Cycle-Bounded Model Checking of PLC Software via Dynamic LBE

Dimitri Bohlender | Daniel Hamm | Stefan Kowalewski

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Informatik 11
Embedded Software
RWTH AACHEN UNIVERSITY

Outline

Introduction

- Model Checking PLC Software
- Motivation

Dynamic LBE-based Cycle-BMC

- Concept
- Experiments

Conclusion

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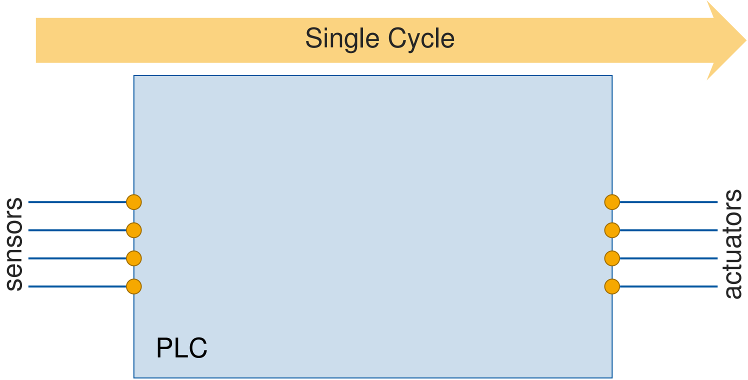
- PLCs are devices tailored to the domain of industrial automation, e.g. for actuating valves of a tank
- Realise reactive systems, repeatedly executing the same task



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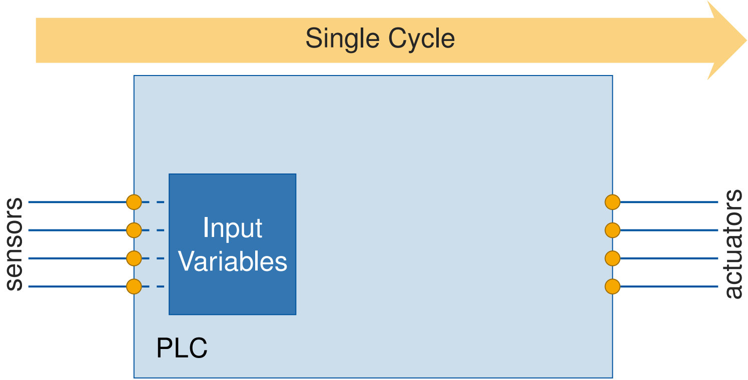

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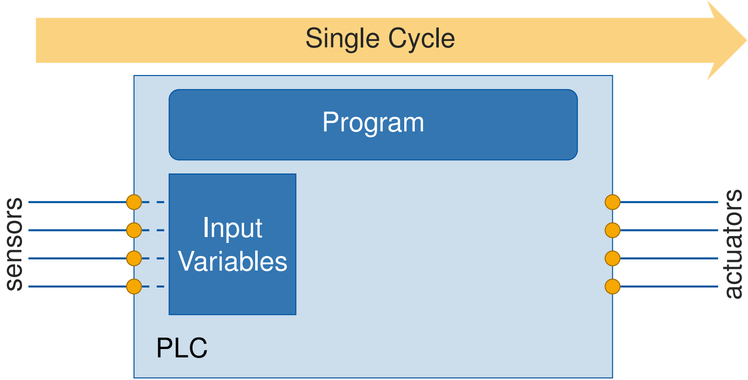

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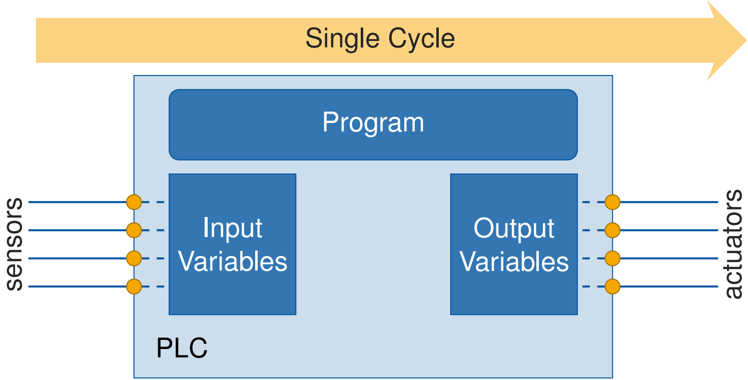

