Semantic Families for Cyber-physical Systems

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BCS FACS - Annual Peter Landin Semantics Seminar 2015

Overview

- Semantics for CPS – time for a change of paradigm?
- Multiple formalisms in CPS modelling
  - Example 1. Testing theories and collaborative tool environments
  - Example 2. Verification of emergent properties
- Conclusions and future work

- **Semantics for CPS – time for a change of paradigm?**
- Multiple formalisms in CPS modelling
    - Example 1. Testing theories and collaborative tool environments
    - Example 2. Verification of emergent properties
- Conclusions and future work

Semantics for CPS – time for a change of paradigm ?

Recall

- The investigation of concurrent systems semantics started somewhere in the seventies of the last century

C. A. R. Hoare:
Communicating Sequential Processes. Commun. ACM 21(8): 666-677 (1978)

Recall

- Since then, a multitude of formalisms has been developed and successfully applied to

- **Development**
  - modelling
  - code generation

- **Verification & Validation**
  - theorem proving
  - model checking
  - simulation
  - testing

Cyber-physical systems

- Systems of collaborating computational elements controlling physical entities

https://en.wikipedia.org/wiki/Cyber-physical_system

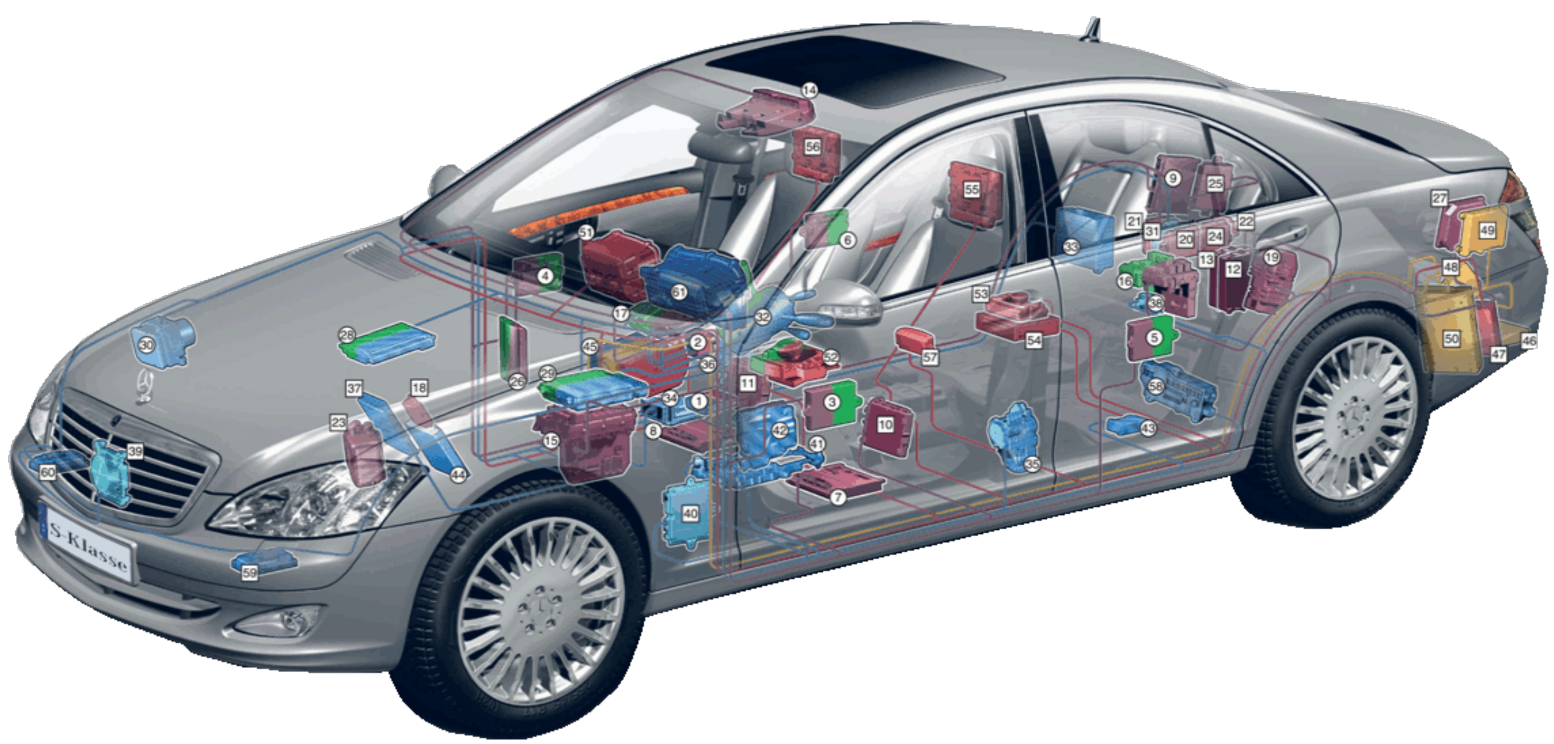


Image courtesy of Daimler AG

Some CPS-characteristics affecting semantic modelling

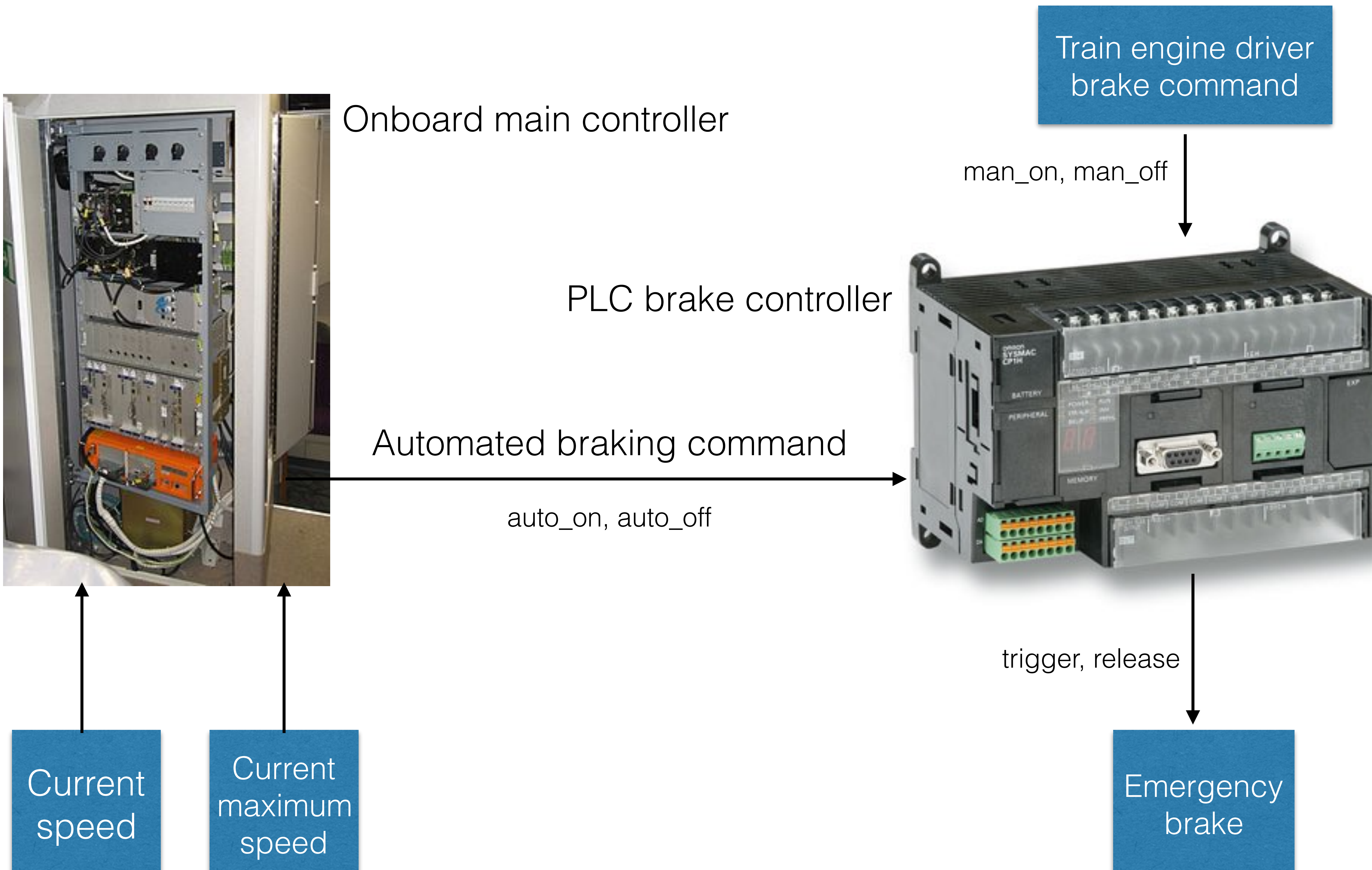
Characteristic	Semantics
Distribution, time-discrete and time-continuous control	☑ Hybrid systems semantics
Modeling using multiple formalisms	**Model, sentence, and theory translation**
Emergent properties	Temporal logic, trace logic – **how to verify in presence of multiple formalisms?**
Dynamic re-configuration	Semantics for object-oriented systems – or can we find something simpler?
Evolution of asserted component behaviours	New paradigms for behavioural assertions?
Large numbers of replicated components	Can the knowledge about replication lead to optimised V&V methods?

