Deductive Verification of Railway Operations

Eduard Kamburjan and Reiner Hähnle

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Technische Universität Darmstadt, Software Engineering Group

Big Picture

Railway Engineering as Software Engineering

Apply tools for distributed software to railway operation procedures.

Infrastructure	=	Data Structure
Operational Rules	=	Programs
Safety Property	=	Logical Formula

Focus: Communication and PZB

Deductive Verification

Definition

"... methods that use an expressive (at least first-order) logic to state that a given target system is correct with respect to some property. Logical reasoning (deduction) is then used to prove validity of such a statement ..."[Beckert and Hähnle 2014]

Program Logics and Traces

First Order Program Logic and specification of traces.

Modeling Railway Operations vs. Modeling Railway Systems

Approach

- Model railway systems as a distributed software system
- Modeling not on implementation level
- Instead: Information flow as described in rule books
- Verify safety properties for all well-formed infrastructures

Modeling Language

Abstract Behavioral Specification Language

- Based on actors and cooperative scheduling
- Executable modeling language
- Multiple static analyses available

```
class Station implements StationInterface{
   StationInterface next = ...
   Unit schedule(Event ev){
       Fut<Int> f = next!request(train(ev));
       this.id = id(ev);
       f.get;
       Int i = await next!request(train(ev));
   }
}
```

Events

A trace is a sequence of events which encodes visible actions

- Invocation (invocEv) - Invocation Reaction (invocREv)
- Suspension (awaitEv) - Reactivation (reacEv)
- Completion (futEv) - Completion Reaction (futREv)

Concurrency system encoded as axioms: e.g.,

- each invocation reaction is predated by invocation

ABS Program Logic

- Connects programs to specifications of state

$$\mathtt{i} \geq 0 \rightarrow [\mathtt{i\ =\ i\ +\ 1}]\mathtt{i} > 0$$

ABS Program Logic

- Connects programs to specifications of state

$$\texttt{i} \geq 0 \rightarrow [\texttt{i = i + 1}]\texttt{i} > 0$$

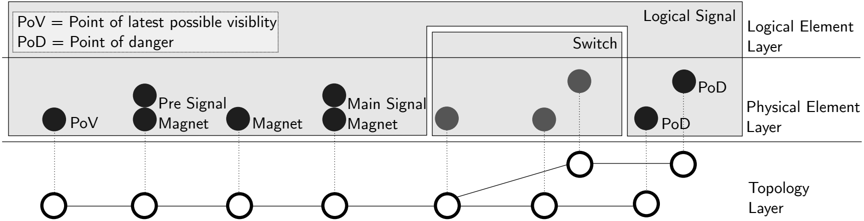
- Describes possible histories of events

$$[\texttt{o!m();}\pi]\phi \leadsto$$
$$\{\texttt{history} := \texttt{history} \circ \langle \mathsf{InvocEv}(X, \texttt{o}, f, \texttt{m}, \epsilon)\rangle\}[\pi]\phi$$

Modeling

Overview

Layers seperate topological aspects from information transmission



Point of Information Flow (PIF)

Infrastructure

Infrastructure is a graph model, where each node has at least one point of information flow.

- Information flow from infrastructure to train
  - signals, magnets,...
- Information flow from train to infrastructure
  - axle counter, balises,...
- Indirect information flow
  - End of switch, crossing,...
- Multiple PIFs per node possible

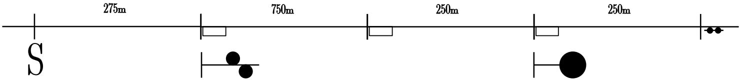
Grouping PIFs in the Graph

Infrastructure

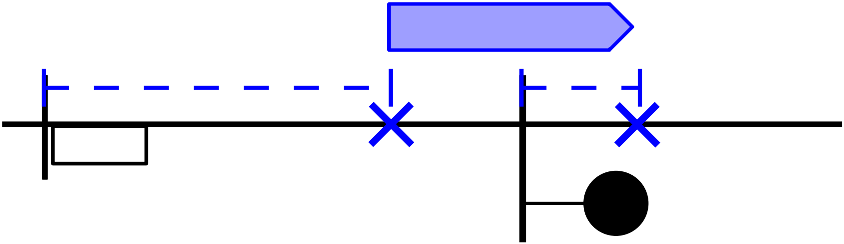
Multiple points of information flow form a logical object, each logical object is assigned to a station

Logical Signal

main signal + pre signal + point of visibility + three magnets + danger point (+ additional signals + ...)



