A Model-Checking Approach to Safe SFCs

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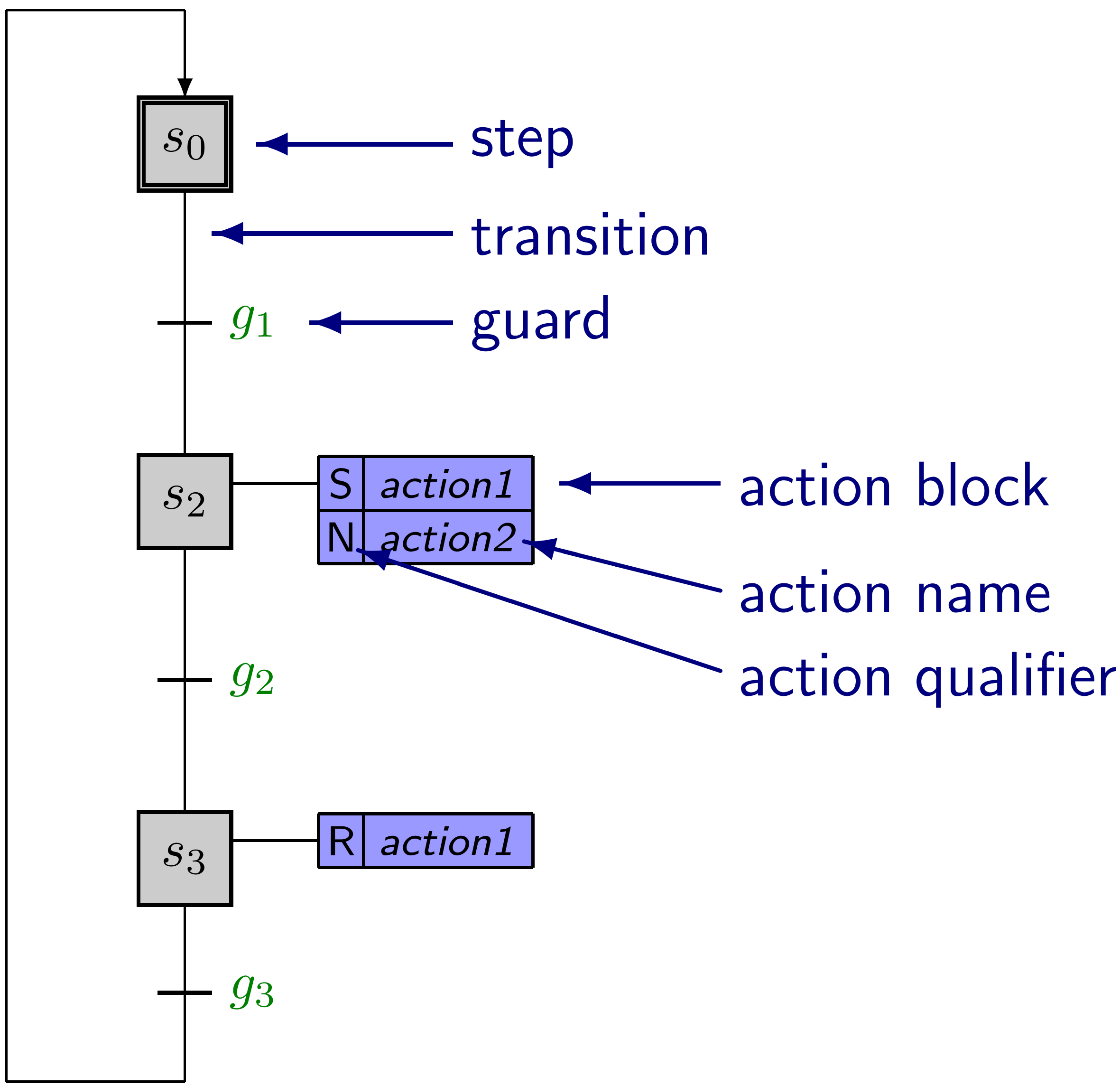
Overview

- Sequential Function Charts (SFCs)
- "Unsafe" and "unreachable" SFCs
- Definition of "safe" SFCs
- Algorithmic checking for "safe" SFCs:
  - Execution model for SFCs
  - Formal specification of "safe"
  - Model checking
- Summary, future work

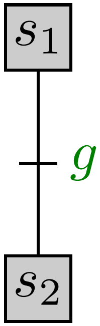
Sequential Function Charts (SFCs)

- Graphical programming language for PLCs
- Based on Petri nets and Grafcet
- Syntax and informal semantics defined in IEC 61131-3
- Concepts:
  - Actions (embedding of other PLC languages)
  - Parallelism
  - Hierarchy

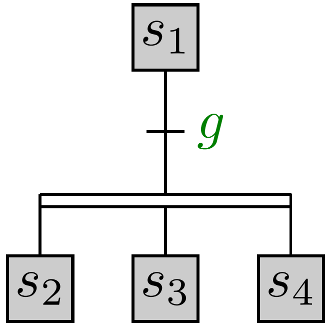
Sequential Function Charts: Components



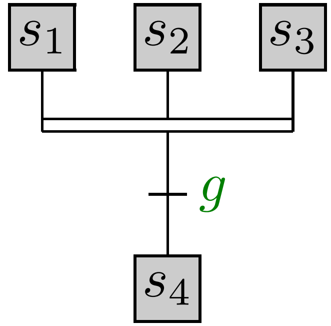
Sequential Function Charts: Transition Types



