Verification of Adaptive Embedded Systems

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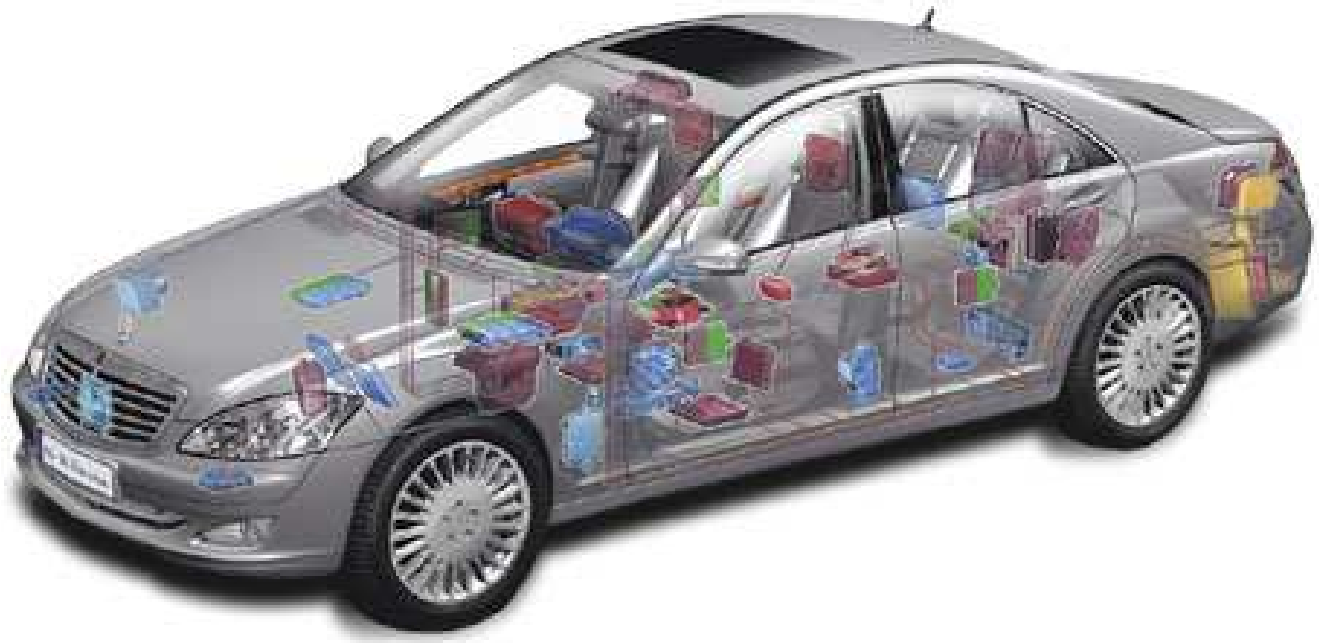
Overview

Why Adaptation in Embedded Systems?

