Trends in Concurrency Theory
The Tester's Perspective

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New Age Concurrency?

- Several observations lead us to the conviction that “time is right” to invest into changes of paradigm in the field of concurrency and its semantic foundations
  - Multi-core systems – the need for **weak memory models**
  - E-commerce – new notions of **distributed database consistency**
  - Cyber-physical systems (CPS) – **dynamic re-configuration, adaptive, emergent properties, collaborative, multi formalism development and V&V …**

Three Topics to Address

- **Multi-formalism support** for CPS modelling and verification
- **Dynamicity** – changing CPS configurations
- **Evolving behaviour** of CPS components

All this is presented from the perspective of **model-based testing**

Multi-formalism support for CPS modelling and verification

Problem Statement

- Different CPS components are developed and verified with **different formalisms**
- This produces **“local” verification results**, presented in different formalisms
- How can we assert the v**alidity of the required emergent properties** of the CPS?

Two Approaches

- Application of the
  - Theory of (Grothendiek) Institutions
  - Unifying Theory of Programming (UTP)

  to translate

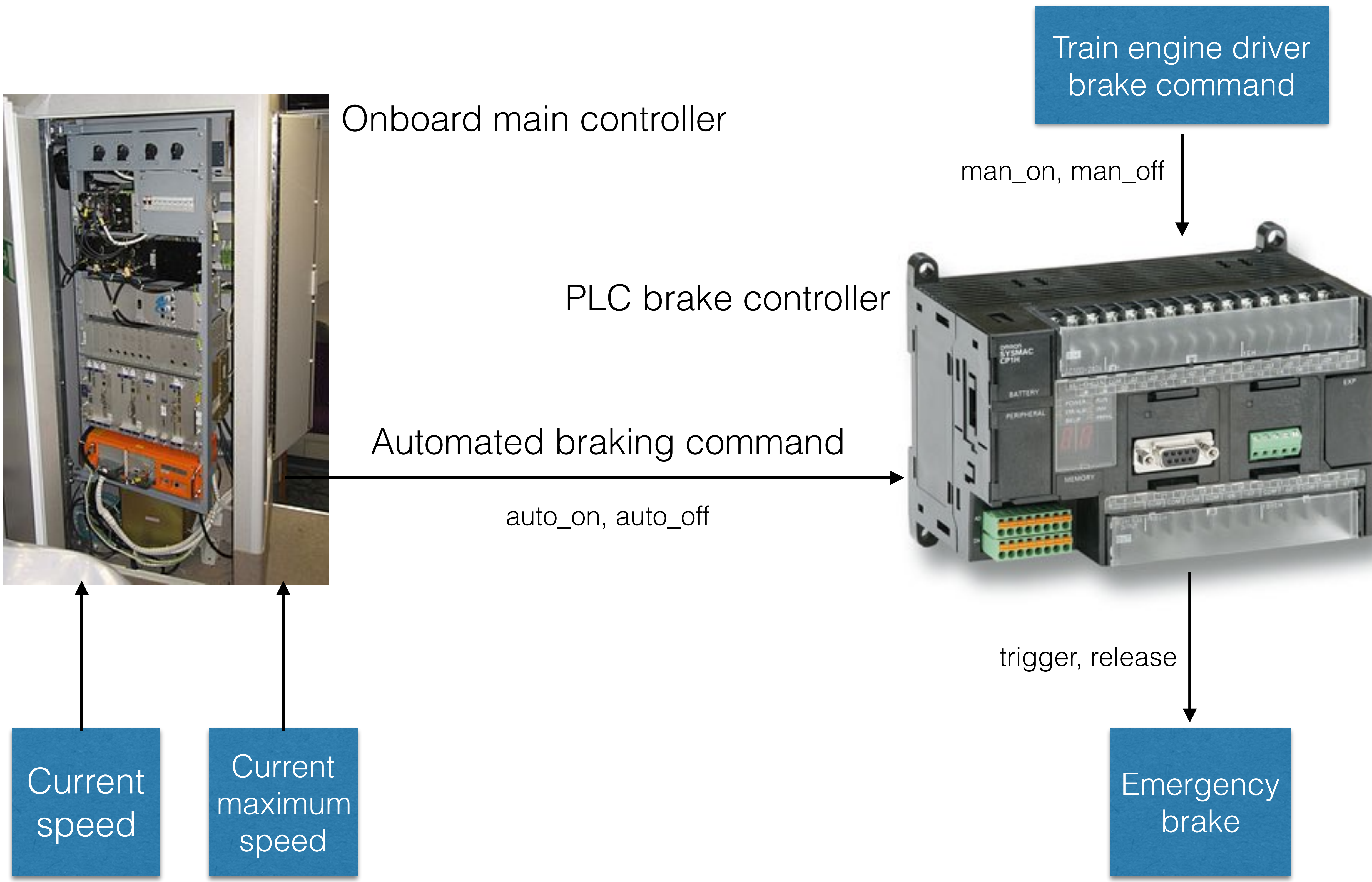
    - theories between different formalisms
    - verification obligations and test cases
    - verification results and test results

  between different formalisms

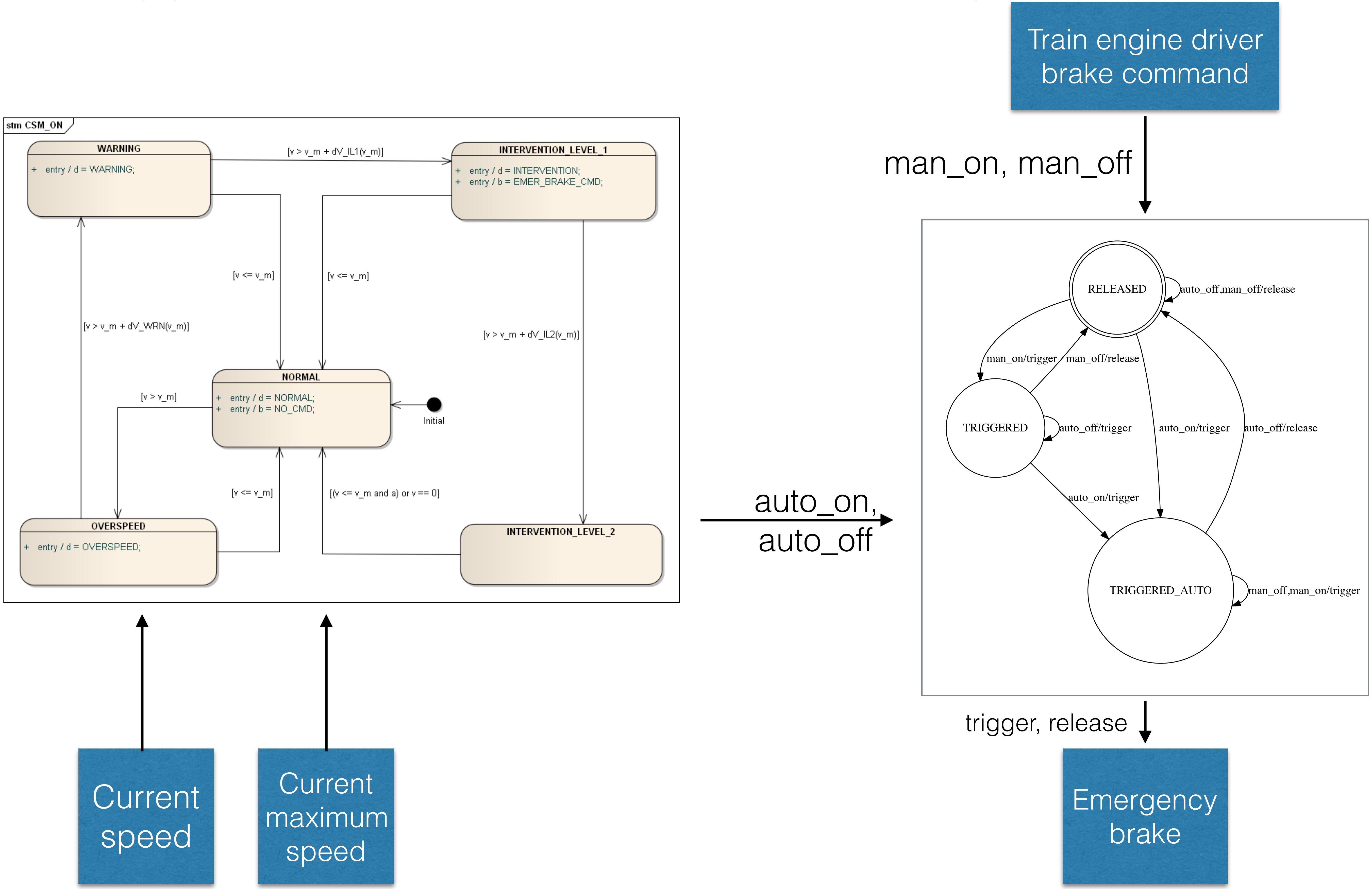
Application scenario

- CPS consists of several components
- Some components are modelled by finite state machines (FSMs)
- Other components are modelled by SysML state machines with Kripke structure semantics

