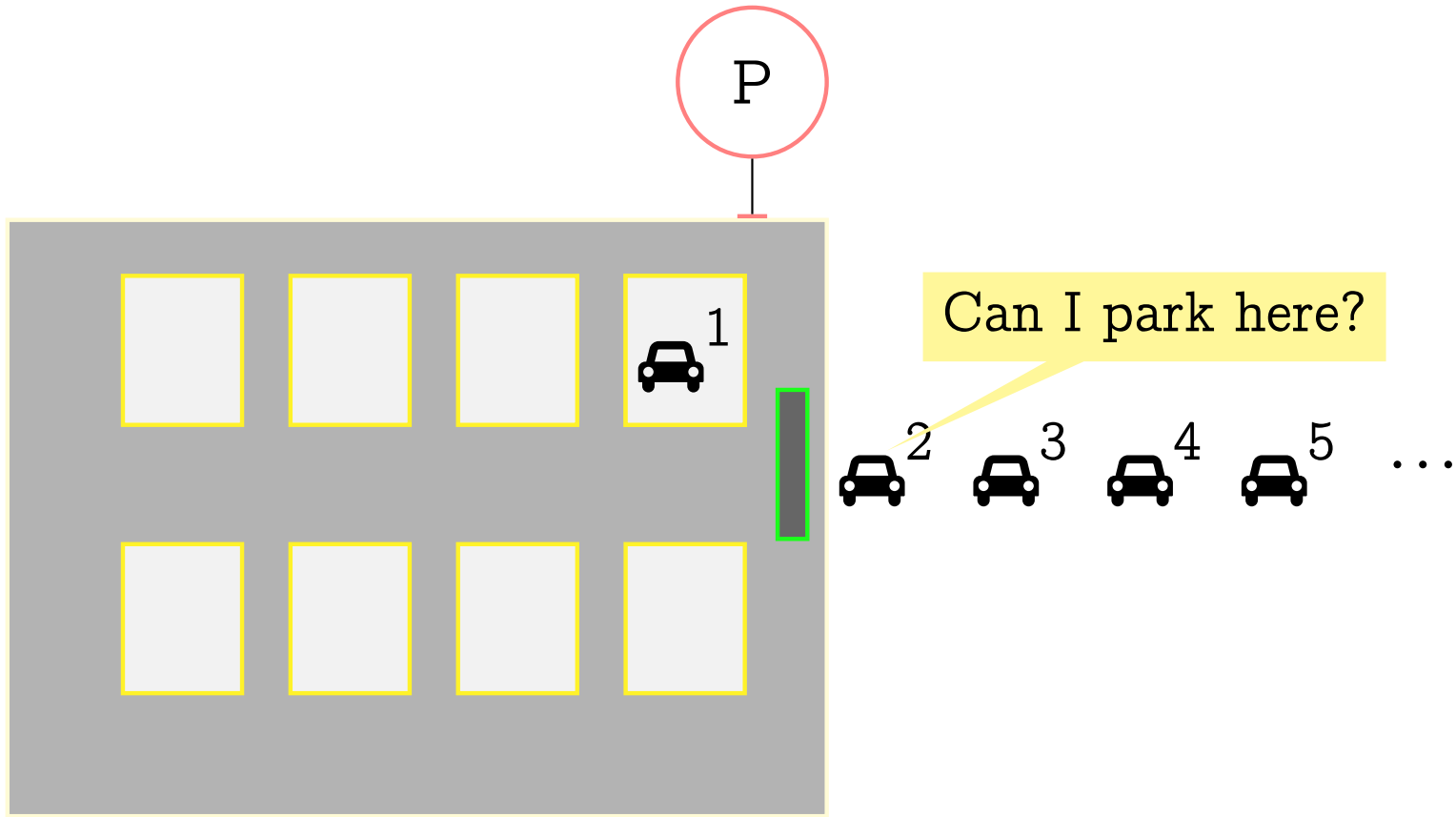
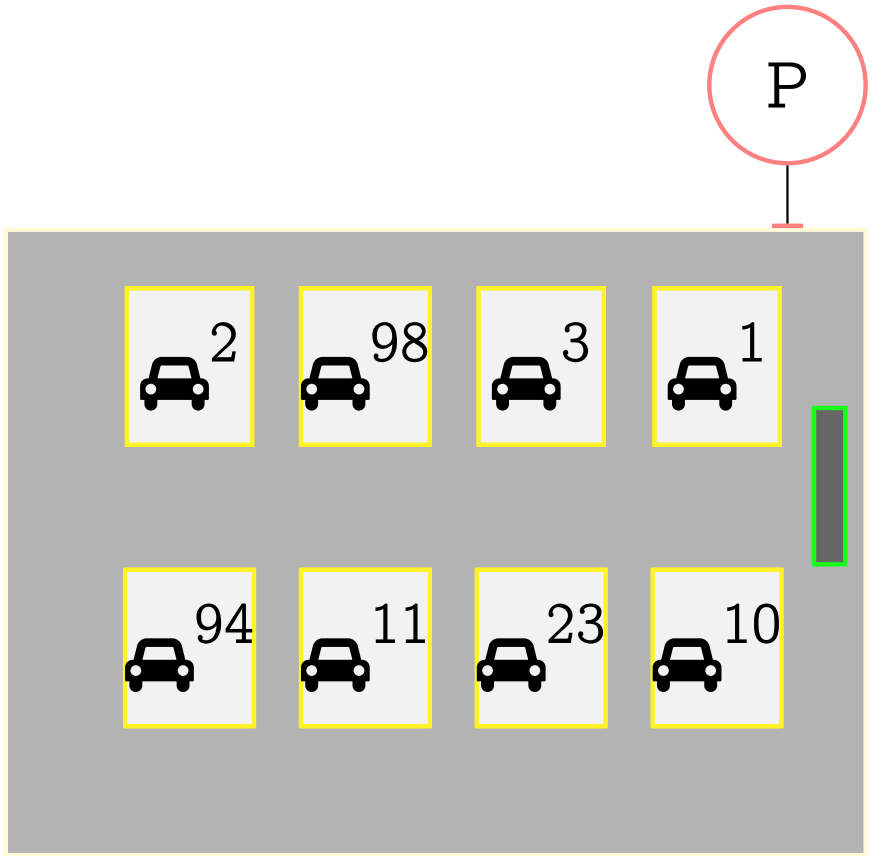


Running example

No parking space



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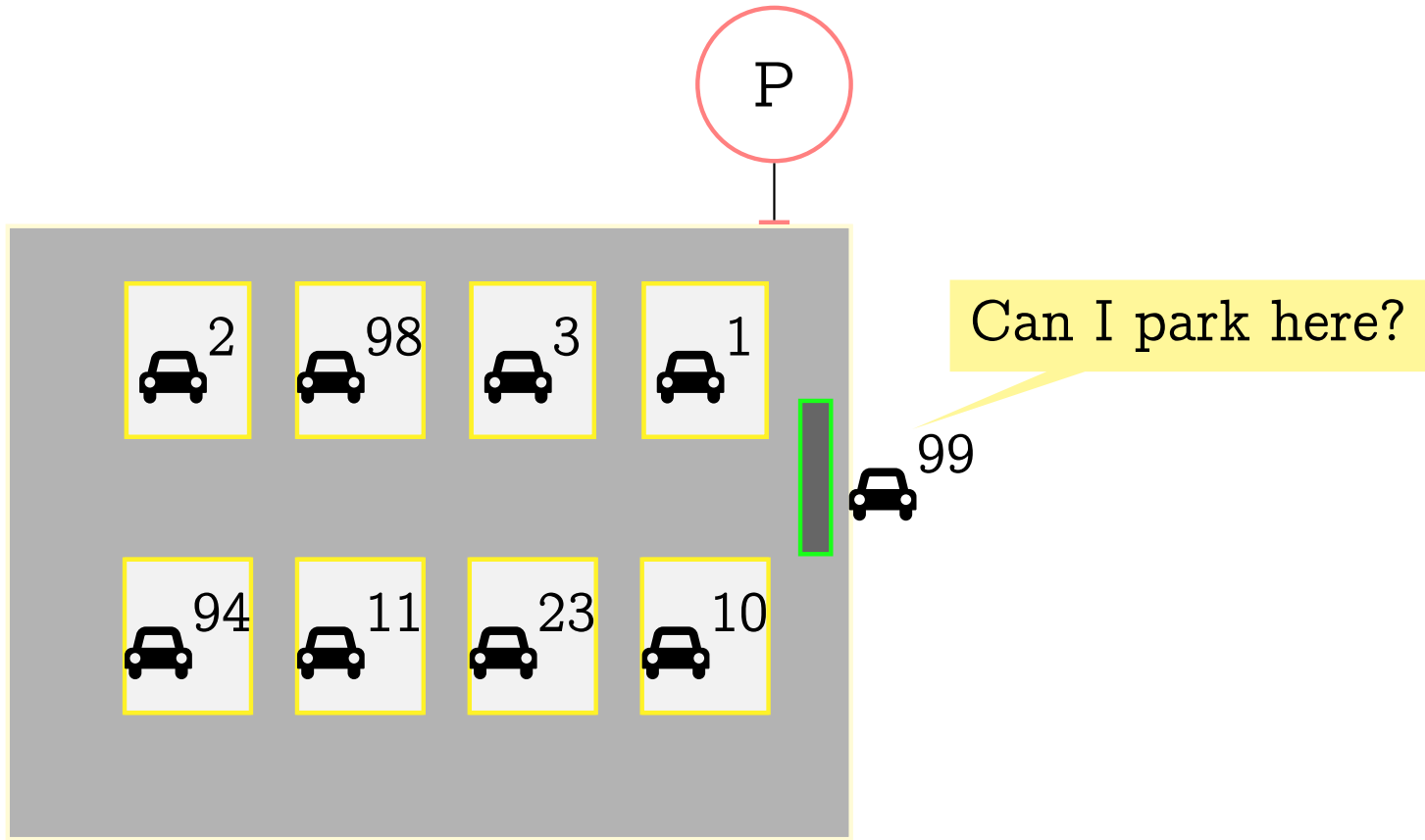