Improve quality and functionality

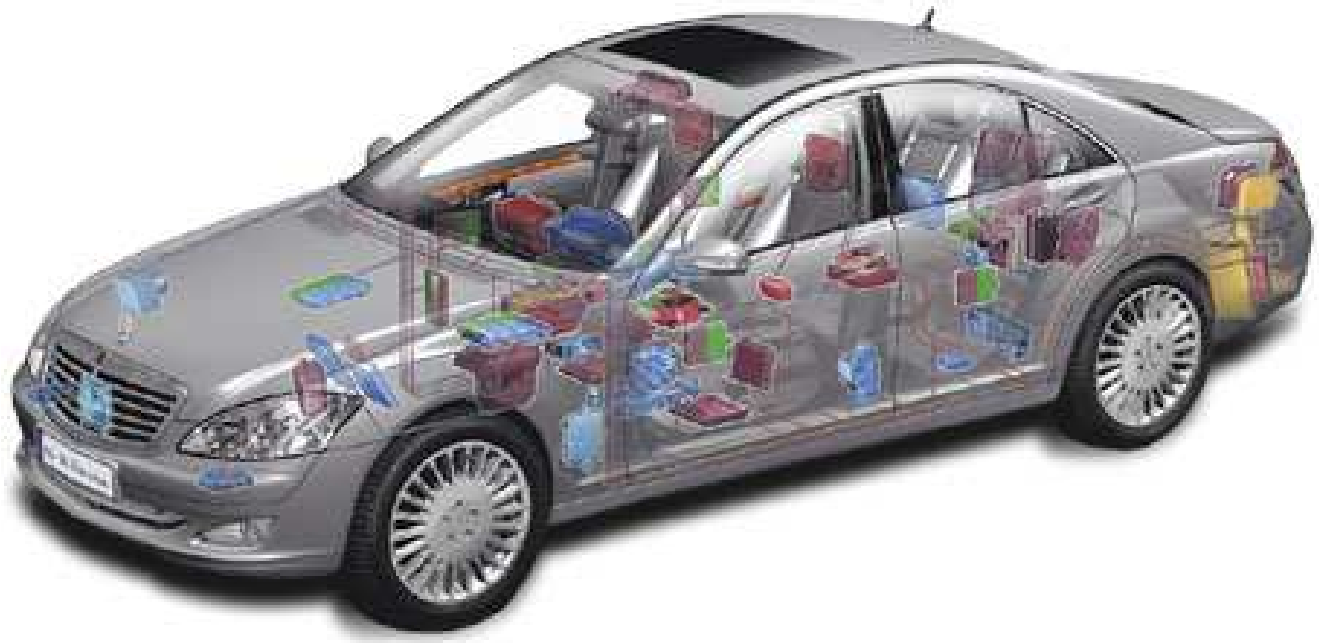
- changing environmental conditions (tunnel, failure of sensors)
- dependability and fault–tolerance (get safely to the next garage)
- customization (adapt to different drivers and their specific needs)



Why Adaptation in Embedded Systems?

Reduce costs

- depending on the situation not all parts are active at the same time
- share common parts of the system that are not used simultaneously
- dynamically adapt the components according to the current situation



Adaptation in Embedded Systems

Challenges regarding verification

- embedded systems are reactive real–time systems
  - verification of functional and temporal behavior
- hybrid systems (interacting analog and digital parts)
  - verification requires abstraction to discrete domains
- safety–critical systems (aviation, automotive industry)
  - legal aspects (“it wasn’t me who pushed the brakes”)

What’s so special about adaptation?

- adaptation has become increasingly complex part
- may trigger further adaptations in other components
- chain reaction of adaptations (up to 80% affected)
- can cause inconsistent and unstable configurations

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Synchronous Languages

Programming model

- perfect synchrony: partitioning into micro and macro steps
- consumption of time explicitly specified by the programmer
- deterministic form of concurrency (processes run in lockstep)

Basic Quartz statements

pause;	consumption of time
nothing;	empty statement
$x = \tau$; / **next**$(x) = \tau$;	immediate/delayed assignment
emit x; / **emit next**(x);	immediate/delayed emission
while (φ) S	loop
if (φ) S_1 **else** S_2	conditional
$S_1\, S_2$	sequential execution
$S_1 \mid S_2$ / $S_1 \parallel S_2$ / $S_1 \mid\mid\mid S_2$	interl./sync./async. parallel execution
[**weak**] **abort** S **when** [**immediate**] (φ)	process abortion
[**weak**] **suspend** S **when** [**immediate**] (φ)	process suspension

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Synchronous Languages

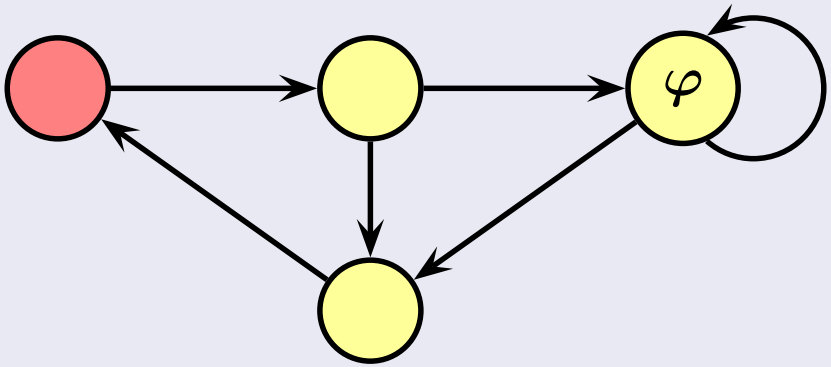
Example

module ABRO(**event** $a, b, r, \&o$) **implements** ABRO_Spec(a, b, r, o) {
  loop {
    abort {
      await(a); || **await**(b);
      emit o;
    } **when**(r);
  }
}

spec ABRO_Spec(**event** a, b, r, o) {
  S1 : A G ($o \rightarrow a \vee b$);
}

Model Checking

System (Kripke structure)



