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Dynamic Clock Elimination in Parametric Timed Automata

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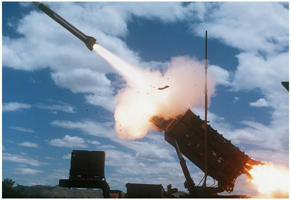
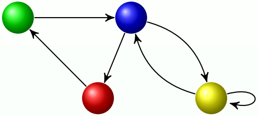
Context: Verifying Complex Timed Systems (1/2)

- Need for early bug detection
  - Bugs discovered when final testing: expensive
  - Need for thorough modeling and verification



Context: Verifying Complex Timed Systems (2/2)

- Use formal methods



A finite model of the system

$AG\neg$●

A formula to be satisfied

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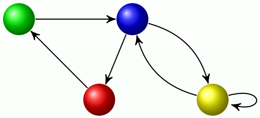

$\overset{?}{\models}$

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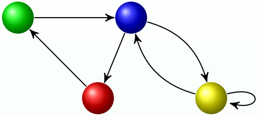

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A finite model of the system

A formula to be satisfied

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

Yes

No

Counterexample

Context: Parameter Synthesis

- Timed systems are characterized by a set of timing constants
  - "The packet transmission lasts for $50\,ms$"
  - "The sensor reads the value every $10\,s$"
  - etc.
- Verification for one set of constants does not 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: What happens if 50 is implemented with 49.99?

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    - Robustness: What happens if 50 is implemented with 49.99?
- Parameter synthesis
    - Consider that timing constants are unknown constants (parameters)
    - Find good values for the parameters

Outline

1. Parametric Timed Automata
2. Motivation: Clock Reduction
3. Dynamic Elimination
4. Experimental Validation
5. Conclusion

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Timed Automaton

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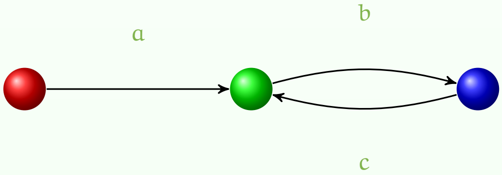
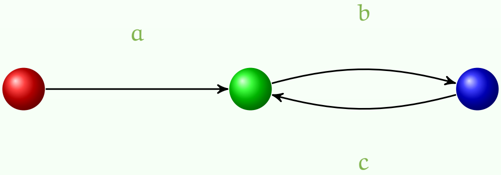


Timed Automaton

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



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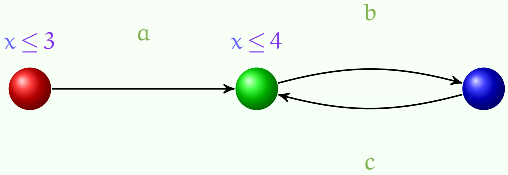

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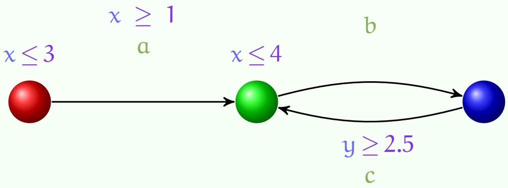

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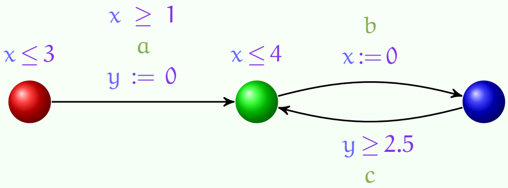

Parametric Timed Automaton (PTA)

- Finite state automaton (sets of locations and actions) augmented with
  - A set X of clocks (i.e., real-valued variables evolving linearly at the same rate [Alur and Dill, 1994])
  - A set P of parameters (i.e., unknown constants), used in guards and invariants [Alur et al., 1993]
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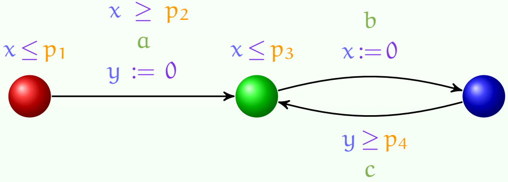

Semantics of Parametric Timed Automata

- State of a PTA: couple (q, C), where
  - q is a location,
  - C is a constraint (conjunction of inequalities) over X and P

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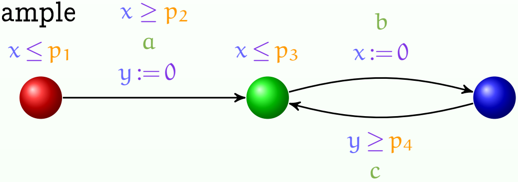
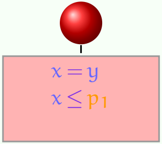


  - Possible path for this PTA



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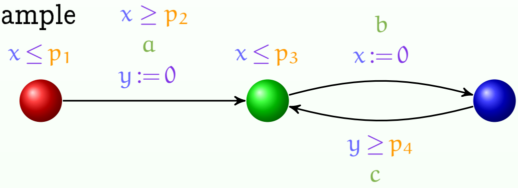