$(\{s_1\}, g, \{s_2\})$



$(\{s_1\}, g, \{s_2, s_3, s_4\})$



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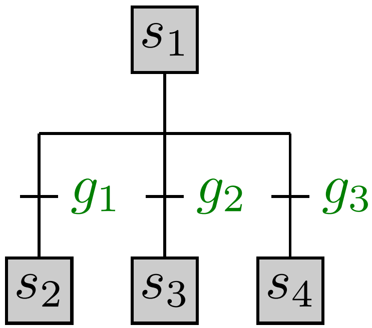

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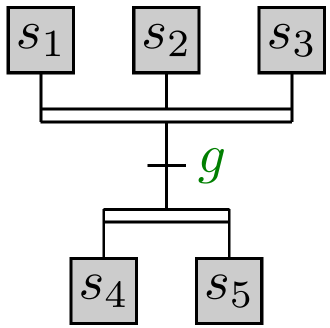
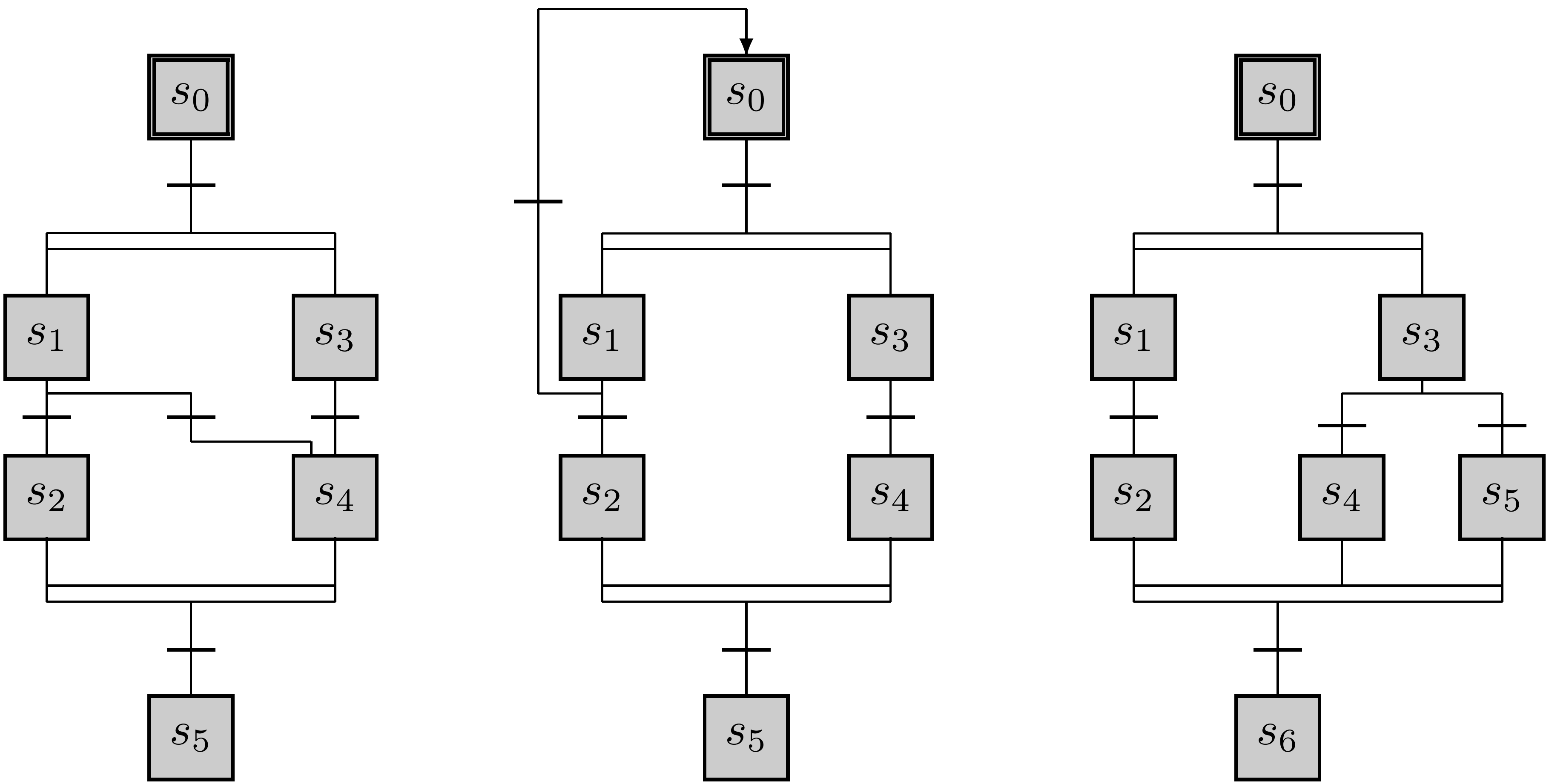


