DEVELOPMENT OF CORRECT SOFTWARE WITH B-METHOD

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DCI FEEI TU Košice

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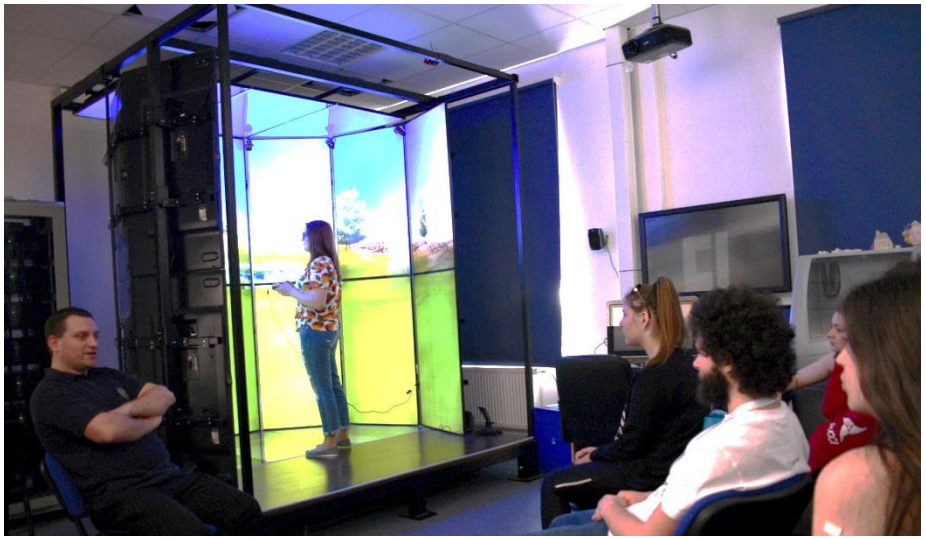
- Department of Computers and Informatics
  FEEI, Technical University of Košice
- https://kpi.fei.tuke.sk/en



This Tutorial

- A practical introduction to the formal software development
  - specification,
  - verification,
  - refinement
- On an example from the railway domain

This Tutorial :: Software Requirements

- Atelier B
  - http://www.atelierb.eu/en/download/
- Java JDK
  - http://www.oracle.com/technetwork/java/javase/downloads/index.html
- TS2JavaConn/TrainDirector Toolset
  - http://hron.fei.tuke.sk/~korecko/FMInGamesExp/resources/allInOneTDTS2J.zip
- Tutorial package
  - http://hron.fei.tuke.sk/~korecko/cefp19/cefp19BmethodPack.zip

B-Method

- Author: Jean-Raymond Abrial
- State based, model-oriented
- For software development
- Based on
  - Zermelo-Fraenkel set theory
  - Dijkstra's weakest precondition calculus
- Sophisticated development process
  - abstract formal specification -> implementation (code)
  - proof of correctness
  - Tool: Atelier B (https://www.atelierb.eu/en)