Trains



Code Example

```
class MainSignal(Node n, Edge track, Signal s)
 implements MainSignal {
  SignalState state = STOP;
  Info triggerFront(Train train, Edge e){
    if ( this.track == e ){
      this.s.setObserver(null);
      return Info( this.state );
    }
    return NoInfo;
  }
  Info triggerBack(Train train, Edge e){
    return NoInfo;
  }
  Unit setState(SignalState newState){...}
}
```

Communication

Three communication protocols among stations

- Change of permit - prevents head-on runs
    - One token per line, only station with token can let trains drive
    - Here “Erlaubnisholtaste”: **A** requires token from **B**
    - **A** only requests when all trains from **B** arrived
    - **B** always releases, except when it is about to use token
    - Other protocol verified in [FTSCS 2016].

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  - Other protocol verified in [FTSCS 2016].
- “Zugmeldebetrieb” - prevents deadlocks
  - Each train is offered and accepted
  - On departure, train is announced
- Block signaling - guarantees free block
  - After setting a signal to “Go”
  - Next signal must block back before “Go” can be set again
  - Blocking back is caused by train passage

Code Example

Part of the method that controls departure of trains

```
while (!permission[line]) { //controls departure
    await expectIn[line] == Nil
    lockedLine[line] = True;
    Bool res = await target!reqPermit(this, line);
    if(res) permission[line] = True;
    lockedLine[line] = False;
}
permissionLocked[line] = True;
```

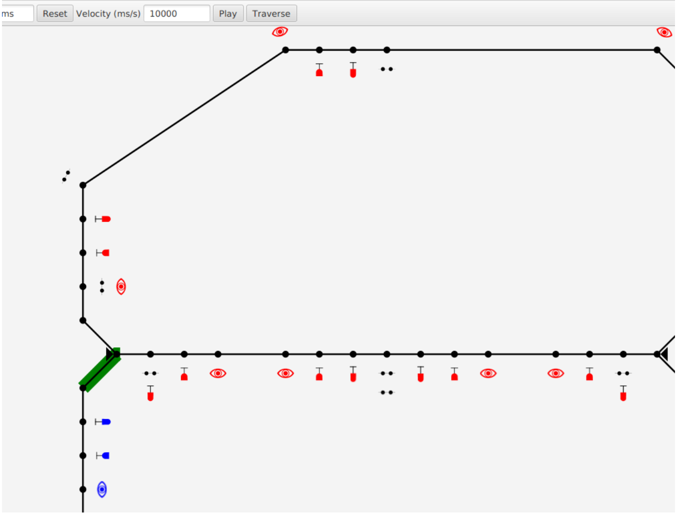
Part of the method that accepts train

```
  await !lockedLine[line] && acquireHalt(line, trackList) != null;
```

Part of `reqPermit`

```
if(permission[line] && !permissionLocked[line]){
   permission[line] = False;
   return True;
}
```

Execution



Code Example

```
productline Examples;
features ETCS1Demo, ETCS2Demo, ETCS3Demo, ...;

delta ETCS1Ex after ETCSRBC when ETCS1Demo;
delta ETCSRBC after ETCSCore
    when ETCS1Demo || ETCS2Demo || ETCS3Demo;
delta ETCSCore
    when ETCS1Demo || ETCS2Demo || ETCS3Demo;

product ETCS1 (ETCS1Demo);
product ETCS2 (ETCS2Demo);
product ETCS3 (ETCS3Demo);

root Scenarios { group oneof { ETCS1Demo,
  ETCS2Demo, ETCS3Demo } }
```