$(\{s_1, s_2, s_3\}, g, \{s_4, s_5\})$

“Unsafe” and “unreachable” SFCs



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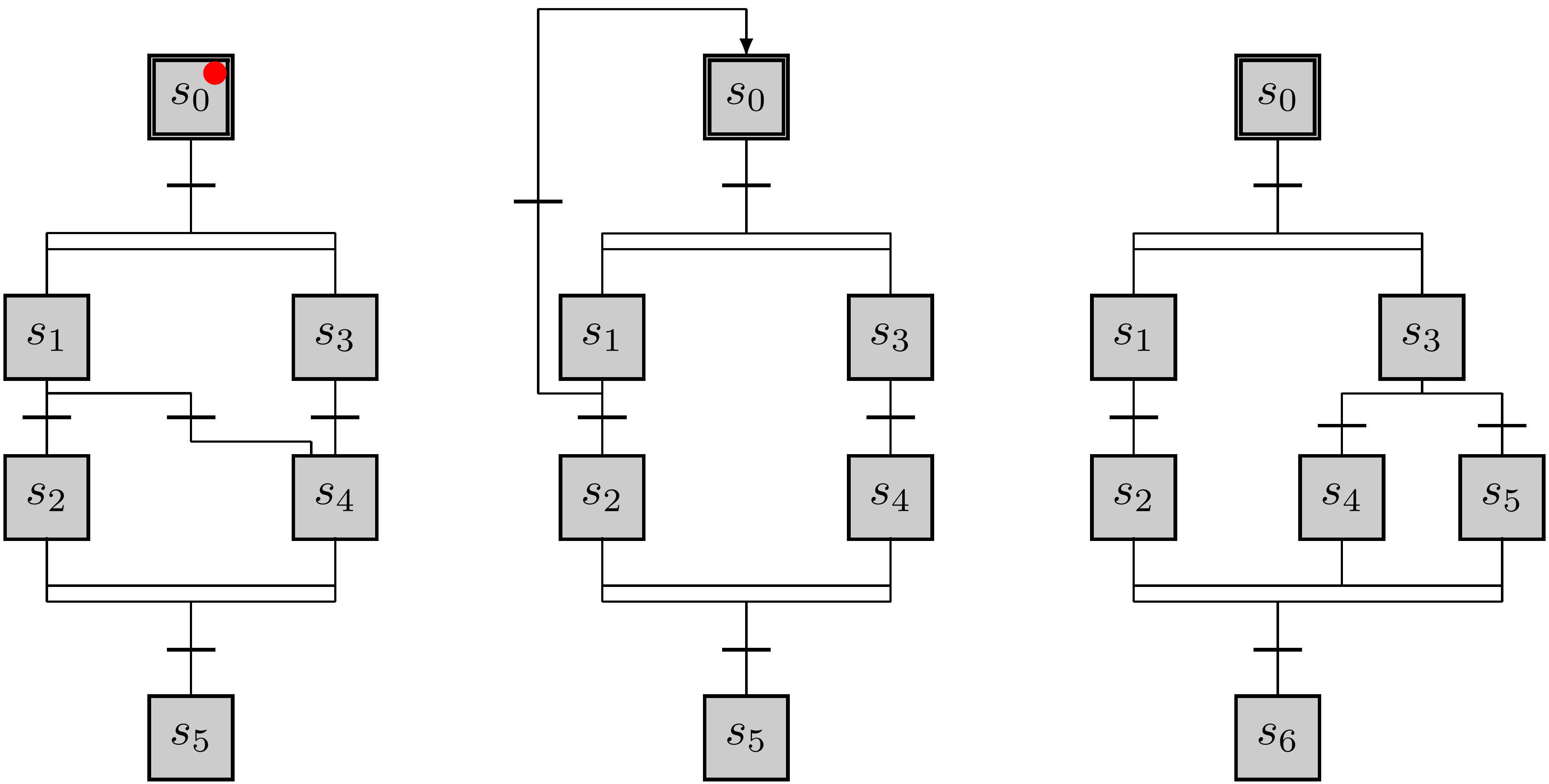