Application scenario – train onboard speed control

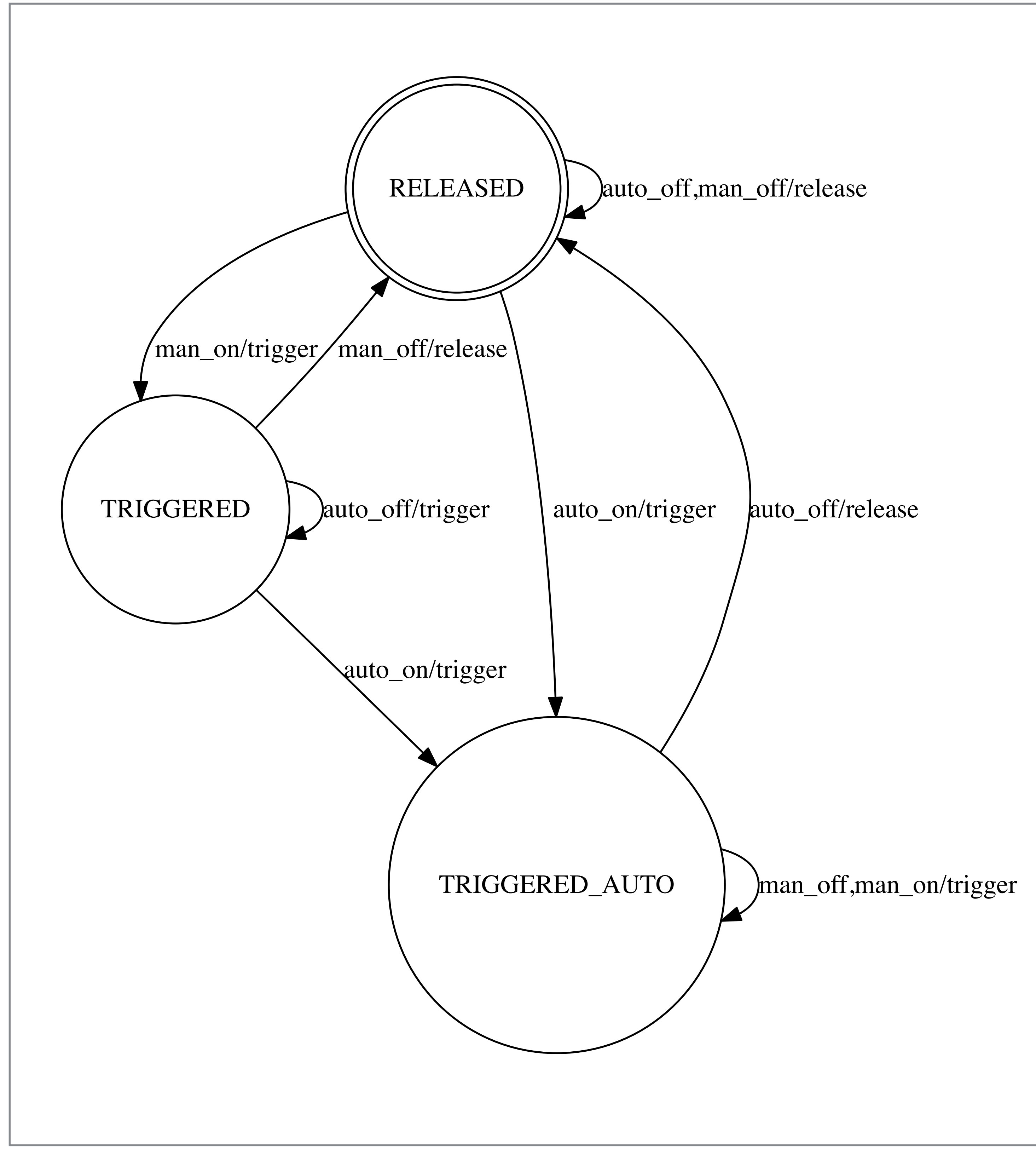


Application scenario – train onboard speed control



Brake controller

- Discrete inputs
- Discrete internal state
- Discrete outputs
- Complete testing strategies available



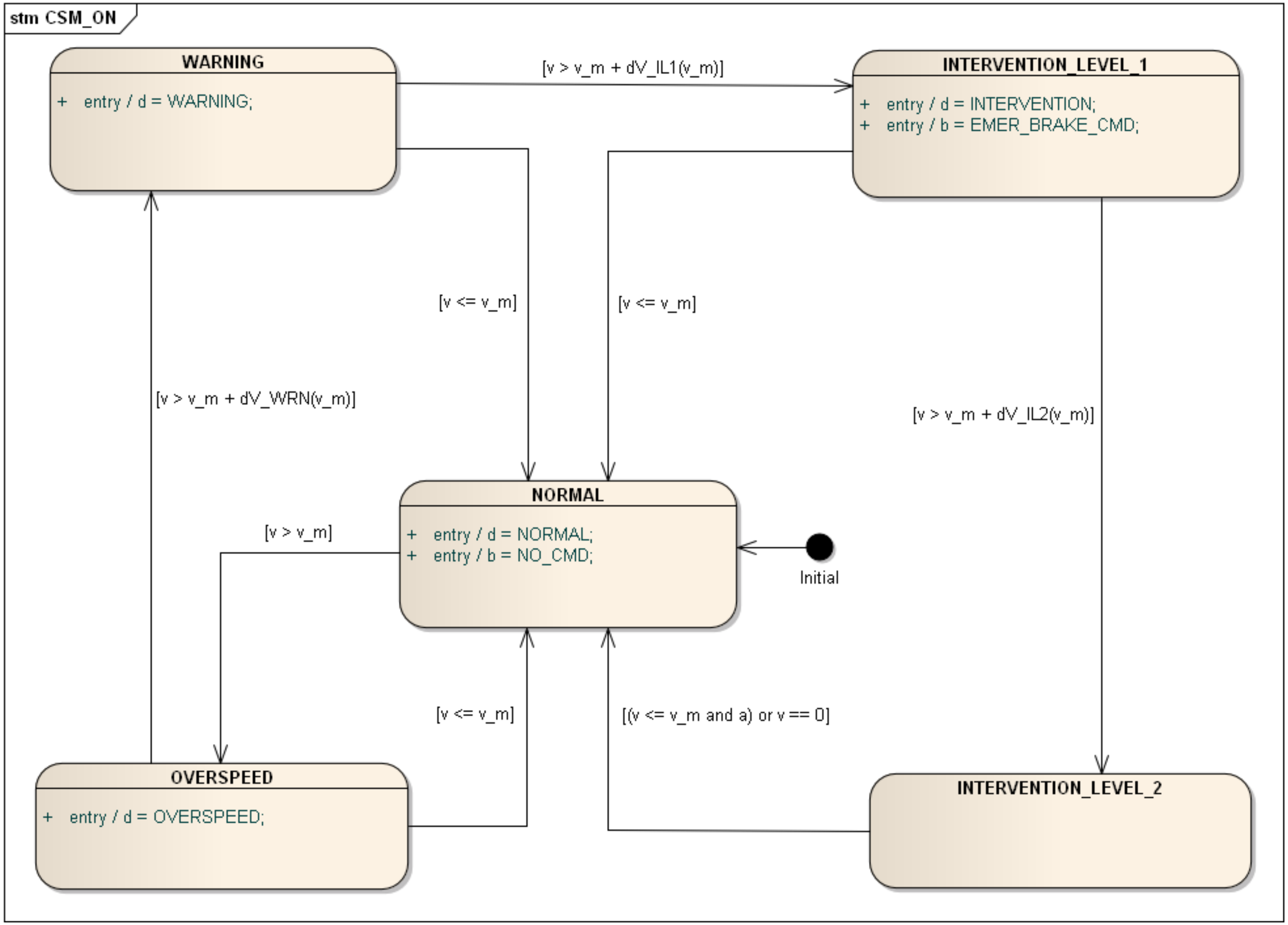
Onboard main controller

- Large input domains – speed
- Discrete internal state
- Discrete outputs

☆Apply input equivalence class testing

☆Can we also apply a complete strategy?