- directed graph
- nodes: configurations
- edges: adaptations
- paths: adaptation sequences

Specification (temporal logic, e.g. CTL or LTL)

- EF φ "there exists a path such that φ eventually holds" (least FP)
- AG φ "φ invariantly holds on all paths" (greatest FP)

Model checking

Does the system satisfy the specification? $\Rightarrow$ Fixpoint computation

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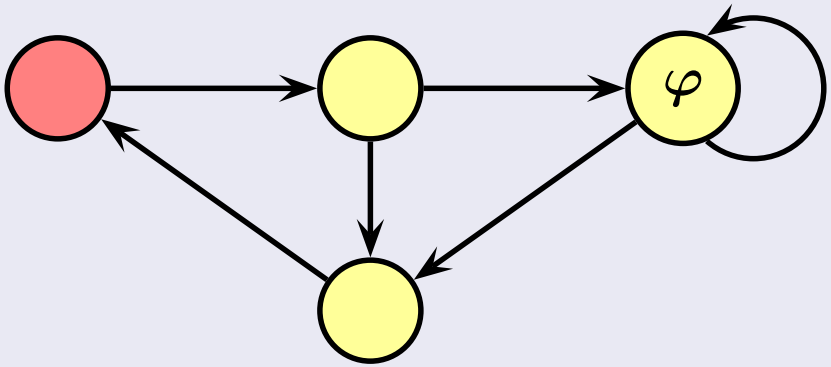

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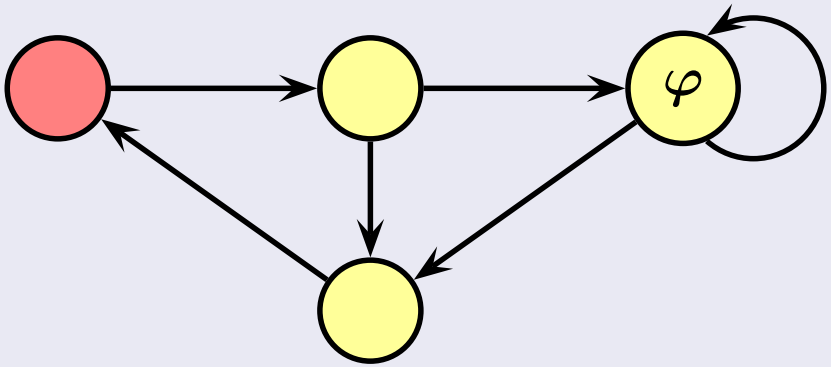