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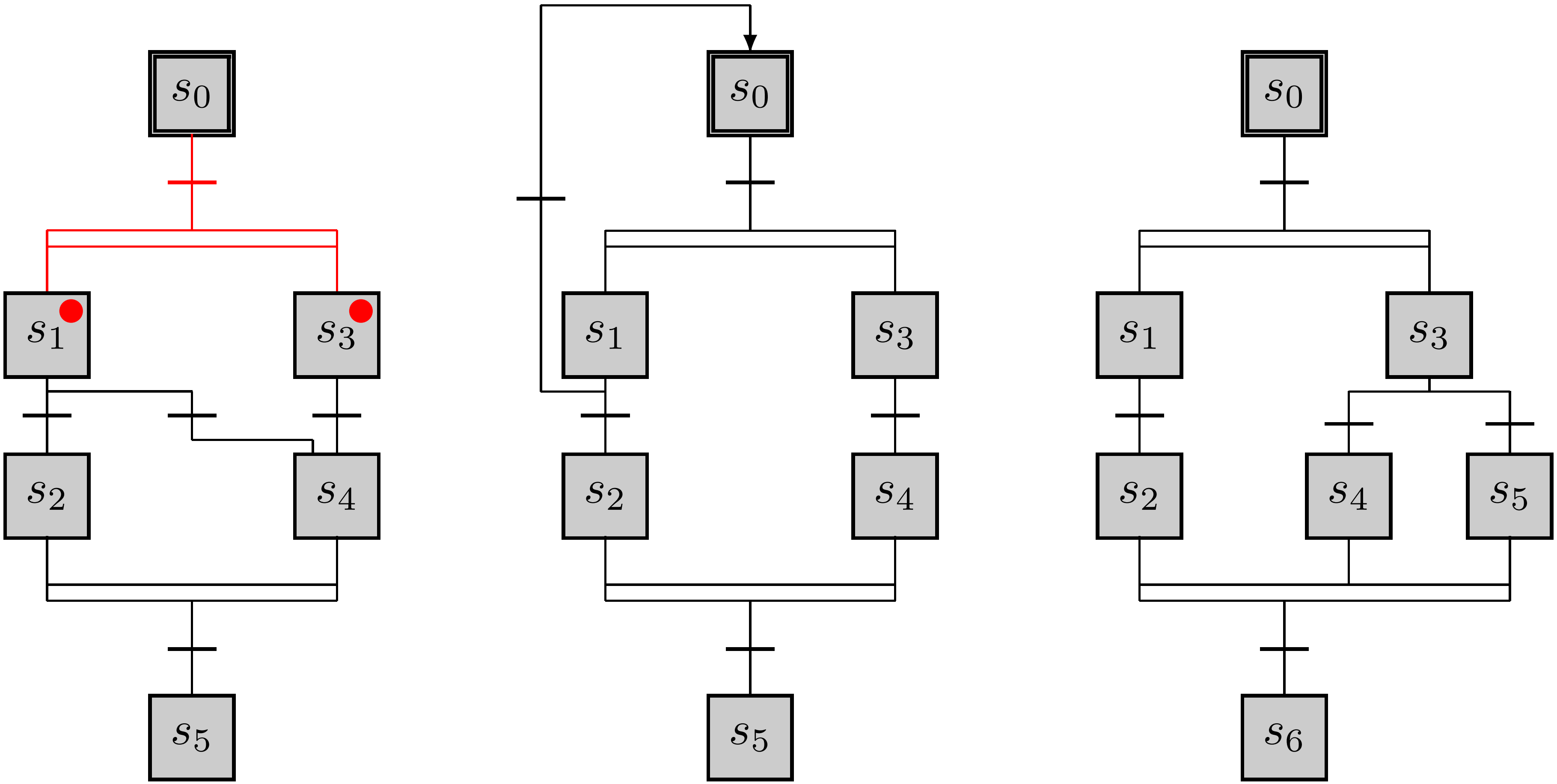

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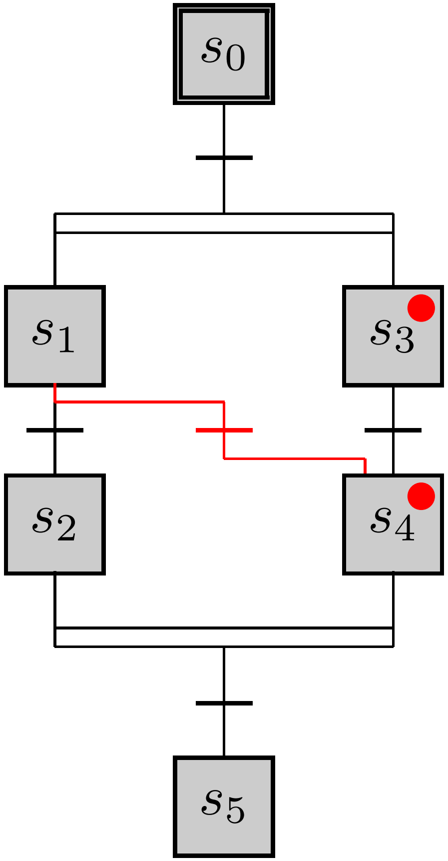