Notion of Safety

Scope

Terminology

- Edge between two PIFs : Track
- Tracks between two signals: Section
- Sections between two stations: Line
- In presentation: between two stations there is only one line

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Assumptions

- German rules differ for driving inside and outside of stations
- We only consider driving outside
- No level crossings
- We ignore faults and assume that infrastructure is well-formed

Well-Formedness

Coherent Encoding

- Relations between elements is coherent, e.g.,
- If a signal is marked as covering section S, then it exists

Correct Encoding

- Designed according to Ril. 819, e.g.,
- Every mainsignal has a presignal

Coherence and Correctness

- Coherence connects the proof to reality
- Correctness connects the safety theorem to reality

Safety on the Line

Theorem (Departure Safety)

If an exit or block signal to section S of line L is set to “Go”:

1. L has no trains driving in the opposite direction
2. S is free from trains going in the same direction

Proof

Methodology

Formalism	Scale
informal	global state
informal	global history
ABS Program Logic	global history
ABS Program Logic	local history

Formalize

Reformulate/Connect

Split

Lemma: Permission change (1) – Informal/global state

Formalism	Scale
informal	global state
informal	global history
ABS Program Logic	global history
ABS Program Logic	local history

"If station A acquires the token for line L from station B, then there is no train on L towards A."

Lemma: Permission change (2) – Informal/global history

Formalism	**Scale**
informal	global state
informal	global history
ABS Program Logic	global history
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"If station A has an completion reaction event for B.`reqPermit` *and reads* `True`*, then at this moment A expects no trains on L."*

Lemma: Permission change (3) – Formal/global history

Formalism	Scale
informal	global state
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ABS Program Logic	global history
ABS Program Logic	local history

Lemma

The following formula holds for all generated histories with a well-formed infrastructure. Let A be a station and L a line with *section* being the first section of L from A and $A.\mathtt{other}(\mathit{section})$ the last.

$$\forall i, f.\ h[i] = \mathrm{futREv}(A, \mathtt{rqPerm}, f, [\mathtt{True}, \mathit{section}]) \rightarrow \\ \sigma[i](A) \models \mathtt{expectIn}(A.\mathtt{other}(\mathit{section})) = \mathtt{Nil}$$

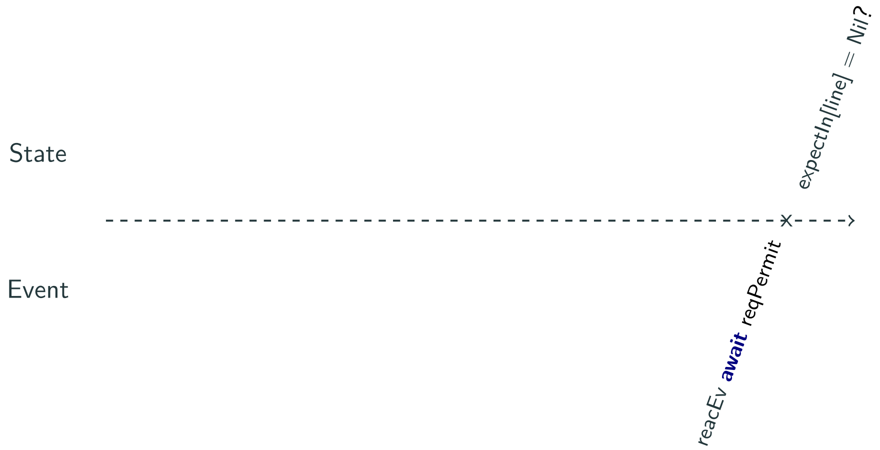
Lemma: Permission change (4)

We identify *section* and $A.\texttt{other}(\textit{section})$ with line

```
while (!permission[line]) { //in method run
    await expectIn[line] == Nil
    lockedLine[line] = True;
    Bool res = await target!reqPermit(this, line);
    if(res) permission[line] = True;
    lockedLine[line] = False;
}
permissionLocked[line] = True;
```

```
Unit offer(Train train, Line line){
  await !lockedLine[line] && acquireHalt(line, trackList) != null;
  expectIn = [train]::expectIn;
}
```