Multiple formalisms in CPS modelling – Example 1. Testing theories and collaborative tool environments

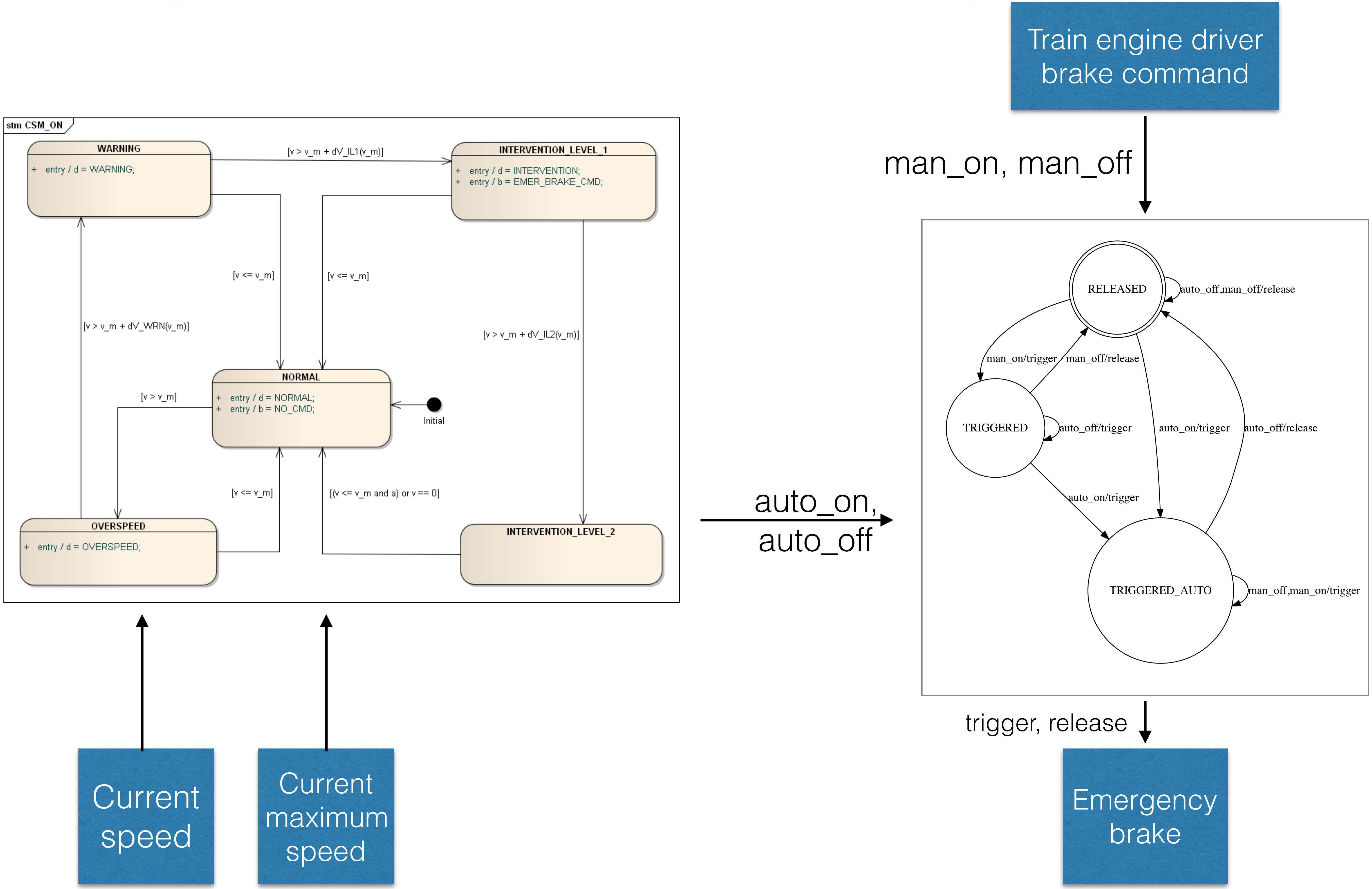
Application scenario

- 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



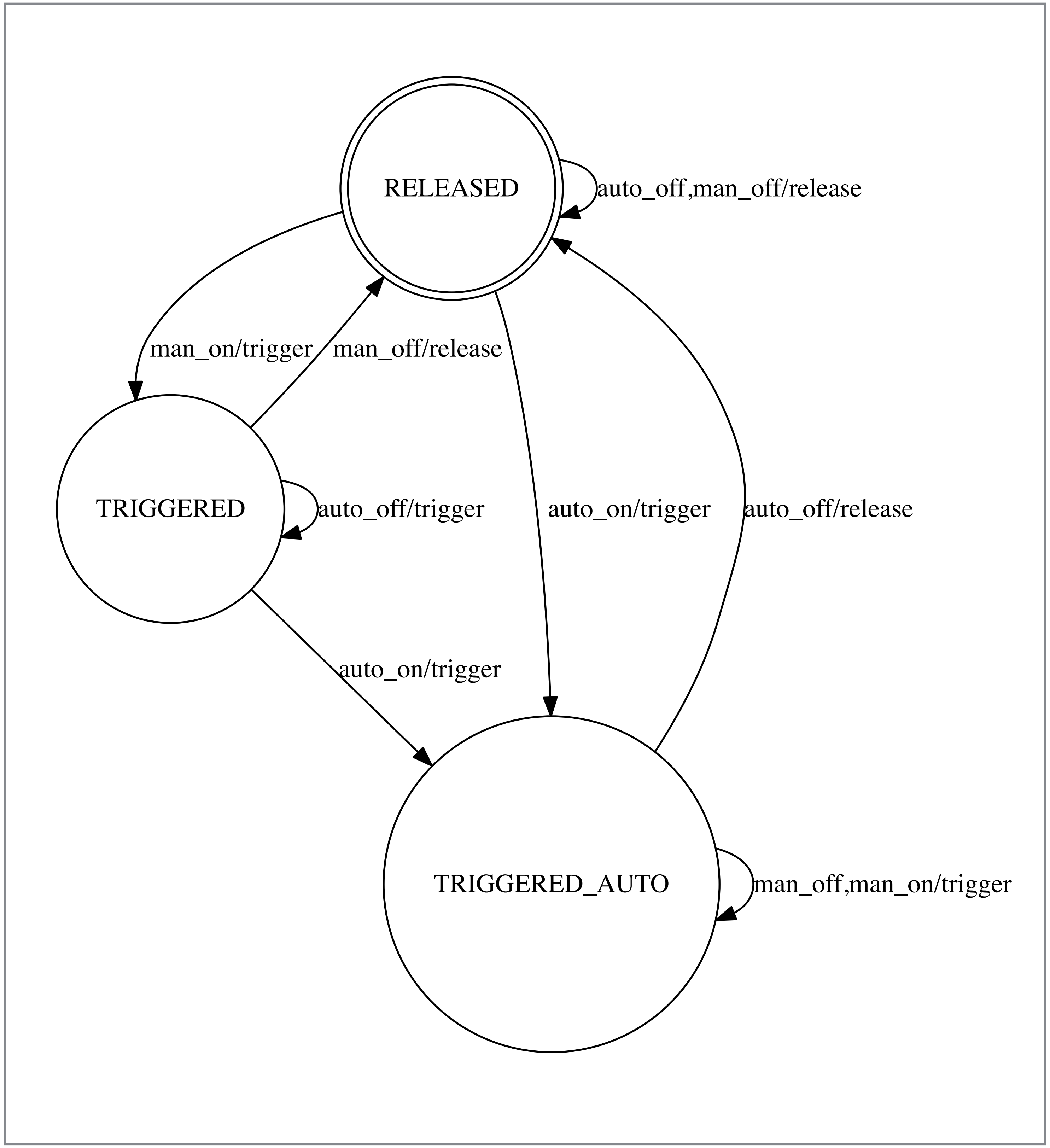
Application scenario – train onboard speed control



- Discrete inputs
- Discrete internal state
- Discrete outputs

⭐Apply **complete FSM testing strategy**

Brake controller



Complete test suites

- Defined with respect to **fault model** (*M*, ≤, *Dom*), that is,
  - a reference model *M*
  - a conformance relation ≤
  - a fault domain *Dom*
- **Complete** = sound + exhaustive
- **Sound** = every *M'* in *Dom* <u>satisfying</u> *M'* ≤ *M* <u>passes</u>
- **Exhaustive** = every *M'* in *Dom* <u>violating</u> *M'* ≤ *M* <u>fails</u>

Complete FSM test suites

- For FSMs, many complete testing strategies exist
  - for deterministic or nondeterministic FSMs
  - for completely defined or incomplete FSMs

Alexandre Petrenko, Nina Yevtushenko:
Adaptive Testing of Nondeterministic Systems with FSM. HASE 2014: 224-228

Robert M. Hierons:
Testing from a Nondeterministic Finite State Machine Using Adaptive State Counting.
IEEE Trans. Computers 53(10): 1330-1342 (2004)

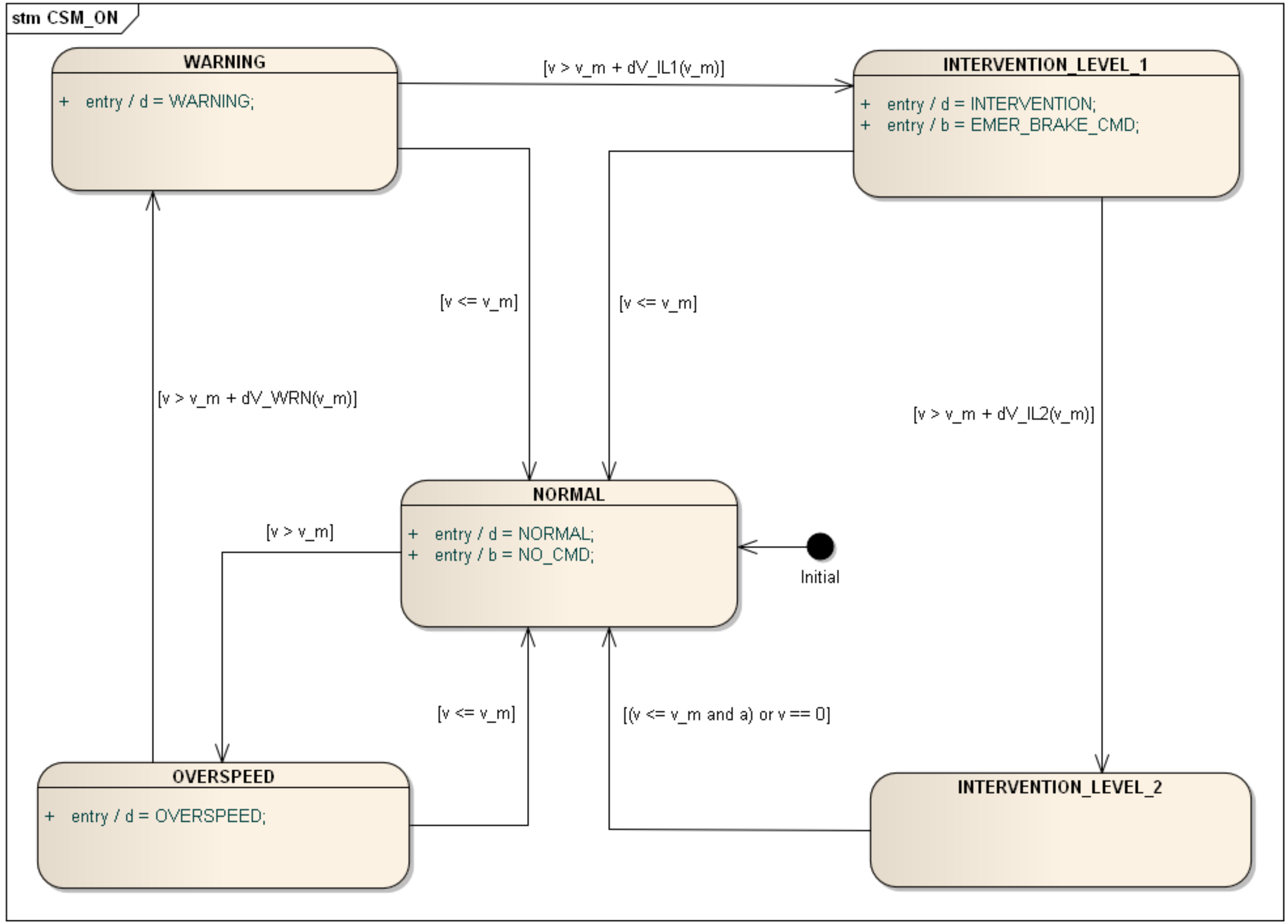
Onboard main controller

- 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**



TTT

- Consider different **semantic domains** with their conformance relations
  - Finite state machines – language equivalence, language containment
  - Kripke structures – I/O-equivalence, I/O-refinement
- Fix a **signature** in each domain
  - Sig_1 – Kripke structures over fixed I/O variables
  - Sig_2 – FSMs over fixed I/O-alphabet

