Integrating Concurrency Theory with State

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Joint work with Helen Treharne

Challenge

- How can we model and reason about systems with complex and detailed state information and complex concurrent or control behaviour?

- How far can we get by integrating formal methods?

State- and event-based formalisms

- Process algebra/concurrency theory:
  - –Good for complex interaction between processes
  - –Focus on patterns of communication and control
  - –Abstract state as much as possible
  - –State tends to be mostly orthogonal

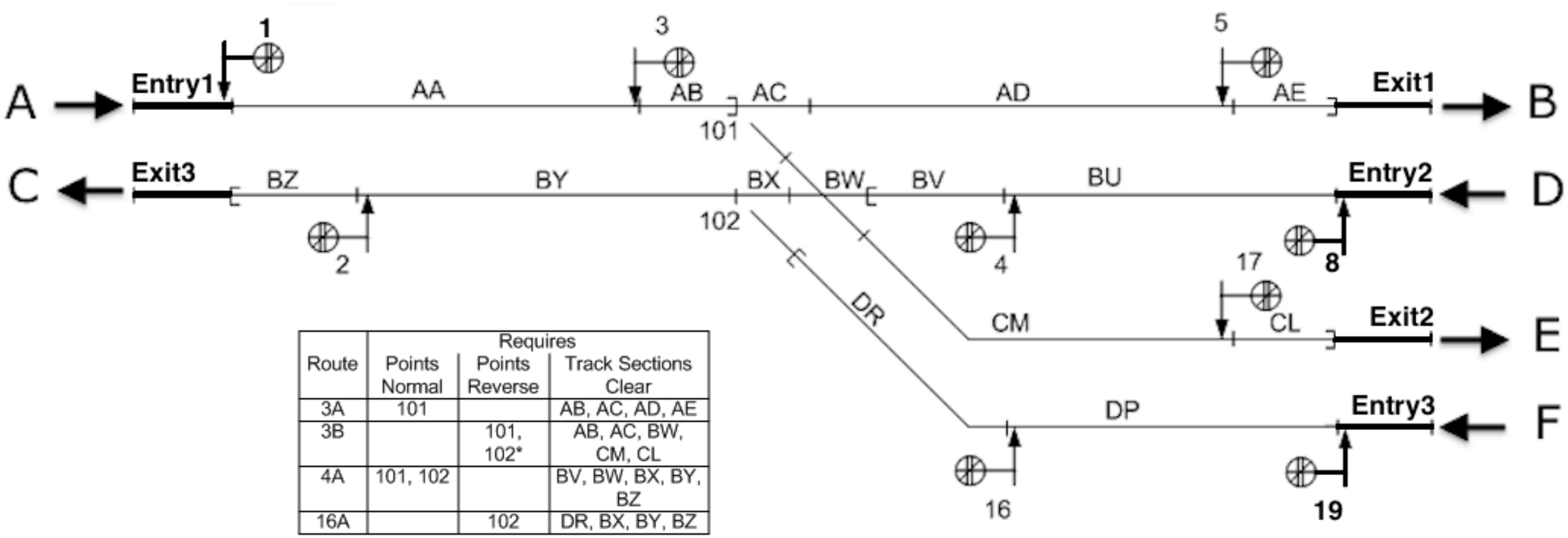
- **Challenge**: handling rich state information

State- and event-based formalisms

- State-based formalisms (Z, B, VDM,…)
  - Suited to data-rich systems and structured state
  - State transitions: specify how and when state is updated
  - Weak or cumbersome notions of flow of control and interaction

- **Challenge**: want to consider higher level behavioural properties (e.g. traces, LTL)

Motivating Example: railways



Route	Requires: Points Normal	Requires: Points Reverse	Requires: Track Sections Clear
3A	101		AB, AC, AD, AE
3B		101, 102*	AB, AC, BW, CM, CL
4A	101, 102		BV, BW, BX, BY, BZ
16A		102	DR, BX, BY, BZ

* flank protection

State:

train locations;

points positions;

signals; locks on routes;

control tables; topology

Trains:

driving rules;

Road map

Application

MDE

Railways

Protocols

fUML

Verification

frameworks

ProB tool

Theorem-proving

Theorems

Formalisms

Common semantic framework

+time

B

CSP

Event-B

Structure of Talk

- B and Event-B for state
- Combination with CSP
- Example: modelling for railway safety
- Incorporating time

Structure of Talk

- **B and Event-B for state**
- Combination with CSP
- Example: modelling for railway safety
- Incorporating time

Classical B machines and control

```
Machine  M1 =                                  n: 0
Variables      n
Invariant      n ∈ {0,1}
Initialisation   n:=0
Operations
  up=
     pre n=0 then n:=n+1 end
 down =
     pre n = 1 then n:=n-1 end
```

* Operations always enabled, but the machine will break (diverge) if they are called outside their preconditions

Classical B machines and control

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n: 1

* Operations always enabled, but the machine will break (diverge) if they are called outside their preconditions

* up can occur as the first event, setting n to 1.

Classical B machines and control

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```

n: 0

* Operations always enabled, but the machine will break (diverge) if they are called outside their preconditions
* up can occur as the first event
* down can occur as the second event

Classical B machines and control

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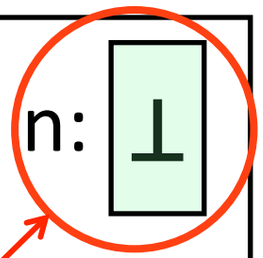

* Operations always enabled, but the machine will break (diverge) if they are called outside their preconditions
* up can occur as the first event
* down can occur as the second event
* a second occurrence of down will diverge the machine

Classical B machines and control

Machine M1 =
Variables n
Invariant n ∈ {0,1}
Initialisation n:=0
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pre n = 1 then n:=n-1 end

n: 0

* Operations always enabled, but the machine will break (diverge) if they are called outside their preconditions

- preconditions do not determine control flow
- they constrain what control flow is necessary to ensure correct behaviour

Classical B machines and control

Machine M1 =
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n: 0

* Operations always enabled, but the machine will break (diverge) if they are called outside their preconditions

$$P = up \rightarrow down \rightarrow P$$

Variant: Event-B for modelling

Machine M1 =
Variables n
Invariant n ∈ {0,1}
Initialisation n:=0
Event up =
when n=0 then n:=n+1 end
Event down =
when n = 1 then n:=n-1 end

n: 0

* Events are enabled when their guard is true, and **blocked** when their guard is false
* up can occur as the first event
* down cannot occur, and will be blocked

* control variables in the guards used to manage control flow
* very cumbersome in practice, and scales badly

B machine semantics

- **Proof obligations** for a consistent machine
  - –Initialisation establishes the invariant
  - –Operations preserve the invariant: they are guaranteed to establish it when called within their preconditions
  - –Machine Invariant captures safety properties on states

- wp semantics used:
  - – for Invariant I and operation PRE P THEN S END:

$$I \wedge P \Rightarrow wp(S, I)$$

Structure of Talk

- B and Event-B for state
- **Combination with CSP**
- Example: modelling for railway safety
- Incorporating time

CSP(-lite)

$$
\begin{aligned}
P \quad ::= \quad & STOP \mid SKIP \mid P;Q \mid \\
& a \rightarrow P \mid c?x \rightarrow P \mid c!v \rightarrow P \mid \\
& P \sqcap Q \mid P \,\Box\, Q \mid \\
& P \parallel Q \mid P \mid\mid\mid Q \mid P \setminus A \\
& X \mid \mu X \,.\, P
\end{aligned}
$$

CSP semantics: sets of observations

- **Traces**: finite sequences of (visible) events:
  traces(P) = { tr | tr can be observed of P }

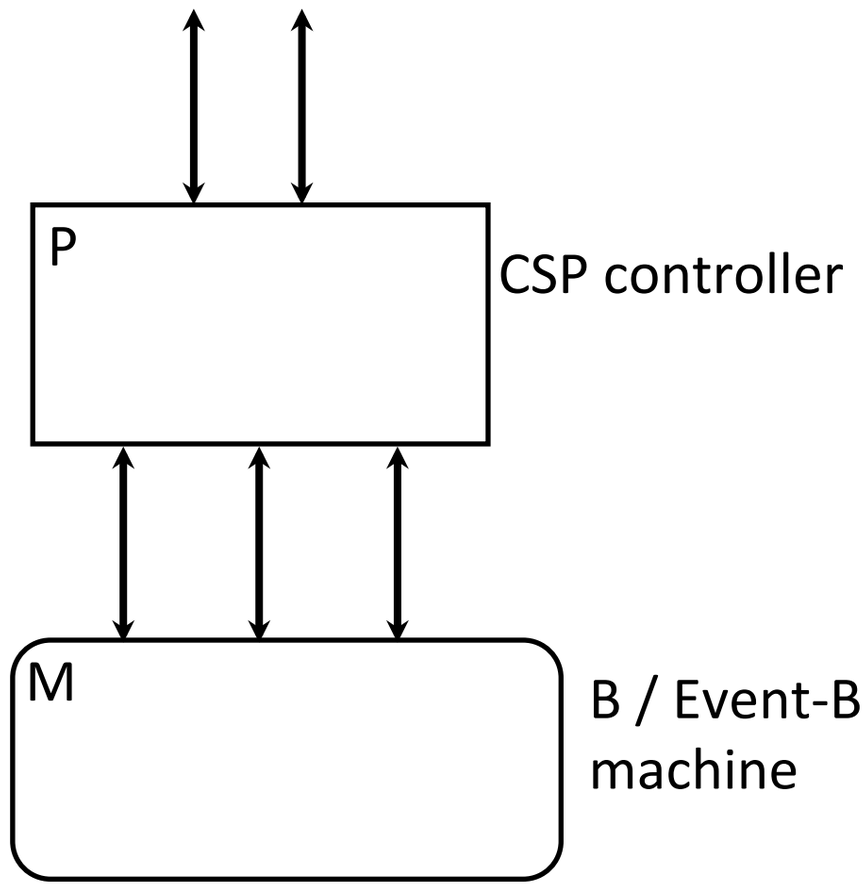
- **Failures**: traces together with refusal sets:
  failures(P) = {(tr,X) | (tr,X) can be observed of P}

- **Divergences**: traces during which the process may diverge:
  divergences(P) = {tr | P may diverge when performing tr}

- **Infinite traces**: infinite sequences of (visible) events:
  infinites(P) = { u | u can be observed of P }

Combining CSP and B

- Some operations in the machine correspond to events in the controller
- The interface is the alphabet of M
- Divergence can occur if an operation of M is called outside its precondition (Classical B)
- Consistency: when P ensures that M does not diverge.



Semantic approach

- The B machine is given a CSP semantics.
- Morgan's wp semantics (1990) for action systems is applicable here, to give CSP semantics for B machines

$$\overline{wp}(S, P) \quad = \quad \neg wp(S, \neg P)$$

$$\begin{aligned}
traces(M) &= \{\langle a_1, a_2, \ldots, a_n \rangle \mid \overline{wp}(init; a_1; a_2; \ldots; a_n \ , \ true\} \\
failures(M) &= \{\langle (a_1, a_2, \ldots, a_n, X) \rangle \mid \overline{wp}(init; a_1; a_2; \ldots; a_n \ , \ \bigwedge_{a \in X} \neg g_a\} \\
divergences(M) &= \{\langle a_1, a_2, \ldots, a_n \rangle \mid \overline{wp}(init; a_1; a_2; \ldots; a_n \ , \ false\}
\end{aligned}$$

CSP||B semantic foundation

- Once M has a CSP semantics then it can be treated as a CSP process, and combined using the CSP operators.
- Thus a controlled component P||M can be given a CSP semantics.
- Want access to tool support available for B and for CSP, and lift the results to the combination.

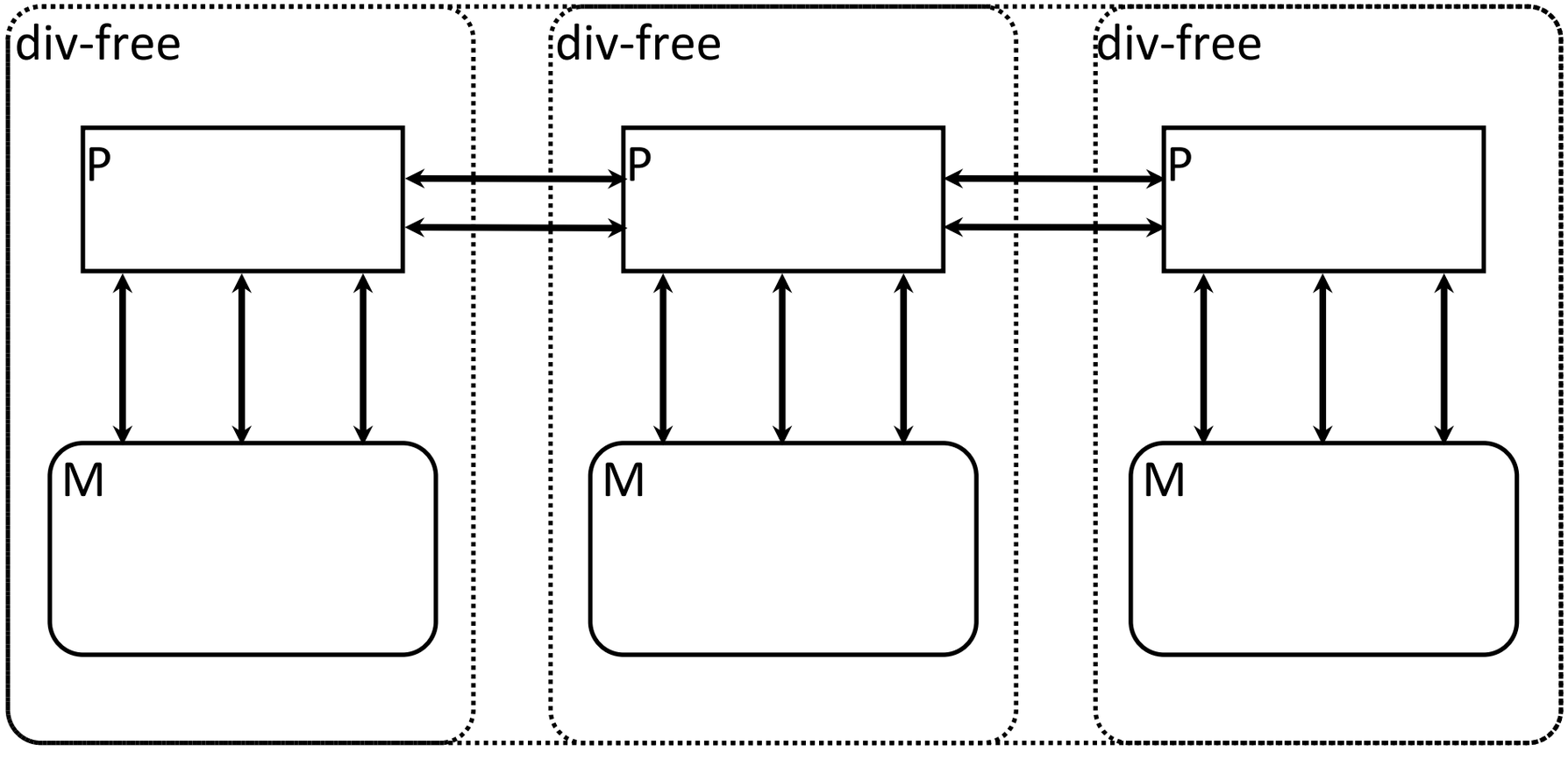
CSP||B and CSP||Event-B

- Various results, theorems and proof rules have been obtained for (combinations of) controlled components:
  - deadlock-freedom (conditions for just checking CSP)
  - divergence-freedom (control loop invariants)
  - refinement is compositional (particular proof rules available to maintain liveness of machines)
  - model-checking with ProB (invariant checking, LTL, CTL ...)