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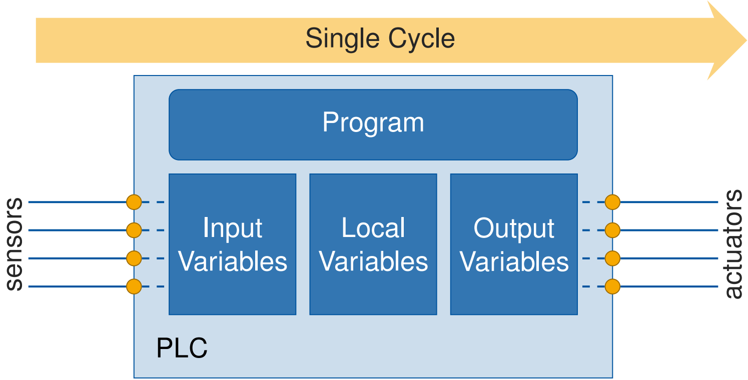

PLC Software

- Programmed via textual and graphical languages from the IEC 61131-3
- Feature no recursion

⇒ Formalised as Control Flow Automaton

- Program may be unstructured
- Program semantics may translate to guards with intersecting conditions

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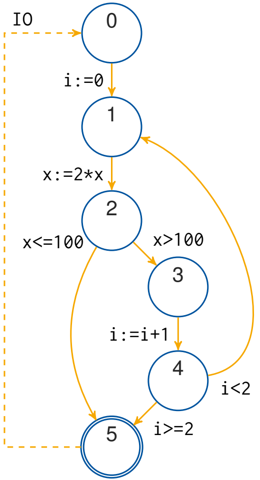

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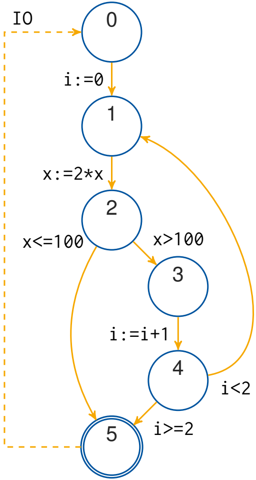

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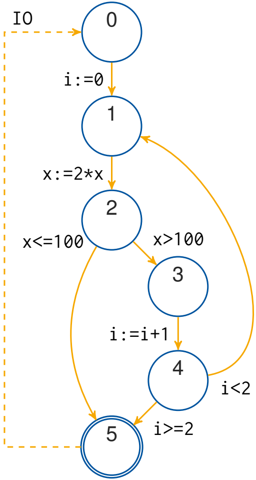

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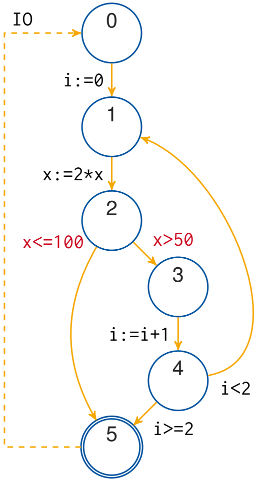

Specifications

- Intermediate states are not observable

⇒ Automation engineers and specs always refer to the observable state

- Most specifications can be formalised via (bounded) temporal logics, e.g. LTL:

$$\Box(\texttt{reset} \rightarrow \bigcirc(\texttt{mode} = 0 \vee \bigcirc\,\texttt{mode} = 0))$$

- Verifier must operate on cycle-step semantics or specs must be adapted:

$$\Box(\texttt{pc} = 5 \wedge \texttt{reset} \rightarrow \bigcirc$$
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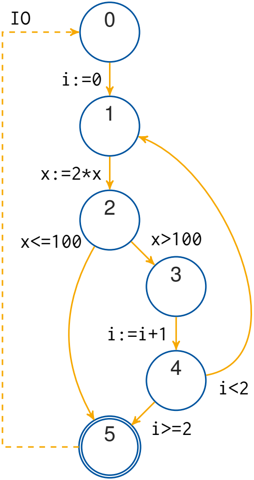