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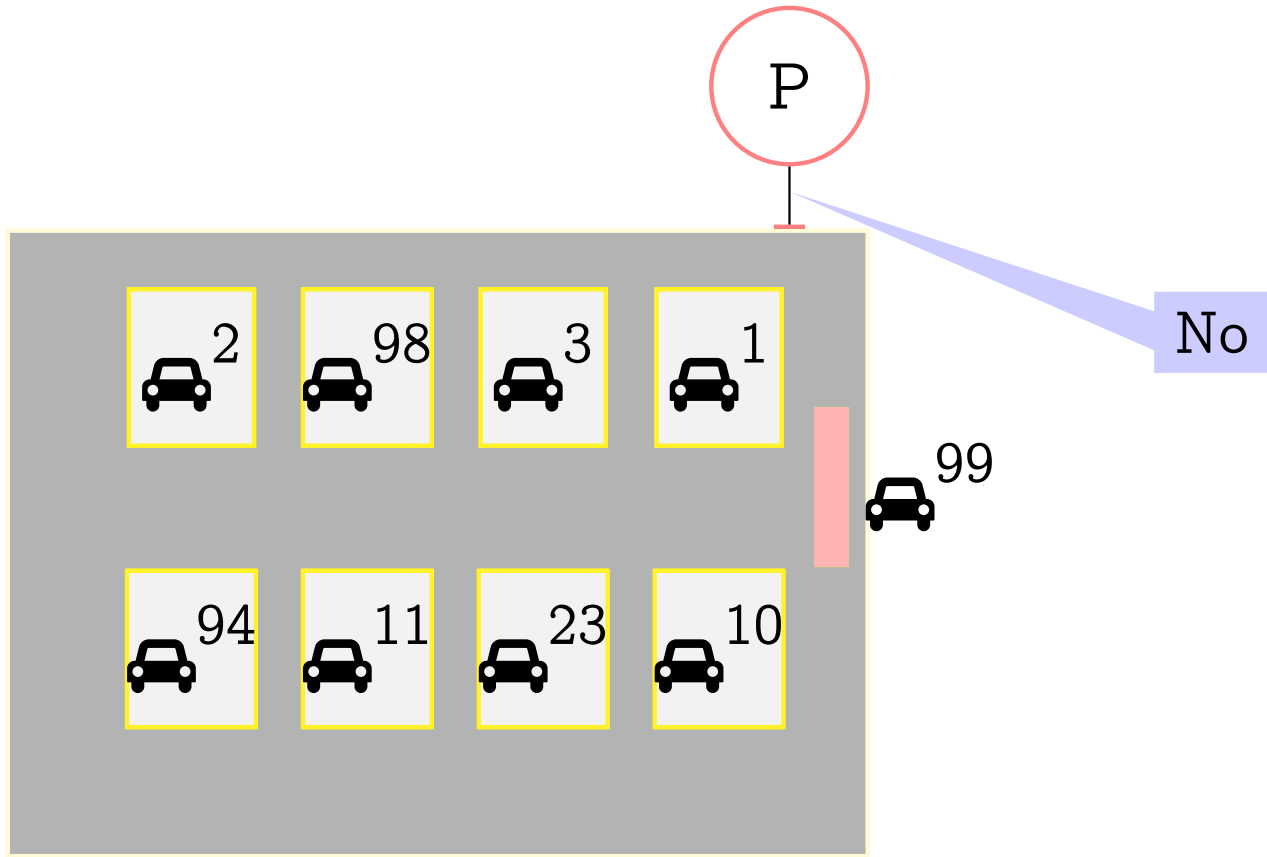

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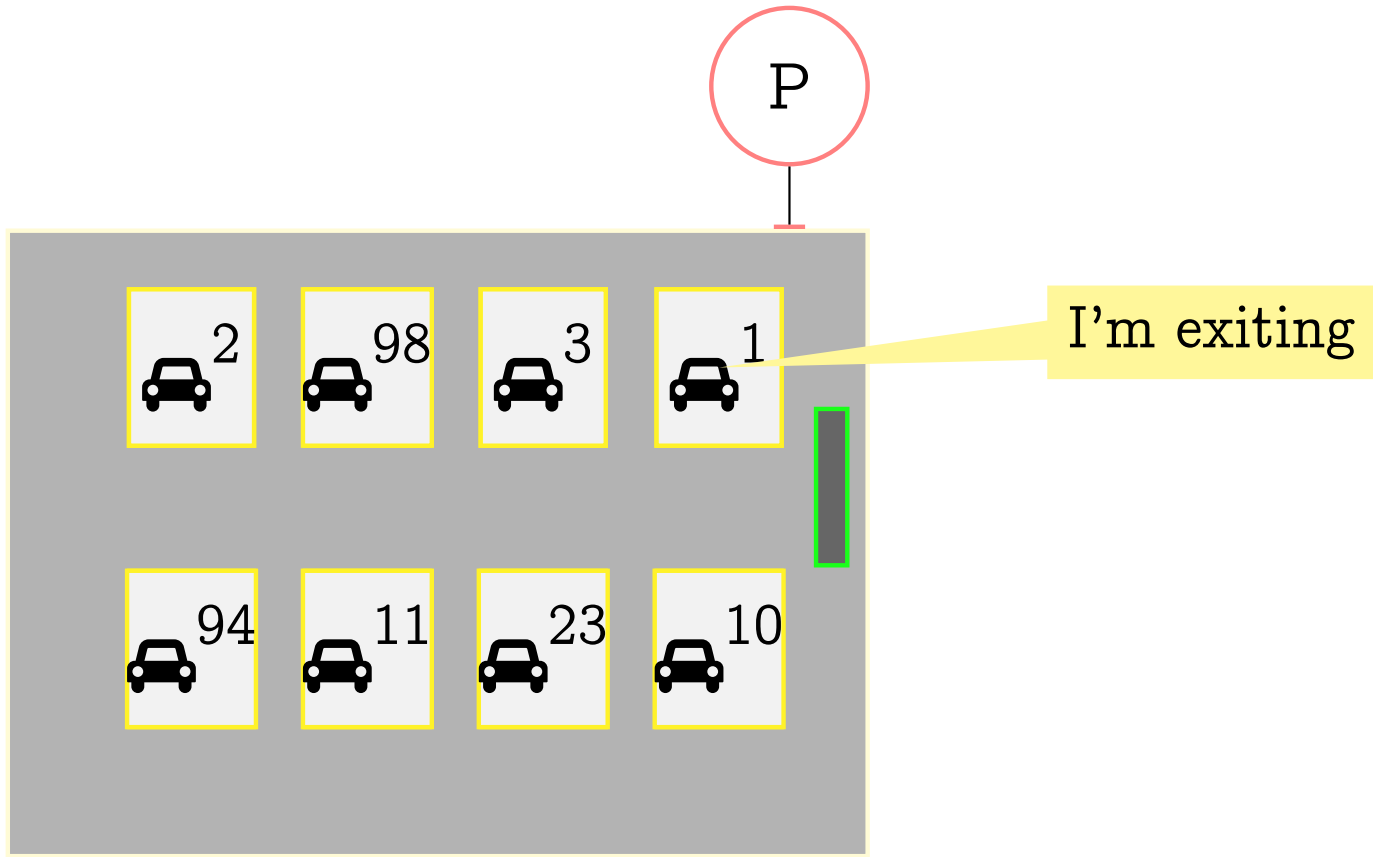

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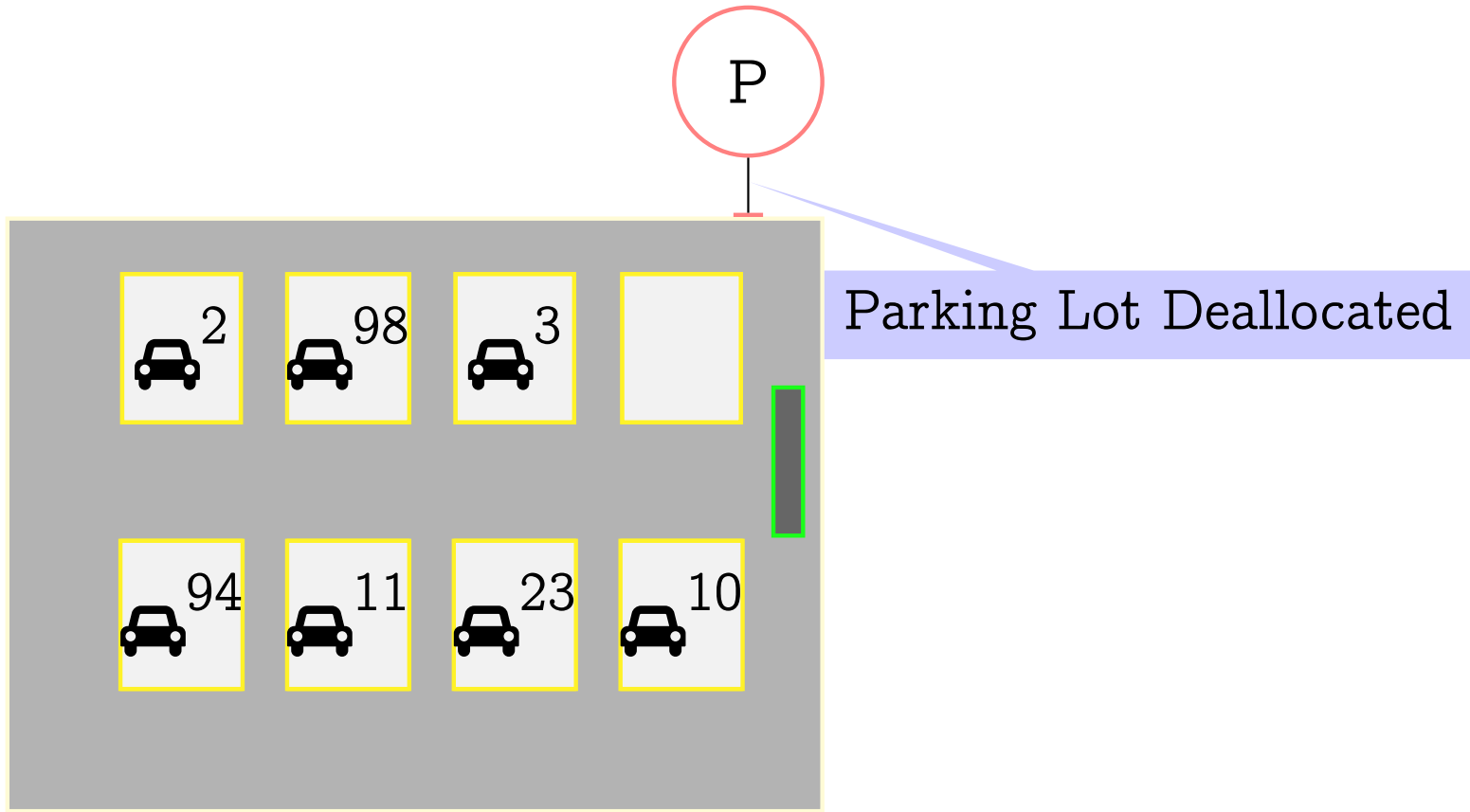

