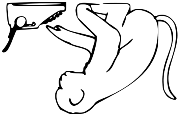
École Temps-Réel 2015
Rennes

IMITATOR Tutorial
Parametric Timed Systems



Étienne ANDRÉ

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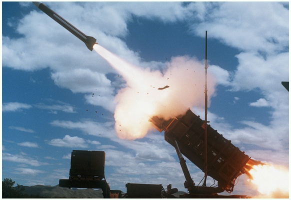
Version: August 26, 2015 (slideshow version)

Context: Verifying critical real-time systems

- Need for early bug detection
  - Bugs discovered when final testing: expensive
  - ⤳ Need for a thorough specification and verification phase



The Therac-25 radiation therapy machine (1/2)

- Radiation therapy machine used in the 1980s
- Involved in accidents between 1985 and 1987, in which patients were given massive overdoses of radiation
    - Approximately 100 times the intended dose!
    - Numerous causes, including race condition

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> *"The failure only occurred when a particular nonstandard sequence of keystrokes was entered on the VT-100 terminal which controlled the PDP-11 computer: an* `X` *to (erroneously) select 25MV photon mode followed by* ↑, `E` *to (correctly) select 25 MeV Electron mode, then* `Enter`*, all within eight seconds."*

The Therac-25 radiation therapy machine (2/2)

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Limits of testing

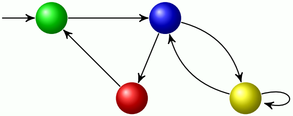
This case illustrates the difficulty of bug detection without formal methods.

Plan: Timed Automata

1. Timed Automata
2. Parametric Timed Automata
3. IMITATOR
4. Perspectives

Model checking concurrent systems

- Use formal methods [Baier and Katoen, 2008]



A model of the system

🔴 is unreachable

A property to be satisfied

Model checking concurrent systems

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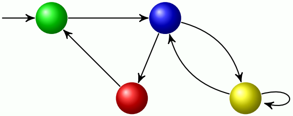

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$\overset{?}{\models}$

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

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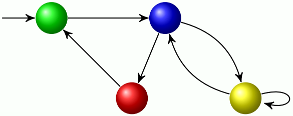

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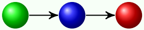
A property to be satisfied

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

Yes

No



Counterexample

Model checking concurrent systems

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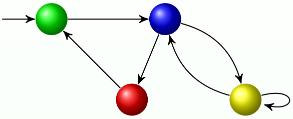

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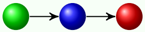
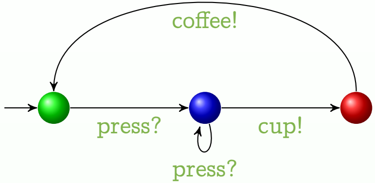


Counterexample

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

A coffee vending machine $\mathcal{A}_C$



- 🟢 Idle
- 🔵 Adding sugar
- 🔴 Delivering coffee

- Example of runs
  - Coffee with no sugar

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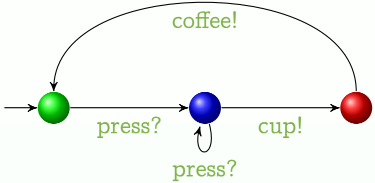

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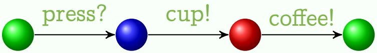

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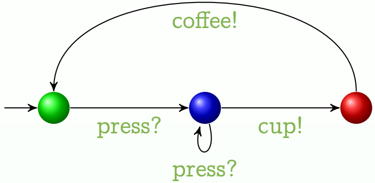

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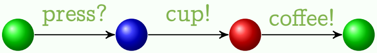

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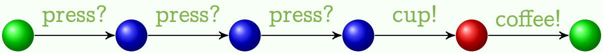

  - And so on

Verification of properties

Decide whether the following properties are satisfied for the coffee vending machine

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Beyond finite state automata

Finite State Automata: powerful formalism to model qualitative aspects of systems

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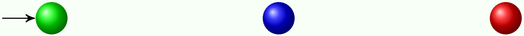
But what about quantitative aspects:

