Using Logic to Escape the Jungle of Data-aware Process Verification

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Free University of Bozen-Bolzano, Italy

seminar @ DTU Compute, 7.9.2023

Motivation

Discovery and verification of BPM processes

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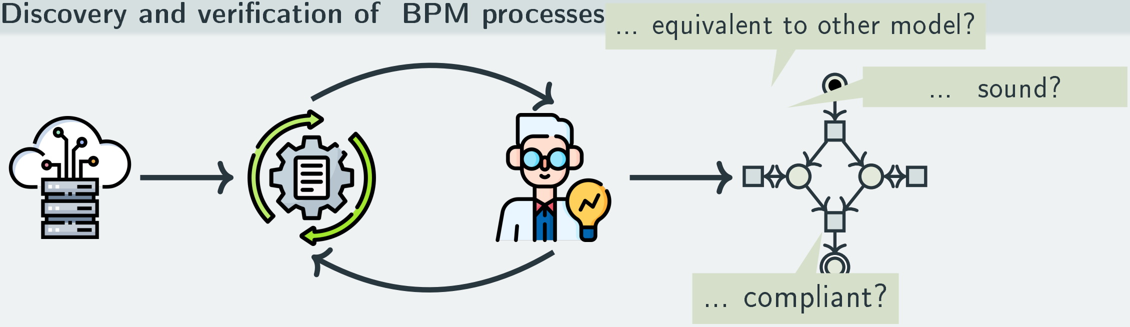

e.g. every order is eventually shipped

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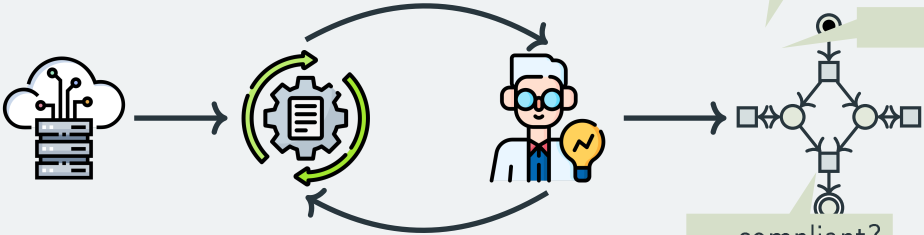

in Petri nets for typical BPM processes, verification tasks can be effectively decided

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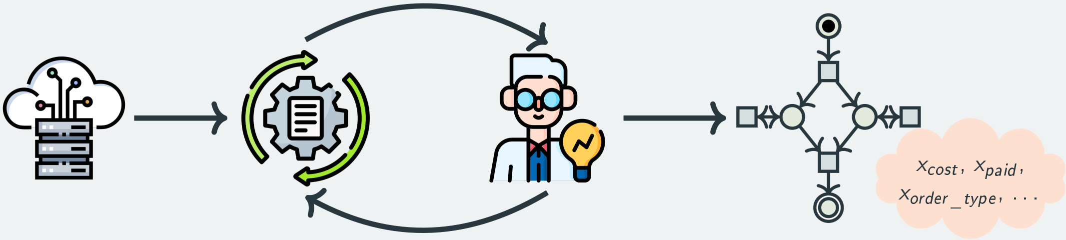
Discovery and verification of data-aware BPM processes



Assumption

data is represented by numeric variables, can be read and written by transitions

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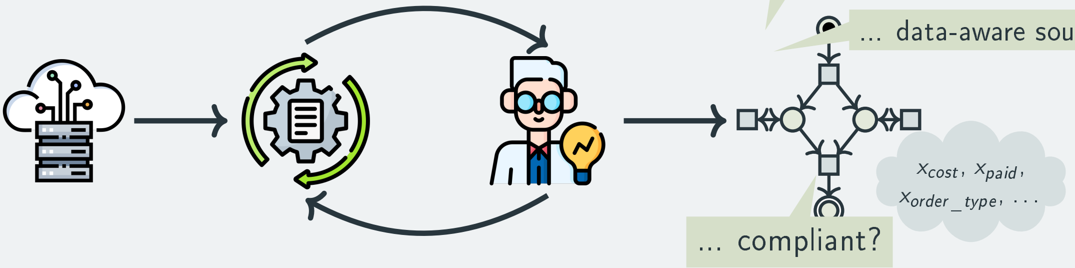

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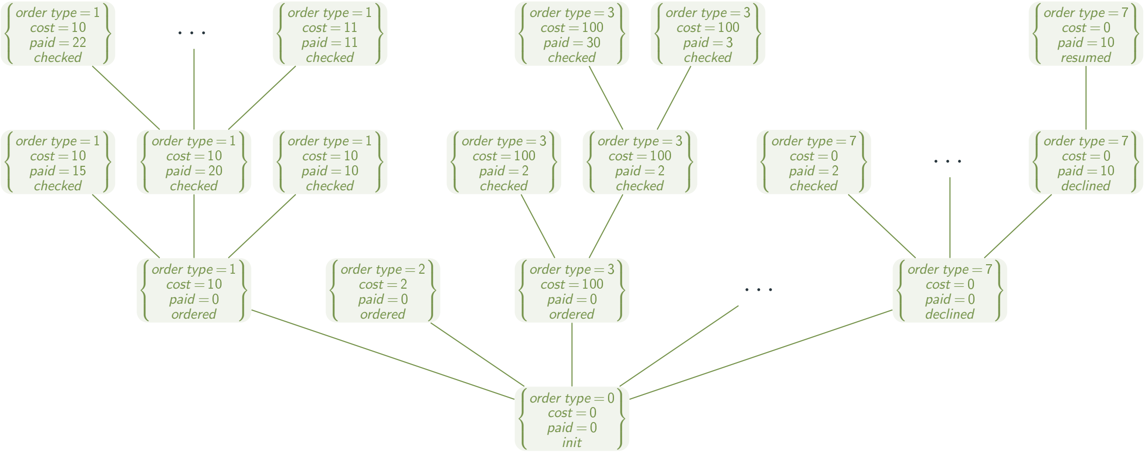

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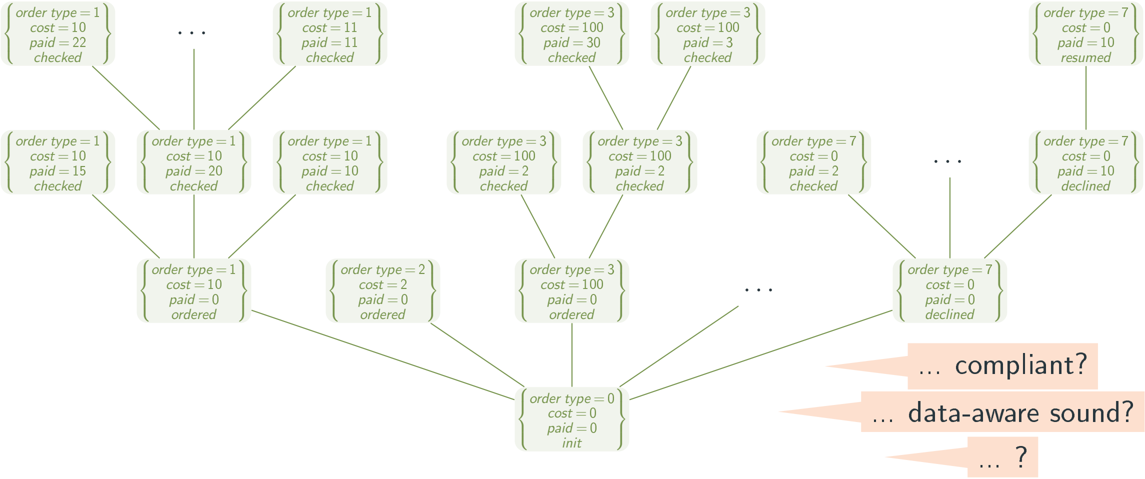

