TIPS'18

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北京，中國

Parametric timed automata: modeling and verifying real-time systems under uncertainty

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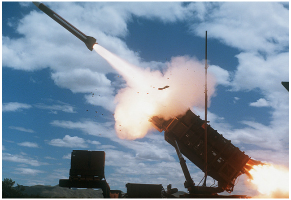
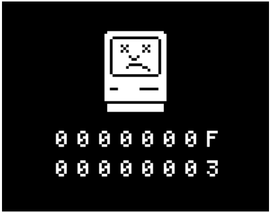
Feat. joint works with Giuseppe Lipari, and Sun Youcheng

Context: Verifying complex timed systems

- Real-time systems are everywhere
  - Hard timing constraints and concurrency
  - Criticality: risk for huge damages in case of unexpected behavior (bug)
  - Bugs discovered when final testing: expensive
  - ⇝ Need for a thorough specification and verification phase



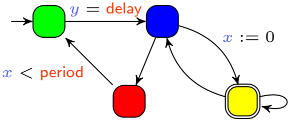
Outline

1. Parametric timed automata
2. Modeling and verifying real-time systems with parameters
3. A case study: Verifying a real-time system under uncertainty
4. Conclusion and perspectives

Outline

Model checking timed concurrent systems

- Use formal methods [Baier and Katoen, 2008]



A model of the system

 is unreachable

A property to be satisfied

Model checking timed concurrent systems

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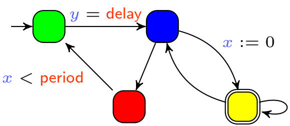

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- Question: does the model of the system satisfy the property?

Model checking timed concurrent systems

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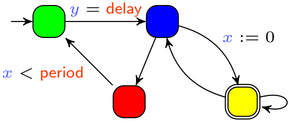

A model of the system

$\models^{?}$

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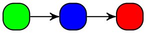
A property to be satisfied

- Question: does the model of the system satisfy the property?

Yes

No



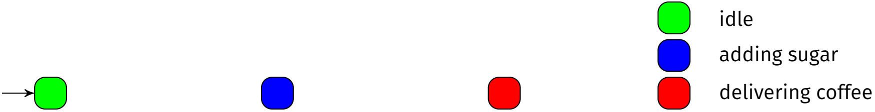
Counterexample

Turing award (2007) to Edmund M. Clarke, Allen Emerson and Joseph Sifakis

Outline

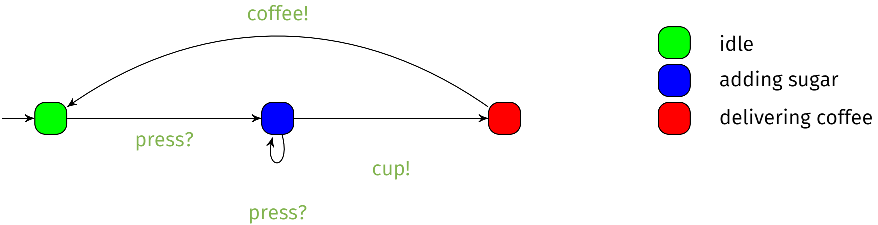
Timed automaton (TA)

- Finite state automaton (sets of locations)



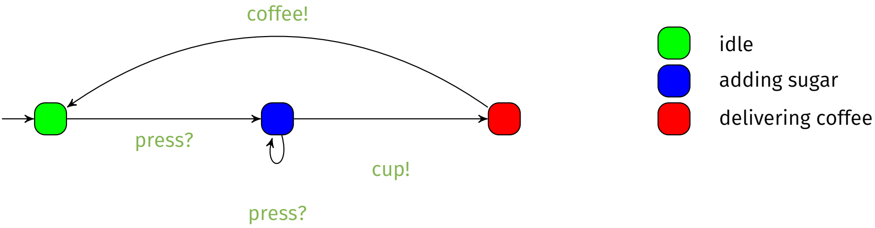
Timed automaton (TA)

- Finite state automaton (sets of locations and actions)



Timed automaton (TA)

- Finite state automaton (sets of locations and actions) augmented with a set X of clocks [Alur and Dill, 1994]
  - Real-valued variables evolving linearly at the same rate



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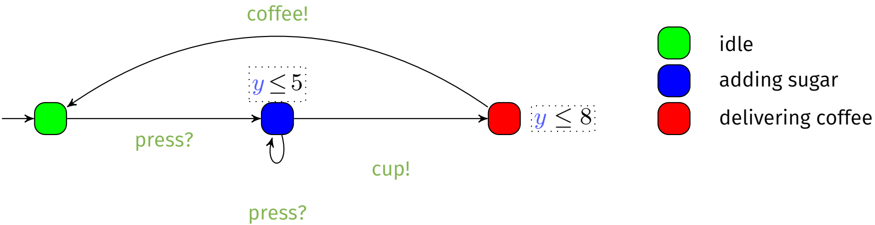
- Features
  - Location invariant: property to be verified to stay at a location



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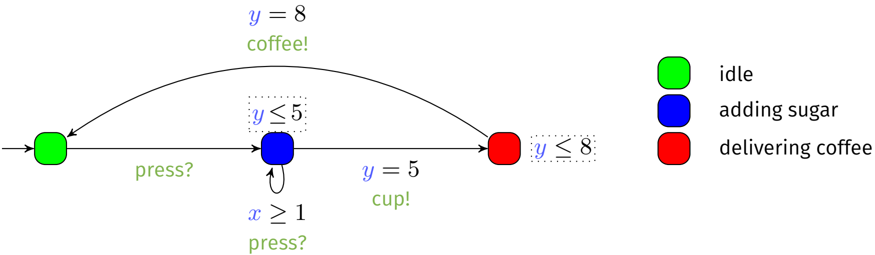

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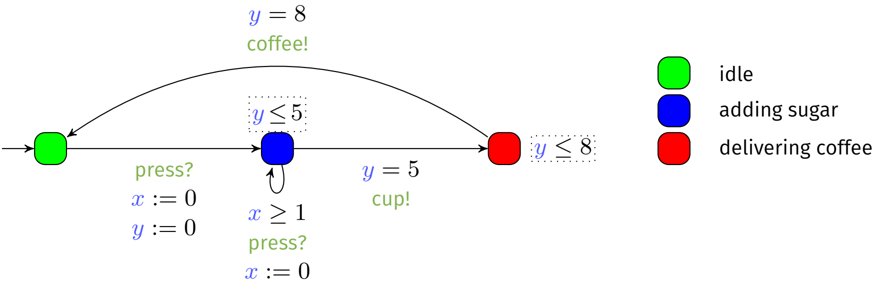
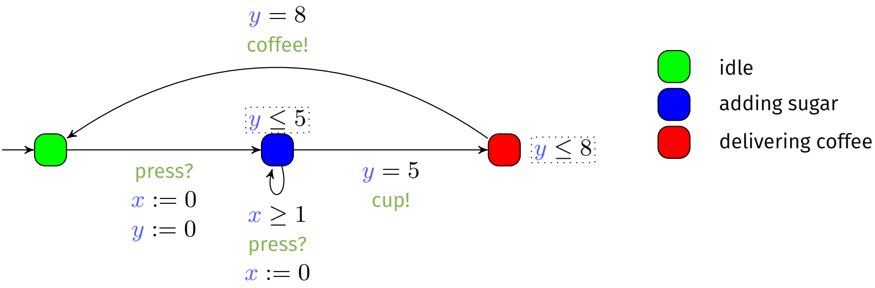
- Features
  - Location invariant: property to be verified to stay at a location
  - Transition guard: property to be verified to enable a transition
  - Clock reset: some of the clocks can be set to 0 along transitions



The most critical system: The coffee machine



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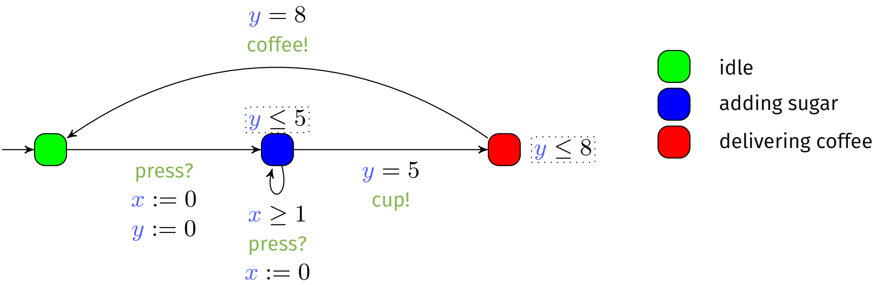
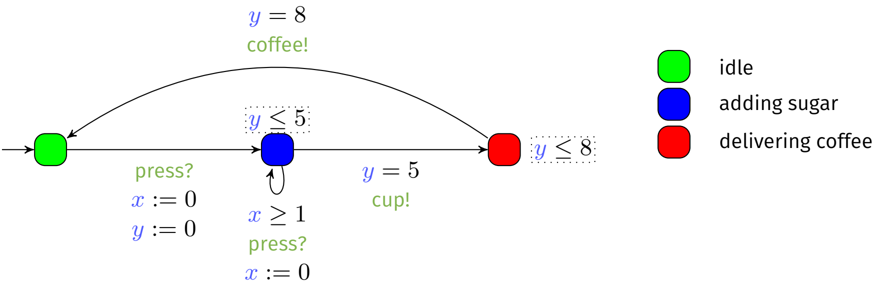


- Example of concrete run for the coffee machine
  - Coffee with 2 doses of sugar

$x =$ 0

$y =$ 0

The most critical system: The coffee machine



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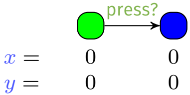

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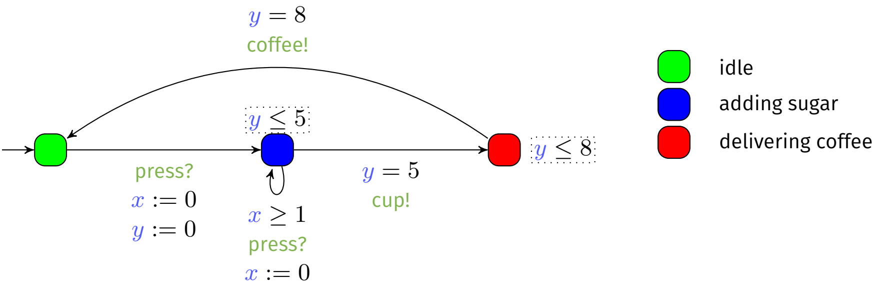

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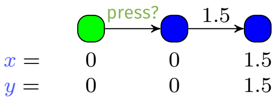