- Time ("the airbag always eventually inflates, but maybe 10 seconds after the crash")
- Temperature ("the alarm always eventually ring, but maybe when the temperature is above 75 degrees")

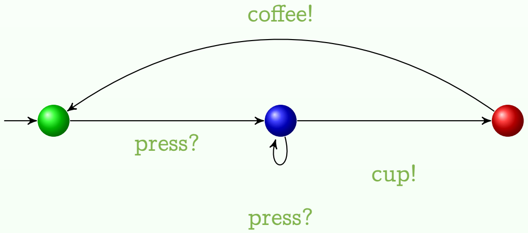
Timed automaton (TA)

- Finite state automaton (sets of locations)



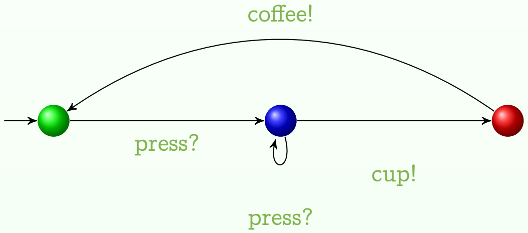
Timed automaton (TA)

- 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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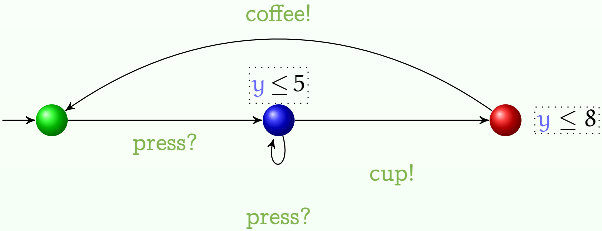

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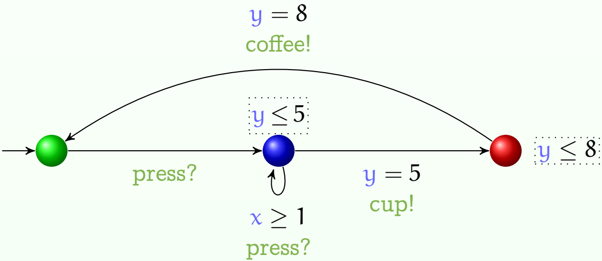

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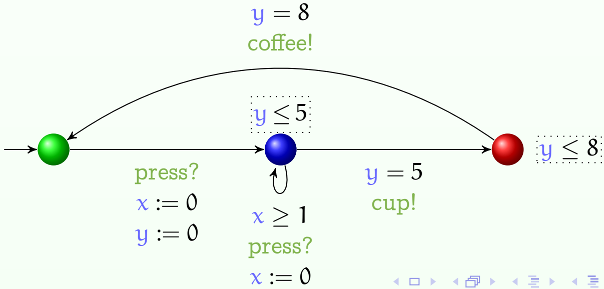
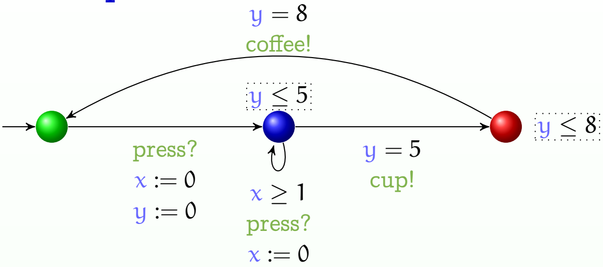
  - Location invariant: property to be verified to stay at a location
  - Transition guard: property to be verified to enable a transition
  - Clock reset: some of the clocks can be set to 0 at each transition



Concrete semantics of timed automata

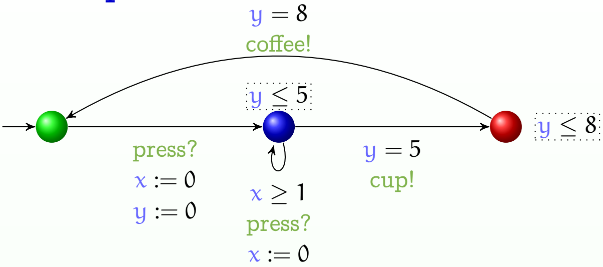
- Concrete state of a TA: pair (l, w), where
  - l is a location,
  - w is a valuation of each clock
- Concrete run: alternating sequence of concrete states and actions or elapsing of time