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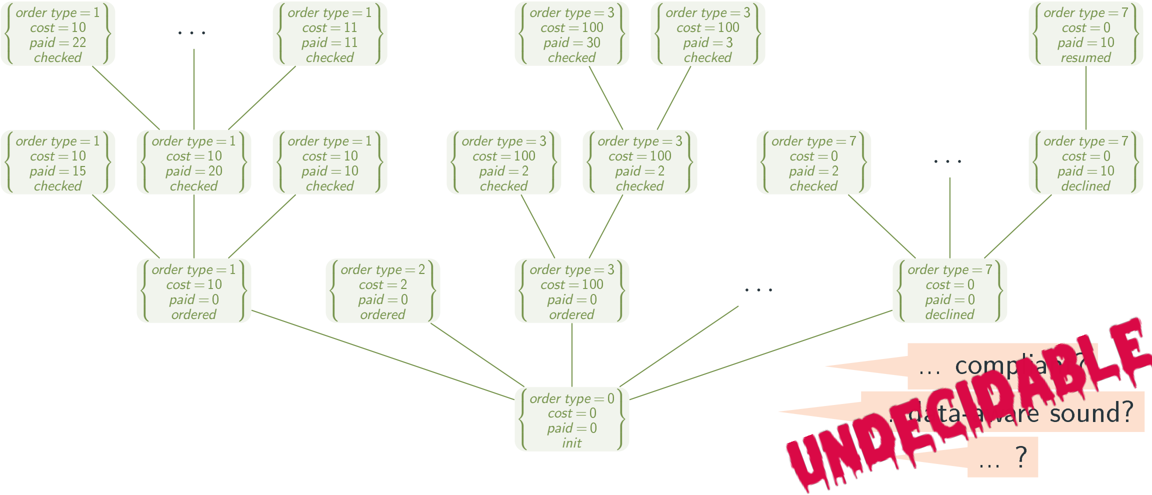

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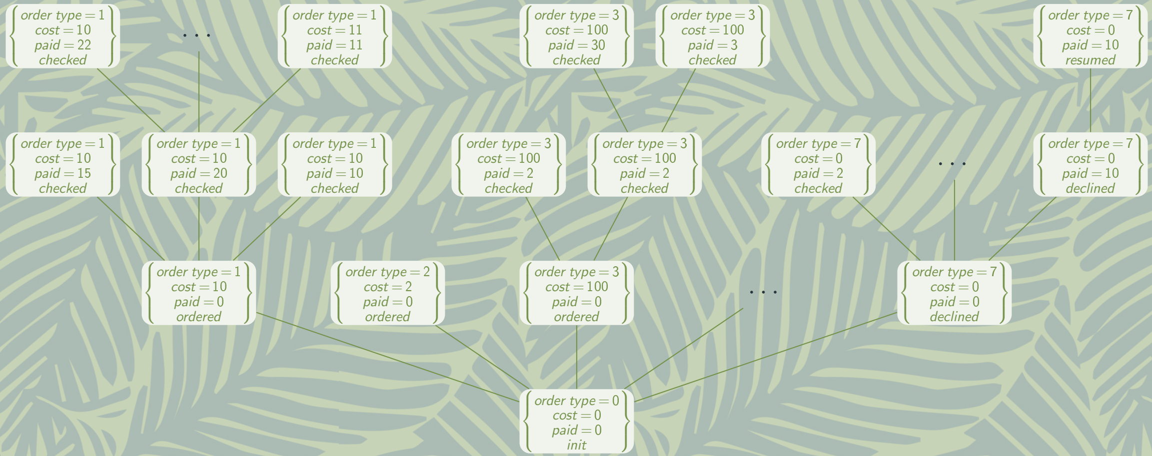

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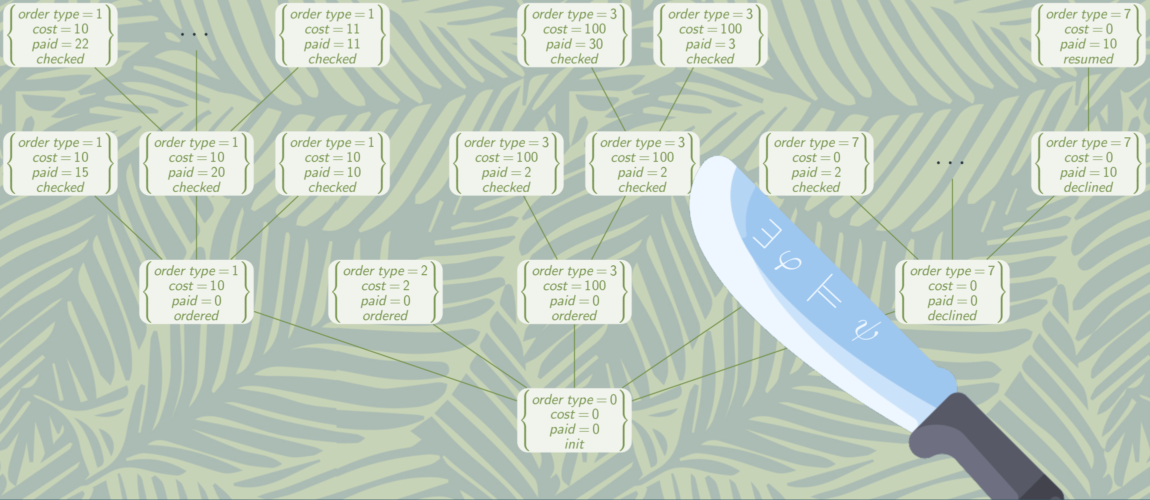

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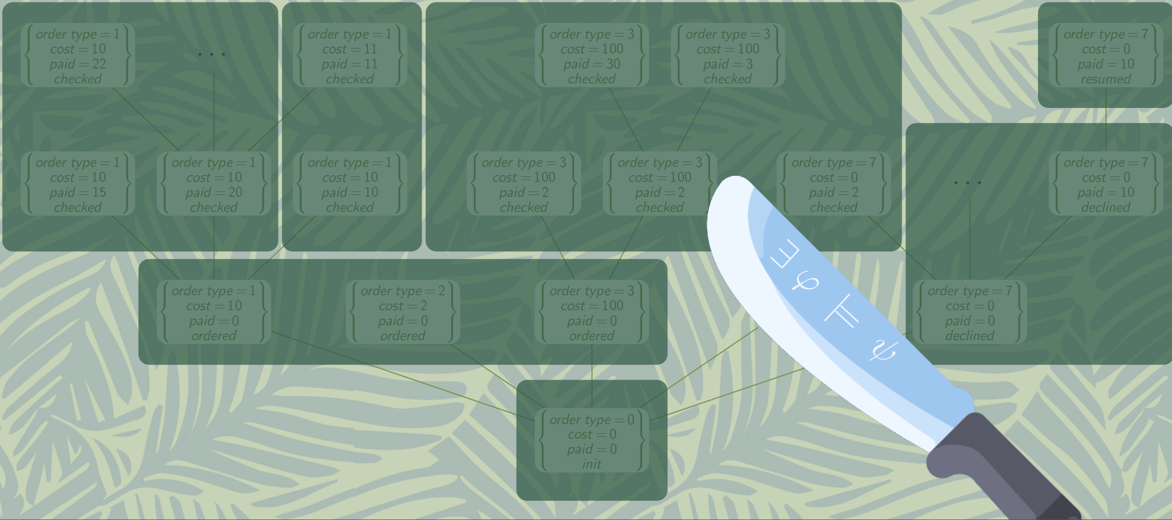