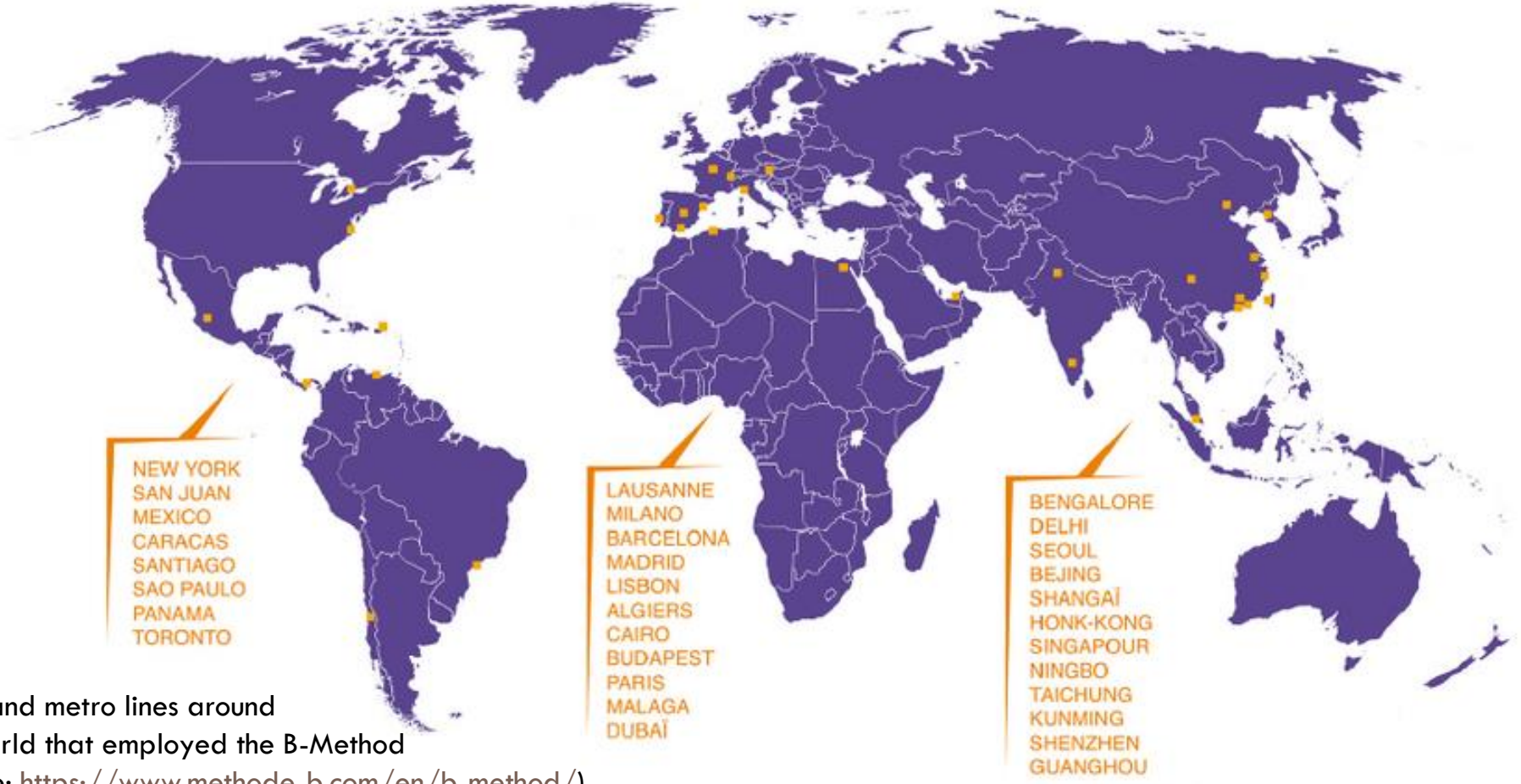
B-Method

- Specification components = B-machines (refinements, implementations)
  - Concept: close to class in OOP
  - state variables +
    invariant (restricts the variables) +
    operations (modify the variables) +
    constants, sets ...

- Links
  - https://www.methode-b.com/en
  - https://www.clearsy.com/en/
  - https://www.atelierb.eu/en

B-Method

- Industrial use
  - Frequently used in the railway domain
    - Including Budapest metro (line M4)