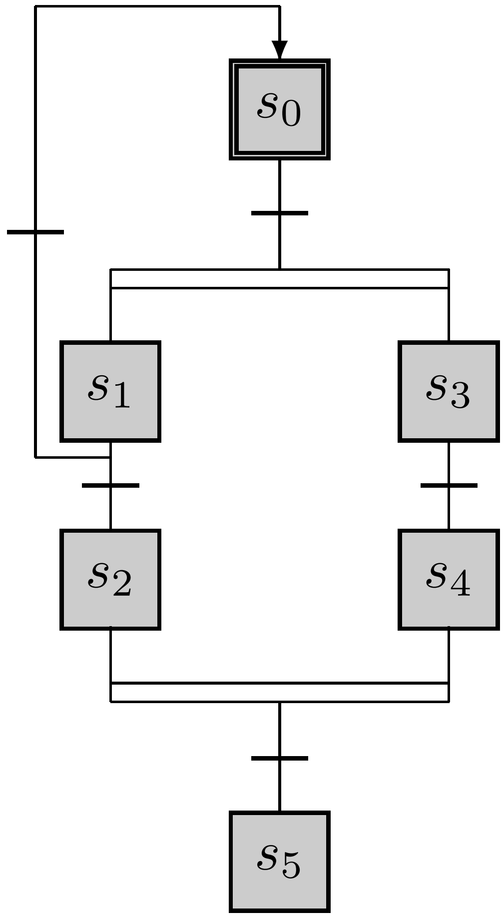

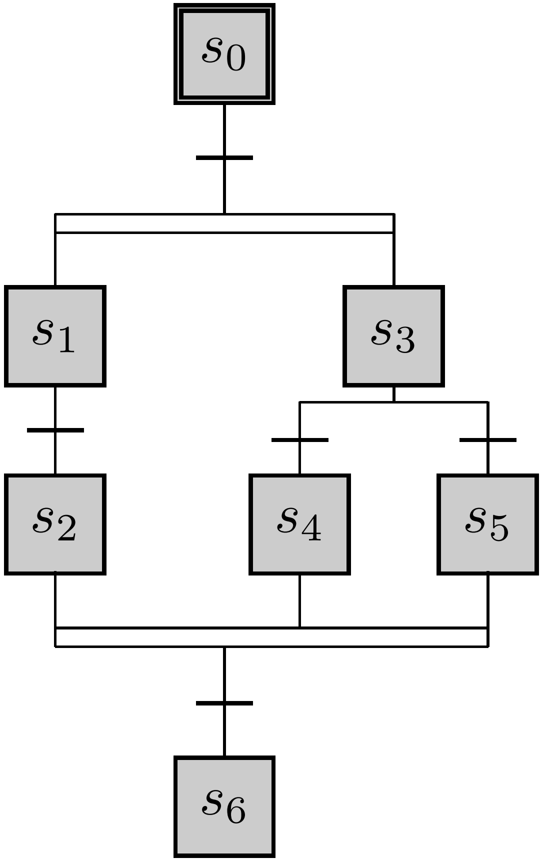

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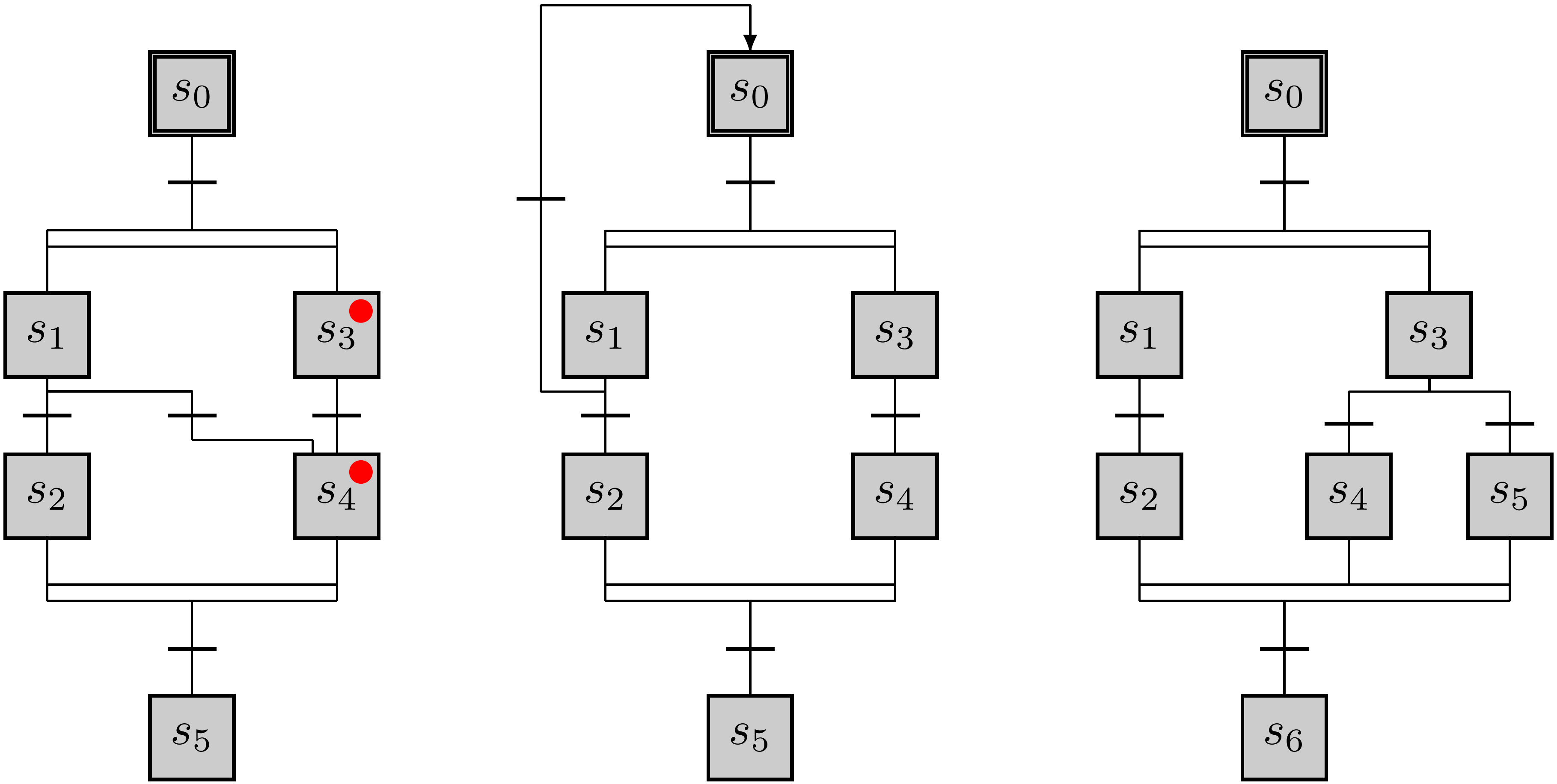