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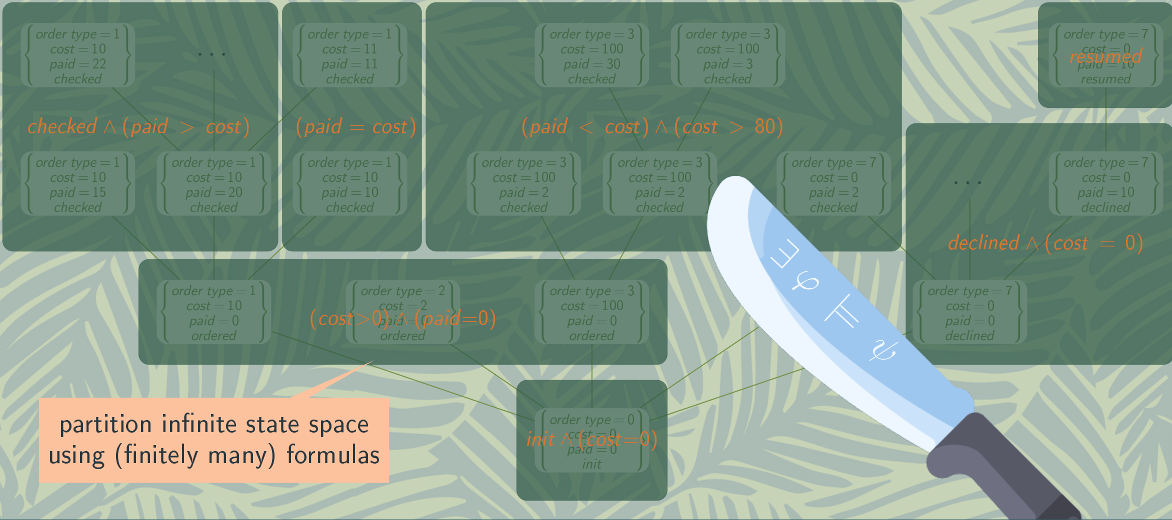
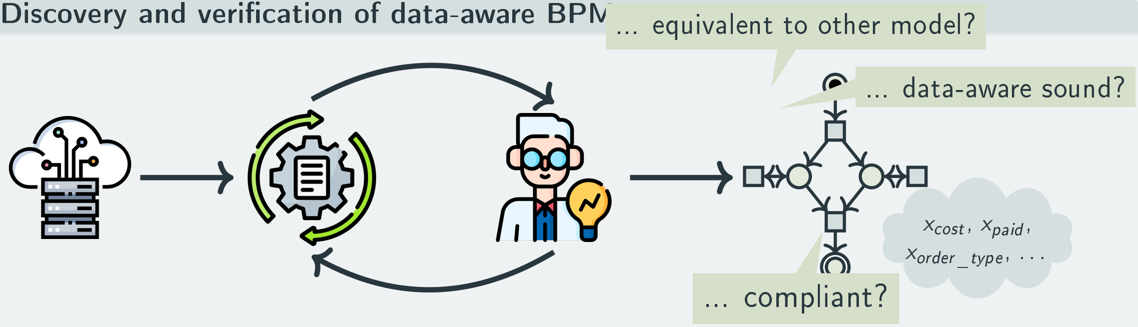


partition infinite state space using (finitely many) formulas

Motivation

Discovery and verification of data-aware BPM



This talk

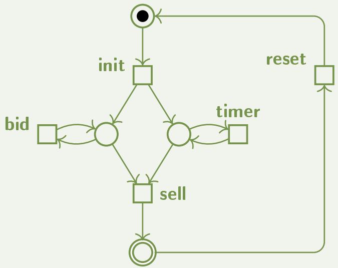
identify classes of data-aware models where verification tasks are decidable

Outline

Data Petri net (DPN)

- based on Petri net
- initial and final markings M_I and M_F

Example (Auction model)



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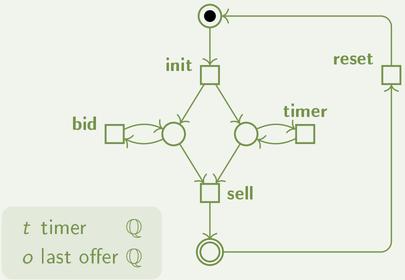

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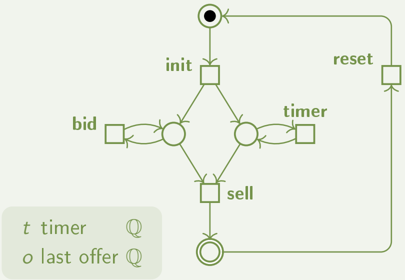

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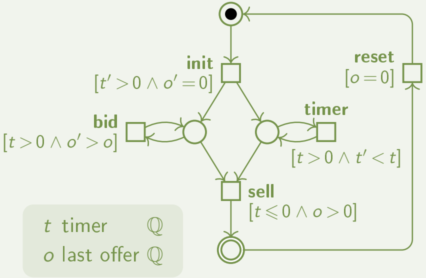

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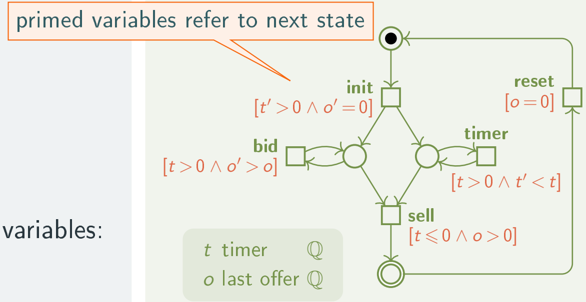

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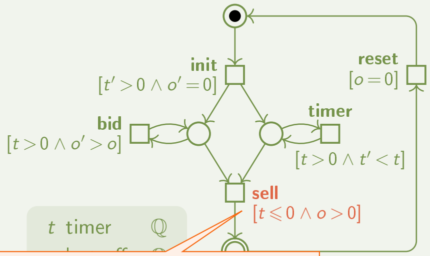

requires that $t \leqslant 0$ and o positive

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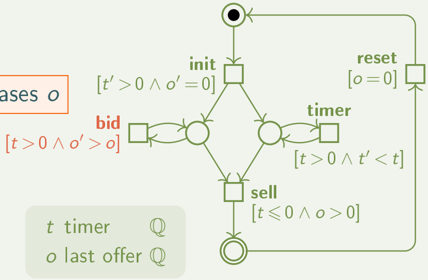

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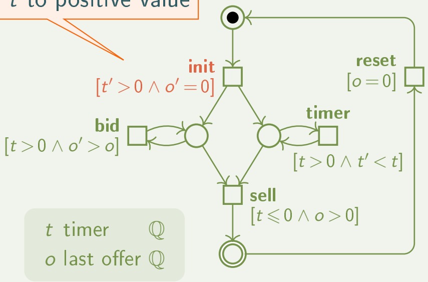
set o to 0 and t to positive value



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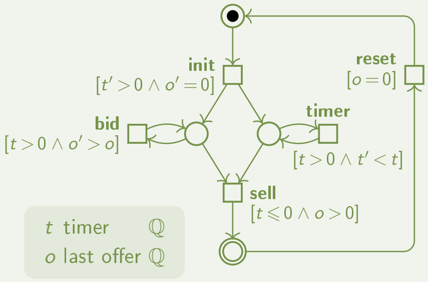

Background logic

- propositional logic + theory of linear arithmetic over integers and rationals
- satisfiability is decidable (SMT solvers), quantifiers can be eliminated

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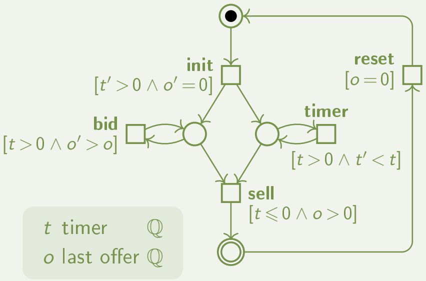