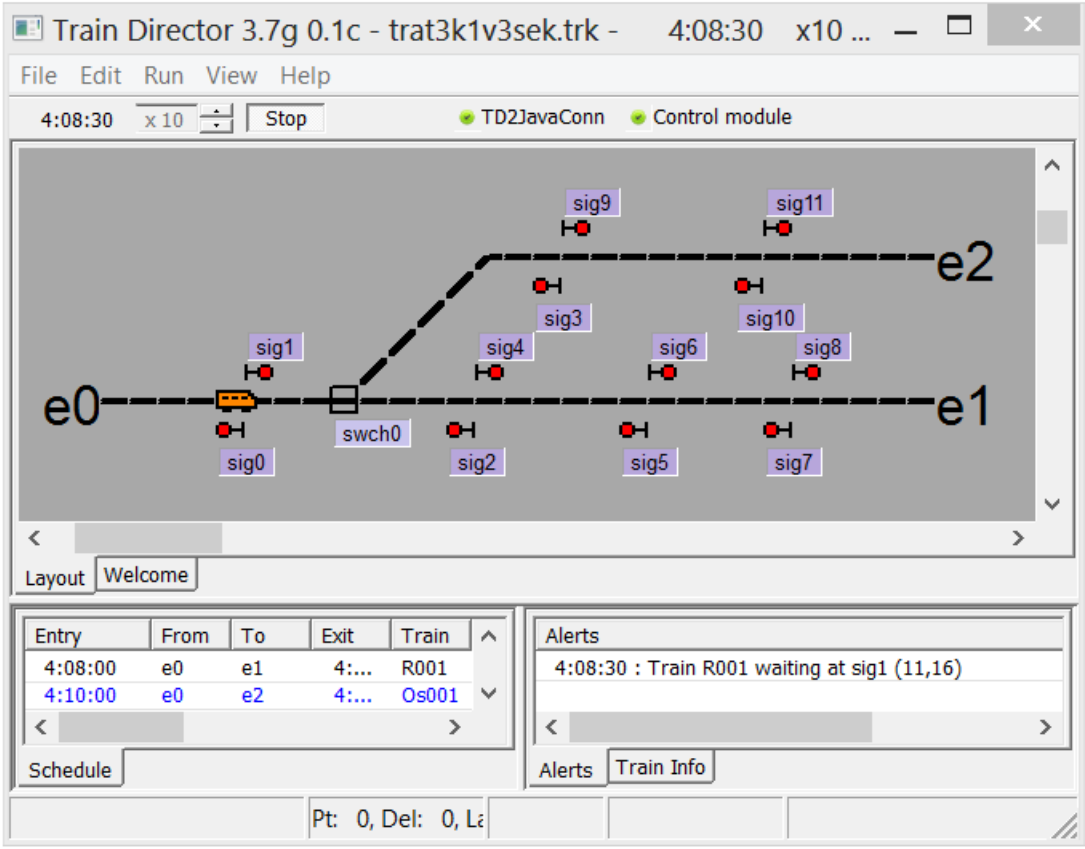
Train and metro lines around the world that employed the B-Method (source: https://www.methode-b.com/en/b-method/)

TD/TS2JC Toolset

- **Train Director**
- **TS2JavaConn**
- **How it works**
- **Scenarios for the tutorial**