Composition results

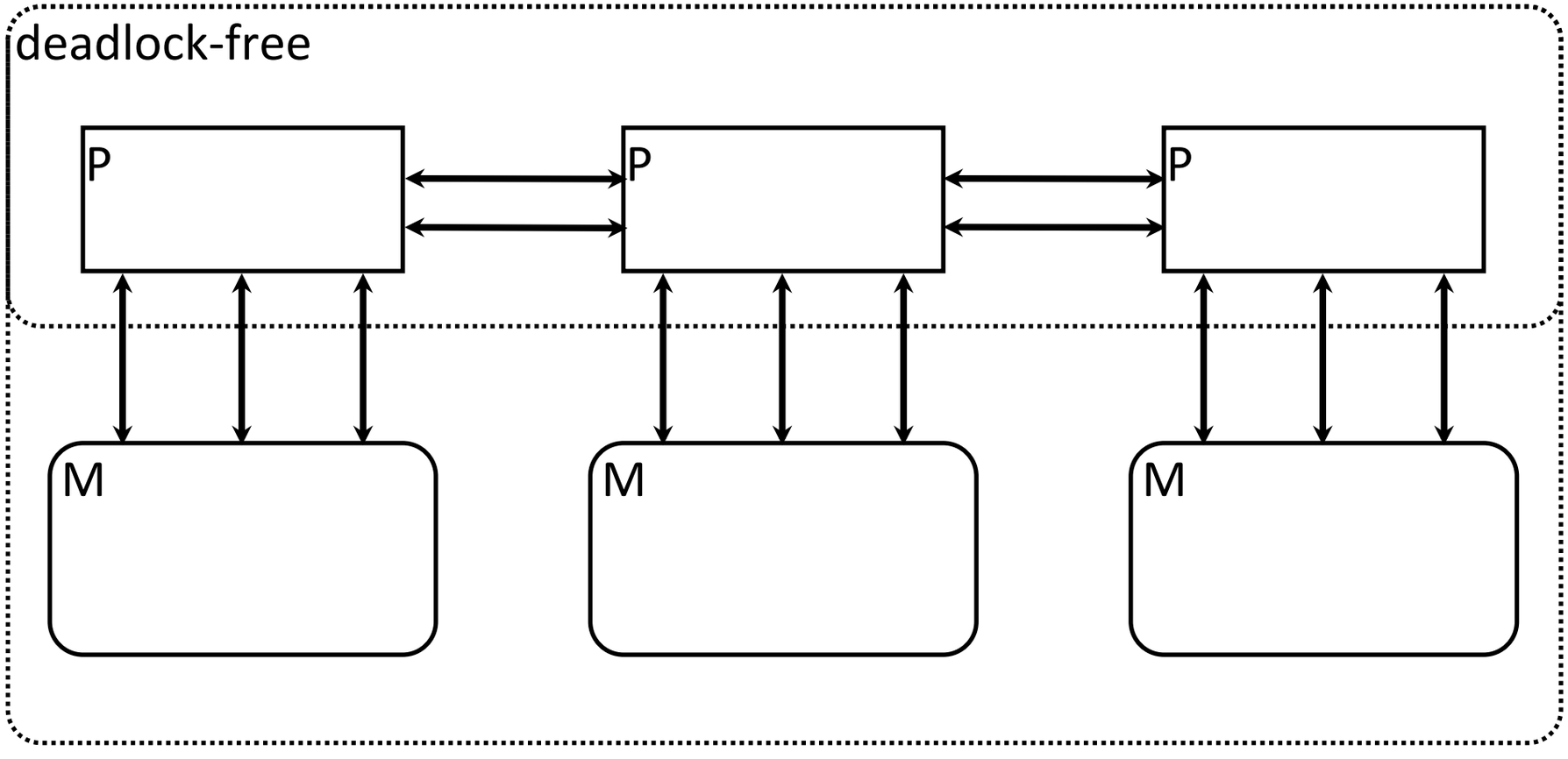
- If each CSP||B controlled component is divergence-free... *(B theorems available)*

  ...then so is their combination



Composition results

- If the combination of CSP controllers is deadlock-free... (…and the combination is divergence-free…)
  …then so is their CSP||B combination



Structure of Talk

- B and Event-B for state
- Combination with CSP
- **Example: modelling for railway safety**
- Incorporating time

Application to Railway modelling

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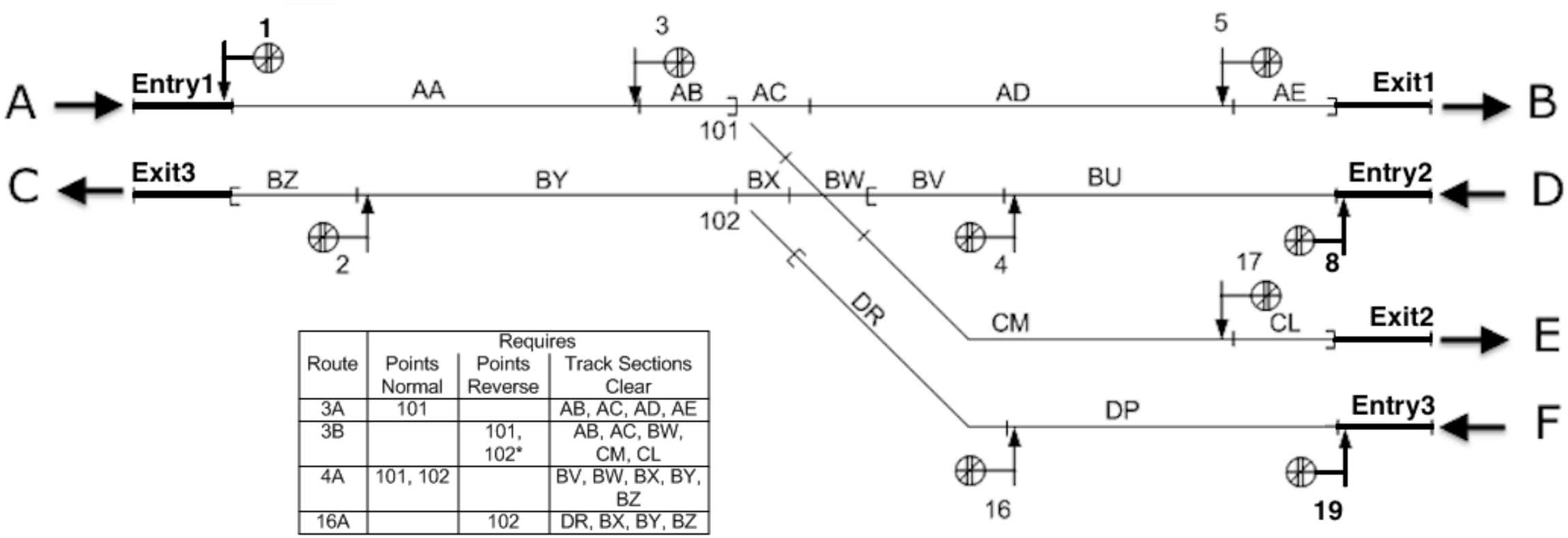
Prifysgol Abertawe

Railway example track plan



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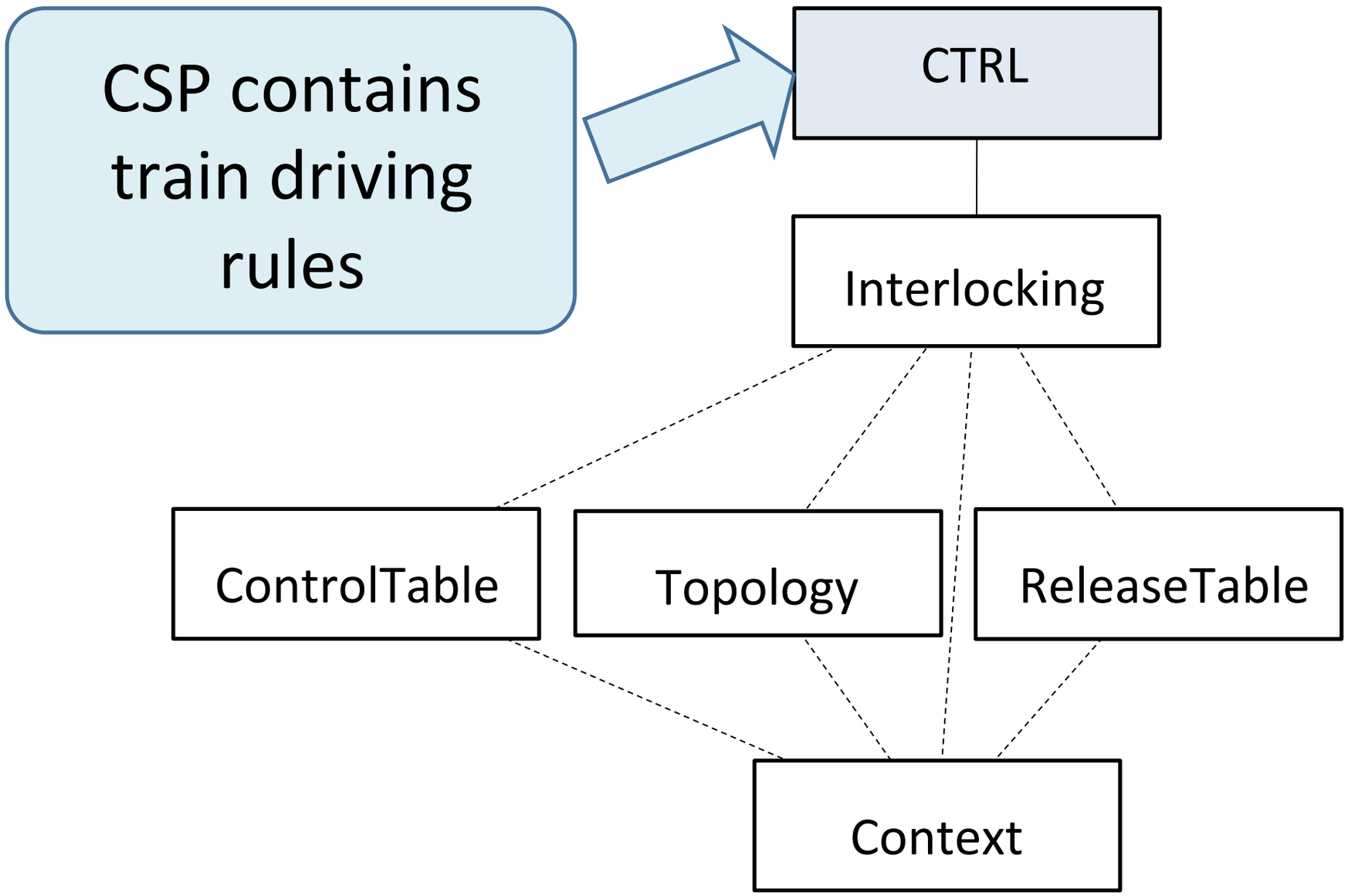
16A		102	DR, BX, BY, BZ

* flank protection

State:
train locations;
points positions;
signals; locks on routes

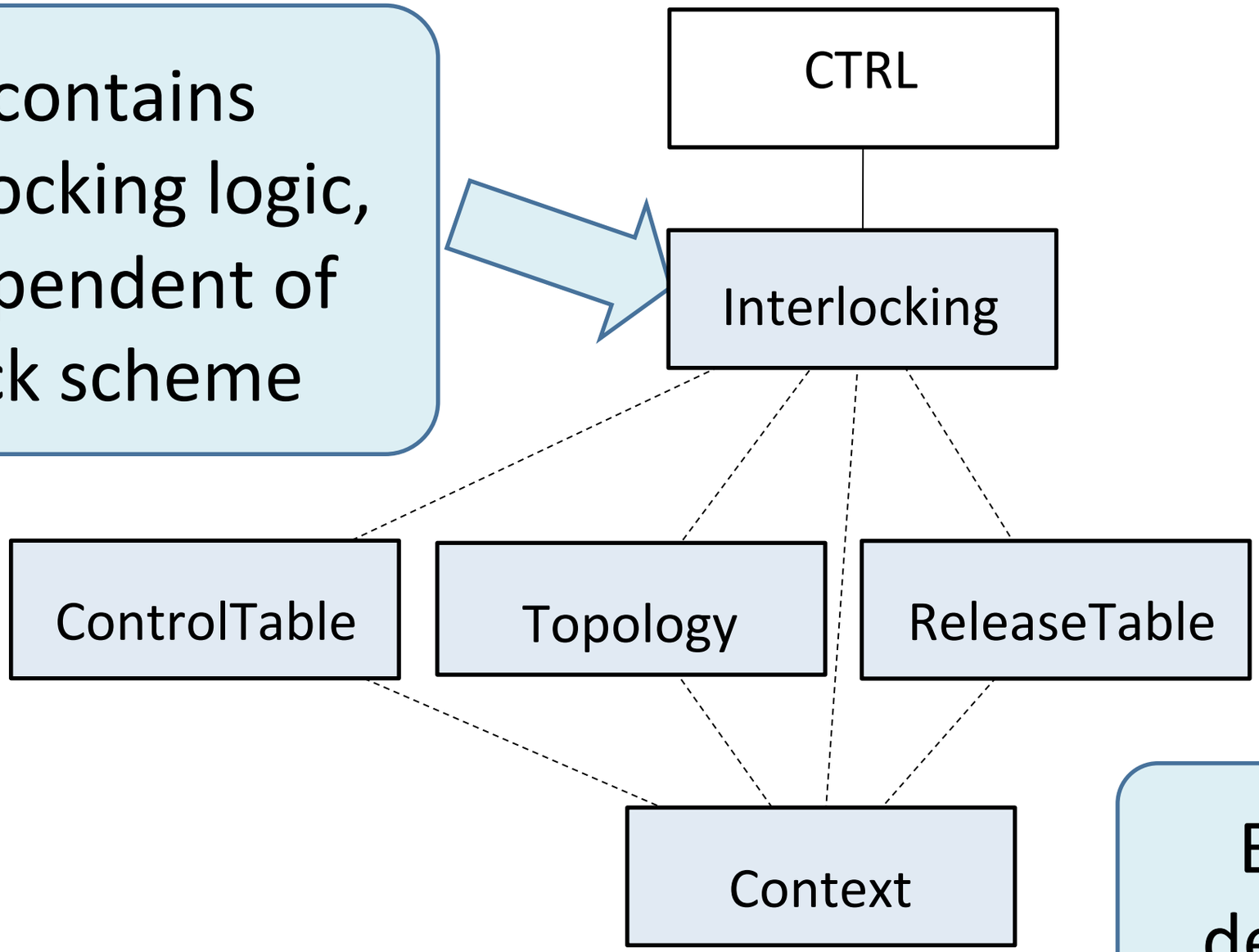
Context:
track topology;
control table;
lock table