Remark

- DPNs can be mined automatically from data [Mannhardt et al 2016, de Leoni 2013]
- used to model BPM processes from various domains [Mannhardt et al 2016, Mannhardt 2018]

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if underlying Petri net is bounded, DPN has finite set of markings: can be unfolded

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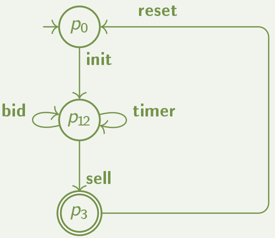

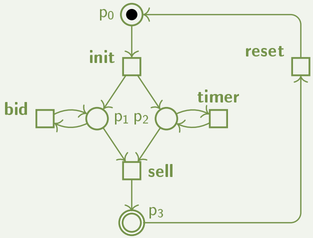

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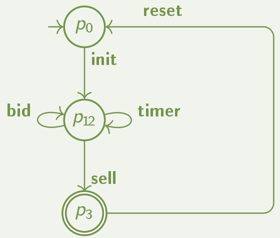

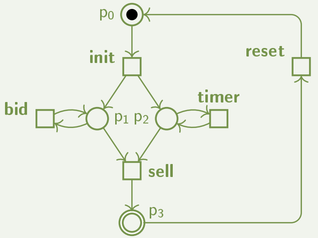

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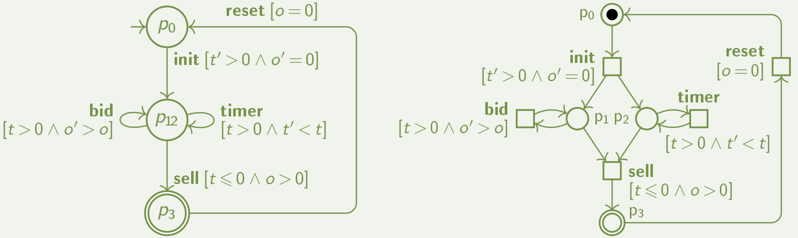

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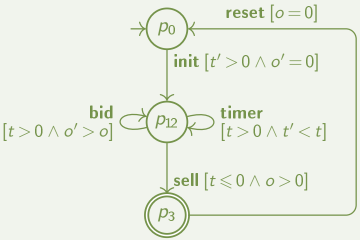

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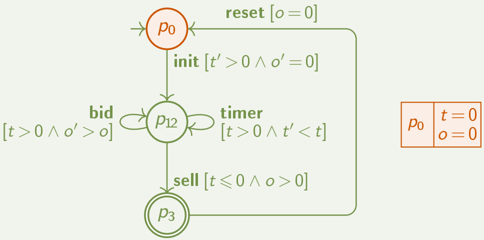

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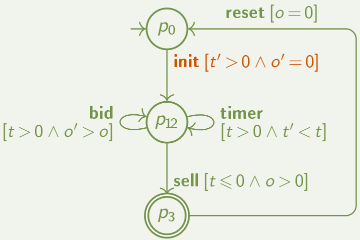

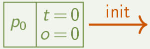

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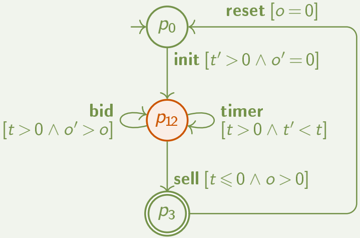

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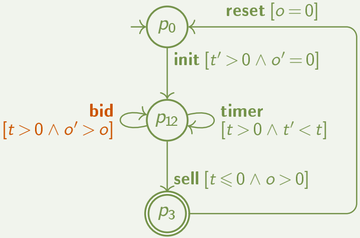

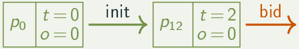

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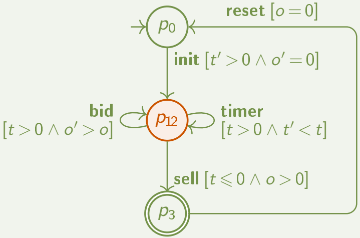

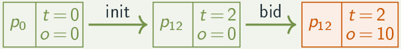

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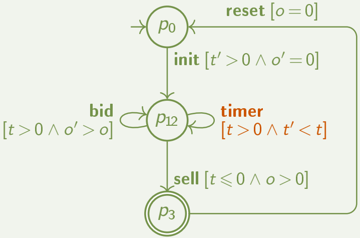

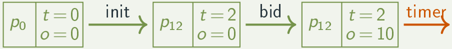

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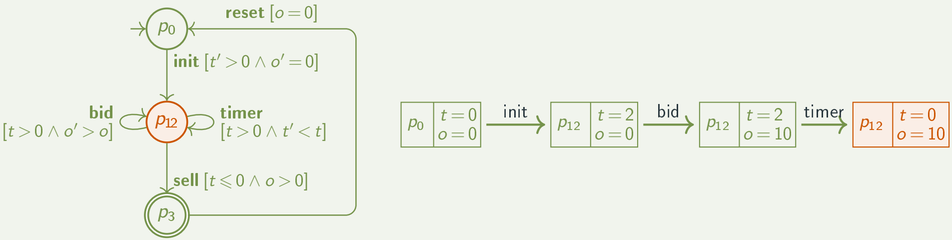

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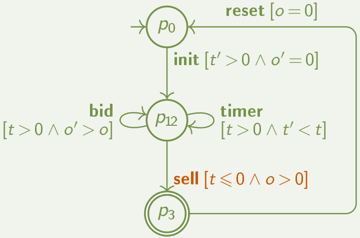

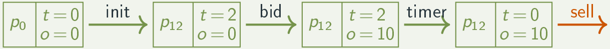

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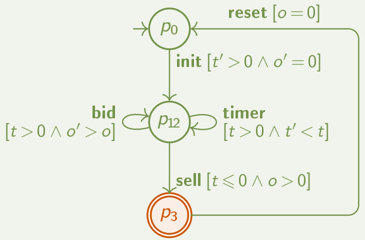

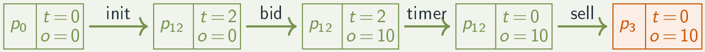

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Definitions

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$$\boxed{p_{12} \;\Big|\; \begin{array}{l} t = 2 \\ o = 0 \end{array}} \xrightarrow[t > 0 \wedge o' > o]{\text{bid}} \boxed{p_{12} \;\Big|\; \begin{array}{l} t = 2 \\ o = 10 \end{array}}$$

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Example

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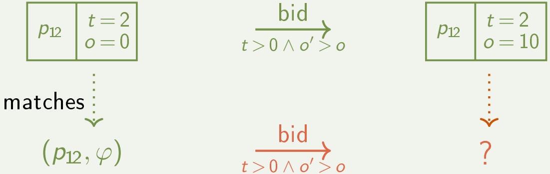
- abstract state



$\varphi = (o = 0) \land (t > 0)$

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$\varphi' = ?$

Definition (Update)

describes how formula φ changes after transition a

for formula φ and transition a in DDSA

$$update(\varphi, a) =$$

Definition (Update)

for formula φ and transition a i

rename variables in formula to auxiliary $\widehat{V} = \{\widehat{v} \mid v \in V\}$

$$update(\varphi, a) = \qquad \varphi(\widehat{V})$$

Definition (Update)

for formula φ and transition a in DDSA

guard must hold, propagate variables that are not written

$$update(\varphi, a) = \quad \varphi(\widehat{V}) \wedge guard_a(\widehat{V}, V) \wedge \bigwedge_{v \notin write(a)} \widehat{v} = v$$

Definition (Update)

∃ quantification to get formula with free variables V

for formula φ and transition a in DDSA

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can get equivalent quantifier-free formula by quantifier elimination