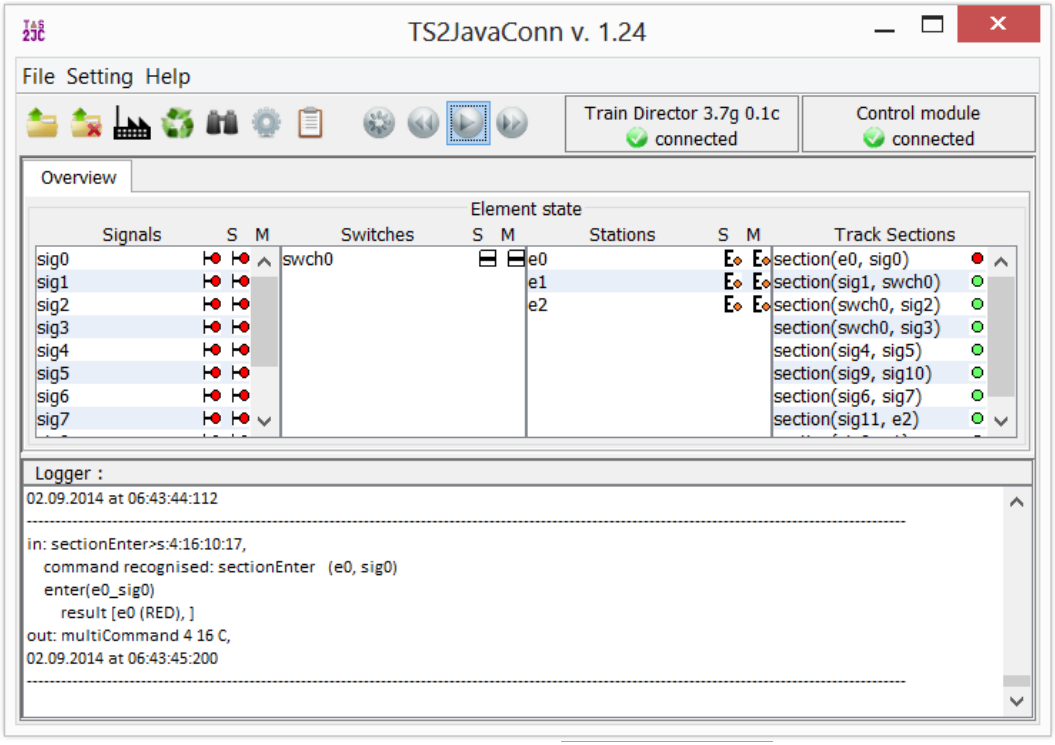
Train Director

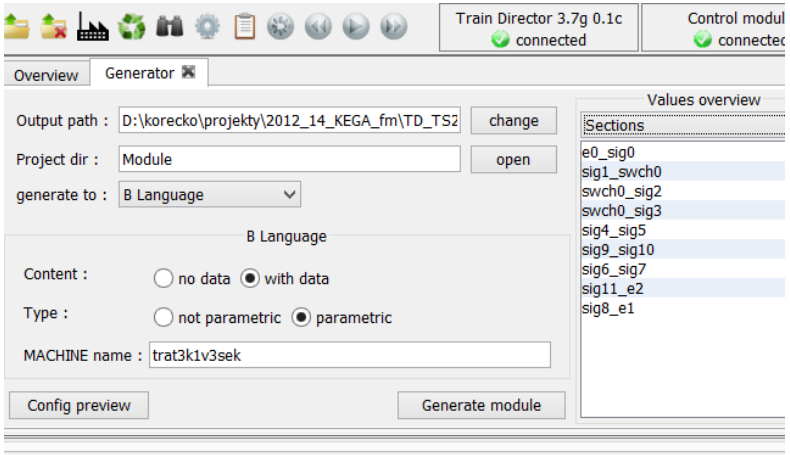
- Centralised traffic control simulator
- Modified by us
  - Enhanced communication interface
  - Internal logic disabled
- to create and simulate scenarios
  - layout + schedule



TS2JavaConn

- Communication between Train Director and control modules
- Generation of control module templates
  - Java, B language, Perfect