Running example

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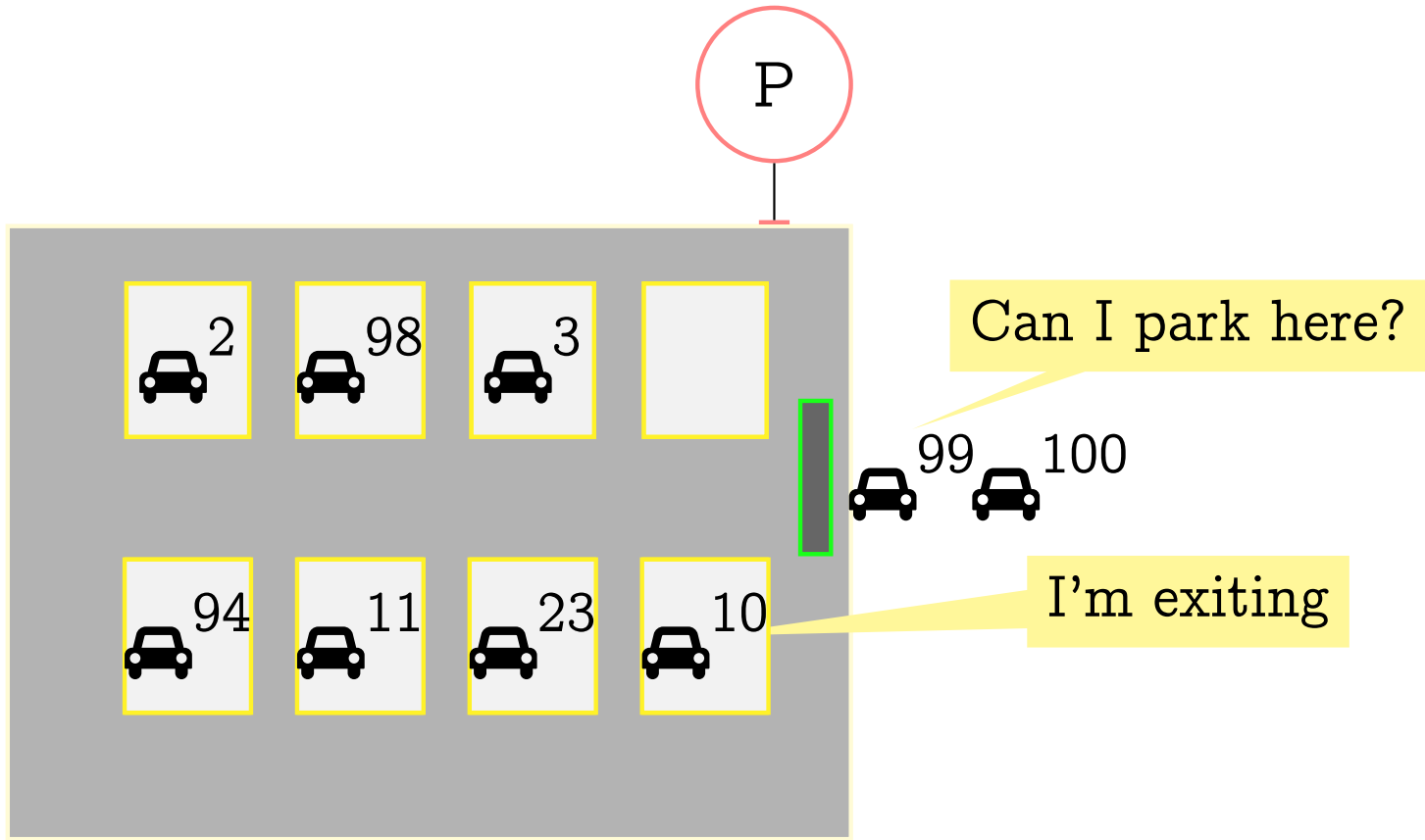
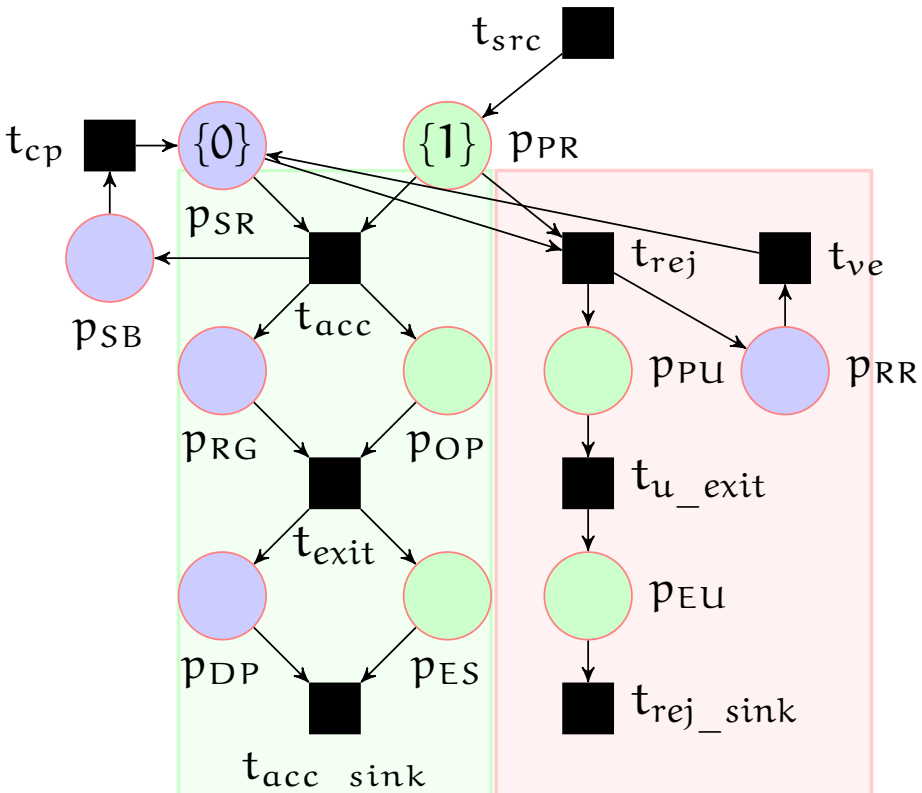


Modelling an Unbounded Client-Server (UCS)



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$$G_s(\forall x)\Big(occupy\_parking\_lot(x) \Rightarrow F_c(exit\_successfully(x))\Big)$$

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The proposed logic: The Monodic* Logic $\mathcal{L}^1_{\mathrm{UCS}}$

The set of client formulae Δ:

$$\Delta ::= p(x) \mid \neg\alpha \mid \alpha \vee \beta \mid \alpha \wedge \beta \mid X_c\alpha \mid F_c\alpha \mid G_c\alpha \mid \alpha\ U_c\ \beta$$

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The set of server formulae Ψ:

$$\Psi ::= q \mid \neg\psi \mid (\exists x)\alpha \mid (\forall x)\alpha \mid \psi_1 \vee \psi_2 \mid \psi_1 \wedge \psi_2 \mid X_s\psi \mid F_s\psi \mid G_s\psi \mid \psi_1\ U_s\ \psi_2$$

where $\psi, \psi_1, \psi_2 \in \Psi$ and $q \in P_s$, the set of atomic server propositions, $\alpha \in \Delta$.

The Monodic Logic $\mathcal{L}^1_{\mathrm{UCS}}$ (contd)

$$\psi = (\exists x)(\exists y)\Big(\big(\mathrm{PR}(x) \wedge \mathrm{PR}(y)\big) \wedge \mathbf{F}_c\big(\mathrm{ES}(x) \wedge \mathrm{ES}(y)\big)\Big)$$

- Is $\psi \in \mathcal{L}^1_{\mathrm{UCS}}$?

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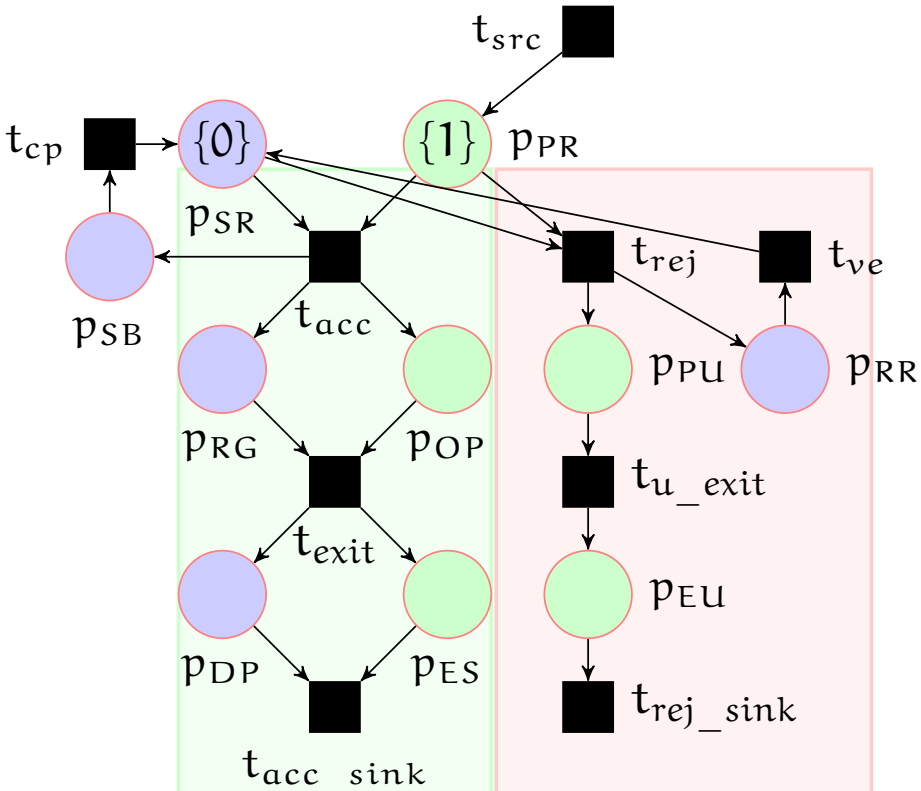
- Is $\psi \in \mathcal{L}^1_{\mathrm{UCS}}$?
- Answer: No. **not a well formed formula in** $\mathcal{L}^1_{\mathrm{UCS}}$

Recall: our model



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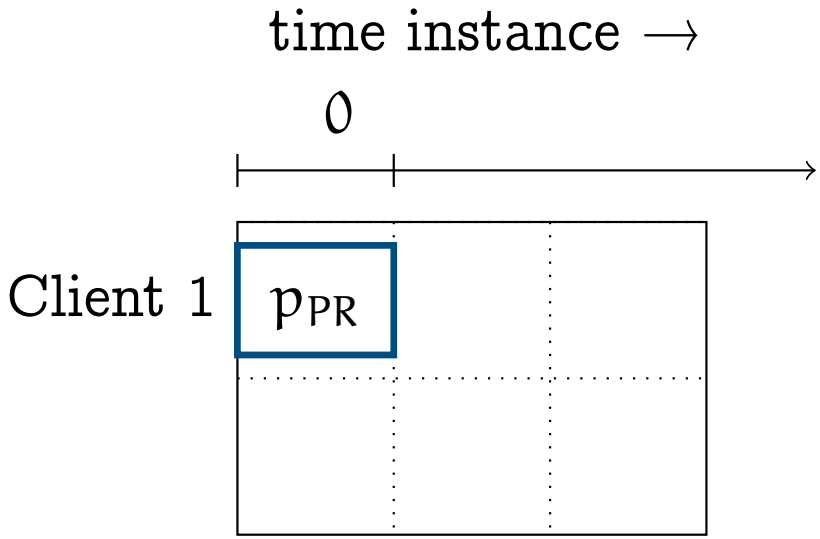
Snapshots of the system + live windows