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$$\boxed{p_{12} \;\Big|\; \begin{array}{l} t=2 \\ o=0 \end{array}} \xrightarrow[t>0 \wedge o'>o]{\text{bid}} \boxed{p_{12} \;\Big|\; \begin{array}{l} t=2 \\ o=10 \end{array}}$$

matches

- abstract state

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is graph with node set of abstract states such that

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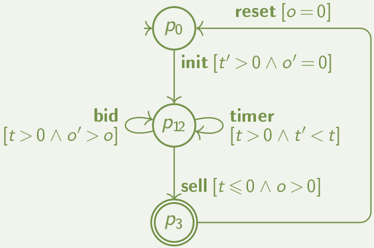
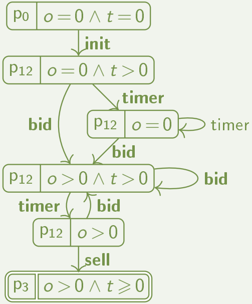
- $(s, \dots) \in N$ is final if s is final in DDSA

Example (Constraint graph for auction model)





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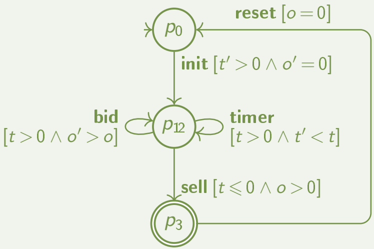

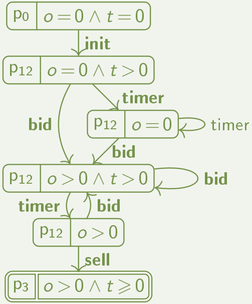

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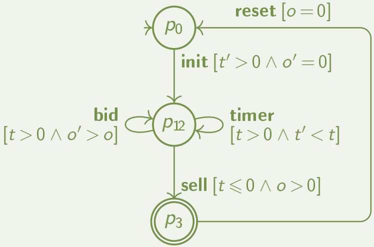

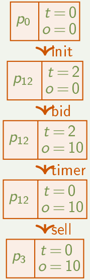

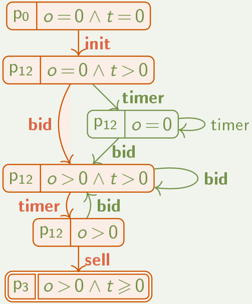

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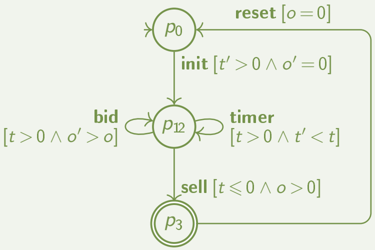

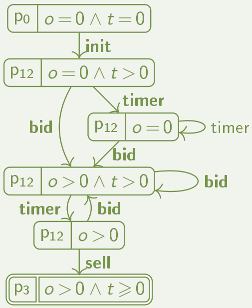

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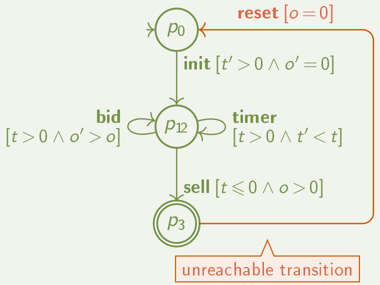

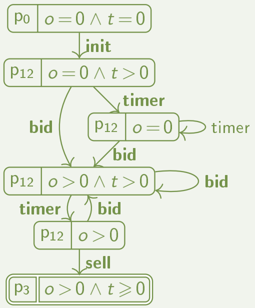

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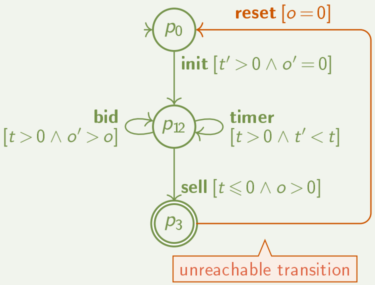

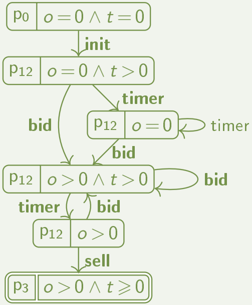

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if CG is finite, reachability is decidable

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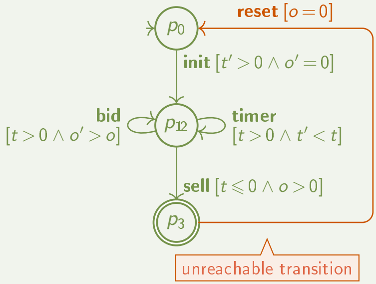

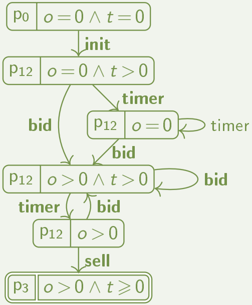

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Caveat

constraint graph can be infinite

Decidability Conditions

formulas in CG are history constraints:
$\exists \ldots \exists$ (conjunctions of renamed transition guards)

Definition (Finite summary)

DDSA has finite summary if set of history constraints is finite

Decidability Conditions

Definition (Finite summary) abstract decidability condition

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Concrete instances of finite summary

[Felli, Montali & W, AAAI 2022]

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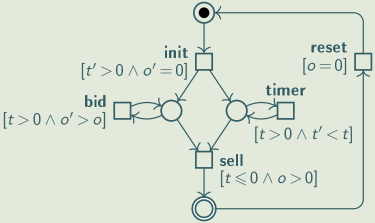
applies to all DPNs mined according to [Mannhardt et al 2016]



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idea: behaviour depends on bounded number of past steps

Decidability Conditions

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DDSA has finite sum

Concrete instance

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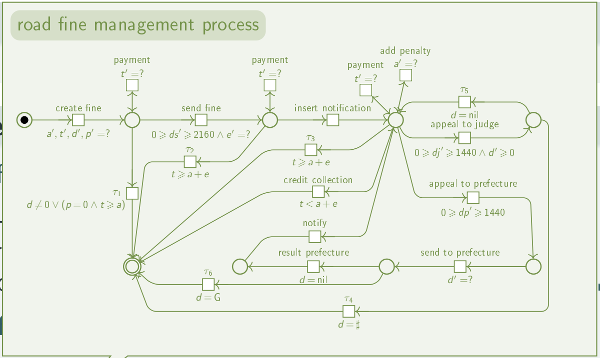

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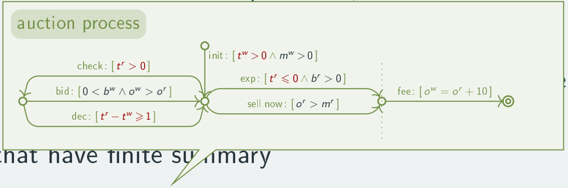

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capture wide range of DPNs from literature

- restrict shape of transition guards:
  - variable-to-variable/constant comparisons over $\mathbb{Q}$: $x < y$, $x \geqslant \frac{1}{2}$, $y = 0$ [Demri & de Souza 2006]
  - integer periodicity constraints over $\mathbb{Z}$: $x = y$, $x < 3$, $y \equiv_5 3$ [Demri 2006, Gascon 2009]
  - gap-order constraints: $x - y \geqslant 2$ [Cerans 1995, Bozzelli & Pinchinat 2014]
- restrict control flow:
  - feedback freedom [Damaggio, Deutsch & Vianu 2012]
  - bounded memory
- DDSA can be decomposed into subsystems that have finite summary
  - into sequential process parts
  - by splitting variables

Outline

Linear-Time Model Checking

Verification problem: Compliance

given DDSA and LTL$_f$ formula ψ with arithmetic constraints:

$$\mathit{constraint} \;\mid\; \mathit{control\ state} \;\mid\; \psi \wedge \psi \;\mid\; \psi \vee \psi \;\mid\; \langle \mathit{action} \rangle \psi \;\mid\; \mathsf{X}\,\psi \;\mid\; \mathsf{F}\,\psi \;\mid\; \mathsf{G}\,\psi \;\mid\; \psi\,\mathsf{U}\,\psi$$

is there a witness run of DDSA that satisfies ψ?