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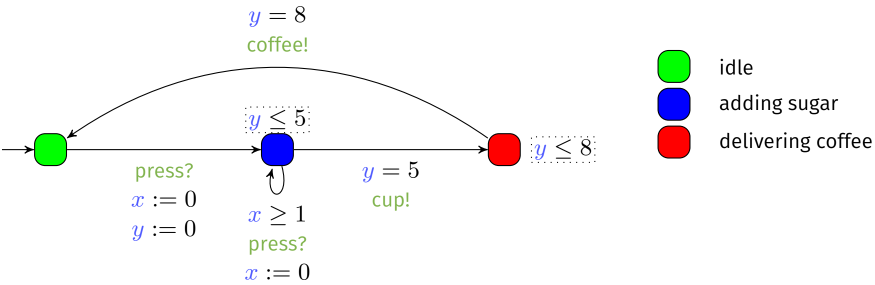

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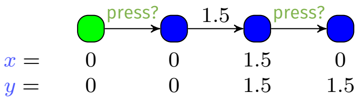

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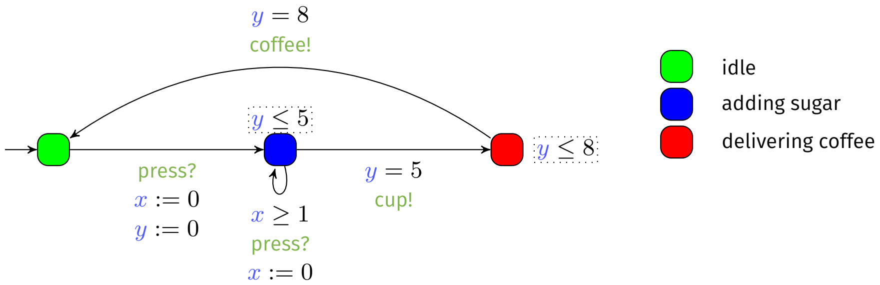

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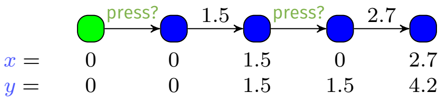

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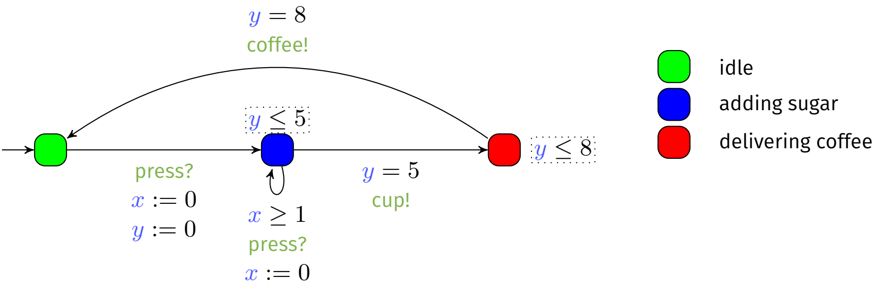

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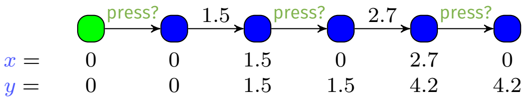

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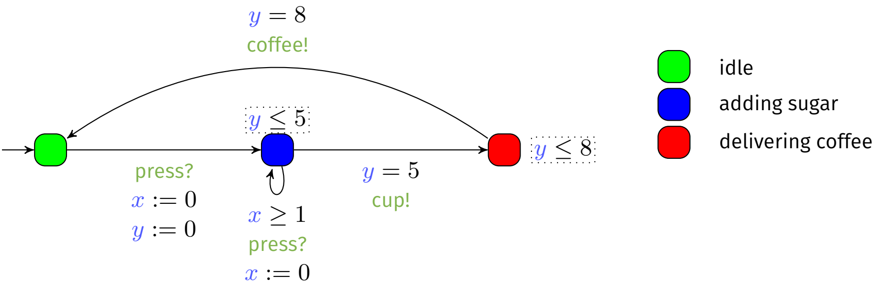

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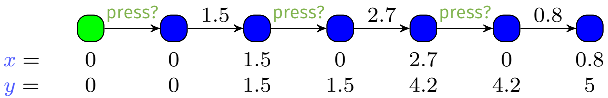

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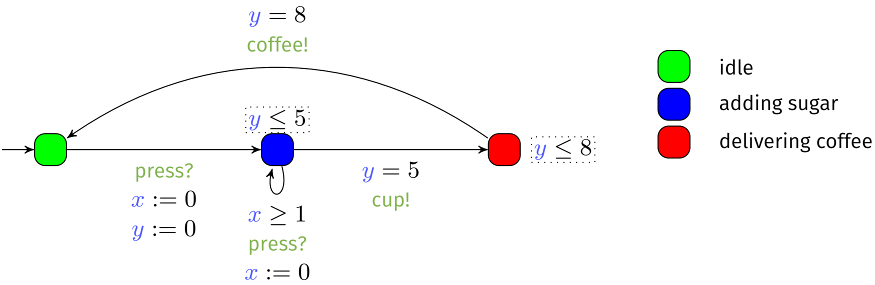

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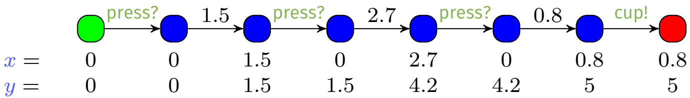

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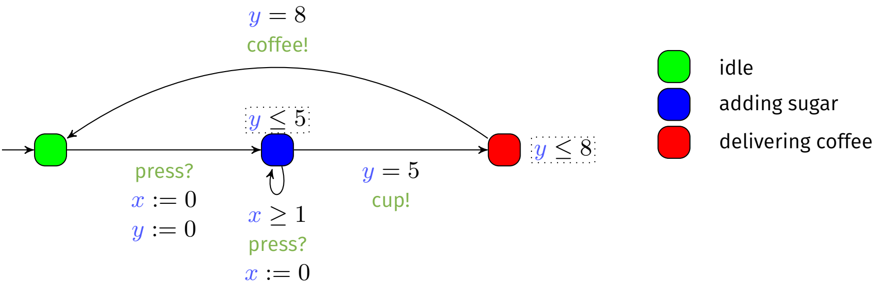

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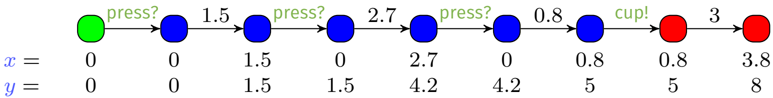

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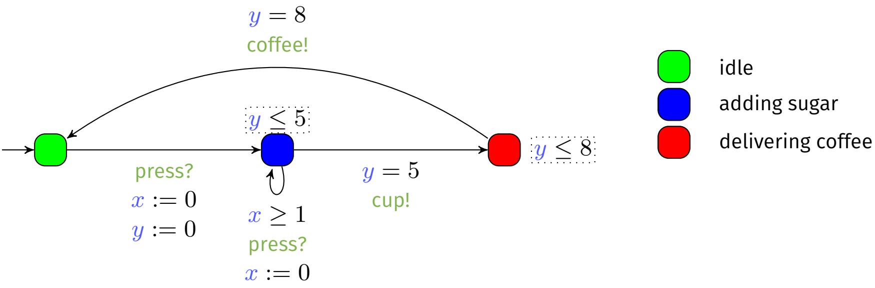

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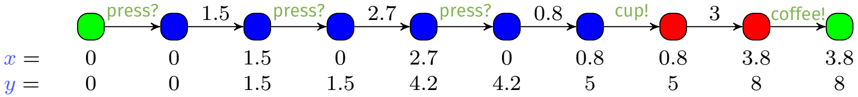


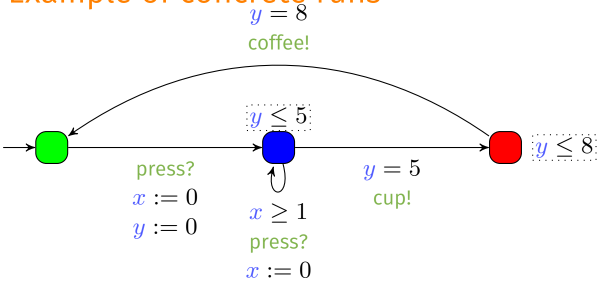
Concrete semantics of timed automata

- Concrete state of a TA: pair (l, w), where
  - l is a location,
  - w is a valuation of each clock

  Example: ( , $\binom{x=1.2}{y=3.7}$)

- Concrete run: alternating sequence of concrete states and actions or time elapse

Example of concrete runs



- Possible concrete runs for the coffee machine

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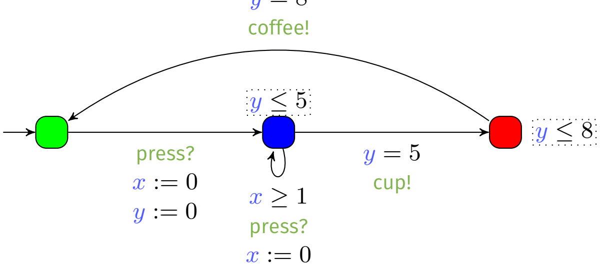
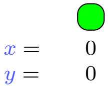


- Possible concrete runs for the coffee machine
  - Coffee with no sugar



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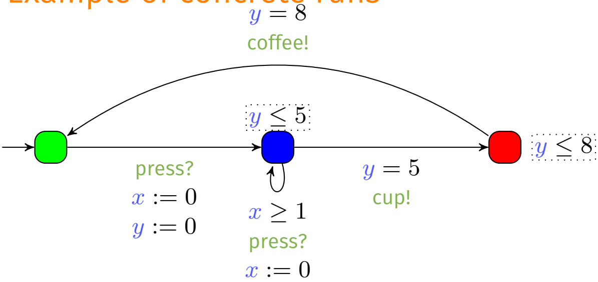
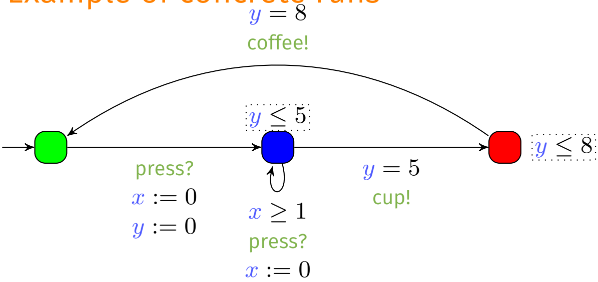


- Possible concrete runs for the coffee machine
  - Coffee with no sugar

$x =$	0	0
$y =$	0	0

Example of concrete runs



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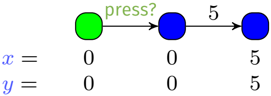