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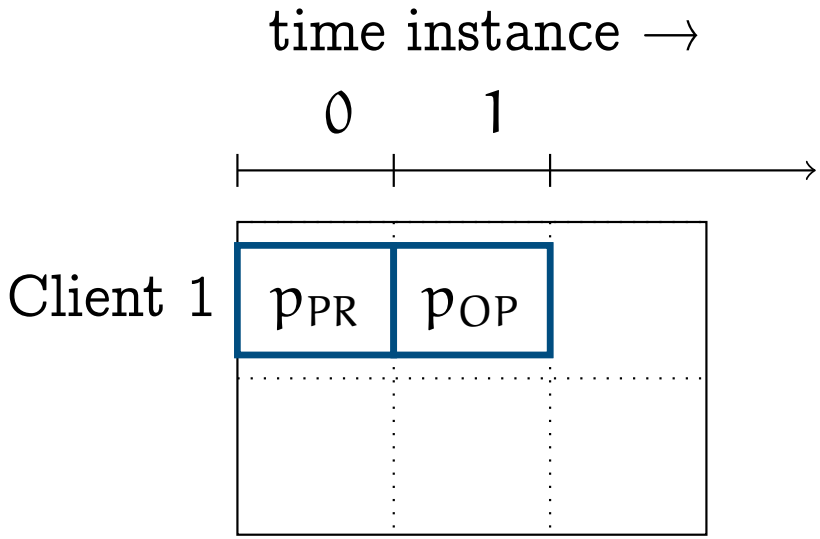
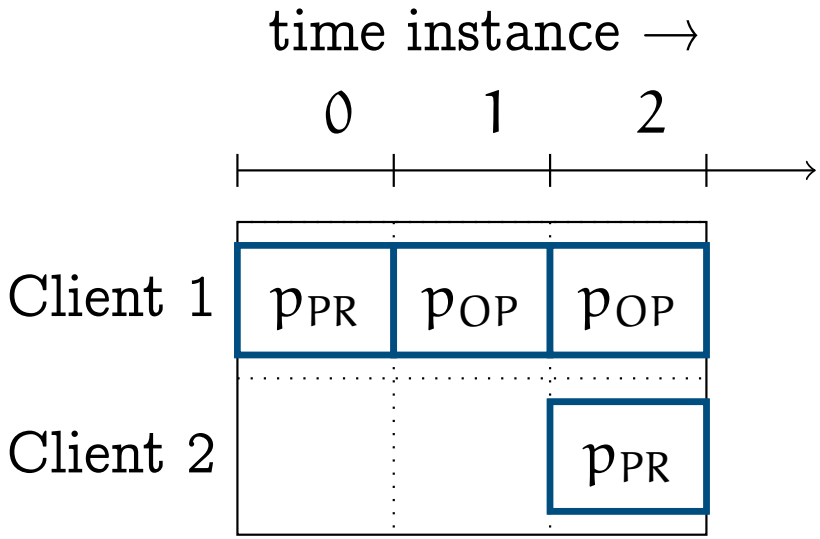
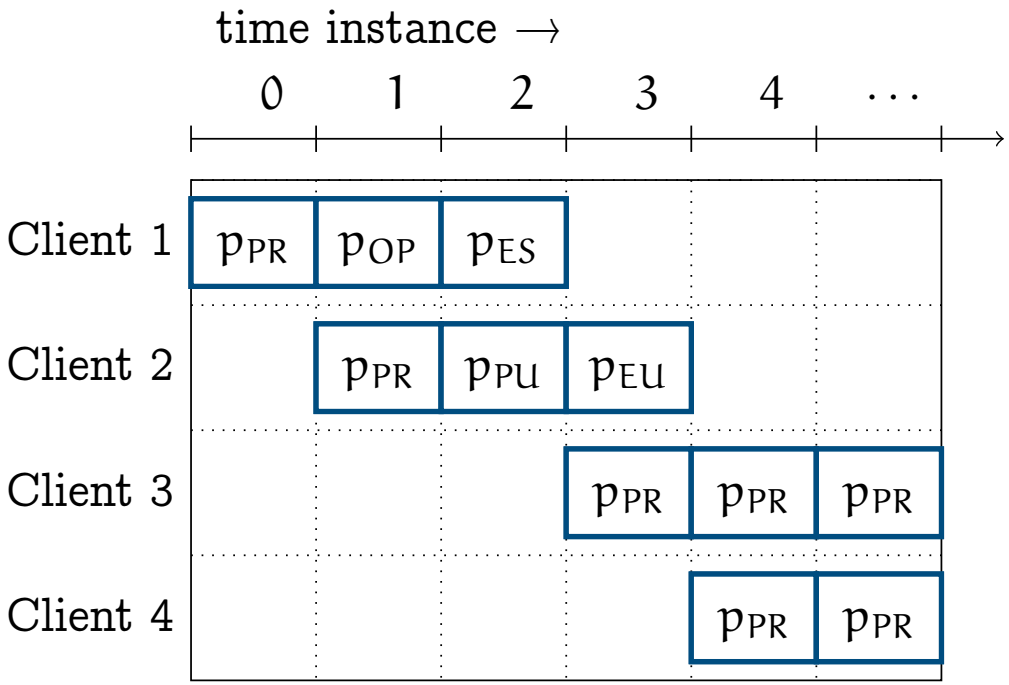


Snapshots of the system + live windows



Snapshots of the system + live windows (contd)



- 4 distinguishable clients, with overlapping *live windows*, with the bound 5.
- client 1 is at p_{PR} at instance 0. i.e, $PR(x)$ is satisfied in client 1 at instance 0.
- For client 1, the *left boundary* is at instance 0 and its *right boundary* is at instance 2.

Formally speaking...

- Let CN be a countable set of client names.

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- Let $\mathfrak{Z} : CN \times \mathbb{N}_0 \to Q$ be a partial mapping describing the local state of each client $a \in CN$ at an instance $i \in \mathbb{N}_0$.
- For instance, $\mathfrak{Z}(a, i) \in q$, means that the local state of each client a at instance i is state q, where $q \in Q$.

Formally speaking...

A model is a triple $M = (\nu, V, \xi)$ where

- ν gives the local behaviour of the server as follows: $\nu = \nu_0\nu_1\nu_2\ldots$, where for all $0 \leq i$, $\nu_i \subseteq P_s$

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- V gives the set of live agents (clients) at each instance. $V = V_0V_1V_2\ldots$, where for all $0 \leq i$, V_i is a finite subset of CN, gives the set of live agents at the ith instance. For every $0 \leq i$, V_i and V_{i+1} satisfy the following properties:
  1. if $V_i \subseteq V_{i+1}$ then for every $a \in V_{i+1} - V_i$ such that $\mathfrak{Z}(a, i+1) \in I$.
  2. if $V_{i+1} \subseteq V_i$ then for every $a \in V_i - V_{i+1}$ such that $\mathfrak{Z}(a, i) \in F$.

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- $\xi = \xi_0\xi_1\xi_2\cdots$, where for all $0 \leq i$, $\xi_i : V_i \to 2^{P_c}$ gives the properties satisfied by each live agent at ith instance.

  Also, $L(\mathfrak{Z}(a, i)) = \xi_i(a)$.

Semantics

$M, i \models (\exists x)\alpha$ iff $\exists a \in CN,\ a \in V_i$ and $M, [x \mapsto a], i \models_x \alpha$.

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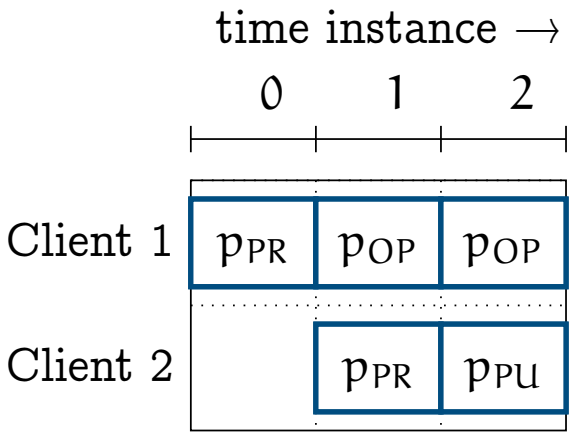

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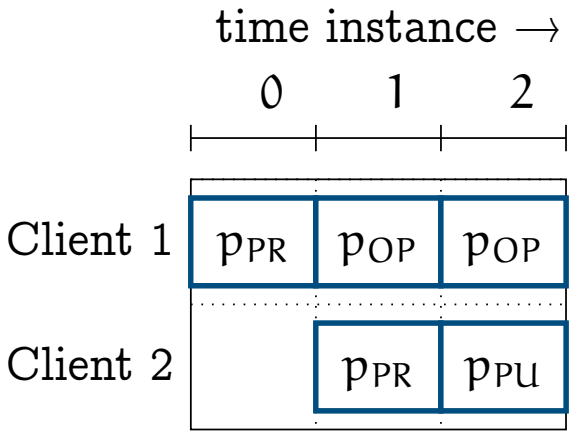

Given $\alpha = OP(x) \vee PR(x)$ and
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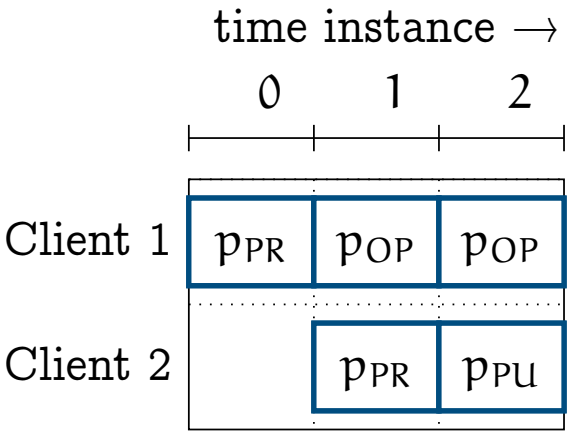
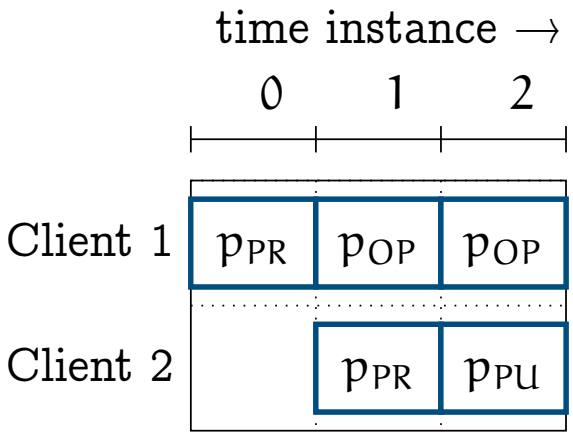


Given $\alpha = OP(x) \vee PR(x)$ and $CN = \{1, 2\}$.

- $M, 0 \models^k (\exists x)(OP(x) \vee PR(x))$.
- $M, 1 \models^k (\exists x)(OP(x) \vee PR(x))$.
- $M, 2 \models^k (\exists x)(OP(x) \vee PR(x))$.

Bounded Semantics

$M, i \models^k (\forall x)\alpha$ iff $\forall a \in CN$, if $a \in V_i$ then $M, [x \mapsto a], i \models^k_x \alpha$



Given $\alpha = ES(x)$ and $CN = \{1, 2\}$.

- $M, 0 \not\models^k (\exists x)(ES(x))$.
- $M, 1 \not\models^k (\exists x)(ES(x))$.
- $M, 2 \not\models^k (\exists x)(ES(x))$.

Bounded Semantics

$M, i \models^k F_s\psi$ iff $\exists j : i \leq j \leq k$, $M, j \models^k \psi$.
Given $\psi = (\exists x)ES(x)$.