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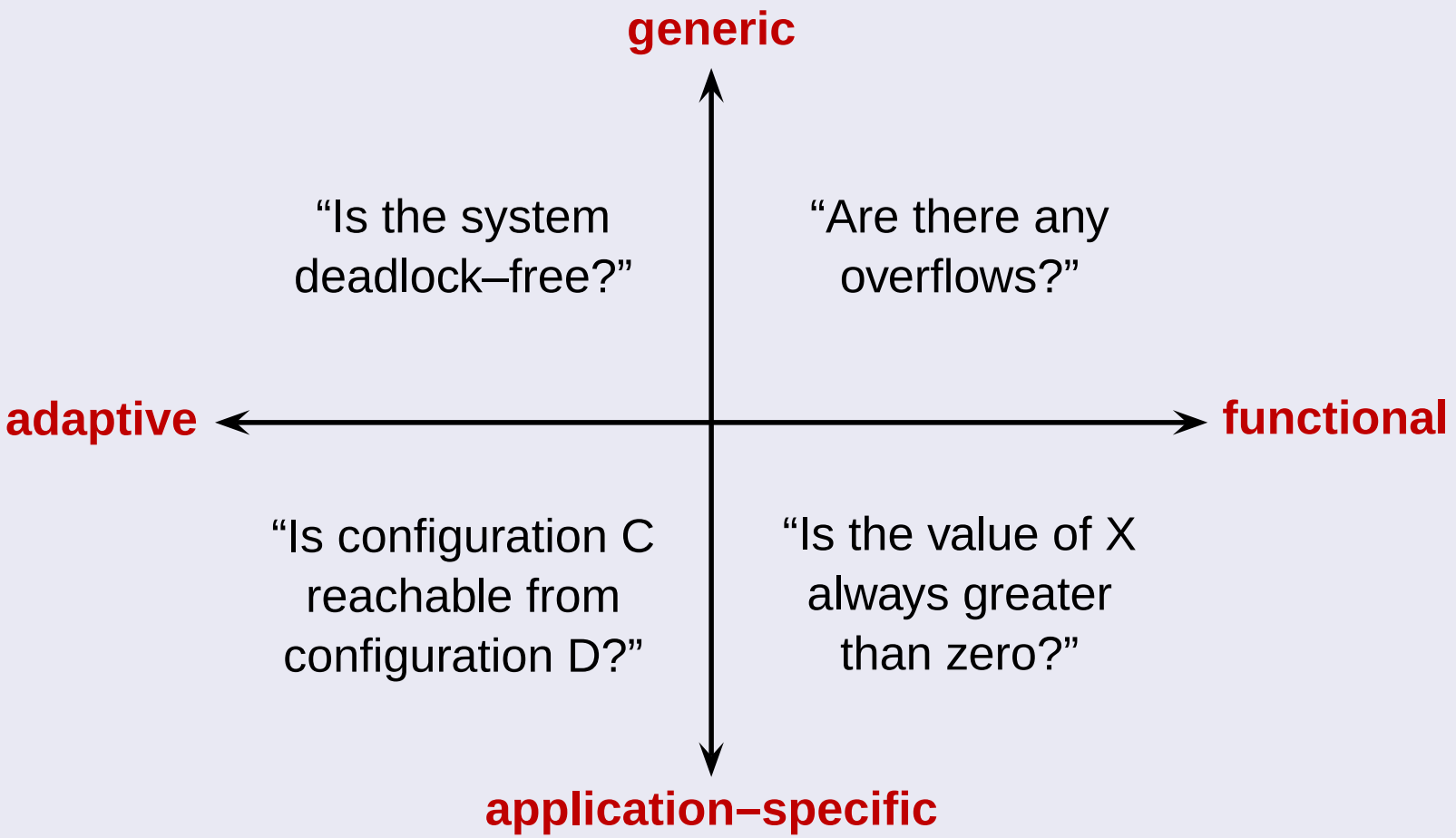
Properties of Adaptive Systems