TTT

- Create a **model map** *T* from sub-domain of *Sig*$_1$ to *Sig*$_2$

$$T : Dom_1 \to Sig_2;$$
$$Dom_1 \subseteq Sig_1$$

- Create a **test case map** T* from test cases of *Sig*$_2$ to test cases of *Sig*$_1$

$$T^* : \mathrm{TC}(Sig_2) \to \mathrm{TC}(Sig_1)$$

- Prove the **satisfaction condition**

Satisfaction condition

Condition 1. The model map is compatible with the conformance relations

$$\forall \mathcal{S}, \mathcal{S}' \in Dom_1 : \mathcal{S}' \leq_1 \mathcal{S} \Leftrightarrow T(\mathcal{S}') \leq_2 T(\mathcal{S})$$

Condition 2. Model map and test case map preserve the *pass* relationship

$$\forall \mathcal{S} \in Dom_1, U \in \mathrm{TC}(Sig_2) : T(\mathcal{S}) \ \underline{\mathrm{pass}_2}\ U \Leftrightarrow \mathcal{S}\ \underline{\mathrm{pass}_1}\ T^*(U)$$

Satisfaction condition,

reflected by commuting diagrams and relational composition

Condition 1

$$
\begin{tikzcd}
T(Dom_1) \arrow[r, "\leq_2"] & T(Dom_1) \\
Dom_1 \arrow[u, "T"] \arrow[r, "\leq_1"] & Dom_1 \arrow[u, "T"']
\end{tikzcd}
$$

$$T; \leq_2 \; = \; \leq_1; T$$

Condition 2

$$
\begin{tikzcd}
T(Dom_1) \arrow[r, "\underline{\text{pass}}_2"] & \mathrm{TC}(Sig_2) \arrow[d, "T^*"] \\
Dom_1 \arrow[u, "T"] \arrow[r, "\underline{\text{pass}}_1"] & T^*(\mathrm{TC}(Sig_2))
\end{tikzcd}
$$

$$\underline{\text{pass}}_1 \;=\; T; \underline{\text{pass}}_2; T^*$$

Recall. Relational composition

$$f \subseteq X \times Y, \quad g \subseteq Y \times Z$$

$$f ; g = g \circ f = \{(x, z) \mid \exists y : (x, y) \in f \wedge (y, z) \in g\}$$

Condition 1

$$\begin{tikzcd}
T(Dom_1) \arrow[r, "\leq_2"] & T(Dom_1) \\
Dom_1 \arrow[u, "T"] \arrow[r, "\leq_1"] & Dom_1 \arrow[u, "T"']
\end{tikzcd}$$

$$T ; \leq_2 \; = \; \leq_1 ; T$$

Condition 2

$$\begin{tikzcd}
T(Dom_1) \arrow[r, "\underline{\mathrm{pass}}_2"] & \mathrm{TC}(Sig_2) \arrow[d, "T^*"] \\
Dom_1 \arrow[u, "T"] \arrow[r, "\underline{\mathrm{pass}}_1"] & T^*(\mathrm{TC}(Sig_2))
\end{tikzcd}$$

$$\underline{\mathrm{pass}}_1 \;\; = \;\; T ; \underline{\mathrm{pass}}_2 ; T^*$$

General theorem for translation of testing theories

Theorem 1. Suppose *(T,T*)* exist and fulfil the satisfaction condition. Then every complete (sound, exhaustive) testing theory established in Sig_2 induces a likewise complete (sound, exhaustive) testing theory on Sig_1

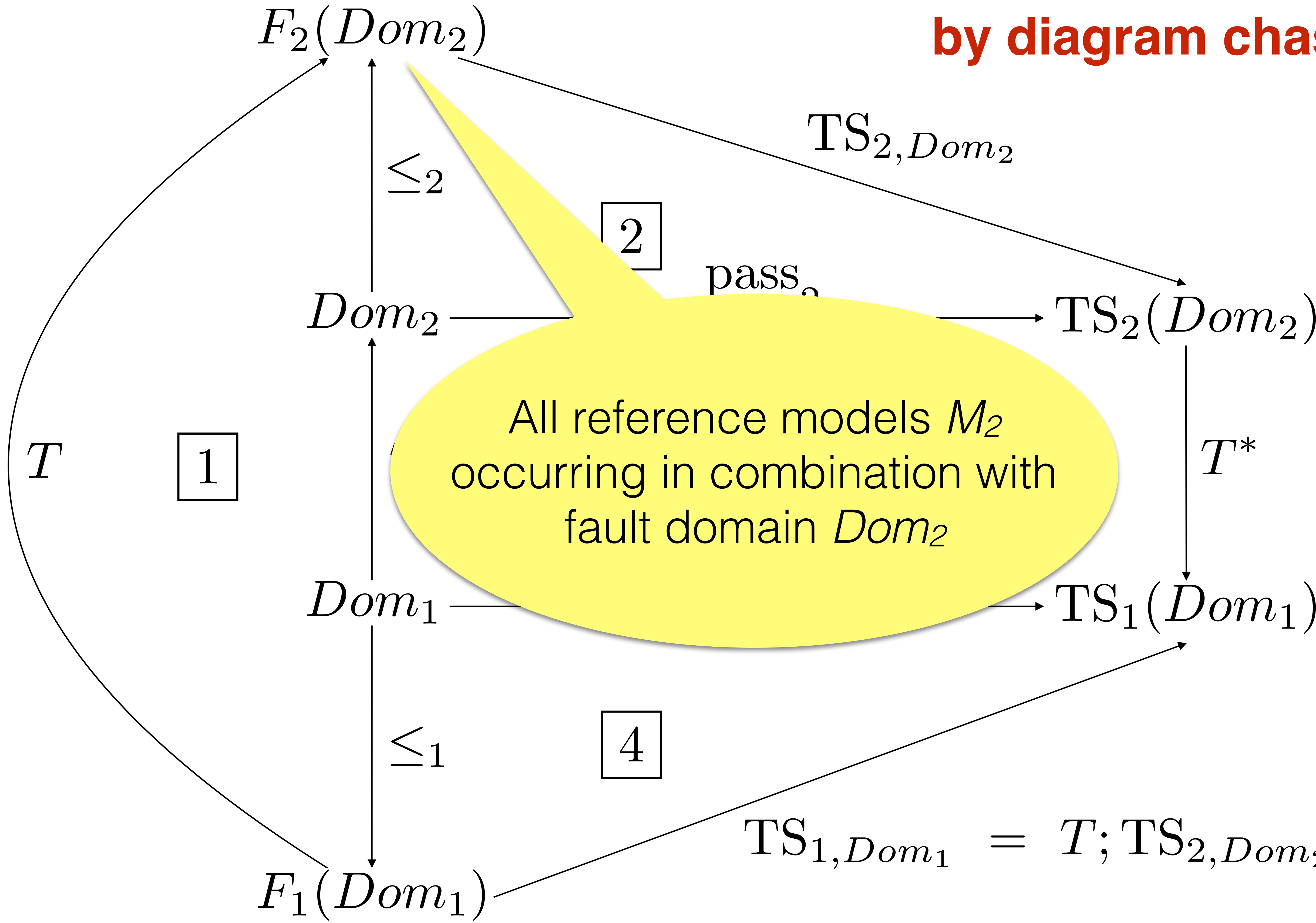
Wen-ling Huang, Jan Peleska:
Complete Model-Based Equivalence Class Testing for Nondeterministic Systems.
Submitted to Formal Aspects of Computing, 2015

Proof of Theorem 1 by diagram chasing

$$
\begin{tikzcd}
F_2(Dom_2) \arrow[dr, "\mathrm{TS}_{2,Dom_2}"] & {} \\
Dom_2 \arrow[u, "\leq_2"'] \arrow[r, "\underline{\mathrm{pass}}_2"] \arrow[ur, phantom, "\boxed{2}"] \arrow[dr, phantom, "\boxed{3}"] & \mathrm{TS}_2(Dom_2) \arrow[d, "T^*"] \\
Dom_1 \arrow[u, "T"'] \arrow[r, "\underline{\mathrm{pass}}_1"] \arrow[d, "\leq_1"] \arrow[dr, phantom, "\boxed{4}"] & \mathrm{TS}_1(Dom_1) \\
F_1(Dom_1) \arrow[uuu, bend left=60, "T"] \arrow[uuu, phantom, bend left=30, "\boxed{1}"] \arrow[ur] & {}
\end{tikzcd}
$$

