Hasso Plattner Institut

IT Systems Engineering | Universität Potsdam

SCHLOSS DAGSTUHL
Leibniz-Zentrum für Informatik

Invariant Checking for Graph Transformation: Applications & Open Challenges

Dagstuhl Seminar 15451 on Verification of Evolving Graph Structures, November 2 - 6, 2015.

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Outline

1. **Inductive Invariant Checking for Graph Transformation Systems**
2. **Applications**

   Cyber-Physical Systems & Safety

   Model Transformations & Correctness
3. **Summary & Open Challenges**

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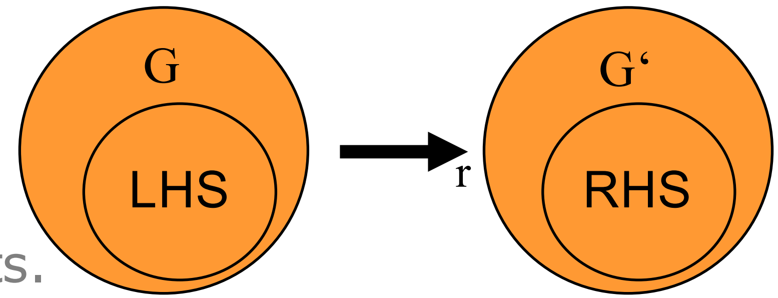
1. Graph Transformation Systems

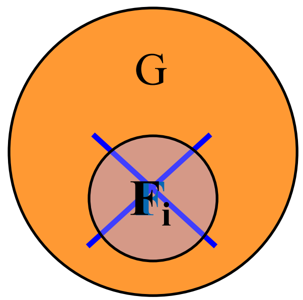
A **graph transformation system** (we omit here NACs) consists of

- a type graph describing all possible model configurations,
- a set of rules R with LHS and RHS, and
- a function $prio: R \rightarrow Int$ which assigns priorities to all rules.

We use graph constraints C (e.g., a set of **forbidden graph patterns** F) for defining unsafe situations.



- A rule r of R is **enabled** if an occurrence of its LHS in a graph G exists.
- A rule r of R is **applied** on graph G by replacing an occurrence of its LHS in G by the RHS (DPO).
- A forbidden graph pattern $\mathbf{F_i}$ in F is **respected** by a graph G if it is not contained.

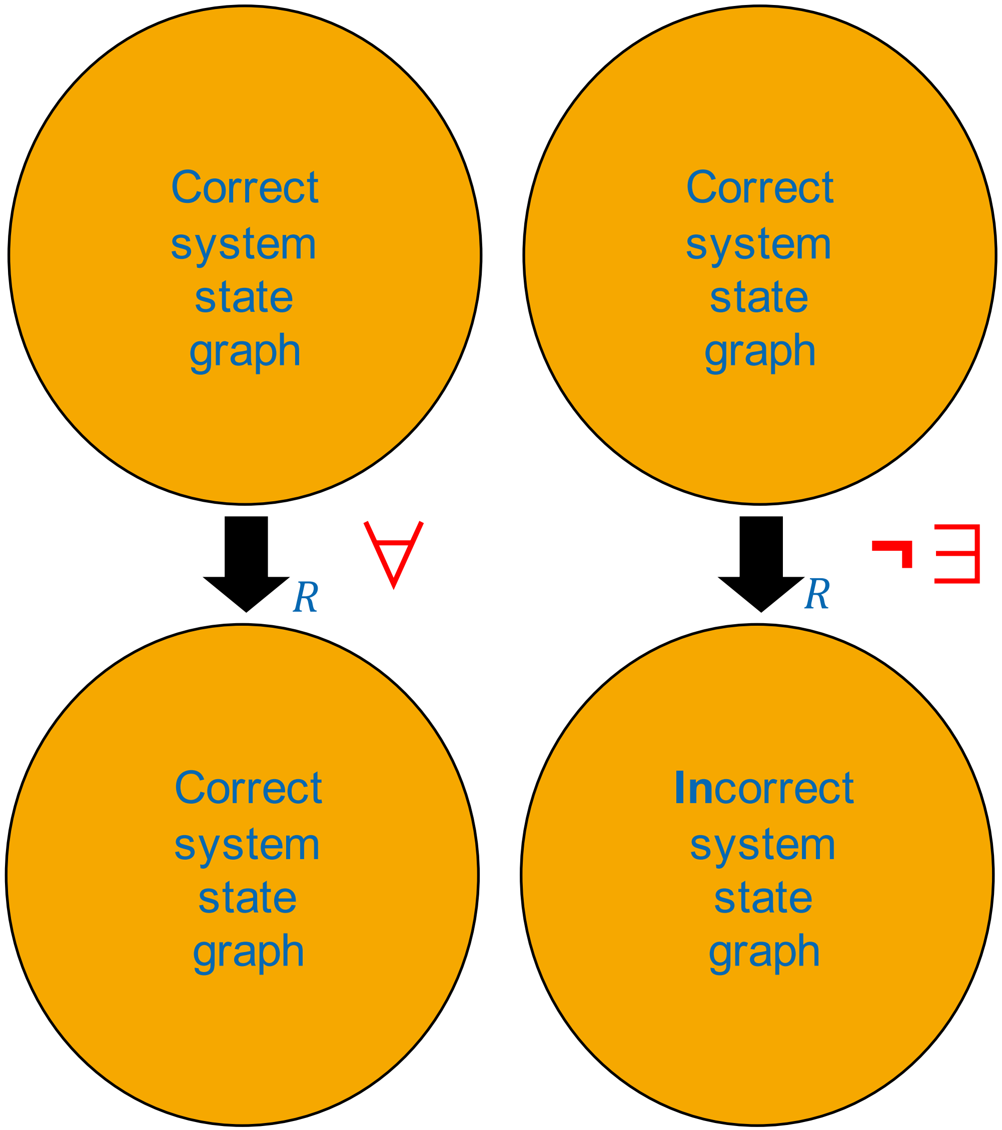


Analysis
- Inductive Invariants -

Def: A graph constraint C is an **inductive invariant for** a set of graph rules R if for all graphs G and H hand with $G \rightarrow_R H$ holds that if G fulfills C then also H fulfills C.

$\forall (G \rightarrow_R H)$:

$$(G \vDash C) \Rightarrow (H \vDash C)$$



Analysis
- Invariant Checking -

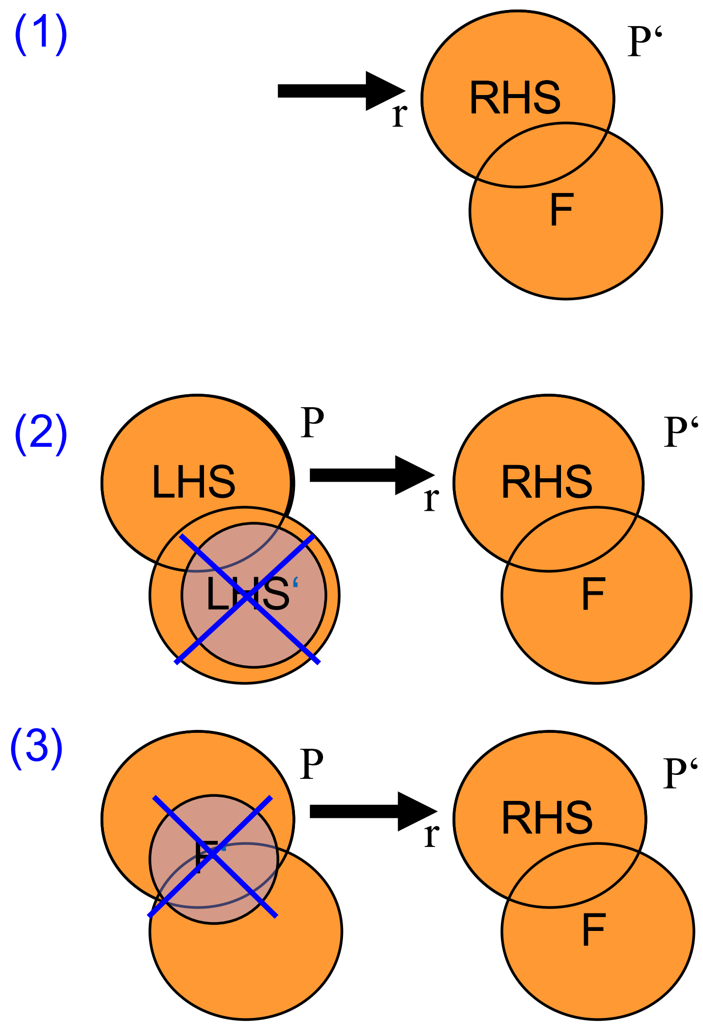
Observation: any possible counter-example must contain an intersection between the nodes of the RHS of the rule and the forbidden graph F. Therefore, if (P,r) is a **counterexample**, then:

(1) exists a P' which is the combination of a RHS of a rule r and a forbidden graph pattern F,

(2) $P \rightarrow_r P'$ (which implies that no rule r' with higher priority can be applied), and

(3) There exists no forbidden graph F' which matches P (as then the graph before was not correct already)

Idea: Algorithm constructs all possible **counterexamples** and checks whether any could be a real one.



Outline

1. **Inductive Invariant Checking for Graph Transformation Systems**

   Applications

   Cyber-Physical Systems & Safety

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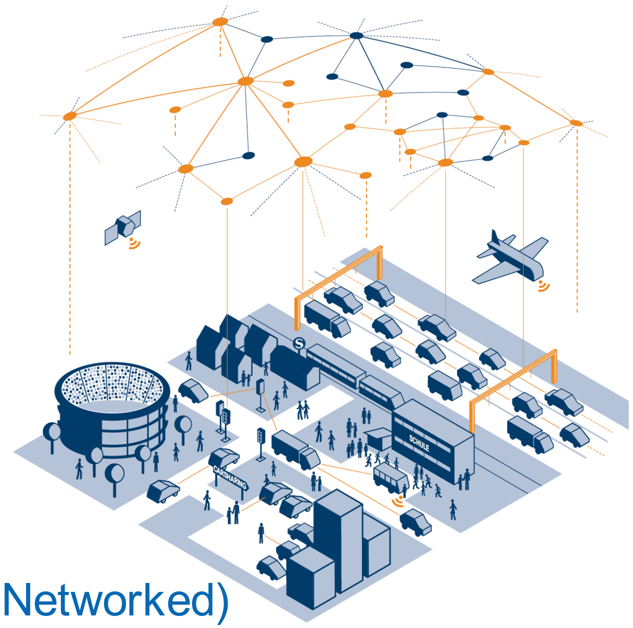
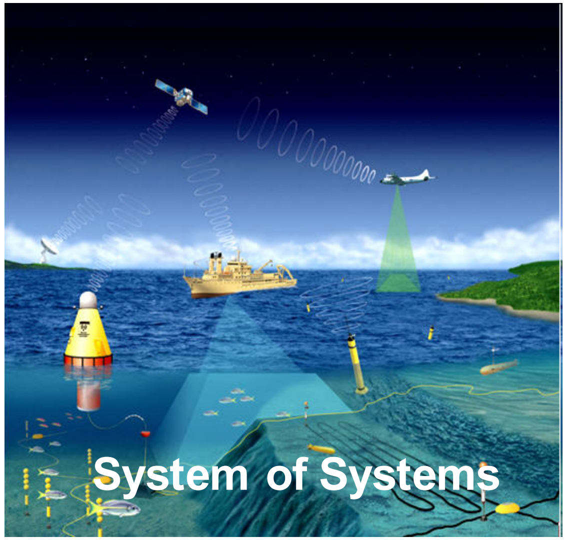
2. Applications: Cyber-Physical Systems & Safety



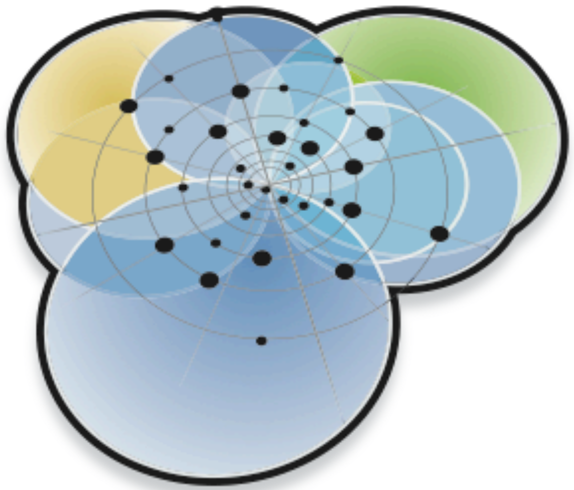
(Networked)
Cyber-Pyhsical Systems

Internet of Things

Smart City



http://oceanservice.noaa.gov/news/weeklynews/nov13/ioos-awards.html



Ultra-Large-Scale Systems

Smart Home

E-Health

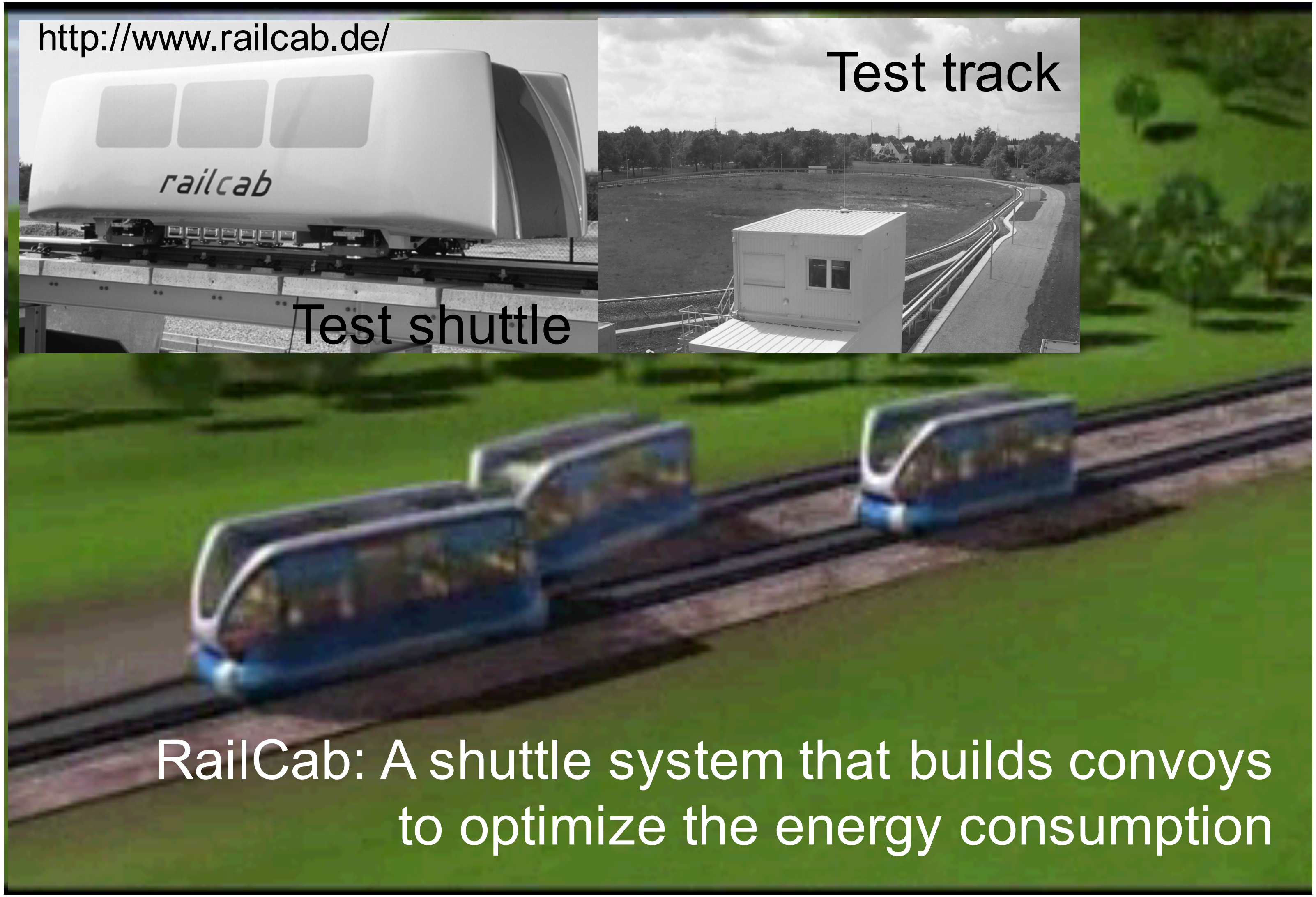
Ambient
Assisted Living

Smart Factory -
E.g. Industry 4.0

Smart Logistic

Micro Grids

Example: RailCab
- Challenges -



Example: RailCab
- Modeling Idea -

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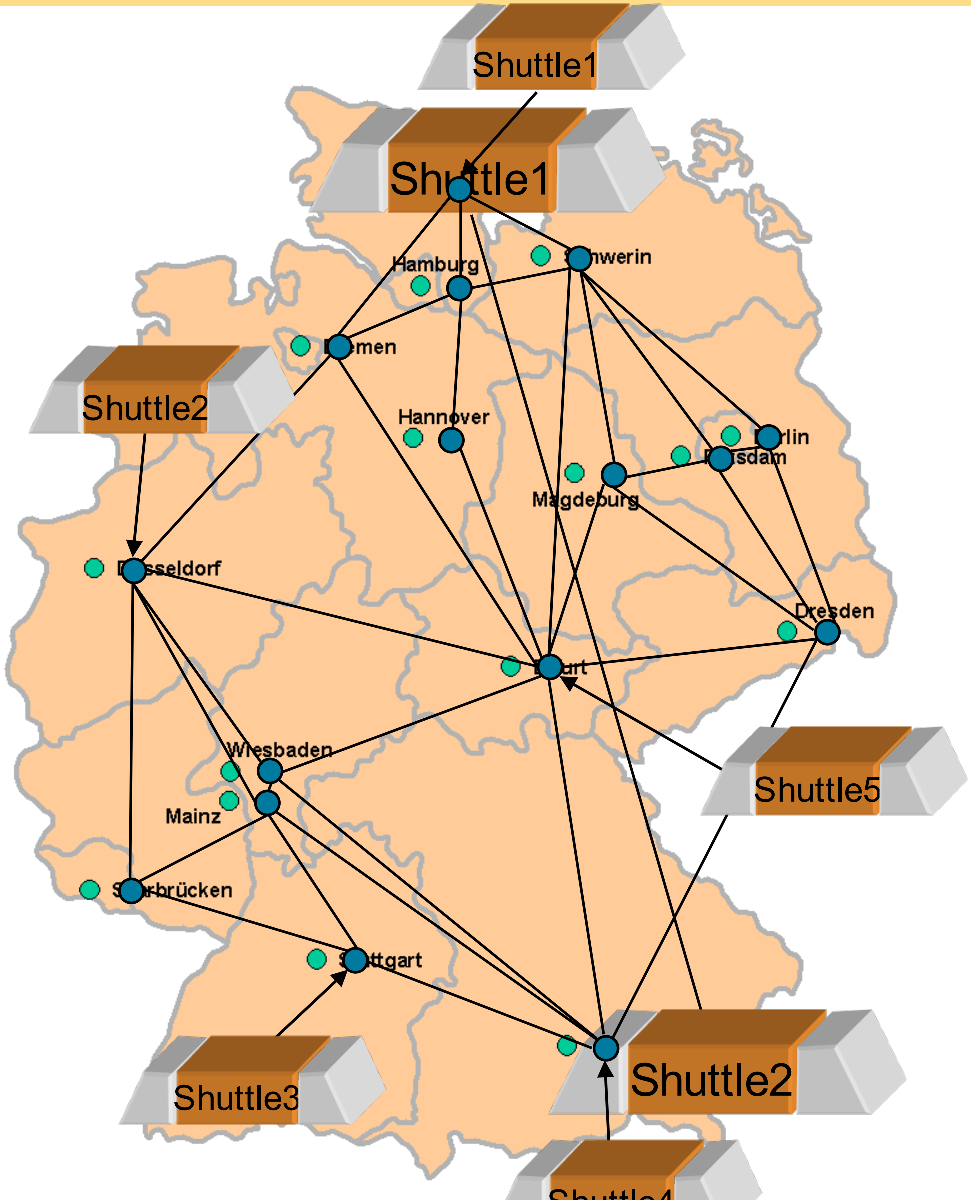