Classification



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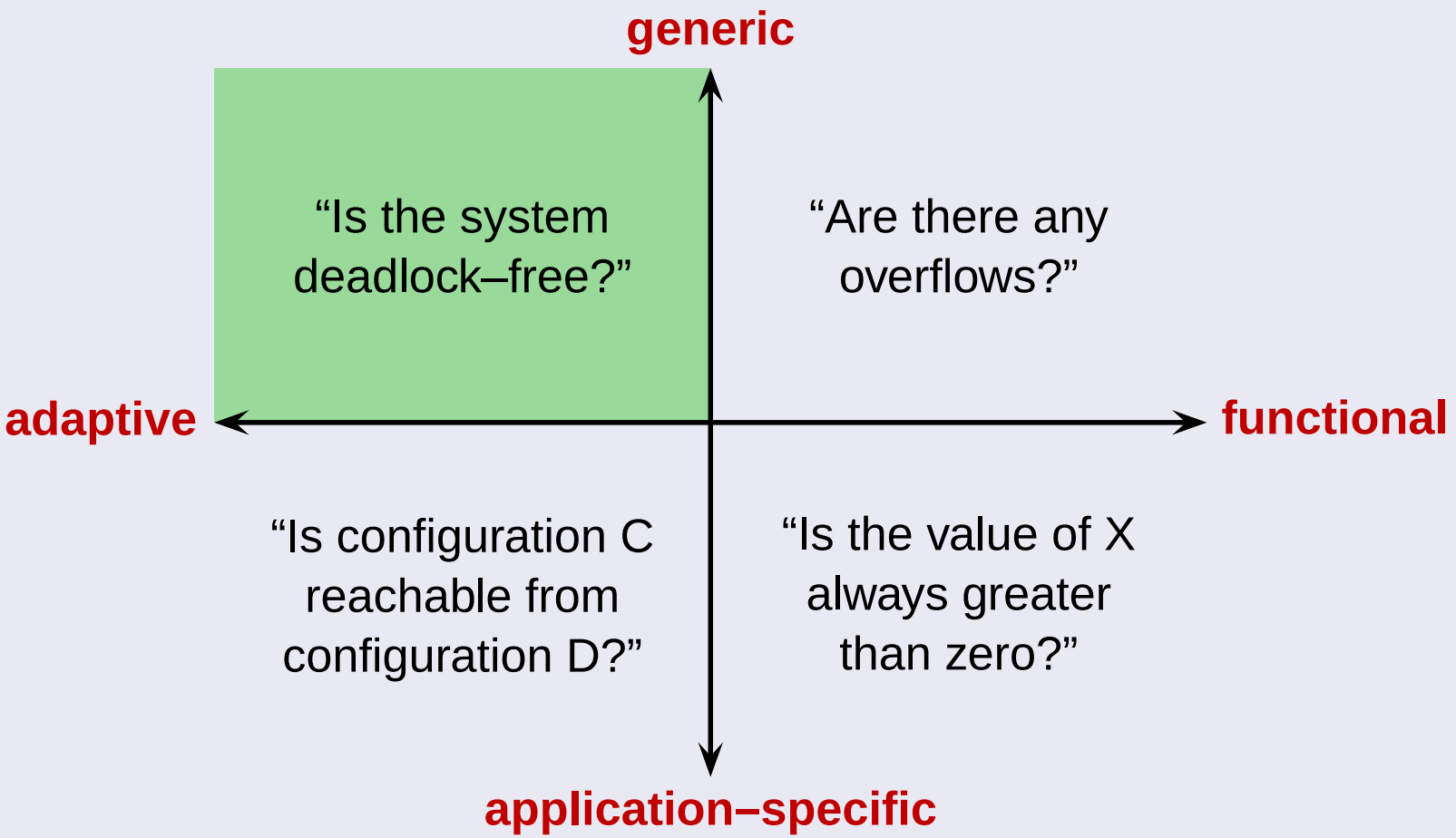

Properties of Adaptive Systems

Generic properties of adaptation behavior (CTL)

1. No module gets stuck in the default configuration ‘off’:

$$\mathrm{AG}(c = \mathit{off} \rightarrow \mathrm{EF}\, c \neq \mathit{off})$$

2. Every module can reach all configurations at all times:

$$\mathrm{AG}(\bigwedge_{i=1}^{n} \mathrm{EF}\, c = \mathit{config}_i)$$

3. No inconsistent states can be reached:

$$\mathrm{AG}(\bigvee_{i=1}^{n} c = \mathit{config}_i)$$

4. No configuration is always only transient:

$$\bigwedge_{i=1}^{n} \mathrm{EFEG}\, c = \mathit{config}_i$$

Stability of Adaptation Behavior

Finite vs. infinite adaptation sequences

- no central authority $\Rightarrow$ chain reaction of adaptations
- finite adaptation sequences usually intended
- infinite adaptation sequences lead to unstable system
- verify that the outputs stabilize if the inputs do not change

