Sokendai Lectures
Tokyo, Japan
物理情報システムのための形式手法

Timed model checking – Part 2

Timed automata

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Partie 2: Timed model checking – Plan

Beyond finite state automata

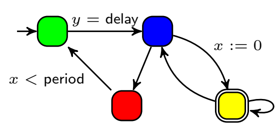
Finite State Automata give a simple syntax and a formal semantics to model **qualitative** aspects of systems

- Executions, sequence of actions
- Modular definitions (parallelism)
- Powerful checking (reachability, safety, liveness...)

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”)

Model checking timed concurrent systems



A timed model of the system

$\overset{?}{\models}$

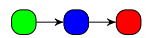
 is unreachable

A **property** to be satisfied

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

Yes

No



Counterexample

Formalisms

Many formalisms were proposed to model and verify timed systems

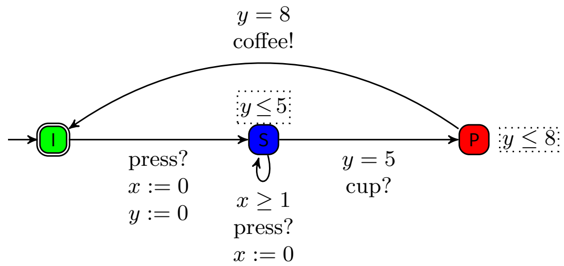
- time(d) Petri nets [Merlin, 1974]
- timed automata [Alur and Dill, 1994]
- timed process algebras [Sun et al., 2009b]
- etc.

We use here **timed automata**

See [Bérard et al., 2005, Srba, 2008, Bérard et al., 2013] for a comparison between timed Petri nets and timed automata

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
  - Can be compared to integer constants in invariants and guards
- 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 at each transition



Formal definition of timed automata

Definition (Timed automaton)

A **timed automaton (TA)** $\mathcal{A}$ is a 7-tuple of the form $\mathcal{A} = (L, \Sigma, \ell_0, L_F, X, I, E)$, where

- L is a finite set of locations,
- $\ell_0 \in L$ is the initial location,
- $L_F \subseteq L$ is the set of accepting (or final) locations,
- Σ is a finite set of actions,
- X is a set of clocks,
- I is the invariant, assigning to every $\ell \in L$ a clock constraint $I(\ell)$, and
- E is a step (or "transition") relation consisting of elements of the form $e = (\ell, g, a, R, \ell')$, also denoted by $\ell \xrightarrow{g,a,R} \ell'$, where $\ell, \ell' \in L$, $a \in \Sigma$, $R \subseteq X$ is a set of clock variables to be reset by the step, and g (the step guard) is a clock constraint.

Clock constraints

Definition (clock constraint)

A **clock constraint** is a conjunction of atomic constraints

What is an atomic constraint?

Various definitions in the literature:

- Originally [Alur and Dill, 1994]: $x \in [c_1, c_2]$ with $c_1 \in \mathbb{N}$ and $c_2 \in \mathbb{N} \cup \{\infty\}$
- Comparing clock values (**diagonal constraints**) $x_1 - x_2 \bowtie c$
  - $\bowtie \in \{<, \leq, =, \geq, >\}$

For now, we assume the following syntax:

- $x \bowtie c$, with $x \in X$ and $c \in \mathbb{N}$

Exercise 1

Draw the TA $\mathcal{A} = (L, \Sigma, l_1, \{l_2\}, X, I, E)$
such that

- $L = \{l_1, l_2, l_3, l_4\}$,
- $\Sigma = \{a_1, a_2, a_3\}$,
- $X = \{x_1, x_2\}$,
- $I(l_1) = x_1 \leq 3$, and $I(l_3) = x_2 \geq 2$,
- $E = \{(l_1, x_1 \geq 2, a_1, \{x_1\}, l_2),$
  $(l_1, x_2 \leq 1, a_2, \emptyset, l_3),$
  $(l_2, x_2 = 1, a_3, \{x_2\}, l_2),$
  $(l_2, \texttt{true}, a_1, \emptyset, l_3),$
  $(l_3, \texttt{true}, a_2, \{x_1, x_2\}, l_4),$
  $(l_4, x_2 > 2, a_3, \emptyset, l_3)\}$

Exercise 2

Give the formal TA corresponding to the timed coffee machine.