☆**TTT = Testing Theory Translation using institutions**



Verification of emergent properties

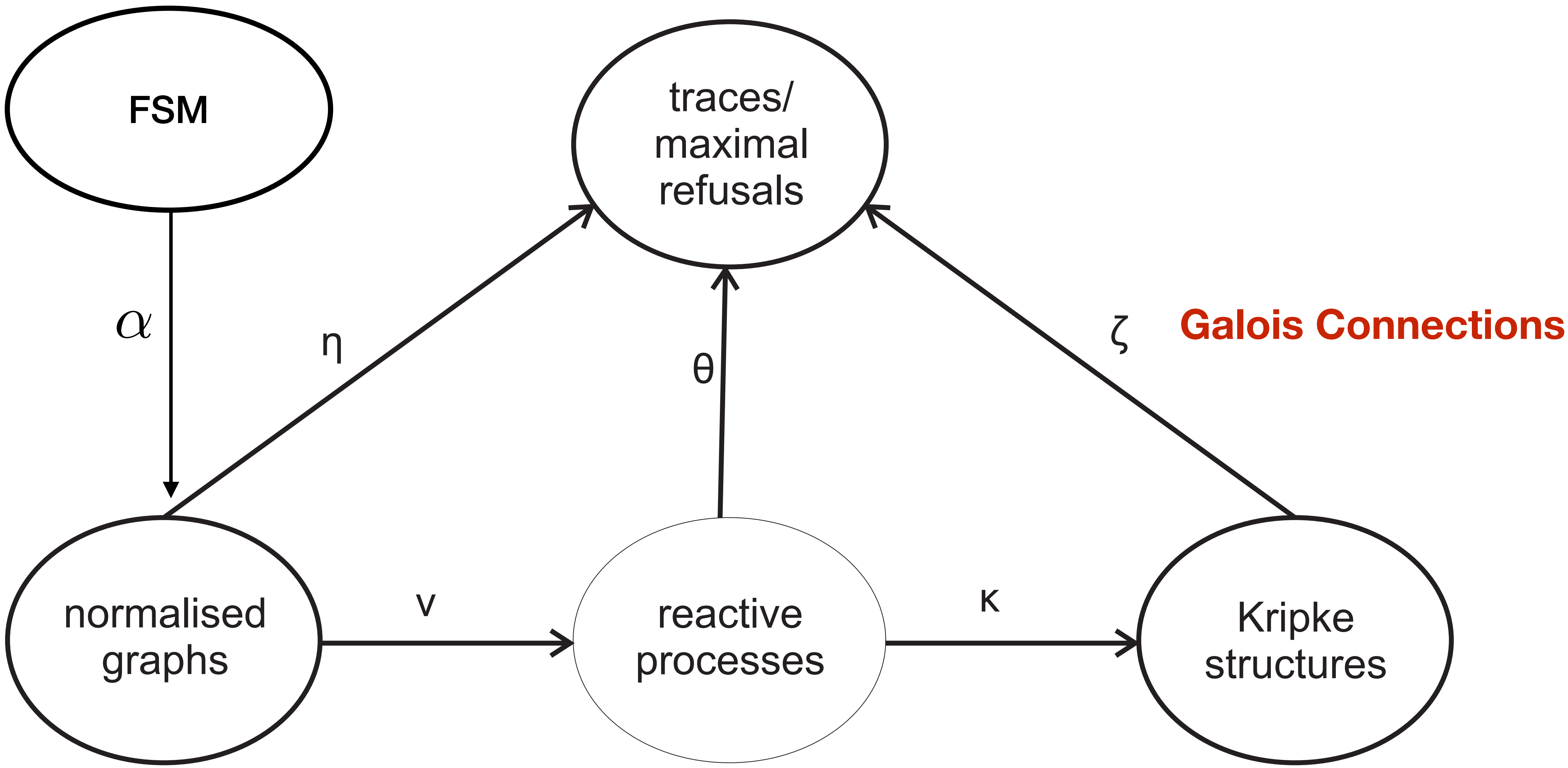
- **Application scenario**
    - Onboard controller has been verified and tested using SysML models with Kripke semantics
    - PLC has been verified and tested using FSM models
        - **Verification objective.** System satisfies emergent property

          EP. *„As long as the speed is above emergency threshold, the emergency brakes stay active and cannot be manually released“*
    - **Technical side condition.** EP shall be specified in CSP trace logic

Verification of emergent properties

- **Problems to be solved**
  - EP can only be specified by referring to properties of both the onboard main controller and the brake controller
  - Properties related to brake controller are specified by FSM I/O sequences **x/y** – e.g. via **intersection with testing automaton**
  - Properties related to Onboard speed controller are specified by, e.g. **LTL formulas with shared I/O variables** as free symbols
  - CSP trace logic formulas are specified over **traces of events and refusal sets**

Linking Theories by UTP



Ana Cavalcanti, Wen-ling Huang, Jan Peleska, **Jim Woodcock**:
CSP and Kripke Structures. ICTAC 2015: 505-523

Dynamicity – changing CPS configuration

Problem Statement

- CPS need cooperating components in **dynamically changing configurations**
- Each component needs to be prepared to
  - **accept/set up/destroy new communication links** from/to other components entering/leaving the configuration
  - enter/leave the configuration itself (**mobility**)

Major Contributions

- **pi-calculus** for dynamic creation of channels
- **Augmented CSP** allowing to simulate Pi-calculus with the means of a “conventional process algebra”
- **Bigraphs** for presenting both topography and communication structure

pi-Calculus and CSP

- Milner's pi-calculus

$$(\nu x)\big(\overline{x}\langle z\rangle.0 \mid x(y).\overline{y}\langle x\rangle.x(y).0\big) \mid z(v).\overline{v}\langle v\rangle.0$$

allows for **dynamic channel creation** and **communication of channel names**

- Roscoe showed that pi-calculus can be simulated by CSP augmented with **throw operator**

$$P \Theta_A Q$$

A.W.Roscoe:
CSP is Expressive Enough for pi.
C.B.Jones et. al. (eds.), Reflections on the work of C.A.R. Hoare, dog 10.1007/978-1-84882-912-1 16, Springer 2010

pi-Calculus and CSP

- Milner's pi-calculus

  $$(\nu x)(\overline{x}\langle z\rangle.0 \mid x$$

  allows for **dynami**
  communication o

As a consequence, "conventional" model checking (e.g. with FDR) can be used to verify mobile process systems

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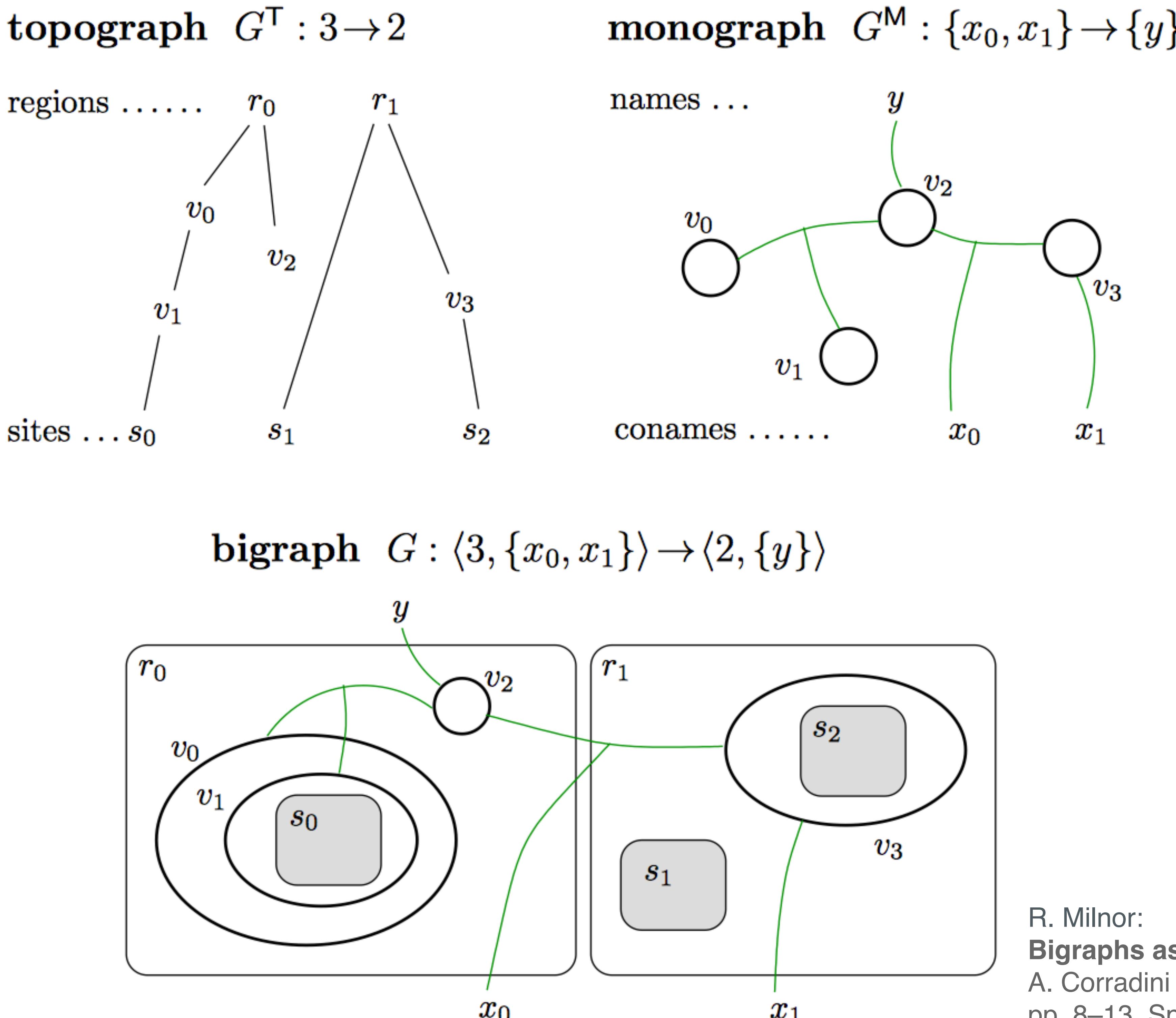
Bigraphs