Stability checking by LTL model checking

- $\varphi_{\text{in}} \Leftrightarrow$ inputs stable for one unit of time
- $\varphi_{\text{out}} \Leftrightarrow$ outputs stable for one unit of time
- $\mathsf{AG}(\mathsf{G}\varphi_{\text{in}} \rightarrow \mathsf{FG}\varphi_{\text{out}})$
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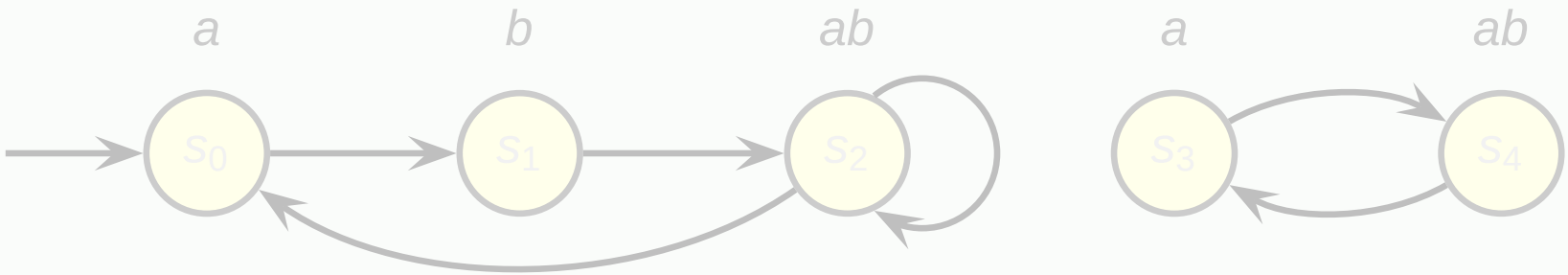
Stability of Adaptation Behavior

Specialized verification procedures for stability

- a path is steady iff the inputs/outputs do not change from time $t \geq 0$
- a state is stable iff for all paths input steadiness $\Rightarrow$ output steadiness
- a Kripke structure is stable iff all reachable states are stable

Example



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Stability can be checked by evaluating two alternation–free formulas.

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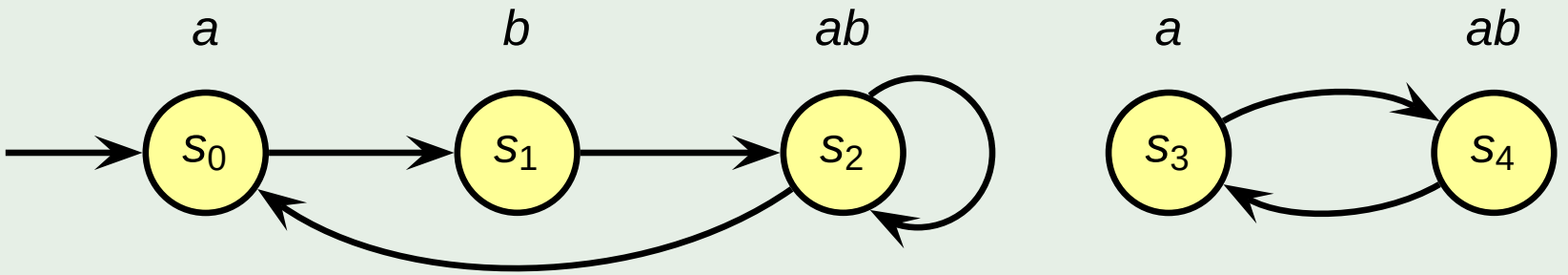

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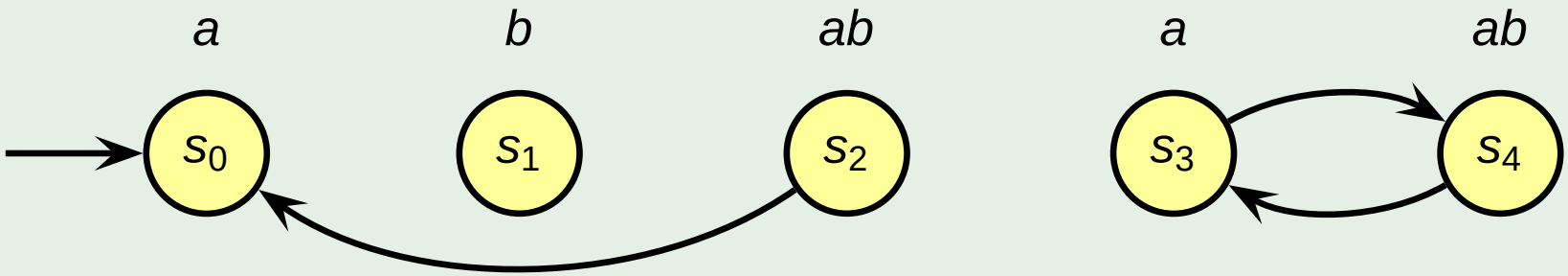