CSP||B Architecture



CSP||B Architecture

B contains interlocking logic, independent of track scheme



B machines defining track scheme

Example of CSP model

$$RW\_CTRL =$$
$$\quad \sqcap_{r \in ROUTE} (request!r?b \rightarrow RW\_CTRL)$$
$$\quad \sqcap$$
$$\quad \sqcap_{r \in ROUTE} (release!r?b \rightarrow RW\_CTRL)$$

$$TRAIN\_OFF(t) = enter!t?newp \rightarrow TRAIN\_CTRL(t, newp)$$

$$TRAIN\_CTRL(t, pos) =$$
$$\quad pos \notin EXIT \wedge pos \in SIGNALHOMES \;\&\; nextSignal!t?aspect \rightarrow$$
$$\quad\quad \textbf{if } aspect == green$$
$$\quad\quad \textbf{then}$$
$$\quad\quad\quad move!t.pos?newp \rightarrow TRAIN\_CTRL(t, newp)$$
$$\quad\quad\quad \sqcap$$
$$\quad\quad\quad stay!t.pos \rightarrow TRAIN\_CTRL(t, pos)$$
$$\quad\quad \textbf{else}$$
$$\quad\quad\quad stay!t.pos \rightarrow TRAIN\_CTRL(t, pos)$$
$$\quad \Box$$
$$\quad pos \notin EXIT \wedge pos \notin SIGNALHOMES \;\&$$
$$\quad\quad move!t.pos?newp \rightarrow TRAIN\_CTRL(t, newp)$$
$$\quad\quad \sqcap$$
$$\quad\quad stay!t.pos \rightarrow TRAIN\_CTRL(t, pos)$$
$$\quad \Box \ \ldots$$

$$ALL\_TRAINS = |||_{t \in TRAIN} \; TRAIN\_OFF(t)$$

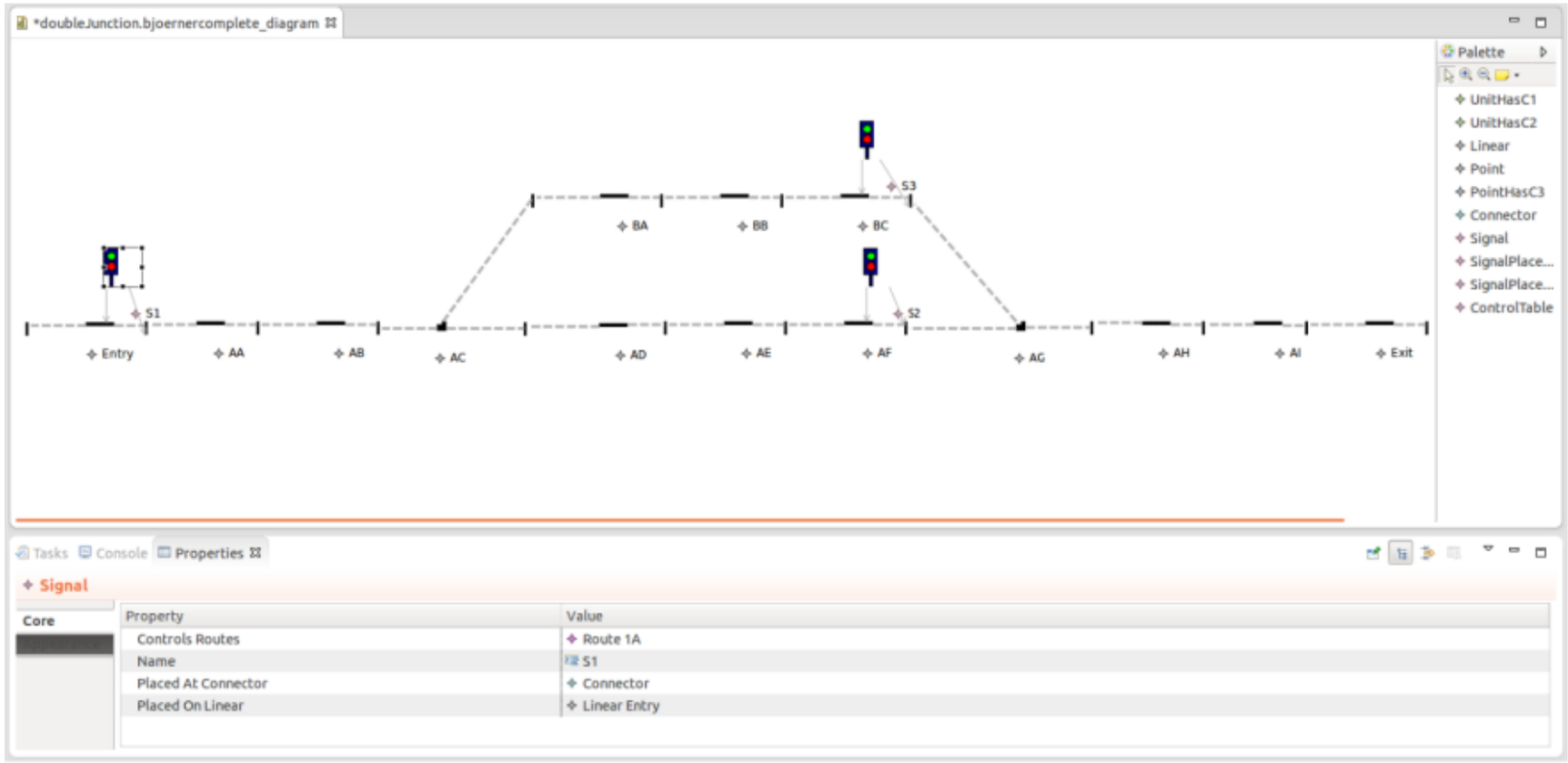
$$move!t.pos?newp \rightarrow \ldots$$

Example of B Interlocking operation

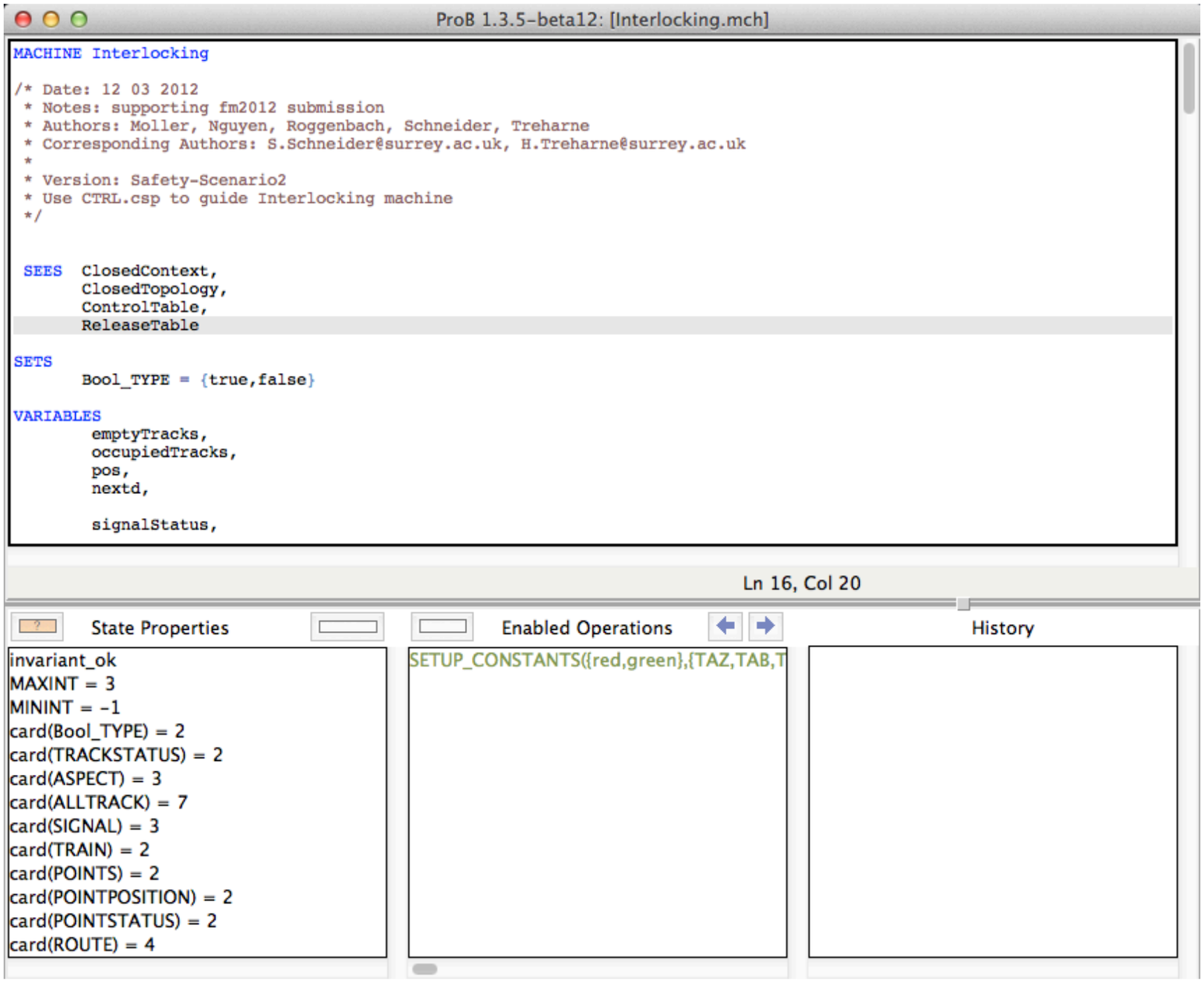
```
currp, newp <-- move(t) =
PRE t : TRAIN & t : dom(pos)
THEN
   IF (pos(t) /: dom(nextd)) THEN
                LET track BE
                  track = nullTrack
                IN
      currp := pos(t) ||
                  pos(t) := track ||
                  newp := track
                END
   ELSE
                LET track BE
                  track = nextd(pos(t))
                IN
                  currp := pos(t) ||
                  pos(t) := track ||
                  newp := track ||
                  currentLocks := currentLocks - releaseTable[{track}] ||
                  IF (pos(t) : ran(homeSignal))
                  THEN
                     signalStatus( homeSignal~(pos(t))) := red
                  END
                END
   END
END;
```

OnTrack: capturing track plans

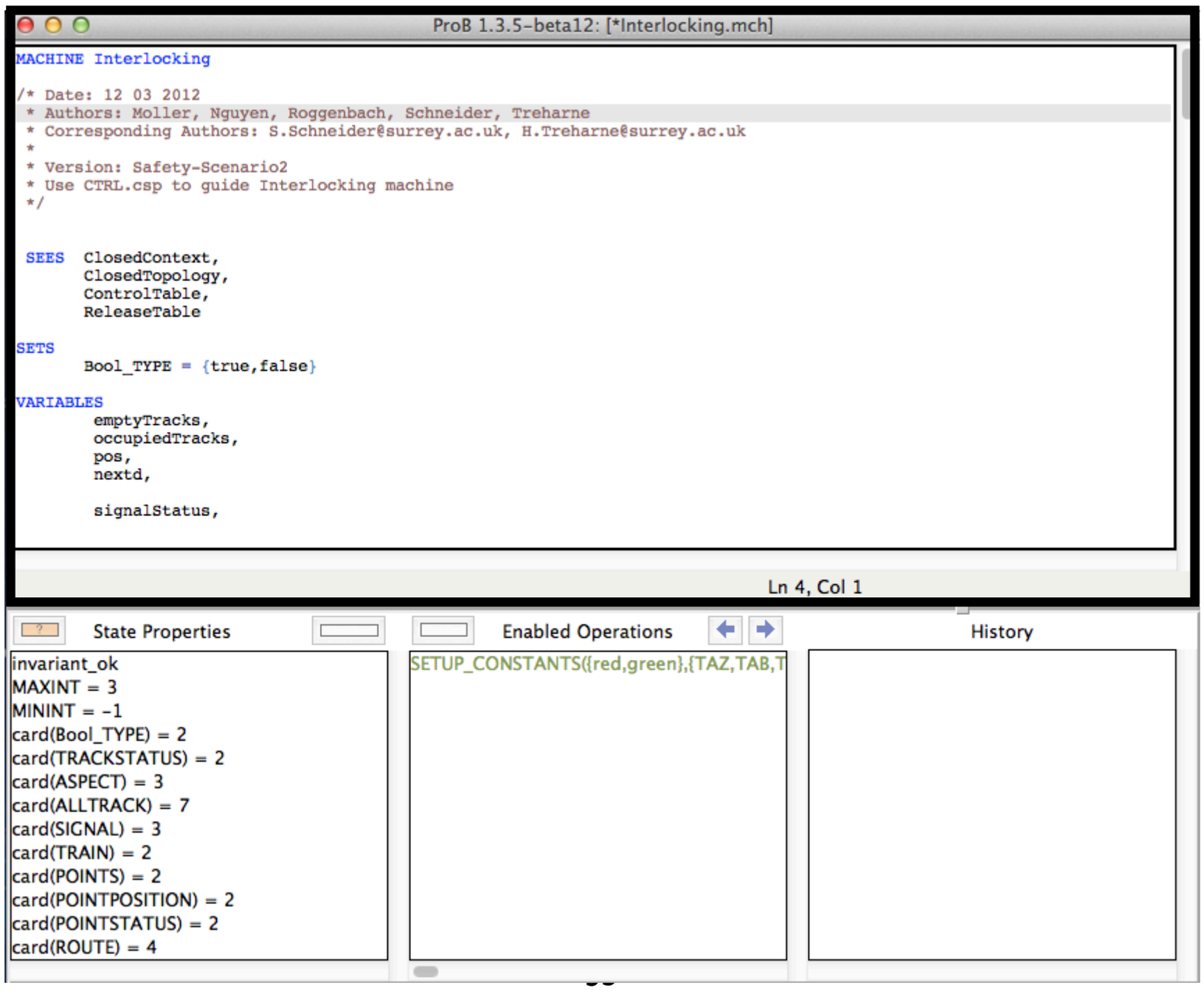
- Model-Driven Engineering: translating railway domain concepts into CSP||Event-B models