Modeling Problem:

- Shuttles move on a topology of tracks
- Arbitrary large topologies

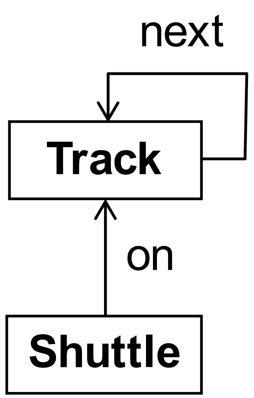
Solution:

- State = Graph
- Reconfiguration rules = graph transformation rules
- Safety properties = forbidden graphs

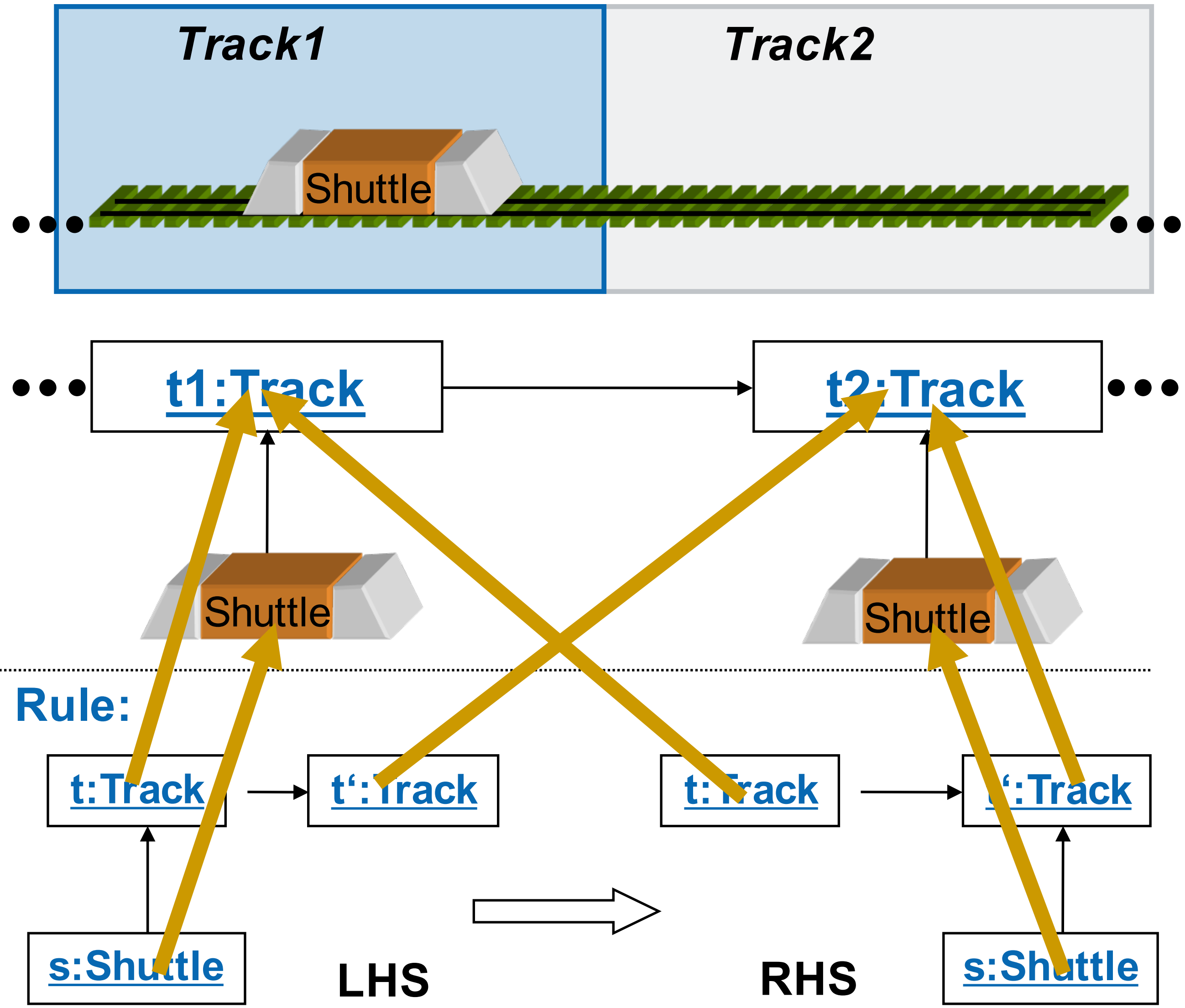
⇨ Formal Verification possible

Example
- A Naïve First Design -

- Map the tracks
- Map the shuttles

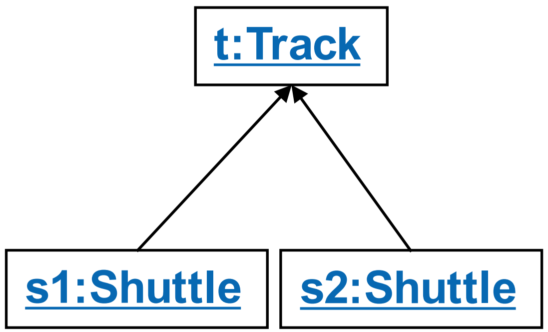


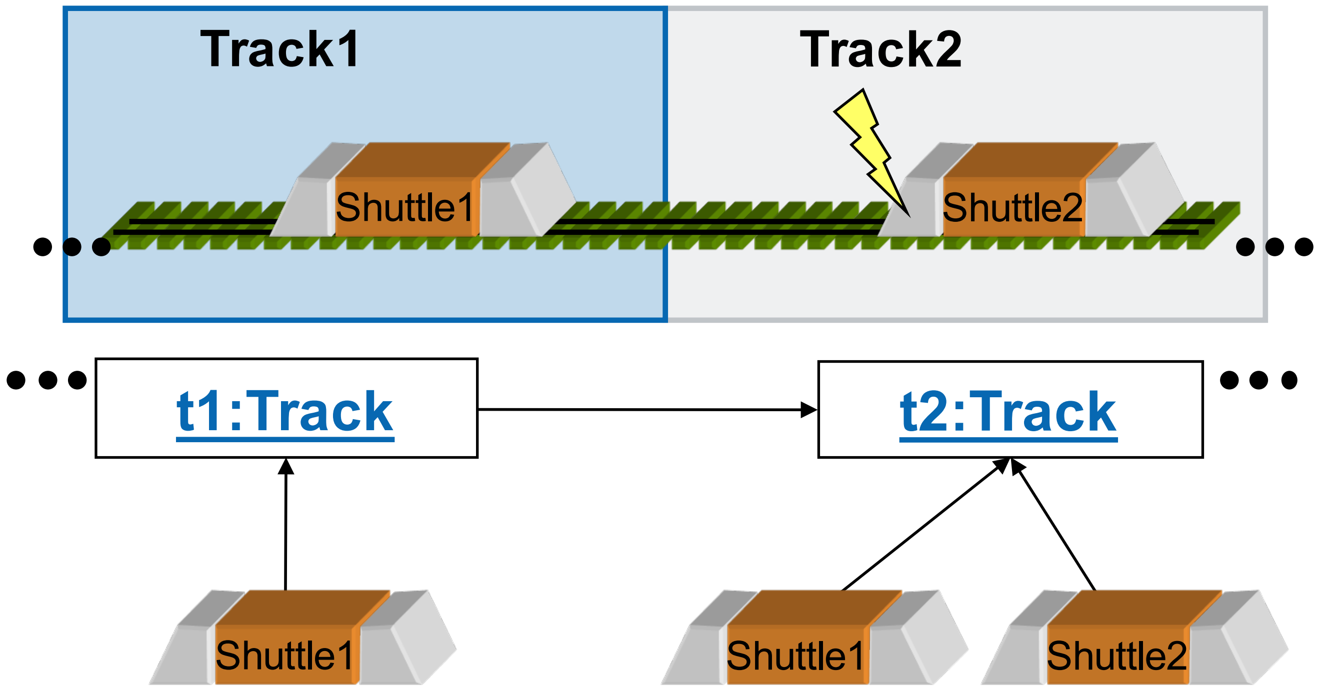
- Map the movement to rules (movement equals dynamic structural adaptation on the abstract level)



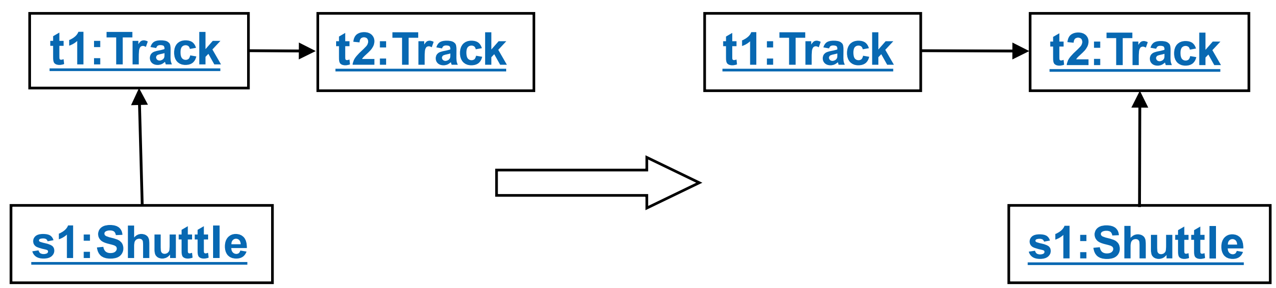
Example
- A Naïve First Design -

Forbidden Graph



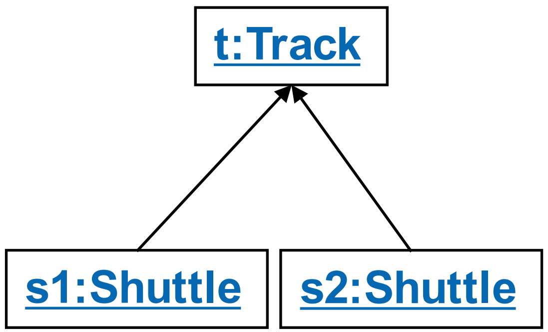


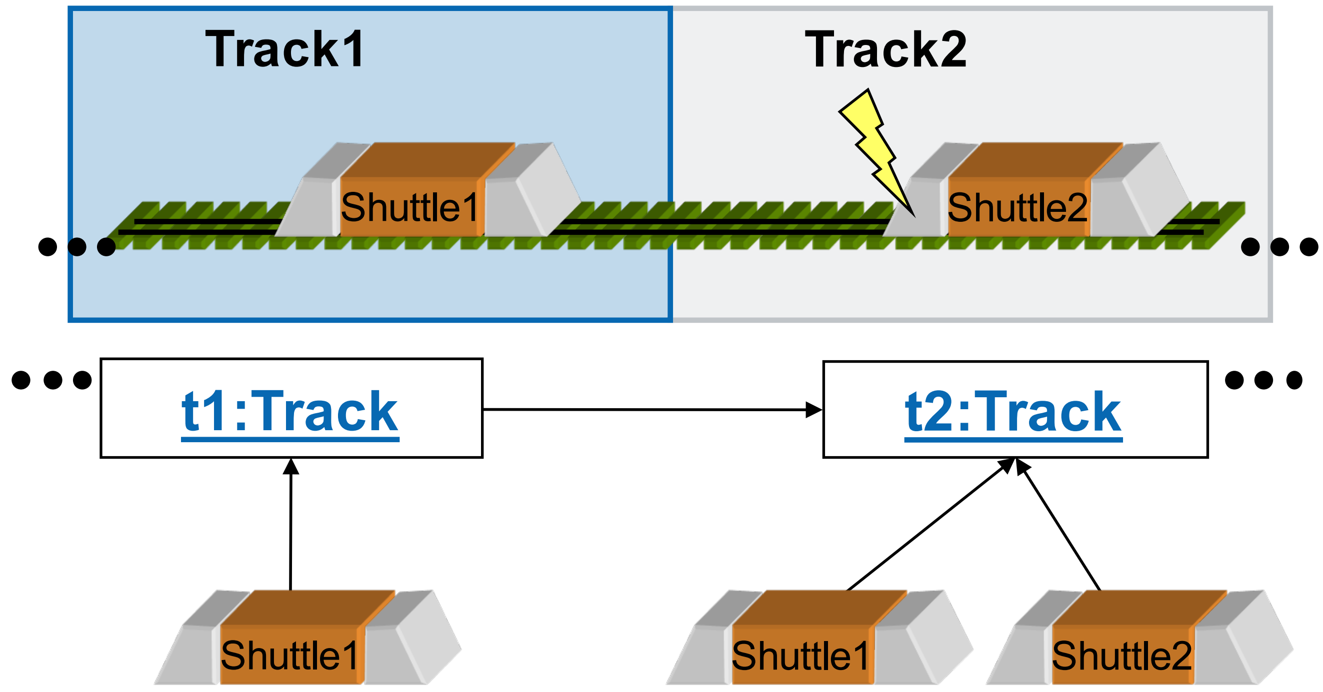
Rule:



Example - Analysis Challenge -

Forbidden Graph





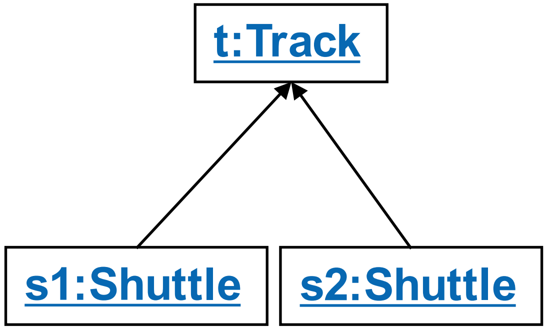
- **Correctness:** all reachable system graphs do not match the forbidden graph pattern

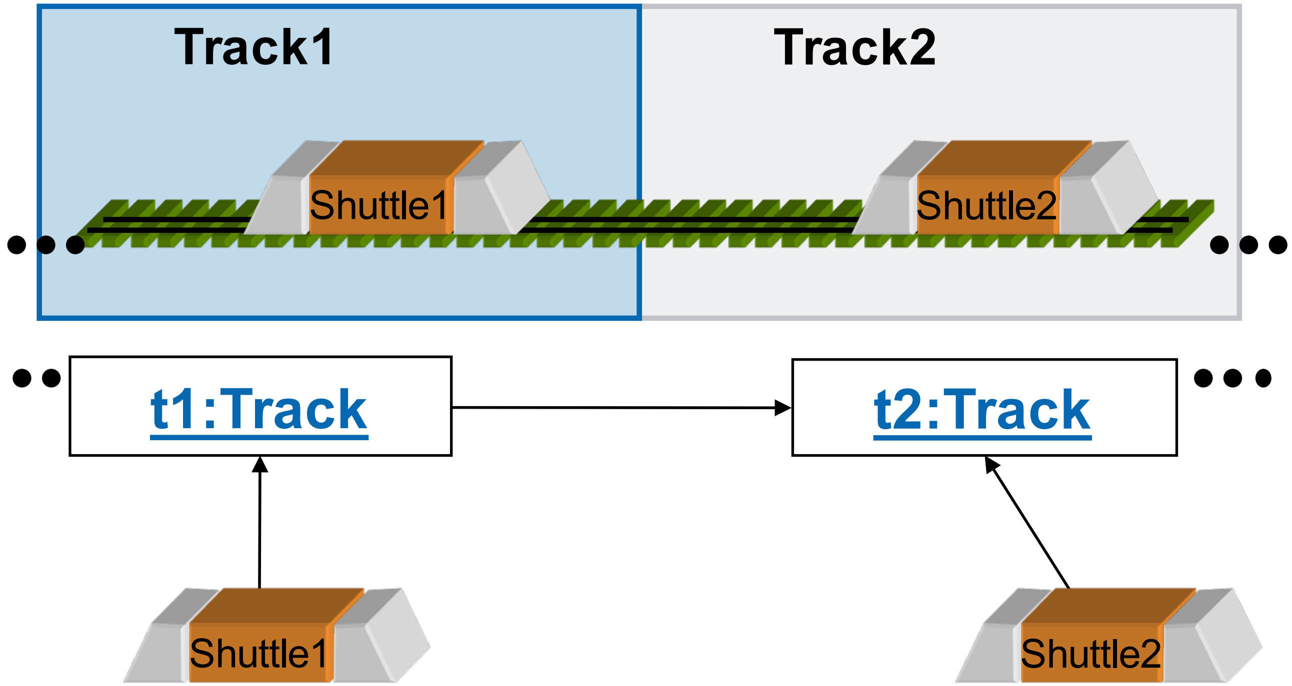
Problems:

- fixed initial topology is **not known** (may change)
- there could be **infinite** many initial topologies
- there could be **infinite** many reachable system state graphs when the topology evolves (new tracks)

Example
- A Naïve Second Design -

Forbidden Graph

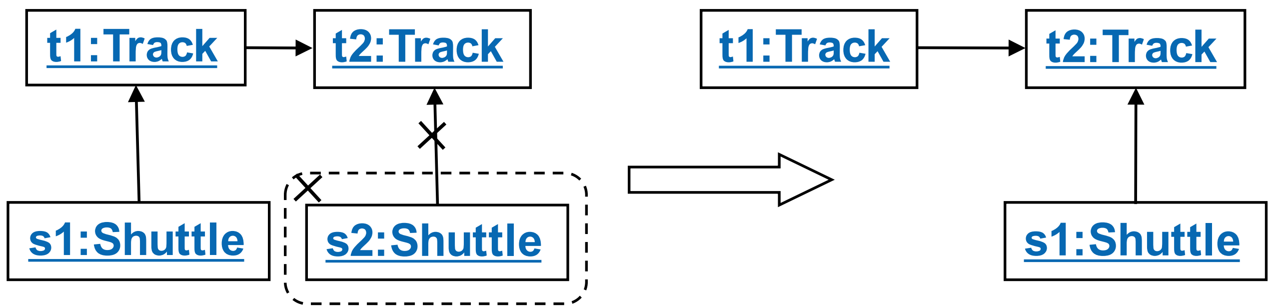




- **Correctness:** all reachable system graphs do not match the forbidden graph pattern

Remark: still too naïve as shuttles require time to break and convoys are not considered

Rule:



Example
- A More Realistic Design -

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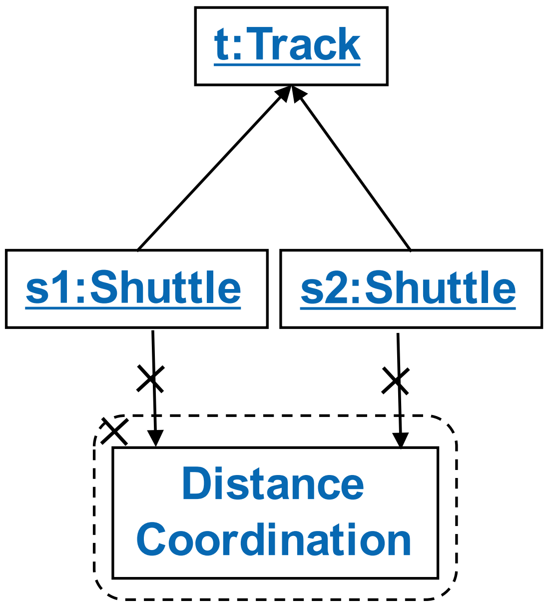
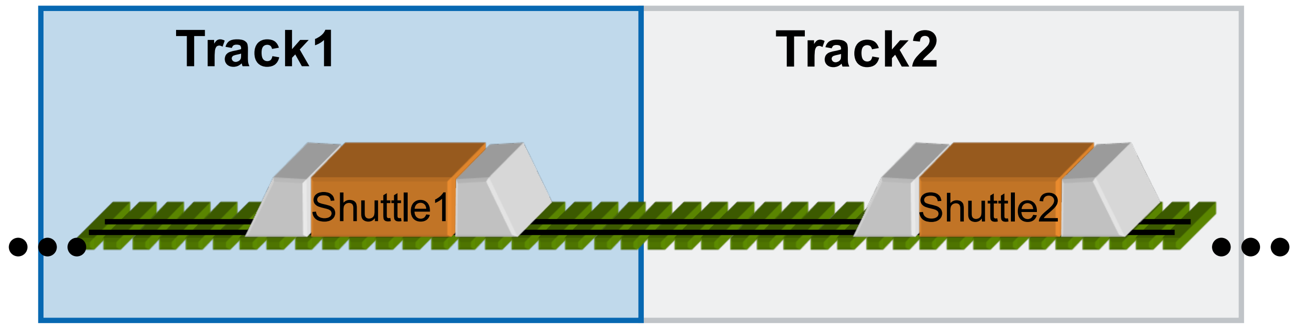
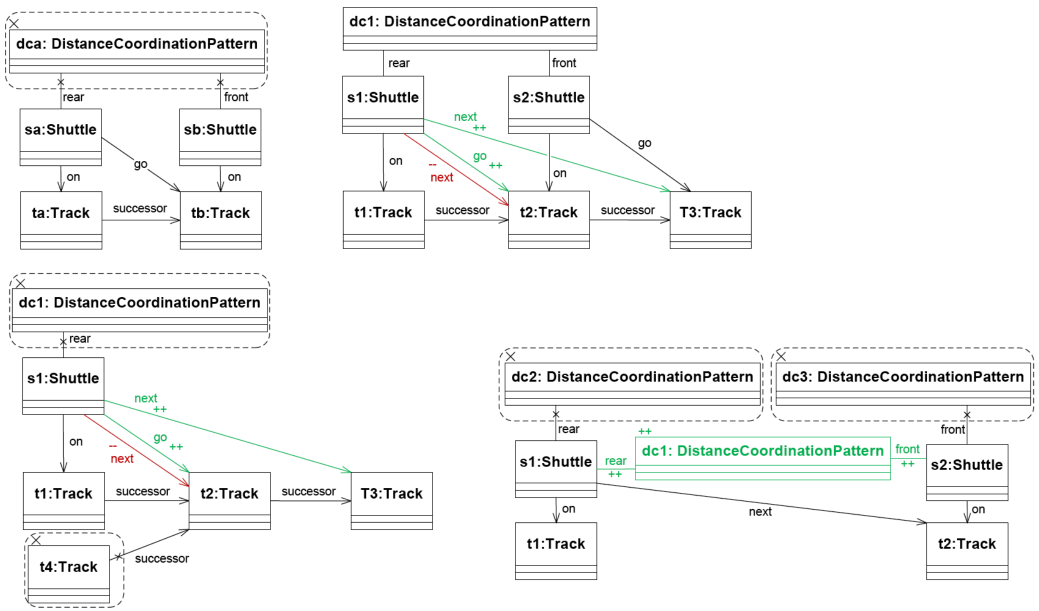
Forbidden Graph





Rules:



Now, the analysis results can guarantee the absence of collisions!

modeling: 6 graph transformation rules and 15 forbidden graphs

Analysis
- Model Checking -

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[ICSE2006]

Model checking:

- Backend tool: the GTS model checker GROOVE
- Topology with only **15** tracks

FUJABA Real-Time Tool Suite

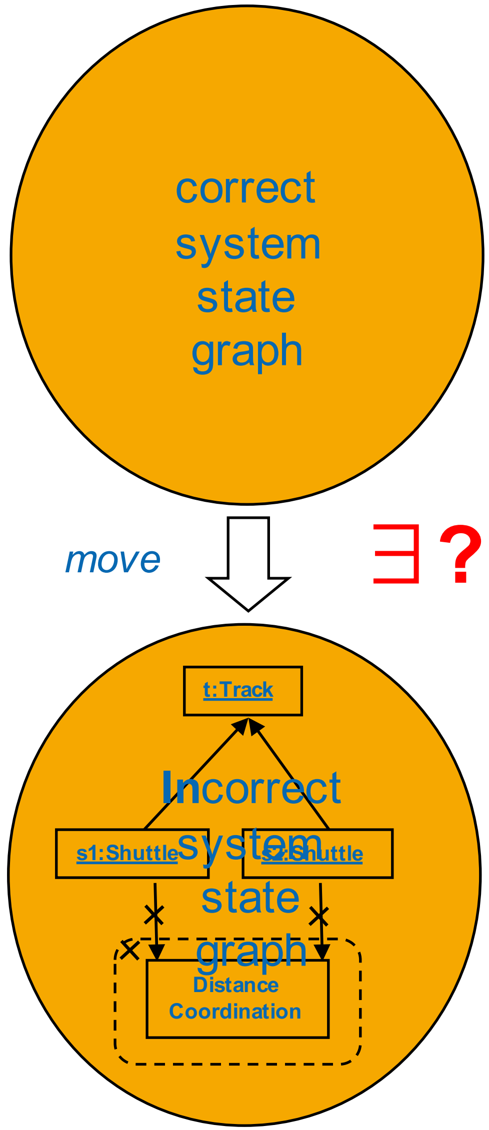
Verification times:

- 3 shuttles ⇨ 2 min
- 4 shuttles ⇨ 7 min
- 5 shuttles ⇨ 55 min
- 6 shuttles ???

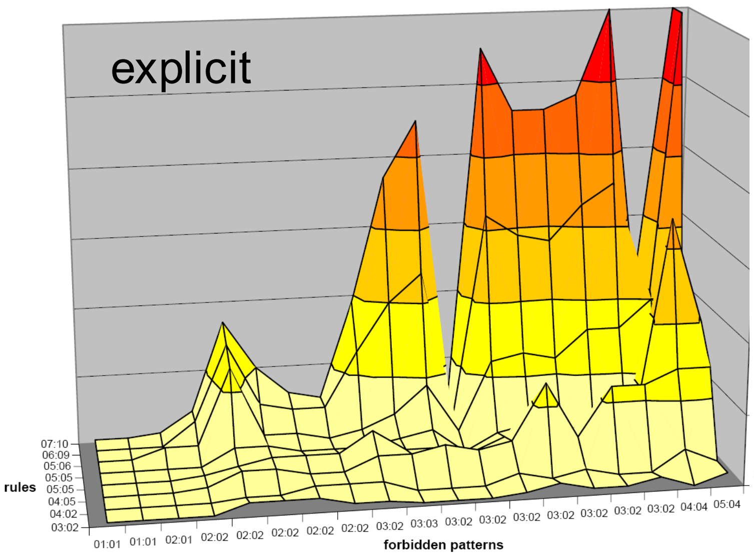
Analysis
- Invariant Checking -

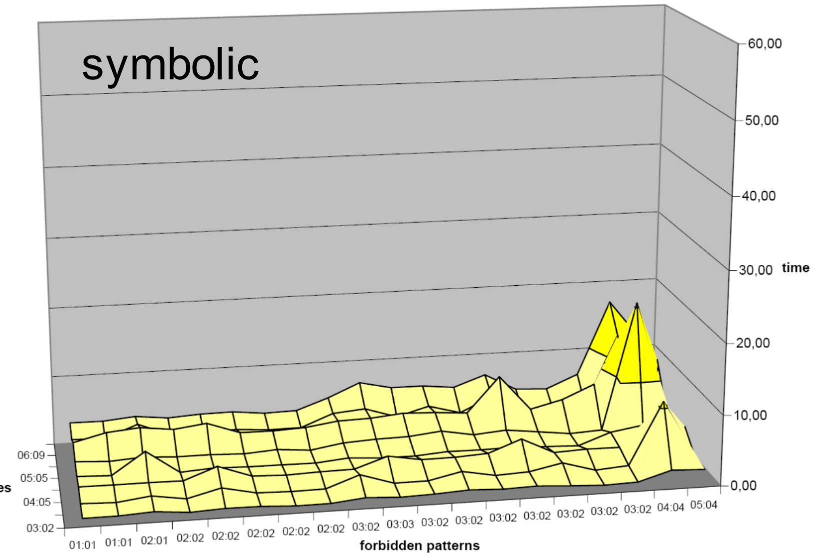
Verification:

- Analyze whether structural changes can lead from safe to unsafe situations (**inductive invariants**)
    - Supports infinite many start configurations specified only by their structural properties
    - Supports infinite state models
    - Produced **counterexamples** allow to incrementally develop the right inductive invariants



Analysis
- Invariant Checking -





[ICSE2006]

The same scaling!

Rule / pattern (nodes:edges)	explicit	symbolic
goDC1(7:10) / invalidDCPattern(5:4)	744 s	11.2 s
goDC2(6:09) / invalidDCPattern(5:4)	170 s	6.5 s
goDC1(7:10) / noDC(4:4)	20 s	16.8 s
goDC2(6:09) / noDC(4:4)	7 s	13.1 s
goDC1(7:10) / unambigousOn(3:2)	60 s	6.1 s
goDC2(6:09) / unambigousOn(3:2)	36 s	2.9 s
goDC1(7:10) / unambigousNext(3:2)	48 s	4.1 s
goDC2(6:09) / unambigousNext(3:2)	33 s	2.1 s

Invariant checking:

- Infinite many initial configurations
- Infinite large models

Verification times:

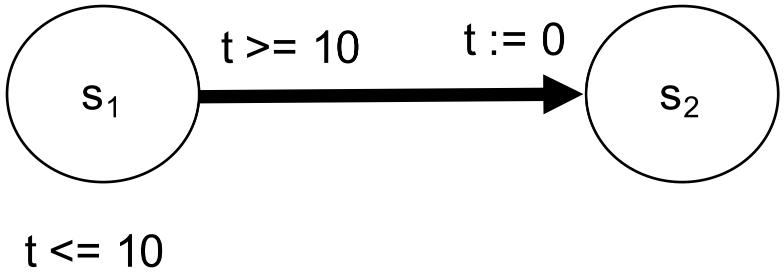
- explicit ⇨ 34 min
- symbolic ⇨ 5 min (Backend tool: CrocoPat)

Semantics & Time

[ISORC2008]

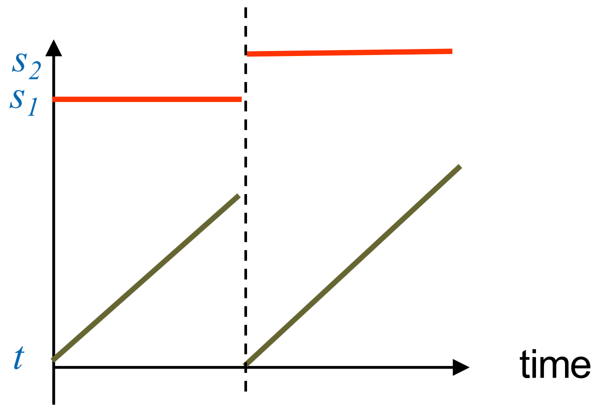
Timed automata

- clock variables with
  - invariants for states
  - conditions and assignments/resets for transitions



Semantics:

- **instantaneous transitions** where no time passes by
- **time transitions** where time can pass by and the automata stays within a state (clock values increase)



Modeling & Time
- Timed GTS (TGTS) -

[ISORC2008]

A **timed graph transformation system** (we omit NACs) consists of

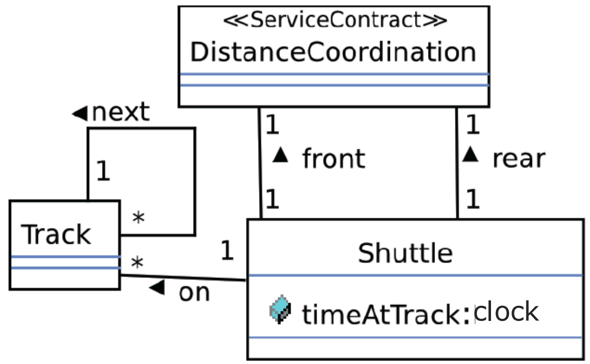
- a type graph describing all possible model configurations and the clocks of each node type,
- a set of rules R with LHS, RHS, clock condition, and clock updates,
- a subet of R of the urgent rules, and
- a function $prio: R \rightarrow Int$ which assigns priorities to all rules.

- A state (G,a) is a graph G plus an evaluation a for all clocks.
- An **instantaneous step** (rule application) $(G,a) \rightarrow_r (G',a')$, where G' results from G applying the GTS rule and a' is derived from a applying the clock update of r, is instantaneous and no time passes.
- A **time step** $(G,a) \rightarrow_\delta (G,a')$ where a' is derived from a by adding the delay δ to each evaluation to deonote the passing of time, which can only happen when in between no urgent rule is enabled.

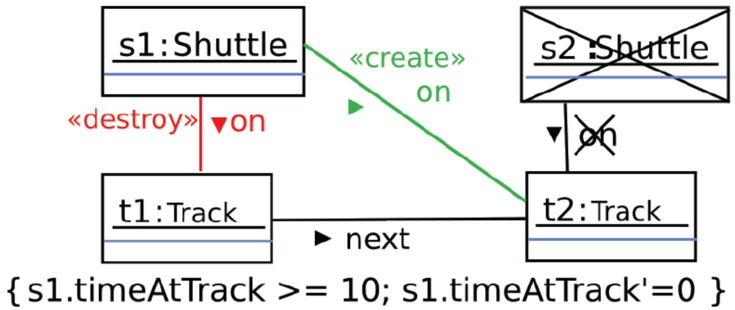
Modeling & Time
- Example -

[ISORC2008]

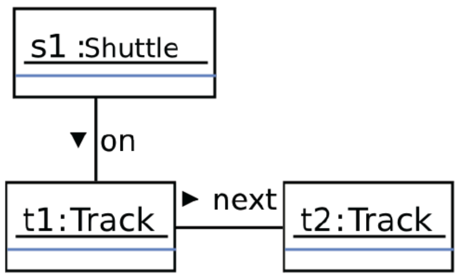
Type graph:

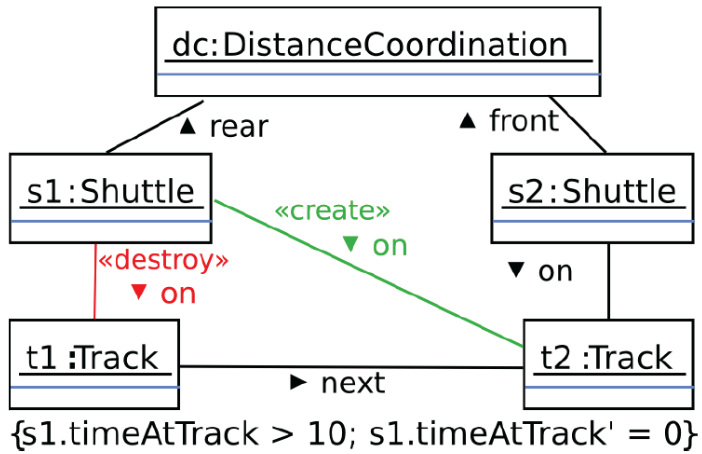


Rules (some only):



Simple instance graph:





modeling: only 4 graph transformation rules and 2 forbidden pattern

Analysis
- Invariant Checking -

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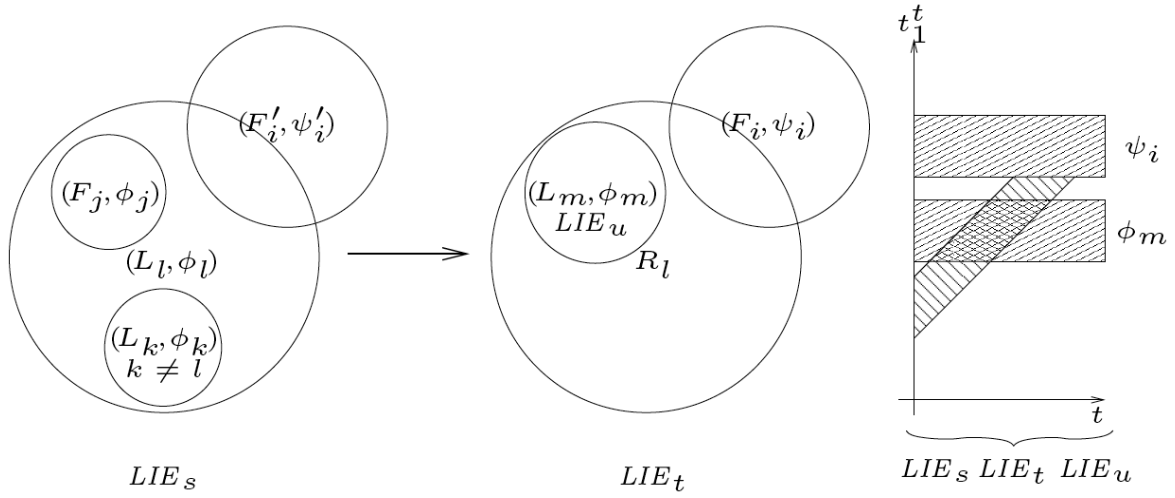

Checker: solve 1) as for GTS and encode 2) using linear inequalities (CPLEX)

[ISORC2008]

1) Determine all source target and applicable rule r such that

- the invariants holds for the source pattern,
- the resulting target pattern potentially breaks the invariant

2) Determine for a counterexample from 1) consisting of a source target and applicable rule r whether

- the resulting target pattern breaks the invariant for t >= 0 and
- no urgent rule is enabled for a t' with 0 <= t' < t.

Summary

- **Modeling:** 4 rules and 2 forbidden pattern with time vs. 6 rules and 15 forbidden pattern for the untimed case
- **Verification:** average of 329 ms for the timed case vs. 5 min for the untimed case

Remark:

- Also a Hybrid GTS and a possible mapping of the 2nd step of the invariant checking problem to a model checker for hybrid automata (PHAVer) has been developed.