- Bigraphs allow for representation of
  - **process topography**
  - **communication topology**
  - **dynamic changes** of the former

Bigraphs



R. Milnor:
Bigraphs as a Model for Mobile Interaction
A. Corradini et al. (Eds.): ICGT 2002, LNCS 2505, pp. 8–13, Springer 2002.

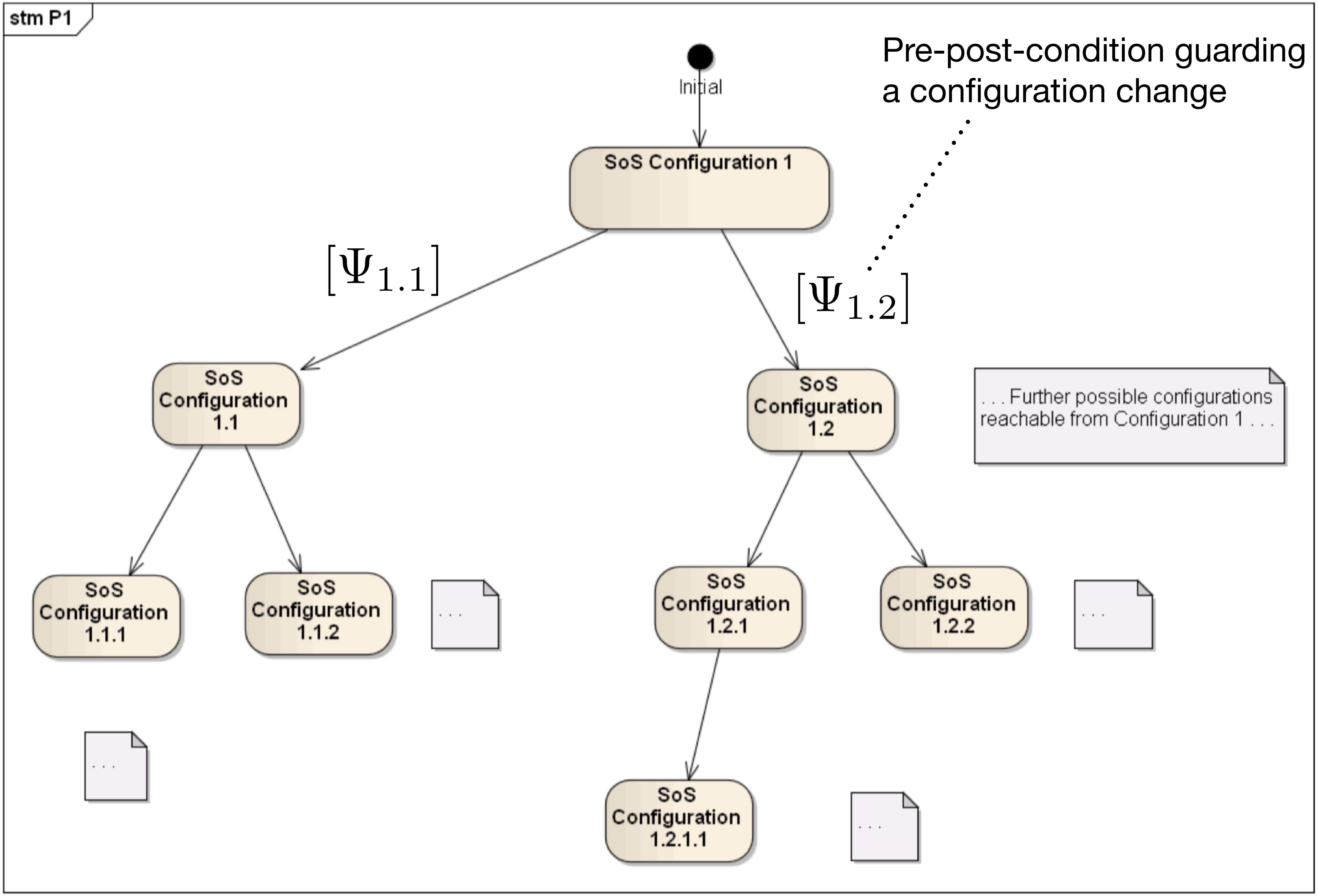
How to Test Dynamic CPS Configurations

- Some things are easier in testing than in general verification
  - Only **safety properties** matter
  - **Tests terminate** after finite amount of time
  - **Finite variability** of HW components implies that only a finite number of configurations can be covered during test execution

How to Test Dynamic CPS Configurations

- Model a **CPS configuration tree**
- Construct **equivalence classes** for configuration changes
- Elaborate **complete testing theory** guaranteeing full fault coverage with finitely many test cases, provided that
  - equivalence classes are adequate
  - CPS components do not have more state equivalence classes than assumed

CPS (or SoS) configuration tree



Evolving behaviour of CPS components

Problem Statement

- CPS components act according to the **rely-guarantee paradigm**

- The **assumptions** component C relies on **may be violated** after some time, due to

  - configuration changes

  - evolving behaviour of other components

- C needs to **adapt its behaviour** to the new environment conditions

What is to be Solved?

- **Detection**. Component needs to “understand” that its assumptions no longer hold
- **Change of belief**. Component needs to update its assumptions about the environment
- **Adaptation**. Component needs to “optimise” its behaviour w.r.t. the new assumptions

Detection

- For **regular safety properties**, the detection problem is completely solved
- Can be implemented efficiently for **hard real-time** applications

Recall. A safety property over atomic propositions AP is regular, if its **bad prefixes** in $(2^{AP})^*$ form a regular language.

Detection

- Therefore, the bad prefix set can be represented by **accepting states of an FSM**

- **One more problem to solve**. CPS component may not know the trace of system observations from the start, since it may join the configuration at a later state

    - Use a **homing algorithm** to determine the FSM state by a sequence of observations

- The detection problem is a **passive testing problem**

Detection – an Example

- Suppose, component C relies on the environment to fulfil safety condition

$$\begin{aligned}\Phi \quad \equiv \quad & s_0 \wedge \mathbf{G}\Big((s_0 \wedge \mathbf{X}(s_1 \wedge a)) \vee \\ & (s_1 \wedge \mathbf{X}((s_0 \wedge b) \vee (s_2 \wedge a))) \vee \\ & (s_2 \wedge \mathbf{X}(s_1 \wedge b))\Big)\end{aligned}$$

with internal state variable s_j and assumption that a or b must occur in every step

