Non-Simultaneity as a Design Constraint

TIME 2020

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Motivations

Invalid resource sharing between CPU cores is problematic:

- security issues (*e.g.* unexpected reads);
- safety issues (*e.g.* memory corruption).

Widespread solution: **critical sections** from non-temporized programming models (*e.g.* mutual exclusion).

- Lack of safety properties (*e.g.* possible deadlocks).
- Dynamic behavior (*e.g.* suboptimal predictability and determinism).
- Fine for most applications.

Motivations (cont.)

Safety-critical systems (*e.g.* airborne navigation):

- strong safety requirements (defects have consequences);
- strip dynamic behaviors (improve predictability and determinism);
- may require worst-case *timing analysis* (real-time);
- starting to use multi-cores instead of mono-cores.

Goal: **enable off-line design of temporized critical sections.**

- Fully static approach requiring no preliminary execution ("good by design").
- Suitable for safety-critical systems with "hard" timing requirements.

Overview

Motivations

System Model
- A temporized model of computation
- Simultaneity in a model of computation

Validating the simultaneity constraints
- Formalization of the problem
- Determination of dates of reachability
- Intersection of dates

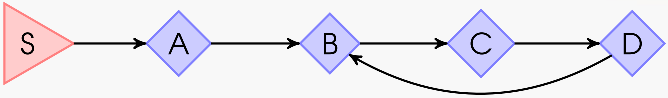
Conclusions and perspectives

Overview

Time-Constrained Automata (TCA)

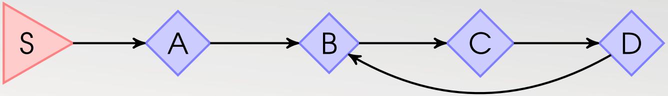
Sequences of computations are encompassed between **temporal constraints**:

- ▷ (*after*): earliest start date;
- ◁ (*before*): deadline;
- ◇ (*synchronization*): a deadline defining an earliest start date.

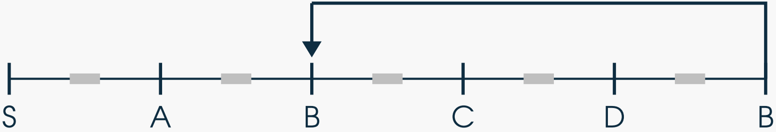


- Nodes denote the temporal constraints.
- Arcs represent the computations that execute between two temporal constraints.

Time-Constrained Automata (TCA) (cont.)



- **Scheduling schemes** can be derived from TCAs.
- Enable concrete execution from a temporal specification.



Original work by Lemerre et al. (2010).

Overview

A Definition of Simultaneity

New semantics added to TCAs: **simultaneity**.

- Applied to windows of computations that execute within a **known and bounded time span** (delimited by synchronous events).
- Two windows of computations are *simultaneous* if their execution *may* **overlap in time**.

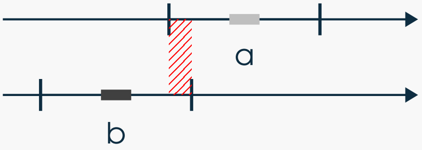


Figure: Execution with simultaneity

System Model

Clear distinction between:

- **model of computation**: embodies the design space (based on TCA); and
- **model of execution**: embodies the run-time of the designed application.

Existing work aim at enforcing **non-simultaneity** as a constraint of the **model of execution** (*i.e.* when generating scheduling schemes).

- Adds another constraint to *schedulability analysis*.
- Difficult fallback when no feasible solution are found.

System Model (cont.)

Our approach to verify **non-simultaneity** properties is based on the **model of computation**.

- Disentangle *non-simultaneity analysis* from *schedulability analysis*.
- Both problems can be solved independently.
- Clear separation between *temporal design* and *execution times* of computations.

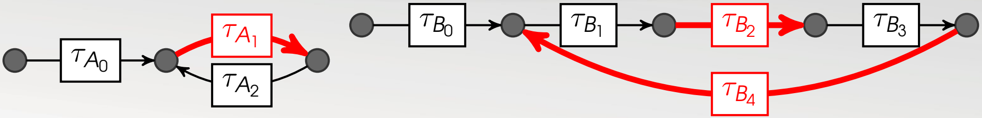
System Model (cont.)

System Model:

- **Time-Constrained Application**: fixed set of (a subset of) TCAs that share a same unique base clock.
- **Synchrony**: clock ticks occur simultaneously on all TCAs.
- **Exclusion groups**: fixed set of *temporal transitions* (*i.e.* named arcs) that shall not overlap in time.
- **Isochrony**: all TCA can be re-written to exhibit arcs of the same length.