Parallel composition of timed automata (1/2)

Just as finite-state automata, timed automata can be composed through **parallel composition** using synchronization actions

$\mathcal{A}_1 = (L_1, \Sigma_1, (\ell_0)_1, (L_F)_1, X_1, I_1, E_1)$
$\mathcal{A}_2 = (L_2, \Sigma_2, (\ell_0)_2, (L_F)_2, X_2, I_2, E_2)$

Then we define $\mathcal{A}_1 \parallel \mathcal{A}_2$ as

Parallel composition of timed automata (2/2)

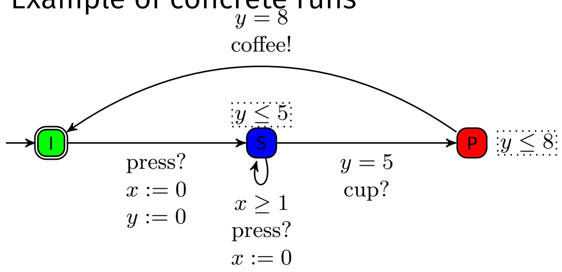
Concrete runs of timed automata

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

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

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

Example of concrete runs



- Possible concrete runs for the coffee machine
  - Coffee with no sugar
  - Coffee with 2 doses of sugar

Timed transition systems

Definition (Timed transition system)

A **timed transition system** (TTS) is a tuple $\mathcal{TTS} = (S, \Sigma, S_0, S_F, \rightarrow)$, where

- S is a set of states;
- Σ is an alphabet of events;
- $S_0 \subseteq S$ is a set of initial states;
- $S_F \subseteq S$ is a set of final (or accepting) states; and,
- $\rightarrow : S \times (\Sigma \cup \mathbb{R}_{\geq 0}) \rightarrow 2^S$ is a transition relation.

We write $s_1 \xrightarrow{a} s_2$ when $(s_1, a, s_2) \in \rightarrow$.

Concrete semantics of timed automata: definition

Definition (Concrete semantics of a TA)

Given a TA $\mathcal{A} = (\Sigma, L, \ell_0, L_F, X, I, E)$, the concrete semantics of $\mathcal{A}$ is given by the timed transition system $(S, E, S_0, S_F, \rightarrow)$, with

- $S = \{(\ell, w) \in L \times \mathbb{R}_{\geq 0}^{|X|} \mid$,
- $S_0 =$ (with $\vec{0} \models I(\ell_0)$), and
- $S_F = \{(\ell, w) \in$,
- $\rightarrow$ consists of the discrete and (continuous) delay transition relations:
  - discrete transitions: $(\ell, w) \xrightarrow{e} (\ell', w')$, if $(\ell, w), (\ell', w') \in S$, there exists $e = (\ell, g, a, R, \ell') \in E$, $w' = w[R]$, and $w \models g$.
  - delay transitions: $(\ell, w) \xrightarrow{d} (\ell, w + d)$, with $d \in \mathbb{R}_{\geq 0}$, if $\forall d' \in [0, d], (\ell, w + d') \in S$.

Notation:

$$w[R](x) = \begin{cases} & \text{if } x \in R \\ & \text{otherwise} \end{cases}$$

Concrete semantics of timed automata: definition (cont.)

We write $(\ell, w) \overset{(d,e)}{\mapsto} (\ell', w')$ or $((\ell, w), (d, e), (\ell', w')) \in \mapsto$ for a combination of a delay and discrete transitions if

$$\exists w'' : (\ell, w) \xrightarrow{d} (\ell, w'') \xrightarrow{e} (\ell', w')$$

Some remarks on the semantics of timed automata:

- Is $\mathcal{TTS}$ finite?
- Is $\mathcal{TTS}$ finitely branching?

Timed words

Definition (timed word)

A **timed word** over an alphabet of actions Σ is a possibly infinite sequence of the form $(a_0, d_0)(a_1, d_1)\cdots$ such that, for all integer $i \geq 0$, $a_i \in \Sigma$ and $d_i \leq d_{i+1}$.