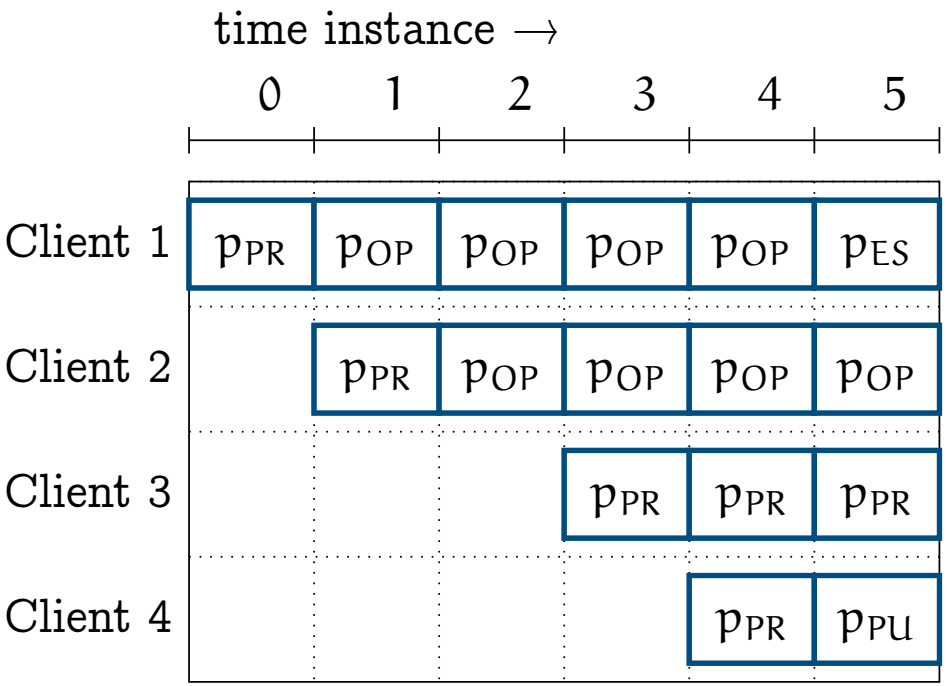


Figure: Snapshot with 4 clients

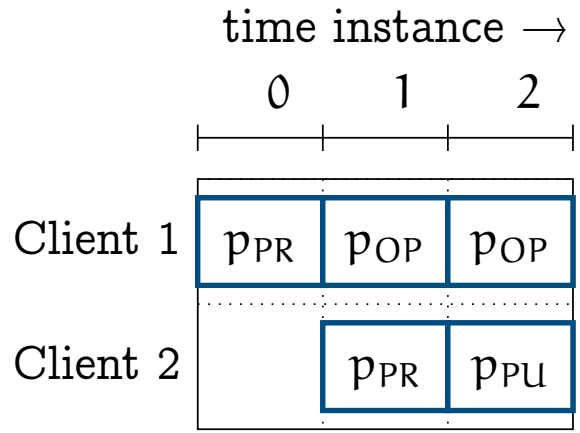


Figure: Snapshot with 2 clients

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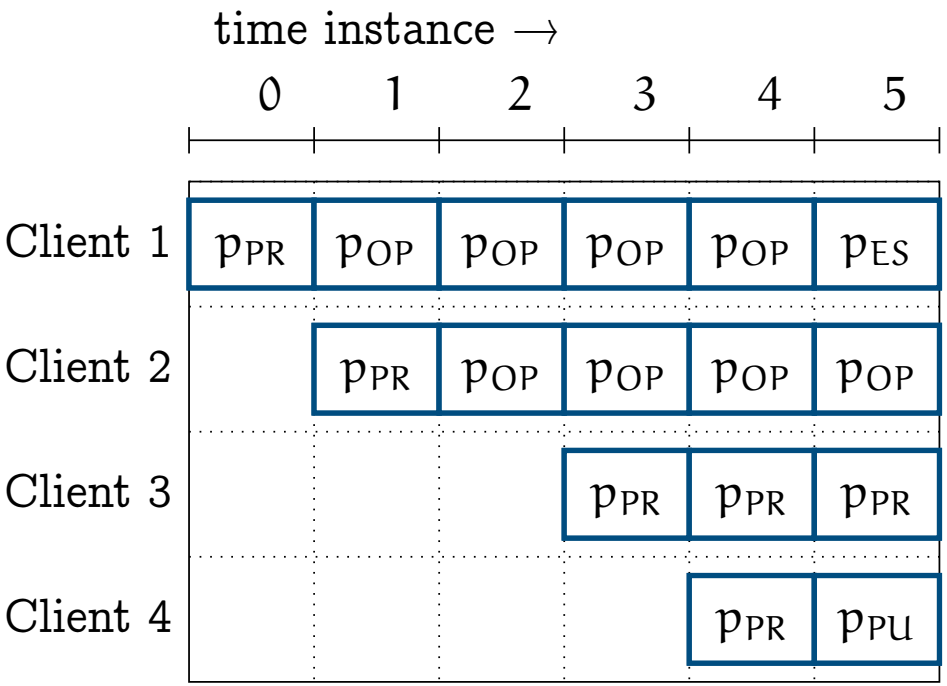

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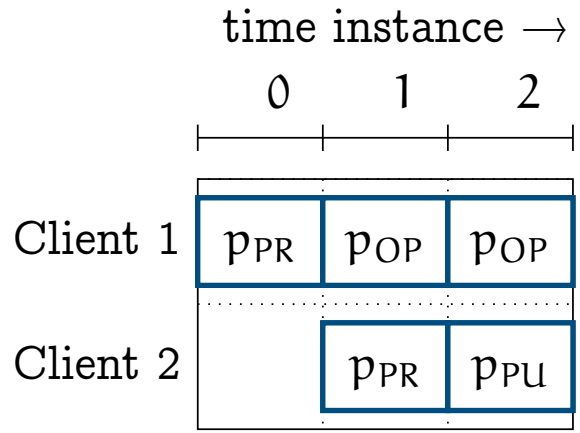

Figure: Snapshot with 2 clients

As shown above $M, 5 \models^k F_s(\exists x)ES(x)$.