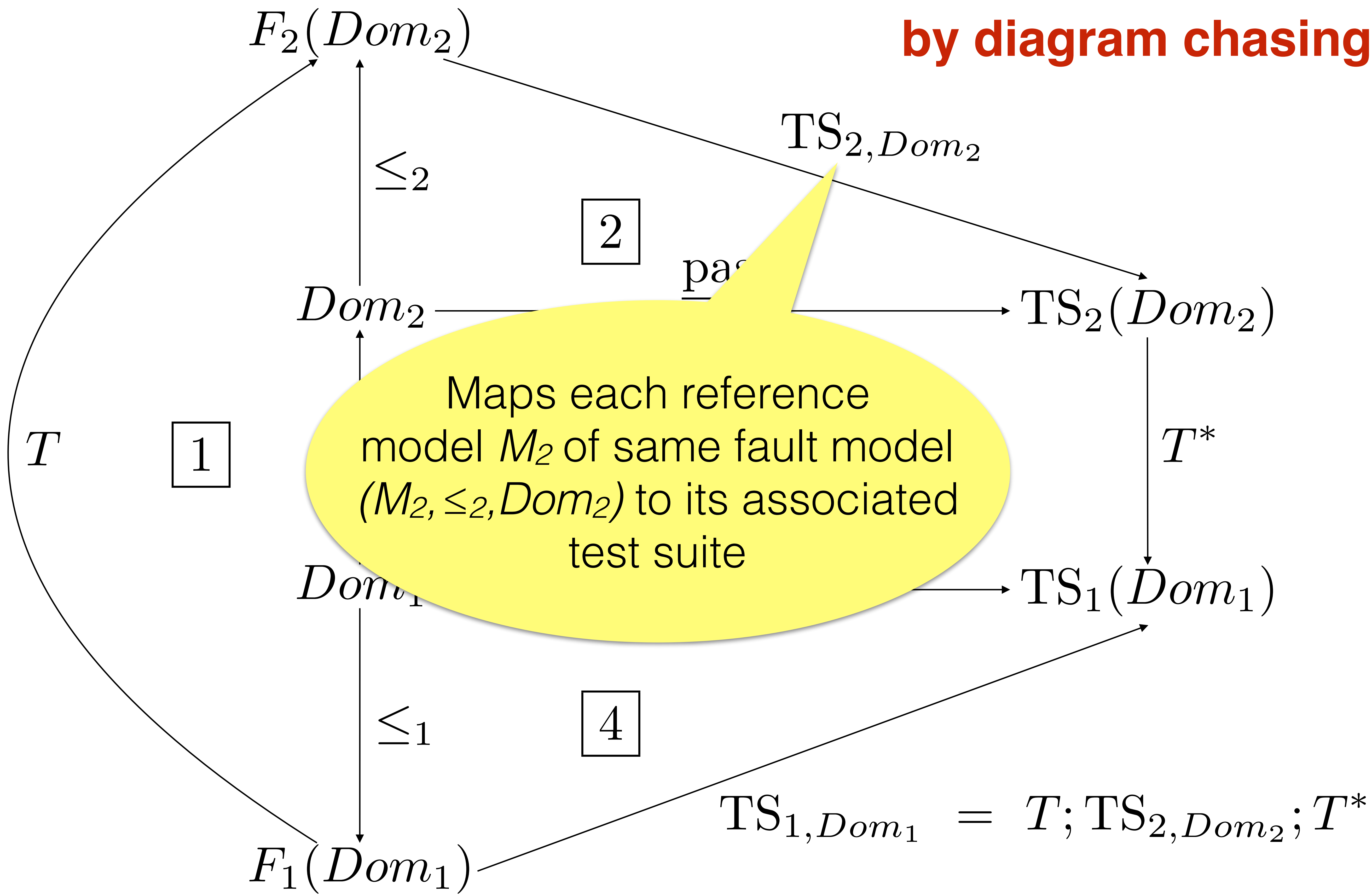
$$\mathrm{TS}_{1,Dom_1} \;=\; T; \mathrm{TS}_{2,Dom_2}; T^*$$