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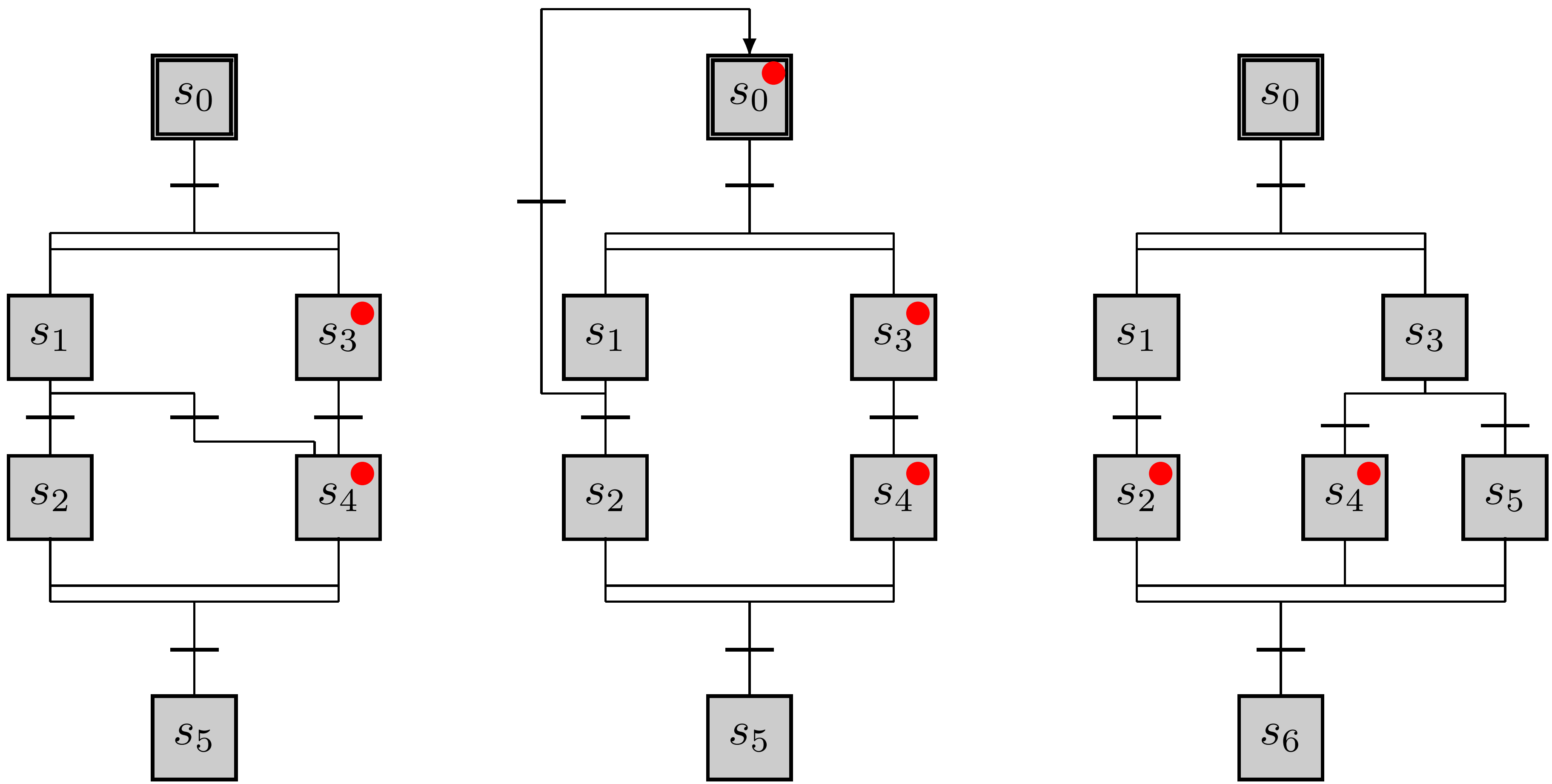

IEC 61131-3 calls these SFCs “unsafe” / “unreachable” . . .