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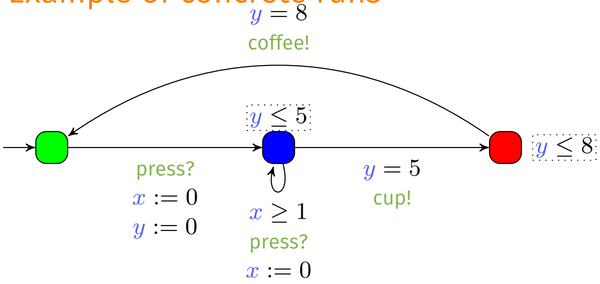

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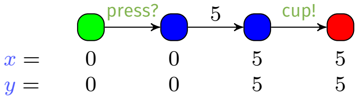

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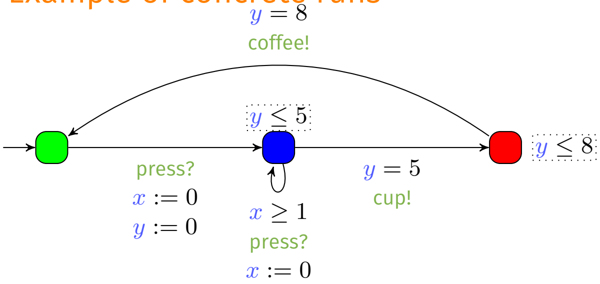

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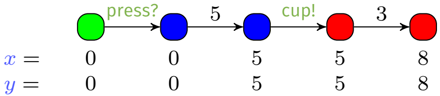

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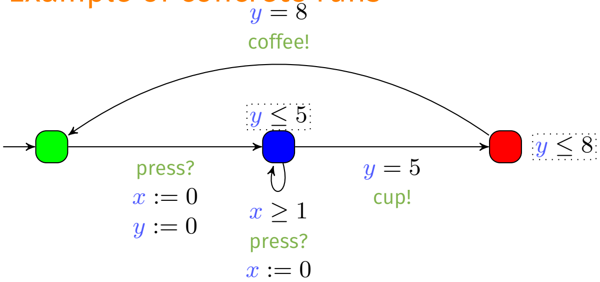

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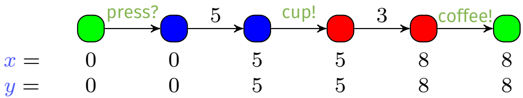

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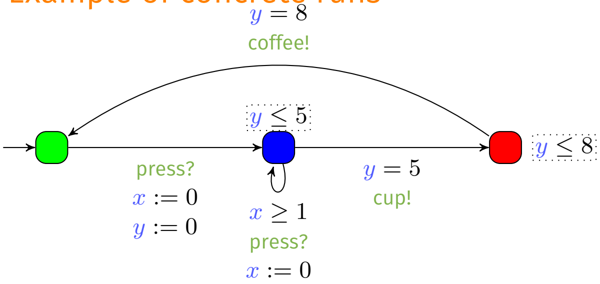

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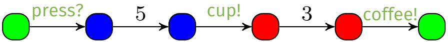

$x =$	0	0	5	5	8	8
$y =$	0	0	5	5	8	8

  - Coffee with 2 doses of sugar

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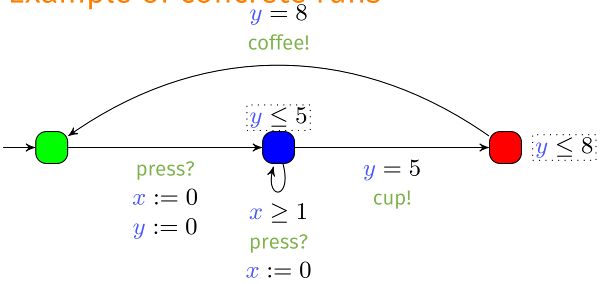
Example of concrete runs



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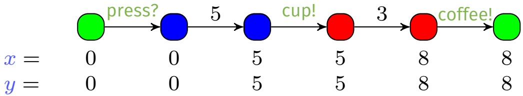

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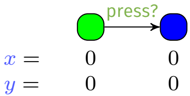

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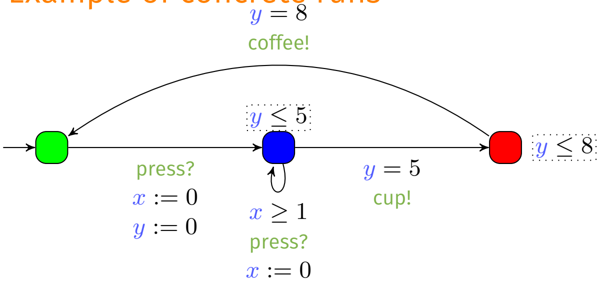

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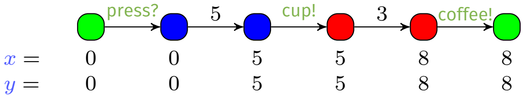

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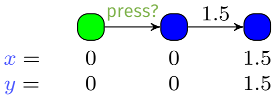

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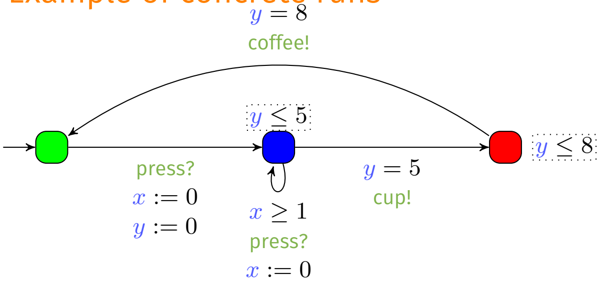

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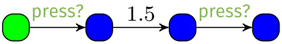
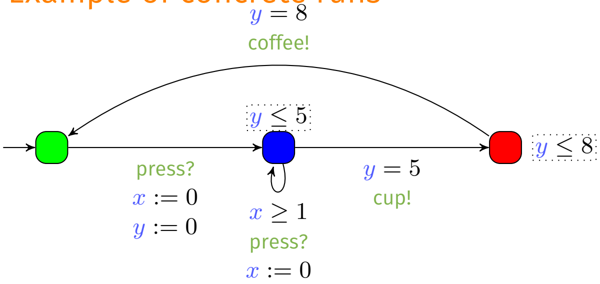


$x =$	0	0	1.5	0
$y =$	0	0	1.5	1.5

Example of concrete runs



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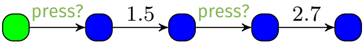
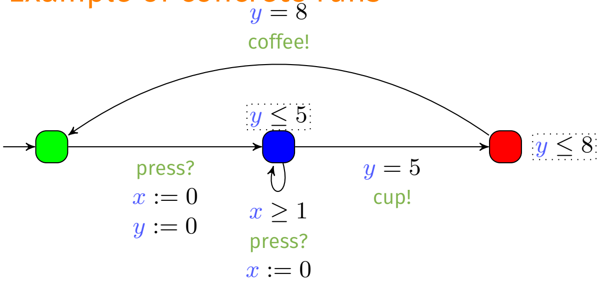


$x =$	0	0	1.5	0	2.7
$y =$	0	0	1.5	1.5	4.2

Example of concrete runs



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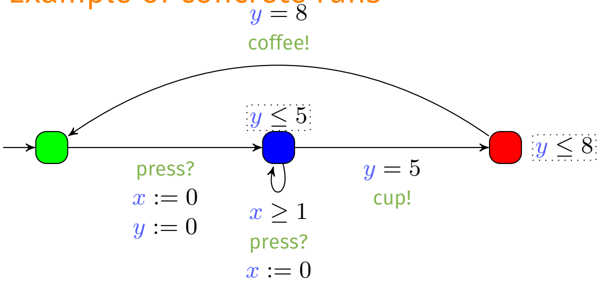

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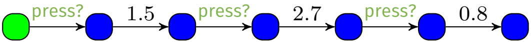
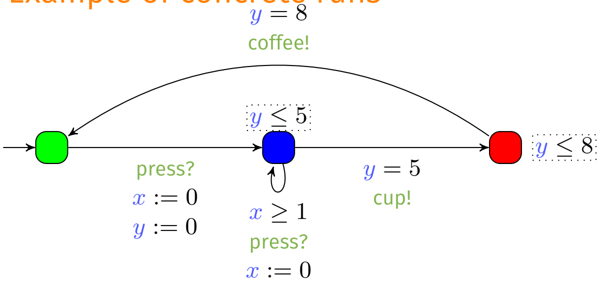


$x =$	0	0	1.5	0	2.7	0	0.8
$y =$	0	0	1.5	1.5	4.2	4.2	5

Example of concrete runs



- Possible concrete runs for the coffee machine
  - Coffee with no sugar

$x =$	0	0	5	5	8	8
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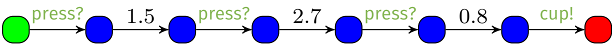
  - Coffee with 2 doses of sugar



$x =$	0	0	1.5	0	2.7	0	0.8	0.8
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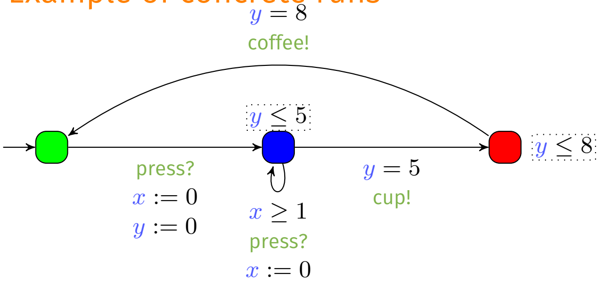

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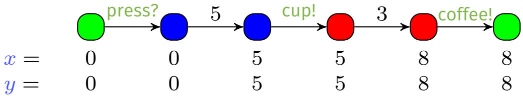

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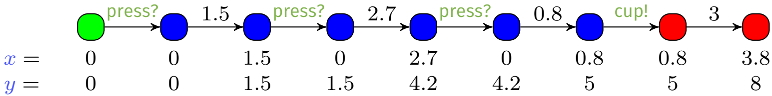

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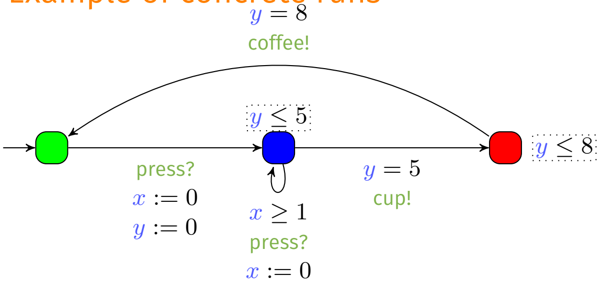

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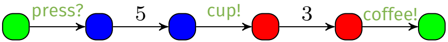

$x =$	0	0	5	5	8	8
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$x =$	0	0	1.5	0	2.7	0	0.8	0.8	3.8	3.8
$y =$	0	0	1.5	1.5	4.2	4.2	5	5	8	8

Timed automata: A success story

- An expressive formalism
  - Dense time
  - Concurrency
- A tractable verification in theory
  - Reachability is PSPACE-complete [Alur and Dill, 1994]
- A very efficient verification in practice
  - Symbolic verification: relatively insensitive to constants
  - Several model checkers, notably UPPAAL [Larsen et al., 1997]
  - Long list of successful case studies

Outline

Beyond timed model checking: parameter synthesis

- Verification for one set of constants does not usually guarantee the correctness for other values
- Challenges
  - Numerous verifications: is the system correct for any value within $[40; 60]$?
  - Optimization: until what value can we increase 10?
  - Robustness [Markey, 2011]: What happens if 50 is implemented with 49.99?
  - System incompletely specified: Can I verify my system even if I don't know the period value with full certainty?