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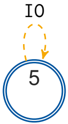

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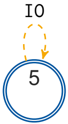

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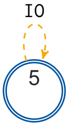

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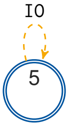

Bounded Model Checking (BMC)

Checks reachability of bad states within k steps from I

$$I(\vec{x}_0) \wedge \bigwedge_{0 \leq i < k} T(\vec{x}_i, \vec{x}_{i+1}) \wedge \bigvee_{0 \leq i \leq k} B(\vec{x}_i)$$

where T characterises the program's step semantics

- Basis of unbounded techniques, e.g. k-Induction
- Unbounded verification might be too hard
- Often used to complement testing, e.g.

  "The first 100 execution cycles are safe"

  helps an engineer with estimating safety

Note: *"The first 100 instructions are safe"* does not

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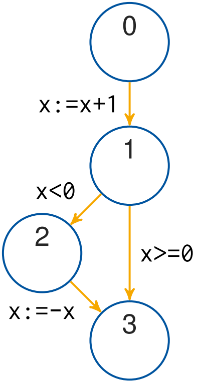
Large-Block Encoding (LBE)

- Combines the semantics of loop-free fragments of a CFA statically

⇒ Less but more complex transitions

- Exponential formula growth of original formulation is avoidable:

$$T(x, x') := \exists_{x_1}\ x_1 = x + 1 \\ \wedge\ (x_1 < 0 \rightarrow x' = -x_1 \\ \vee\ \ x_1 \geq 0 \rightarrow x' = x)$$



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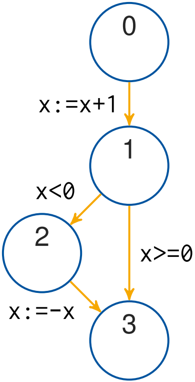

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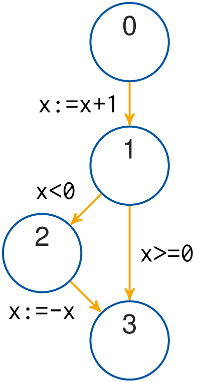

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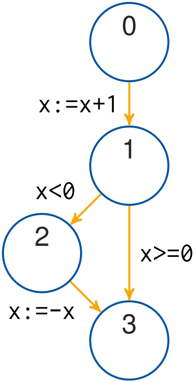

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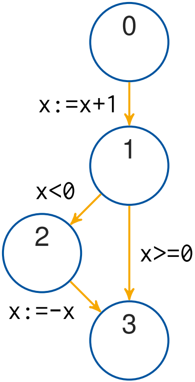

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Dynamic LBE

- Combines the semantics of all feasible paths dynamically
- Efficiency based on combination of several traits

Dynamic	Symbolic execution (with merging)
$\Rightarrow$	Loop unrolling & no unreachable code
Compact	LBE-style with auxiliary variables for blocks
$\Rightarrow$	Path(s) selection & no exponential growth
Incremental	Uses one monotonically growing solver instance
$\Rightarrow$	Incremental SAT solving under assumptions

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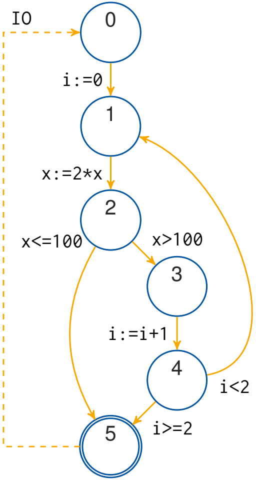

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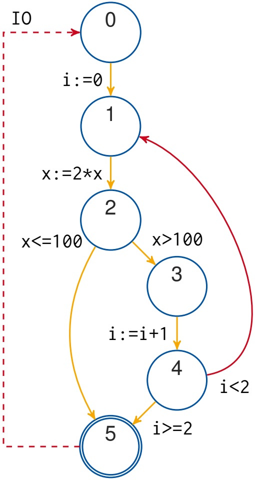