Proof of Theorem 1 by diagram chasing

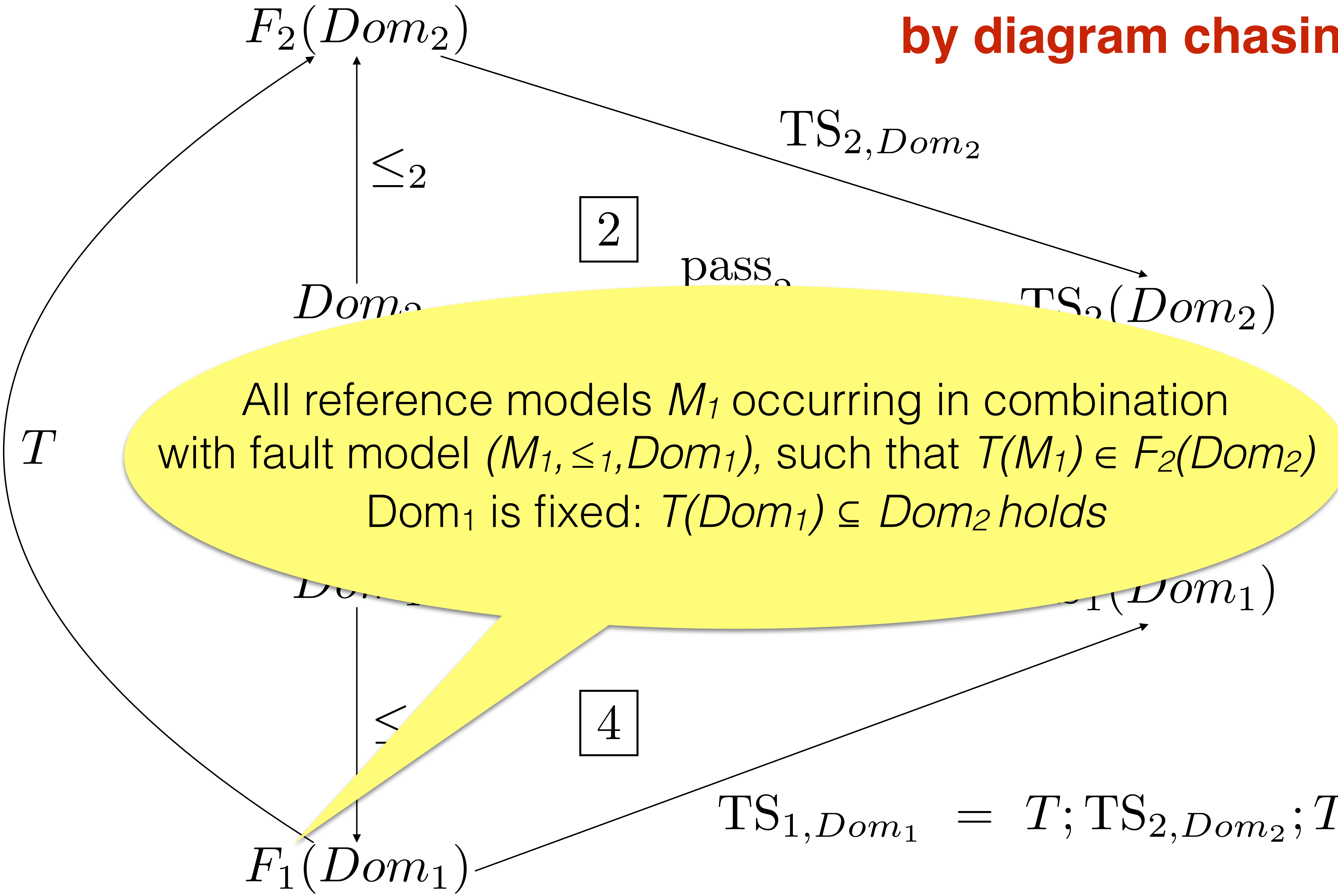


$$\mathrm{TS}_{1,Dom_1} \;=\; T;\mathrm{TS}_{2,Dom_2};T^*$$

Proof of Theorem 1 by diagram chasing

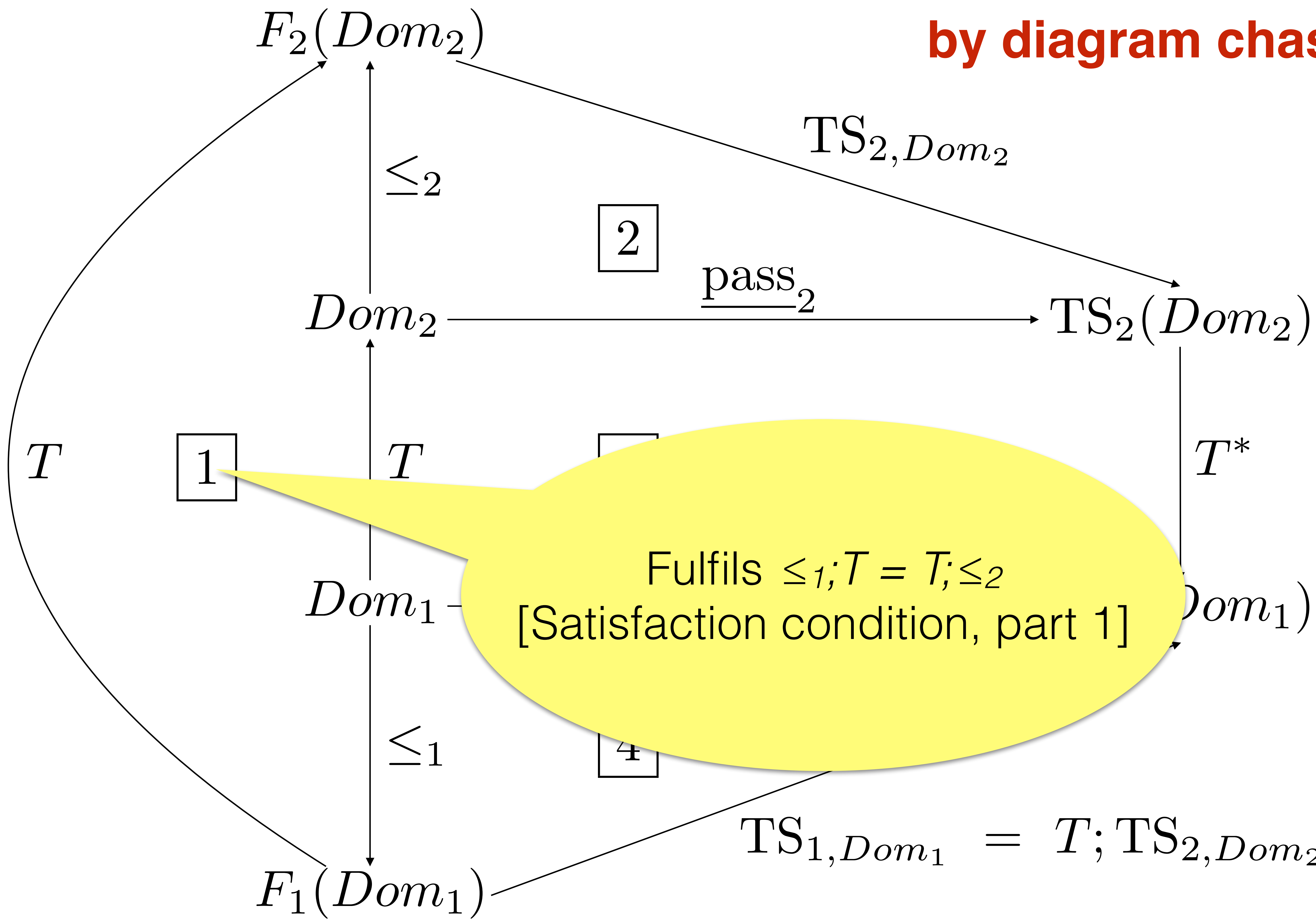


Proof of Theorem 1 by diagram chasing



$$\mathrm{TS}_{1,Dom_1} \;=\; T;\mathrm{TS}_{2,Dom_2};T^*$$

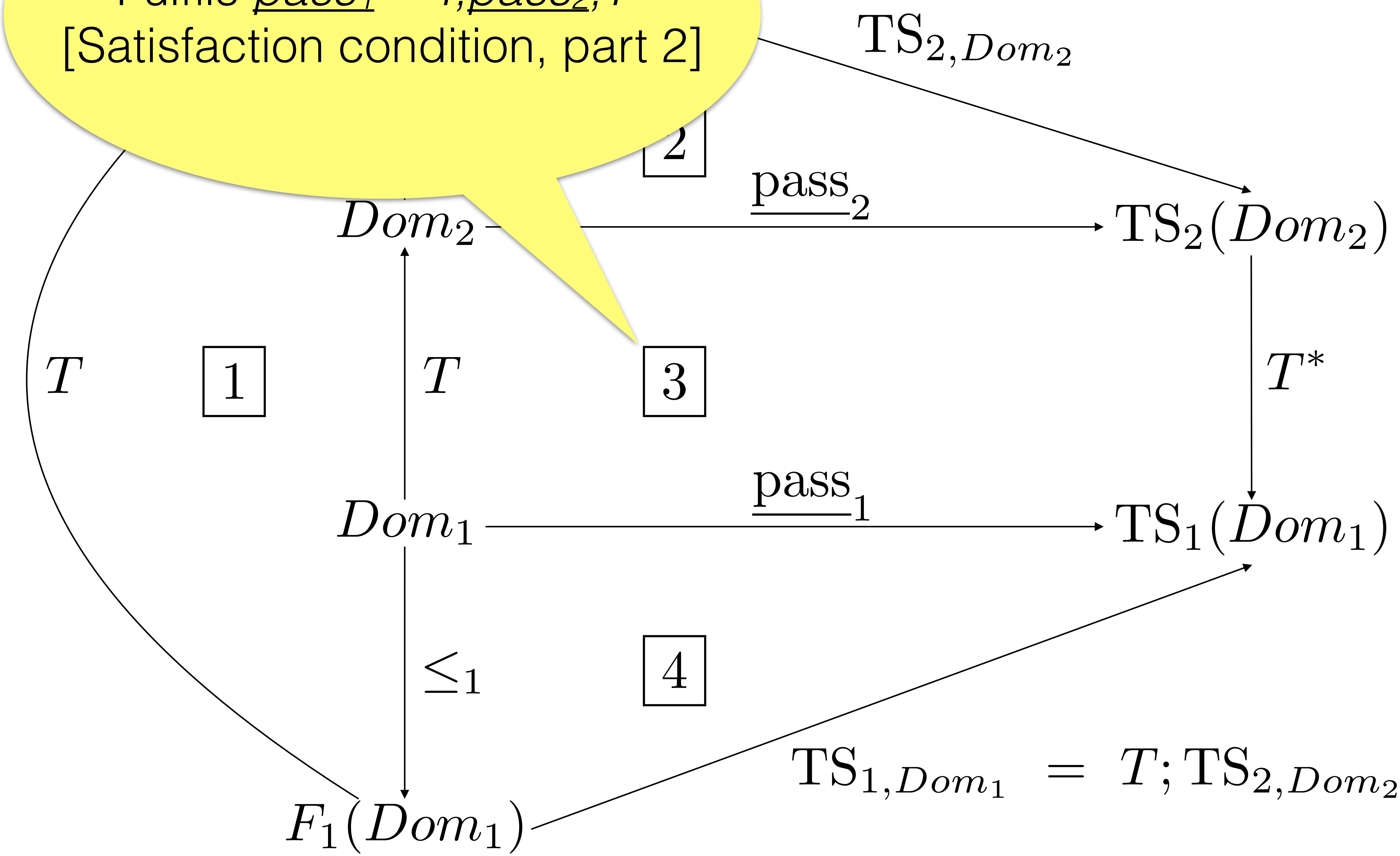
Proof of Theorem 1 by diagram chasing



$$\mathrm{TS}_{1,Dom_1} \;=\; T;\mathrm{TS}_{2,Dom_2};T^*$$

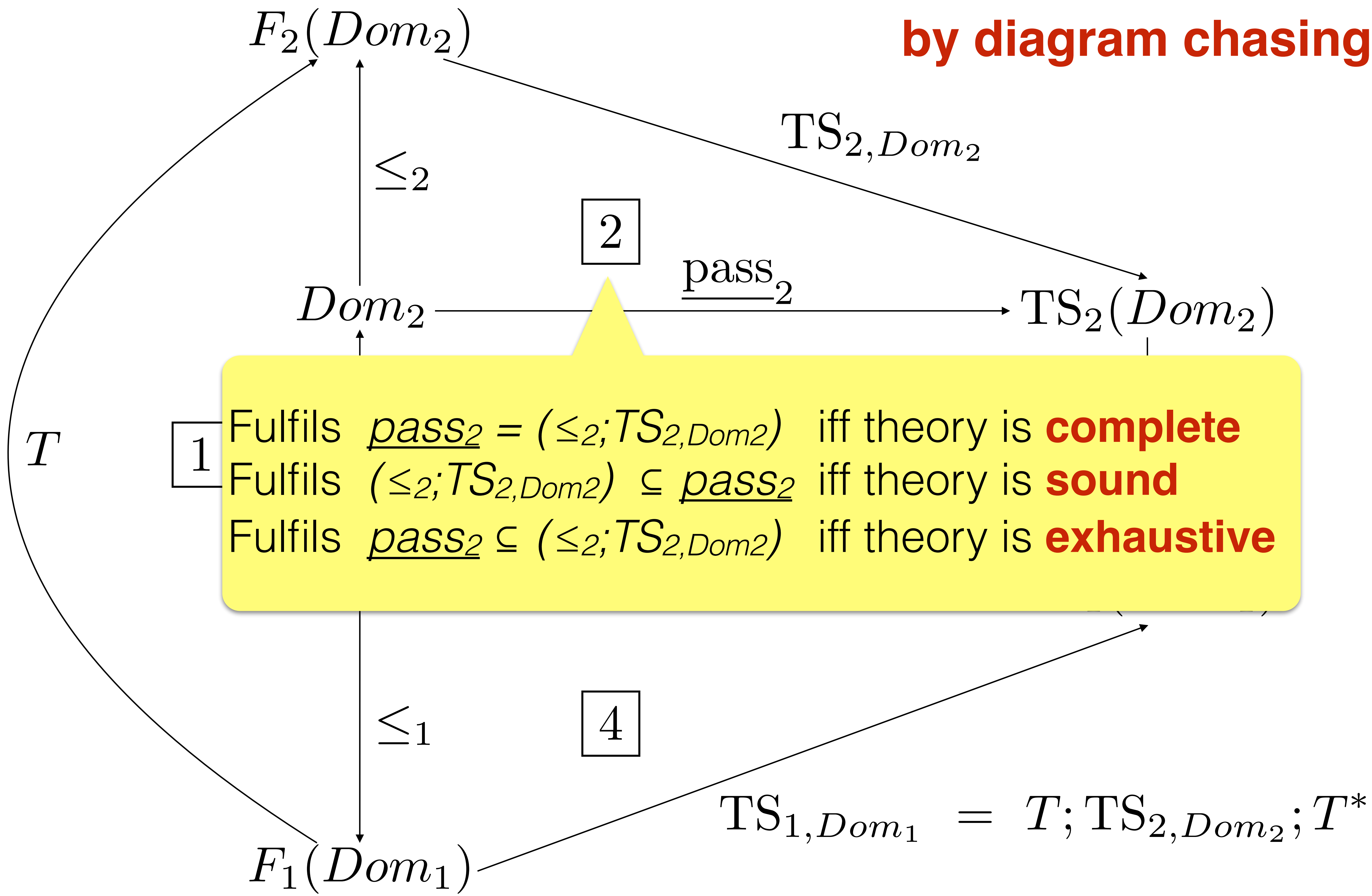
Proof of Theorem 1 by diagram chasing

Fulfils *pass₁ = T;pass₂;T** [Satisfaction condition, part 2]