Examples of concrete runs



- Possible concrete runs for the coffee machine

Examples of concrete runs



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

x	0
y	0

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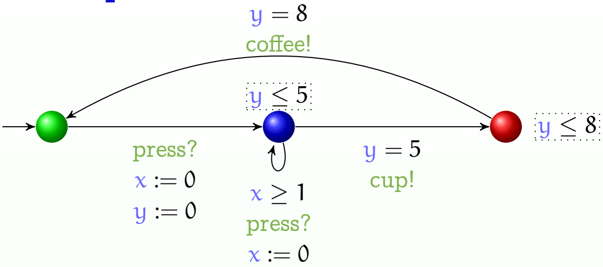

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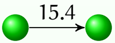
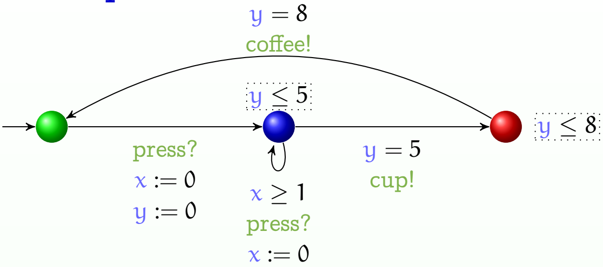


x	0	15.4
y	0	15.4

Examples of concrete runs



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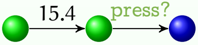

x	0	15.4	0
y	0	15.4	0

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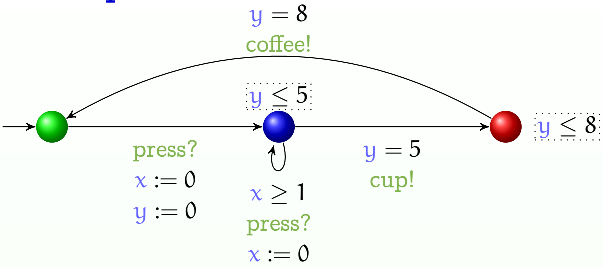

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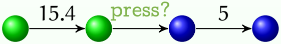
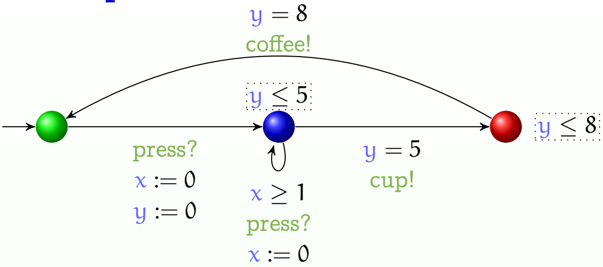


x	0	15.4	0	5
y	0	15.4	0	5

Examples of concrete runs



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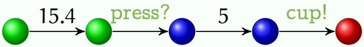

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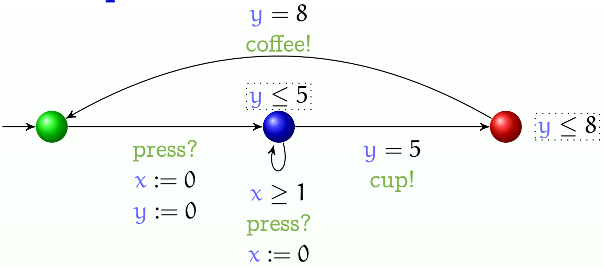

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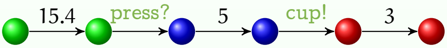

x	0	15.4	0	5	5	8
y	0	15.4	0	5	5	8

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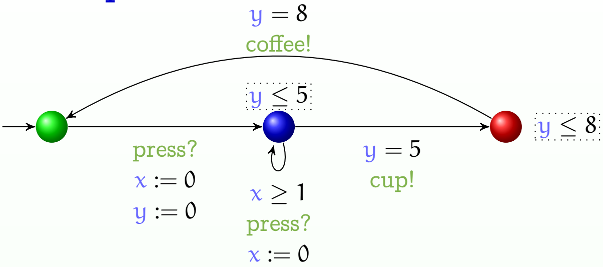