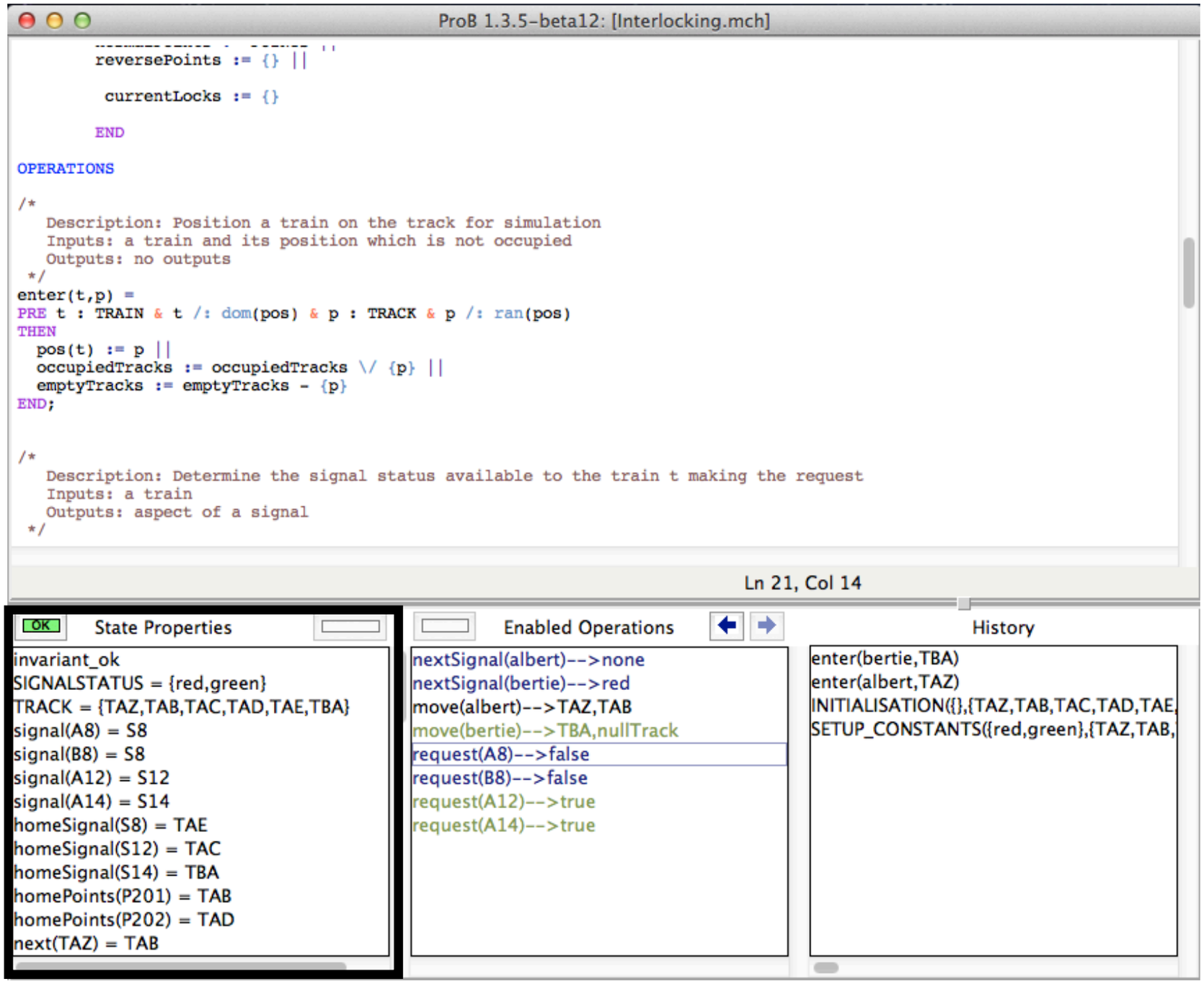
ProB model checker for B (Leuschel) can check CSP||B combinations



The Model panel



State and invariant panel



Enabled operations

ProB 1.3.5-beta12: [Interlocking.mch]

```
        reversePoints := {} ||

         currentLocks := {}

        END

OPERATIONS

/*
   Description: Position a train on the track for simulation
   Inputs: a train and its position which is not occupied
   Outputs: no outputs
 */
enter(t,p) =
PRE t : TRAIN & t /: dom(pos) & p : TRACK & p /: ran(pos)
THEN
  pos(t) := p ||
  occupiedTracks := occupiedTracks \/ {p} ||
  emptyTracks := emptyTracks - {p}
END;


/*
   Description: Determine the signal status available to the train t making the request
   Inputs: a train
   Outputs: aspect of a signal
 */
```

Ln 21, Col 14

OK State Properties

```
invariant_ok
SIGNALSTATUS = {red,green}
TRACK = {TAZ,TAB,TAC,TAD,TAE,TBA}
signal(A8) = S8
signal(B8) = S8
signal(A12) = S12
signal(A14) = S14
homeSignal(S8) = TAE
homeSignal(S12) = TAC
homeSignal(S14) = TBA
homePoints(P201) = TAB
homePoints(P202) = TAD
next(TAZ) = TAB
```

Enabled Operations

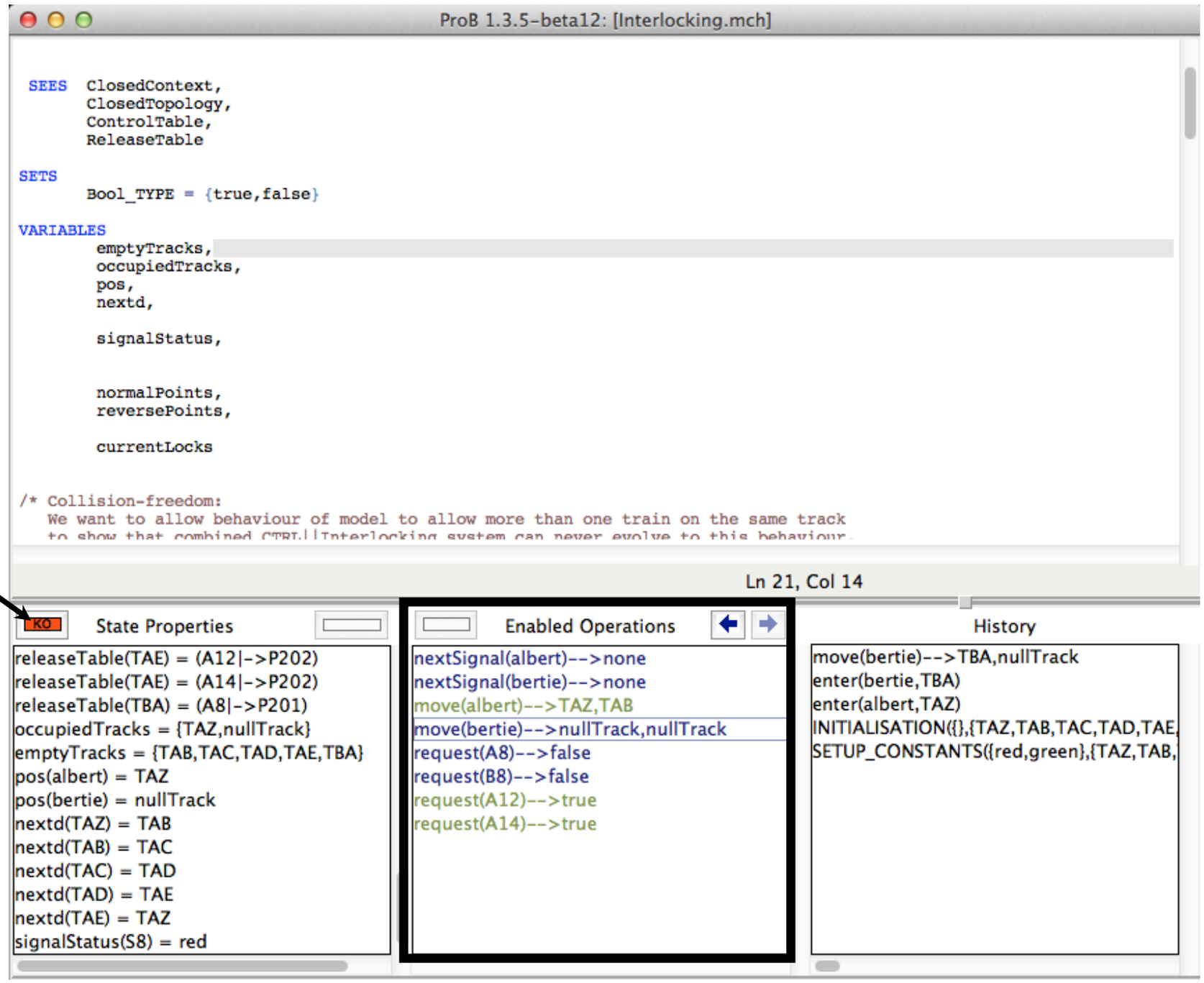
```
nextSignal(albert)-->none
nextSignal(bertie)-->red
move(albert)-->TAZ,TAB
move(bertie)-->TBA,nullTrack
request(A8)-->false
request(B8)-->false
request(A12)-->true
request(A14)-->true
```

History

```
enter(bertie,TBA)
enter(albert,TAZ)
INITIALISATION({},{TAZ,TAB,TAC,TAD,TAE,
SETUP_CONSTANTS({red,green},{TAZ,TAB,
```