Lemma: Permission change (5) – Proof Outline



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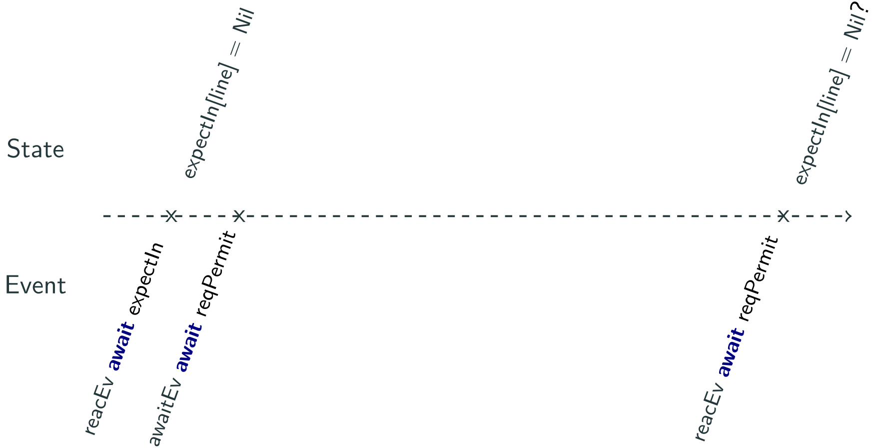

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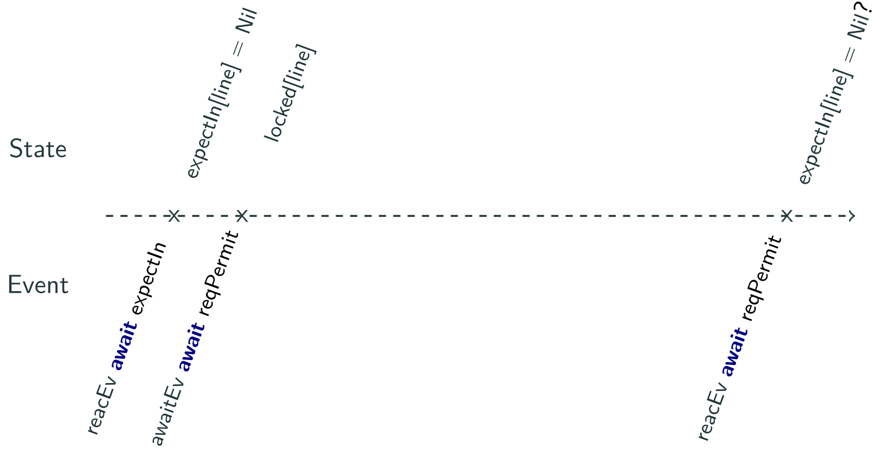

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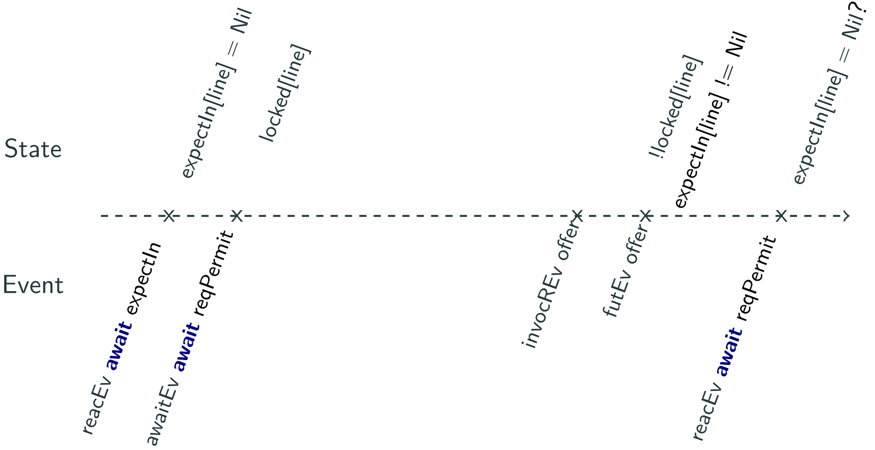