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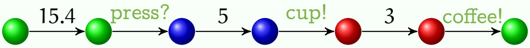

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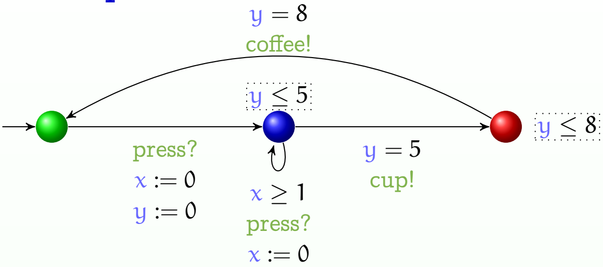

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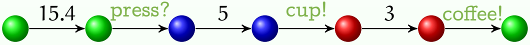

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  - Coffee with 2 doses of sugar

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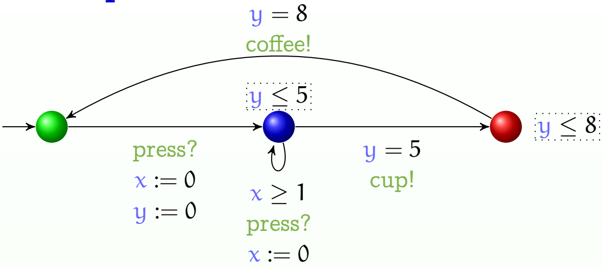

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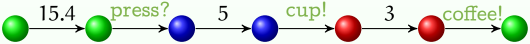

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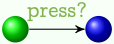

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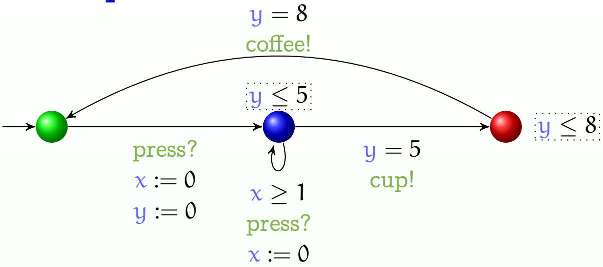

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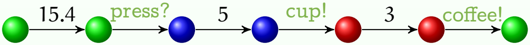

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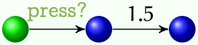
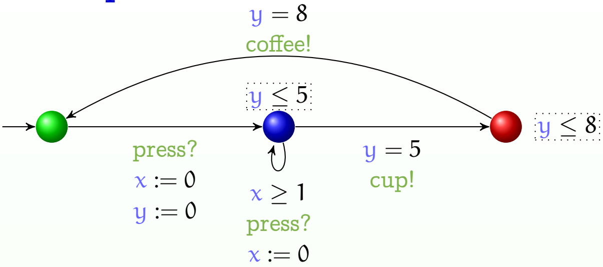


x	0	0	1.5
y	0	0	1.5

Examples of concrete runs



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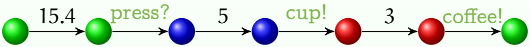

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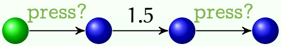

x	0	0	1.5	0
y	0	0	1.5	1.5

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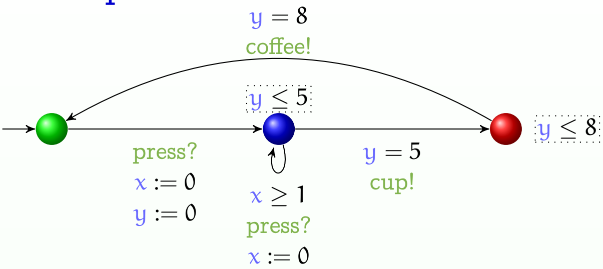

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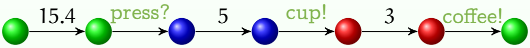