Non-simultaneity is ensured by the *safety property* that, for each exclusion group of a time-constrained application, their temporal transitions **never** overlap in time.

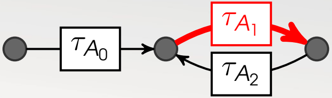
Example 1 - Simple



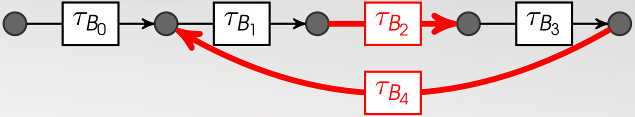
TCA A TCA B

One exclusion group: $\{\tau_{A_1}, \tau_{B_2}, \tau_{B_4}\}$.

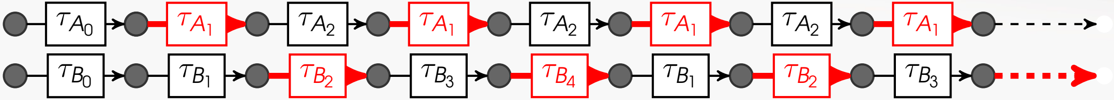
Example 1 - Simple



TCA A



TCA B

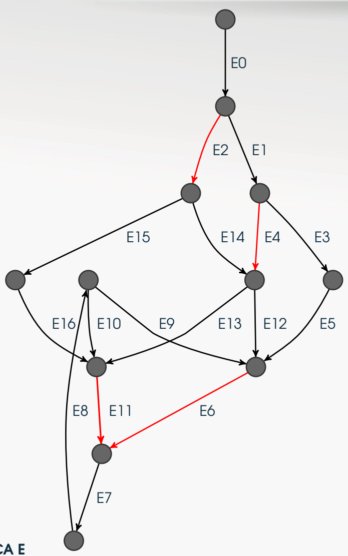


Superposition of "unfolded" graphs of TCAs A and B

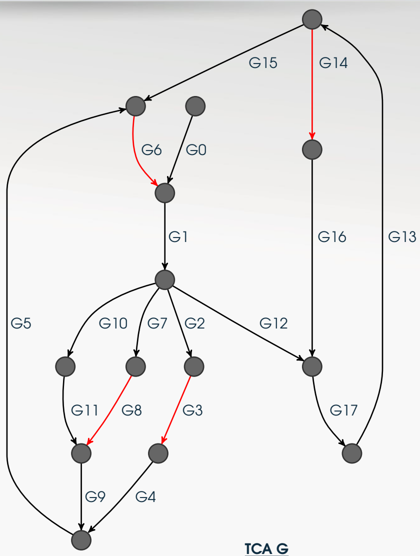
One exclusion group: $\{\tau_{A_1}, \tau_{B_2}, \tau_{B_4}\}$.

Hints that the non-simultaneity property holds. **Can we be sure?**

Example 2 - Is it a non-simultaneous system?



TCA E



TCA G

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Formalization of the problem

Goal: **determine dates of reachability for every temporal transition.**

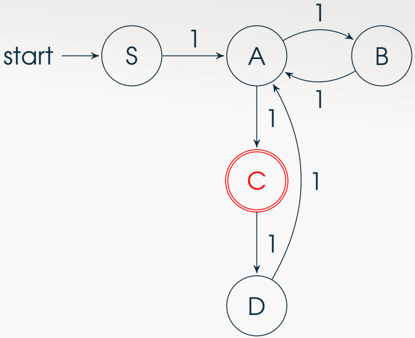

Figure: Finite automaton formalizing the set of dates at which state C is reachable.

Formalization of the problem (cont.)

Goal: **determine dates of reachability for every temporal transition.**

An isochronous TCA can be understood as a **finite automaton**, where:

- each state (but the initial one) can be marked as **accepting**;
- the increment of time, associated to every arc, can be seen as the **symbol of a unary alphabet**;
- the set of dates at which a state can be reached is given by **the length of the words that lead to this state**.

The set of dates at which a **state** can be reached is expressed as the **regular language over a unary alphabet** accepted by the automaton where only this state is marked as accepting.

Formalization of the problem (cont.)

Goal: **determine dates of reachability for every temporal transition.**

Each regular **unary language** can be represented as the union of a finite number of arithmetic progressions of the form $\{c + dk | k \in \mathbb{N}\}$, where:

- $c \in \mathbb{N}$ is the offset;
- $d \in \mathbb{N}$ is the period.

These are the sets of **word lengths**, and therefore are **dates**.