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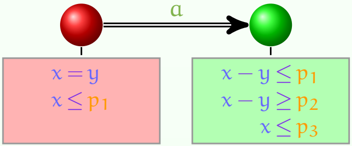

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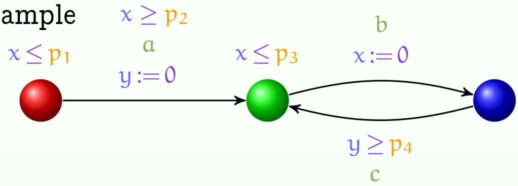

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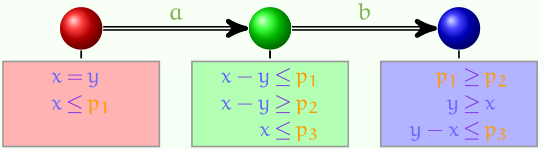
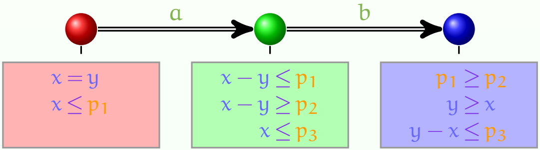


Traces

- Trace over a PTA: time-abstract path
  - Finite alternating sequence of locations and actions



$x = y$
$x \leq p_1$

$x - y \leq p_1$
$x - y \geq p_2$
$x \leq p_3$

$p_1 \geq p_2$
$y \geq x$
$y - x \leq p_3$

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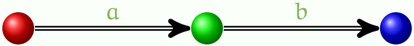

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2. Motivation: Clock Reduction
3. Dynamic Elimination
4. Experimental Validation
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Reducing the number of clocks

- The fewer clocks, the more efficient model checking is [Bengtsson and Yi, 2003]
- Consequence: State space reduction
  - Smaller constraints (represented as arrays, matrices, etc.)
  - Less states (due to side-effect merging)
- Clock reduction native in some formalisms
  - ☺ Parametric time Petri nets [Traonouez et al., 2009]
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  - ☹ . . . but not in PTA

Reducing the number of clocks: Some approaches

- Clock elimination in non-parametric timed automata [Daws and Yovine, 1996]
    - Detection of (in)active clocks
    - Detection of clocks equal to each other
    - Relatively easy in a non-parametric setting (use of Difference Bound Matrices)
- (Tentative) elimination of the global clocks in a network of timed automata in a distributed setting [Balaguer and Chatain, 2012]
- Native elimination in other formalisms [Traonouez et al., 2009, Sun et al., 2013]
    - Translation from timed automata?

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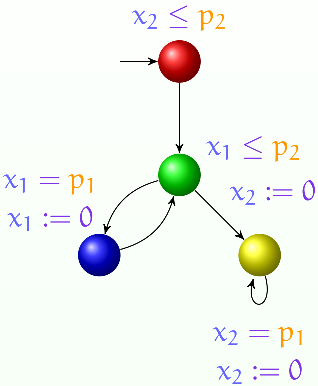
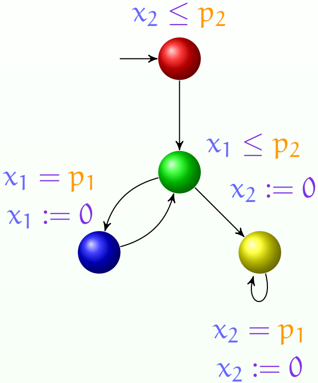
Principle

- Inactive clocks
  - In 🔵, the value of x_2 is useless. It will not be used until its next reset when entering 🟡.



Principle

- Inactive clocks
  - In ●, the value of x_2 is useless. It will not be used until its next reset when entering ●.
- Goal: detect and eliminate inactive clocks
  - ⇒ Smaller memory
  - ⇒ Less states
  - ⇒ Better termination



Assumptions

Remark

Detecting really useless clocks would require us to know the future, hence to perform the analysis… which we want to avoid

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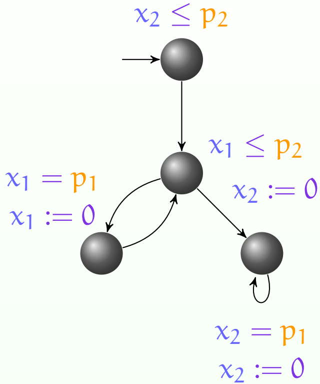
- Assumptions
  - Static a priori detection of the useless clocks
  - Local clocks only
  - Dynamic elimination during the analysis
- Consequence: possible under-approximation of the set of eliminated clocks

Static Detection

- Backward marking algorithm for a clock x
    - Goal: mark all locations where x is useful
    - Start by marking the locations where x is used (invariant or outgoing guard)
    - Iterate in a backward manner until a reset is found
    - Stop when reaching fixpoint

Example for x_1:



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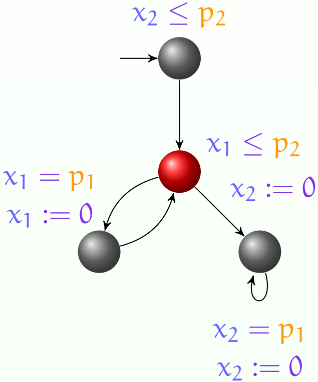

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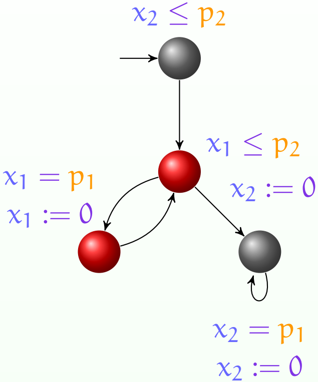

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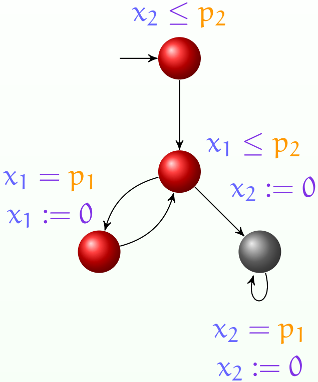

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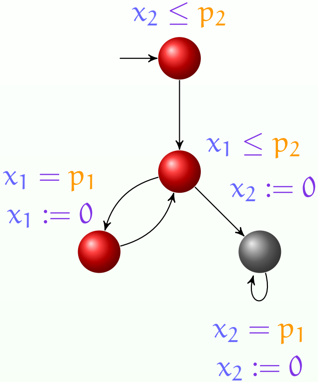

Hence, x_1 can be eliminated when in ● .

Dynamic Elimination

- Clocks can be eliminated on-the-fly when computing a new state
  - Refer to the static table of the useless clocks in the current location

- Elimination à la Fourier-Motzkin [Schrijver, 1986]
  - So as not to modify the relationship between other clocks and parameters
    Costly operation

    Example: $x_1 \leq x_2 \leq p_2$ becomes $x_1 \leq p_2$ after elimination of x_2

Characterization

- Bijection between the sets of traces without and with elimination of the clocks
    - All linear-time properties (LTL) can be checked using this optimization
    - The inverse method can be applied [André and Soulat, 2013]
- Bijection between the sets of parametric paths without and with elimination of the clocks
    - Optimization suitable to perform parametric model checking

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IMITATOR

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  - "Inverse Method for Inferring Time AbstracT BehaviOR"
  - 10 000 lines of OCaml code
  - Makes use of the PPL library [Bagnara et al., 2008]
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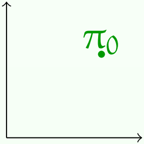

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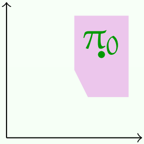

Experiments

			IM			IM_{dyn}			Comparison	
Example	$\lvert X\rvert$	$\lvert P\rvert$	$\lvert S\rvert$	$\lvert T\rvert$	t	$\lvert S\rvert$	$\lvert T\rvert$	t	$\lvert S\rvert$	t
Figure 2	2	2	-	-	loop	2	2	0.007	0	0
Figure 3	2	2	-	-	loop	6	8	0.006	0	0
AndOr	4	12	11	11	0.047	11	11	0.050	100	106
SPSMALL	10	26	31	30	0.580	31	30	0.584	100	101
Train	3	6	78	94	0.100	61	76	0.072	78	72
BRP	7	6	429	474	3.50	429	474	3.21	100	92
CSMA/CD$_6$	3	3	13,365	14,271	19.6	13,365	14,271	19.5	100	99
RCP	5	6	327	518	0.68	181	282	0.41	55	60
AAM06	3	8	1,497	1,844	8.28	768	997	2.92	51	35
AM02	3	4	182	215	0.392	182	215	0.386	100	98
BB04	6	7	806	827	25.4	806	827	27.2	100	107
CTC	15	21	1,364	1,363	83.4	201	291	2.52	15	3.0
LA02	3	5	6,290	8,023	710	4,932	7,154	473	78	67
LPPRC10	4	7	78	102	0.375	78	102	0.395	100	105

Sources: `http://www.lsv.ens-cachan.fr/Software/imitator/dynamic/`

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Conclusion

- Extension of dynamic clock elimination to parametric automata
- Preserves linear-time parametric model checking
- Often leads to state space reduction and memory reduction
- Surprisingly little noticeable overhead, even when the number of clocks remains constant
  - ⇒ Optimization could be added as default in IMITATOR

Perspectives

- Integration of further state space reduction techniques [André et al., 2013]
- Improvement of the internal representation of constraints
  - Relying on the Parma Polyhedra Library [Bagnara et al., 2008]
  - Future work: remove dimensions when eliminating clocks
- Extension to the multi-core setting [Laarman et al., 2013]

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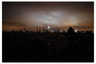
Additional explanations

Explanations 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)

Allusion to any plane crash
(Picture actually from the happy-ending US Airways Flight 1549, 2009)

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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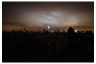

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