Linear-Time Model Checking

evaluated over finite traces

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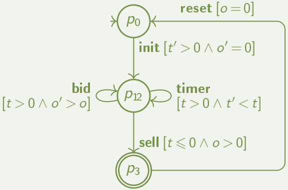
Example



- $\mathsf{F}\,((o=100) \wedge \mathsf{G}\,(p_3 \rightarrow o \neq 100))$: witness exists
  it is possible that bid of 100€ does not win

Linear-Time Model Checking

Verification problem: Compliance

given DDSA and LTL$_f$ formula ψ with arithmetic constraints:

$$\mathit{constraint} \mid \mathit{control\ state} \mid \psi \land \psi \mid \psi \lor \psi \mid \langle \mathit{action} \rangle \psi \mid \mathsf{X}\,\psi \mid \mathsf{F}\,\psi \mid \mathsf{G}\,\psi \mid \psi\,\mathsf{U}\,\psi$$

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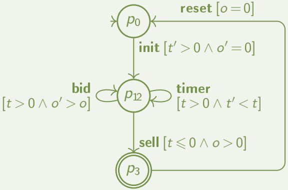

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Linear-Time Model Checking

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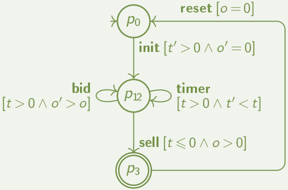

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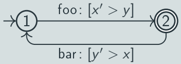
Fact

can construct finite automaton (NFA) accepting exactly those runs that satisfy LTL$_f$ property

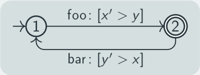
Model checking approach



DDSA

Model checking approach

check $\mathsf{F}\,(y > 5)$



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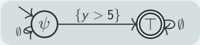

DDSA

NFA for ψ

Model checking approach

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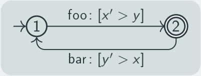

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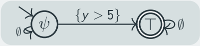
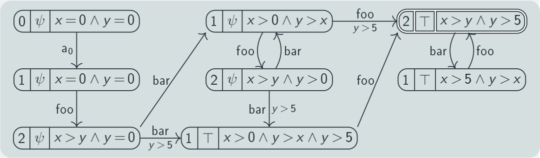


$\mapsto$



DDSA

NFA for ψ

product automaton $\mathcal{N}$

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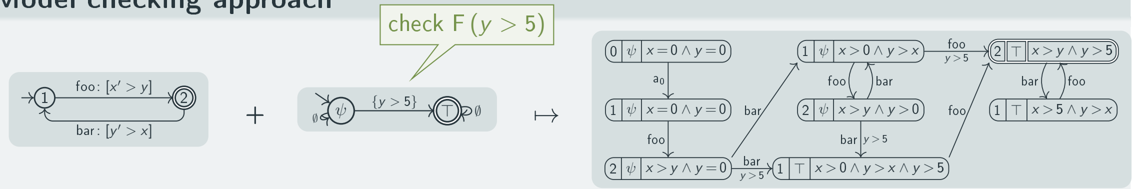

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- **nodes** are triples (DDSA state, NFA state, formula)

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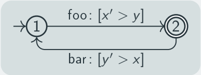

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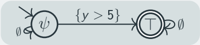

NFA for ψ

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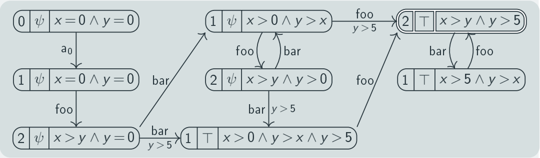

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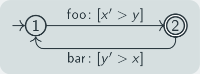

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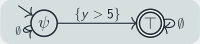
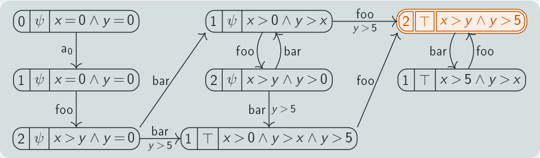


↦



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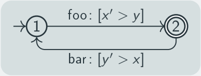

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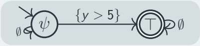

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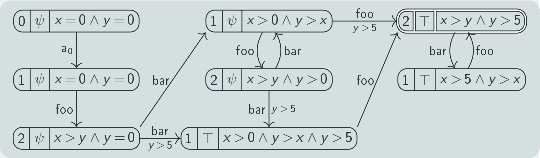

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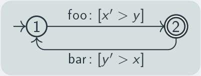
Theorem

- *product automaton has final node iff DDSA admits witness for* ψ

[Felli, Montali & W, AAAI 2022]

Model checking approach



DDSA

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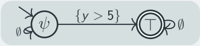

NFA for ψ

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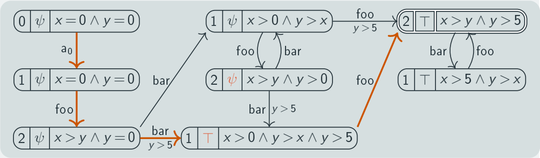

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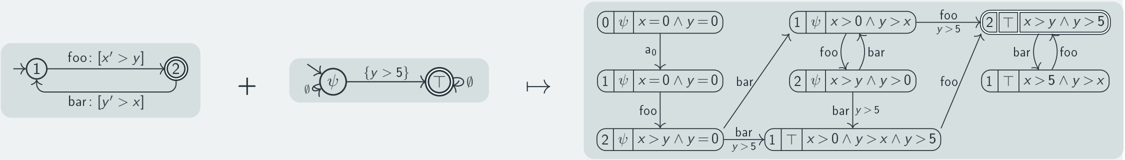
Theorem

can use SMT solver to extract witness from accepting path

- *product automaton has final node* *iff* *DDSA admits witness for* ψ

[Felli, Montali & W, AAAI 2022]

Model checking approach



DDSA | NFA for ψ | product automaton $\mathcal{N}$

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- *product automaton has final node iff DDSA admits witness for ψ*
- *LTL$_f$ model checking is decidable if DDSA has finite summary with respect to ψ*

[Felli, Montali & W, AAAI 2022]

Data-aware Soundness

Definition

DPN is data-aware sound if

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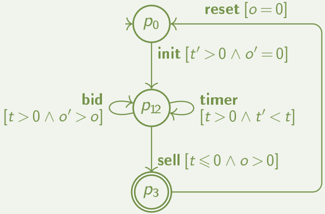

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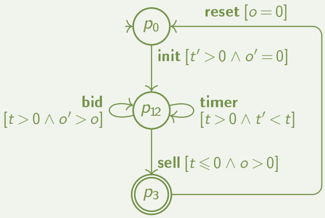

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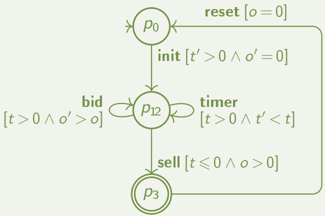

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Soundness checking approach

[Felli, Montali & W, CAiSE 2022]

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Soundness checking approach

[Felli, Montali & W, CAiSE 2022]

if DDSA has finite summary, data-aware soundness is decidable

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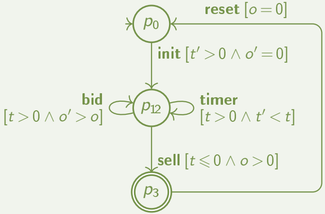