Definition (timed word associated with a concrete run)

Given a concrete run ρ $(l_0, w_0)(d_0, e_0)(l_1, w_1)\cdots(d_i, e_i)(l_i, w_i)\cdots$, the **timed word associated with** ρ is

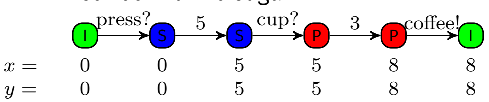
$$(\mathsf{Act}(e_0), d_0)(\mathsf{Act}(e_1),$$

Notation: $\mathsf{Act}(e_i)$ denotes the action of edge e_i

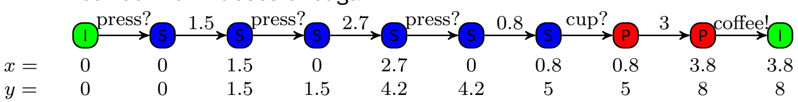
Timed words: exercise

Give the (formal) run and the associated timed words associated with the two example runs of the coffee machine:

- Coffee with no sugar



- Coffee with 2 doses of sugar



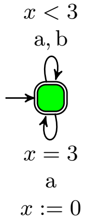
Timed language

Definition (timed language)

Given a TA $\mathcal{A}$, the **timed language** of $\mathcal{A}$ is the set of timed words associated with the runs of $\mathcal{A}$ ending in a location

Timed language: Example 1

Give the timed language of the following automaton [Alur and Dill, 1994]



Timed language: Example 2

Give the timed language of the following automaton

Timed language: Example 3

Give the timed language of the coffee machine

Accepting locations?

Timed automata may or may not be equipped with accepting locations

Often, timed automata with no accepting locations are called **timed safety automata** [Henzinger et al., 1994]

In that case the timed language can be defined as:

- All possible timed words read by the automaton
- All possible maximal timed words read by the automaton
  - Maximal: infinite or that cannot be extended
- All possible infinite timed words read by the automaton

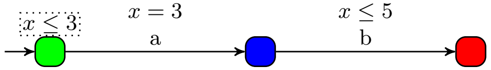
Theorem

The expressive power of timed safety automata is strictly less than timed automata with accepting locations [Henzinger et al., 1995]

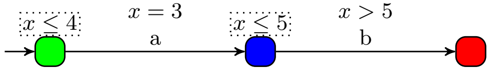
Deadlocks and timelocks

Timed automata can be subject to two annoying behaviors:

- **Deadlock**: similar to finite state automata
  - Can be a problem of



- **Timelock**: coming from the timed nature of TAs
  - Can



The Zeno problem (1/2)

Definition (Zeno run)

A run is Zeno if it contains an **infinite** number of actions in **finite** time.

- Example of TA containing at least one Zeno run

- Example of TA containing only non-Zeno runs

The Zeno problem (2/2)

Problem (Zeno runs)

An infinite number of actions in finite time is **impossible in practice**

- *Processors have finite precision*

Zeno runs must be **pruned** *when performing model checking*

Some solutions:

- Transform the TA (with an additional clock) [Tripakis, 1999, Tripakis et al., 2005, Bowman and Gómez, 2006, Gómez and Bowman, 2007]
- Transform the zone graph [Herbreteau et al., 2012]
- Consider a different but closely related formalism [Sun et al., 2013]
- Transform the TA on-the-fly [Wang et al., 2015]

Example: Railroad gate controller [Alur et al., 1993b]

Design three timed automata in parallel:

1. The **train**: once it is approaching (action $\mathrm{approach}$), it will come in (action in) after at least 5 time units, then go out (action out) and finally exit (action exit) after at most 6 time units
2. The **gate**: upon reception of a lower signal, starts to lower; once it is down, and upon reception of a raise signal, the gate raises again; the time to lower and to raise the gate is an interval $[1, 3]$
3. The **controller**: once a train approaches (action $\mathrm{approach}$), it triggers the lower signal within $[2, 3]$ time units; then, once the train exits (action exit), it triggers the raise signal again within $[2, 4]$ time units

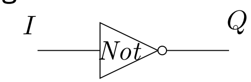
All TAs are cyclic, i. e., repeat the same behavior forever.