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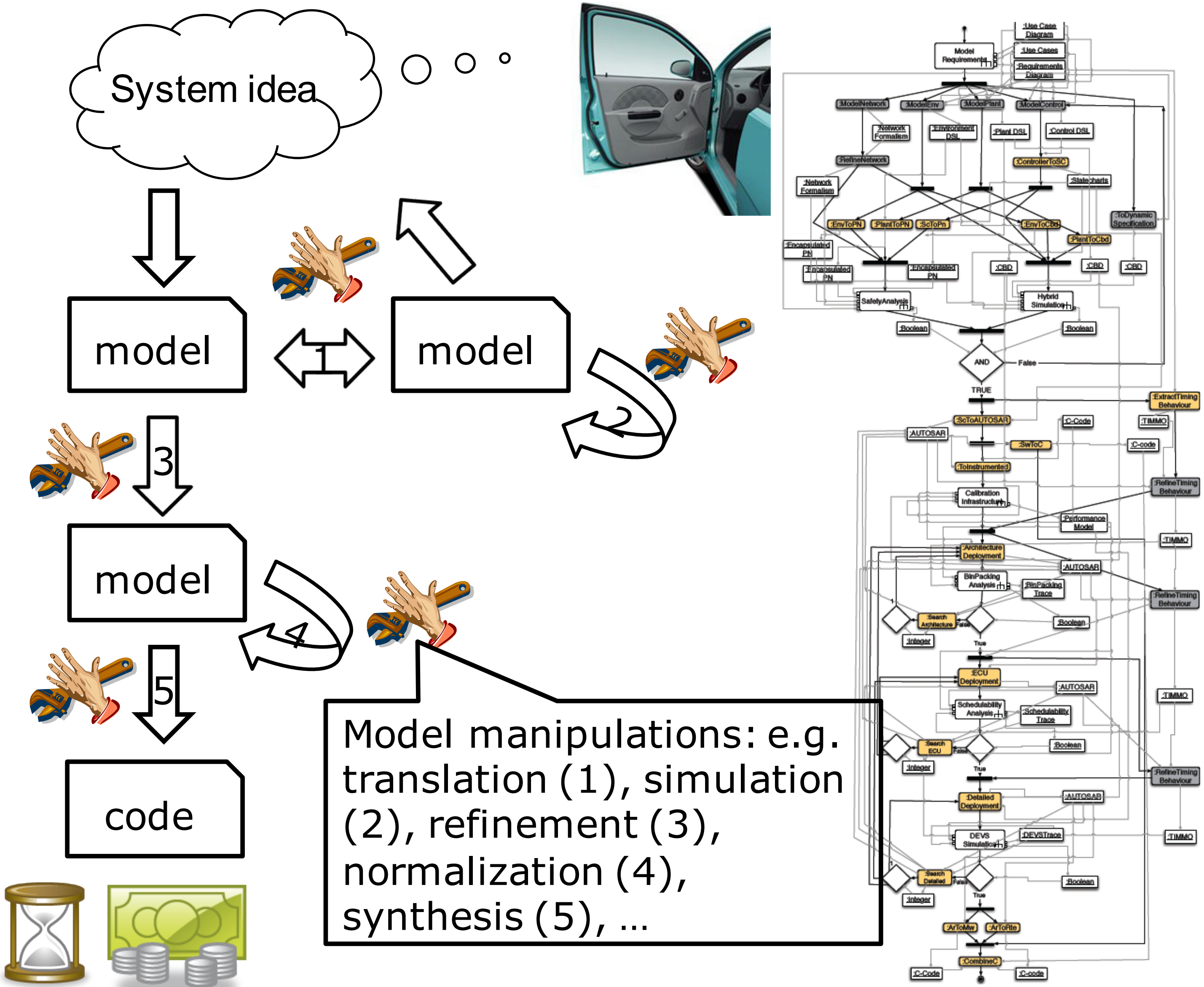
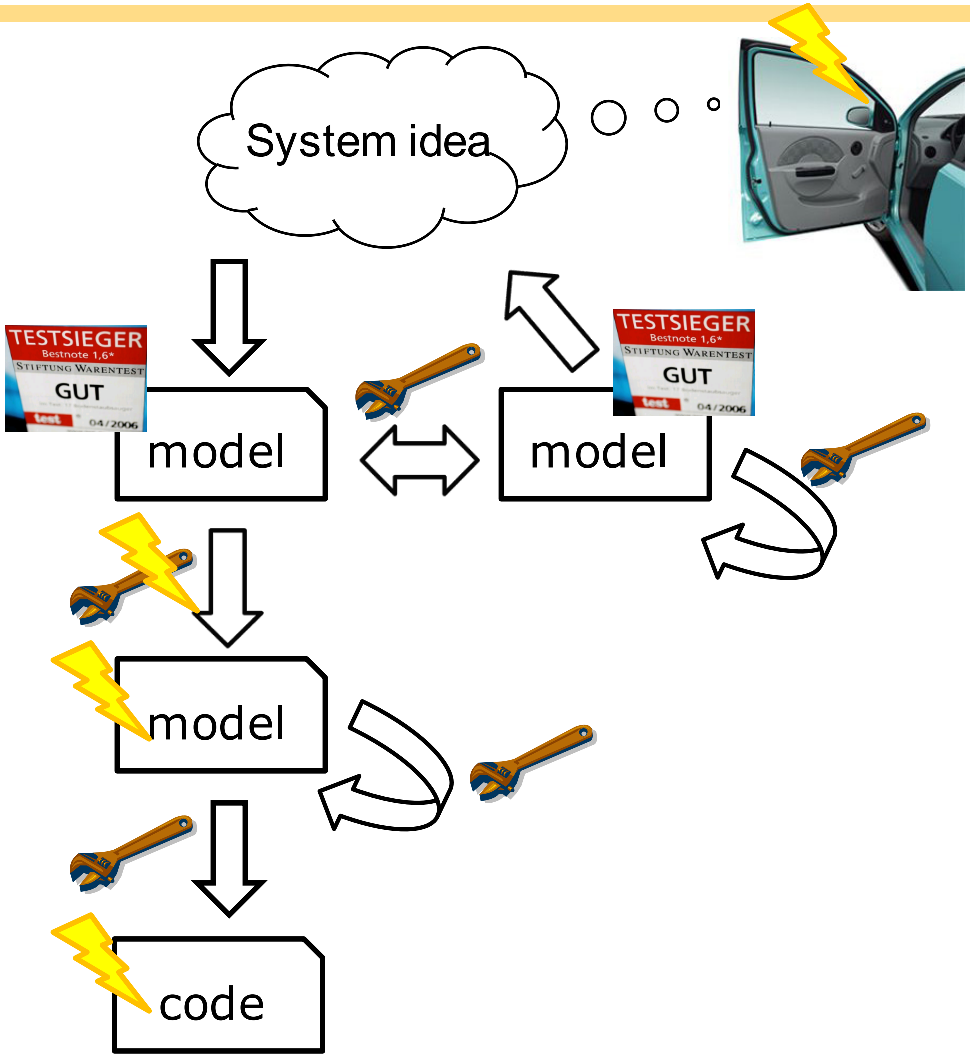
Why Model Transformations?

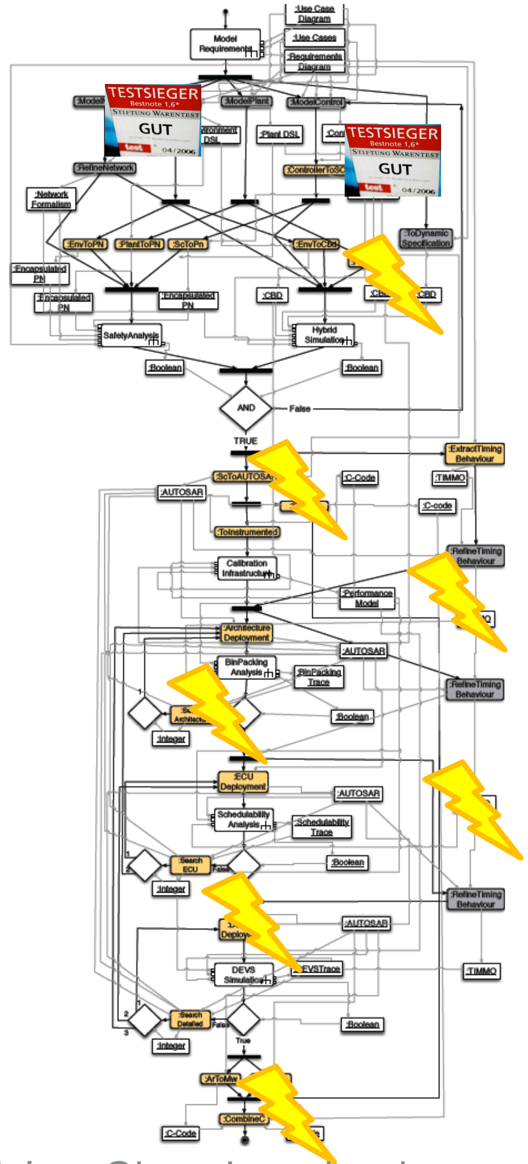
„The Heart and Soul of Model-Driven Engineering“ [SK03]



[Lucio+14]

Correct Model Transformations





Model Transformations in a Nutshell

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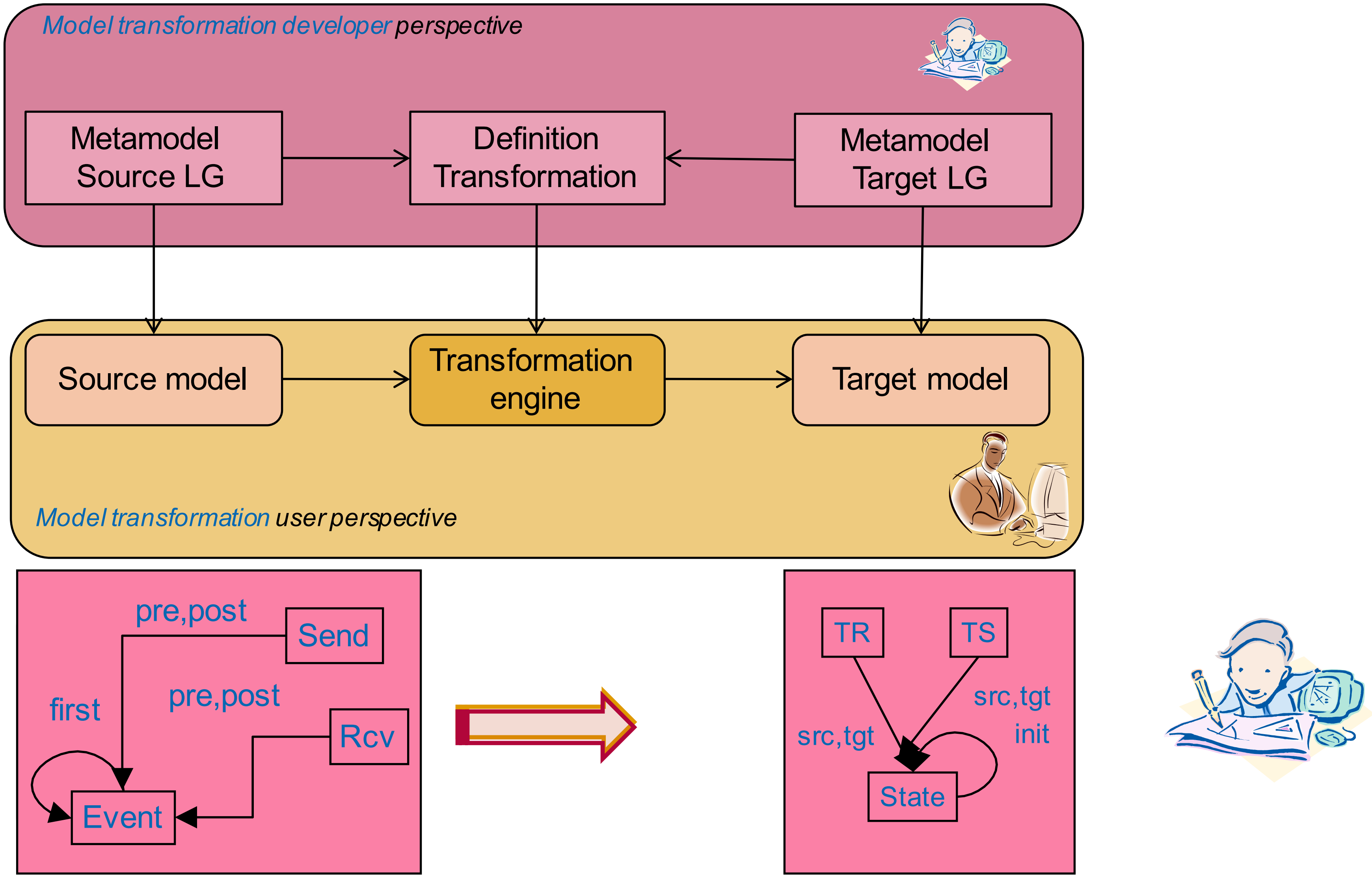
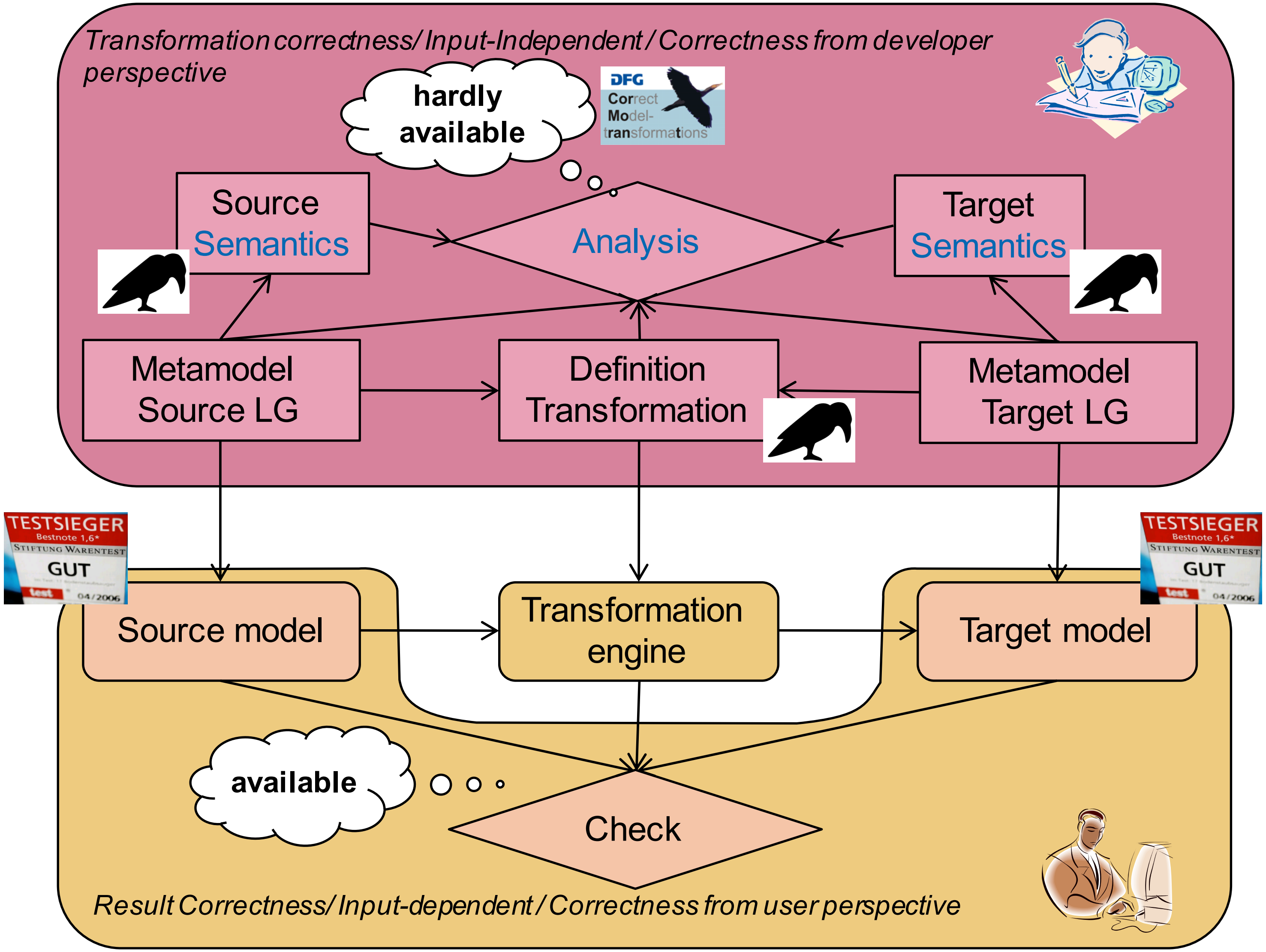
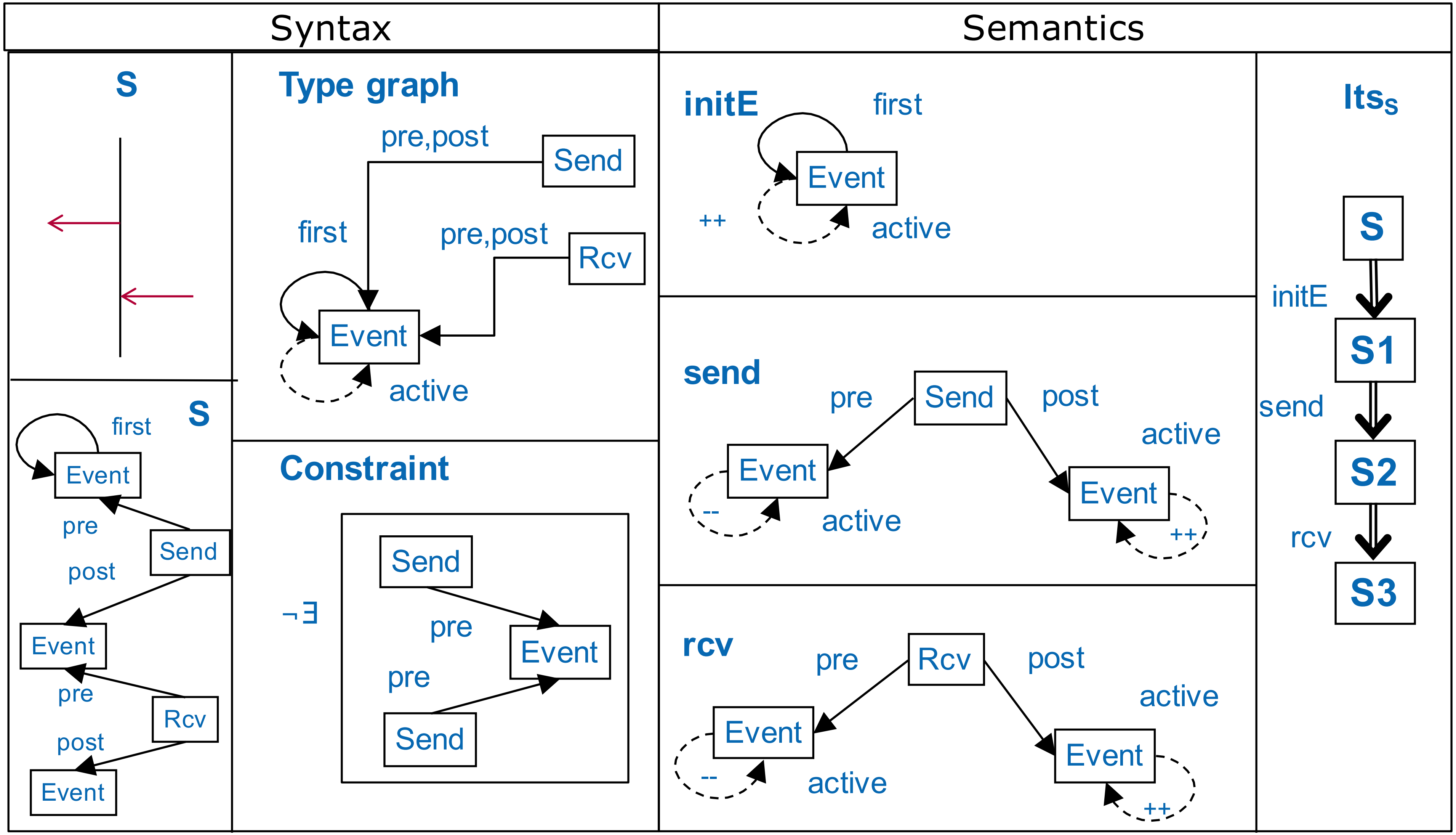