Example trace. $a.b.a.a.b.a.b.b\ldots$

Detection

b follows a – at most two more a’s than b’s

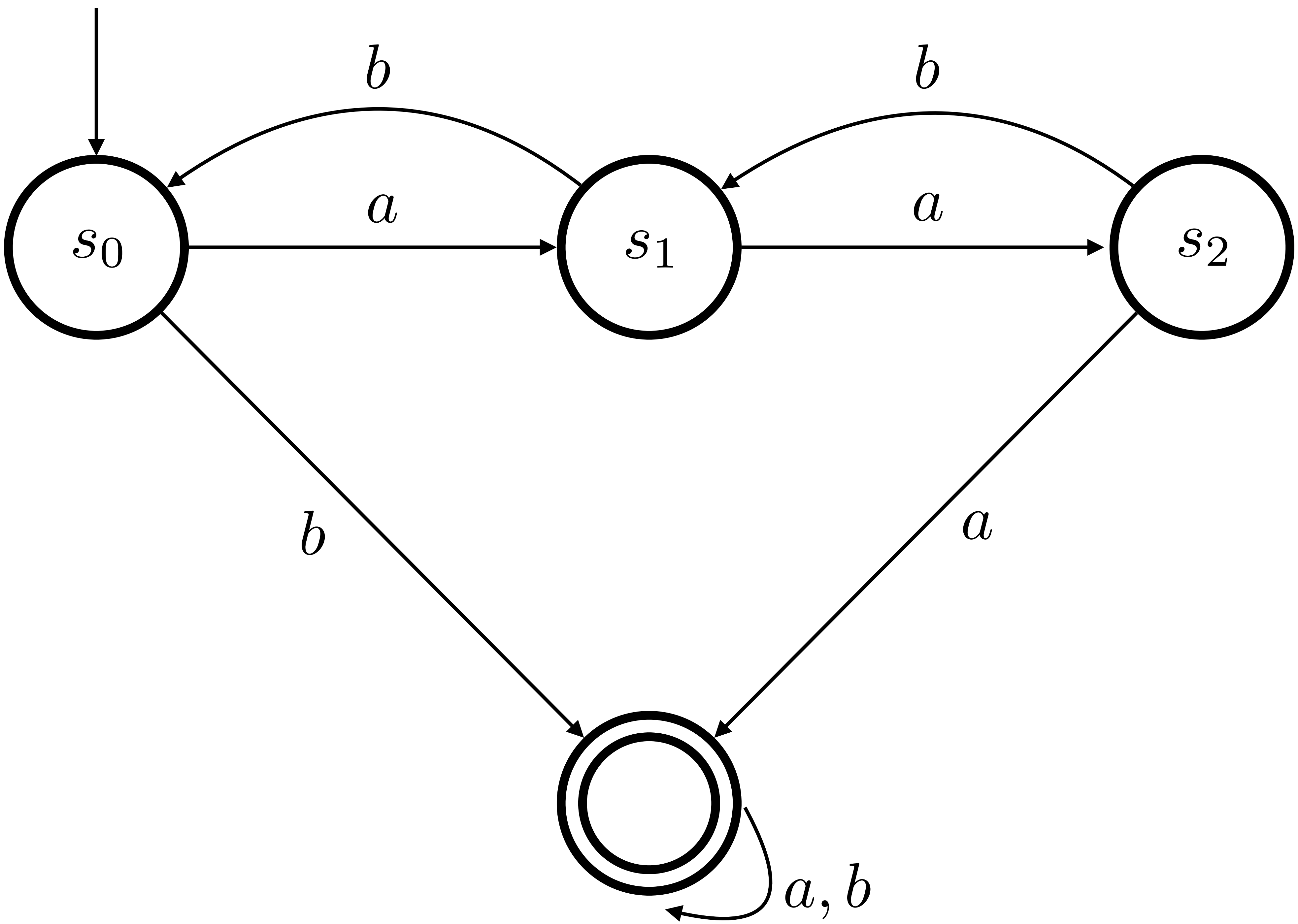
- Suppose, component C
  safety condition

$$\Phi \equiv s_0 \wedge \mathbf{G}\Big((s_0 \wedge \mathbf{X}(s_1 \wedge a)) \vee (s_1 \wedge \mathbf{X}((s_0 \wedge b) \vee (s_2 \wedge a))) \vee (s_2 \wedge \mathbf{X}(s_1 \wedge b))\Big)$$

with internal state variable s_j and assumption that a or b must occur in every step

Example trace. $a.b.a.a.b.a.b.b\ldots$

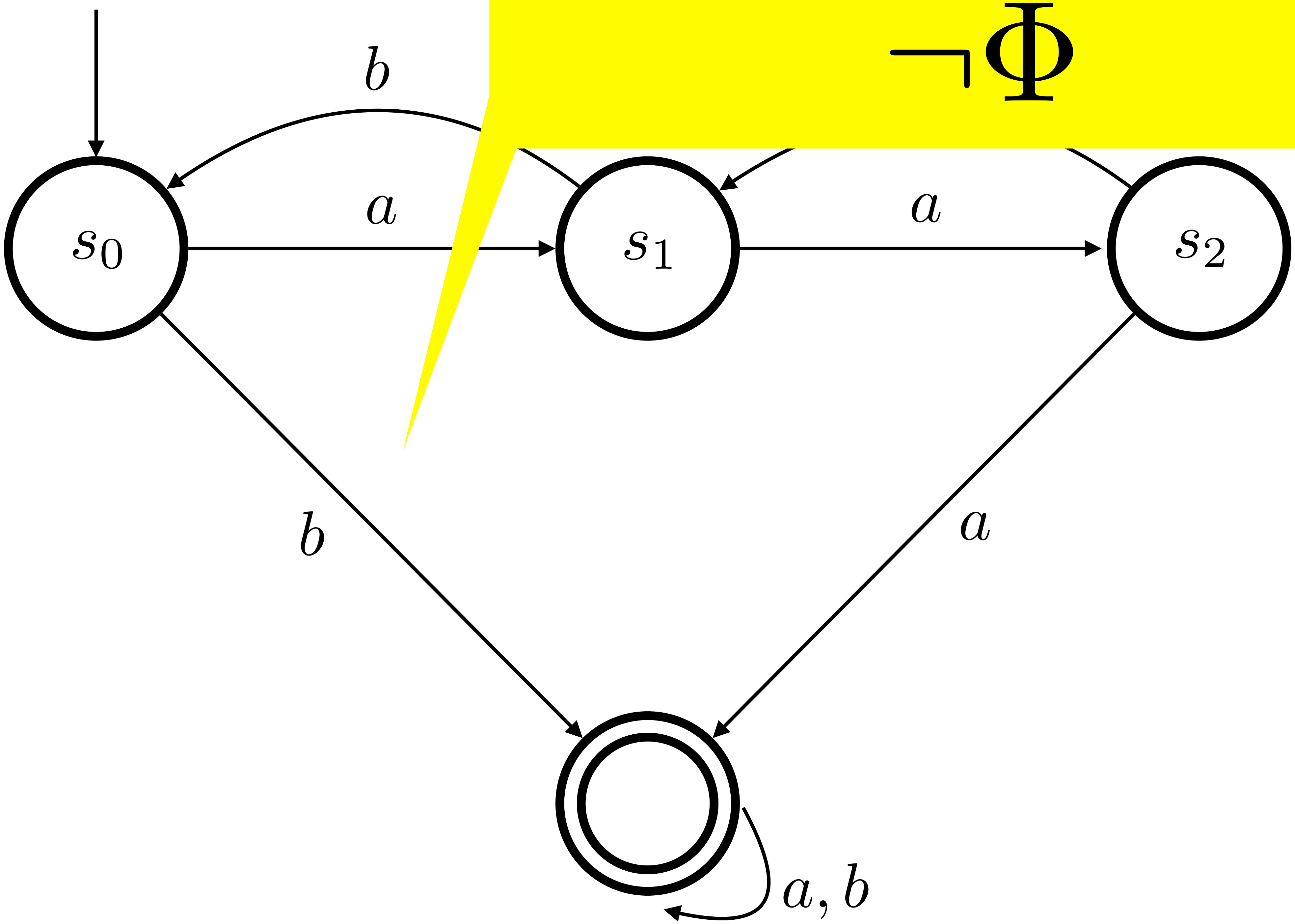
Example (continued). FSM modelling bad prefixes of the safety condition