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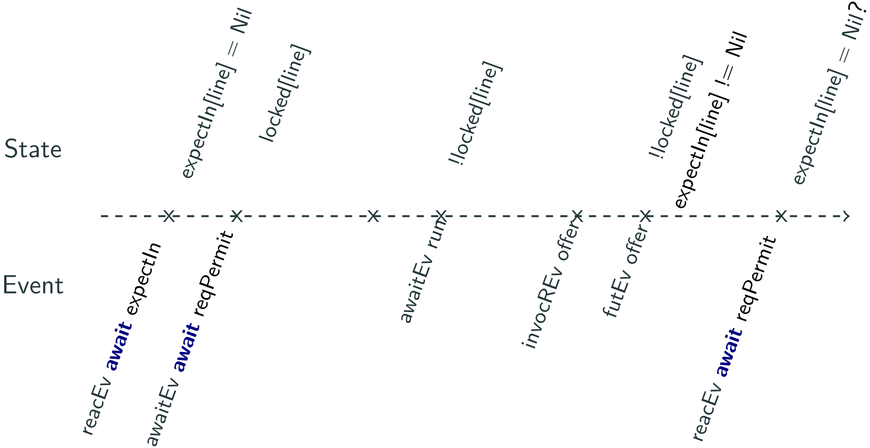

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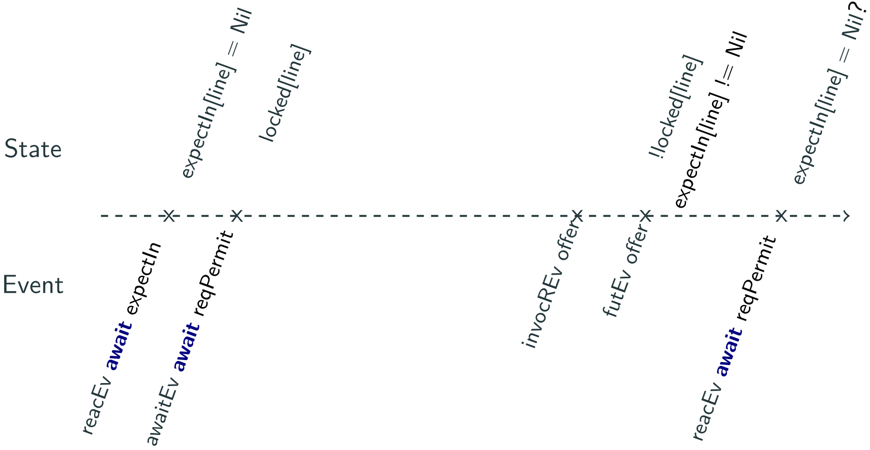

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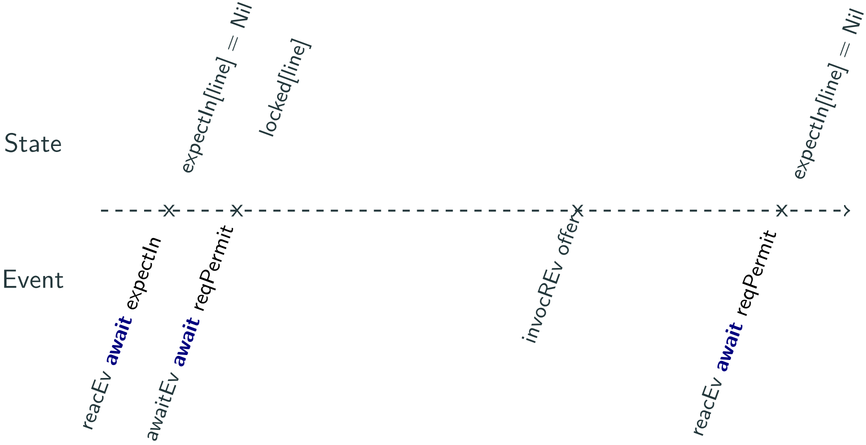