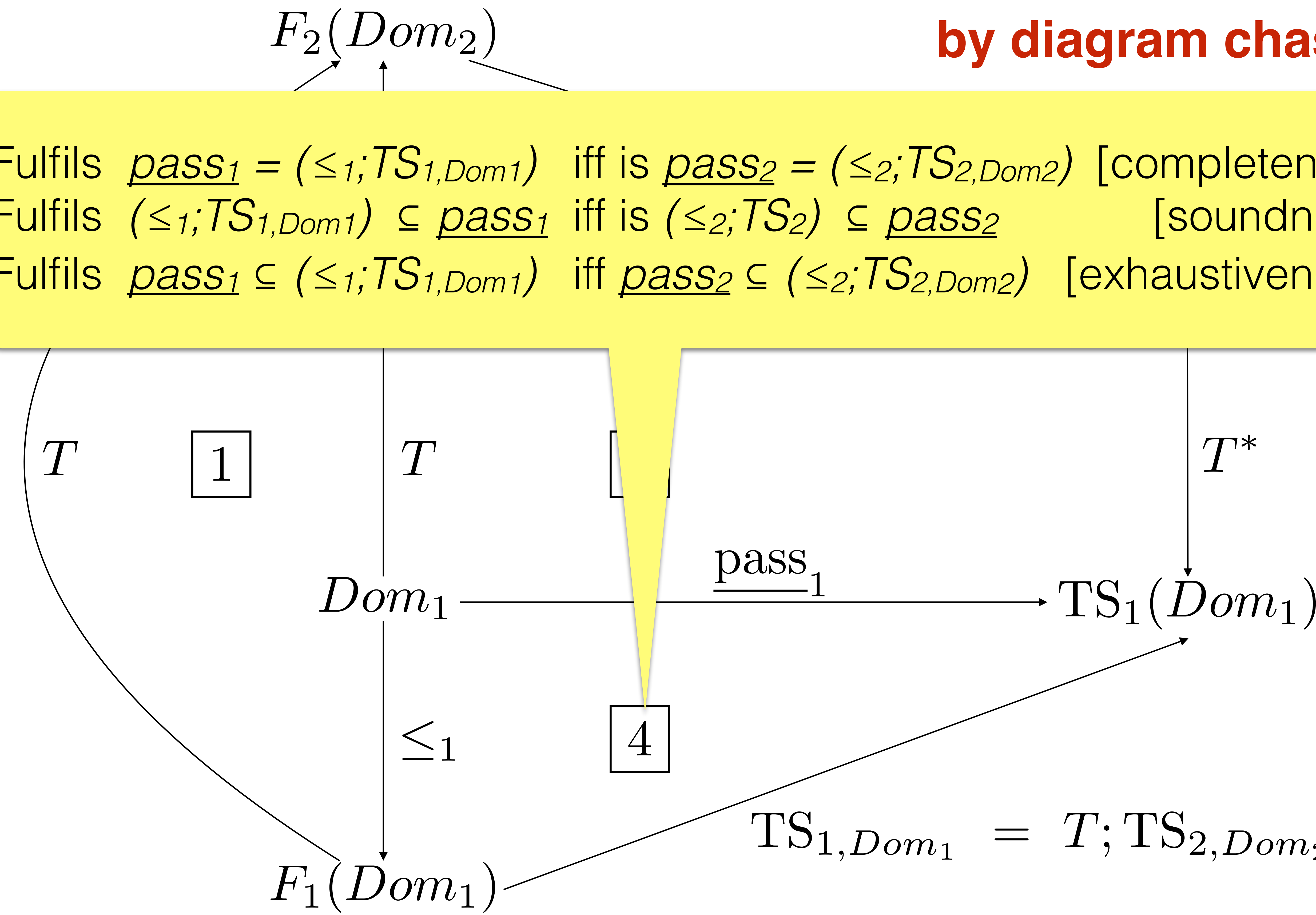


$$\mathrm{TS}_{1,Dom_1} \;=\; T;\mathrm{TS}_{2,Dom_2};T^*$$

Proof of Theorem 1 by diagram chasing



Proof of Theorem 1 by diagram chasing



Fulfils $\underline{pass_1} = (\leq_1;TS_{1,Dom1})$ iff is $\underline{pass_2} = (\leq_2;TS_{2,Dom2})$ [completeness]

Fulfils $(\leq_1;TS_{1,Dom1}) \subseteq \underline{pass_1}$ iff is $(\leq_2;TS_2) \subseteq \underline{pass_2}$ [soundness]

Fulfils $\underline{pass_1} \subseteq (\leq_1;TS_{1,Dom1})$ iff $\underline{pass_2} \subseteq (\leq_2;TS_{2,Dom2})$ [exhaustiveness]

$$TS_{1,Dom_1} = T; TS_{2,Dom_2}; T^*$$

Proof of Theorem 1 by diagram chasing

$$
\begin{tikzcd}[column sep=huge]
F_2(Dom_2) \arrow[dr, "\mathrm{TS}_2"] & \\
Dom_2 \arrow[u, "\leq_2"'] \arrow[r, "\underline{\mathrm{pass}}_2"] \arrow[ur, phantom, "\boxed{2}"] & \mathrm{TS}_2(Dom_2) \arrow[d, "T^*"] \\
Dom_1 \arrow[u, "T"'] \arrow[d, "\leq_1"'] \arrow[r, green, thick, "\underline{\mathrm{pass}}_1"] \arrow[ur, phantom, "\boxed{3}"] & \mathrm{TS}_1(Dom_1) \\
F_1(Dom_1) \arrow[ur] \arrow[uuu, bend left=60, "T", "\boxed{1}"'] \arrow[r, phantom, "\boxed{4}"] &
\end{tikzcd}
$$

$$\mathrm{TS}_1 = T; \mathrm{TS}_2; T^*$$

Proof of Theorem 1 by diagram chasing

$$
\begin{tikzcd}
F_2(Dom_2) \arrow[dr, "\mathrm{TS}_2"] \arrow[dr, phantom, "\boxed{2}"'] & \\
Dom_2 \arrow[u, "\leq_2"'] \arrow[r, "\underline{\mathrm{pass}}_2"] \arrow[dr, phantom, "\boxed{3}"] & \mathrm{TS}_2(Dom_2) \arrow[d, "T^*"] \\
Dom_1 \arrow[u, "T"'] \arrow[r, "\underline{\mathrm{pass}}_1"] \arrow[d, "\leq_1"] \arrow[dr, phantom, "\boxed{4}"] & \mathrm{TS}_1(Dom_1) \\
F_1(Dom_1) \arrow[ur, "\mathrm{TS}_1 = T; \mathrm{TS}_2; T^*"'] \arrow[uuu, bend left=60, "T"] \arrow[uuu, phantom, bend left=30, "\boxed{1}"] &
\end{tikzcd}
$$

Proof of Theorem 1 by diagram chasing

$$
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Dom_1 \arrow[u, "T"] \arrow[r, "\underline{\mathrm{pass}}_1"] \arrow[d, "\leq_1"] \arrow[dr, phantom, "\boxed{4}"] & \mathrm{TS}_1(Dom_1) \\
F_1(Dom_1) \arrow[ur, swap, "\mathrm{TS}_1 = T; \mathrm{TS}_2; T^*"] \arrow[uuu, bend left=60, "T"] \arrow[uuu, phantom, "\boxed{1}"] &
\end{tikzcd}
$$

Proof of Theorem 1 by diagram chasing

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F_2(Dom_2) \arrow[dr, "\mathrm{TS}_2"] & \\
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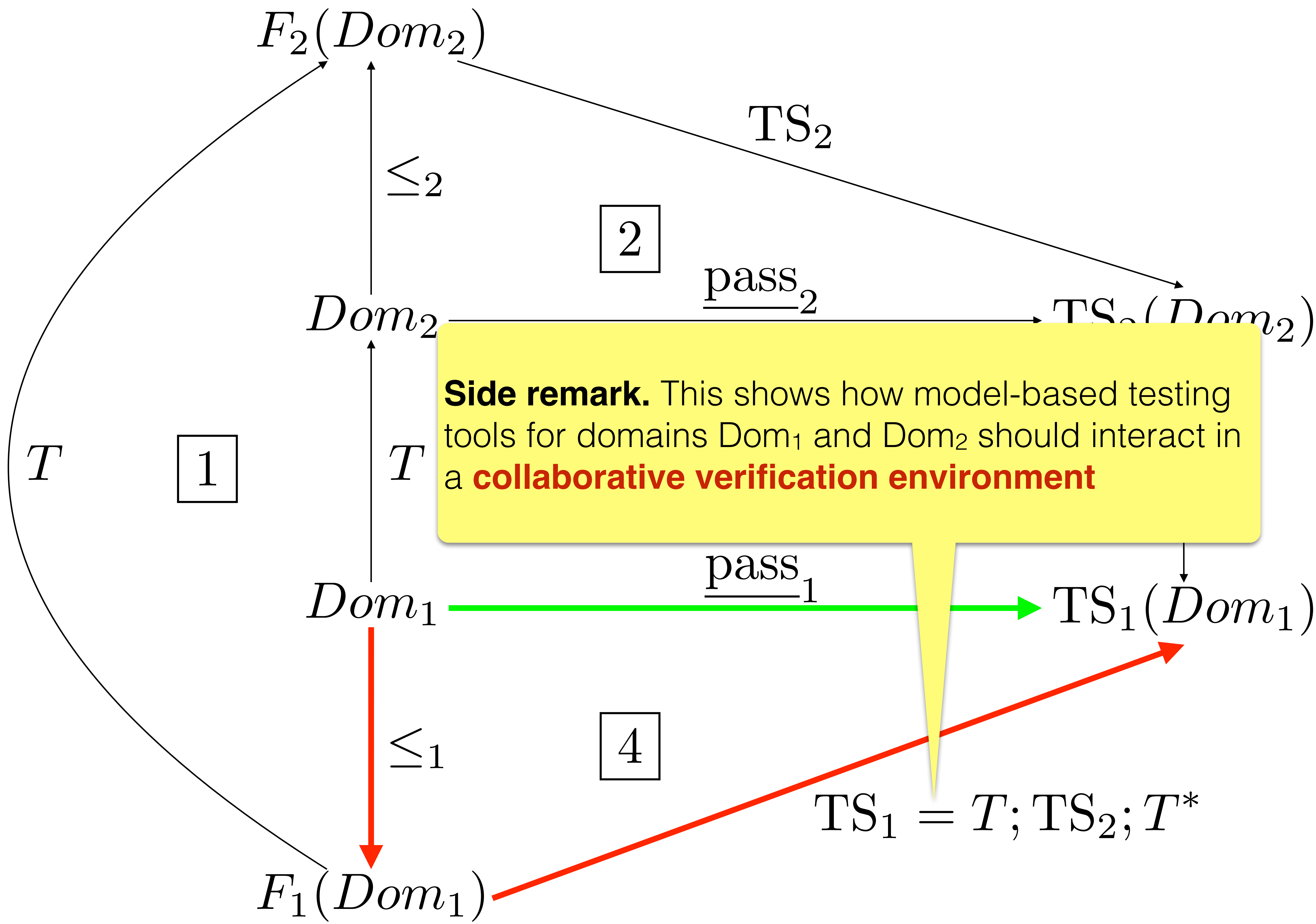
Dom_1 \arrow[u, "T"'] \arrow[r, "\underline{\mathrm{pass}}_1"] \arrow[d, "\leq_1"] \arrow[dr, phantom, "\boxed{4}"] & \mathrm{TS}_1(Dom_1) \\
F_1(Dom_1) \arrow[ur, "\mathrm{TS}_1 = T; \mathrm{TS}_2; T^*"'] \arrow[uuu, bend left=60, "T", "\boxed{1}"'] &
\end{tikzcd}
$$

Proof of Theorem 1 by diagram chasing

$$
\begin{tikzcd}
F_2(Dom_2) \arrow[drr, "\mathrm{TS}_2"] \arrow[dr, phantom, "\boxed{2}"] & & \\
Dom_2 \arrow[u, "\leq_2"'] \arrow[rr, "\underline{\mathrm{pass}}_2"] \arrow[dr, phantom, "\boxed{3}"] \arrow[d, phantom, "\boxed{1}" {left, xshift=-6ex}] & & \mathrm{TS}_2(Dom_2) \arrow[d, "T^*"] \\
Dom_1 \arrow[u, "T"'] \arrow[rr, "\underline{\mathrm{pass}}_1"] \arrow[d, "\leq_1"] \arrow[dr, phantom, "\boxed{4}"] & & \mathrm{TS}_1(Dom_1) \\
F_1(Dom_1) \arrow[uuu, bend left=60, "T"] \arrow[urr, "\mathrm{TS}_1 = T; \mathrm{TS}_2; T^*"'] & &
\end{tikzcd}
$$