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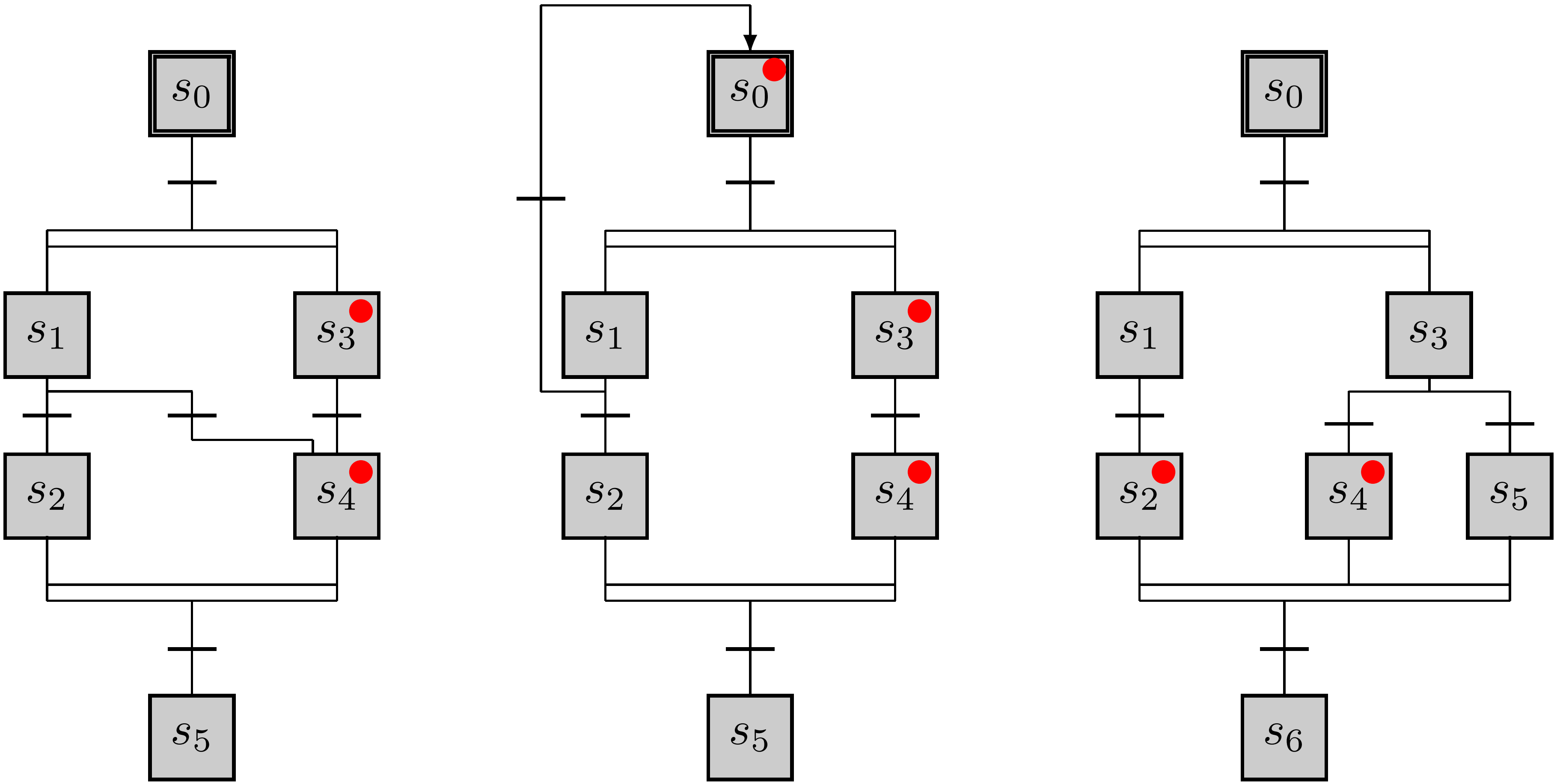

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But construction still possible in many programming environments!

“Safe” SFCs

“Safe” = absence of “unsafe” and “unreachable”

Informal (graphical):

- no jumps between parallel branches
- no jumps out of parallel branches
- every opening parallel branch is closed correctly

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Formal (Petri net execution model):

- In each execution there is at most one token in each step.
- For every closing parallel transition there is an execution that uses this transition.

Check for “Safe” SFCs = Reachability Problem

“Safe” as reachability:

1. No state can be reached in which more than one token can enter a step.
2. For every closing parallel transition a state is reachable in which this transition can be used.