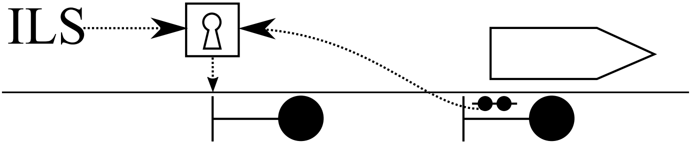
Lemma: Permission change (6) – Formal/local history

- All steps are formal, most are easily verified
- To connect history and state, we can state a local invariant

$$\forall \texttt{Train}\ T.\ \forall \texttt{Line}\ \text{line}.$$
$$\mathit{last}(h) = \text{futEv}(\textbf{self}, \texttt{offer}, f, [T, \text{line}]) \rightarrow$$
$$\textbf{self}.\texttt{lockedLine}[\text{line}] = \texttt{False}$$

- Verified with the KeY-ABS theorem prover
- Use similar argument on `permissionLocked` to establish that a train only leaves when the station has the permission

Lemma: Train Involvement (1)



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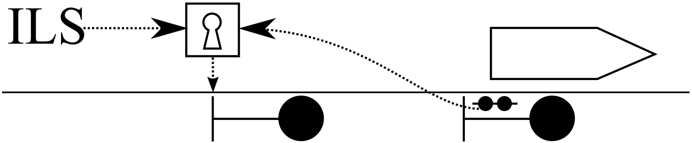

Well-formedness assumption: At $t = 0$, all trains are in stations

Lemma: Train Involvement (2)

Formalism	Scale
informal	global state
informal	global history
ABS Program Logic	global history
ABS Program Logic	local history

1) "If a non-entry signal S is set to "Go", then the covered section is free of trains going away from it."

Formalism	Scale
informal	global state
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ABS Program Logic	local history

2) "If a signal S is set to "Go" twice, then a train triggered the point of danger of the next signal at some time in between."

Lemma: Train Involvement (3)

Formalism	Scale
informal	global state
informal	global history
ABS Program Logic	global history
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Lemma

The following formula holds for all histories generated by the model in with a well-formed infrastructure. Let A be a station and S a signal.

$$\forall i.\ \Big(h[i] = \mathsf{invocREv}(A, S, \mathtt{setGo}, f, []) \rightarrow$$
$$\forall j.\ \big(j < i \wedge h[j] = \mathsf{invocREv}(A, S, \mathtt{setGo}, f', []) \rightarrow$$
$$\exists\ \mathtt{PoD}\ P. \exists k.\ j < k < i \wedge$$
$$h[k] = \mathsf{invocREv}(P, \mathtt{next}(S.covers), \mathtt{trigger}, f'', [])\big)\Big)$$

Lemma: Train Involvement (4) – Proof Outline

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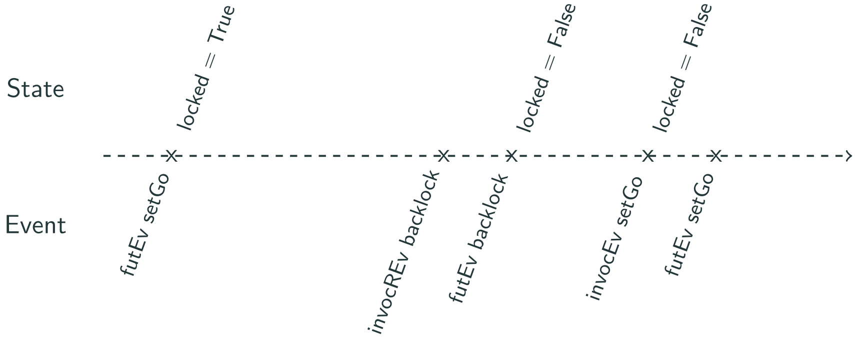