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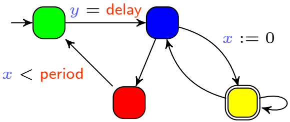
- Parameter synthesis
  - Consider that timing constants are unknown constants (parameters)

timed model checking



A model of the system

$\stackrel{?}{\models}$

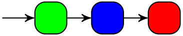
 is unreachable

A property to be satisfied

- Question: does the model of the system satisfy the property?

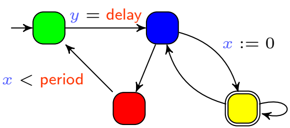
Yes

No



Counterexample

Parametric timed model checking



A model of the system

$\overset{?}{\models}$

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A property to be satisfied

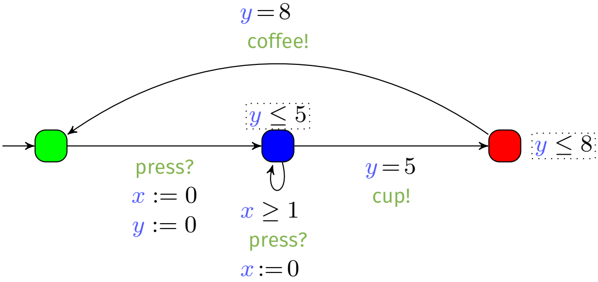
- Question: for what values of the parameters does the model of the system satisfy the property?

Yes if...

$$2\text{delay} > \text{period} \\ \land \text{period} < 20.46$$

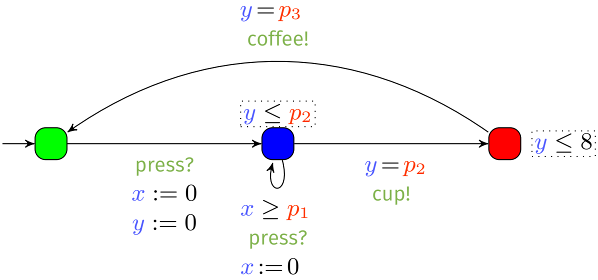
Parametric Timed Automaton (PTA)

- Timed automaton (sets of locations, actions and clocks)



Parametric Timed Automaton (PTA)

- Timed automaton (sets of locations, actions and clocks) augmented with a set P of parameters [Alur et al., 1993b]
  - Unknown constants compared to a clock in guards and invariants



Notation: Valuation of a PTA

- Given a PTA $\mathcal{A}$ and a parameter valuation v, we denote by $v(\mathcal{A})$ the (non-parametric) timed automaton where each parameter p is valuated by $v(p)$

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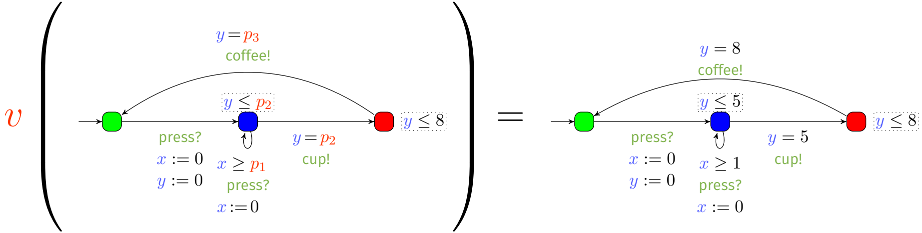

with $v : \begin{cases} p_1 & \rightarrow & 1 \\ p_2 & \rightarrow & 5 \\ p_3 & \rightarrow & 8 \end{cases}$

Symbolic semantics of parametric timed automata

- Symbolic state of a PTA: pair (l, C), where
  - l is a location,
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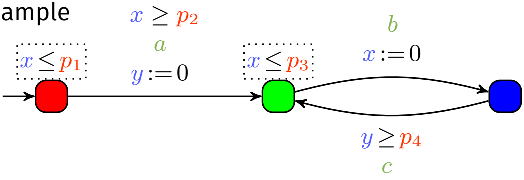

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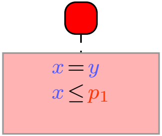

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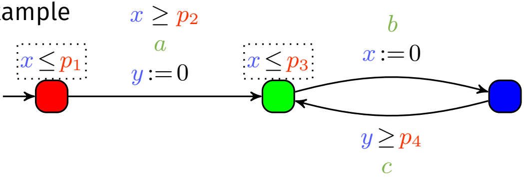

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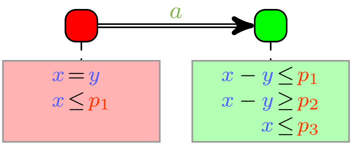

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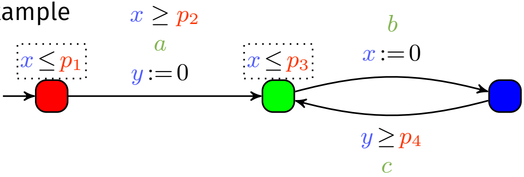

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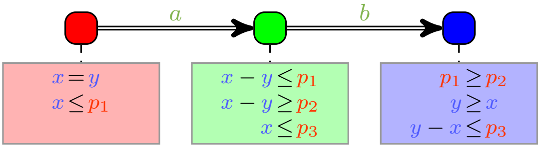
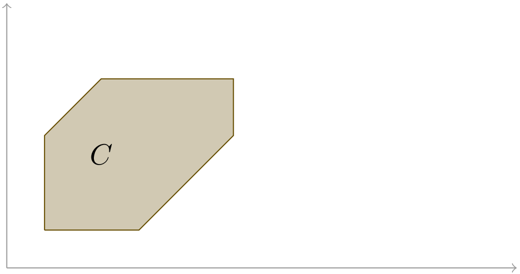


Symbolic semantics of PTA: Illustration

$$C' = [(C \cap g)]_R \cap I(l'))^{\nearrow} \cap I(l'))$$



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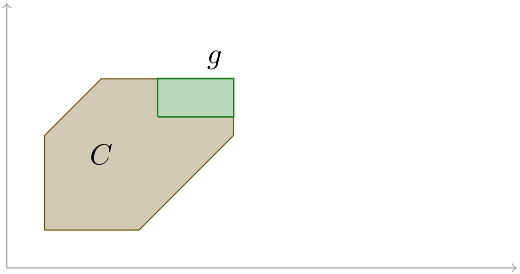

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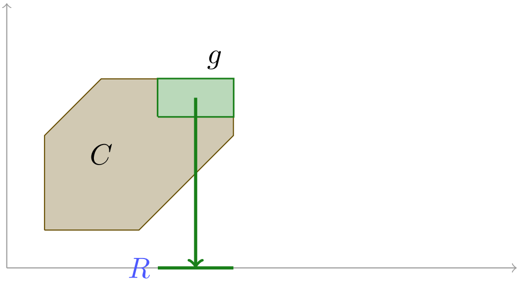

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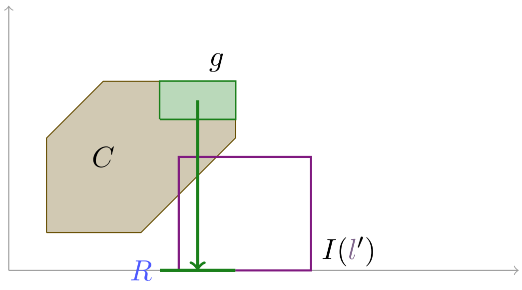

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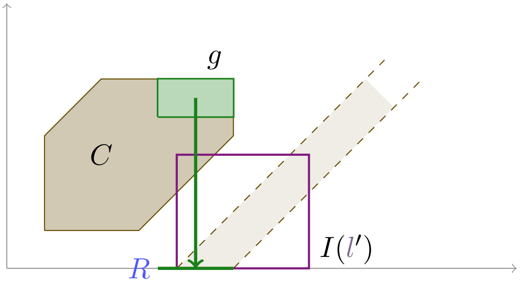

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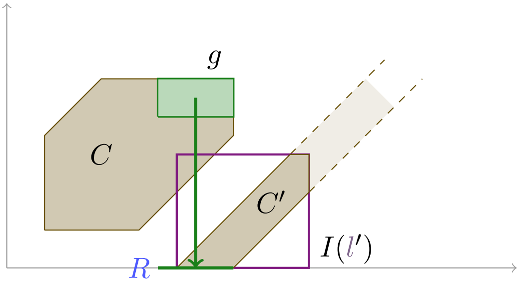
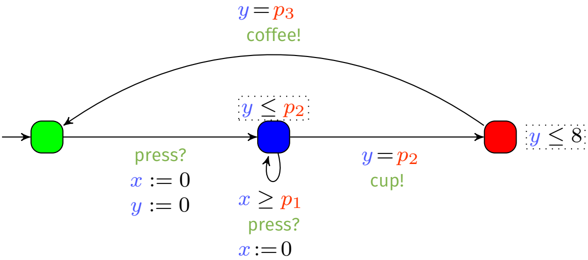
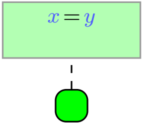


Symbolic exploration: Coffee machine





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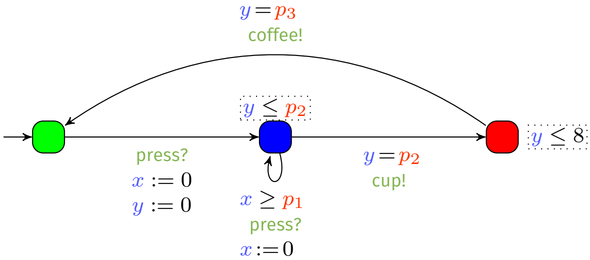