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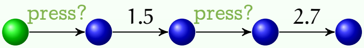

x	0	0	1.5	0	2.7
y	0	0	1.5	1.5	4.2

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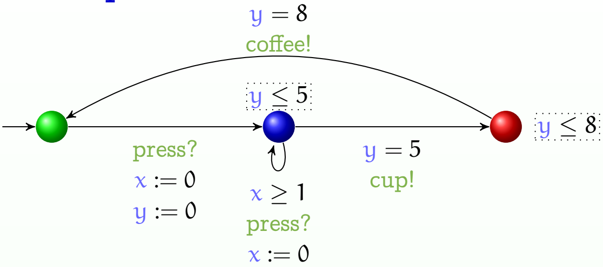

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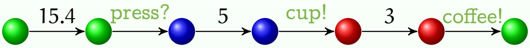
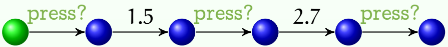


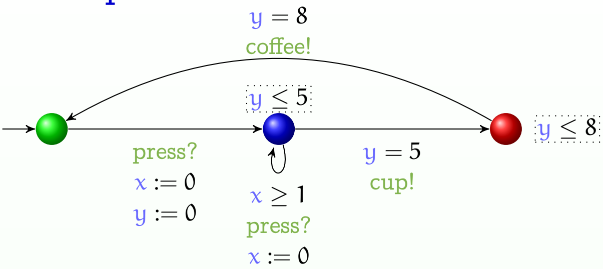
x	0	15.4	0	5	5	8	8
y	0	15.4	0	5	5	8	8

  - Coffee with 2 doses of sugar



x	0	0	1.5	0	2.7	0
y	0	0	1.5	1.5	4.2	4.2

Examples of concrete runs



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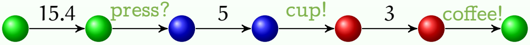

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y	0	15.4	0	5	5	8	8

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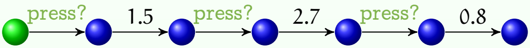
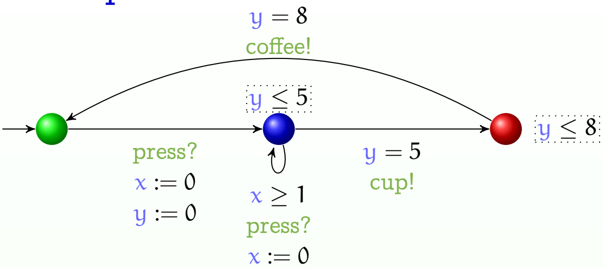


x	0	0	1.5	0	2.7	0	0.8
y	0	0	1.5	1.5	4.2	4.2	5

Examples of concrete runs



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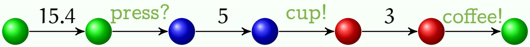

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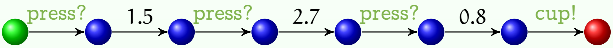

x	0	0	1.5	0	2.7	0	0.8	0.8
y	0	0	1.5	1.5	4.2	4.2	5	5

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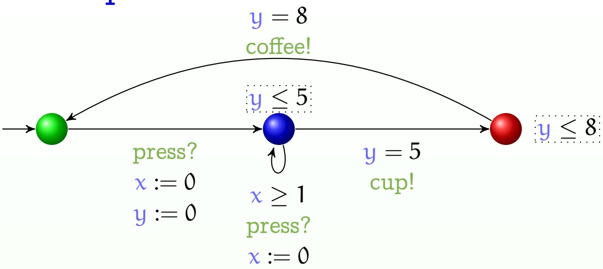

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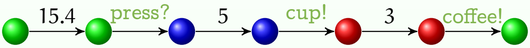