Example (continued). condition

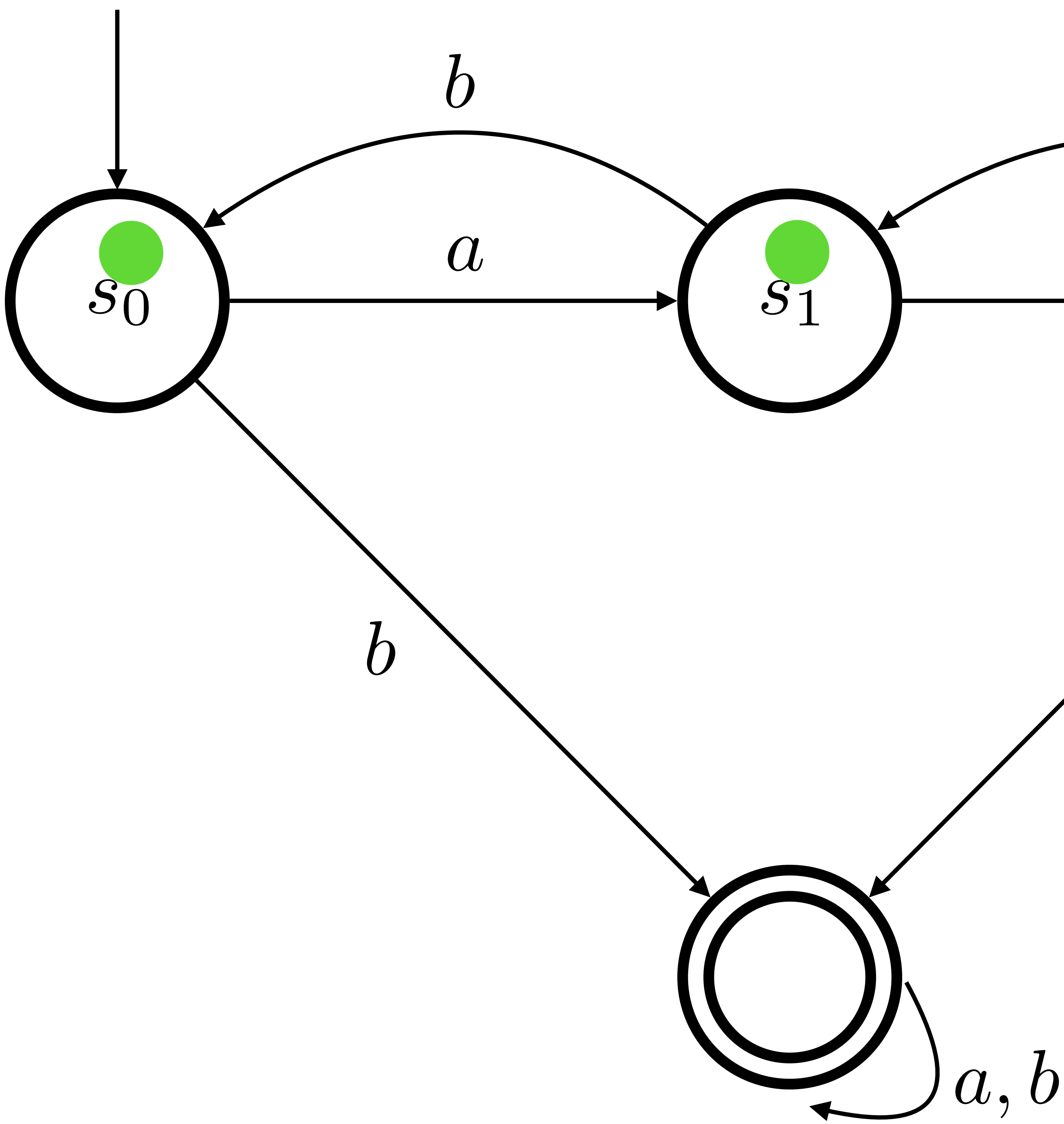
Can be generated, for example with ltl2ba from

$$\neg\Phi$$



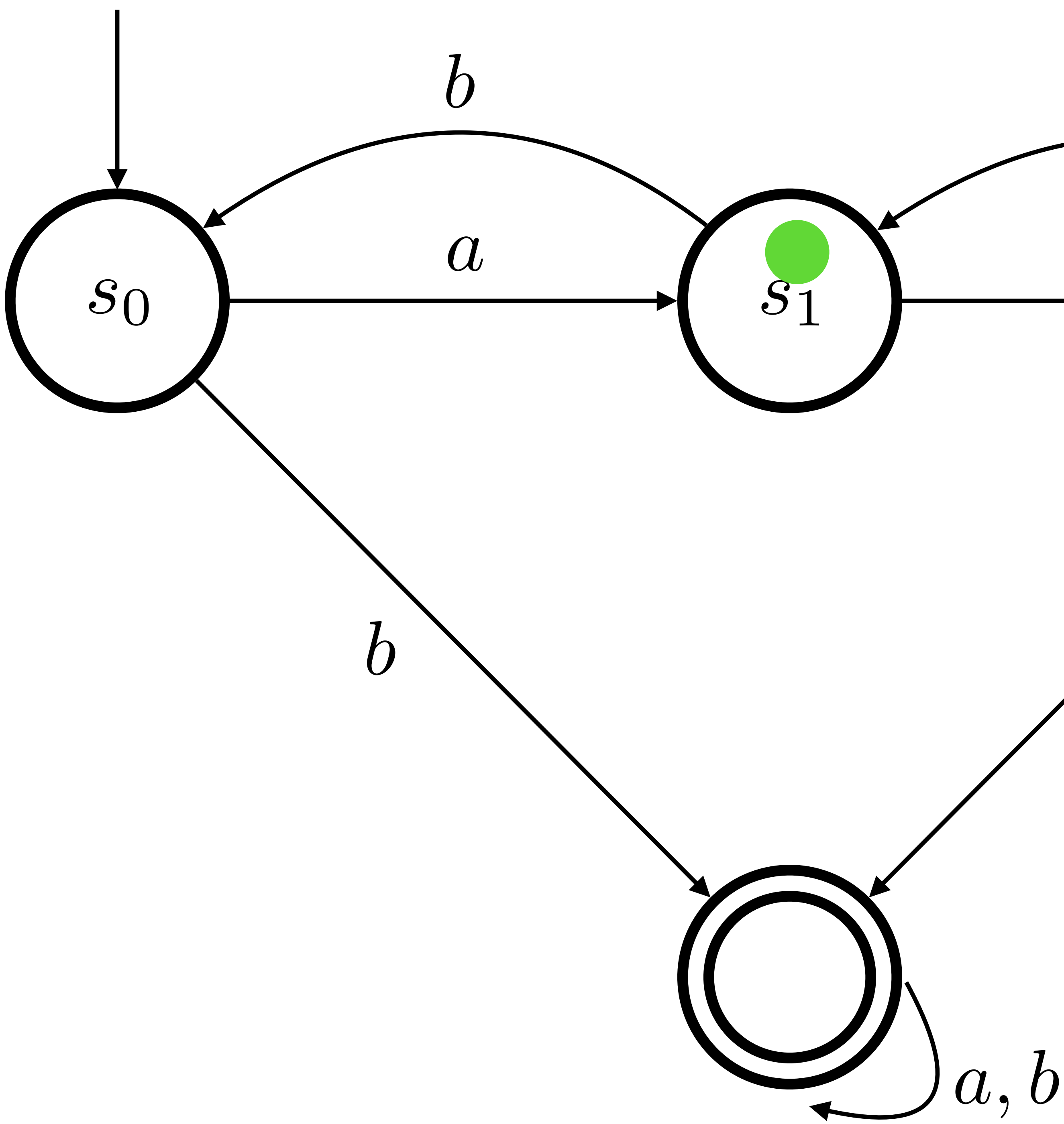
Example (continued). Application of the homing algorithm