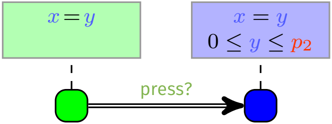

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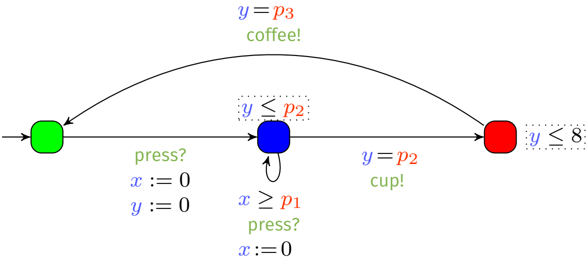

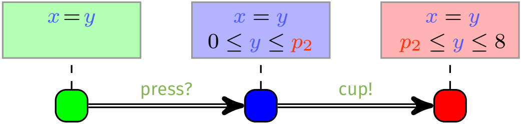

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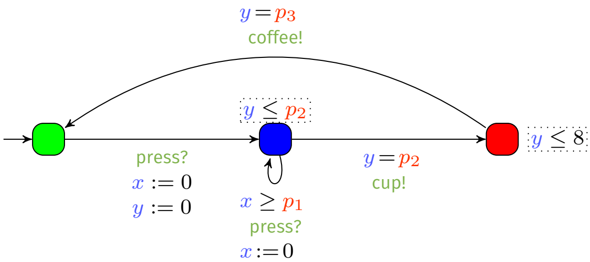

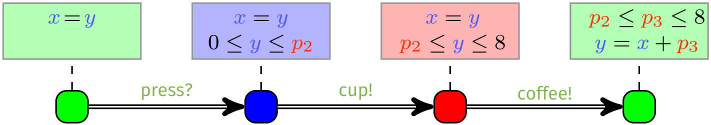

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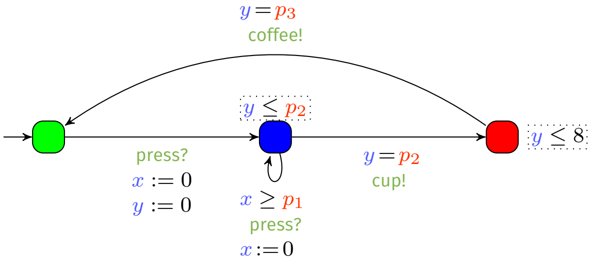

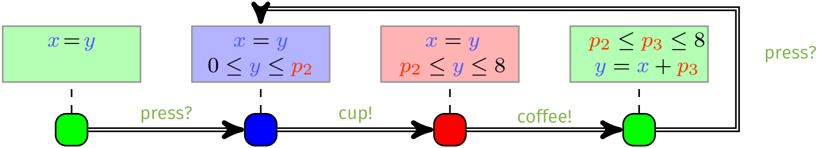

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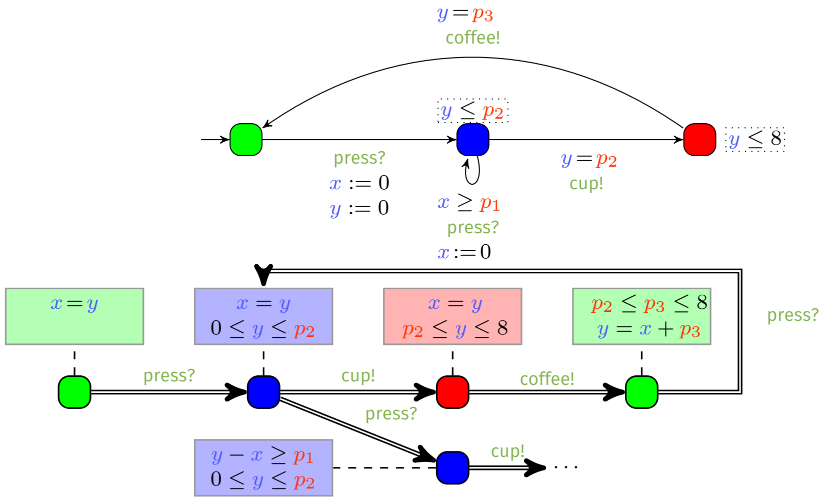

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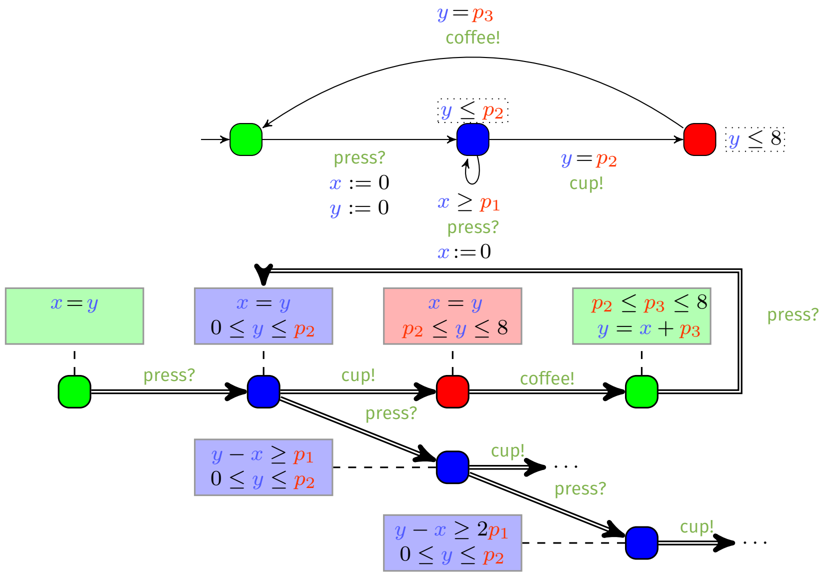

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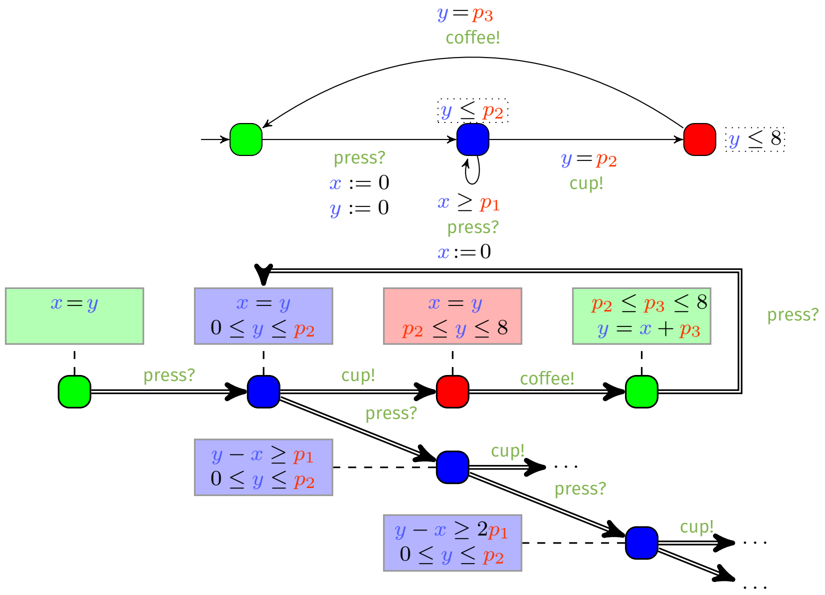

Why studying decidability?

If a decision problem is undecidable, it is hopeless to look for algorithms yielding exact solutions (because that is impossible)

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However, one can:

- design semi-algorithms: if the algorithm halts, then its result is correct
- design algorithms yielding over- or under-approximations

Decision and computation problems for PTA

- EF-Emptiness "Is the set of parameter valuations for which a given location l is reachable empty?"

  Example: "Does there exist at least one parameter valuation for which I can get a coffee with 2 sugars?"

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Bad news

All interesting problems are undecidable for (general) parametric timed automata.

[ÉA, STTT 2017]

Outline

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Context: Hard real-time embedded systems

- Modern hard real-time embedded systems are distributed in nature
- Many of them have critical timing requirements:
  - automotive systems (modern cars have 10-20 embedded boards connected by one or more CAN bus)
  - avionics systems (several distributed control boards connected by one or more dedicated networks)

- It is very important to check that all tasks meet their deadlines

Schedulability analysis

Real-time system:

- Set of tasks (with a period, a WCET and a deadline)
- One processor (uniprocessor) or more (multiprocessor)
- Scheduling policies: fixed priority (FPS), earliest deadline first (EDF)...

Definition (Schedulability analysis)

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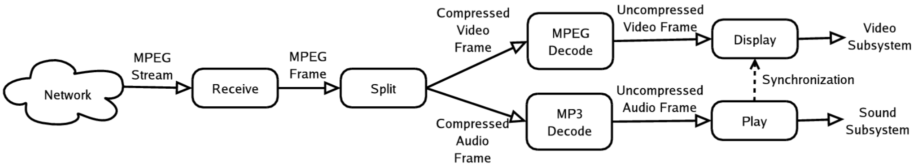
In general, schedulability analysis is hard

Real-time pipelines

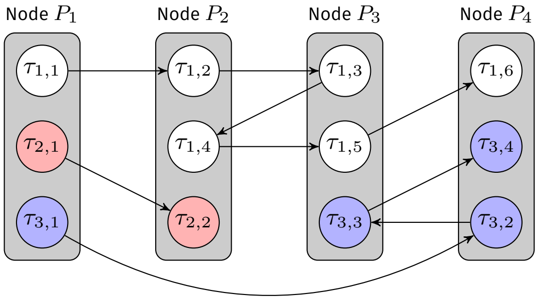
- Many real-time applications can be modeled as pipelines (also called transactions) of tasks



- Executed on a distributed (or multicore) system
- Activated cyclically (periodic or sporadic)
- Using preemption
  - Lower-priority tasks can be temporarily interrupted by a higher-priority task

Model

- A set of pipelines $\{\mathcal{P}^{(1)}, \dots, \mathcal{P}^{(p)}\}$ distributed over m nodes
- Each pipeline $\mathcal{P}^{(i)}$ is a chain of n_i tasks $\{\tau_{i,1}, \dots, \tau_{i,n_i}\}$
- Pipeline $\mathcal{P}^{(i)}$ has an end-to-end (E2E) deadline D_i and period T_i

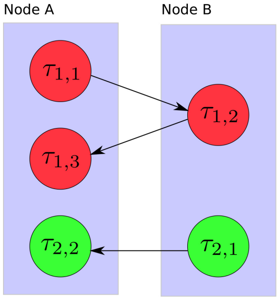


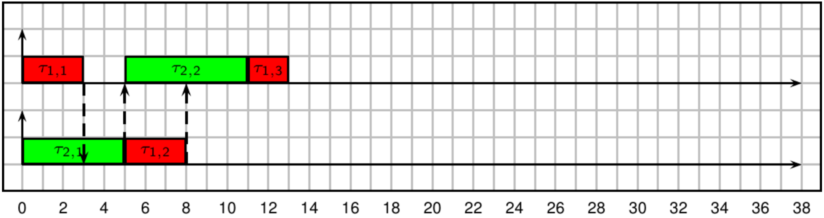
- Scheduling Problem: Guarantee that all pipelines complete before their E2E deadlines