Side remark. This shows how model-based testing tools for domains Dom_1 and Dom_2 should interact in a **collaborative verification environment**

TTT application

- **Theorem 2.** Every complete (sound, exhaustive) FSM testing theory for

  - language equivalence or

  - language containment

  induces a complete (sound, exhaustive) **equivalence class partition testing theory** with analogous conformance relations for Kripke structures with **infinite input domains**, bounded nondeterminism, and finite internal state and finite outputs

Wen-ling Huang, Jan Peleska:
Complete Model-Based Equivalence Class Testing.
Int J Softw Tools Techno Transfer,
DOI 10.1007/s10009-014-0356-8., 2014

Wen-ling Huang, Jan Peleska:
Complete Model-Based Equivalence Class Testing for Nondeterministic Systems.
Submitted to Formal Aspects of Computing, 2015

TTT-application

- **Step 1. Transform the transition relation**
  - Create a transition relation of the model
  - Separate input variables, internal model variables, and output variables, by enumerating the latter
  - Aggregate sequences of transitions between transient states into a single transition leading to a quiescent post-state

TTT-application

- Step 1. Transform the transition relation
  - This leads to transition relation of the form

$$
\begin{aligned}
\mathcal{R} \quad &\equiv \quad \bigvee_{i \in \mathrm{IDX}} \big(\alpha_i \wedge (\boldsymbol{m}, \boldsymbol{y}) = (\boldsymbol{d}_i, \boldsymbol{e}_i) \wedge (\boldsymbol{m}', \boldsymbol{y}') = (\boldsymbol{d}_i, \boldsymbol{e}_i)\big) \\
&\vee \quad \bigvee_{(i,j) \in J} \big(g_{i,j} \wedge (\boldsymbol{m}, \boldsymbol{y}) = (\boldsymbol{d}_i, \boldsymbol{e}_i) \wedge (\boldsymbol{m}', \boldsymbol{y}') = (\boldsymbol{d}_j, \boldsymbol{e}_j)\big)
\end{aligned}
$$

with

- Stability conditions α_i
- Jump conditions $g_{i,j}$
- Only input variables occur free in $\alpha_i, g_{i,j}$

TTT-application

- **Step 2. Calculation of input equivalence classes**
  - Each satisfiable solution of

$$\Phi_f \equiv \bigwedge_{i \in \mathrm{IDX}} g_{i,f(i)} \text{ with } f : \mathrm{IDX} \to \mathrm{IDX} \text{ permutation}$$

  specifies one input equivalence class

TTT-application

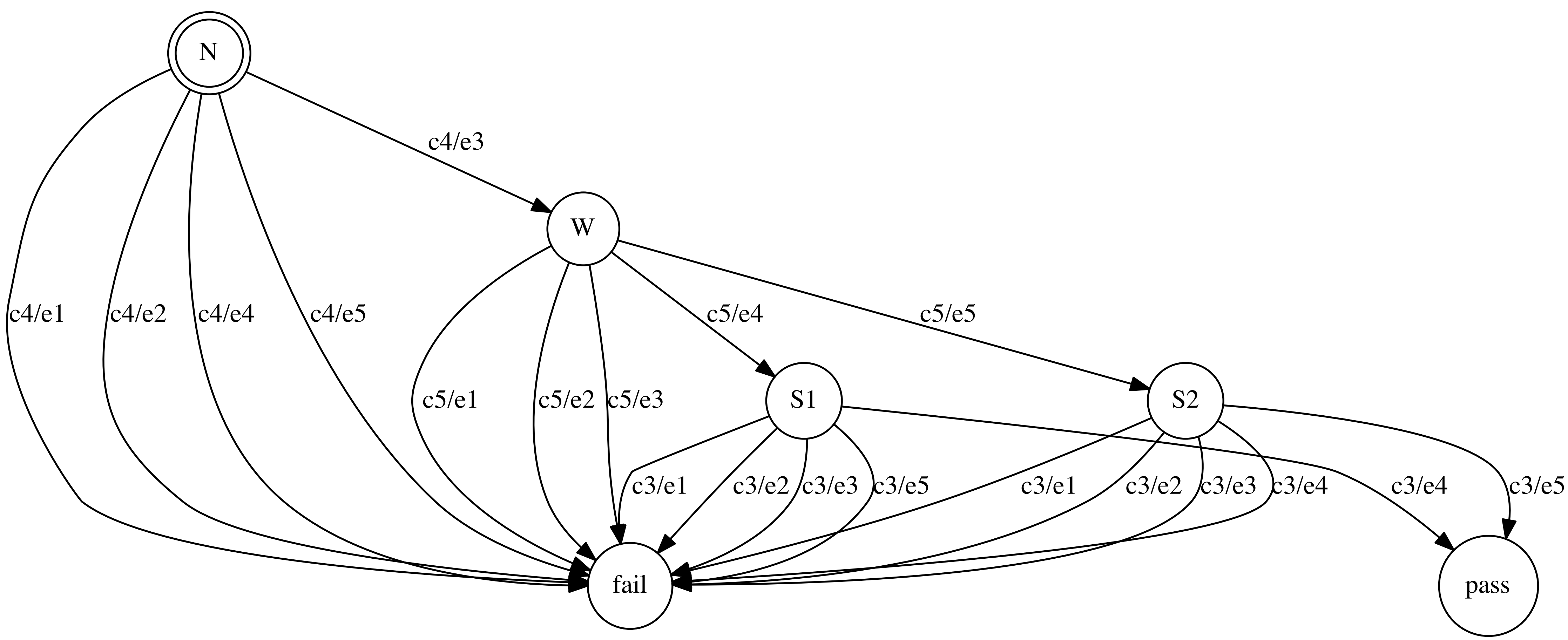
- **Step 3. Creation of the model map**
  - Map Kripke model to minimal, observable FSM with

$$
\begin{aligned}
\text{Input alphabet} \quad \Sigma_I &= \quad \{\Phi_f \mid \Phi_f \text{ is feasible}\} \\
\text{Output alphabet} \quad \Sigma_O &= \quad \text{finite output domain of Kripke model} \\
\text{Internal states} \quad Q &= \quad \{q_i \mid i \in \mathrm{IDX}\} \\
\text{Transition relation} \quad h &= \quad \{(q_i, \Phi_f, \boldsymbol{e}_j, q_j) \mid f(i) = j\}
\end{aligned}
$$

TTT-application

- **Step 4. Creation of the test case map**
  - FSM test cases are acyclic, terminating, single-input, output-complete FSMs
  - FSM test cases interact with the FSM to be tested via language intersection as „parallel operator“
  - FSM test inputs state-dependent value to SUT
  - FSM test accepts SUT output and transits into next state with new input or into fail state