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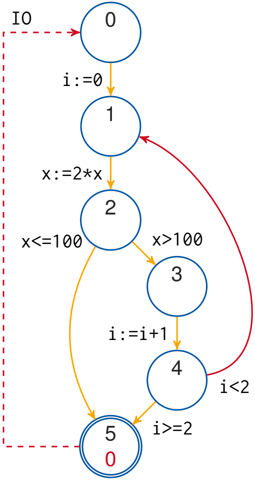

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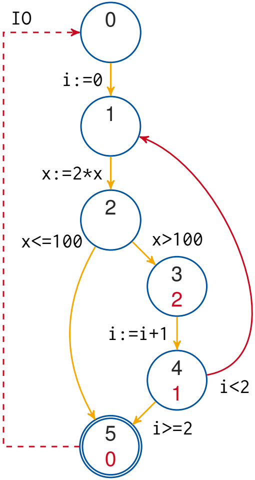

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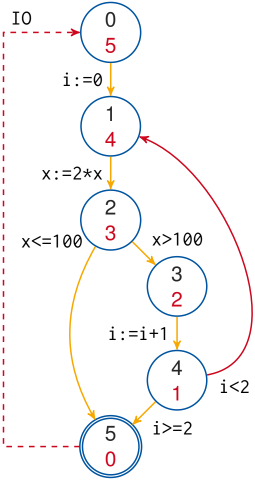

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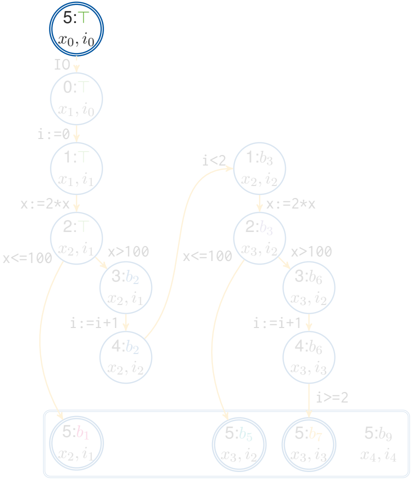

$x_0 = 0, i_0 = 0,$

$i_1 = 0,$

$x_2 = 2 \cdot x_1,$

$b_1 \rightarrow true, b_1 \rightarrow x_2 \leq 100,$

$b_2 \rightarrow true, b_2 \rightarrow x_2 > 100,$

$b_2 \rightarrow i_2 = i_1 + 1,$

$b_3 \rightarrow b_2, b_3 \rightarrow i_2 < 2,$

$\ldots$

$b_9 \rightarrow b_1 \vee b_5 \vee b_7,$

$b_1 \rightarrow x_4 = x_2 \wedge i_4 = i_1,$

$b_5 \rightarrow x_4 = x_3 \wedge i_4 = i_2,$

$b_7 \rightarrow x_4 = x_3 \wedge i_4 = i_3$

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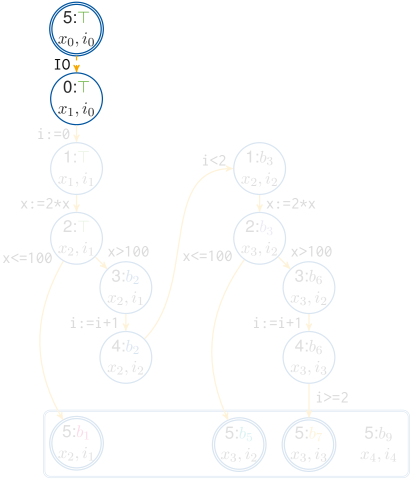

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$b_3 \to b_2, b_3 \to i_2 < 2,$

$\dots$

$b_9 \to b_1 \vee b_5 \vee b_7,$

$b_1 \to x_4 = x_2 \wedge i_4 = i_1,$

$b_5 \to x_4 = x_3 \wedge i_4 = i_2,$

$b_7 \to x_4 = x_3 \wedge i_4 = i_3$

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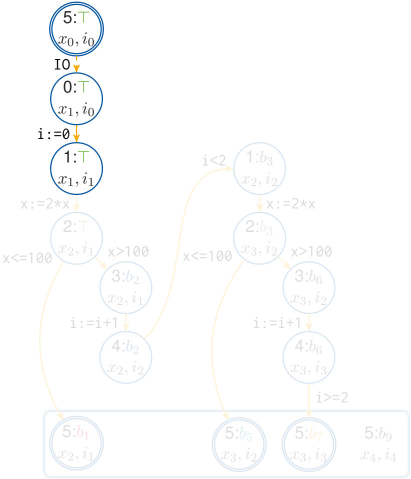