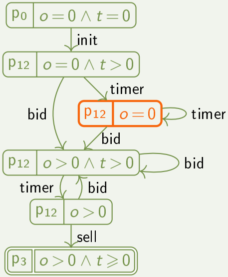

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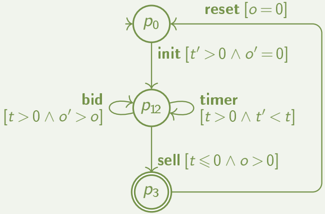

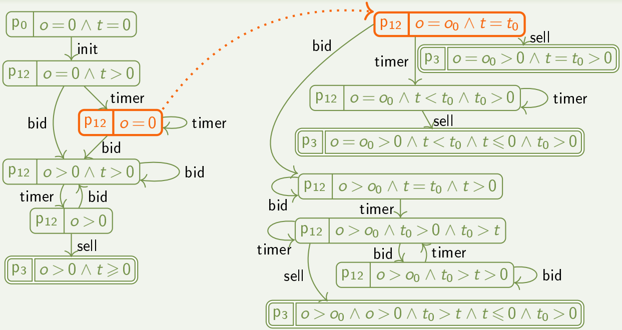

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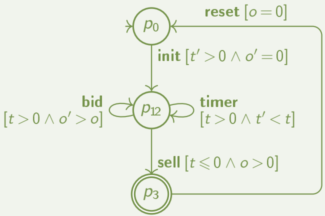

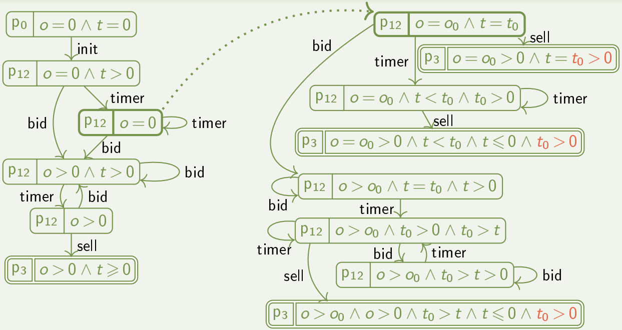

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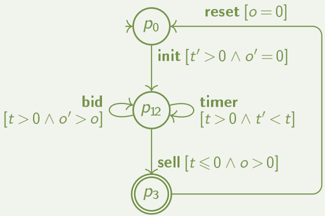

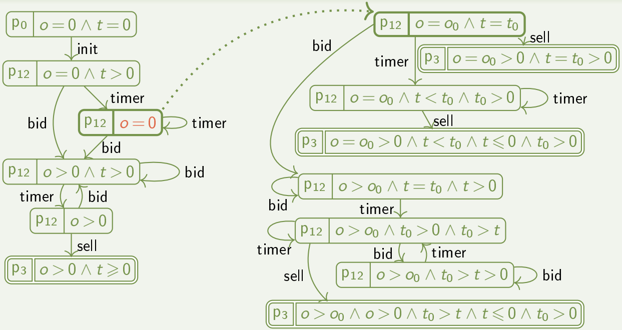

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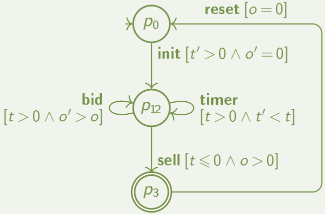

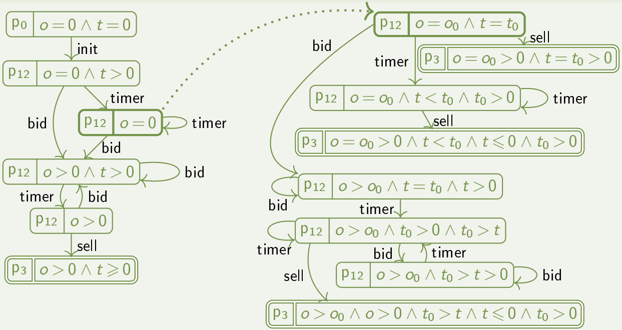

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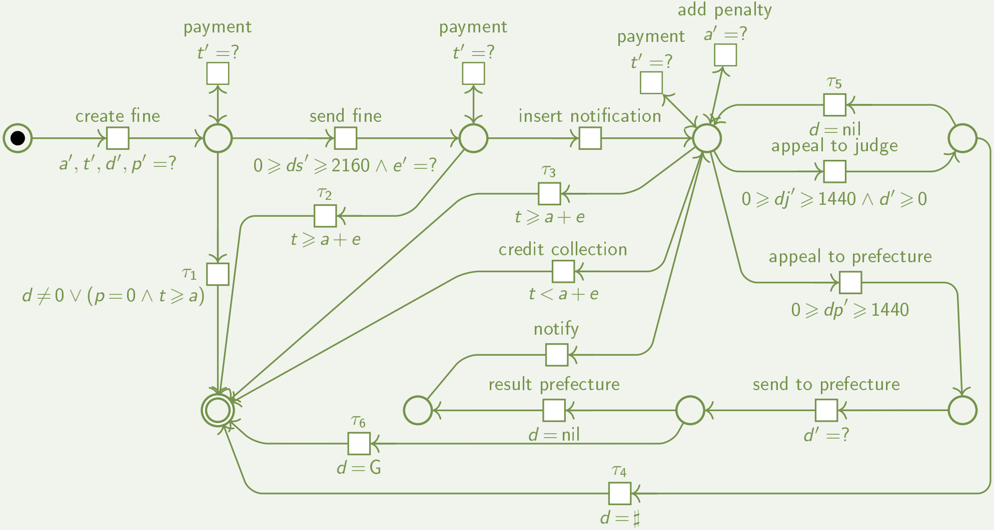
Branching-time model checking

use similar approach to obtain CTL* model checking procedure

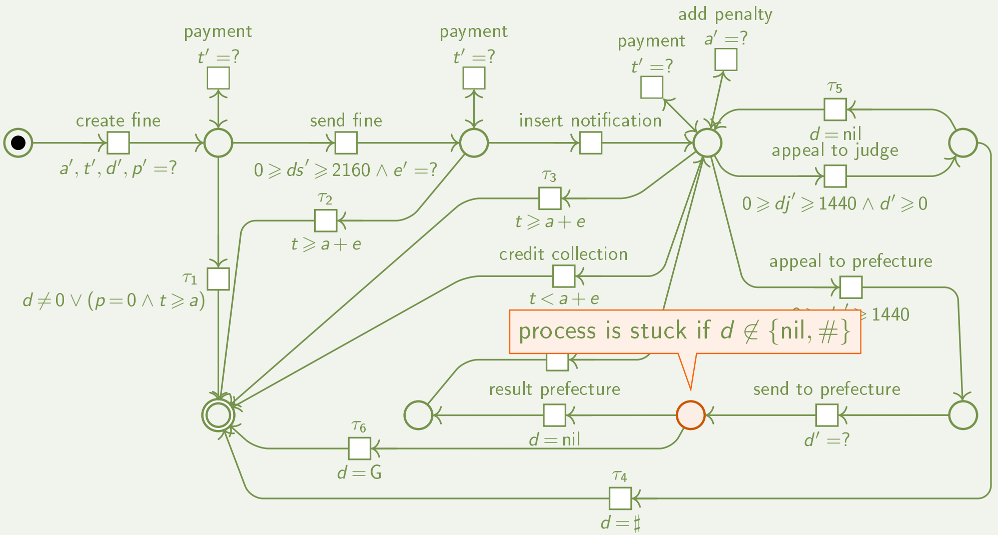
[Felli, Montali & W, IJCAR 2022]

Example (Road fine management process)



[Mannhardt et al 2016]

Example (Road fine management process) not data-aware sound



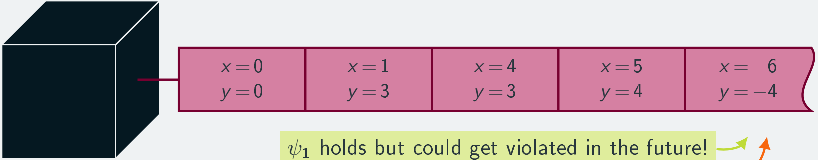
[Mannhardt et al 2016]

Monitoring Arithmetic Temporal Properties

given a trace of values, check current and possible future satisfaction of LTL_f properties like

- $\psi_1 = (y \geqslant 0)\ \mathsf{U}\ (x > y \wedge \mathsf{G}\,(x > y))$
- $\psi_2 = \mathsf{G}\,(x' > x) \wedge \mathsf{F}\,(x = 2)$

x' is value of x looking one trace instant ahead



ψ_1 holds but could get violated in the future!