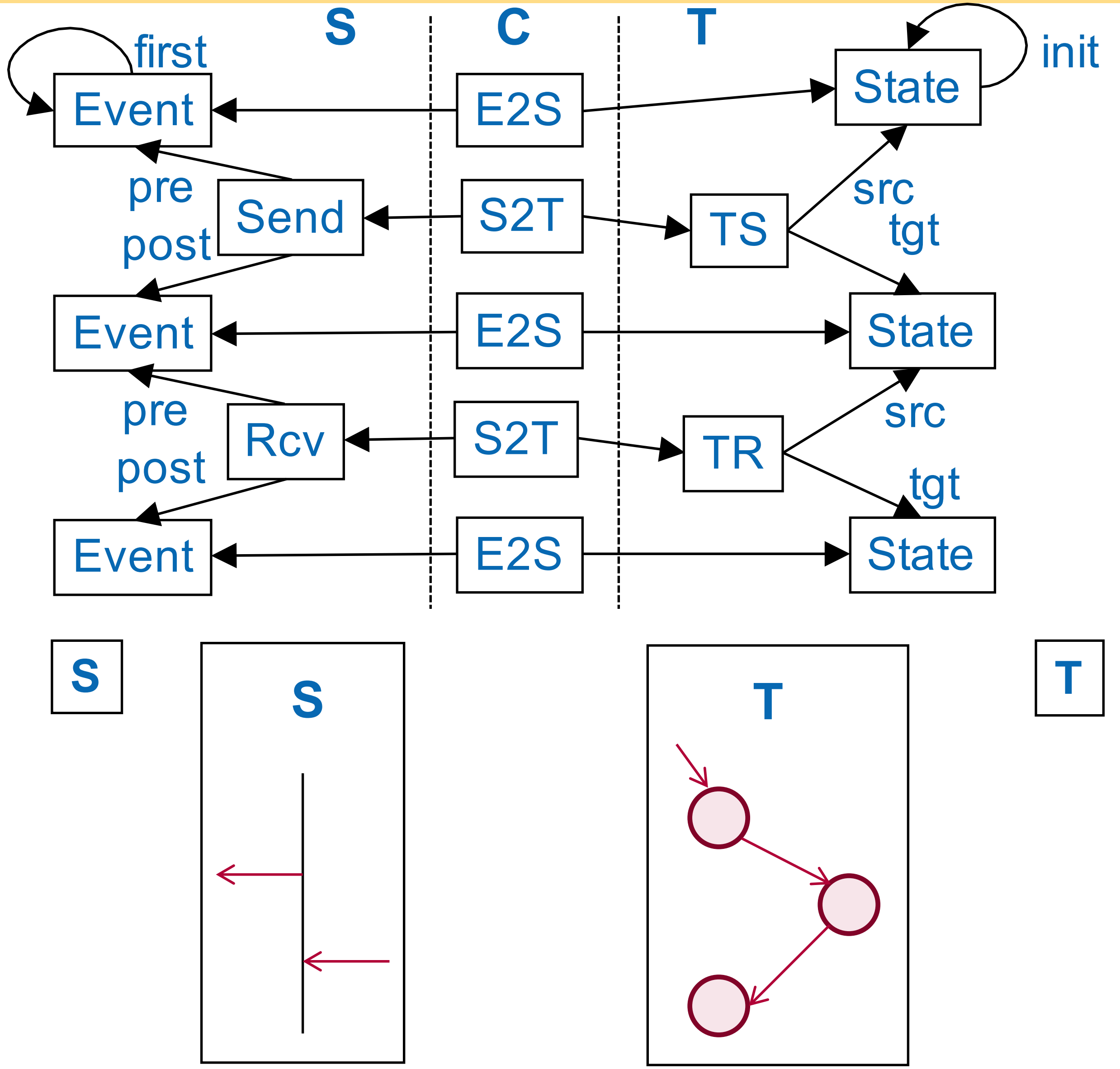
Correct Model Transformations



Behavior Definition using Graph Transformation



Behavior Preservation via Bisimulation



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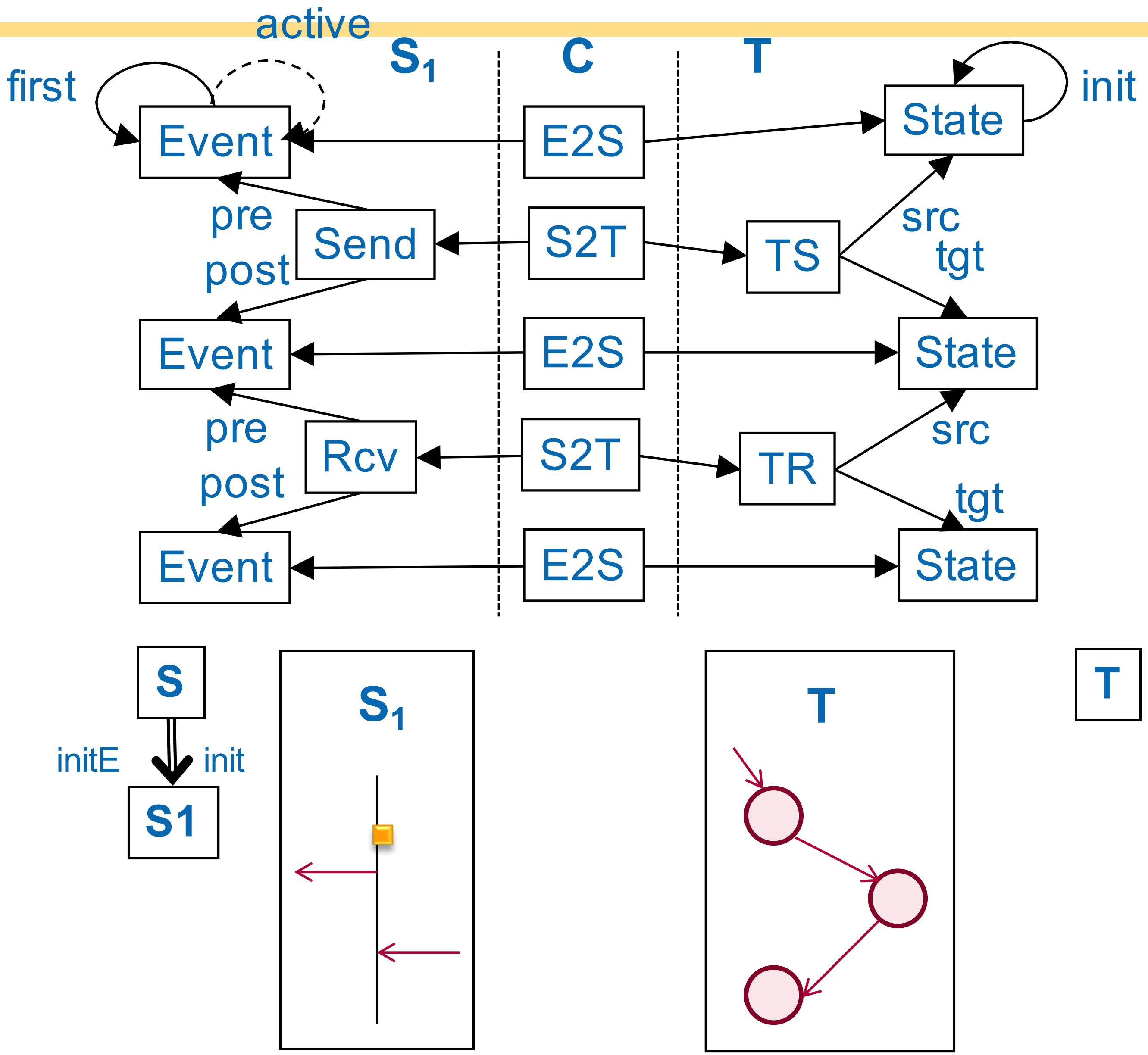
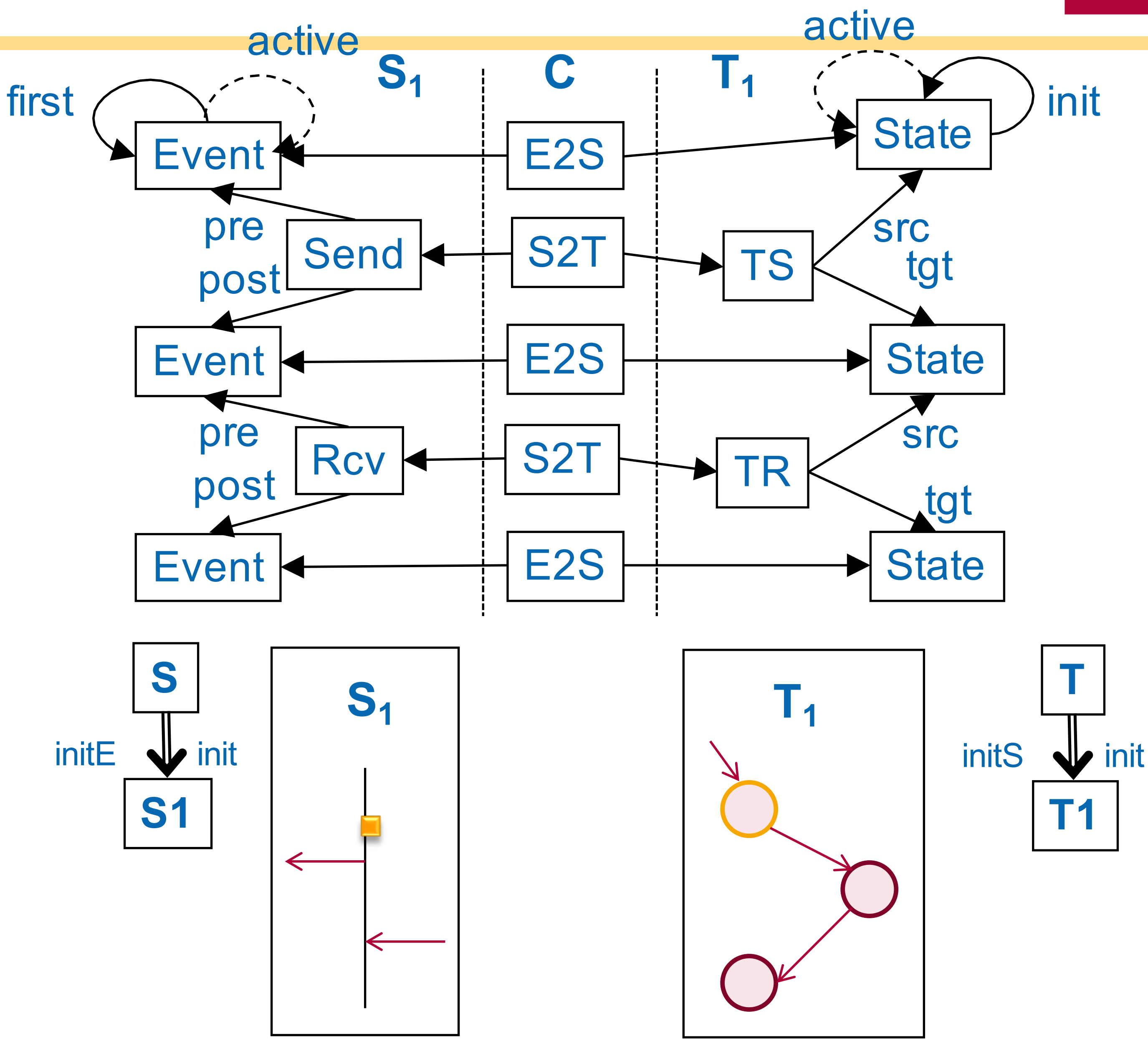


Behavior Preservation via Bisimulation



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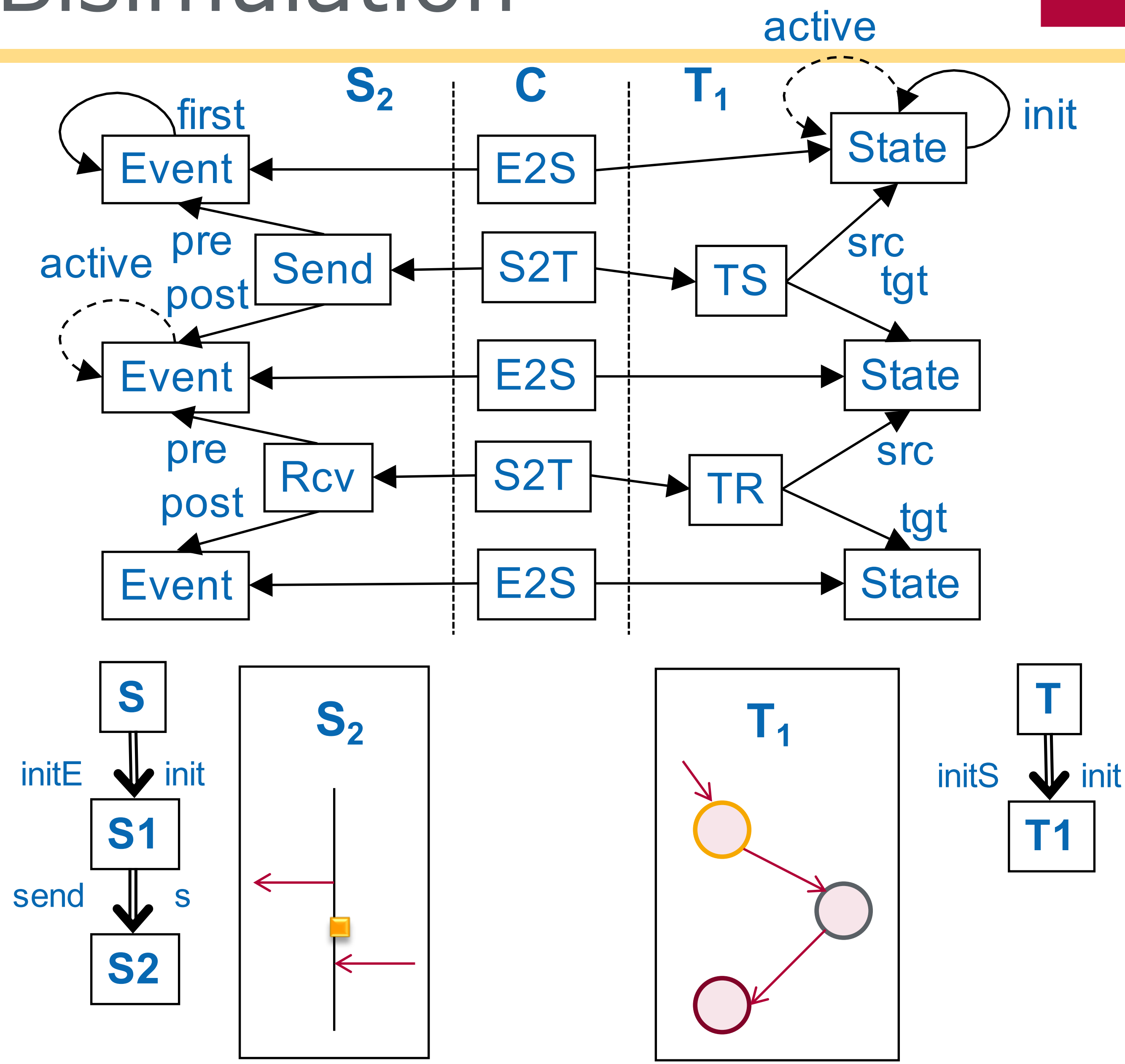

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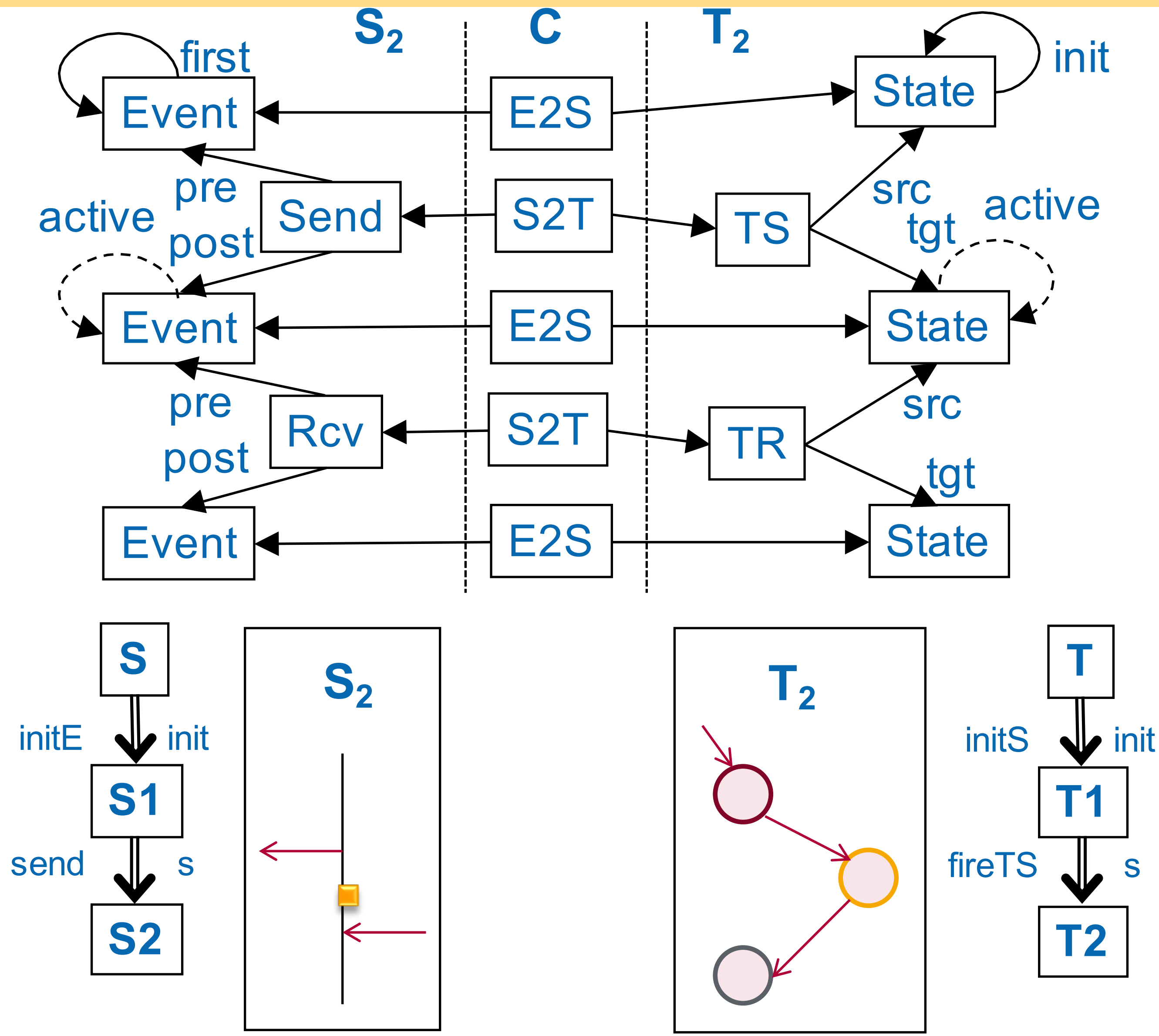

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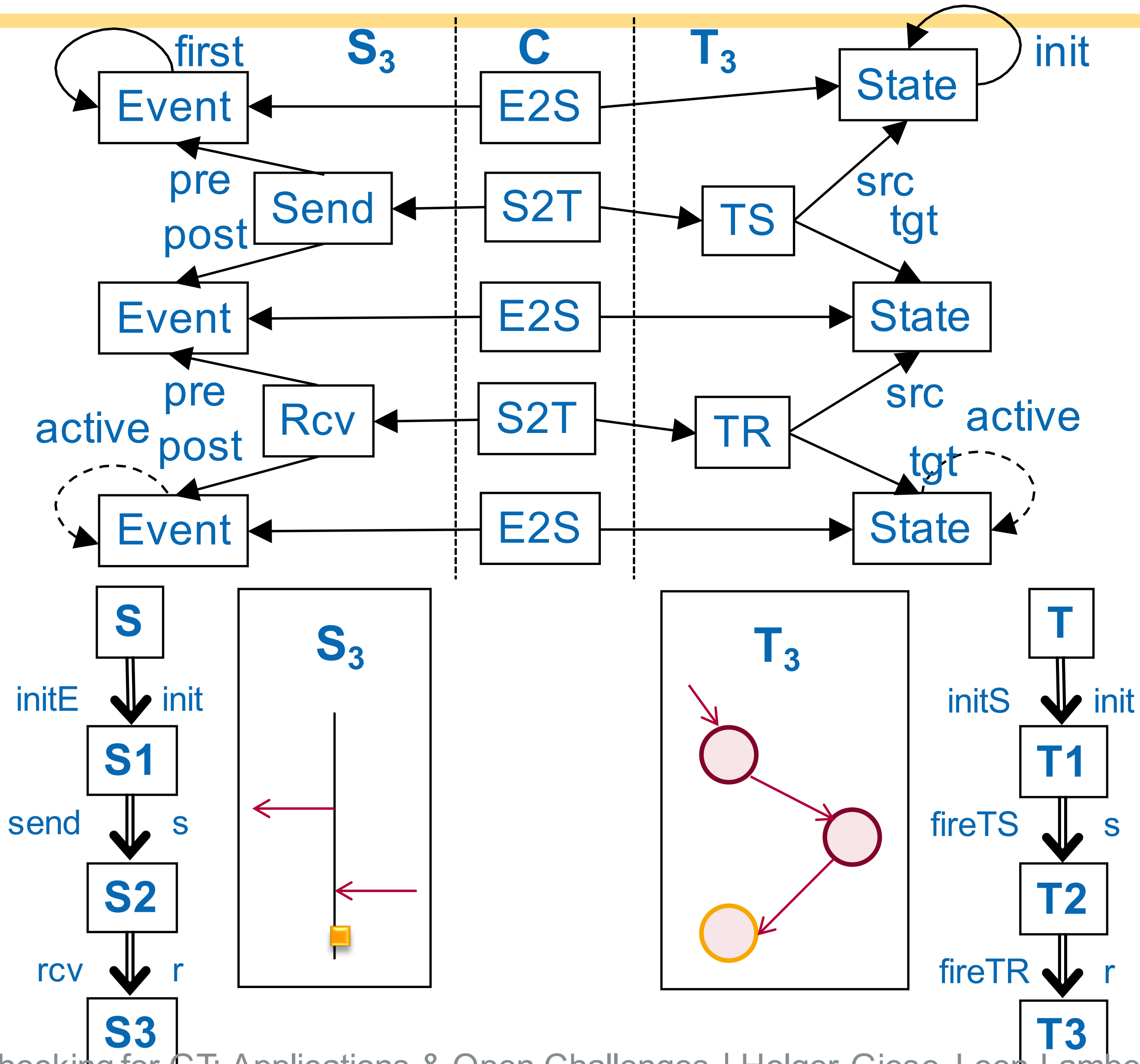