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$\ldots$

$b_9 \to b_1 \vee b_5 \vee b_7,$

$b_1 \to x_4 = x_2 \wedge i_4 = i_1,$

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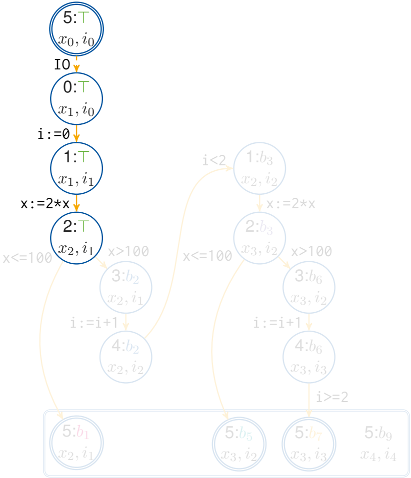
Dynamic LBE Example



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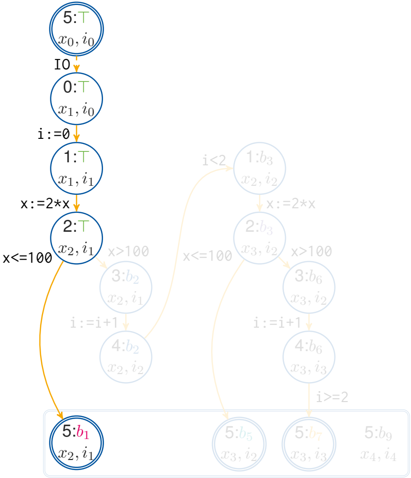

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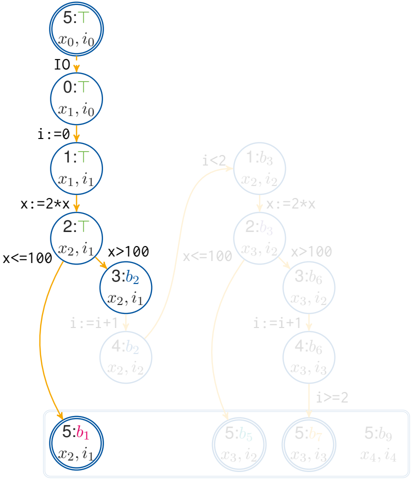

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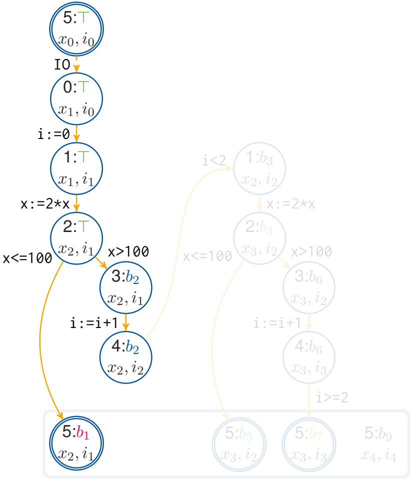

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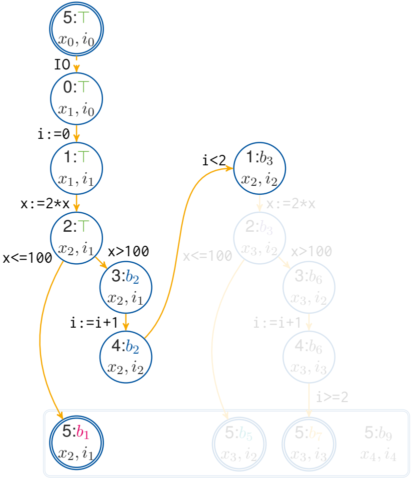