Example: Railroad gate controller (train)

Example: Railroad gate controller (gate)

Example: Railroad gate controller (controller)

Example: A hardware gate



The output Q reacts to the change of the input I (actions $I^{\uparrow}$ and $I^{\downarrow}$) after a delay $[5, 9]$

[Chevallier et al., 2009]

Example: A nuclear power plant

Design a PTA modeling a nuclear power plant:

- At first, the plant is in normal mode.
- Suddenly, it may start to heat (action $\mathrm{startHeating}$).
- At that point, a timer is set; after p_2 time units, the timer will trigger an alarm (action alarm).
- Then, p_3 time units later, a watering system (action $\mathrm{watering}$) starts.
- This watering system lasts for at most p_4 time units, after which the plant is cool again (action cool) and goes back to the normal mode.
- However, p_1 time units after the plant starts to heat, the plant may explode at any time (action boom)—unless of course it is cool again.

Example: A nuclear power plant (solution)

Example: A real-time system

Design a (network of) timed automata modeling the following components:

1. a periodic task T_1 of period 5 with offset 2, best and worst case execution times in $[3, 4]$
2. a sporadic task T_2 of minimum interarrival time 20, best and worst case execution times in $[1, 2]$
3. a non-preemptive scheduler with fixed priority

Example: A real-time system (solution)

Timed temporal logics

- Specify properties on the order **and the delays** between events
- No X operator because

TCTL (Timed CTL) [Alur et al., 1993a]

TCTL expresses formulas on the **order** and the **time** between the **future** events **for some or for all paths**, using a set of atomic propositions AP

- **Timed** extension of CTL

Quantifiers over paths:

$$\varphi ::= p \in AP \mid \neg p \mid \varphi \vee \varphi \mid \varphi \wedge \varphi \mid \mathsf{E}\psi \mid \mathsf{A}\psi$$

Quantifiers over states:

$$\psi ::= \varphi \mathsf{U}_I \varphi$$

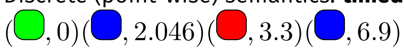
I is an interval of the form $[a,b]$, $[a,b)$, $(a,b]$, (a,b), $[a,\infty)$, or (a,∞), where $a,b \in \mathbb{N}$

Semantics of TCTL: discrete vs. continuous

Two semantics:

- Continuous semantics: **signals**

- Discrete (point-wise) semantics: **timed words**



Are they equivalent?

Continuous semantics of TCTL

$s \models p$	iff	p holds at the current position
$s \models \neg p$	iff	p does not hold at the current position
$s \models \varphi \wedge \psi$	iff	$s \models \varphi \wedge s \models \psi$
$s \models \varphi \vee \psi$	iff	$s \models \varphi \vee s \models \psi$
$s \models \mathsf{E}\psi \mathsf{U}_I \varphi$	iff	there exists a future path and $t \in I$ for which ψ holds until t and φ holds at t
$s \models \mathsf{A}\psi \mathsf{U}_I \varphi$	iff	for all future paths, there exists $t \in I$ for which ψ holds until t and φ holds at t

Illustrating TCTL operators

Discrete semantics of TCTL [Bouyer et al., 2017]

Informal description of the U (the rest is similar):

$s \models \mathsf{E}\psi\mathsf{U}_I\varphi$ iff there exists $n > 0$ such that φ holds from point n (with the time of point n within I) and for each $0 < m < n$, ψ holds at point m

Note: strict version of the U, considered in [Bouyer et al., 2017] (not necessarily standard)

Semantics of TCTL: discrete vs. continuous (example)

Exhibit a word and a TCTL formula for which:

1. the formula holds under the continuous but not the discrete semantics
2. the formula holds under the discrete but not the continuous semantics

An example TA:

A concrete run ω (continuous semantics):

Equivalent run ρ in the discrete semantics:

TCTL: Examples

- "Whatever happens, the plane will never crash in the next 10 minutes"
- "I may get a job within one year"
- "I am sure to get a job within one year"
- "Whenever a fire breaks, it is sure that the alarm will start ringing at least 5 seconds and at most 10 seconds later"
- "Whatever happens, I will love you for 2 years after we marry"

TCTL: Examples (coffee machine)

- "Whenever the button is pressed, a coffee is necessarily eventually delivered within 10 units of time."
- "It must never happen that the button can be pressed twice within 1 unit of time."
- "It must never happen that the button can be pressed twice within a time strictly less than 1 unit of time."