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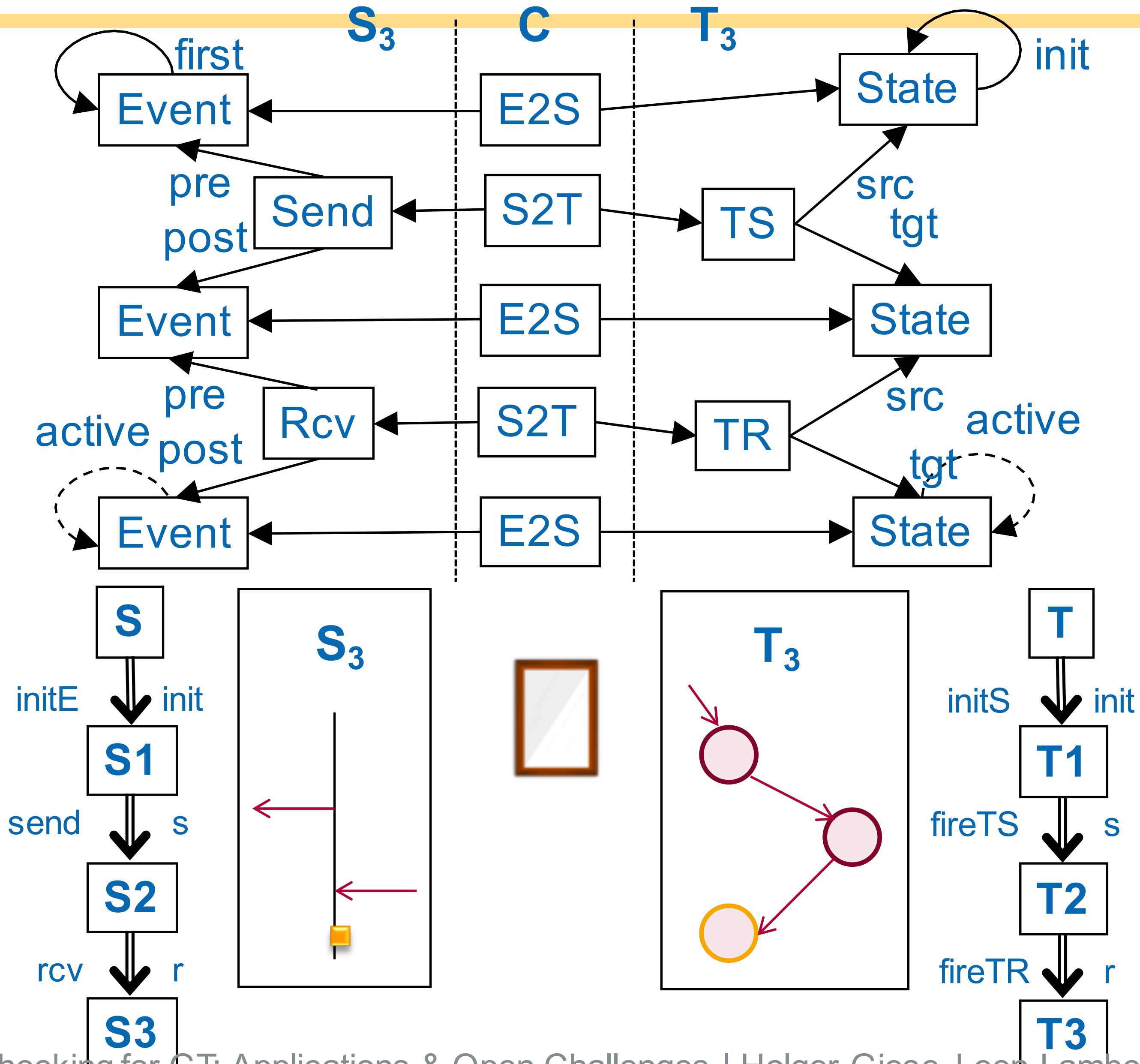

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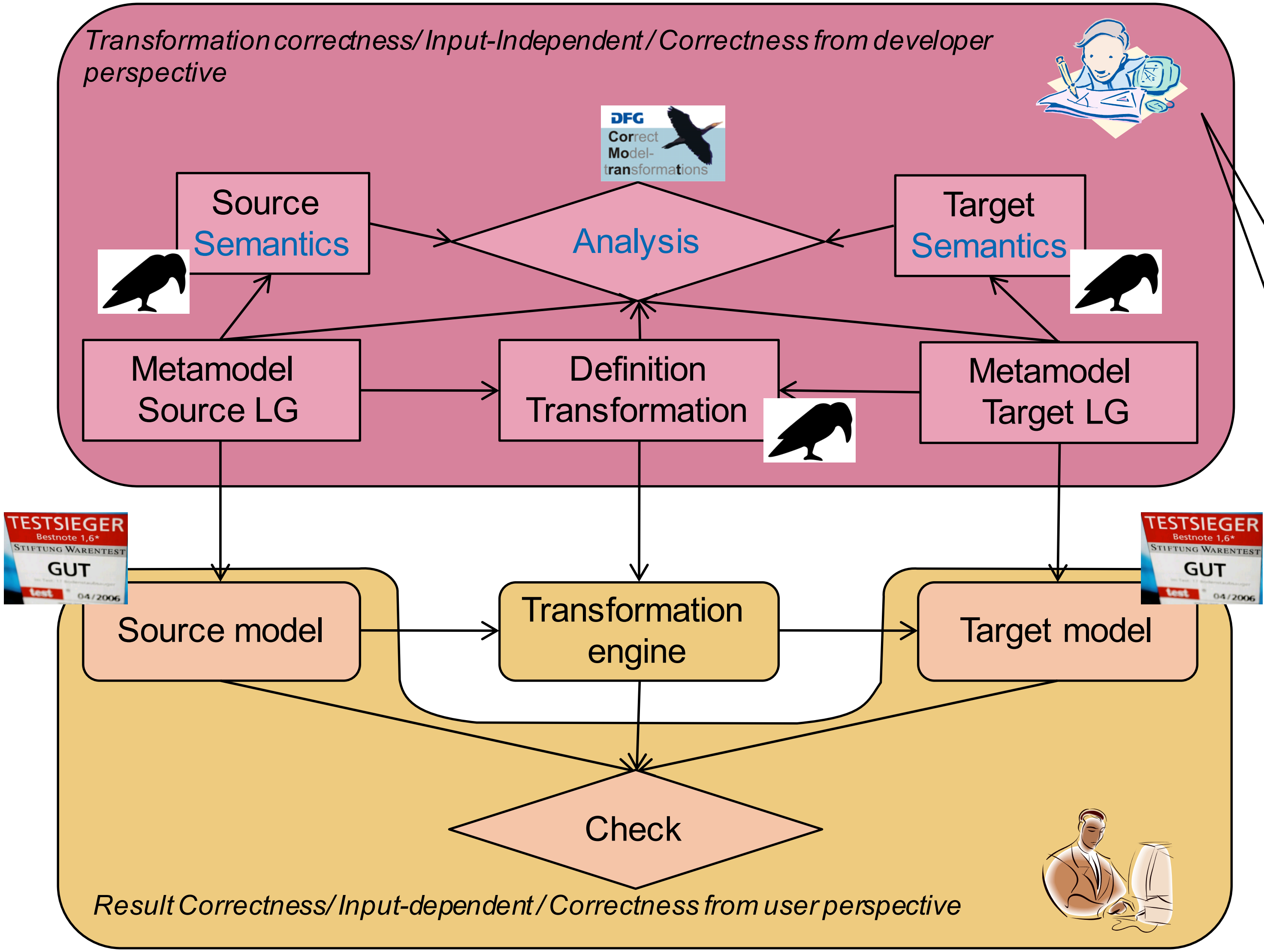
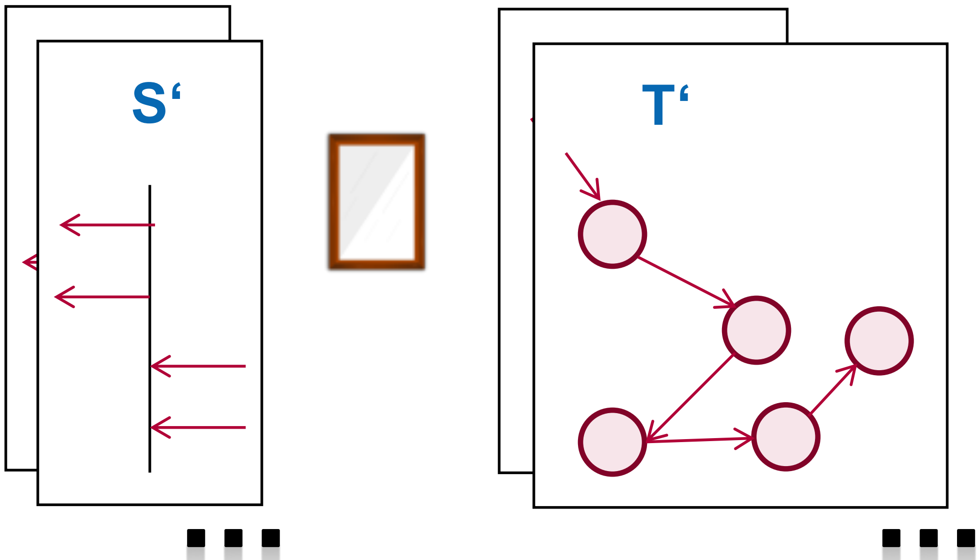


LTSs of **each** source and target model of the MT bisimilar?

Behavior Preservation
Two-Step Algorithm

1. **MT definition only allows source and target models that are in the bisimulation relation**
2. Behavior definitions of source and target modeling languages preserve bisimulation relation



Behavior Preservation Two-Step Algorithm

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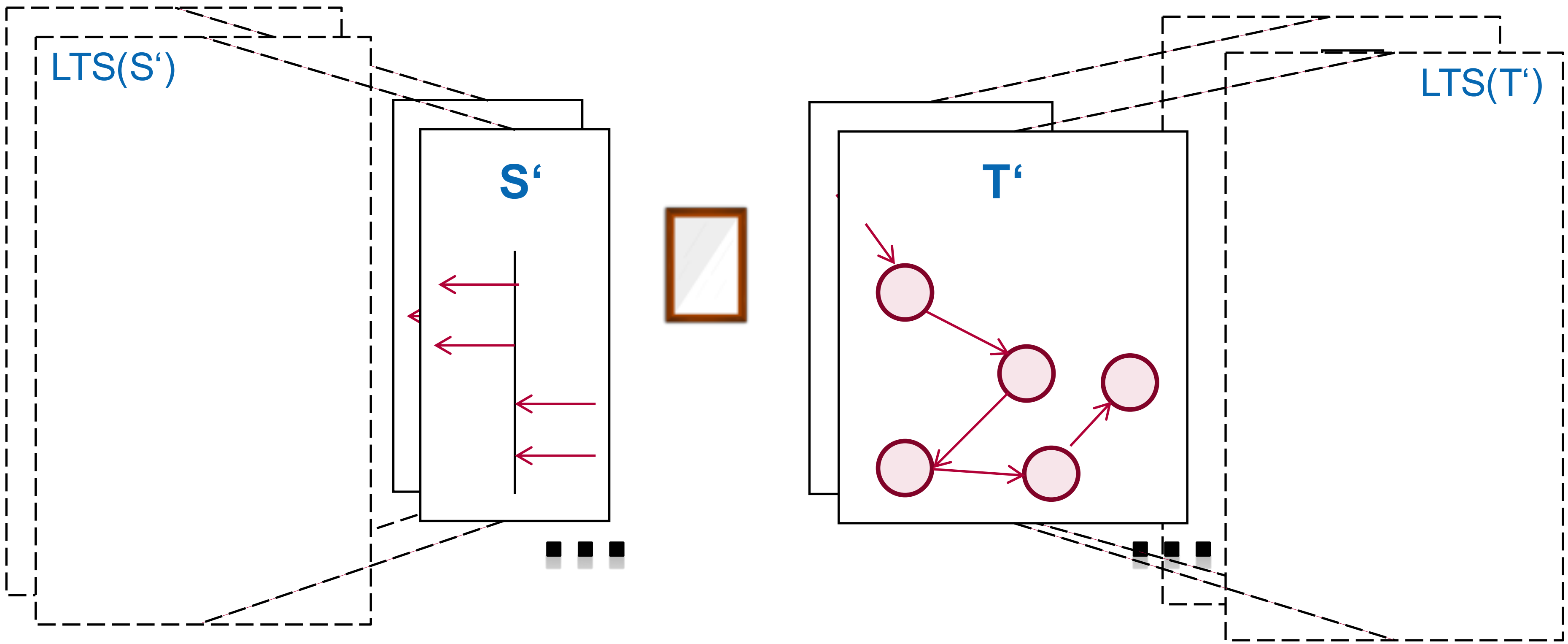

Behavior Preservation Two-Step Algorithm

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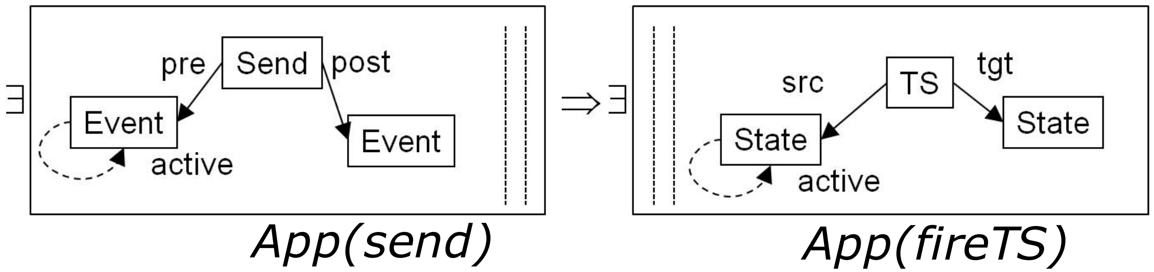
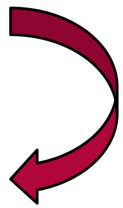
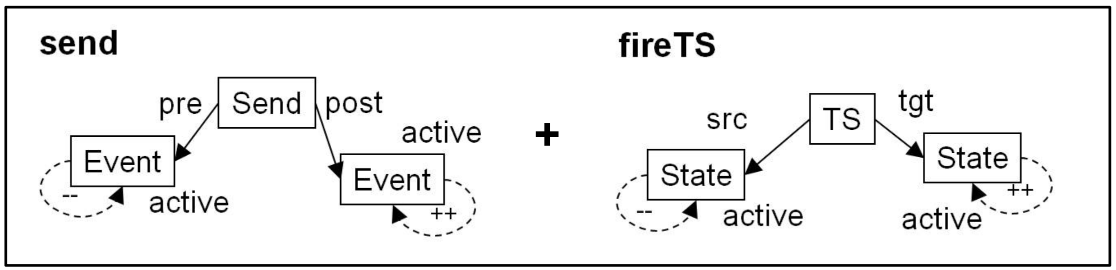