FSM test case

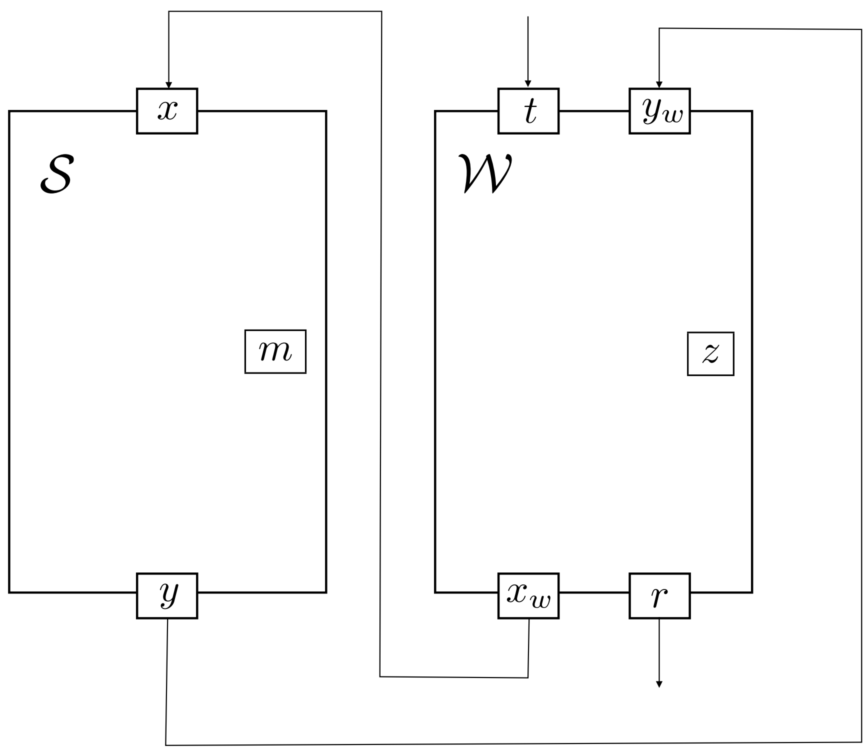


TTT-application

- **Step 4. Creation of the test case map**

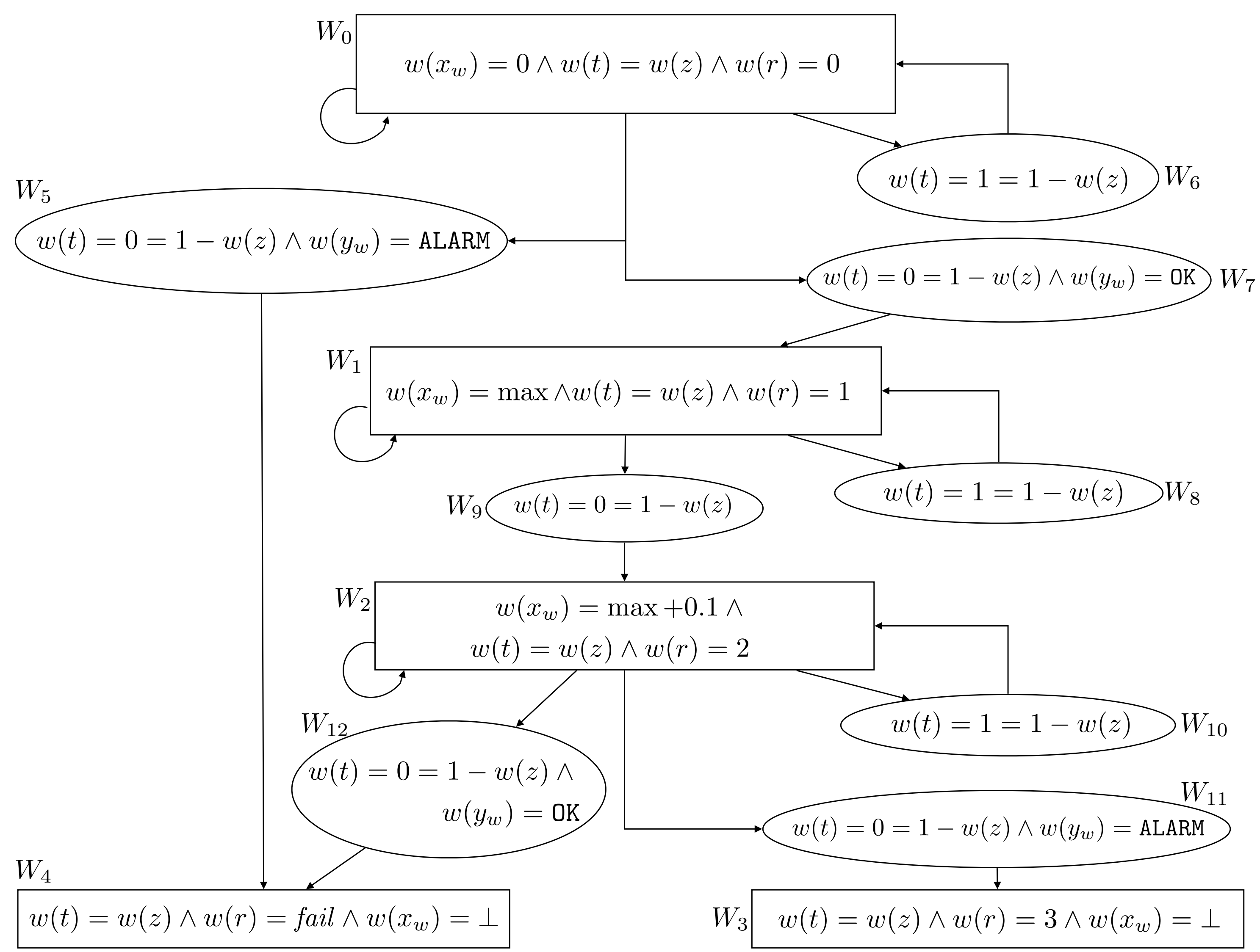
    - Kripke structure test cases interact (this is one option) synchronously with the SUT

    - In contrast to FSM test cases, inputs to the SUT are strictly separated from monitoring of outputs



TTT-application

- **Step 4. Creation of the test case map**
  - Consequently, one FSM test step leads to a more complex Kripke test step involving several transitions



TTT-application

- **Step 5. Proof of the satisfaction condition**
  - The proof is independent on the selection of representatives from each equivalence class, whenever this class occurs as an input in an FSM test case
  - Consequently, the test strategy for Kripke structures can be combined with random selection of input data from each class

Theory translation – model-theoretic underpinning

- **Alternative A. Theory of Institutions**

Test case map above corresponds to **sentence translation map** in theory of institutions – Need **Grothendiek Institutions**

Razvan Diaconescu: **Institution-independent Model-Theory.** Birkhäuser Verlag, Basel, Boston, Berlin, 2008

Joseph A. Goguen, Rod M. Burstall: **Institutions: Abstract Model Theory for Specification and Programming.** J. ACM 39(1): 95-146 (1992)

- Semantics for CPS – time for a change of paradigm?
- **Multiple formalisms in CPS modelling**
  - Example 1. Testing theories and collaborative tool environments
  - **Example 2. Verification of emergent properties**
- Conclusions and future work

Multiple formalisms in CPS modelling – Example 2. Verification of emergent properties

Recall – train onboard speed control

Train engine driver brake command

man_on, man_off

Onboard main controller

PLC brake controller

Automated braking command

auto_on, auto_off

trigger, release

Current speed

Current maximum speed

Emergency brake

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**

Verification of emergent properties

- **Observations**
  - FSM I/O-events x/y can be mapped to CSP channel events x.y
  - FSM parallel composition by intersection is similar to synchronous channel communication of CSP processes
  - CSP failures models can be represented by normalised transition graphs

A.W. Roscoe:
Model-Checking CSP. In **A Classical Mind: Essays in Honour of C.A.R. Hoare.**
Prentice Hall International (UK), 1994

Alternative approach

- **Alternative B. Approach based on Unifying Theories of Programming UTP**
  - „Programs are predicates“ – no distinction between models and sentences
  - Theories are made up from alphabets, signatures, and healthiness conditions
  - Conformance is expressed by implication $[P \Rightarrow Q]$ („P refines Q“)
  - Model, sentence, and theory translation is enabled by the existence of Galois connections

Jifeng He, C. A. R. Hoare: Unifying theories of programming. RelMiCS 1998: 97-99

Verification of emergent properties

- **Procedure**
  - Create UTP theories for
    - ◆ Sub-class of Kripke structures (sequential nondeterministic programs) with LTL safety formulas for property specifications,
    - ◆ FSMs with property specification by testing automata
    - ◆ CSP failures model with failures (= trace/refusal) specifications
      P ***sat*** *S(tr,ref)*
    - ◆ CSP transition graphs with CSP-like specifications
      G ***sat*** *S(tr,ref)*

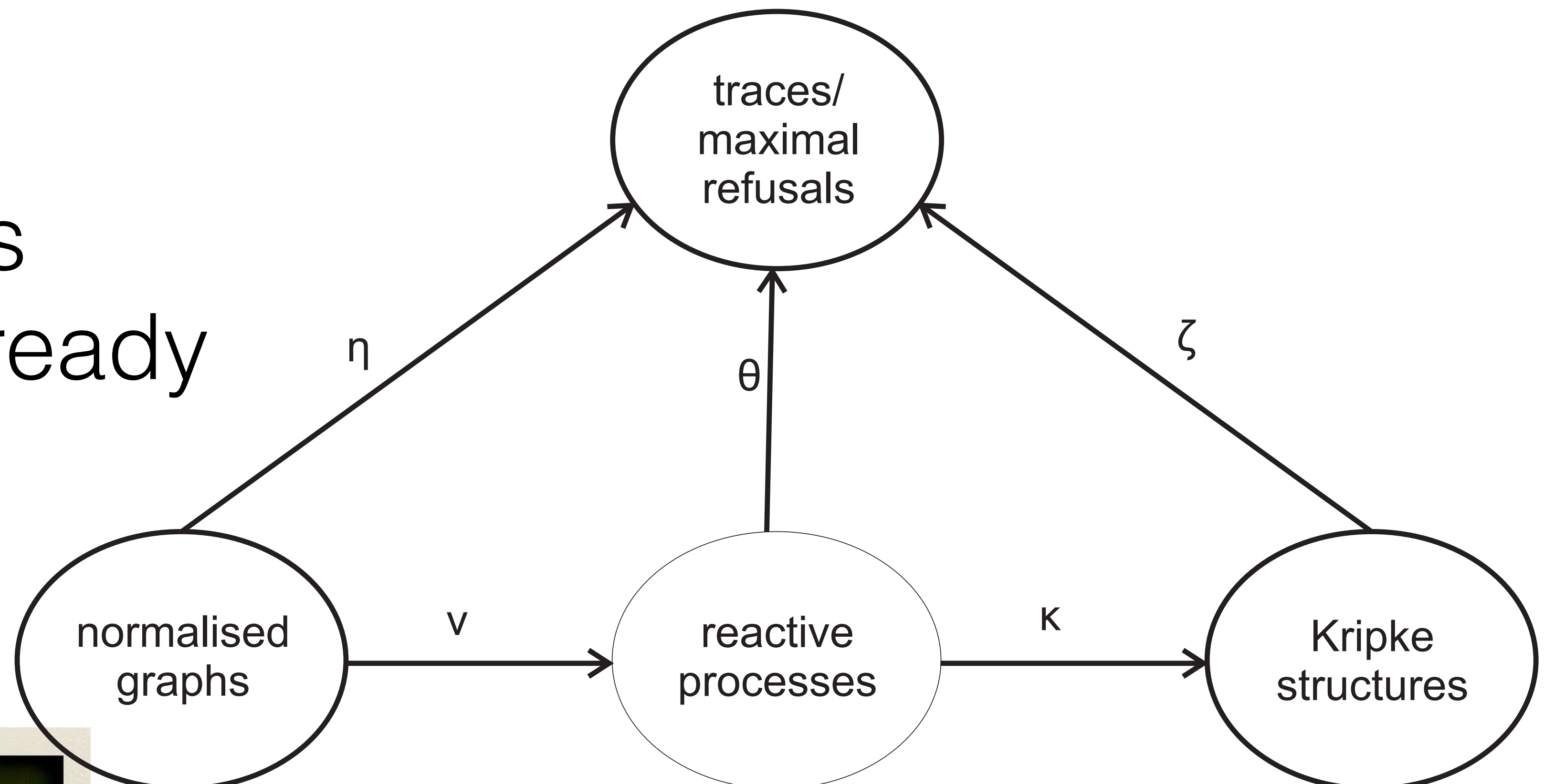
Verification of emergent properties

- **Procedure**
  - Create Galois connections
    - CSP failures models ⇄ CSP transition graphs
    - Sequential nondeterministic programs ⇄ CSP transition graphs
    - FSMs ⇄ CSP transition graphs
  - This allows us to
    - lift the local properties of FSM and Kripke structure to local CSP assertions
    - deduce the required satisfaction relation on CSP level by means of compositional reasoning

Theory translation – model-theoretic underpinning

Application example

- Some of these Galois connections have already been established



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

Conclusions and future work

Conclusions

- We have identified characteristics of CPS challenging the existing semantic approaches to concurrent systems

- Potential solutions to the problems of

  - theory translation

  - verification of emergent properties in presence of multiple formalisms

  have been proposed

Future work

- Evolution of asserted behaviour
  - Inspiration from AI. **Belief systems** and belief revision – CPS components should act optimally in relation to the current status of belief – belief revision should only be necessary within specified boundaries
- Semantic navigation
  - A network of semantics offering different degrees of abstraction
  - Network nodes are connected by **theory translation mappings** – Galois Connections?
- Dynamic re-configuration
  - Simpler methods are available for **bounded-length model investigation**, as used in bounded model checking and model-based testing

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