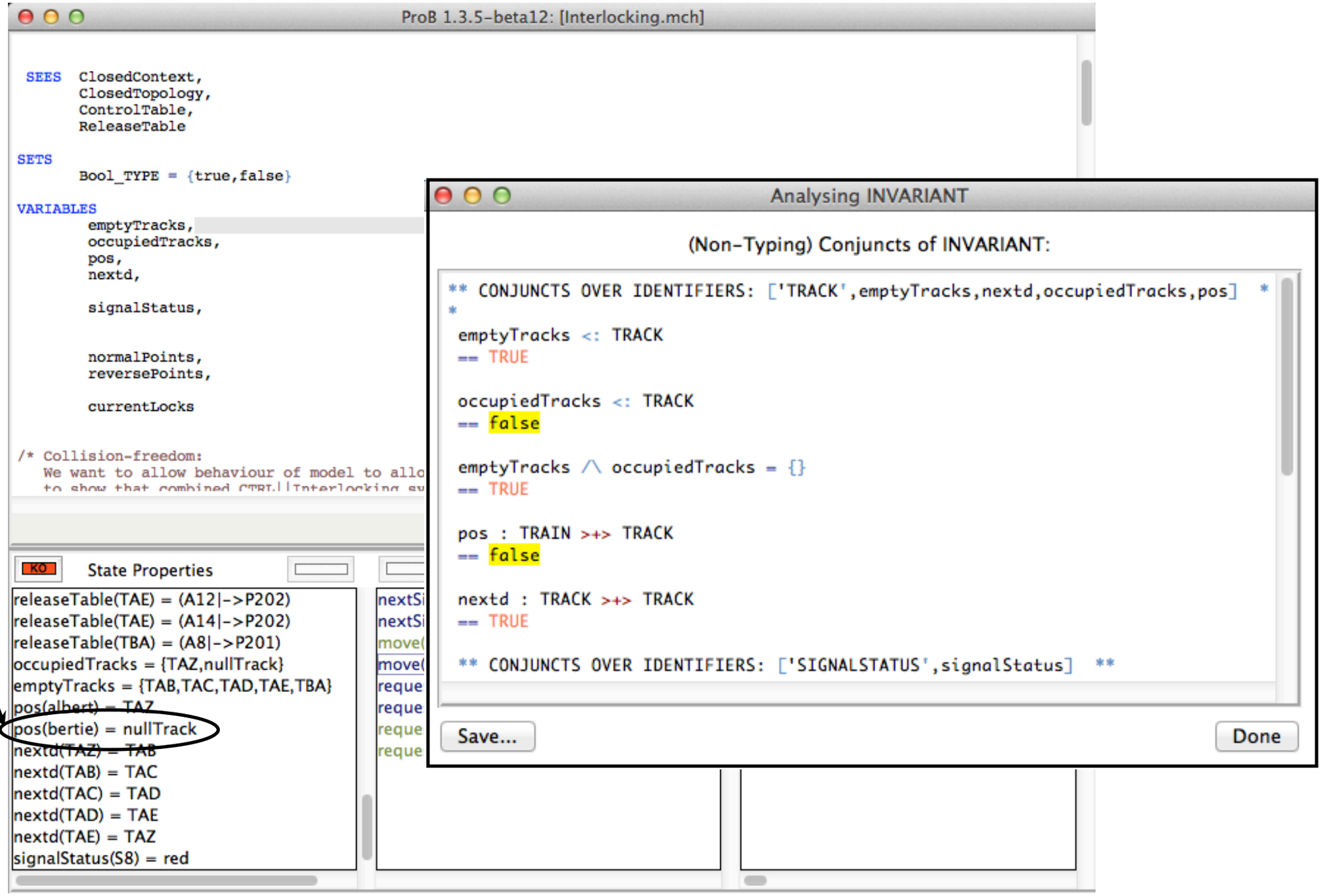
If train moves through a red light…

invariant violation

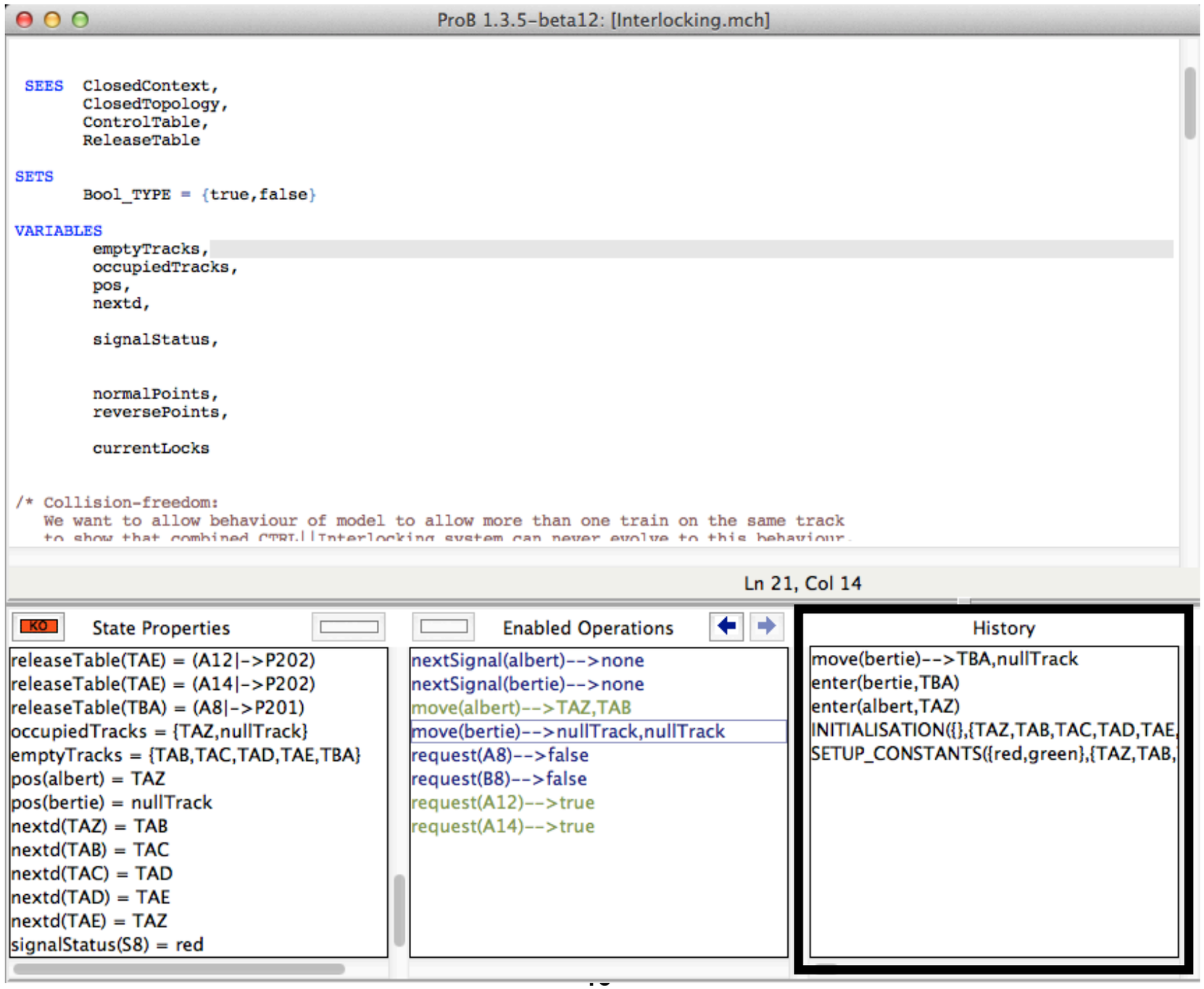


Analysing the invariant

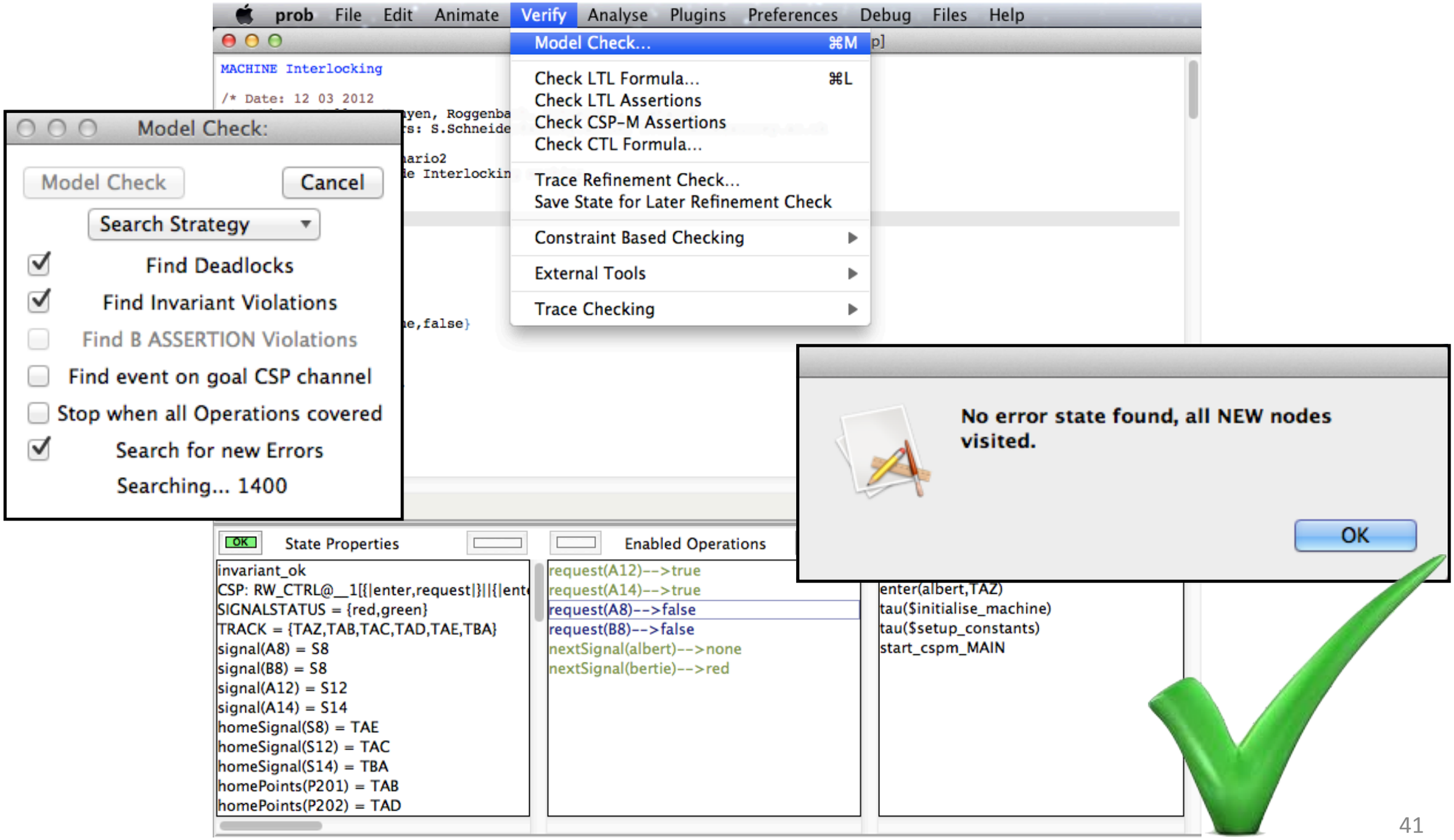
invariant violation



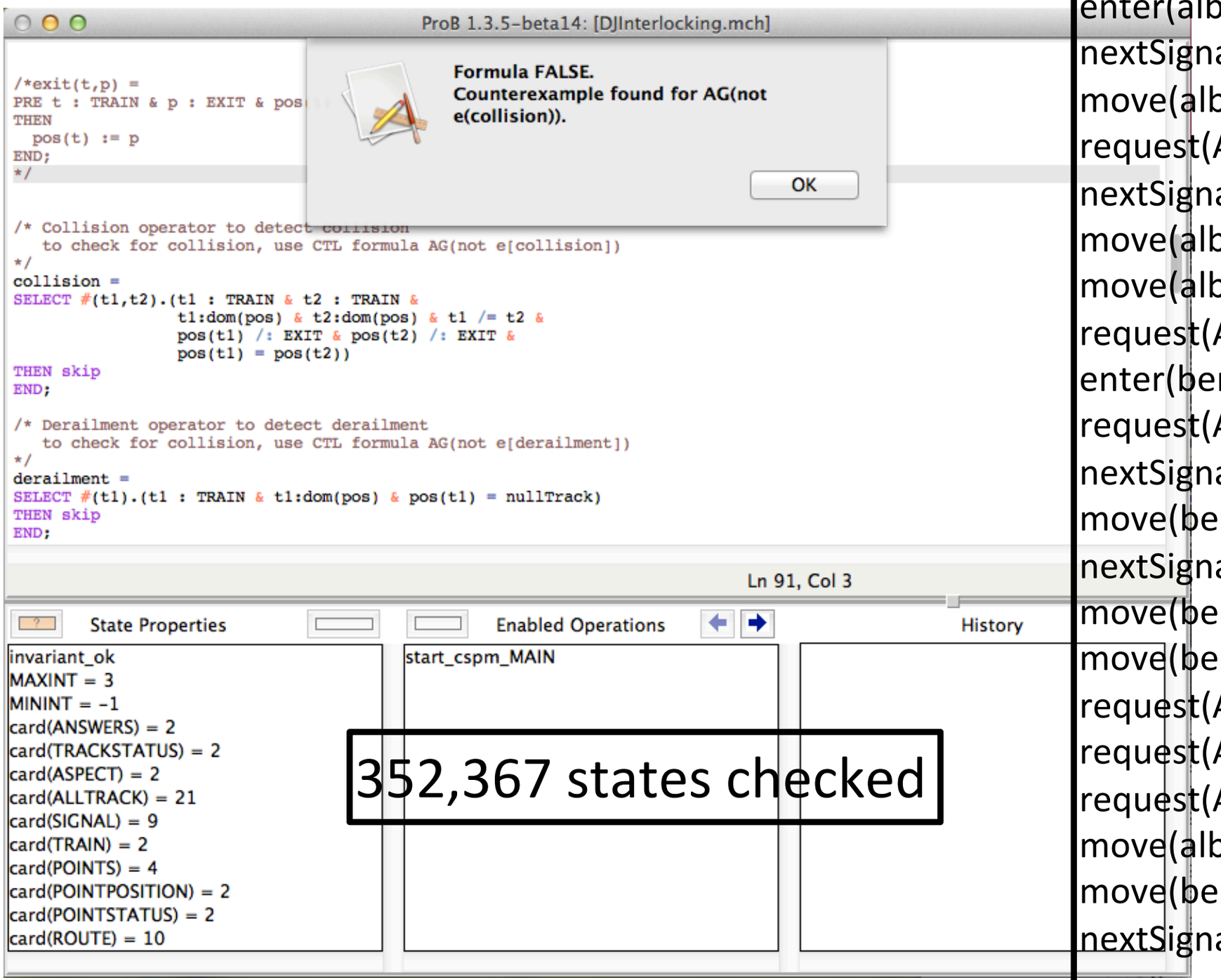
History panel: operations performed so far



Checking safety conditions



Scenario - Faulty Tracks in "ClearTable"



request(A1)-->yes
enter(albert,Entry1)
nextSignal(albert)-->green
move(albert)-->Entry1,AA
request(A3)-->yes
nextSignal(albert)-->green
move(albert)-->AA,AB
move(albert)-->AB,AC
request(A1)-->yes
enter(bertie,Entry1)
request(A3)-->yes
nextSignal(bertie)-->green
move(bertie)-->Entry1,AA
nextSignal(bertie)-->green
move(bertie)-->AA,AB
move(bertie)-->AB,AC
request(A16)-->yes
request(A5)-->yes
request(A2)-->yes
move(albert)-->AC,AD
move(bertie)-->AC,AD
nextSignal(albert)-->green

Where we're at

- Engineers understand/agree with the models (train driving rules; track interlocking rules)
- The combined semantics also provides a foundation for compositional results on complex track plans:
  - Finitisation: limiting the number of trains to include in a safety analysis
  - Coverings: breaking down a complex track plan into manageable fragments that can be independently checked

Structure of Talk

- B and Event-B for state
- Combination with CSP
- Example: modelling for railway safety
- **Incorporating time**

Introducing time

railway designers are also interested in network capacity

Challenge: Introducing time

- We want to introduce time to CSP||Event-B
- Natural and obvious approach: use Timed CSP as the control language and manage all the time in there
  - leave the B models as untimed, embedded in the timed CSP semantic framework
- … but not quite so simple...