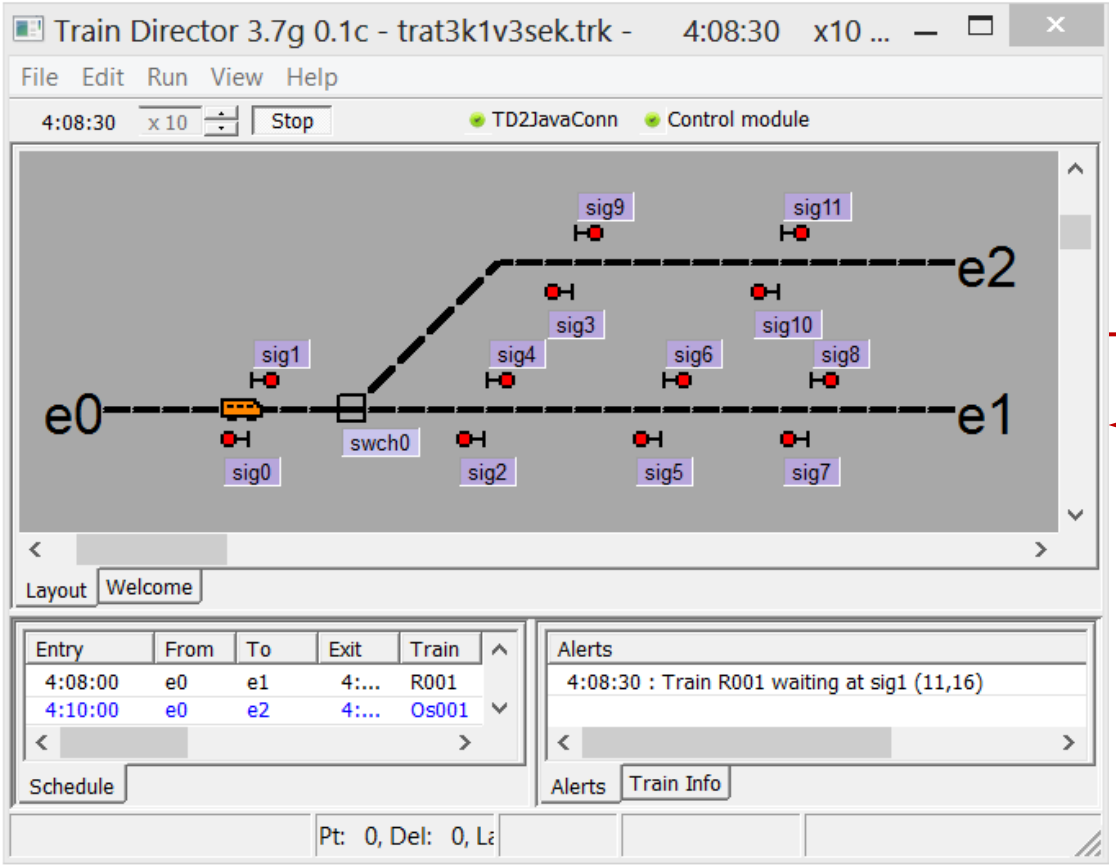
Control module

- reactive system
- Java application (developed using FM) + configuration file

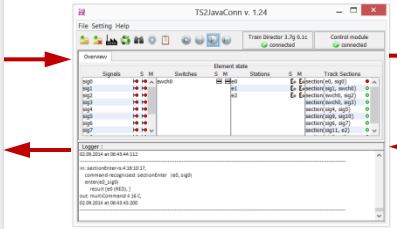
- getters
  - signals, switches, (sections)
- methods responding to events from TD
    - requestEnter
    - requestGreen
    - sectionLeave
    - sectionEnter

TD/TS2JC: How it works

Train Director



TS2JavaConn

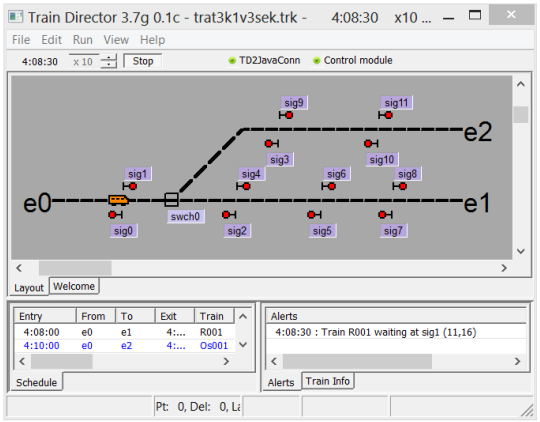


Control module

```
public class Controller3way3secTr {
…
 public Controller3way3secTr() {
this.trN = new CntrlSimpleTrack(1);
this.trD = new CntrlSimpleTrack(2);
this.trS = new CntrlSimpleTrack(3);
this.cntrl3waytrack = new
Cntrl3WayTrack();   }
…
```

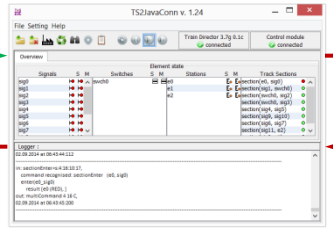
TD/TS2JC: How it works

Train Director



requestGreen
sig1, e1, R001

TS2JavaConn



Control module

```
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…
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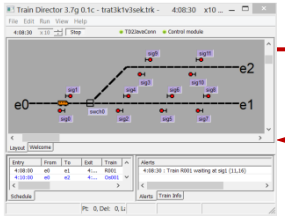
this.trN = new CntrlSimpleTrack(1);
this.trD = new CntrlSimpleTrack(2);
this.trS = new CntrlSimpleTrack(3);
this.cntrl3waytrack = new
Cntrl3WayTrack();   }
…
```

