Synchronous Closing of Timed SDL Systems for Model Checking

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Model checking

- pro: automatic ("push-button") verification method

$$p \models \varphi$$

- con:
  - state-space explosion
  - how to obtain the model from a piece of software?
- additional techniques:
  1. abstraction:
     (a) data abstraction: replace concrete domains by finite, abstract ones
     (b) control abstraction, i.e., add non-determinism
  2. system decomposition

Model checking in theory (and practice)

- in theory
  1. cut out a sub-component
  2. model its environment abstractly, i.e.,

  $\Rightarrow$ add an environment *process* which
     - closes the sub-component
     - shows more behavior than the real environment

     $\Rightarrow$ *in extremis:* add chaos-process
  3. push the button . . .
- in practice
  - components and interfaces might be large
  - closing is tedious
  - model checkers don't often work with abstract data

Specification Description Language (SDL)

- standardized (in various versions)
- standard spec. language for telecom applications
- characteristics:
  - control structure: communicating finite-state machines
  - communication: asynchronous message passing
  - data: various basic and composed types
  - timers and time-outs
  - bells and whistles: graphical notation, structuring mechanisms, OO, . . .

Model checking open SDL systems

- three more specific problems
  1. infinite data domains
  2. asynchronous input queues: $\Rightarrow$ state explosion
  3. chaotic timer behavior
- three specific solutions
  1. one-valued data abstraction $\hat{=}$ no external data
  2. three-valued timer abstraction
  3. no asynchronous communication with environment