Timed CSP

- Timed language:

$$
\begin{aligned}
P \quad ::= \quad & STOP \mid SKIP \mid WAIT\ t \mid P;Q \mid \\
& a \rightarrow P \mid c?x \rightarrow P \mid c!v \rightarrow P \mid \\
& P \sqcap Q \mid P \,\Box\, Q \mid P \overset{t}{\triangleright} Q \mid \\
& P \parallel Q \mid P \,|||\, Q \mid P \setminus A \\
& X \mid \mu X \,.\, P
\end{aligned}
$$

- (recursions time-guarded)

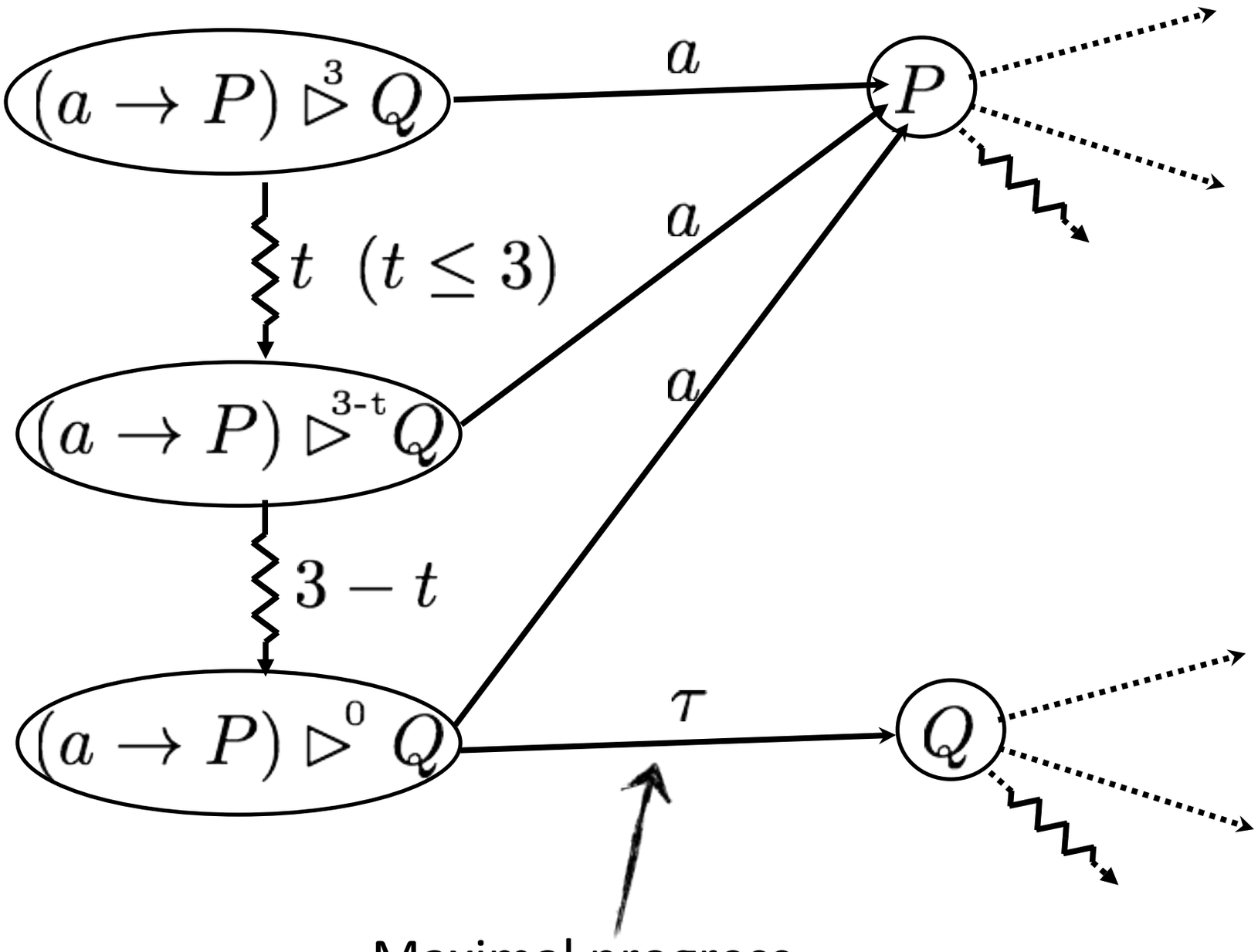
Timed CSP transitions

$$(a \to P) \xrightarrow{a} P$$

$$(a \to P) \overset{2}{\rightsquigarrow} (a \to P)$$

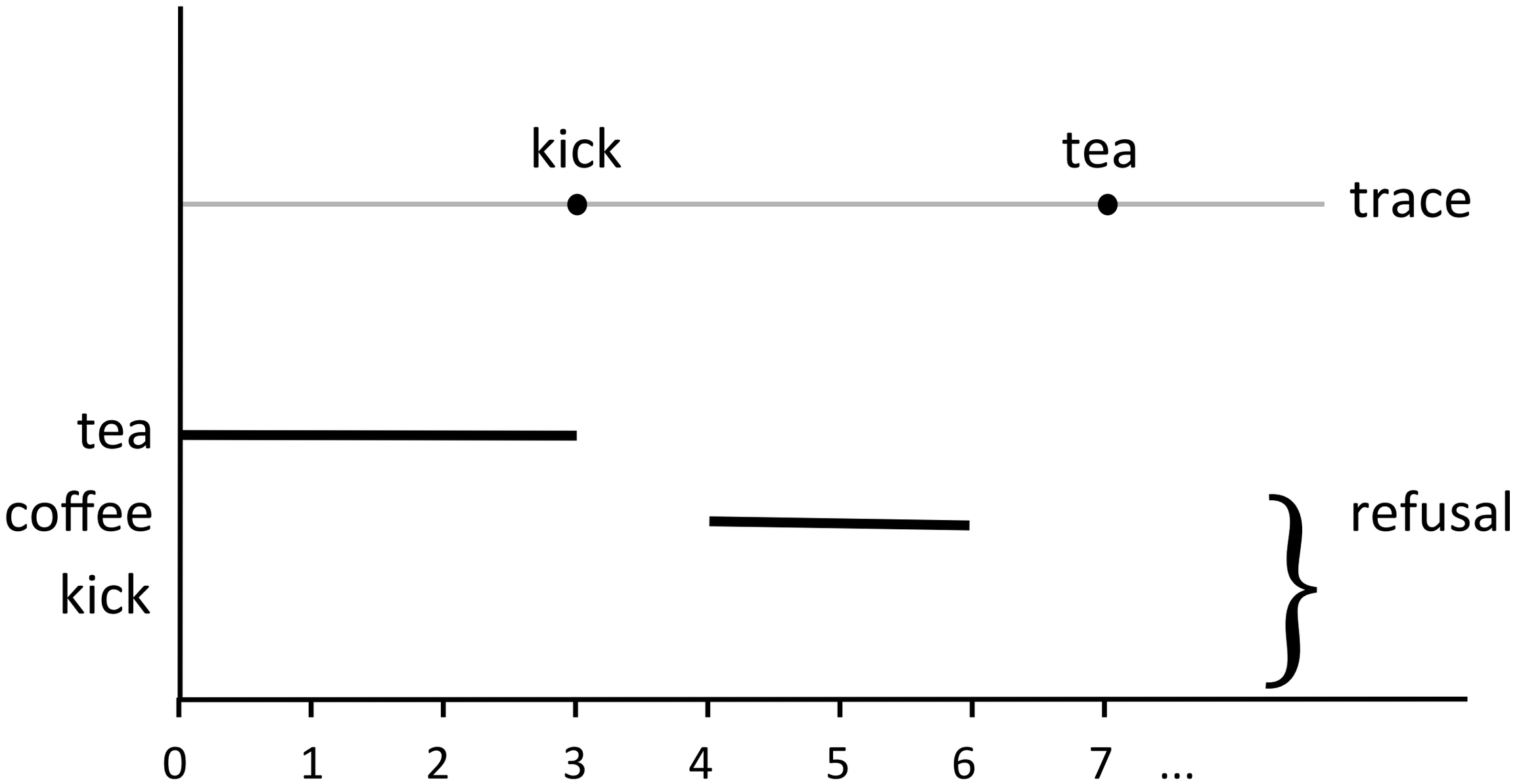
$$(P \overset{7}{\triangleright} Q) \overset{2}{\rightsquigarrow} (P' \overset{5}{\triangleright} Q)$$

Example fragment of a timed transition system



Observations for denotational semantics: Timed Failures

$$(coffee \rightarrow STOP) \,\square\, (kick \rightarrow tea \rightarrow STOP)$$



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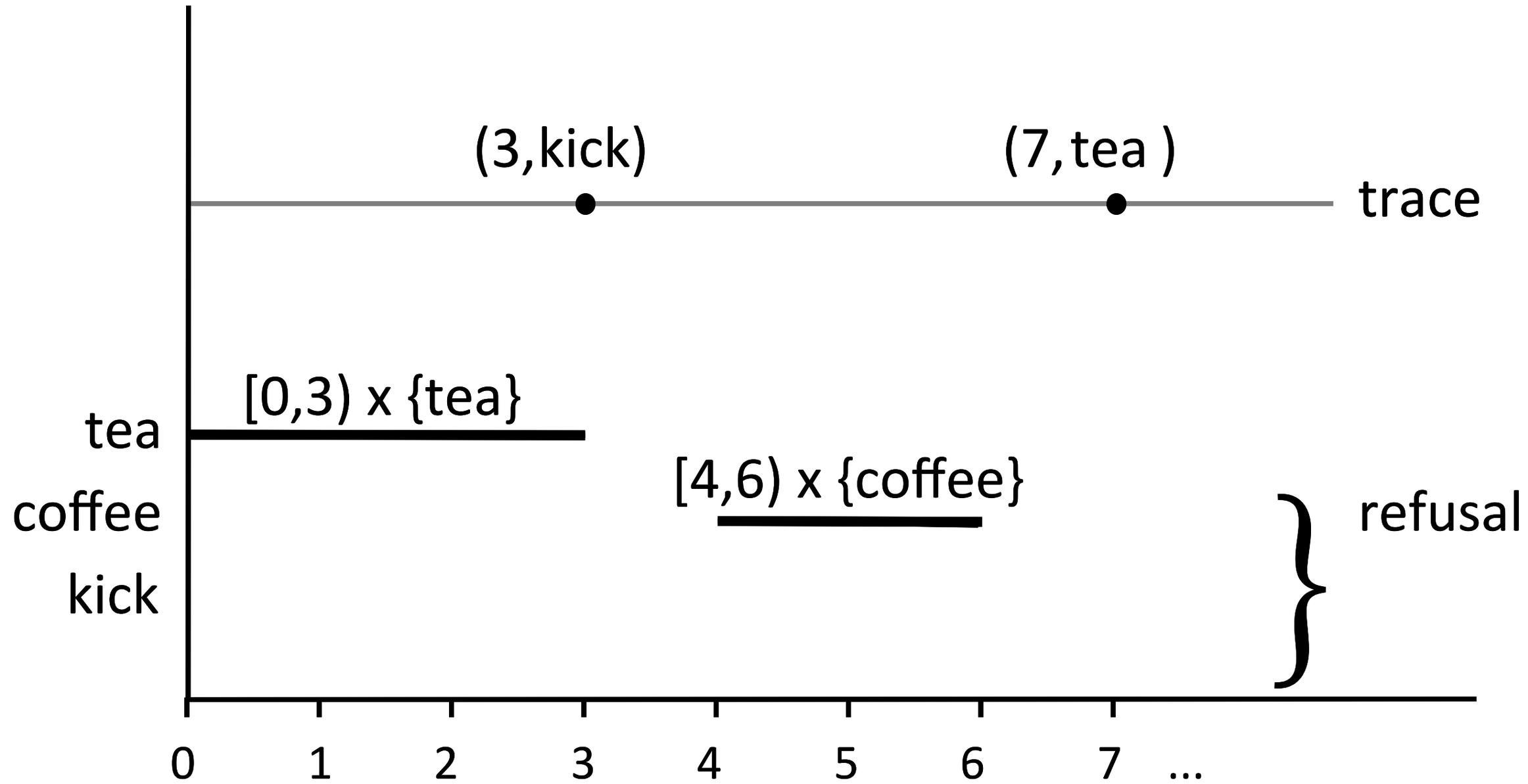
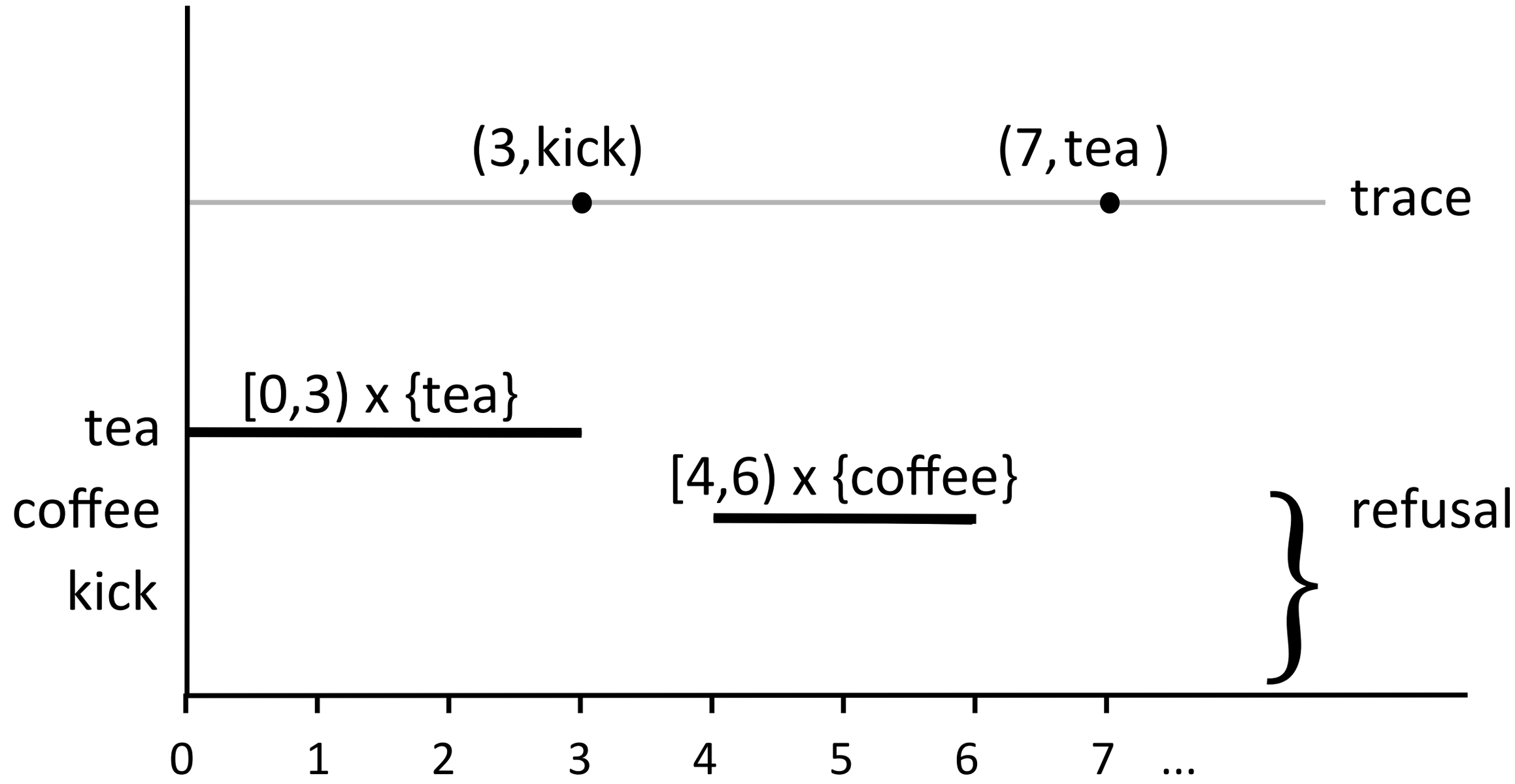