Implementation

Verifying $G_s \exists x (F_c(p_0(x)))$

```
 evname: cToken_4_1
 evname: cToken_4_2
 evname: cToken_4_3
 evname: cToken_4_4
 evname: cToken_4_5
 evname: sToken_4_1
LOG: done with initializing empty token variables
LOG: sysObj.MAX_TOKENS_LIMIT before initial marking: 1
LOG: constructed initial Marking
LOG: constructed the complete Transition Function
LOG: nochange constraint added
LOG: UNSAT
LOG: UNSAT
LOG: UNSAT
LOG: UNSAT
LOG: ----------------------------run 5 ----------------------------------
 evname: cToken_5_0
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 evname: cToken_5_2
 evname: cToken_5_3
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```

Contributions

- Part 1: Verification of Unbounded Client-Server (UCS) using Petri Nets and Linear Temporal Logic with integer arithmetic
- Part 2: Verification of UCS with distinguishable clients using ν-nets and properties specified in monodic First Order Logic

What if clients had an internal structure?

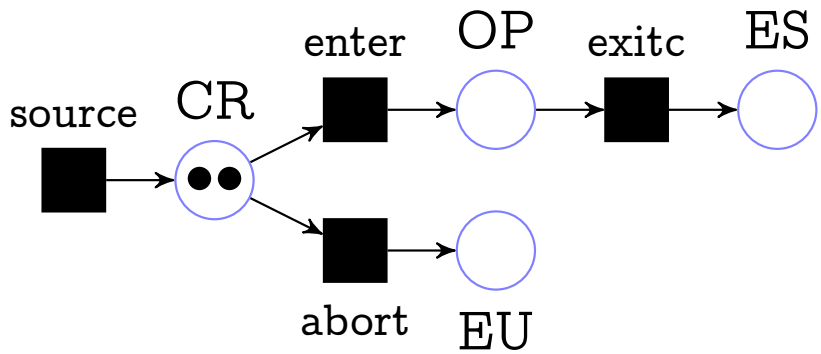


Figure: Petri net N_3 depicting client behaviour

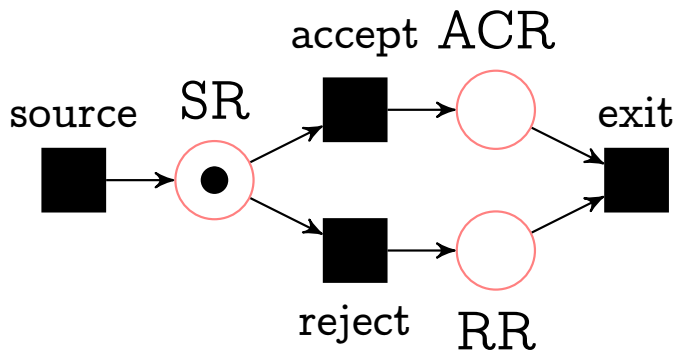


Figure: Petri net N_3 depicting server behaviour

Question: What properties of the system are we interested in?

- **Reachability:** Is $\mu_1 = \langle \mathtt{SR}, \{\!\{\mathtt{client1CR}, \mathtt{client2CR}\}\!\} \rangle$ a reachable marking?
- **Coverability:** Given $\mu_1 = \langle \mathtt{SR}, \{\!\{\mathtt{client1CR}, \mathtt{client2OP}\}\!\} \rangle$ and $\mu_2 = \langle \mathtt{SR}, \{\!\{\mathtt{client1OP}, \mathtt{client2CR}, \mathtt{client3OP}\}\!\} \rangle$.

  Then, is $\mu_1 \preceq \mu_2$?

Modelling UCS via Elementary Object Systems

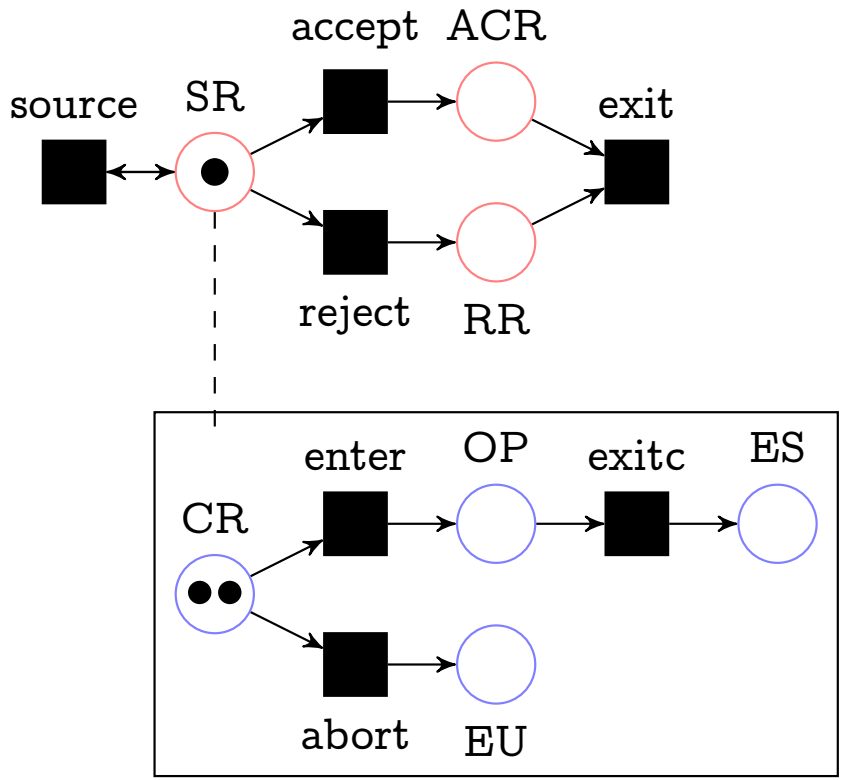
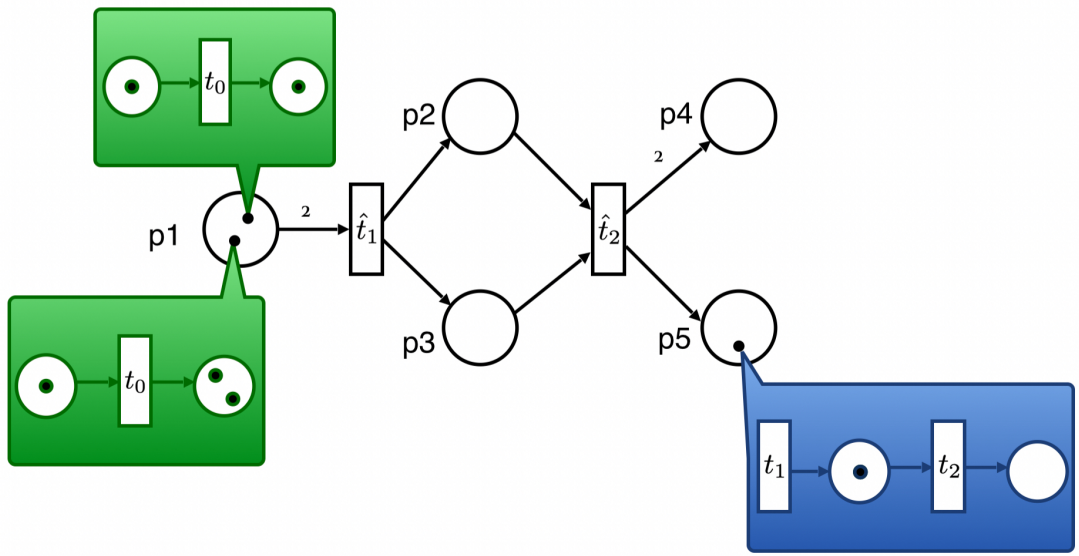


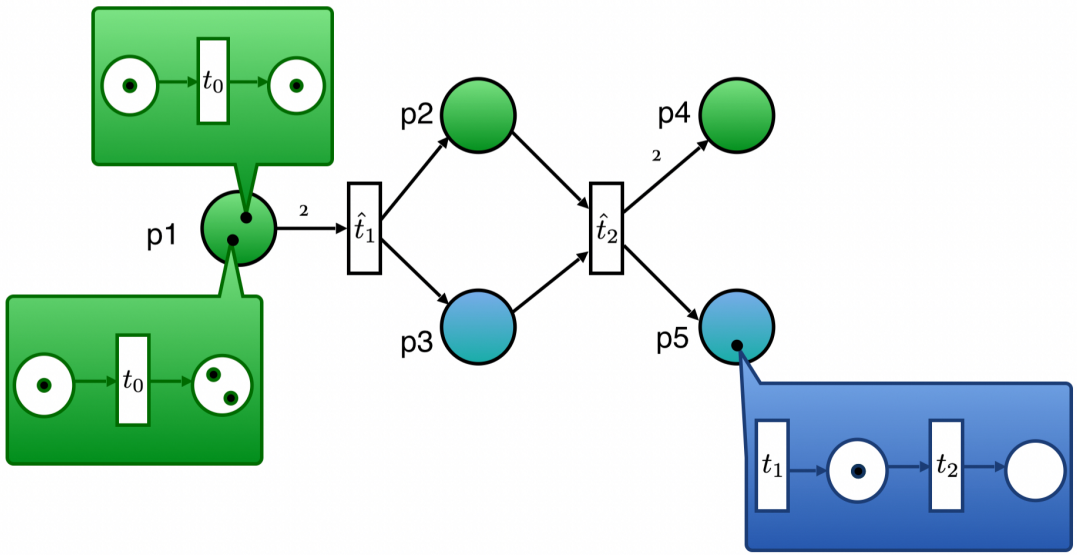
Figure: EOS modeling the single server (unbounded) multiple client system

What are EOSs?

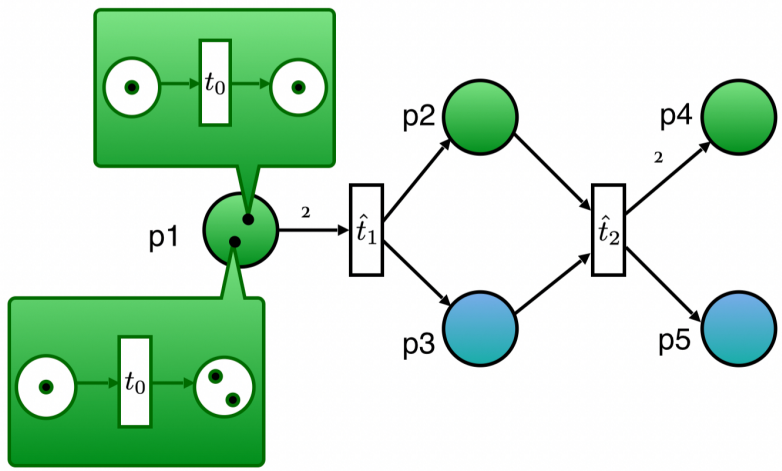
EOS – nested markings



EOS – typed places



EOS – object autonomous events



EVENTS

$e_1 = \left(id_{p_1}, t_0\right)$

$e_2 = \left(\hat{t}_1, \varnothing\right)$

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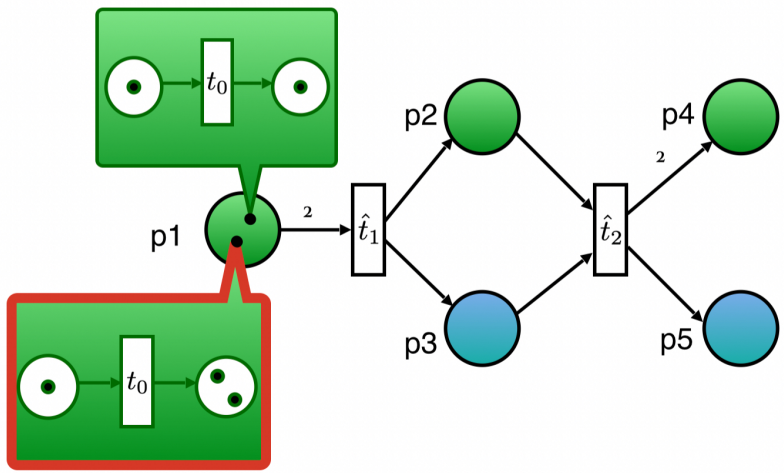

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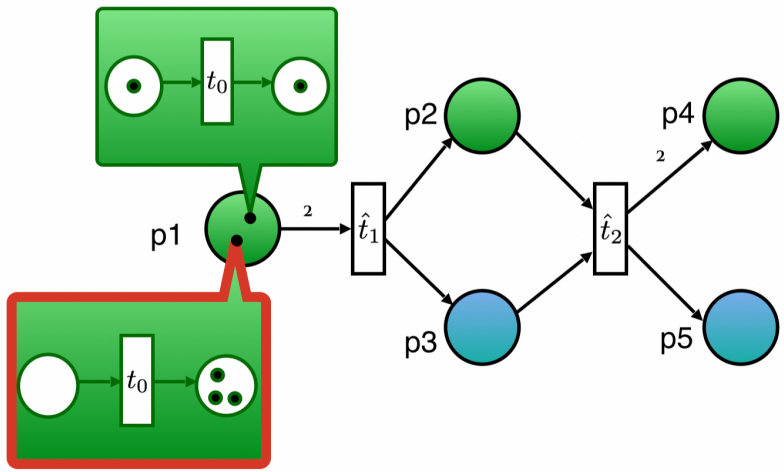

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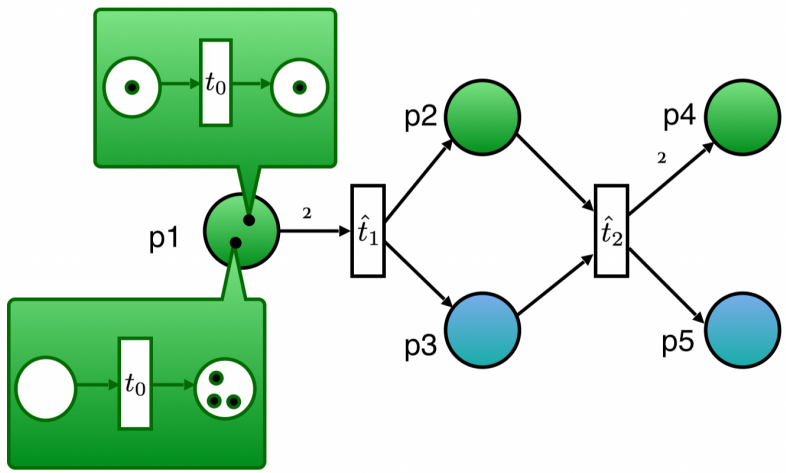

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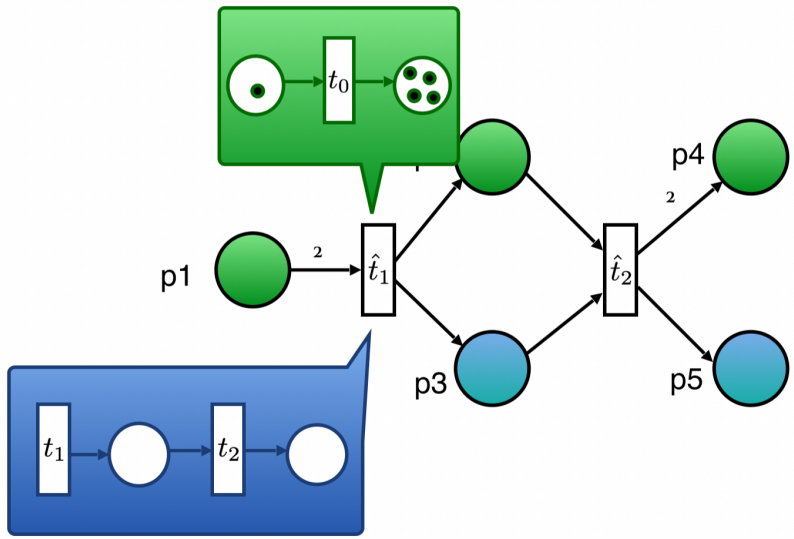

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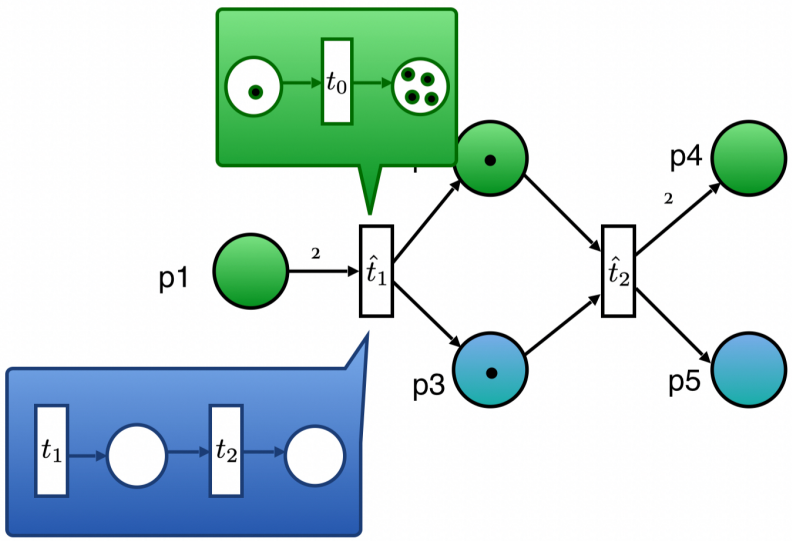

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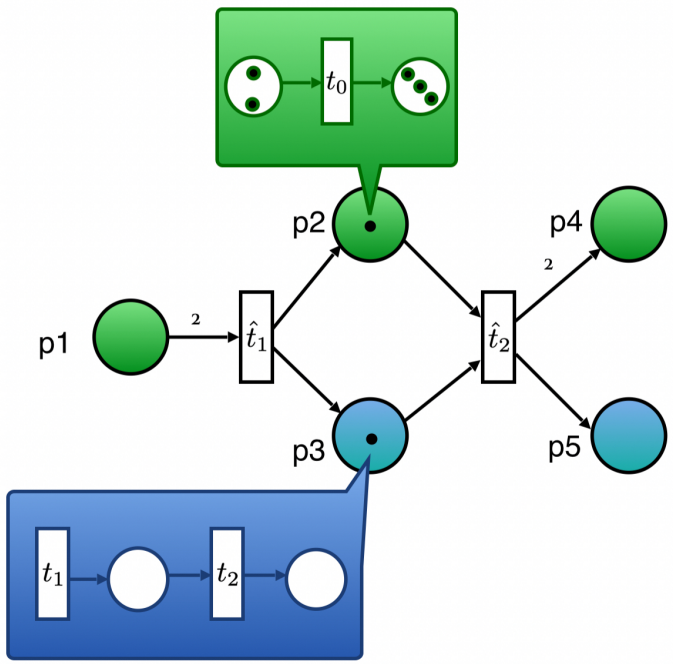