Activations, jitter, deadline

- An example

Task	Per.	E2E	Comp.	Resp.	Jitter	prio
$\tau_{1,1}$	15		3	3	0	HI
$\tau_{1,2}$	-		3	8	0-2	LO
$\tau_{1,3}$	-	15	2	13	3	LO
$\tau_{2,1}$	12		5	6	0	HI
$\tau_{2,2}$	-	12	6	?	0-1	ME





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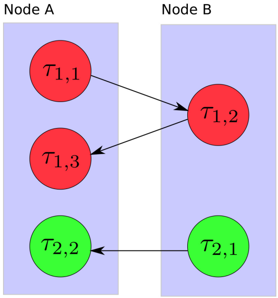
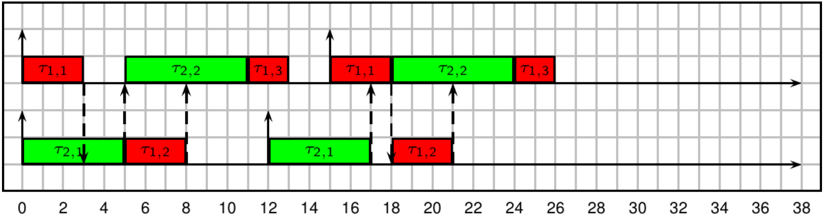
$\tau_{2,1}$	12		5	6	0	HI
$\tau_{2,2}$	-	12	6	?	0-1	ME

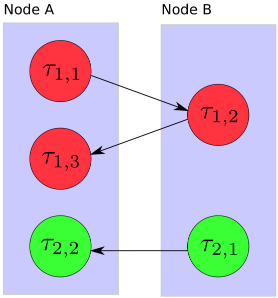


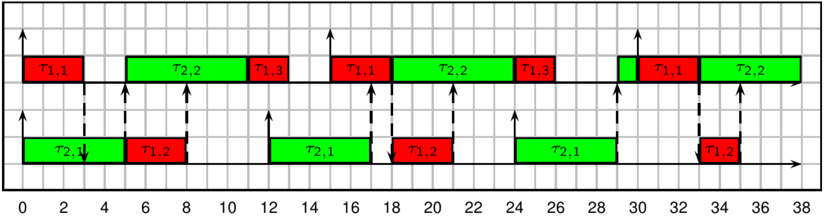


Activations, jitter, deadline

- An example

Task	Per.	E2E	Comp.	Resp.	Jitter	prio
$\tau_{1,1}$	15		3	3	0	HI
$\tau_{1,2}$	-		3	8	0-2	LO
$\tau_{1,3}$	-	15	2	13	3	LO
$\tau_{2,1}$	12		5	6	0	HI
$\tau_{2,2}$	-	12	6	**14**	0-1	ME





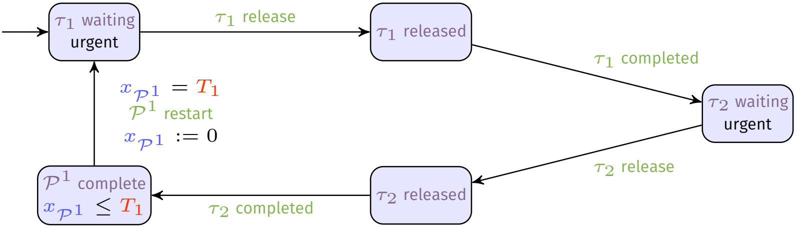
Outline

Enriching the model with parameters

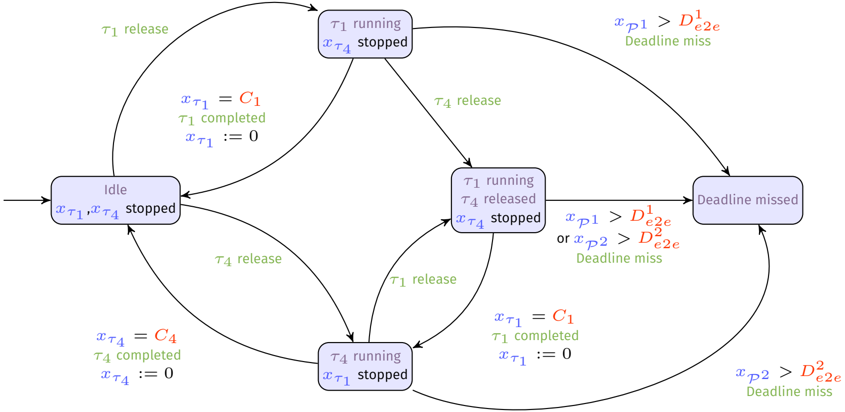
- A task is identified by three parameters:
  - C_i is the worst-case computation time (or worst-case transmission time, in case it models a message)
  - R_i is the task worst-case response time, i. e., the worst case finishing time of any task instance relative to the activation of its pipeline.
  - J_i is the task worst-case activation jitter, i. e., the greatest time since its activation that a task must wait for all preceding tasks to complete their execution

- A parameter of major interest is the computation time

Modeling a task / pipeline



Modeling the fixed priority scheduler (preemptive)



Actually a PTA extended with stopwatches [Sun et al., 2013]

an extension of stopwatch automata [Adbeddaïm and Maler, 2002]

Schedulability analysis with parametric model checking

Goal: parametric schedulability analysis

Given a real-time system and a scheduling policy, synthesize valuations (deadlines, periods...) such that the system is schedulable.

Modeling a real-time system with PTAs

- Each task or chain of task: one PTA
- Each scheduler: one PTA
- Use stopwatches to model preemption

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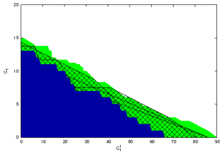
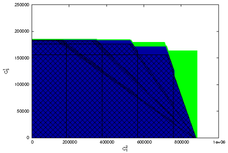
Modeling a real-time system with PTAs

- Each task or chain of task: one PTA
- Each scheduler: one PTA
- Use stopwatches to model preemption

Comparison with analytical methods [Sun, Soulat, Lipari, André, Fribourg, FTSCS'13]

- Slower but much better in terms of completeness
- And can evaluate robustness



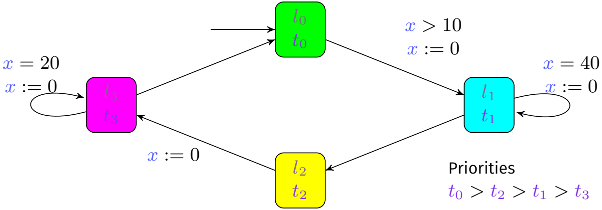


Outline

A unified formalism: Parametric task automata

Extension of task automata [Norström et al., 1999, Fersman et al., 2007] with parameters

[André, FMICS'17]



Task	B	W	D
t_0	0	1	2
t_1	4	4	20
t_2	0	1	4
t_3	2	2	10

A unified formalism: Parametric task automata

Extension of task automata [Norström et al., 1999, Fersman et al., 2007] with parameters

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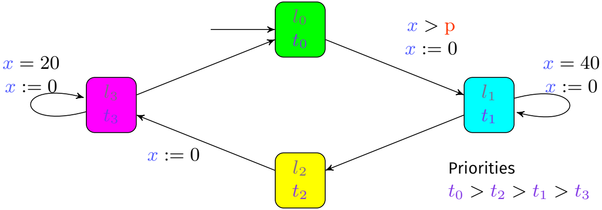

Task	B	W	D
t_0	0	1	2
t_1	4	4	20
t_2	0	1	p'
t_3	2	2	10

A unified formalism: Parametric task automata

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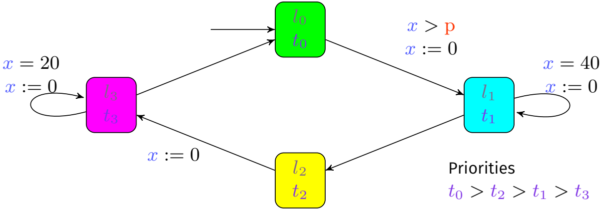

Task	B	W	D
t_0	0	1	2
t_1	4	4	20
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t_3	2	2	10

Parametric task automata can model

- Preemption
- Periodic tasks, sporadic tasks, pseudo-periodic tasks...
- Dependencies between tasks
- Offset, jitter
- Uncertainty
- Uniprocessor only

Parametric task automata: theory and practice

Schedulability-emptiness ("is the set of valuations for which the system is schedulable empty?")

- Undecidable in general
- Decidable under some assumptions [André, FMICS'17]

Parametric task automata: theory and practice

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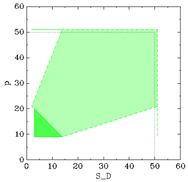
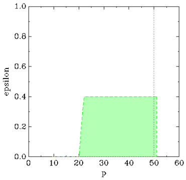
Implementation in IMITATOR

- Translation into a network of parametric stopwatch automata
- Schedulability analysis
- Parametric and/or robust schedulability analysis





Outline

Parametric verification of real-time systems

Many problems can be reduced to parametric reachability (EFsynth): find parameter valuations for which a given state is (un)reachable

- ☹ This problem is undecidable for PTAs and many subclasses

  [ÉA, STTT 2017]

- ☺ But we can still compute part (and often all) of the solution

Interesting problems:

- Find parameter valuations for which no deadline violation occurs (i. e., for which the system is schedulable)
- Compute the worst-case computation time
- Find the parametric WCET when the jitter is unknown

Parametric model checking applied to schedulability analysis

Advantages: Very expressive (in fact Turing-complete)

- ☺ Periodic tasks, sporadic tasks...
- ☺ Task dependencies
- ☺ Data transmission
- ☺ Jitters, offsets
- ☺ Uncertainty
- ☺ All possible schedulers

Drawback: slow (intractable for very large systems)

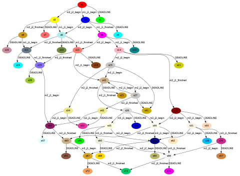
- ☹ limited to small or medium-sized systems

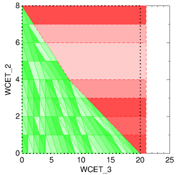
Outline

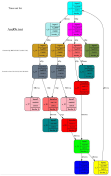
IMITATOR

- A tool for modeling and verifying timed concurrent systems with unknown constants modeled with parametric timed automata
  - Communication through (strong) broadcast synchronization
  - Rational-valued shared discrete variables
  - Stopwatches, to model schedulability problems with preemption

- Synthesis algorithms
  - (non-Zeno) parametric model checking (using a subset of TCTL)
  - Language and trace preservation, and robustness analysis
  - Parametric deadlock-freeness checking