Bisimulation constraint

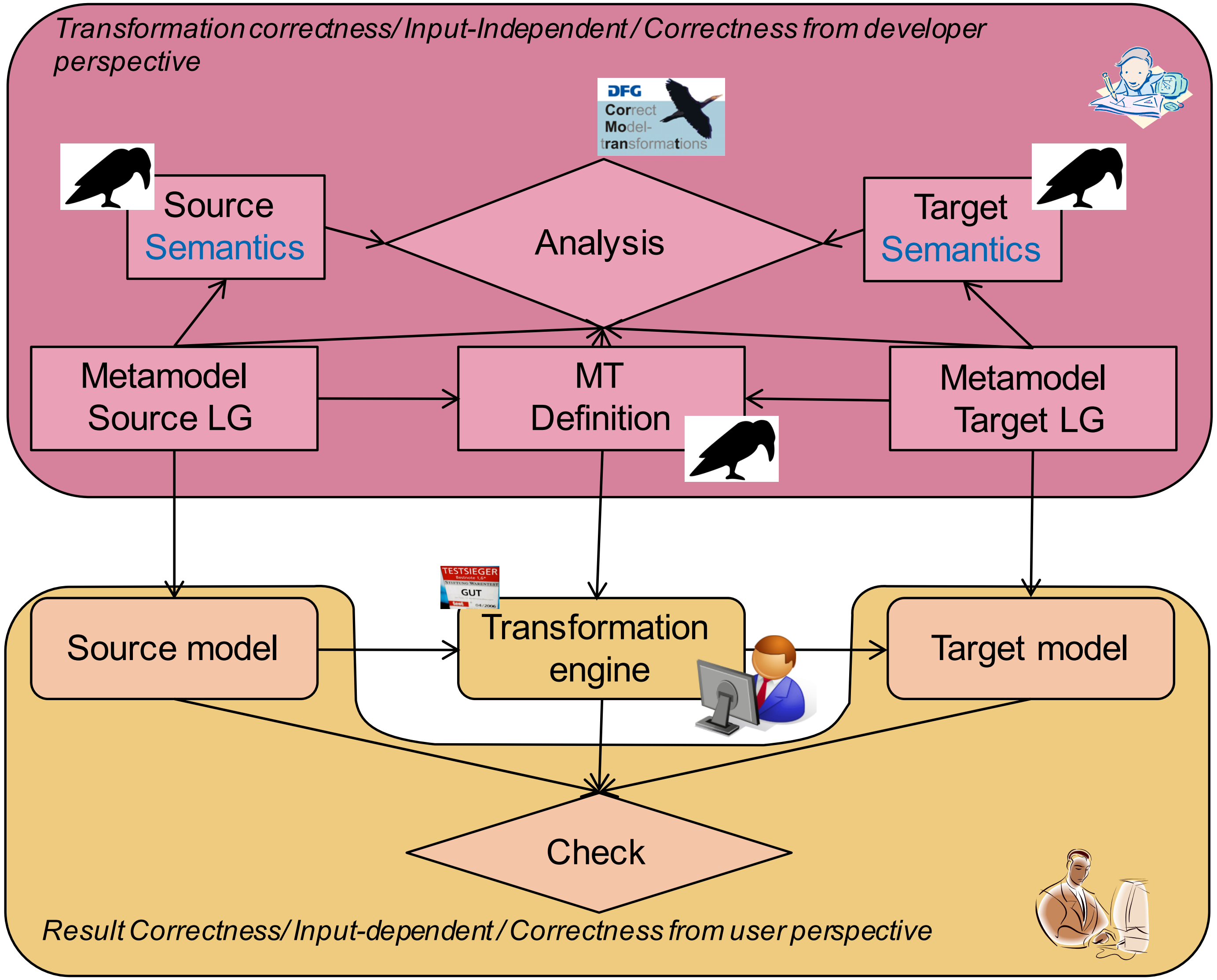


invariant



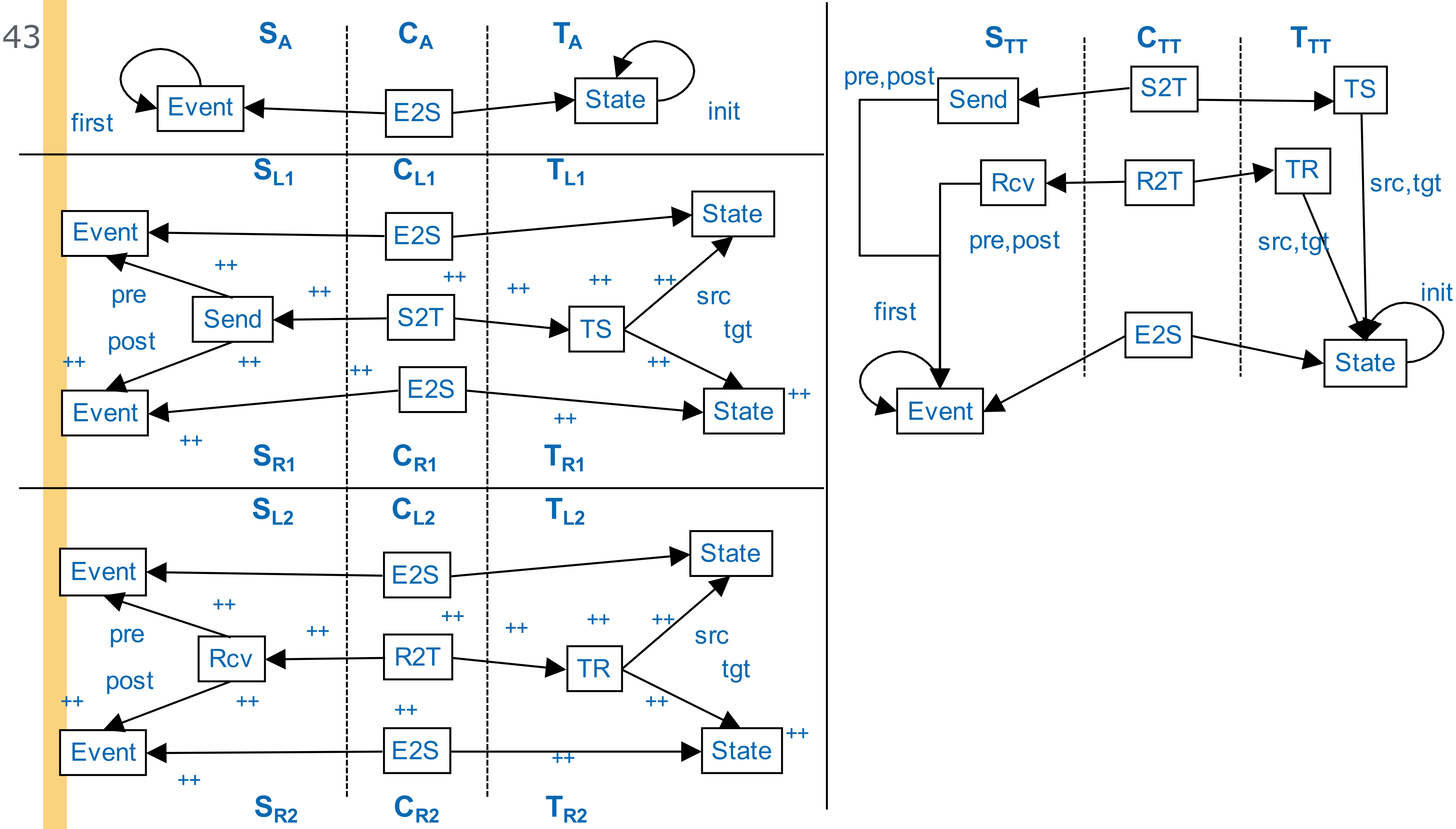
Parallel application source + target rules

Behavior Preservation

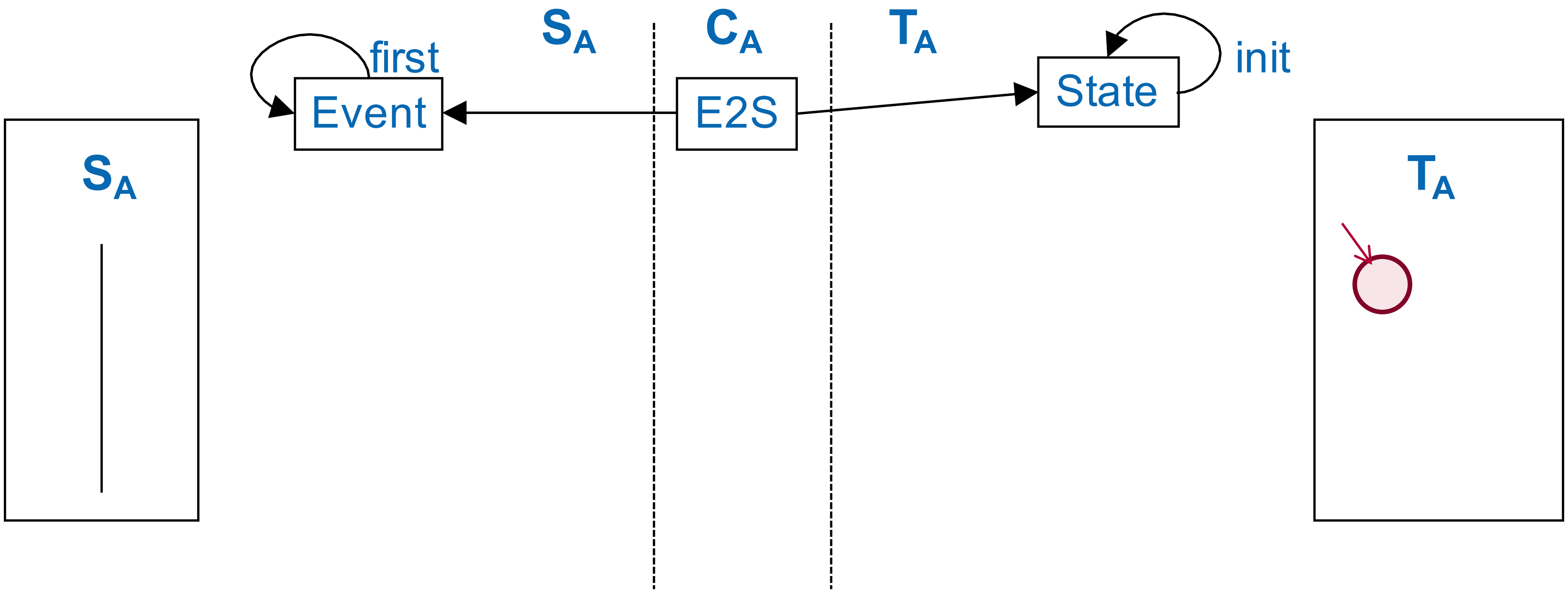


MT languages can be *operational* (e.g. QVT Operational), *relational* (e.g. TGGs, QVT Relational) or *hybrid* (e.g. ATL)

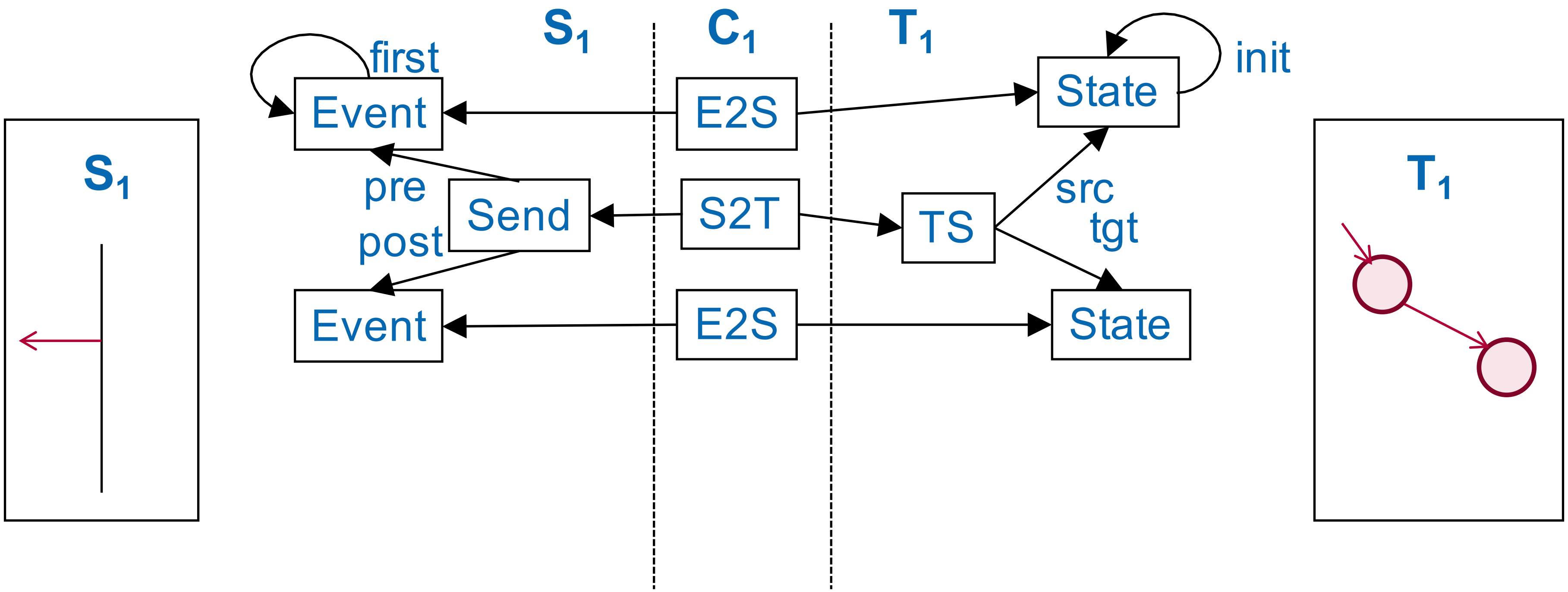
Triple Graph Grammar = Relational Specification



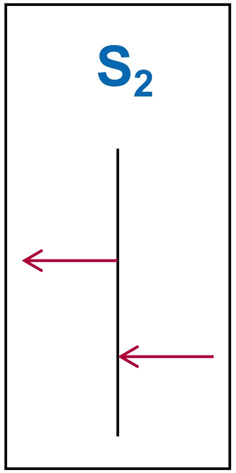
Triple Graph Grammar = Relational Specification

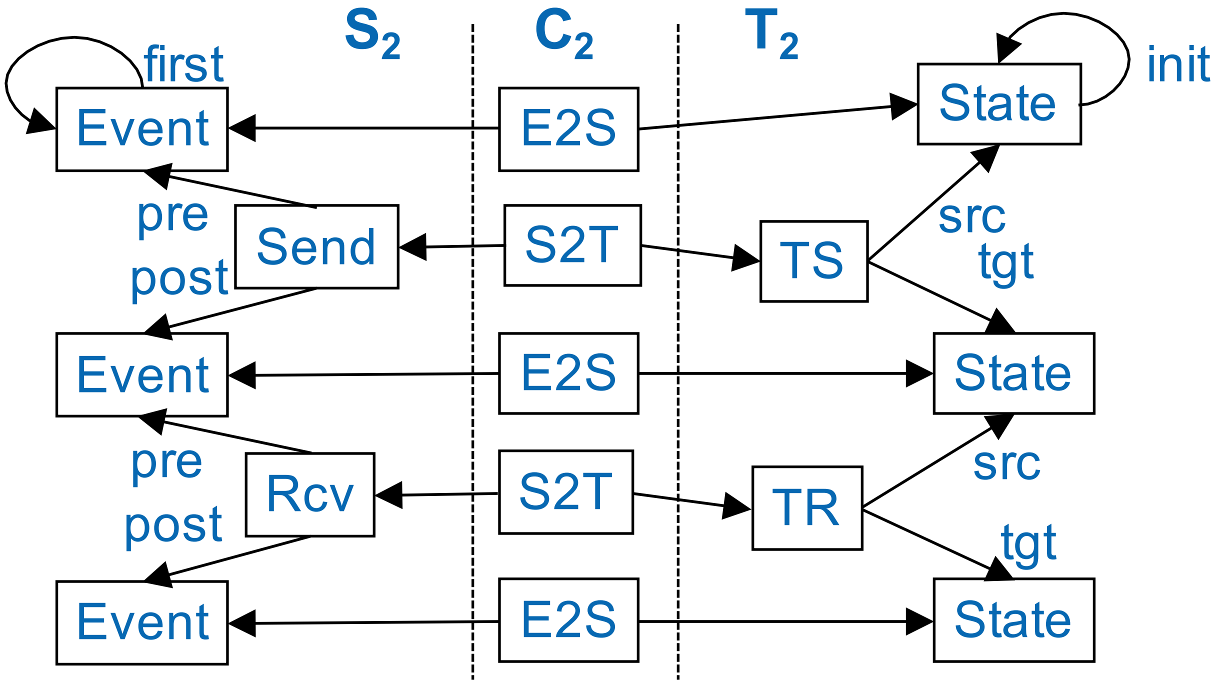


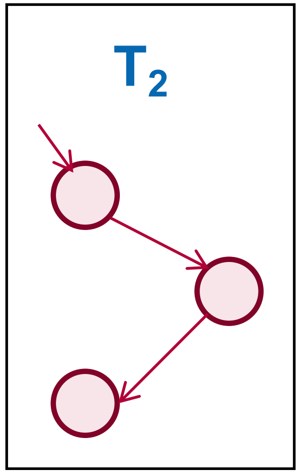
Triple Graph Grammar = Relational Specification



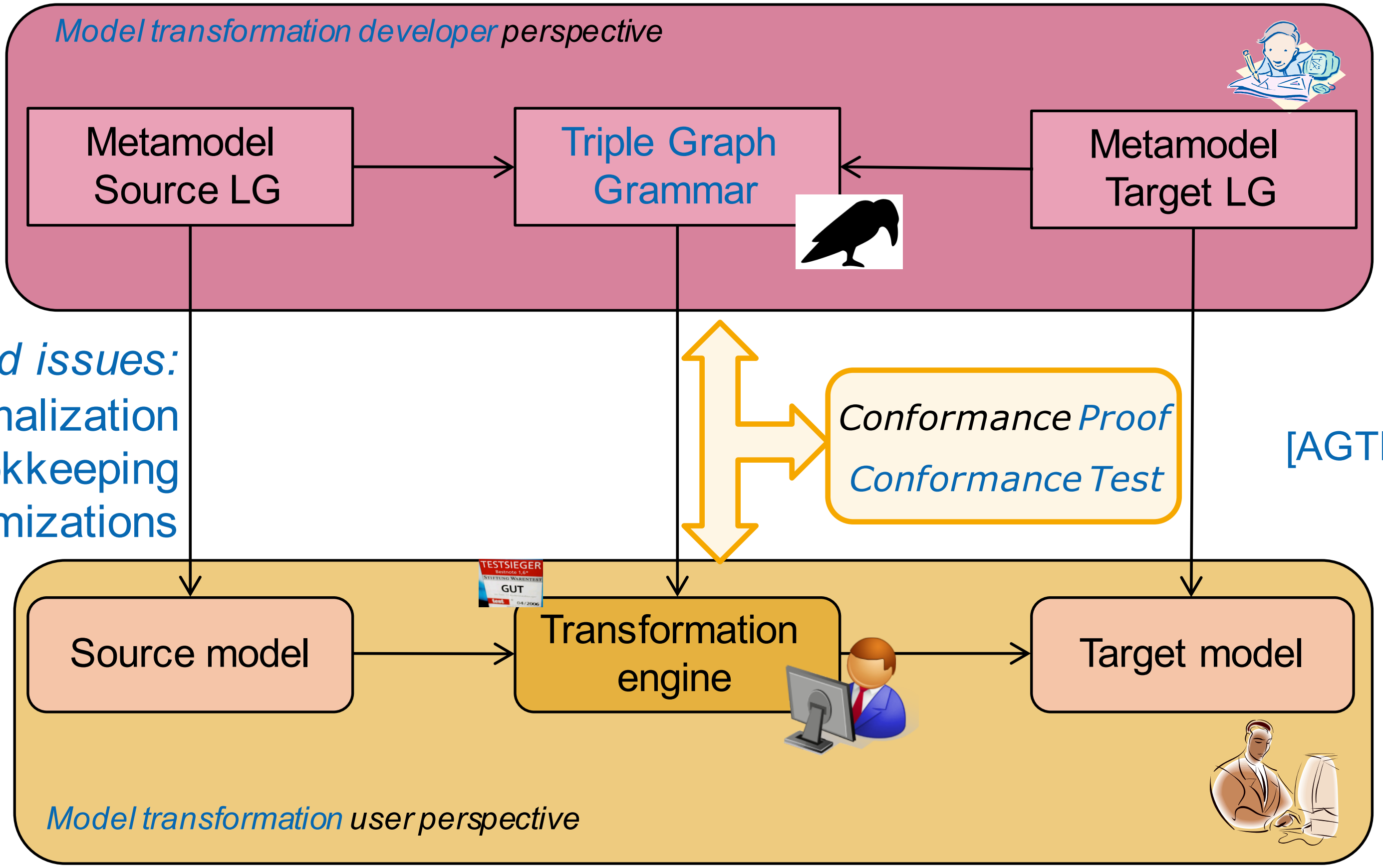
Triple Graph Grammar = Relational Specification







Conformance Checking Relational Specification ~ Implementation



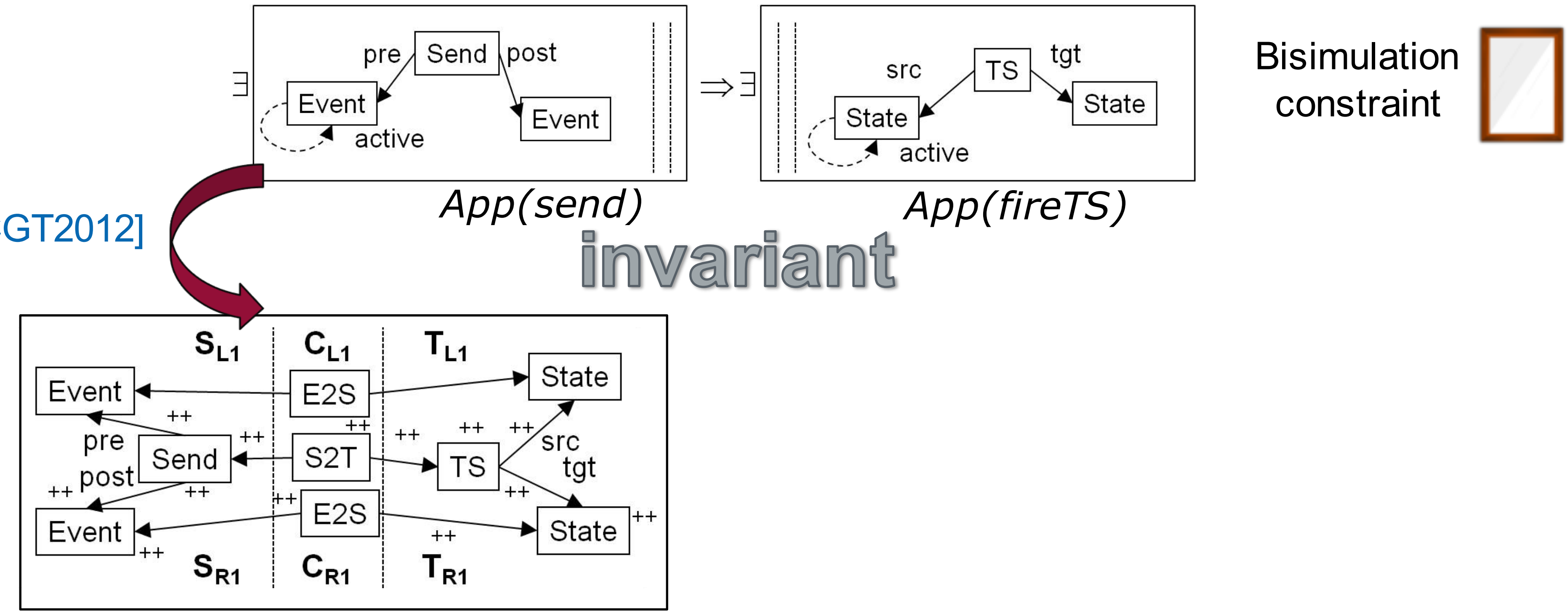
Advanced issues:
- TGG formalization
- Bookkeeping
- Optimizations