Observations for denotational semantics: Timed Failures

$$\langle\ [0,3) \times \{tea\}\ ,\ (3, kick)\ ,\ [4,6) \times \{coffee\}\ ,\ (7, tea)\ ,\ \emptyset\ \rangle$$



Timed CSP and B/Event-B: issues

- "leave the B models as untimed, embedded in the timed CSP semantic framework"

- 1. wp semantics doesn't give timed CSP semantics (even for "untimed" machines)
  - no refusals during the trace
- 2. machines react and change state instantly
  - they are not "time guarded"
- 3. need to include divergence (abort) in machines (for B, but not for Event-B)

1. Timed refusal testing

$$P1 \quad = \quad (coffee \rightarrow STOP) \,\Box\, (kick \rightarrow tea \rightarrow STOP)$$
$$\sqcap\, (tea \rightarrow STOP) \,\Box\, (kick \rightarrow coffee \rightarrow STOP)$$

$$P2 \quad = \quad (coffee \rightarrow STOP) \,\Box\, (kick \rightarrow coffee \rightarrow STOP)$$
$$\sqcap\, (tea \rightarrow STOP) \,\Box\, (kick \rightarrow tea \rightarrow STOP)$$

1. Timed refusal testing

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$$\langle\, [0,3) \times \{tea\}\ ,\ (3, kick)\ ,\ [4,6) \times \{coffee\}\ ,\ (7, tea)\ ,\ \emptyset\, \rangle$$

Timed CSP semantics?
Now need to distinguish these two:

Machine VM1 =
Variables n
Invariants n ∈ {0,1,2}
Initialisation n:=0 ⊓ n:=1
Operations
tea =
  when n=0 then n:=2 end
coffee =
  when n = 1 then n:=2 end
kick =
  when n<2 then n:=1-n end

Machine VM2 =
Variables n
Invariants n ∈ {0,1,2}
Initialisation n:=0 ⊓ n:=1
Operations
tea =
  when n=0 then n:=2 end
coffee =
  when n = 1 then n:=2 end
kick =
  when n<2 then skip end

$$P = (tea \rightarrow STOP) \stackrel{3}{\triangleright} (kick \rightarrow tea \rightarrow STOP)$$

$P \parallel VM1$ can't refuse tea for ever, $P \parallel VM2$ can

Untimed refusal traces and wp

$$\langle X_0, a_1, X_1, a_2, X_2, \ldots \rangle \in refusal\ traces(M) \iff$$

$\exists\ P_0\ ,\ P_1\ ,\ \ldots$

1. $\overline{wp}(init, P_0)$

$P_0 \Rightarrow \overline{wp}(a_1, P_1)$

$\vdots$

$P_i \Rightarrow \overline{wp}(a_{i+1}, P_{i+1})$

2. $\text{for each } i\text{: } P_i \Rightarrow \bigwedge_{a \in X_i} \neg g_a$

Example: $\langle\ \{tea\}\ ,\ kick\ ,\ \emptyset\ ,\ tea\ ,\ \emptyset \rangle$

$\overline{wp}(init, P_0)$

$P_0 \Rightarrow \overline{wp}(kick, P_1)$

$P_1 \Rightarrow \overline{wp}(tea, P_2)$

$P_0:\ \ n = 1$	$\neg g_{tea}:\ \ n \neq 0$
$P_1:\ \ n = 0$	$\bigwedge_{a \in X_1} \neg g_a:\ \ true$
$P_2:\ \ true$	$\bigwedge_{a \in X_2} \neg g_a:\ \ true$

Defining timed refusals via wp: relating timed and untimed observations

$$\langle\ \aleph_0\ ,\ (t_1, a_1)\ ,\ \aleph_1\ ,\ (t_2, a_2)\ ,\ \aleph_2\ \ldots\ \rangle \in timed\ failures(M) \iff$$

$$\langle\ \sigma(\aleph_0)\ ,\ a_1\ ,\ \sigma(\aleph_1)\ ,\ a_2\ ,\ \sigma(\aleph_2)\ \ldots\ \rangle \in refusal\ traces(M)$$

Just the events; times removed

NB: True for "untimed" B machines, because state changes are instant and states are stable between transitions.
Not true for arbitrary timed CSP processes

$$\langle\ [0,3) \times \{tea\}\ ,\ (3, kick)\ ,\ [4,6) \times \{coffee\}\ ,\ (7, tea)\ ,\ \emptyset\ \rangle$$

$$\langle\ \{tea\}\ ,\ kick\ ,\ \{coffee\}\ ,\ tea\ ,\ \emptyset\ \rangle$$

Timed CSP: Fixed Point theory

- Reed&Roscoe 1988 (+ see Schneider 1999):
  - Semantic model is a complete metric space
    - » d(P,Q) is 2^{-t} , where P and Q first differ at time t
  - Recursions are time guarded
  - Recursions are contraction mappings, giving unique fixed points
  - No divergences (processes don't go infinitely fast). Infinite internal transitions (e.g. from internal loops) take infinite time.

$$\mu X \,.\, (send!v \rightarrow (rec?ack \rightarrow STOP) \stackrel{3}{\triangleright} X)$$

$$\mu X \,.\, (rec1?x \rightarrow Q) \stackrel{3}{\triangleright} ((rec2?x \rightarrow R) \stackrel{3}{\triangleright} X)$$

Timed CSP semantics?
Instant response

Machine VM1 =
Variables n
Invariants n ∈ {0,1,2}
Initialisation n:=0 ⊓ n:=1
Operations
tea =
  when n=0 then n:=2 end
coffee =
  when n = 1 then n:=2 end
kick =
  when n<2 then n:=1-n end

$$
\begin{aligned}
M0 &= tea \rightarrow STOP \,\Box\, kick \rightarrow M1 \\
M1 &= coffee \rightarrow STOP \,\Box\, kick \rightarrow M0 \\
VM1 &= M0 \sqcap M1
\end{aligned}
$$

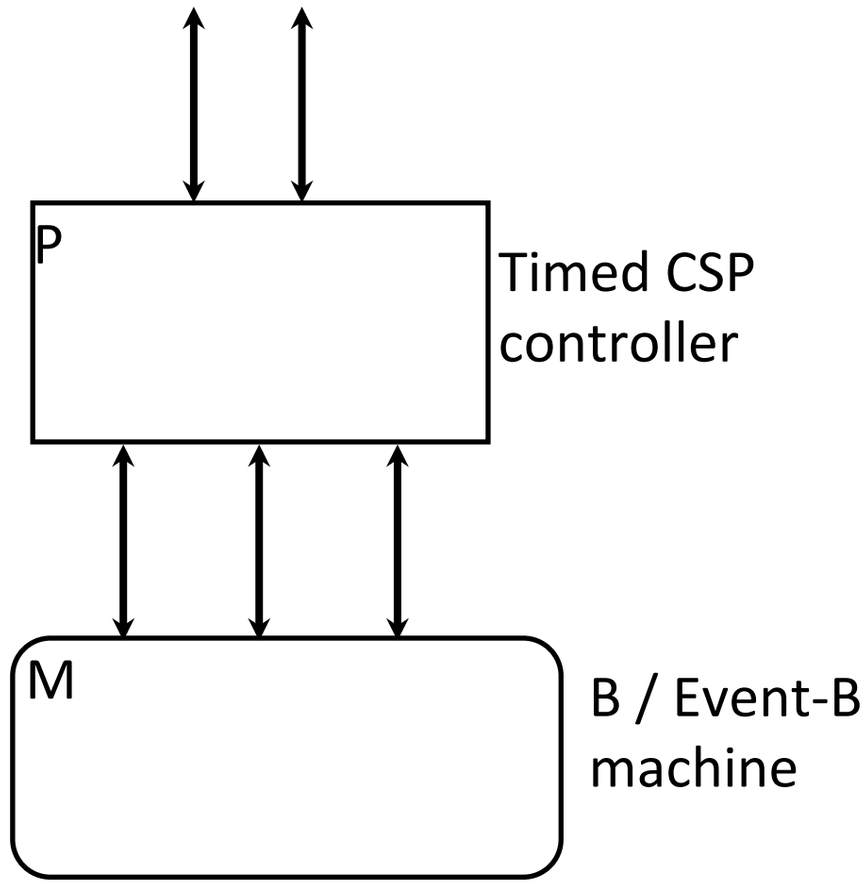
$$VM1 \backslash \{kick\}$$

A more recent semantics for timed CSP... ...does what we need

- Ouaknine&Worrell, "Timed CSP = Closed Timed ε-Automata", Nordic Journal of Computing 10 (2), 2003.
- Gives a more elaborate semantics for Timed CSP, including the following features in the language:
  - Arbitrarily fast processes (non-time-guarded recursions permitted)
  - Divergences (infinite tau loops in zero time), zeno processes?
  - Timestops and urgent events
- Semantics
  - cpo rather than cms
  - operational semantics (claimed to match denotational)

Combining Timed CSP and B / Event-B

- P and M both have a Ouaknine/ Worrell timed failures semantics.
- So P||M also has a semantics.
- The B machine can go arbitrarily fast...
- ...but in practice is driven by the Timed CSP controller, which we can make sure (and verify) is well-behaved: no divergences, no timestops, time-guarded loops.

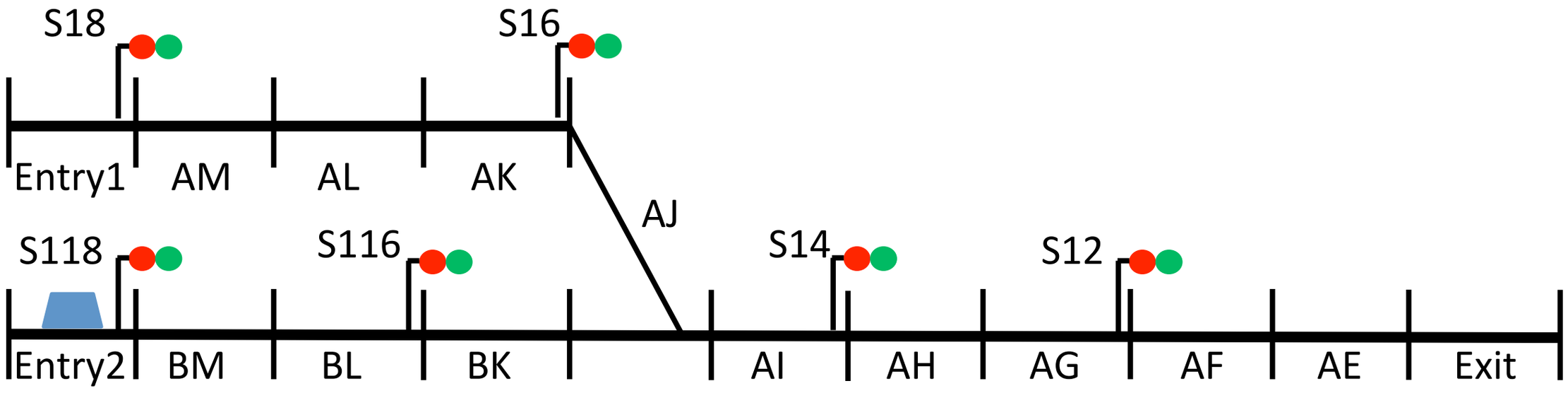


Further Challenges and Questions

- What are the best ways to manage (large) state with concurrency?
- Time? Probabily? Mobility ??
- Hierarchical use
- Pragmatics: more integrated tool support

Exploring the detailed trace

enter(bertie,Entry2)
request(R118A)-->yes
nextSignal(bertie)-->green
move(bertie)-->Entry2,BM
request(R116A)-->yes
move(bertie)-->BM,BL
nextSignal(bertie)-->green
move(bertie)-->BL,BK
move(bertie)-->BK,AJ
move(bertie)-->AJ,AI



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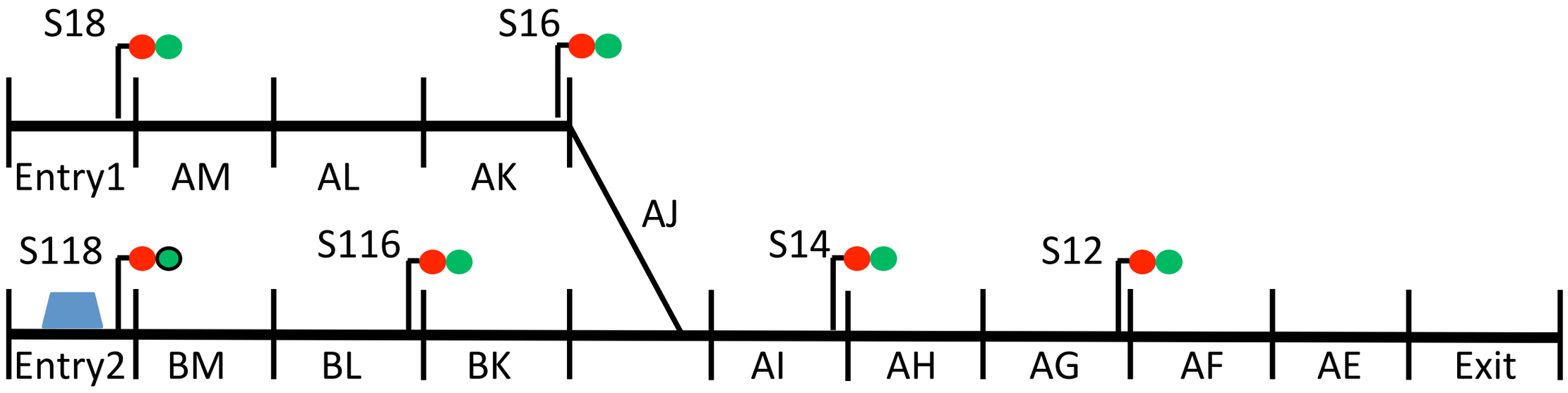