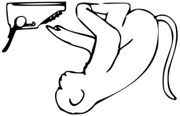
IMITATOR

Under continuous development since 2008 [André et al., FM'12]

A library of benchmarks

- Communication protocols
- Schedulability problems
- Asynchronous circuits
- …and more

Free and open source software: Available under the GNU-GPL license



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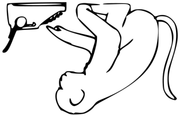


Try it!

www.imitator.fr

Some success stories

- Modeled and verified an asynchronous memory circuit by ST-Microelectronics
- Parametric schedulability analysis of a prospective architecture for the flight control system of the next generation of spacecrafts designed at ASTRIUM Space Transportation [Fribourg et al., 2012]
- Verification of software product lines [Luthmann et al., 2017]
- Offline monitoring [ÉA, Hasuo, Waga @ ICECCS'18]
- Formal timing analysis of music scores [Fanchon and Jacquemard, 2013]
- Solution to a challenge related to a distributed video processing system by Thales

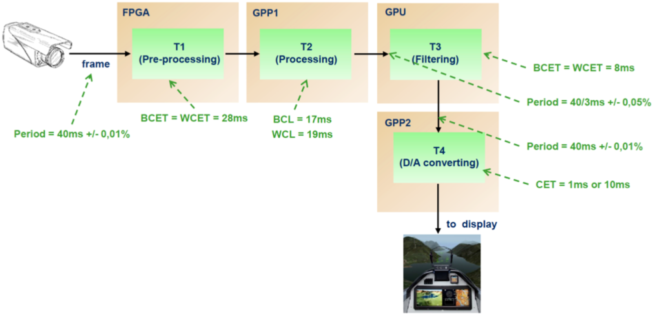
Outline

The FMTV 2015 Challenge (1/2)

Challenge by Thales proposed during the WATERS 2014 workshop
Solutions presented at WATERS 2015

System: an unmanned aerial video system with uncertain periods

- Period constant but with a small uncertainty (typically 0.01 %)
- Not a jitter!



The FMTV 2015 Challenge (2/2)

Goal

Compute the end-to-end BCET and WCET times for a buffer size of $n = 1$ and $n = 3$

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- ☹ Not a typical parameter synthesis problem?
  - No parameters in the specification

The FMTV 2015 Challenge (2/2)

Goal

Compute the end-to-end BCET and WCET times for a buffer size of $n = 1$ and $n = 3$

☹ Not a typical parameter synthesis problem?

- No parameters in the specification

☺ A typical parameter synthesis problem

- The end-to-end time can be set as a parameter… to be synthesized
- The uncertain period is typically a parameter (with some constraint, e. g., $P1 \in [40 - 0.004, 40 + 0.004]$)

Methodology

1. Propose a PTA model with parameters for uncertain periods and the end-to-end time

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5. Eliminate all parameters but the end-to-end time

Note: not eliminating parameters allows one to know for which values of the periods the best / worst case execution times are obtained.

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5. Eliminate all parameters but the end-to-end time
6. Exhibit the minimum and the maximum

Note: not eliminating parameters allows one to know for which values of the periods the best / worst case execution times are obtained.

To build the PTA model

- Uncertainties in the system:
  - $P1 \in [40 - 0.004, 40 + 0.004]$
  - $P3 \in [\frac{40}{3} - \frac{1}{150}, \frac{40}{3} + \frac{1}{150}]$
  - $P4 \in [40 - 0.004, 40 + 0.004]$

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- Parameters:
  - P1_uncertain
  - P3_uncertain
  - P4_uncertain

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  - $P4 \in [40 - 0.004, 40 + 0.004]$
- Parameters:
  - P1_uncertain
  - P3_uncertain
  - P4_uncertain
- The end-to-end latency (another parameter): $\mathrm{E2E}$
- Others:
  - the register between task 2 and task 3: discrete variable $\mathrm{reg}_{2,3}$
  - the buffer between task 3 and task 4: $n = 1$ or $n = 3$

Simplification

- T1 and T2 are synchronised; T1, T3 and T4 are asynchronised
  - (exact modeling of the system behaviour is too heavy)

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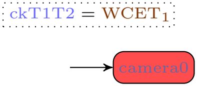
- T1 and T2 are synchronised; T1, T3 and T4 are asynchronised
  - (exact modeling of the system behaviour is too heavy)
- We choose a single arbitrary frame, called the target one
- We assume the system is initially in an arbitrary status
  - This is our only uncertain assumption (in other words, can the periods deviate from each other so as to yield any arbitrary deviation?)

The initialization automaton



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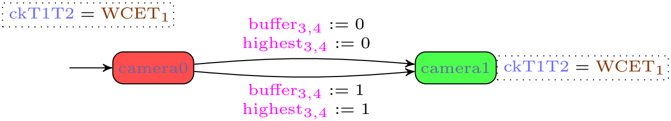

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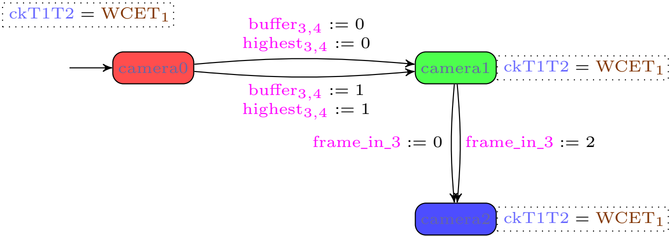

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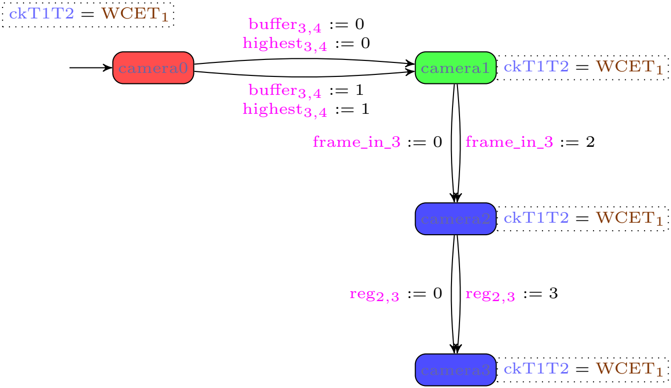

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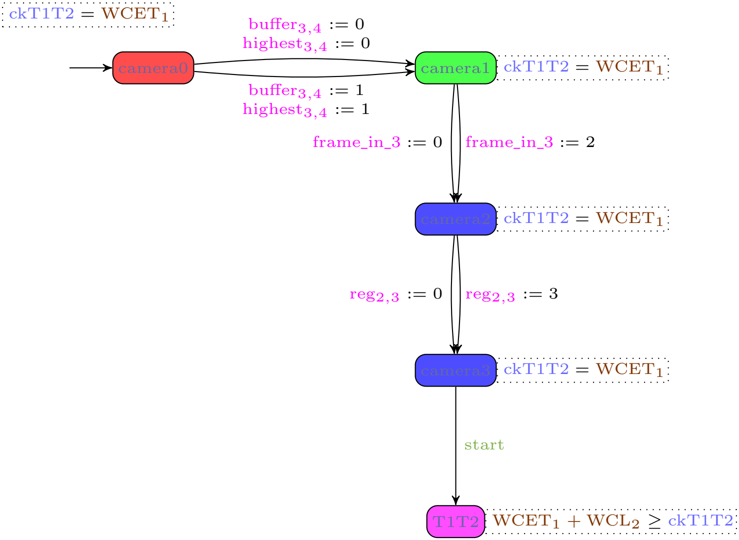

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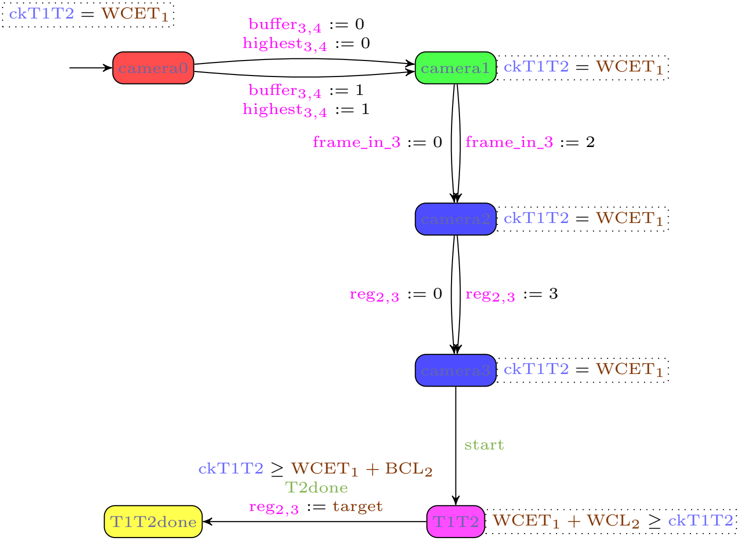
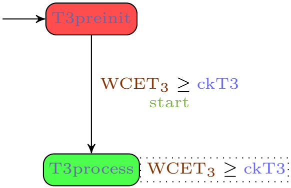
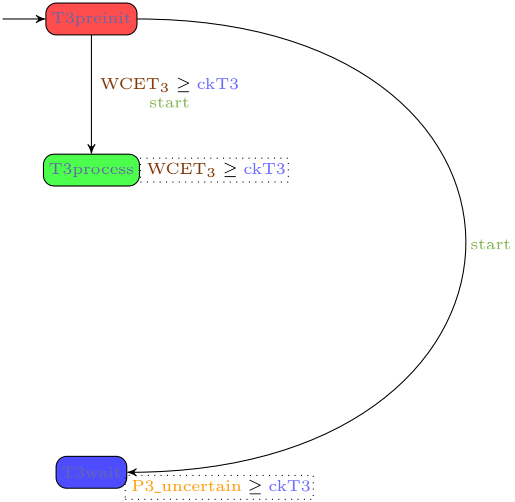