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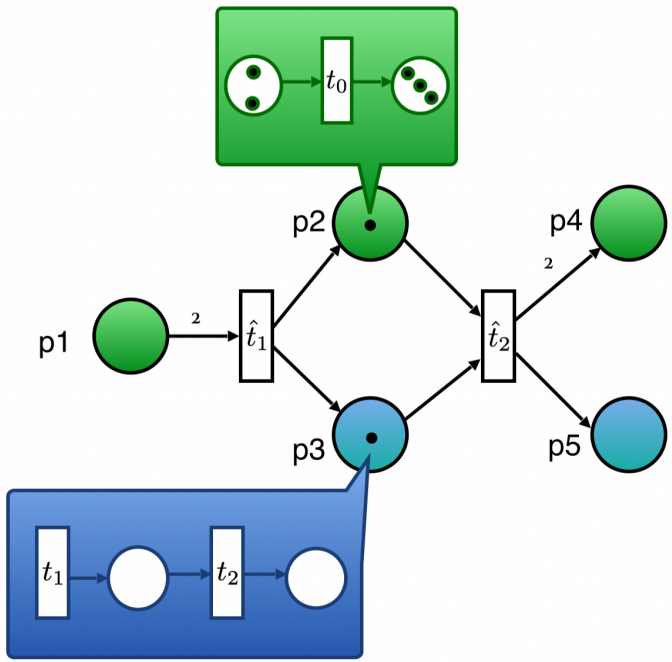
EOS – synchronization events



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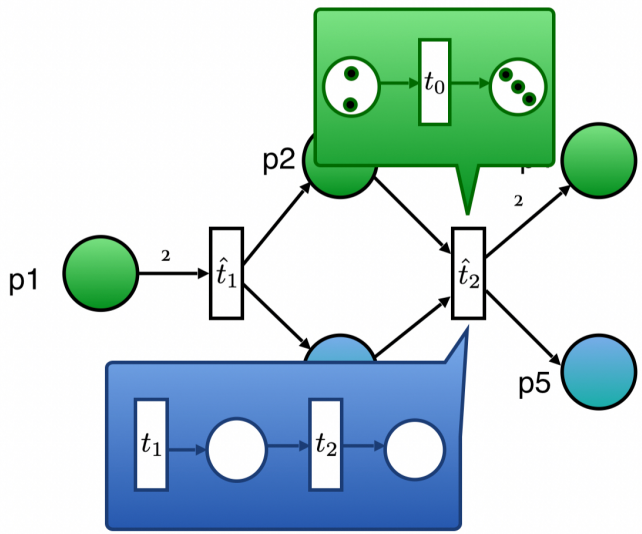

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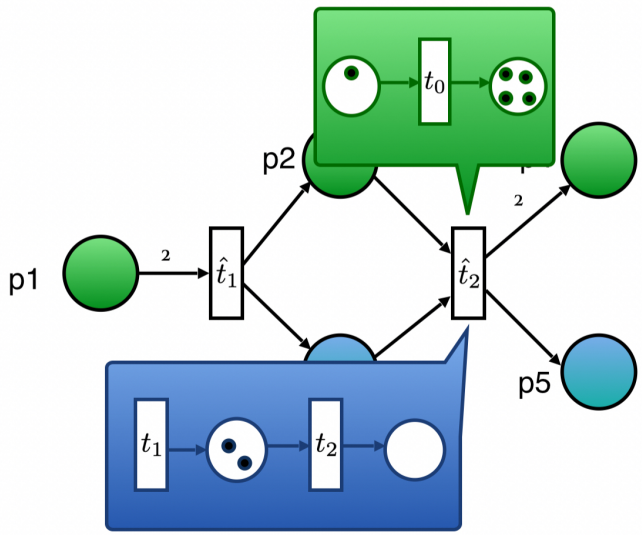

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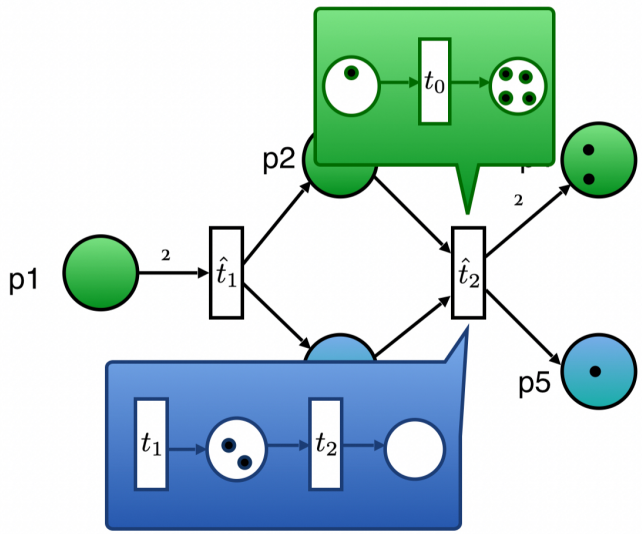

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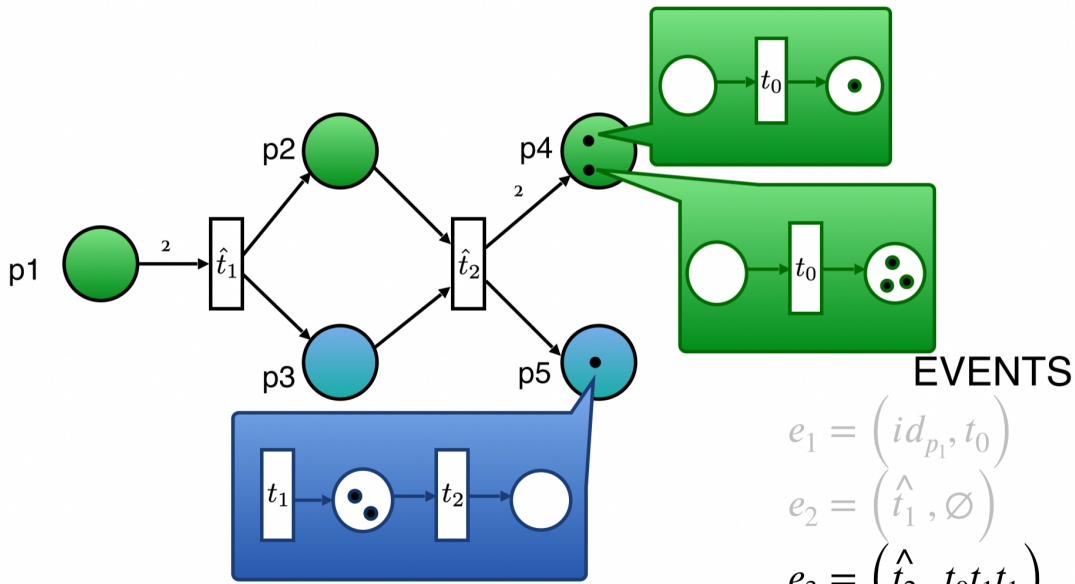
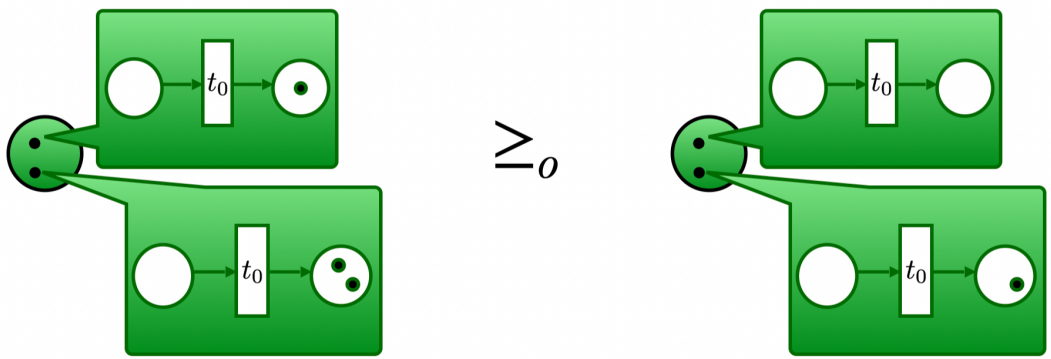
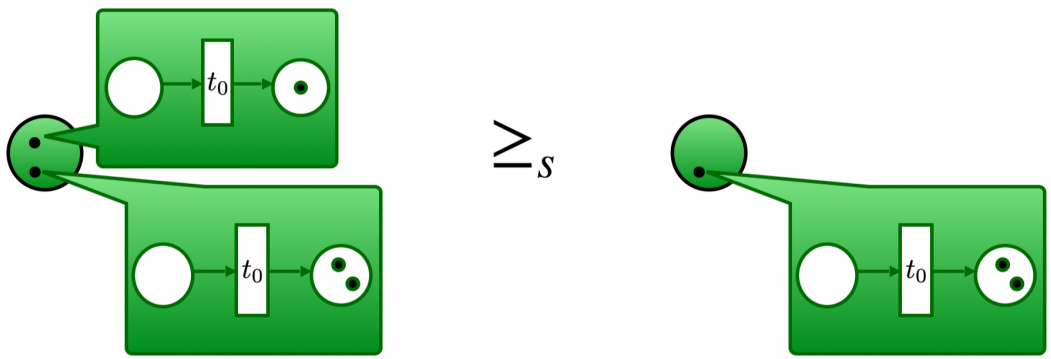


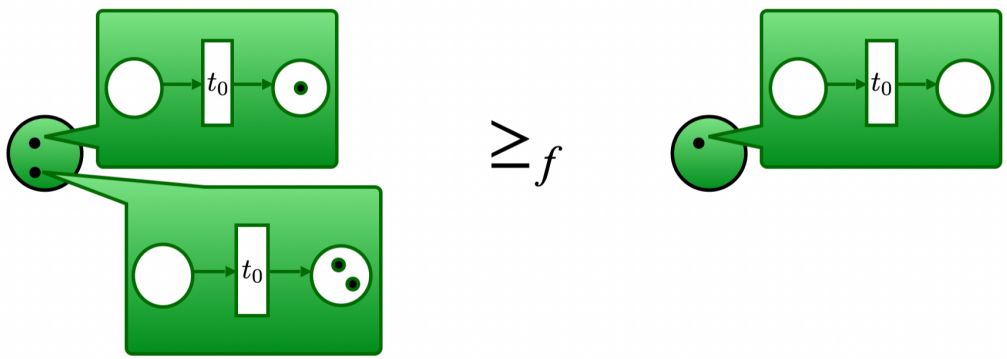
Object lossiness



System lossiness



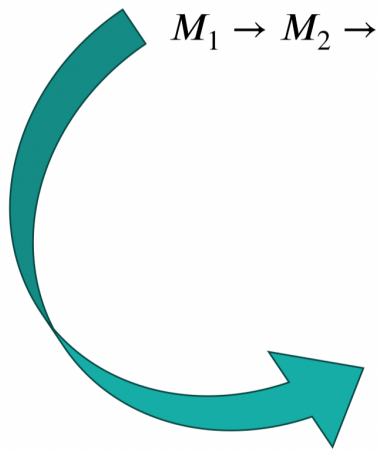
Full lossiness



$(\preccurlyeq, \ell)$-lossy runs

Perfect runs: only standard steps

$M_1 \to M_2 \to M_3 \to \dots$



$(\preccurlyeq, \ell)$-runs: at most $\ell \leq |\mathbb{N}|$ steps of type $\preccurlyeq$

$M_1 \to M_2 \succcurlyeq M'_3 \to M'_4 \succcurlyeq M'_5 \succcurlyeq M'_6 \to M_7 \to \dots$

$(\preccurlyeq, \ell)$-lossy problems

Is the system **robust** up to ℓ occurrences of $\preccurlyeq$?

$(\preccurlyeq, \ell)$-lossy problems

Is the system **robust** up to ℓ occurrences of $\preccurlyeq$?

$(\preccurlyeq, \ell)$-deadlock freeness

Input

An EOS E and an initial marking M.

Output

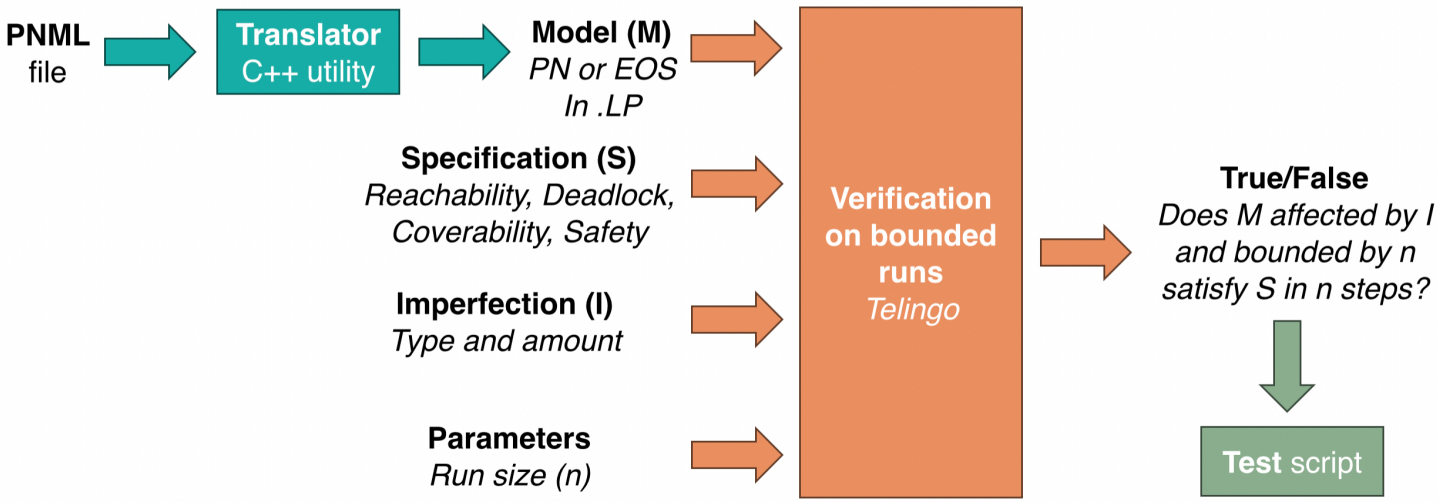
Is there a $(\preccurlyeq, \ell)$-run from M to a marking where no event is enabled?

Decidability Results (PNSE'24)

	Problems	$\preccurlyeq_f$	$\preccurlyeq_o$	$\preccurlyeq_s$
Conservative EOS	0-reach	**Undec** [Bußı4]	**Undec** [Bußı4]	**Undec** [Bußı4]
	cover	**Dec** [Bußı4]	**Undec** (2CM)	**Undec** (2CM)
	ℓ-reach/cover	**Dec** (Comp.)	**Undec** (Comp.)	**Undec** (Comp.)
	ω-reach/cover	**Dec** (Comp.)	**Undec** (Comp.)	**Undec** (Comp.)
EOS	0-reach	**Undec** [Bußı4]	**Undec** [Bußı4]	**Undec** [Bußı4]
	cover	**Undec** [Bußı4]	**Undec** (cEOS)	**Undec** (cEOS)
	ℓ-reach/cover	**Undec** (Gadget)	**Undec** (cEOS)	**Undec** (Comp.)
	ω-reach/cover	**Dec** (WSTS)	**Undec** (cEOS)	**Undec** (Comp.)

[Bußı4] Köhler-Bußmeier, Michael. 'A Survey of Decidability Results for Elementary Object Systems'. 1 Jan. 2014 : 99 – 123.

Prototype (CILC'24)



Why bounded verification?

Problems on general EOS	$\preccurlyeq_f$	$\preccurlyeq_o$	$\preccurlyeq_s$
0-reach	U	U	U
0-cover	U	U	U
ℓ -reach/cover	U	U	U
ω-reach/cover	D	U	U

F. Di Cosmo, S. Mal, T. Prince, *Deciding Reachability and Coverability in Lossy EOS*, PNSE'24

Why Telingo?

Telingo is **declarative** and supports **temporal constraints**

- E.g., `:- &tel(>? (lossy >(>? lossy)` allows at most one lossy step