Initial checking state



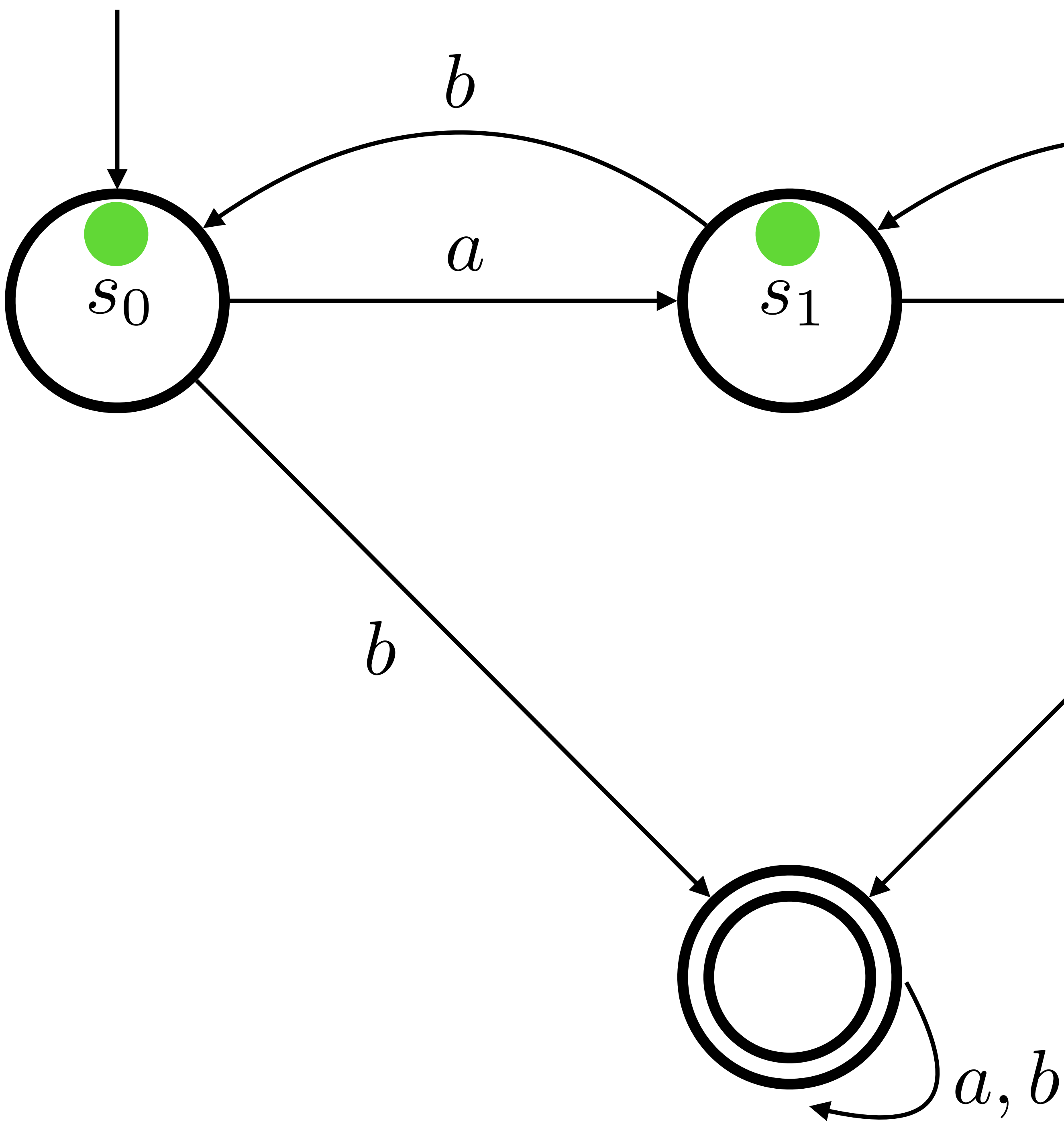
Example (continued). Application of the homing algorithm

Observation b



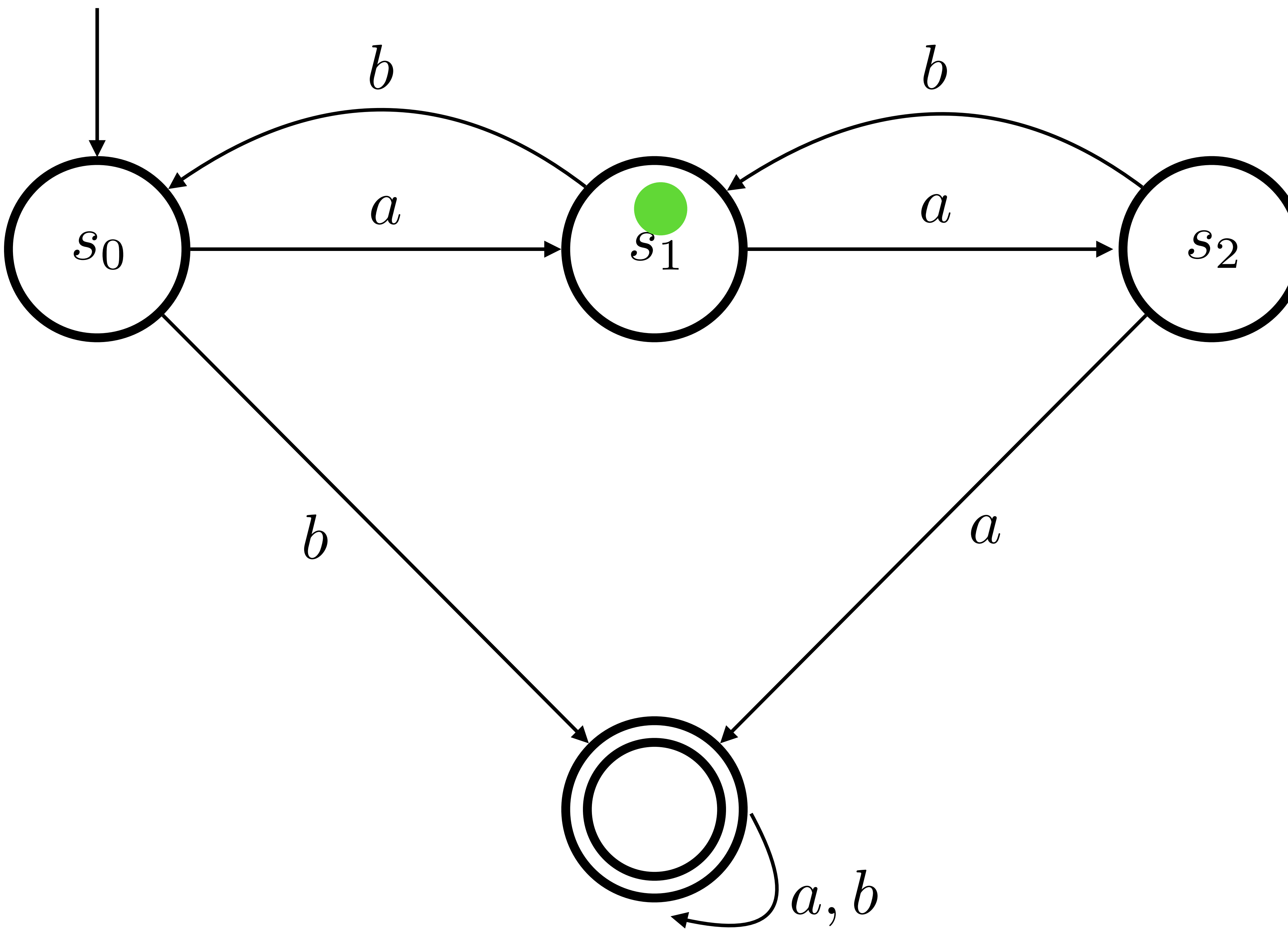
Example (continued). Application of the homing algorithm

Observation b – post-state



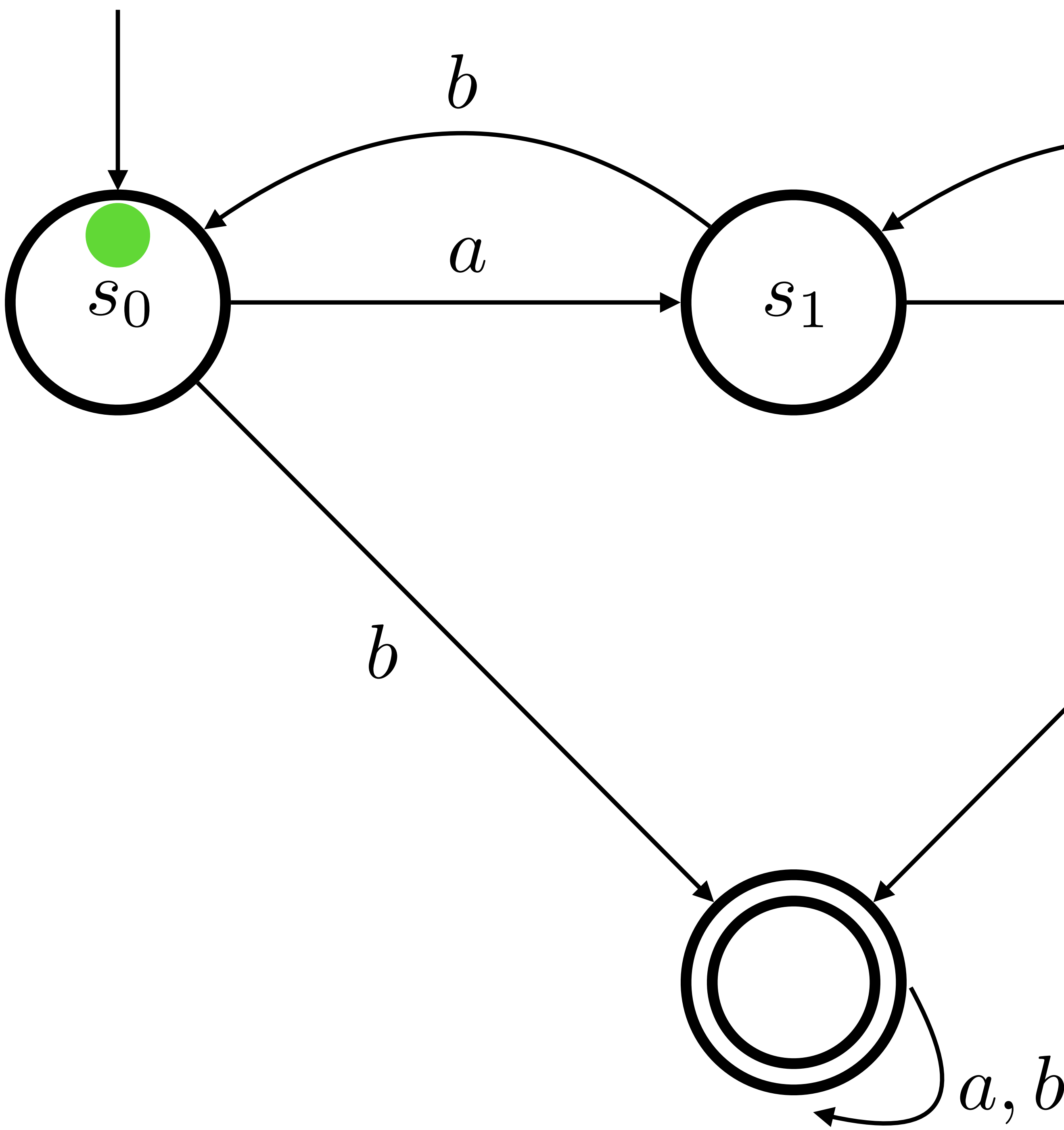
Example (continued). Application of the homing algorithm