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$\Rightarrow$ **Checking by model checking (Cadence SMV):**

- Abstraction of SFCs
- Modelling of SFC executions in CaSMV
- Definition of “safe” in CaSMV

CaSMV model for SFCs: Variables

Abstraction of the token flow:

- no program variables
- no actions
- guards are replaced by unconstrained Boolean variables
- one Boolean variable s_i for each step
  ($\mathtt{s}_i = true$: step s_i has a token)

State changes of the variables:

- discrete transition system
- relation "`next`" between old and new values

CaSMV model for SFCs: Transitions

Activity of step s_i in the next cycle:

$$\mathtt{next(s}_i\mathtt{)} \equiv \mathtt{s}_i\textit{\_will\_be\_entered} \vee (\mathtt{s}_i \wedge \mathtt{s}_i\textit{\_will\_not\_be\_left})$$

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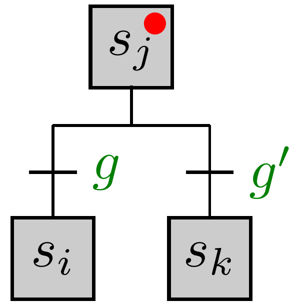

$$\texttt{s}_i\textit{\_will\_be\_entered} \equiv$$

$$\left(\exists t = (S, g, T) \in \mathit{Tr} : s_i \in T \wedge \texttt{next(g)} \wedge \bigwedge_{s_j \in S} \texttt{s}_j\right.$$

$$\left.\wedge\, \forall t' = (S, g', T') \in \mathit{Tr} \setminus \{t\} : \texttt{next(g}'\texttt{)} \Rightarrow \bigwedge_{s_k \in T' \setminus T} \neg\texttt{next(s}_k\texttt{)}\right)$$

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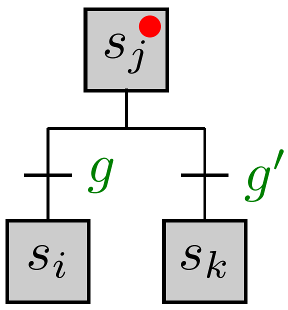

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Step s_i will not be left in the next cycle:

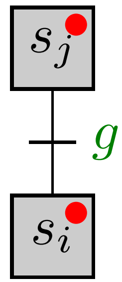
$$\texttt{s}_i\textit{\_will\_not\_be\_left} \equiv \neg\exists(S, g, T) \in Tr : s_i \in S \wedge \texttt{next(g)} \wedge \bigwedge_{s_j \in S} \texttt{s}_j$$

Requirement 1: At most one token in a step

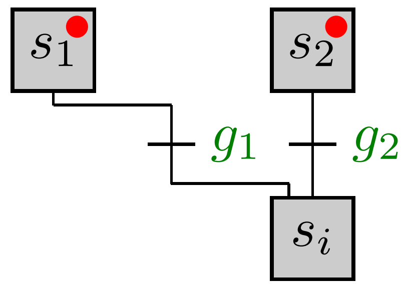
More than one token in a step:

$$\texttt{next(}\texttt{token\_overflow}\texttt{)} \equiv \bigvee_{s_i \in St} \Big($$

$$\Big(\mathtt{s}_i \wedge \bigvee_{\substack{(S,g,T)\in Tr\\ S\neq T}} \big(s_i \in T \wedge \texttt{next(g)} \wedge \bigwedge_{s_j \in S} \mathtt{s}_j\big)\Big)$$



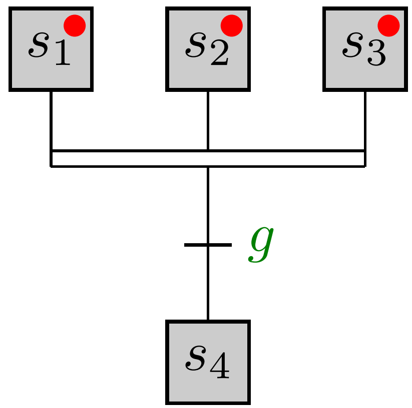
$$\vee \Big(\bigvee_{\substack{(S_1,g_1,T_1)\in Tr\\ (S_2,g_2,T_2)\in Tr\\ S_1\cap S_2=\emptyset}} \big(s_i \in T_1 \cap T_2 \wedge \texttt{next(g1)} \wedge \texttt{next(g2)} \wedge \bigwedge_{s_j \in S_1 \cup S_2} \mathtt{s}_j\big)\Big)\Big)$$



CaSMV specification: `SPEC AG !token_overflow`

Requirement 2: Closing parallel transitions

We show for each transition $(S, g, T) \in Tr$ with $|S| > 1$:
There exists an execution in which all $s_i \in S$ are acitve.



CaSMV specification: `SPEC EF` $\&_{s_i \in S} \mathtt{s}_i$

Implemented as a tool:

- Input: SFC in IEC 61131-3 or Siemens syntax
- Output: CaSMV code and CTL specification

Output of CaSMV:

- OK – SFC is “safe”
- Error trace (helpful to locate the problem)

$\Rightarrow$ requires only minimal interaction by the user

Summary and Future Work

Summary

- The problem of “unsafe” and “unreachable” SFCs
- Algorithmic approach to check for “safe” SFCs:
  - abstract CaSMV model
  - tool-supported automatic verification

Future work

- Embed tool into PLC programming environments
- Combine with other automated verification approaches, e.g., static analysis