[AGTIVE11, SoSyM12]

Behavior Preservation Two-Step Algorithm

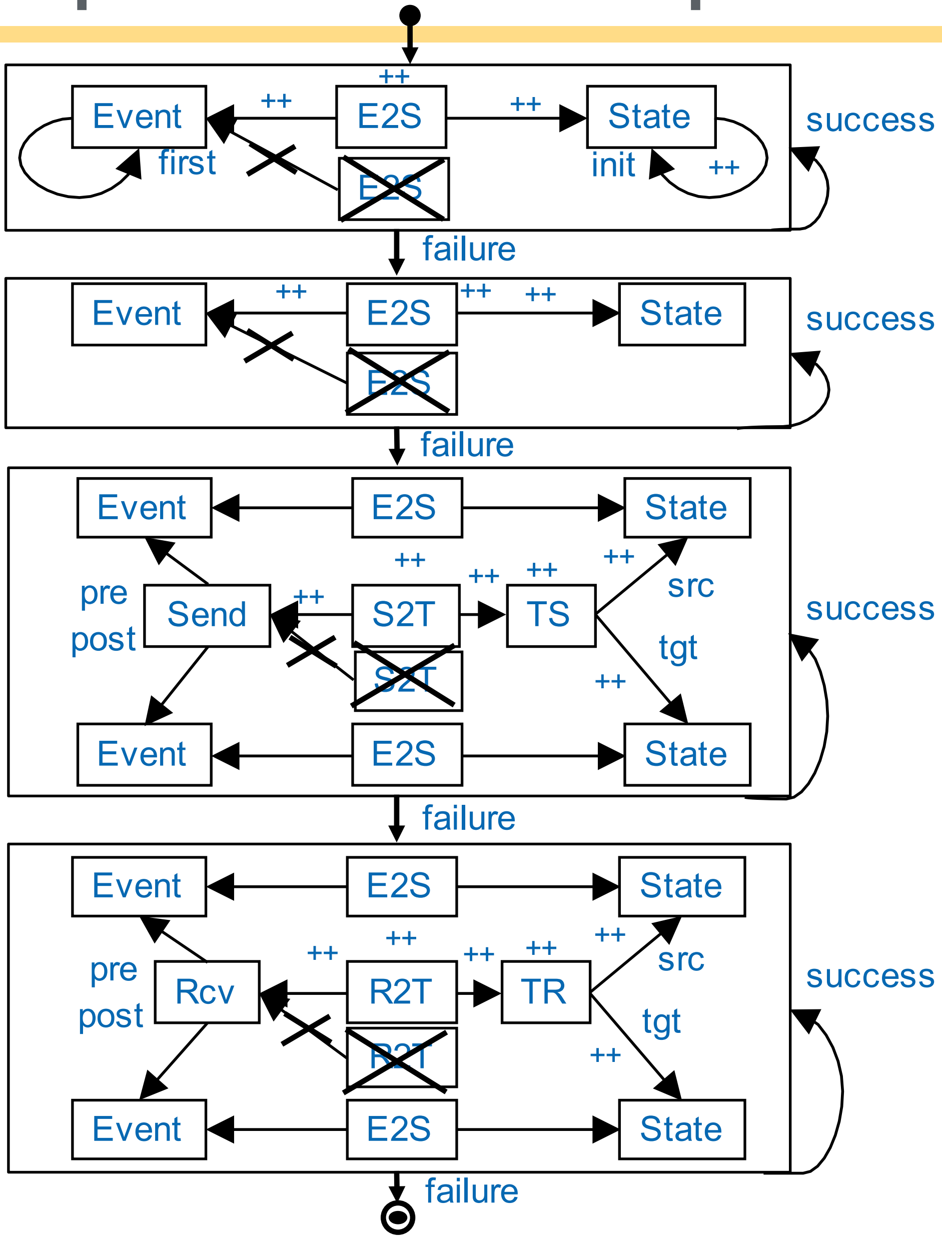
1. **MT definition only allows source and target models that are in the bisimulation relation**
   - **Relational definition (TGGs)** vs. Operational definition (SDs)

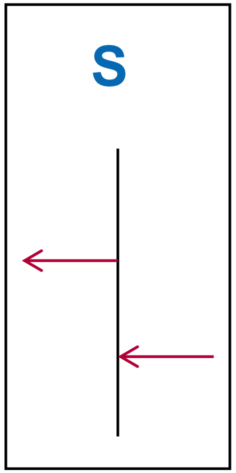
[ICGT2012]

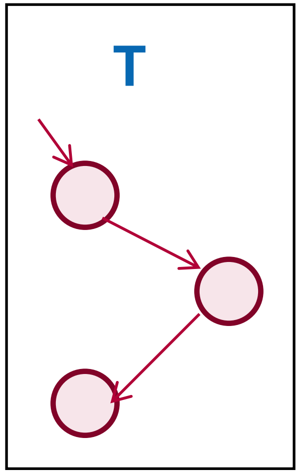


TGG rules

Story Diagrams Operational Specification



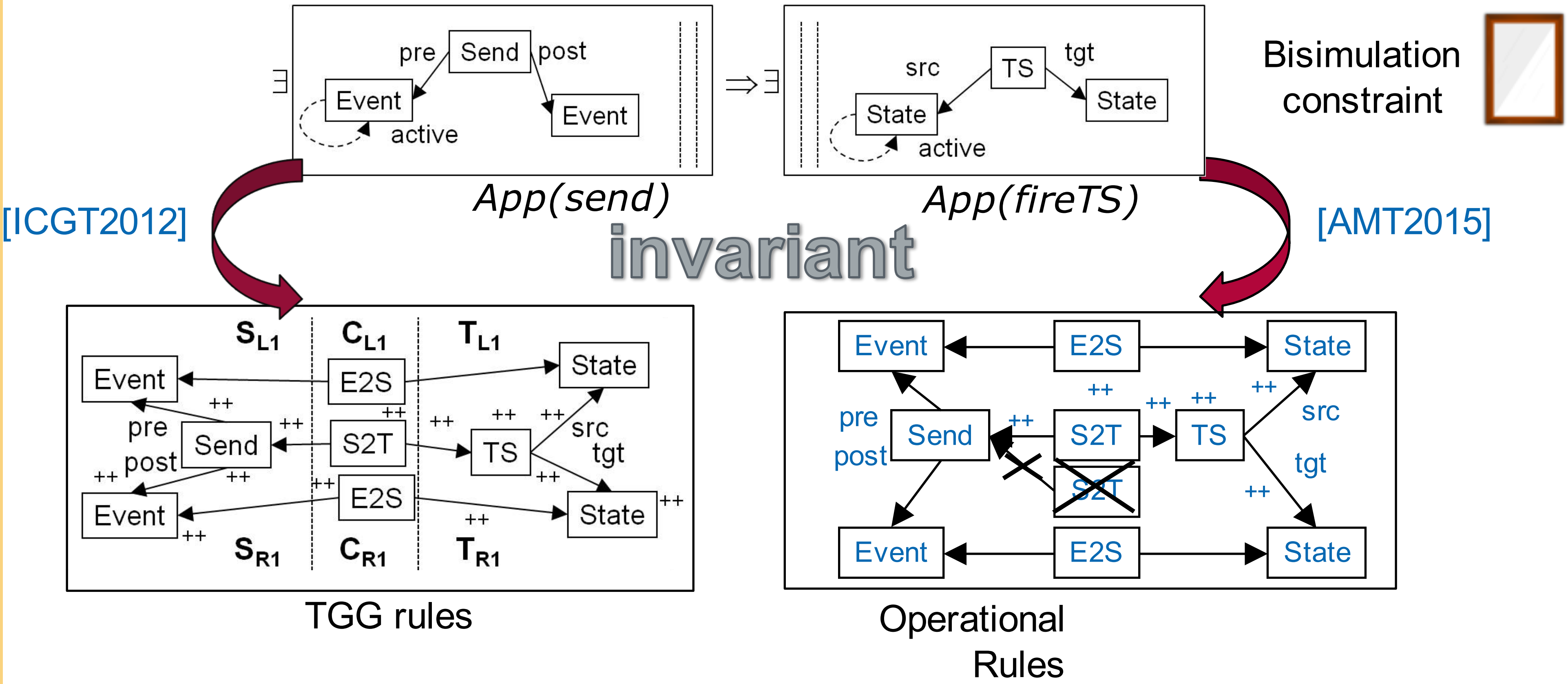




Behavior Preservation
Two-Step Algorithm

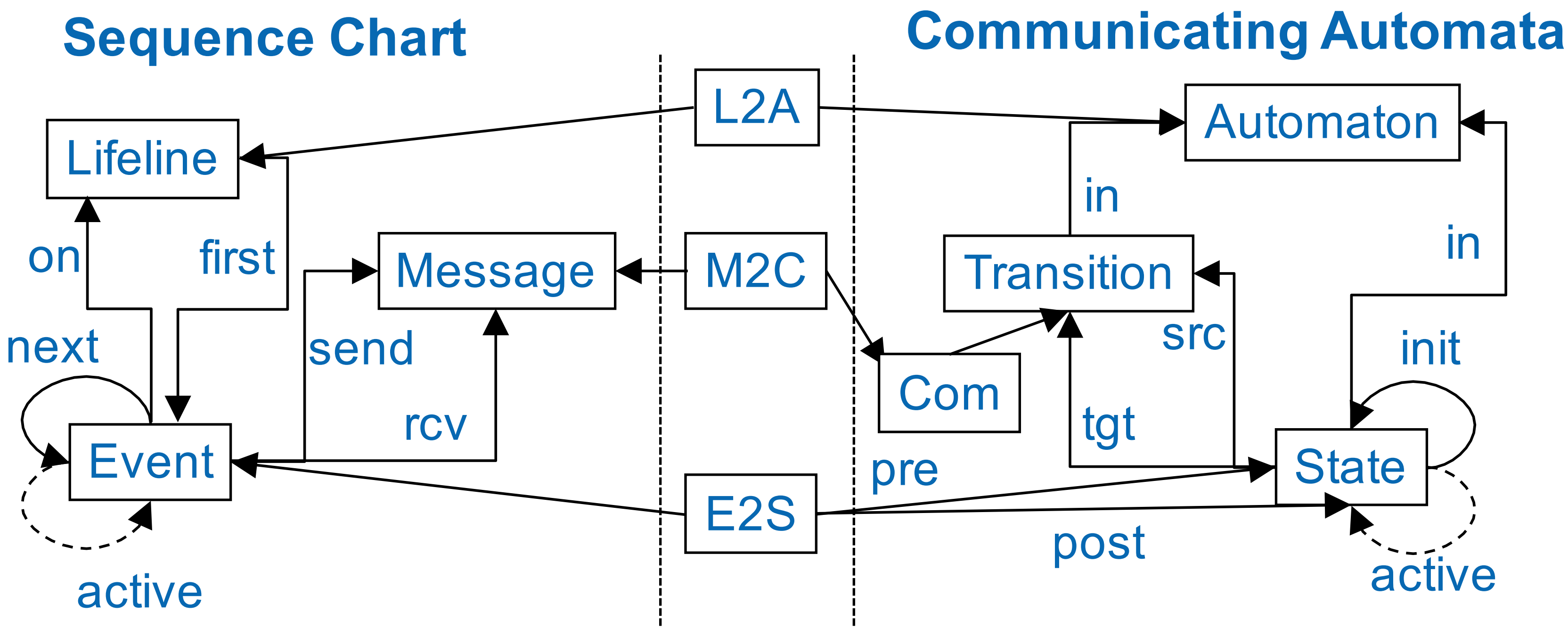
1. MT definition only allows source and target models that are in the bisimulation relation

- Relational definition (TGGs) vs. **Operational definition (SDs)**



Behavior Preservation More Advanced

- Addressing non-deterministic behavioral rule application
  - Case Study Sequence Charts 2 Communicating Automata
- Addressing not only behavioral equivalence, but also e.g. behavioral refinement



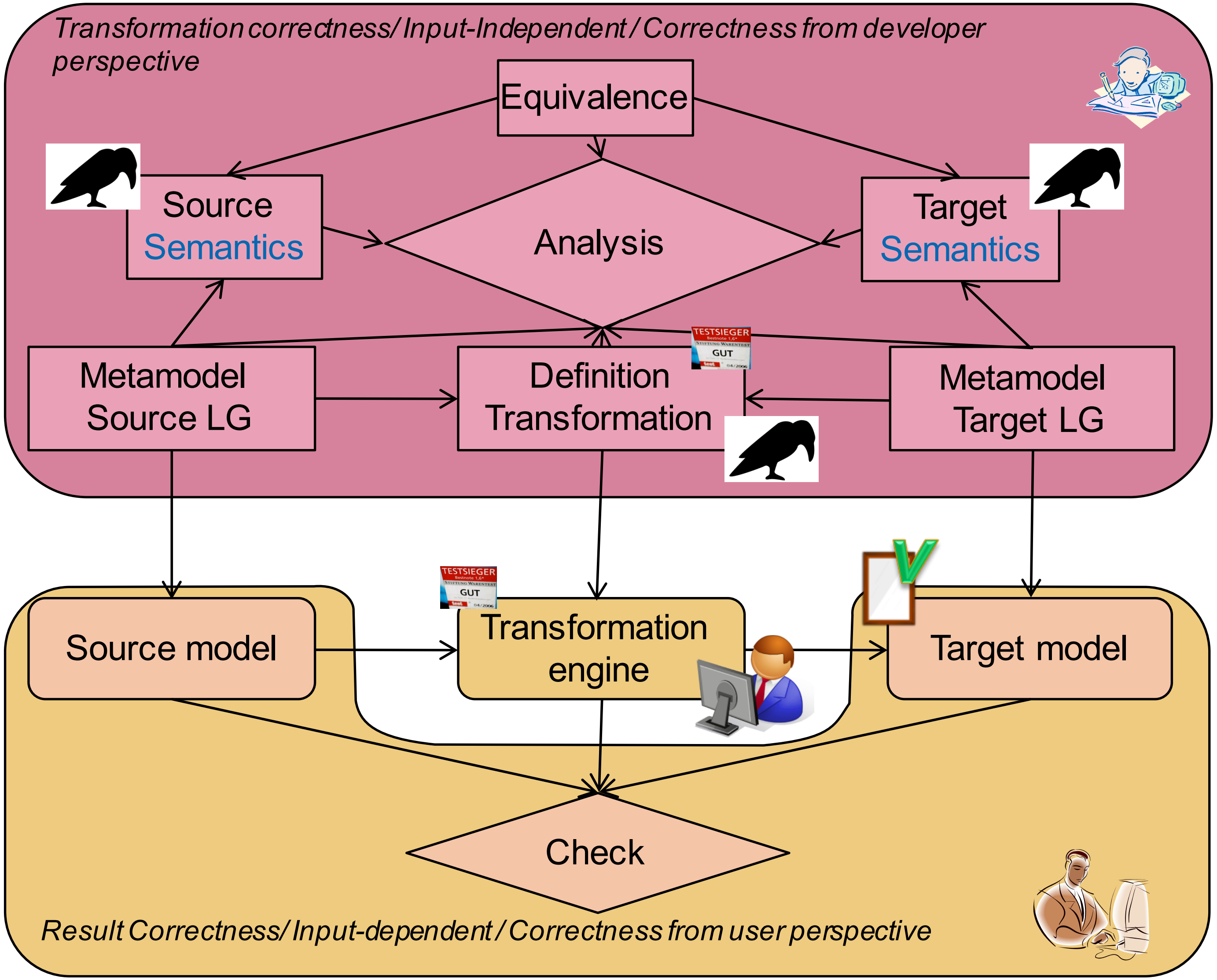
Tool Support

Hasso Plattner Institut

[ICGT2015]

					without advanced implication check				with advanced implication check			
	Characteristics		SeekSat/ProCon		Invcheck-total		Invcheck-partial		Invcheck-total/imp		nvcheck-partial/imp	
Example	Check	Complexity	time (s)	result	time (s)	result	time (s)	result	time (s)	result	time (s)	result
MT - Simple - Semantics	subproblem	4	20	true	<1	true	<1	true	<1	true	<1	true
MT - Simple - Semantics	subproblem	4	20	true	<1	true	<1	true	<1	true	<1	true
MT - Complex - TGG	subproblem	4	<1	true	<1	true	<1	true	<1	true	<1	true
MT - Complex - TGG	subproblem	4	<1	true	<1	true	<1	true	<1	true	<1	true
MT - Complex - Semantic	subproblem	5	10	true	<1	true	<1	true	<1	true	<1	true
MT - Complex - Semantic	subproblem	5	9	true	<1	true	<1	true	<1	true	<1	true
MT - Simple - Semantics	subproblem	11	40	true	<1	true	<1	true	<1	true	<1	true
MT - Complex - TGG	subproblem	11	<1	true	<1	true	<1	true	<1	true	<1	true
MT - Complex - Semantic	subproblem	12		out of memory		timeout	<1	false negatives		timeout	<1	true
MT - Complex - Semantic	subproblem	17	17	true	<1	false negatives	<1	false negatives	<1	true	<1	true
MT - Complex - TGG	subproblem	20		timeout	<1	true	<1	true	<1	true	<1	true
MT - Simple - Semantics	subproblem	30	20	true	<1	true	<1	true	<1	true	<1	true
MT - Simple - Semantics	subproblem	70	40	true	<1	true	<1	true	<1	true	<1	true
MT - Complex - Semantic	subproblem	72		timeout	<1	false negatives	1	false negatives	1,5	true	1,5	true
MT - Simple - Semantics	subproblem	78	6,5	true	<1	true	<1	true	<1	true	<1	true
MT - Complex - Semantic	subproblem	188		out of memory	1,5	false negatives	2,5	false negatives	<1	true	<1	true
Car Platooning	subproblem	258	<1	true	<1	true	<1	true	<1	true	<1	true
Car Platooning	subproblem	610	<1	true	<1	true	<1	true	<1	true	<1	true
MT - Simple - Semantics	subproblem	807		timeout	<1	true	<1	true	<1	true	<1	true
Car Platooning	complete	947	<1	false	<1	false negatives	<1	false negatives	3	false	3	false
MT - Simple - TGG	subproblem	2778	220	true	1,5	false negatives	1	false negatives	1,5	true	1	true
MT - Simple - TGG	subproblem	2778	226	true	1,25	false negatives	1	false negatives	1,25	true	1	true
MT - Simple - Semantics	complete	3870		timeout	1,5	true	1	true	1,5	true	1	true
MT - Simple - TGG	complete	5556	562	true	2	false negatives	2	false negatives	2,25	true	1,75	true
MT - Complex - Semantic	subproblem	607312		out of memory		timeout	90	false negatives		timeout	<1	true
MT - Complex - Semantic	complete	607500		out of memory		timeout	95	false negatives		timeout	<1	true
MT - Complex - TGG	complete	1817622		timeout		timeout	~100min	true		timeout	~50min	true

Summary
Correct Model Transformations



Outline

1. **Inductive Invariant Checking for Graph Transformation Systems**
2. **Applications**

Cyber-Physical Systems & Safety

Model Transformations & Correctness

Summary & Open Challenges

3. Summary

- **Invariant checking** can be used to
  - establish state properties required for safety (e.g., forbidden hazarduous situations) for systems where the state space can be captured by evolving graph structures or
  - verify complex properties of model transformations such as behavior preservation from the developer perspective.
- **More expressive variants** can lead to more compact models and also less scalability issues (e.g., more natural encoding of time).
- The feature of our invariant checking that somehow minimal **counterexamples** are generated helps to incrementally develop the right inductive invariants.

Open Challenges

1) Oftentimes very strong inductive invariants are required that are not very intuitive.
   ➡ Support debugging of semantics and invariants
   ➡ Support automated strengthening of the inductive invariants
2) Expressiveness of the GTS variants (e.g., data, OO concepts, time, etc.) and the related invariant checker support is sometimes a limited factor.
   ➡ Support more GTS variants and invariants
   ➡ Native vs. non-native GT invariant checking
3) Scalability of the invariant checker
   ➡ Special support for specific cases (behavioral rules, TGGs, ...)
   ➡ Native vs. non-native GT invariant checking

Thank you!

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