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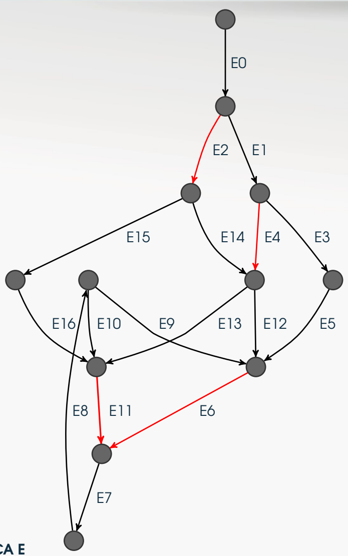
Determination of dates of reachability

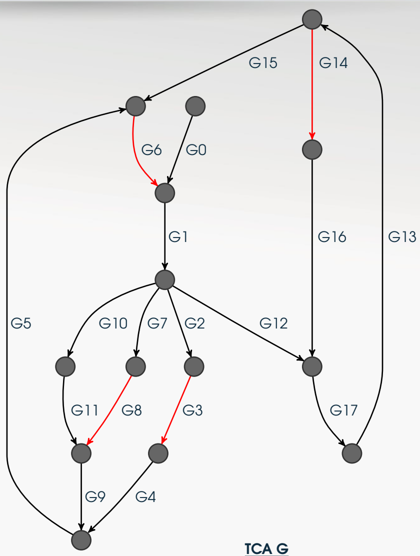
- Original algorithm designed by Sawa (2013).
  - Used to determine the dates at which **one state** reachable.
  - Time complexity (for one automaton): $O(n^2(n+m))$.
  - **As-is**, yields a total time complexity in $O(n^3(n+m))$.
- Algorithm has been tailored to preserve the original complexity when processing $n-1$ times the same "core" automaton where only the single accepting state changes.

Overview

Reminder - find overlapping arcs



TCA E



TCA G

Intersection of dates

An empty intersection of dates implies the non-simultaneity property holds.
With:

- G: exclusion group (set of temporal transitions).
- $\mathscr{D}_\tau$: dates at which τ is activated (set of arithmetic progressions).

Solving **linear diophantine** equation $\alpha x + \beta y = \gamma$.

- $(\alpha, \beta, \gamma) \in \mathbb{N}^3$ given by the values of arithmetic transitions.
- Solution in $\mathbb{Z}^2$ iff. $\mathrm{gcd}(\alpha, \beta) \mid \gamma$.
- We are interested in solutions in $\mathbb{N}^2$ (dates).
- *Here*, if we have solutions in $\mathbb{Z}^2$, there also exist infinite solutions in $\mathbb{N}^2$.

Intersection of dates (cont.)

For each pair of temporal transitions in G, if there are **no** solution to the **linear diophantine equation**, then the intersection of dates is **empty**.

- Arcs originating from a state are reachable at this set of dates.
- Intersection of dates is empty $\Longrightarrow$ non-simultaneity within G $\square$

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KRONO-SAFE Safe design in real-time

Overview

Conclusions

- **Model of computation** based on TCA to express **non-simultaneity** as a **design constraint**.
- Express a **safety property** over parallel systems, ensuring that litigious sequences of computations can **never run simultaneously**.
- **Robust**, standalone verification technique based on a formalization of reachable dates.

Help build systems with non-simultaneity as a design constraint, enabling safe resources sharing from the ground up.

- Perspectives: help in the identification of critical transitions.

Safe design in real-time

Non-Simultaneity as a Design Constraint

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Intersection of dates

Let $D_a = \{c_a + d_a k | k \in \mathbb{N}\}$ and $D_b = \{c_b + d_b k | k \in \mathbb{N}\}$ for set of dates for temporal transitions a and b in G. $D_a \cap D_b = \emptyset$ iff. the **linear diophantine** equation $\alpha x + \beta y = \gamma$ has a solution, with:

- $(x, y) \in \mathbb{Z}^2$;
- $\alpha = d_a$;
- $\beta = -d_b$;
- $\gamma = c_b - c_a$.

Intersection of dates (cont.)

Solution in $\mathbb{Z}^2$ iff. $\gcd(\alpha, \beta) \mid \gamma$.

- D_a and D_b have in common an infinite set of dates, since for any solution (x_0, y_0) the set of solutions $\{(x_0 + d_b k, y_0 + d_a k) | k \in \mathbb{Z}\}$ can always be built.
- This set of solutions in $\mathbb{Z}^2$ contains an infinite number of pairs where both members are in $\mathbb{N}^2$.

This general form has simplifications when one (or both) set of dates are singletons.

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