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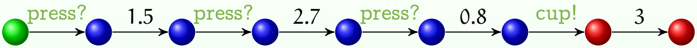

x	0	0	1.5	0	2.7	0	0.8	0.8	3.8
y	0	0	1.5	1.5	4.2	4.2	5	5	8

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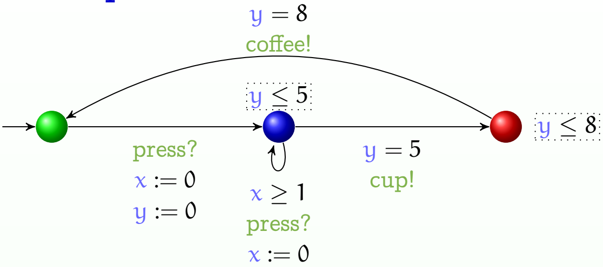

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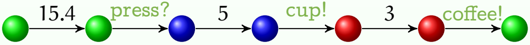

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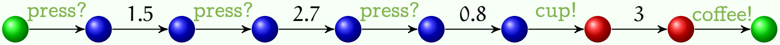

x	0	0	1.5	0	2.7	0	0.8	0.8	3.8	3.8
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Verification of (timed) properties

Decide whether the following properties are satisfied for the timed coffee vending machine

- "It is possible to get a coffee with 5 doses of sugar."

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- "Once the cup is delivered, coffee will come next within 2 seconds."

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Plan: Parametric Timed Automata

1. Timed Automata
2. Parametric Timed Automata
3. IMITATOR
4. Perspectives

Motivation

- Challenge 1: systems incompletely specified
  - Some delays may not be known yet, or may change

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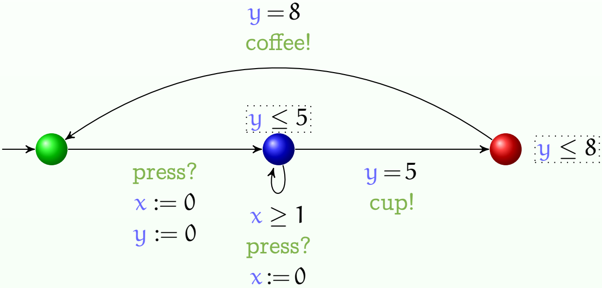
- Challenge 4: Avoidance of numerous verifications
  - If one of the timing delays of the model changes, should I model check again the whole system?
- A solution: Parametric analysis
  - Consider that timing constants are unknown (parameters)
  - Find good values for the parameters s.t. the system behaves well

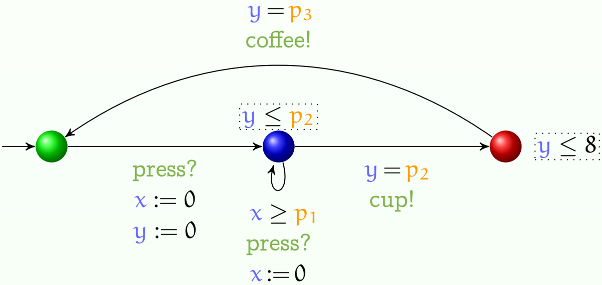
Parametric Timed Automaton (PTA)

- 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., 1993]
  - Unknown constants used in guards and invariants



Decision and computation problems for PTA

- Emptiness “Does there at least one parameter valuation for which I can get a coffee with 2 sugars?”

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  $\surd$
- Synthesis "What are all parameter valuations such that one can always eventually get a coffee?"
  $0 \leq p_2 \leq p_3 \leq 8$

Software supporting parametric timed automata

Specification and verification of parametric models using parametric timed automata are supported by several software

- HyTech (also hybrid automata) [Henzinger et al., 1997]
- PHAVer (also hybrid systems) [Frehse, 2005]
- Roméo (also parametric time Petri nets) [Lime et al., 2009]
- Imitator [A. et al, 2012]

Plan: IMITATOR

1. Timed Automata
2. Parametric Timed Automata
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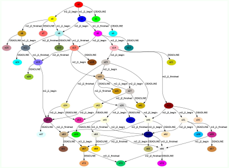
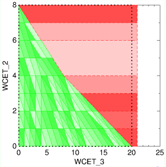
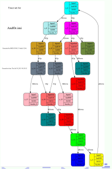
IMITATOR

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

- Verification
  - Computation of the symbolic state space
  - Parametric model checking (using a subset of TCTL)
  - Language and trace preservation, and robustness analysis
  - Behavioral cartography