Observation b.b



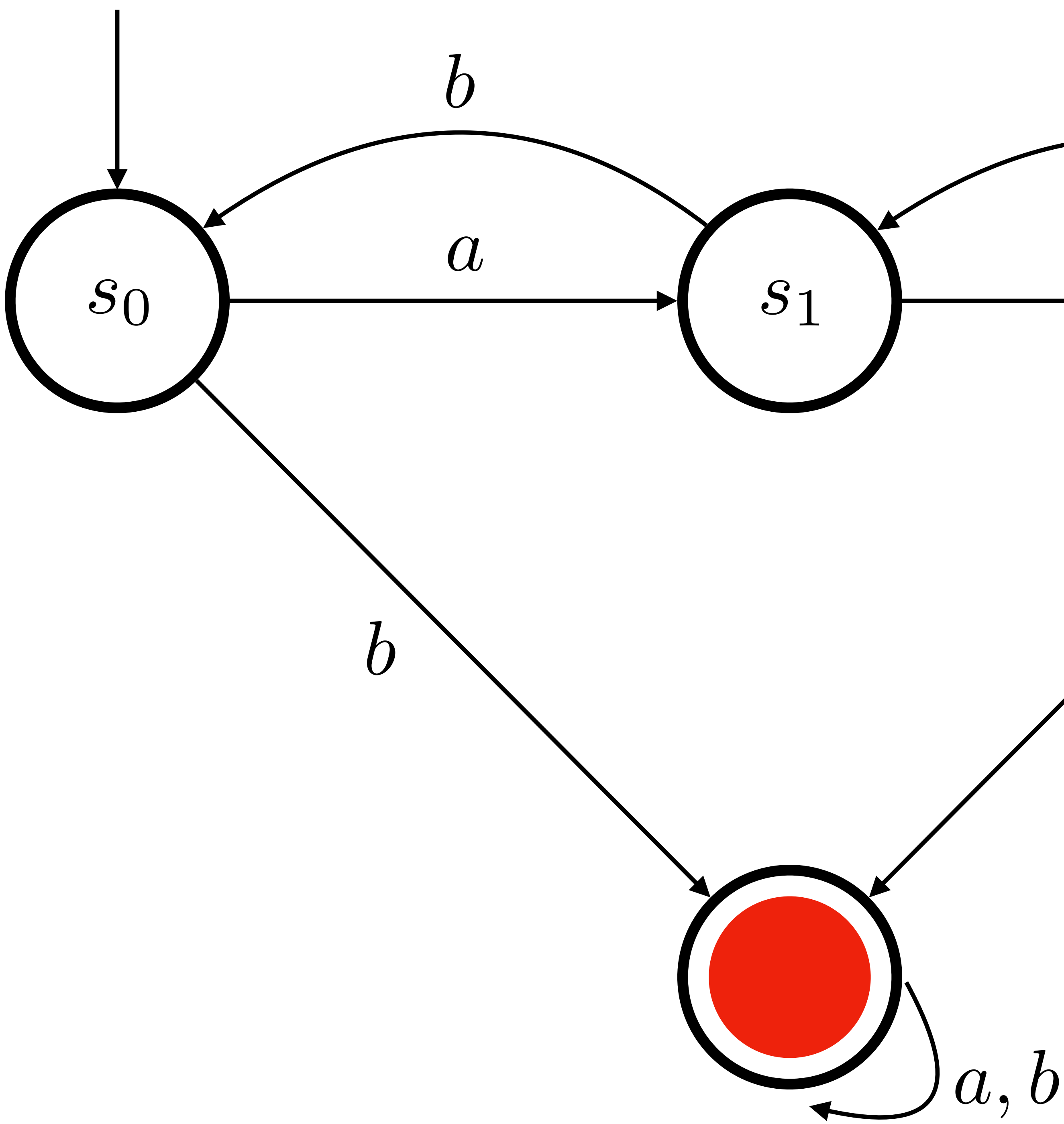
Example (continued). Application of the homing algorithm

Observation b.b – post-state



Example (continued). Application of the homing algorithm

Observation b.b.b – safety-violation



Change of Belief

- Different options with different complexity
  - **Assumptions are just “true”** – components can adapt to any environment behaviour (examples from control theory)
  - **Expected violations** of assumptions – **fault-tolerant adaptation** of behaviour under new, pre-defined assumptions
  - **Unexpected violations** of assumptions – new valid assumptions need to be extracted from observations (apply **machine learning**, construct temporal properties reflecting environment behaviour)

Change of Belief

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Can this be achieved in hard real-time?

Adaptation

- Solved, as far as
  - basic laws of **control theory** can be applied
  - optimal behaviour can be specified as mathematical boundary value problem or general optimisation problem
- Can be modelled by **Hybrid Automata**, if discrete changes between different control laws/optimisation methods are required

Adaptation

- Open questions
  - **Q1.** After change of belief system consisting of (temporal) logic formulas: how can we defined the **optimal behaviour** w.r.t. goals and belief system ?
  - **Q2.** If such a temporal logic formula for optimal behaviour could be found, could it become possible to **synthesise** the new component behaviour on the fly in hard real-time?

A Tentative Solution for Q1

- Specialised problem statement
  - If, due to changes in the environment behaviour, a CPS component can no longer fulfil its original guarantees, is there a possibility to specify a graceful degradation of behaviour in a well-founded way?
- Suggestion from testing theory
  - Classify component outputs according to criticality
  - Identify outputs of “negligible” criticality
  - Realise behaviour that is equivalent to the original specification, with all outputs of negligible criticality identified

Conclusion

- We discussed 3 topics of new-age concurrency
  - Multi-formalism support for CPS development and verification
  - Modelling and testing of dynamically changing CPS configurations
  - Modelling and testing evolving behaviour of CPS
- We have seen that many “mechanisms” and approaches already exist to tackle these challenges
- Do we need more — a comprehensive new theory & formalism, instead of a “bag of special solutions” ?

Further Reading

- About cyber-physical systems and mobile and channels

A.W. Roscoe. CSP is Expressive Enough for π. In C.B. Jones et al. (eds.), Reflections on the Work of C.A.R. Hoare, DOI 10.1007/978-1-84882-912-1 16, Springer, 2010.

Jim Woodcock, Andy Wellings, and Ana Cavalcanti. Mobile CSP. In M. Cornelio and B. Roscoe (Eds.): SBMF 2015, LNCS 9526, pp. 39–55, 2016. DOI: 10.1007/978-3-319-29473-5 3, Springer, 2016.

- About testing and equivalence classes

Wen-ling Huang and Jan Peleska. Complete model-based equivalence class testing for nondeterministic systems. DOI 10.1007/s00165-016-0402-2 BCS © 2016 Formal Aspects of Computing (2017) 29: 335–364

Acknowledgements

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