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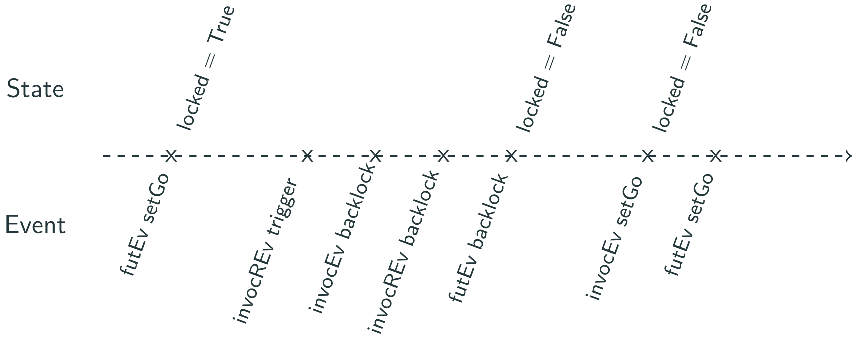

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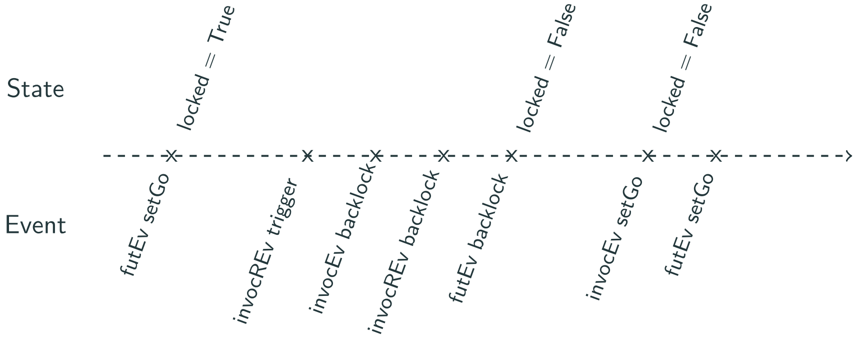

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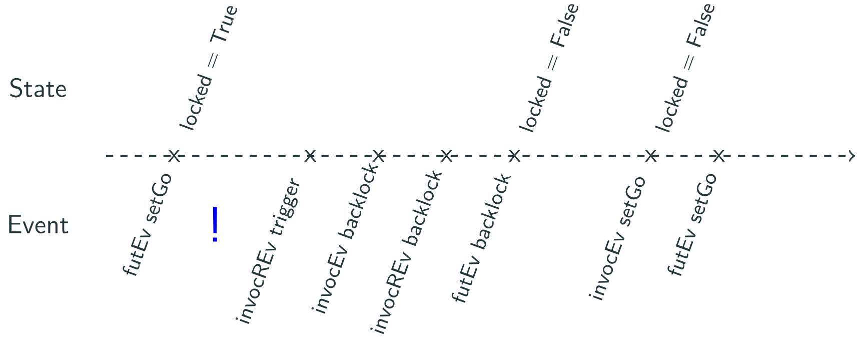

Theorem

Theorem (Departure Safety)

If an exit or block signal to section S of line L is set to "Go":

1. L has no trains driving in the opposite direction
2. S is free from trains going in the same direction

- Additionally to Lemmas, use of well-formedness is needed
- Result holds for any well-formed infrastructure

Conclusion

Aspects of Active Objects and Deductive Verification

+ Verification not bound to concrete infrastructure
+ Verification does not bound size of infrastructure
+ Combines interaction, simulation and formal analysis
- Not fully automatic

Conclusion

Summary

- Deductive Verification allows verification of procedures
- Split safety and well-formedness, needs no concrete infrastructure
- Tools for distributed software generalize to railway operations

Future Work

- Modeling of all relevant rulebooks and infrastructure elements
    - Level crossings, special signals
    - ETCS L2+3
- Safety proofs in presence of faults and inside of stations
- Application of further tools (e.g., deadlock analysis)

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