Task T3

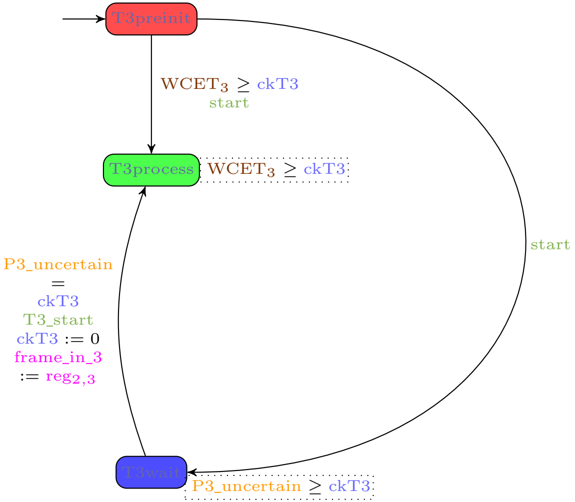
Task T3



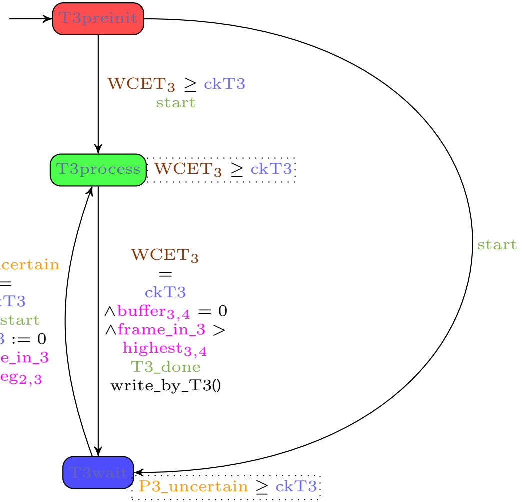
Task T3


T3preinit
WCET$_3$ ≥ ckT3
start
T3process
WCET$_3$ ≥ ckT3
start
T3wait
P3_uncertain ≥ ckT3

Task T3

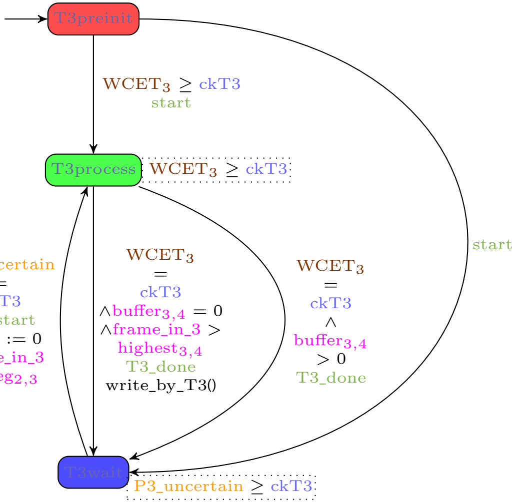

T3preinit
WCET₃ ≥ ckT3
start
T3process
WCET₃ ≥ ckT3
start
P3_uncertain
=
ckT3
T3_start
ckT3 := 0
frame_in_3
:= reg2,3
T3wait
P3_uncertain ≥ ckT3

Task T3

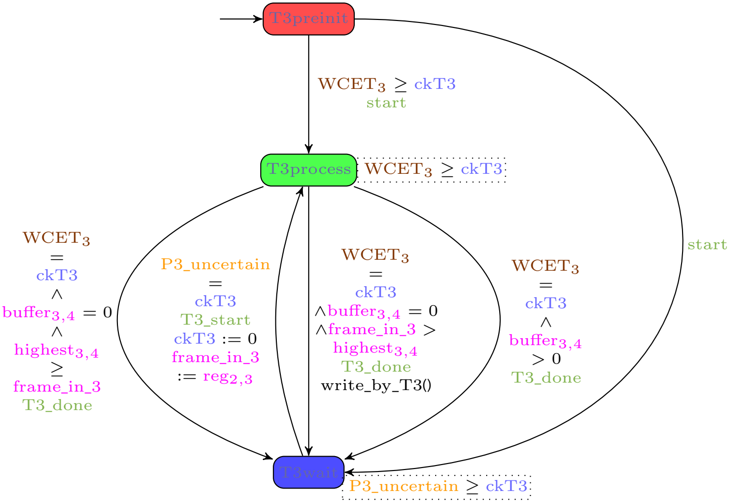


T3preinit
WCET$_3$ ≥ ckT3
start
T3process
WCET$_3$ ≥ ckT3
start
P3_uncertain
=
ckT3
T3_start
ckT3 := 0
frame_in_3
:= reg$_{2,3}$
WCET$_3$
=
ckT3
∧buffer$_{3,4}$ = 0
∧frame_in_3 >
highest$_{3,4}$
T3_done
write_by_T3()
T3wait
P3_uncertain ≥ ckT3

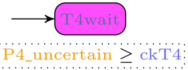
Task T3


T3preinit
WCET$_3$ ≥ ckT3
start
start
T3process
WCET$_3$ ≥ ckT3
P3_uncertain
=
ckT3
T3_start
ckT3 := 0
frame_in_3
:= reg$_{2,3}$
WCET$_3$
=
ckT3
∧buffer$_{3,4}$ = 0
∧frame_in_3 >
highest$_{3,4}$
T3_done
write_by_T3()
WCET$_3$
=
ckT3
∧
buffer$_{3,4}$
> 0
T3_done
T3wait
P3_uncertain ≥ ckT3

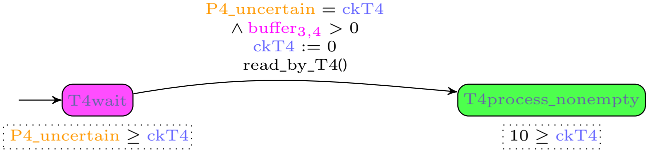
Task T3


T3preinit
WCET3 ≥ ckT3
start
T3process
WCET3 ≥ ckT3
WCET3 = ckT3 ∧ buffer3,4 = 0 ∧ highest3,4 ≥ frame_in_3
T3_done
P3_uncertain = ckT3
T3_start
ckT3 := 0
frame_in_3 := reg2,3
WCET3 = ckT3 ∧buffer3,4 = 0 ∧frame_in_3 > highest3,4
T3_done
write_by_T3()
WCET3 = ckT3 ∧ buffer3,4 > 0
T3_done
start
T3wait
P3_uncertain ≥ ckT3

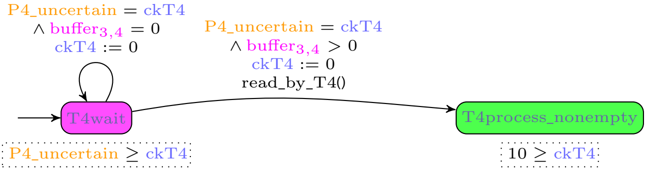
Task T4



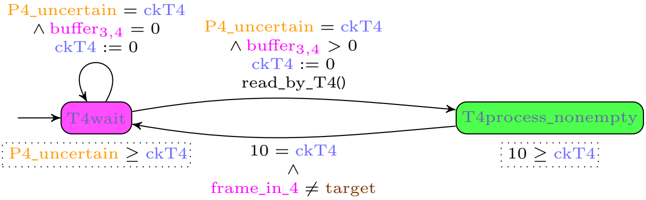
Task T4


P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
T4wait
T4process_nonempty
P4_uncertain ≥ ckT4
10 ≥ ckT4

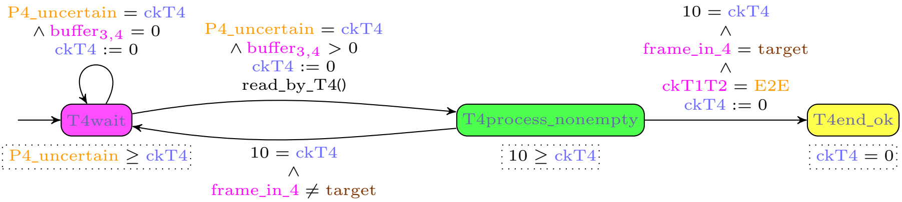
Task T4


P4_uncertain = ckT4
∧ buffer3,4 = 0
ckT4 := 0
P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
T4wait
T4process_nonempty
P4_uncertain ≥ ckT4
10 ≥ ckT4

Task T4


P4_uncertain = ckT4
∧ buffer3,4 = 0
ckT4 := 0
P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
T4wait
T4process_nonempty
P4_uncertain ≥ ckT4
10 = ckT4
∧
frame_in_4 ≠ target
10 ≥ ckT4

Task T4



P4_uncertain = ckT4
∧ buffer3,4 = 0
ckT4 := 0
P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
10 = ckT4
∧
frame_in_4 = target
∧
ckT1T2 = E2E
ckT4 := 0
T4wait
T4process_nonempty
T4end_ok
P4_uncertain ≥ ckT4
10 = ckT4
∧
frame_in_4 ≠ target
10 ≥ ckT4
ckT4 = 0

Results

E2E latency results for $n = 1$ and $n = 3$

	$n = 1$	$n = 3$
min E2E	63 ms	63 ms
max E2E	145.008 ms	225.016 ms

Results obtained using IMITATOR in a few seconds

[ÉA, Lipari, Sun @ WATERS'15]

Outline

Summary

- Finite-state automata
  - ☺ Mostly decidable results
  - ☺ Efficient model checking algorithms
  - ☹ Miss the quantitative aspects
  - ☺ Many powerful tools
- Timed automata
  - ☺ Finite abstract semantics
  - ☺ Some decidable results
  - ☹ Some undecidable results
  - ☺ Several powerful tools
- Parametric timed automata
  - ☺ Very expressive
  - ☹ No finite abstract semantics
  - ☹ Almost only undecidability results
  - ☺ Some powerful tools

Perspectives

Address harder problems

- Thales challenge: what is the minimum time between two lost frames? (due to the uncertain periods)
    - Requires to model check thousands of frame processings

Improve the efficiency of parameter synthesis techniques

- Distributed parameter synthesis
    - Distribution over a cluster [ÉA, Coti, Nguyen @ ICFEM 2015]
    - Multi-core synthesis [Laarman et al., 2013]
    - Distributed synthesis based on locations [Zhang et al., 2016]
- Machine learning [Li et al., 2017]

Beyond (parametric) timed automata

Beyond time...

- Cost, temperature, energy
  - Hybrid automata [Alur et al., 1993a, Alur et al., 1995]
    - Very expressive, but often undecidable
    - Some interesting software (including SpaceEx [Frehse et al., 2011])

Probabilities

- Useful when a property cannot be proved with full certainty
  - Communication protocols, failures...
- Another way to model systems known with limited precision

Security

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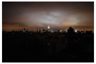
Additional explanation

Explanation for the 4 pictures in the beginning



Allusion to the Northeast blackout (USA, 2003)
Computer bug
Consequences: 11 fatalities, huge cost
(Picture actually from the Sandy Hurricane, 2012)

Error screen on the earliest versions of Macintosh

Allusion to the sinking of the Sleipner A offshore platform (Norway, 1991)
No fatalities
Computer bug: inaccurate finite element analysis modeling
(Picture actually from the Deepwater Horizon Offshore Drilling Platform)

Allusion to the MIM-104 Patriot Missile Failure (Iraq, 1991)
28 fatalities, hundreds of injured
Computer bug: software error (clock drift)
(Picture of an actual MIM-104 Patriot Missile, though not the one of 1991)

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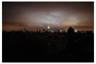

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