IMITATOR

Under continuous development since 2008

A library of benchmarks

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

Open source: Available under the GNU-GPL license

GPL 3 Free Software

Free as in Freedom

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GPL
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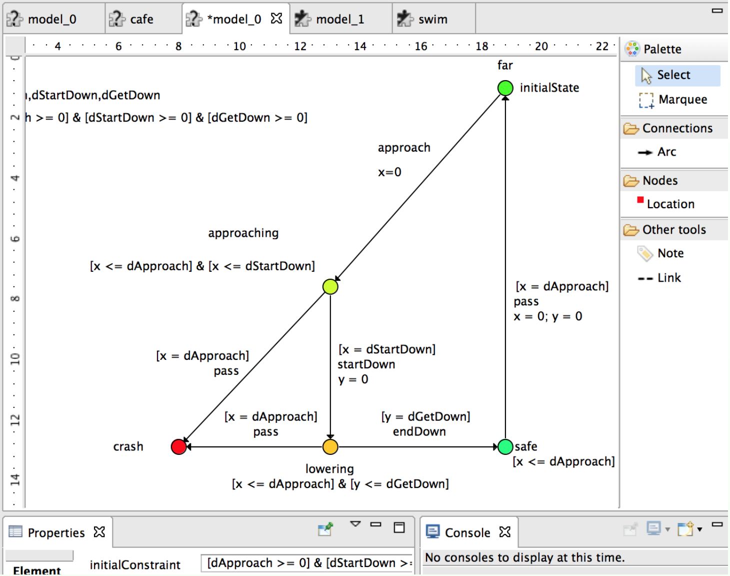
Try it!

www.imitator.fr

Some success stories

- Modeled and verified an asynchronous memory circuit by ST-Microelectronics
  - Project ANR Valmem
- 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]
- Solution to a challenge related to a distributed video processing system by Thales
- Formal timing analysis of music scores [Fanchon and Jacquemard, 2013]

Graphical user interface using *CosyVerif*



initialConstraint [dApproach >= 0] & [dStartDown >:

No consoles to display at this time.

Outline of the practical session

1. Perform parameter synthesis for a railway crossing system
2. Specify and verify the coffee machine
3. . . . and if you are fast: a free bonus exercise!

Plan: Perspectives

1. Timed Automata
2. Parametric Timed Automata
3. IMITATOR
4. Perspectives

Perspectives

- “Small detail”: all known problems for PTA are undecidable
  - No big deal: semi-algorithms, approximations, etc.
  - Challenge: find decidable subclasses
- Other parametric models
  - Number of processes (“discrete” parameters)
  - Challenge: combine different types of parameters (discrete + continuous)

General References

- Systems and Software Verification (Béatrice Bérard, Michel Bidoit, Alain Finkel, François Laroussinie, Antoine Petit, Laure Petrucci, Philippe Schnoebelen), Springer, 2001
- Principles of Model Checking (Christel Baier and Joost-Pieter Katoen), MIT Press, 2008
- The Inverse Method (Étienne André and Romain Soulat), ISTE and Wiley & Sons, 2013

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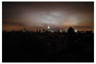
Additional explanation

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)

```
0000000F
00000003
```

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)

License

Source of the graphics (1)

Titre: Clock 256
Auteur: Everaldo Coelho
Source: `https://commons.wikimedia.org/wiki/File:Clock_256.png`
Licence: GNU LGPL

Title: Smiley green alien big eyes (aaah)
Author: LadyofHats
Source: `https://commons.wikimedia.org/wiki/File:Smiley_green_alien_big_eyes.svg`
License: public domain

Title: Smiley green alien big eyes (cry)
Author: LadyofHats
Source: `https://commons.wikimedia.org/wiki/File:Smiley_green_alien_big_eyes.svg`
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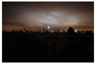
Source of the graphics (2)



Title: Hurricane Sandy Blackout New York Skyline
Author: David Shankbone
Source: `https://commons.wikimedia.org/wiki/File:Hurricane_Sandy_Blackout_New_York_Skyline.JPG`
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