ψ_2 does not hold and will never hold in the future!

Monitoring Arithmetic Temporal Properties

given a trace of values, check current and possible future satisfaction of LTL_f properties like

- $\psi_1 = (y \geqslant 0)\ \mathsf{U}\ (x > y \wedge \mathsf{G}\,(x > y))$
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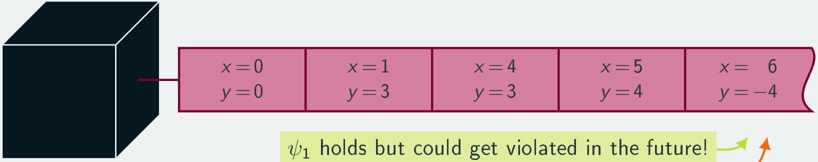


ψ_1 holds but could get violated in the future!

ψ_2 does not hold and will never hold in the future!

Results

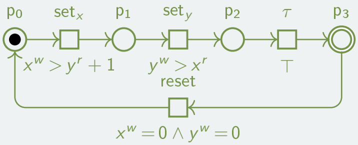
- developed monitoring procedure
- use finite summary approach to identify classes of properties where problem is decidable

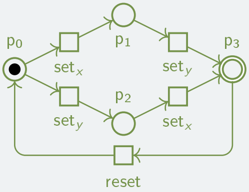
[Felli, Montali, Patrizi & W, AAAI 2023]

Process Equivalence

Verification problem

given two DPNs, do they have the same sets of configurations, and/or the same language?





Results

- can be determined using constraint graphs
- decidable for finite summary systems

talk at BPFM workshop at BPM next week!

Implementation

Arithmetic DDS Analyzer (ada)

- input DPN (+ LTL_f or CTL_f^* property)
- checks for decidability conditions, visualizes CG/product automaton
- performs LTL_f, CTL_f^* model checking, soundness checking, and monitoring
- computes witness/counterexample
- written in Python, using Z3/Yices/CVC5 for SMT solving and quantifier elimination

`https://ltl.adatool.dev` `https://soundness.adatool.dev`

`https://ctlstar.adatool.dev`

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Experiments

- about 60 DPNs (20 from literature, 40 artificial)
- all DPNs from literature are in some decidable class for LTL_f (but not CTL_f^*) model checking

Implementatic

Arithmetic DD

- input DPN (
- checks for d
- performs LT
- computes wi
- written in P

I

Experiments

- about 60 DF
- all DPNs fro

process	property	sat	time	checks	$\lvert\mathcal{B}\rvert$	$\lvert\mathcal{N}^{\psi}_{\mathcal{B},b}\rvert$
road fines (1)	no deadlock	✗	7.0s	8161	9	2052
	$\mathsf{AG}\,(p_7 \to \mathsf{E\,F}\,\mathit{end})$	✓	7.6s	7655		1987
road fines (2)	no deadlock	✓	15m27s	247563	9	4927
	$\mathsf{AG}\,(p_7 \to \mathsf{E\,F}\,\mathit{end})$	✓	16m7s	246813		4927
road fines (3)	no deadlock	✗	9s	9179	9	1985
	$\mathsf{AG}\,(p_7 \to \mathsf{E\,F}\,\mathit{end})$	✓	6.6s	6382		1597
	$\mathsf{EF}\,(dS \geqslant 2160)$	✗	11.5s	17680		1280
hospital billing	no deadlock	✓	20m59s	1234928	17	23147
	$\mathsf{EF}\,(p16 \wedge \neg \mathit{closed})$	✓	10m20s	669379		10654
sepsis (1)	no deadlock	✓	1m36s	139	301	44939
	$\mathsf{AG}\,(\mathit{sink} \to t_{tr} < t_{ab})$	✗	30.1s	170		22724
	$\mathsf{AG}\,(\mathit{sink} \to t_{tr} + 60 \geqslant t_{ab})$	✓	32s	153		22538
sepsis (2)	no deadlock	✓	7m24	4524	301	161242
	$\mathsf{A}\,(\neg \mathit{lacticAcid}\ \mathsf{U}\ \langle \mathrm{diagnostic}\rangle \top)$	✓	3m53s	5734		74984
board: register	no deadlock	✓	1.4s	12	7	27
board: transfer	no deadlock	✓	1.4s	27	7	51
board: discharge	no deadlock	✓	1.5s	25	6	67
	$\mathsf{AG}\,(p_2 \wedge o_1{=}207 \to \mathsf{AG}\ o_1{=}207)$	✓	1.5s	94		91
	$\mathsf{AG}\,(\mathsf{EF}\,\langle \mathrm{tra}\rangle \top \wedge \mathsf{EF}\,\langle \mathrm{his}\rangle \top)$	✓	1.5s	27		98
	$\neg \mathsf{E}\,(\mathsf{F}\,\langle \mathrm{tra}\rangle \top \wedge \mathsf{F}\,\langle \mathrm{his}\rangle \top)$	✓	1.4s	56		43
credit approval	no deadlock	✓	1.7s	470	6	230
	$\mathsf{AG}\,(\langle \mathrm{openLoan}\rangle \top \to \mathit{ver} \wedge \mathit{dec})$	✓	13.2s	14156		645
	$\mathsf{A}\,(\mathsf{F}\,(\mathit{ver} \wedge \mathit{dec}) \to \mathsf{F}\,\langle \mathrm{openLoan}\rangle \top)$	✗	3.7s	3128		316
package handling	no deadlock	✓	2.7ss	1025	16	693
	no deadlock (τ_1)	✓	2.5s	1079		398
	$\psi_{k1} = \mathsf{EF}\,\langle \mathrm{fetch}\rangle \top$	✗	2.6s	850		343
	$\psi_{k2} = \mathsf{EF}\,\langle \tau_6\rangle \top$	✗	2.4s	875		336
auction	no deadlock	✗	10.8s	1683	5	186
	$\mathsf{EF}\,(\mathrm{sold} \wedge d > 0 \wedge o \leqslant t)$	✗	6.4s	1180		79
	$\mathsf{EF}\,(b{=}1 \wedge o > t \wedge \mathsf{F}\,(\mathrm{sold} \wedge b > 1))$	✓	26.5s	4000		263

Conclusion

Summary

- for Data Petri nets with arithmetic constraints:
  verification procedures for LTL_f, CTL^*_f, data-aware soundness
- decision procedure if DPN satisfies finite summary property: new decidability results
- implemented and tested on processes from BPM

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Take-home message

- finite constraint graphs are powerful tool for verification
- many relevant verification tasks are decidable for "practical" Data Petri nets

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Take-home message

- finite constraint graphs are powerful tool for verification
- many relevant verification tasks are decidable for "practical" Data Petri nets

Future work

- further SMT theories, e.g. allow guards to refer to database
- discover more expressive transition guards for DPNs :)

Marco Montali

Paolo Felli

Fabio Patrizi

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