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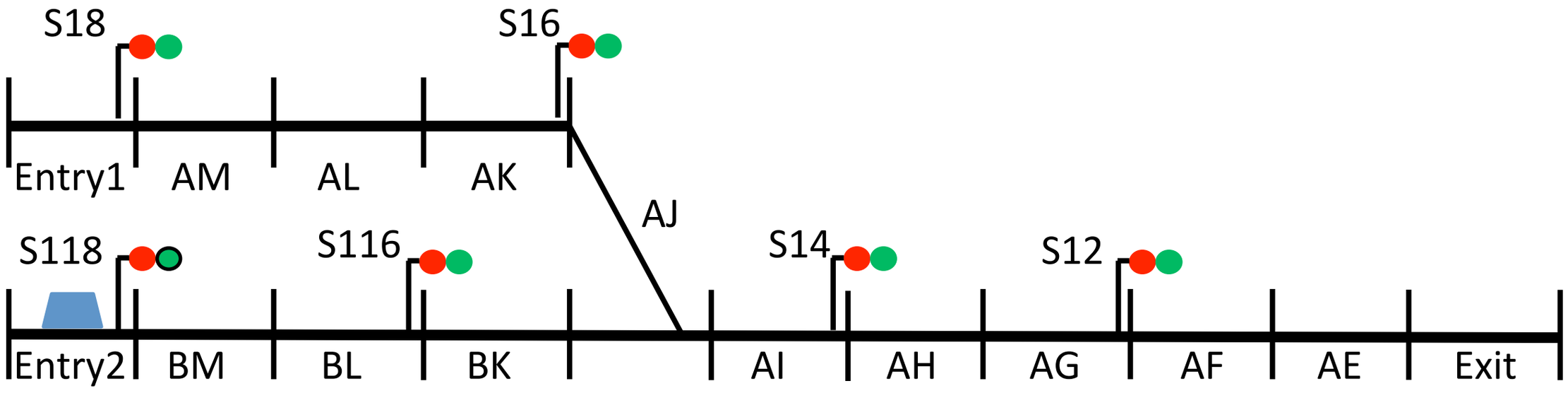

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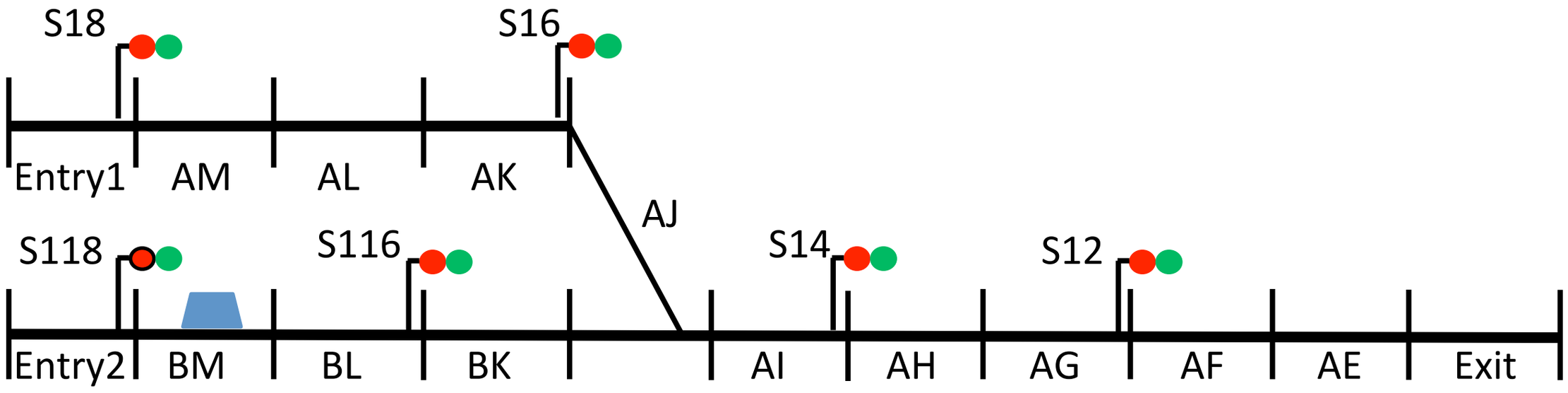

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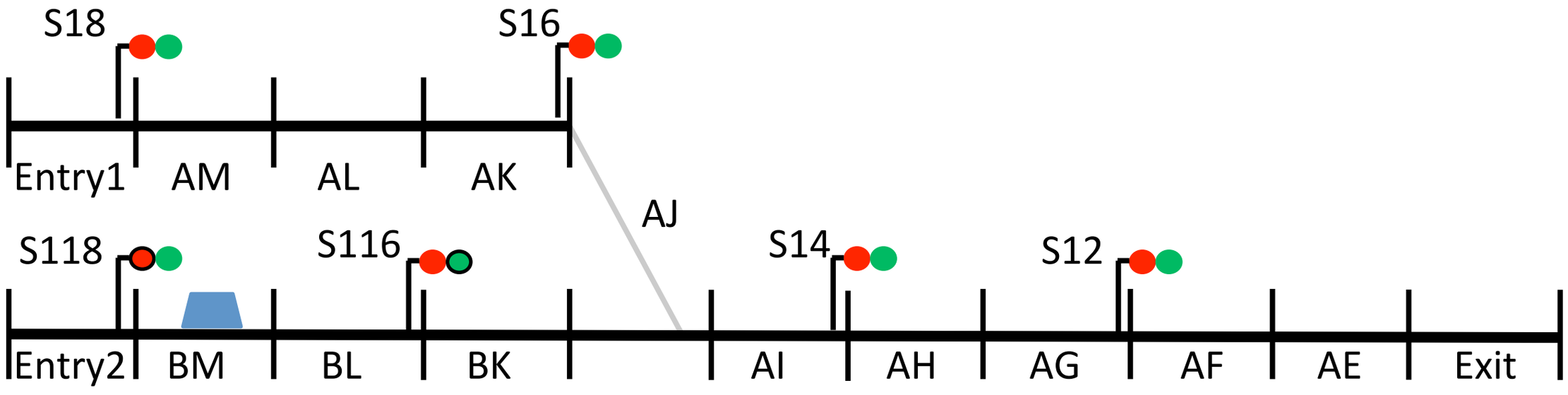

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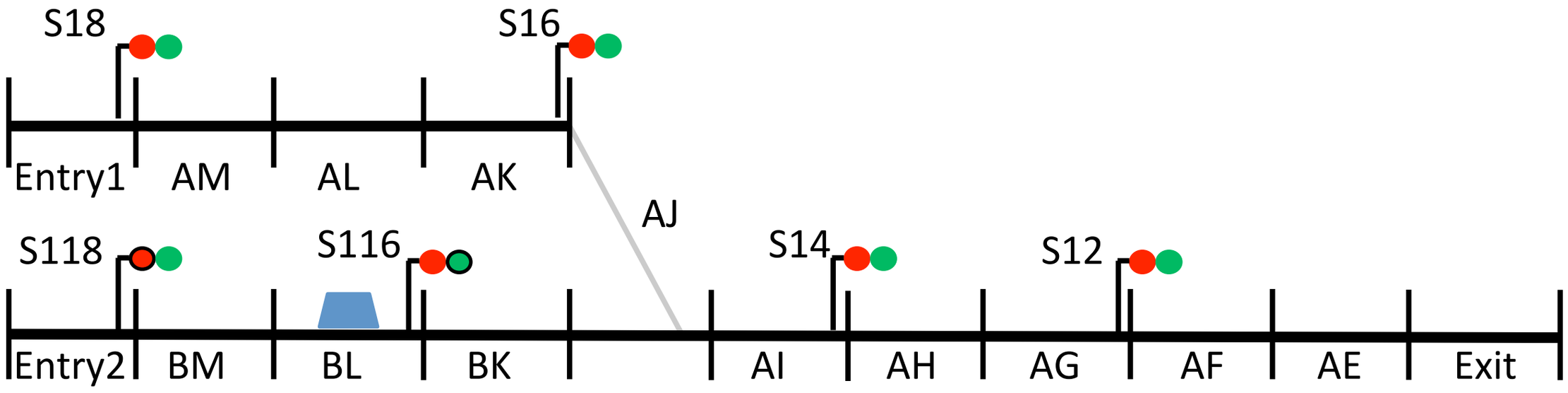

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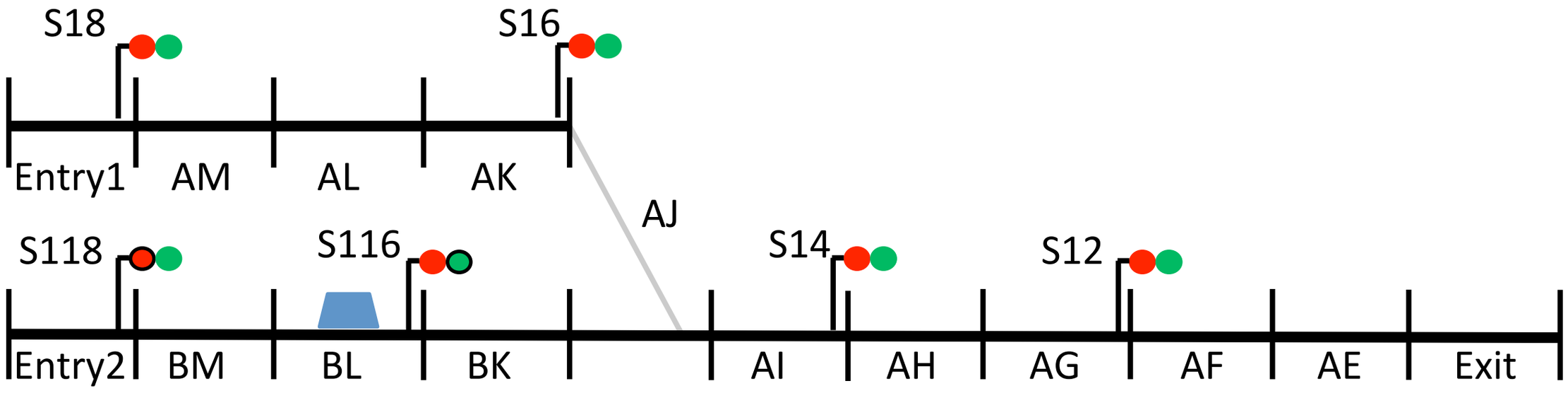

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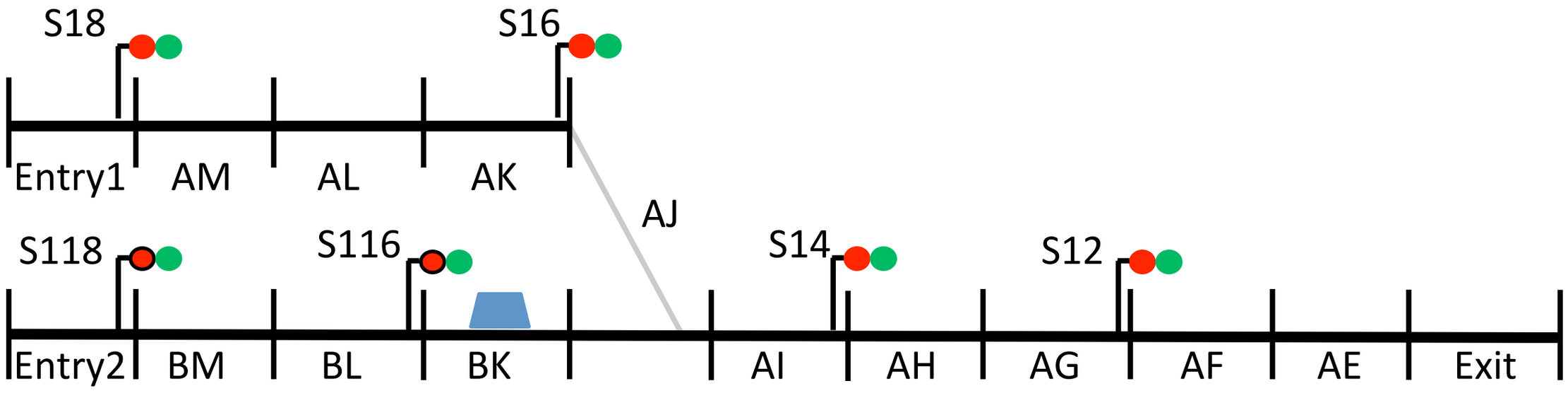

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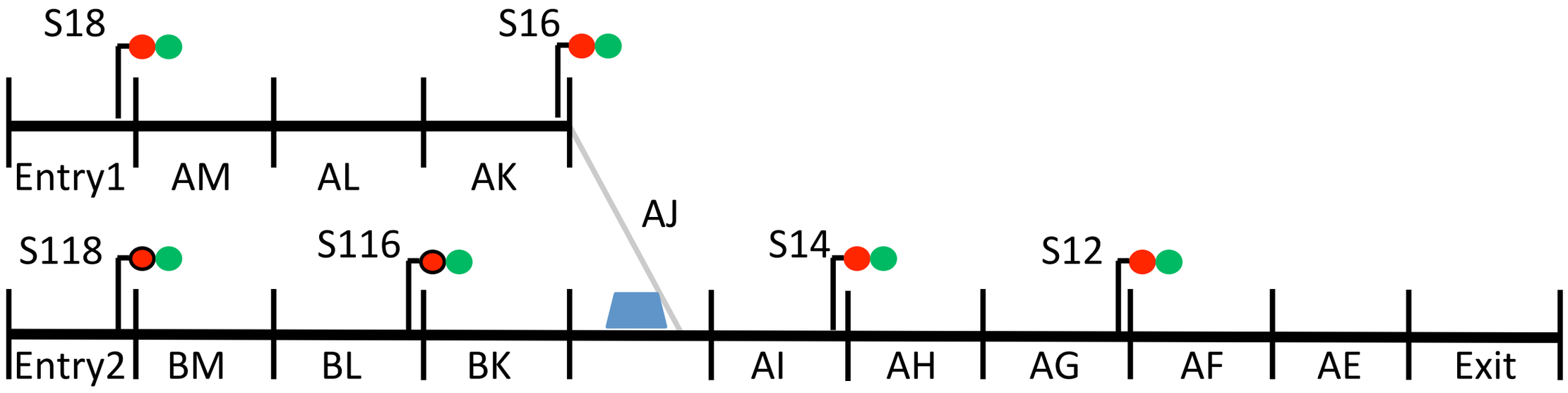

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