Other timed temporal logics

- MTL: linear time [Koymans, 1990]
  - Can be seen as a **timed extension of LTL** (just as TCTL is a timed extension of CTL)
  - Variant: MITL [Alur et al., 1996]
    - Variant of MTL disallowing punctuality
- STL: to reason about **signals** [Maler and Nickovic, 2004]
- etc.

See, e. g., [Bouyer et al., 2017] for a partial survey

Observers for timed automata

Observers (both untimed and timed) can be used for timed automata

Just as for FA:

- A TA observer is an automaton that **observes** the system behavior
- It synchronizes with other automata's actions
- It can **read** the clocks of the system, and/or feature its own clock(s)
- It must be non-blocking
  - Pay attention to timelocks or deadlocks!
- Its location(s) give an indication on the system property

Then verifying the property reduces to a reachability condition on the observer (in parallel with the system)

The expressive power of observers for timed automata has been studied in [Aceto et al., 1998, Aceto et al., 2003]

Exercise: An observer for the coffee machine

Design an observer for the coffee machine verifying that it must never happen that the button can be pressed twice within a time strictly less than 1 unit of time.

What is decidability?

Definition

A decision problem is **decidable** if one can design an algorithm that, for any input of the problem, can answer yes or no (in a finite time, with a finite memory).

“given three integers, is one of them the product of the other two?”

“given a context-free grammar, does it generate all strings?”

“given a Turing machine, will it eventually halt?”

“given a timed automaton, does there exist a run from the initial state to a given location ℓ?”

Why studying decidability?

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

However, one can:

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

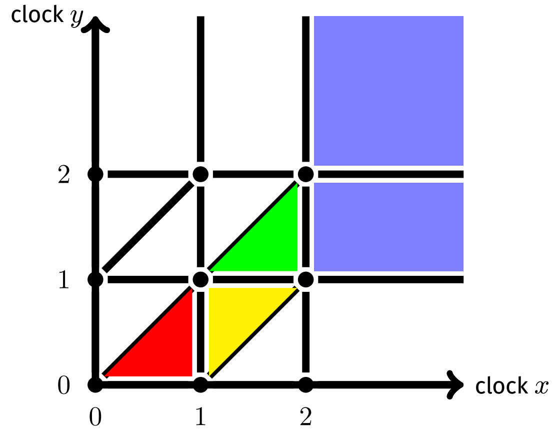
Problem: an infinite concrete semantics

- Time is **dense**: transitions can be taken anytime
  - **Infinite** number of timed runs
  - **Infinite** number of states
  - **Infinitely** branching structure
  - Model checking needs a **finite** structure!

Dense time

- A first remark: Some runs are **equivalent**
  - Taking the $\mathrm{press?}$ action at $t = 1.5$ or $t = 1.57$ is equivalent w.r.t. the possible actions
- Idea: reason with abstractions
  - **Region automaton** [Alur and Dill, 1994], and **zone automaton**
  - Example: in location , all clock values in the following zone are equivalent
    $$y \leq 5 \land y - x \geq 4$$
  - This abstraction is **finite**

Regions



Inspired by a similar LaTeX illustration by Patricia Bouyer

Region graph construction

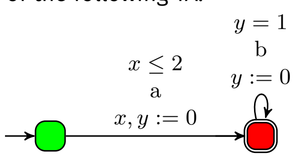
Two successors:

- time-elapsing
- clock reset

(see white board for the graph construction)

Region graph construction: exercise

Construct the region graph of the following TA:



On the region graph finiteness

Is the region graph of TAs finite?