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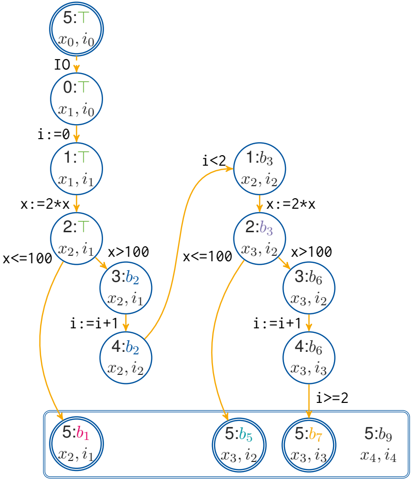

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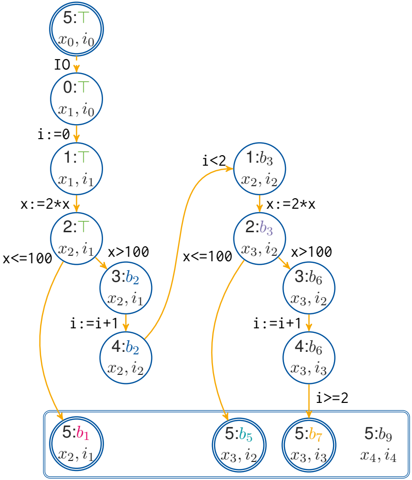

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Cycle-BMC

- k iterations of DLBE will yield the symbolic contexts:

$$\underbrace{(l_{\text{EoC}}, true, \vec{x}_0)}_{c_0}, \underbrace{(l_{\text{EoC}}, b_1, \vec{x}_1)}_{c_1}, \dots, \underbrace{(l_{\text{EoC}}, b_k, \vec{x}_k)}_{c_k}$$

⇒ At this point the solver will *effectively* contain

$$I(\vec{x}_0) \wedge \begin{pmatrix} b_1 \to T_1(\vec{x}_0, \vec{x}_1) \wedge b_1 \to true \\ \wedge \dots \\ \wedge b_k \to T_{k-1}(\vec{x}_{k-1}, \vec{x}_k) \wedge b_k \to b_{k-1} \end{pmatrix}$$

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Experiments on implementation of PLCopen Safety library:

- Single modules implementing particular safety concepts
- User examples combine those

Specifications:

- Only invariants are supported by all tools
- Wrapped CFA in bounded for-loop and translated to C / SMV

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- ARCADE.PLC: Built Cycle-BMC prototype upon this frontend
- CPACHECKER: Adjustable-/LBE with predicate abstraction
- ESBMC: Unrolls programs & optimises verification conditions
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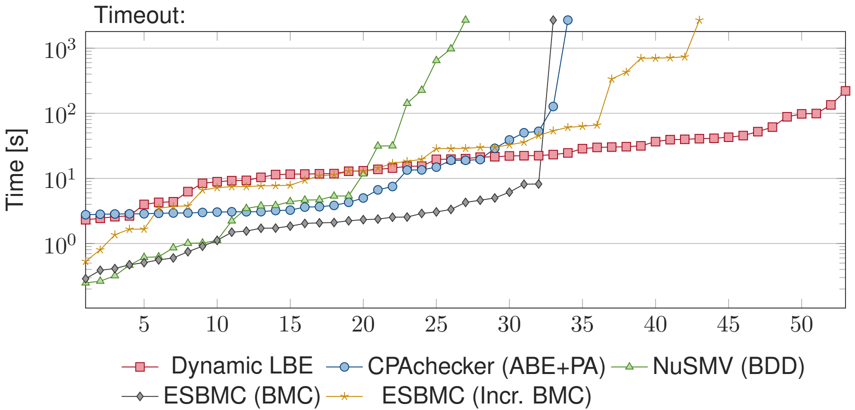

Summary

- PLC software specs refer to observable states only
- Using existing solutions is not always possible / feasible
- Dynamic LBE is a generic approach to unrolling and encoding CFA semantics in a fully incremental way

⇒ Enabled efficient Cycle-BMC without reformulation of specs

Future Work:

- Encoding is compatible with abstraction refinement

⇒ Unroll loops iteratively & evaluate calls lazily

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