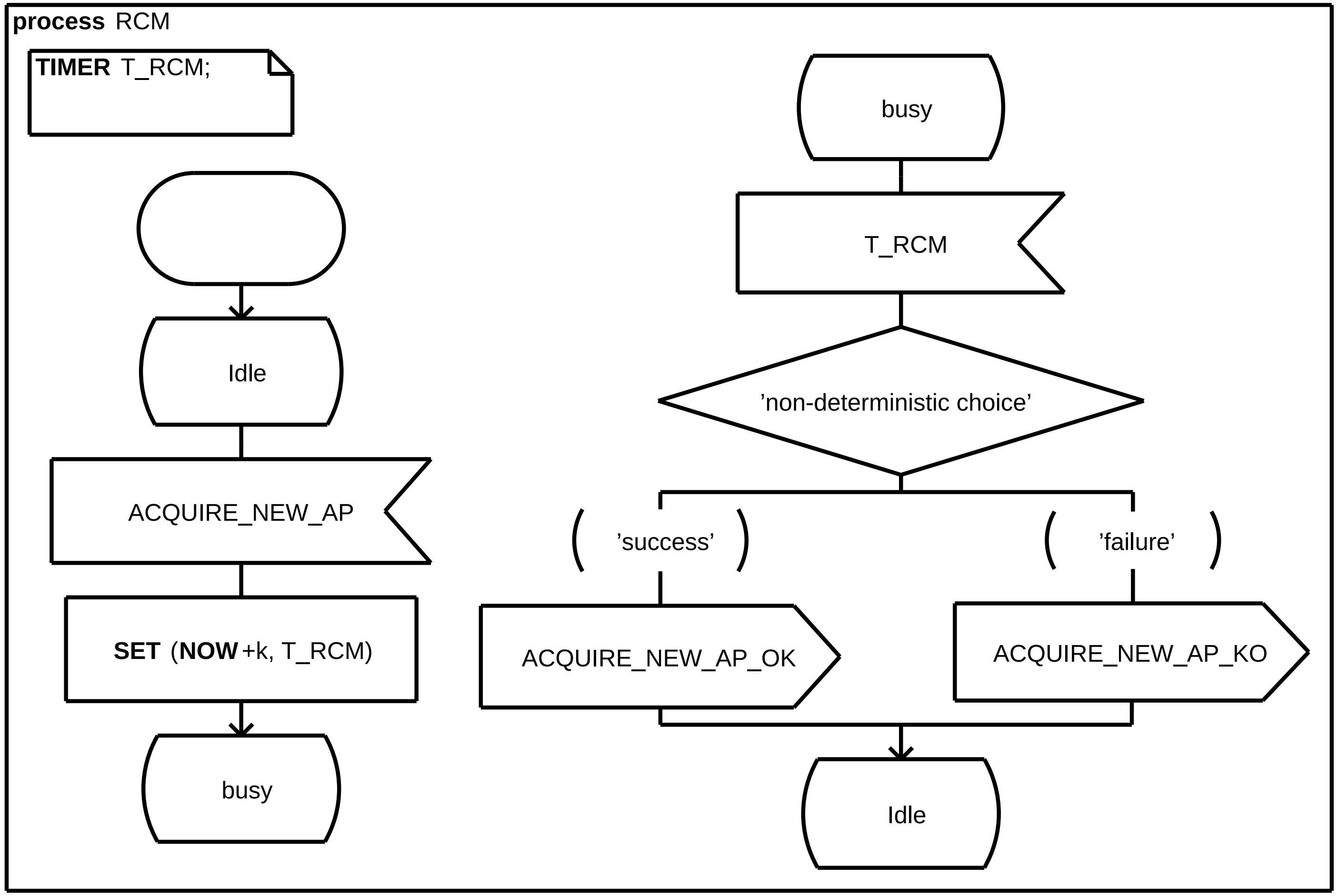
Goal

- yielding a closed system
- safe abstraction
- automatic transformation

Roadmap

1. (sketch of) syntax
2. SO-semantics of SDL
   (a) local and global rules
   (b) semantics of timers
3. eliminating external data via data-flow analysis
4. dealing with chaotic timers
5. synchronous instead of asynchronous environment $\Rightarrow$ eliminating external queues

Syntax: Example



Syntax

- labelled edges $l \longrightarrow_\alpha \hat{l}$ connecting locations
- actions α:

input	$c?s(x)$
output	$g \rhd c!P(s,e)$
assignment	$g \rhd x := e$

with guards g, signals s, processes P, channels c

Semantics (local)

- straightforward operational small-step semantics
  - interleaving semantics
  - top-level concurrency
  - channel queues between processes
- local process configuration:
  1. location/control state
  2. valuation of variables

$\Rightarrow$ labelled steps between configurations, e.g.

$$\frac{l \longrightarrow_{c?s(x)} \hat{l} \in Edg}{(l, \eta) \rightarrow_{c_i?(s,v)} (\hat{l}, \eta[x \mapsto v])} \text{ INPUT}$$

Timers in SDL

- no real-time
- discrete-time semantics, as in [HP89] and as in the DTSpin ("discrete time Spin") model-checker [BD98, DTS00]

$\Rightarrow$ time evolves by ticking down (active) timer variables

- timer: active or deactivated
- timeout possible: if active timer has reached 0
- modelled by time-out guards (cf. [BDHS00])

Syntax for timers

- guarded actions involving timers

set	$g \triangleright set\ t := e$	(re-)activate timer for period given by e.
reset	$g \triangleright reset\ t$:	deactivate
timeout	$g_t \triangleright reset\ t$	perform a timeout, thereby deactivate t

- note: timeout is guarded by "timer-guard" g_t, i.e.,$t = 0$

Parallel composition

- standard product construction
- message passing using the labelled steps
- note: tick step = counting down active timers:
  - can be taken only when no other move possible except input, i.e.,

$$\sigma \rightarrow_{tick} \sigma[t \mapsto (t-1)] \quad \text{iff} \quad blocked(\sigma)$$

What's next

- goal:
  - abstract data from outside: chaotic data value $\mathbb{T}$
  - only synchronous external communication
- side-condition
  - verification with DTSpin model checker (tools):
    - there are no abstracted data
    - we cannot re-implement tick
  - keep it simple

The need for data-flow analysis

- abstractly: replace external $c?s(x)$ by receiving $\mathbb{T}$
- better: remove communication parameters

$\Rightarrow$ remove all variables (potentially) influenced by x, as well (and transitively so)

$\hat{=}$ forward slice/cone of influence

eliminating external data

1. data-flow analysis: mark all variable instances potentially influenced by chaos
2. transform the program, using that marking

Data-flow analysis

- control-flow given by SDL-automata
- propagate $\mathbb{T}$ through control-flow graph, via abstract effect per action = node, e.g.:

$$f(c?s(x))\eta^\alpha \quad = \quad \begin{cases} \eta^\alpha[x \mapsto \top] & c \text{ external} \\ \eta^\alpha[x \mapsto \bigvee\{[\![e]\!]_{\eta^\alpha} \mid \alpha_{n'} = g \triangleright c!s(e)] & \text{else} \end{cases}$$

- constraint solving: minimal solution for

$$\eta^\alpha_{post}(n) \geq f_n(\eta^\alpha_{pre}(n))$$

$$\eta^\alpha_{pre}(n) \geq \bigvee\{\eta^\alpha_{post}(n') \mid (n', n) \text{ in flow relation}\}$$