- Example with two clocks x, y:

Solution: k-extrapolation

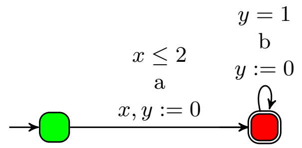
- Idea: "all integer (resp. rational) clock valuations above the greatest constant k of the TA are equivalent" [Alur and Dill, 1994]

With this additional technicality, there is a **finite number** of regions in a TA

Extrapolation: illustration

Extrapolation: exercise

Construct the region graph (with the k-extrapolation) of the following TA:



Zone construction for timed automata

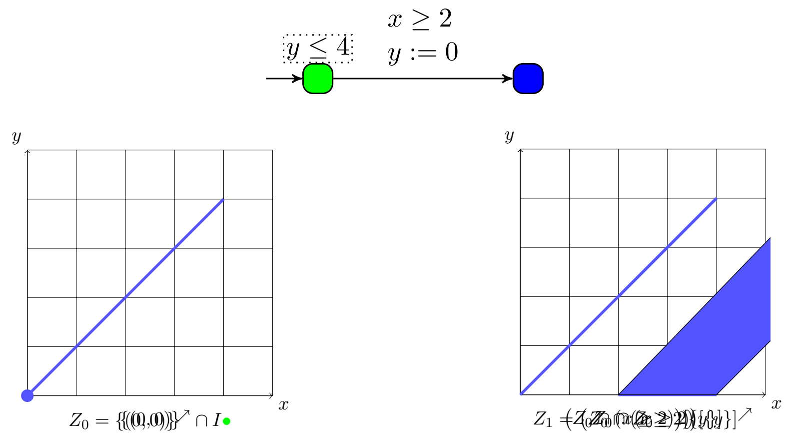
- **Objective**: group all concrete states reachable by the same sequence of discrete actions
- **Symbolic state**: a location ℓ and a (infinite) set of states Z
- For timed automata, Z can be represented by a **convex polyhedron** with a special form called **zone**, with constraints

$$-d_{0i} \leq x_i \leq d_{i0} \text{ and } x_i - x_j \leq d_{ij}$$

- Computation of successive reachable symbolic states can be performed **symbolically** with polyhedral operations: for edge $e = (\ell, a, g, R, \ell')$:

$$\mathsf{Succ}\big((\ell, Z), e\big) = \Big(\ell', \big((Z \cap g)[R] \cap I(\ell')\big)^{\nearrow} \cap I(\ell')\Big)$$

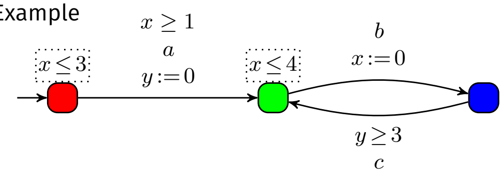
Zone construction for timed automata: Example



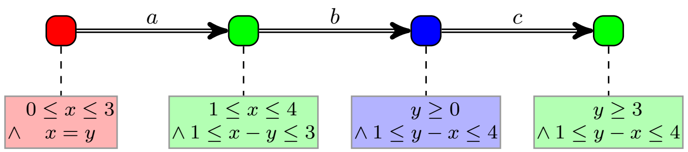
TikZ animation based on a LaTeX code by Didier Lime

Zone graph of timed automata

- **Abstract state** of a TA: pair (ℓ, C), where
  - ℓ is a location, and C is a constraint on the clocks ("**zone**")
- **Abstract run**: alternating sequence of **abstract states** and actions
- Example



  - Possible abstract run from the zone graph of this TA



On the zone graph finiteness

Is the zone graph of TAs finite?

- Example:

Solution: k-extrapolation

- Idea: "all clock valuations above the greatest constant k of the TA are equivalent" [Bengtsson and Yi, 2003]
- Can we do more efficient?
  - L/U-abstractions [Behrmann et al., 2006]
  - Lazy abstractions [Herbreteau et al., 2013]

With this additional technicality, there is a **finite number** of reachable zones in a TA

More on zones

- Symbolic states can be efficiently computed using Difference Bound Matrices (**DBM**s)
- $isReachable$ can be applied to the abstract semantics of timed automata (the underlying finite transition system)
- The zone graph is theoretically larger than the region graph but practically smaller
  - **On-the-fly** construction
  - Various **optimization** techniques

Decision problems for timed automata

The finiteness of the region automaton allows us to check properties

☺ **Reachability** of a location (PSPACE-complete) [Alur and Dill, 1994]

☺ **Liveness** (Büchi conditions)

☺ **TCTL** model-checking [Alur and Dill, 1994]

Some problems impossible to check using the zone graph (but still decidable)

☺ **non-Zenoness** emptiness check [Gómez and Bowman, 2007]