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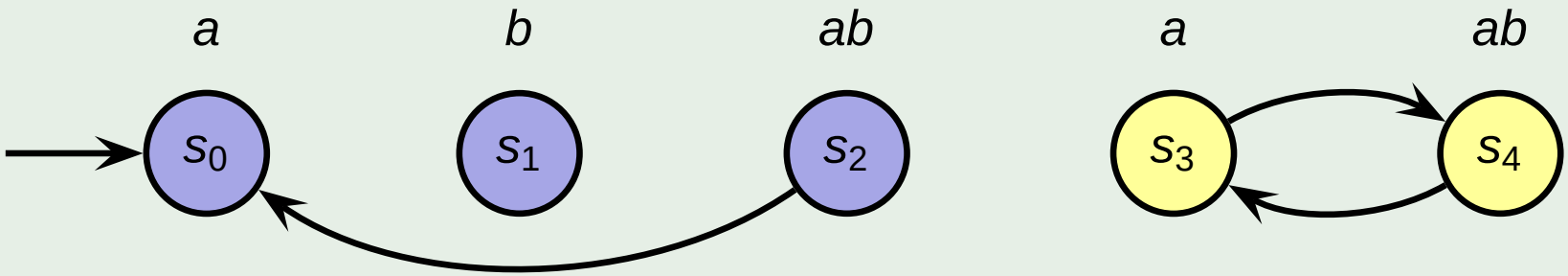

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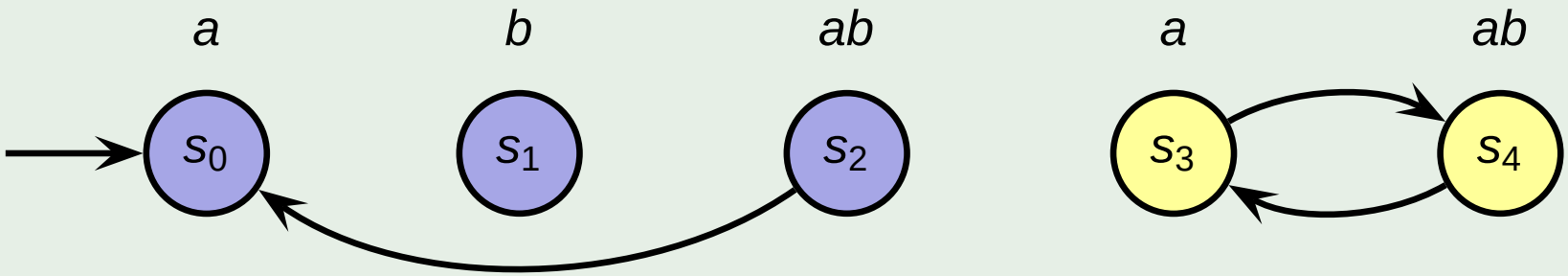

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Experimental Results

Traction control system

- Fraunhofer Institute for Experimental Software Engineering (IESE)
- Software Technology Group, University of Kaiserslautern
- 28 modules, 70 configurations, $>$ 2000 lines of Quartz code
- 151 generic specifications concerning adaptation behavior

Generic specifications of adaptation behavior

event variables	min. [s]	avg. [s]	max. [s]	total [s]
no	< 1	5	222	782
yes	< 1	2	143	298

Stability of adaptation behavior

LTL model checking: $>$ 1h

specialized procedure: 1723s

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Summary and Conclusion

Adaptive embedded systems

- cost–efficient way to increase dependability of embedded systems
- verification particularly important in safety–critical areas, e.g. cars
- translate high–level model via formal rep. to synchronous program
- standard and specialized algorithms for verifying adaptation behavior

Directions for future work

- support for hybrid systems (real numbers)
- timing analysis (worst case execution time)
- predicate abstraction and refinement
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