Worklist algo (pseudo-code)

input : the fbw−graph of the program
output: $\eta^\alpha_{pre}, \eta^\alpha_{post}$;

$\eta^\alpha(n) = \eta^\alpha_{init}(n)$;
$WL = \{n \mid \alpha_n = c?s(x), c \notin out(\bar{P})\}$;

repeat
  pick $n \in WL$;
  let $S = \{n' \in succ(n) \mid f_n(\eta^\alpha(n) \not\leq \eta^\alpha(n')\}$
  in
    for all $n' \in S$: $\eta^\alpha(n') := f(\eta^\alpha(n))$;
    $WL := WL \backslash n \cup S$;
until $WL = \emptyset$;

$\eta^\alpha_{pre}(n) = \eta^\alpha(n)$;
$\eta^\alpha_{post}(n) = f_n(\eta^\alpha(n))$

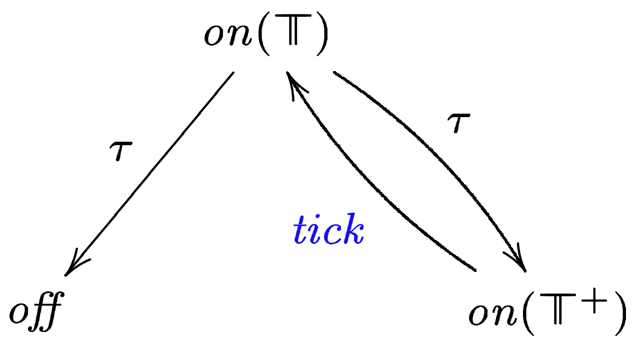
What about time?

- so far: we ignored timers
- timers can be influenced by external data
- chaotic timeout for an active timer:
  1. it can happen now, or
  2. eventually in the future
- remember: time steps (ticks) have least priority!

Timer abstraction

- three abstract values:

1. arbitrarily active
2. active, but not 0 (no time-out possible)
3. de-activated

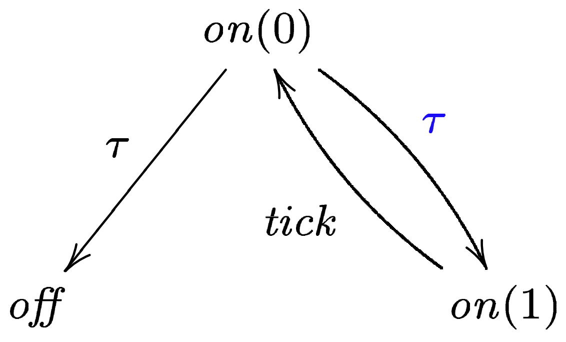


- arbitrary expiration time $\Rightarrow$ non-deterministic setting from $on(\mathbb{T})$ to $on(\mathbb{T}^+)$.

Transformation rules

- using result of the flow analysis
- inference rule(s) for each syntax construct, e.g.,

$$\frac{[\![t]\!]_{\eta_l^\alpha} = \top}{l \longrightarrow_{g_t \,\triangleright\, reset\ t} \longrightarrow_{set\ t:=\mathbf{1}}\ l \in Edg^\sharp} \text{ T-NoTimeout}$$



- transformation yields a safe abstraction

Conditions on the environment

- closing environment is an abstraction of the rest of the system
- but: rest of the system is composed asynchronously

$\Rightarrow$ Question: when is it safe (no behavior lost) to replace asynchronous comm. with the environment by synchronous one.

$\Rightarrow$ environment process must be
  - input enabled
  - not reactive

- e.g., most abstract environment (“chaos”) is ok

Conditions on the environment (cont'd)

- $tick$-step only if all queues empty $\Rightarrow$ restrictions apply only per time slice

  A run is tick-separated =
  - it contains no zero-time cycle
  - for every time slice of the run holds:
    - no output action, or
    - no input except *input discard* and no output over two different channels.
- A process is tick-separated = all runs are tick-separated

Soundness result

Transformation of S into $S^\sharp$:

1. removing external data (using data-flow analysis)
2. making external communication synchronous

Theorem: The transformed system is closed, and a safe abstraction of the original one.

- i.e.,

$$\text{if } S^\sharp \models \varphi \text{ then } S \models \varphi,$$

where φ is an LTL-formula (which does not mention chaotically influenced variables)

Related work

- software testing
- VERISOFT, C, untimed [CGJ98]
- filtering [DP98] [Pas00]
- module checking:
  - checking open systems
  - e.g. MOCHA [AHM+98]

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