Some undecidable problems

☹ **universality** of the timed language [Alur and Dill, 1994]

☹ timed **language inclusion** [Alur and Dill, 1994]

- Some decidable subclasses
  [Alur and Dill, 1994, Ouaknine and Worrell, 2003, Ouaknine and Worrell, 2004]
  [Abdulla et al., 2008, Bertrand et al., 2011]

Syntactic variants of timed automata

Variants of the syntax with consequences on the decidability

- Can we use **diagonal** constraints (“$x - y$”)? [Bouyer, 2003]
- Can we **reset** clocks to constants $\neq 0$? [Bouyer et al., 2004]
- Can we reset clocks to other clocks? [Bouyer et al., 2004]
- Can we reset clocks to unknown constants? [André et al., 2019]
- Can we **stop** the elapsing of some clocks? [Cassez and Larsen, 2000]

Further challenges

- Controller synthesis [Sankur et al., 2013, Bacci et al., 2018]
  - **Game theory**
- Timed language inclusion (using TA as a **specification language**)
  - Decidable subclasses [Ouaknine and Worrell, 2003, Ouaknine and Worrell, 2004]
  - Practical algorithms [Wang et al., 2017]
- Robustness [De Wulf et al., 2004, Bouyer et al., 2013, Bacci et al., 2018]
- Distributed algorithms [Laarman et al., 2013, Zhang et al., 2016]

Still a very **active research field**!

Software supporting timed automata

Timed automata have been successfully used since the 1990s

Tools for modeling and verifying models specified using TA

- HyTech (also hybrid, parametric timed automata) [Henzinger et al., 1997]
- Kronos [Yovine, 1997]
- TReX (also parametric timed automata) [Annichini et al., 2001]
- **Uppaal** [Larsen et al., 1997]
- **Roméo** (parametric time Petri nets) [Lime et al., 2009]
- **PAT** (also other formalisms) [Sun et al., 2009a]
- **IMITATOR** (also parametric timed automata) [André et al., 2012]

Some case studies and application domains

- Scheduling and **real-time systems**
  [Fehnker, 1999, Abdeddaïm and Maler, 2001, Adbeddaïm et al., 2006, Abdeddaïm and Masson, 2012]
- **Protocols**
  - Bounded retransmission protocol [D'Argenio et al., 1997]
  - Audio-video protocol [Havelund et al., 1997]
  - Fast Reservation Protocol [Tripakis and Yovine, 1998]
  - IEEE 1394a root contention protocol [Simons and Stoelinga, 2001]
- **Hardware** circuits
  [Bozga et al., 2002, Chevallier et al., 2009]
- **Health** and biology [Schivo et al., 2014]
- **Monitoring** [Waga et al., 2016, Waga et al., 2018]
- Survey on the industrial use of Uppaal [Larsen et al., 2018]

What's beyond timed automata...?

- Stopping clocks: **stopwatch automata** [Cassez and Larsen, 2000]
  - ☹ Undecidable
  - ☺ Interesting application domains
- Adding costs: **energy** [Behrmann et al., 2001, Alur et al., 2004]
- Enriching TA with **tasks** [Fersman et al., 2007]
- Adding unknown parameters [Alur et al., 1993b]
- Allowing non-linear clocks: **hybrid** automata [Henzinger, 1996, Asarin et al., 2012]
- Adding **probabilities** [Kwiatkowska et al., 2002]
  - Statistical model checking [Legay et al., 2010]

Towards a parametrization...

- Challenge 1: **systems incompletely specified**
  - Some delays may not be known yet, or may change
- Challenge 2: **Robustness** [Markey, 2011]
  - What happens if 8 is implemented with 7.99?
  - Can I **really** get a coffee with 5 doses of sugar?
- Challenge 3: **Optimization of timing constants**
  - Up to which value of the delay between two actions $\mathrm{press?}$ can I still order a coffee with 3 doses of sugar?
- Challenge 4: **Avoiding 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

Source and references

General references

- **Timed Automata: Semantics, Algorithms and Tools** [Bengtsson and Yi, 2003]
- **Systems and Software Verification** [Bérard et al., 2001]
- **Principles of Model Checking** [Baier and Katoen, 2008]
- **Timed temporal logics** [Bouyer et al., 2017]

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