- The meaning of lossy is declared orthogonally to EOS specification

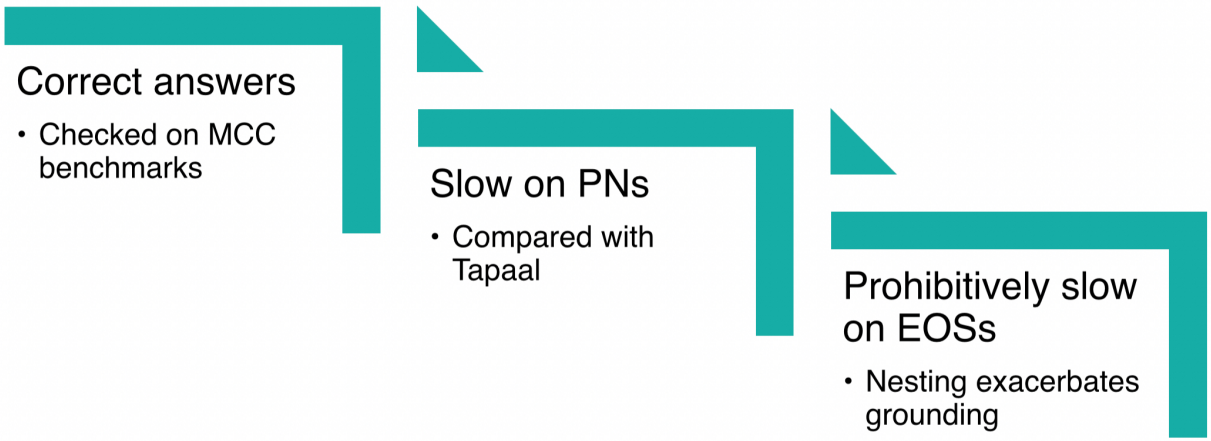
Telingo **returns finite runs**

- Perfectly matches bounded verification

Encoding of PNs and EOSs is **elegant in ASP**

- E.g., when compared to SMT – R. Phawade, T. Prince, S. Sheerazuddin et al., *Bounded Model Checking for Unbounded Client Server Systems,* Arxiv (2022)

Correctness and performances



problem	lossiness	−imax =5 (s)	−imax =10 (s)	−imax =20 (s)	TAPAAL (s)
deadlock	none	UNSAT in 0.052	SAT in 0.622	SAT in 82.754	SAT in $5e-6$
deadlock	any	SAT in 0.009	SAT in 0.010	SAT in 0.009	NA
1-safeness	none	UNSAT in 0.010	UNSAT in 0.014	UNSAT in 0.027	UNSAT in 0
1-safeness	any	UNSAT in 0.013	UNSAT in 0.018	UNSAT in 0.032	NA

Table 1
Comparative Results with TAPAAL for the Eratosthenes-PT-010 PN from the MCC benchmarks [12].

Contributions

- Part 1: Verification of Unbounded Client-Server (UCS) using Petri Nets and Linear Temporal Logic with integer arithmetic
- Part 2: Verification of UCS with distinguishable clients using ν-nets and properties specified in monodic First Order Logic
- Part 3: Verification of UCS where the clients have internal structure using Elementary Object Systems and properties specified in Linear Temporal Logic

List of publications:

1. Ramchandra Phawade, Tephilla Prince, S. Sheerazuddin: Bounded Model Checking for Unbounded Client Server Systems. Arxiv (2022)
2. Tephilla Prince: On Verifying Unbounded Client-Server Systems. Springer EUMAS 2023: 465-471
3. Francesco Di Cosmo, Tephilla Prince: Bounded Verification of Petri Nets and EOSs using Telingo: An Experience Report. CILC 2024
4. Francesco Di Cosmo, Soumodev Mal, Tephilla Prince: Deciding Reachability and Coverability in Lossy EOS. PNSE@Petri Nets 2024: 74-95

List of publications (ongoing):

5 Francesco Di Cosmo, Soumodev Mal, Tephilla Prince: Decidability and Complexity of Reachability and Coverability in Lossy EOS (Under review at TopNOC)

6 Ramchandra Phawade, Tephilla Prince, S. Sheerazuddin: Bounded Model Checking for Unbounded Client Server Systems. (Yet to be submitted to TopNOC)

7 Ramchandra Phawade, Tephilla Prince, S. Sheerazuddin: A Monodic Logic for Verifying Unbounded Client-Server Systems (yet to be submitted)

Appendix

Bounded Semantics

$M, [x \mapsto a], i \models^k_x F_c \alpha$ iff
$\exists j : i \leq j \leq k$, $a \in V_j$ and $M, [x \mapsto a], j \models^k_x \alpha$.

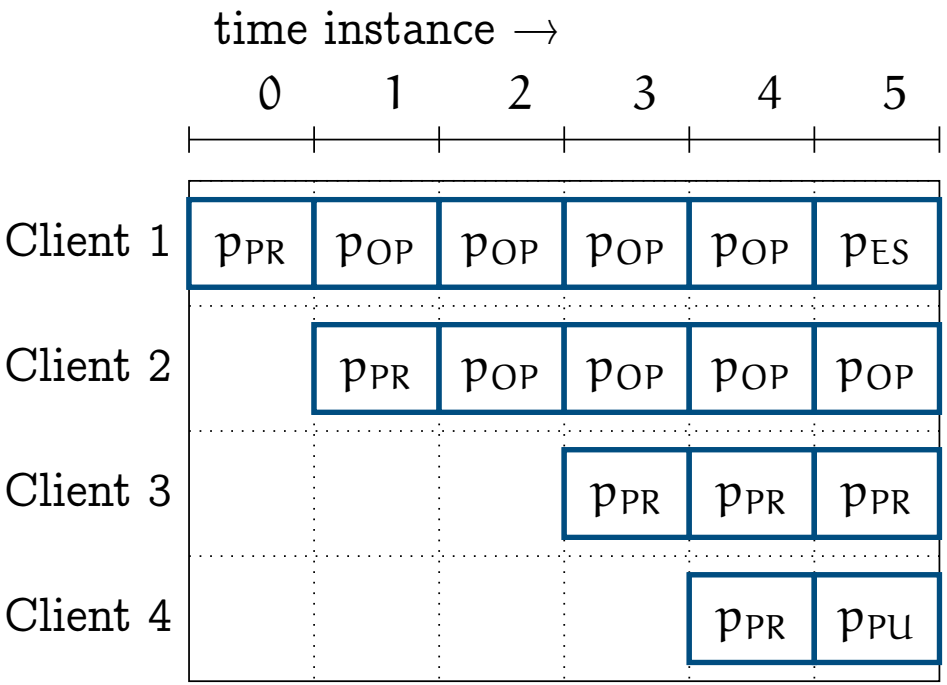


Figure: Snapshot with 2 clients

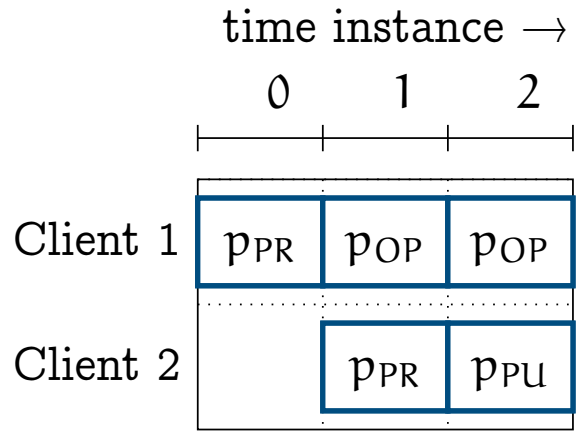


Figure: Snapshot with 4 clients

Given $\alpha = \mathrm{PR}(x)$. The above formula is satisfiable for all clients in both figures.