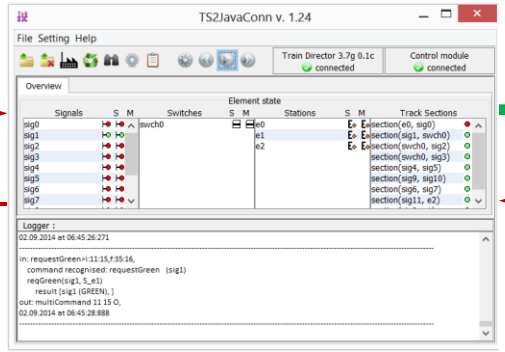
TD/TS2JC: How it works

TS2JavaConn

Train Director



requestGreen
sig1, e1, R001



reqGreen(sig1,S_e1)

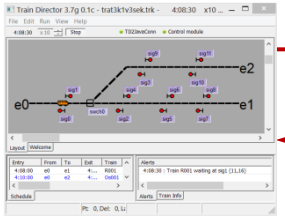
Control module

```
public class Controller3way3secTr {
…
 public Controller3way3secTr() {
this.trN = new CntrlSimpleTrack(1);
this.trD = new CntrlSimpleTrack(2);
this.trS = new CntrlSimpleTrack(3);
this.cntrl3waytrack = new
Cntrl3WayTrack();   }
…
```

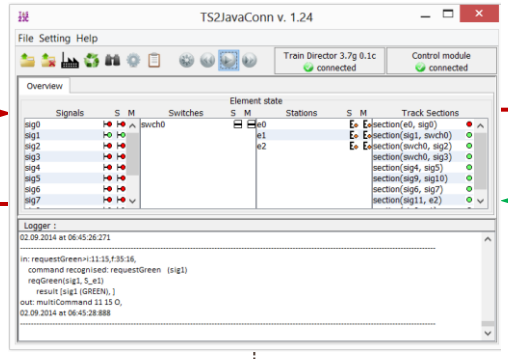
```
entryIndexStationName=S_%name%
requestGreen=reqGreen
requestGreenParams=%SIGNALS%,%STATIONS.f%
```

TD/TS2JC: How it works

Train Director



TS2JavaConn



reqGreen(sig1,S_e1)

1←getSig(sig1)

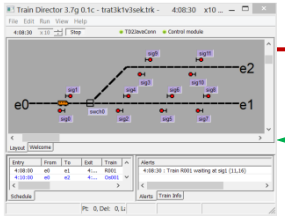
Control module

```
public class Controller3way3secTr {
…
public Integer
getSig(Controller3way3secTr.SIGNALS sg)
…
public Integer
getSwch(Controller3way3secTr.SWITCHES sw)
…
public void
reqGreen(Controller3way3secTr.SIGNALS sg_data,
Controller3way3secTr.STATIONS st) {
```

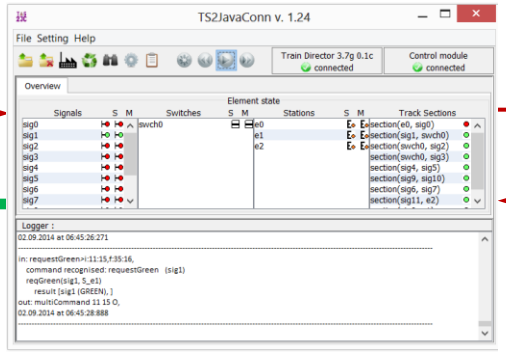
sigState=%int%
sigIndex=SIGNALS
getSignalNames=getSig
getSignalParams=%SIGNALS

TD/TS2JC: How it works

Train Director



TS2JavaConn



Control module

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this.trD = new CntrlSimpleTrack(2);
this.trS = new CntrlSimpleTrack(3);
this.cntrl3waytrack = new
Cntrl3WayTrack();   }
…
```

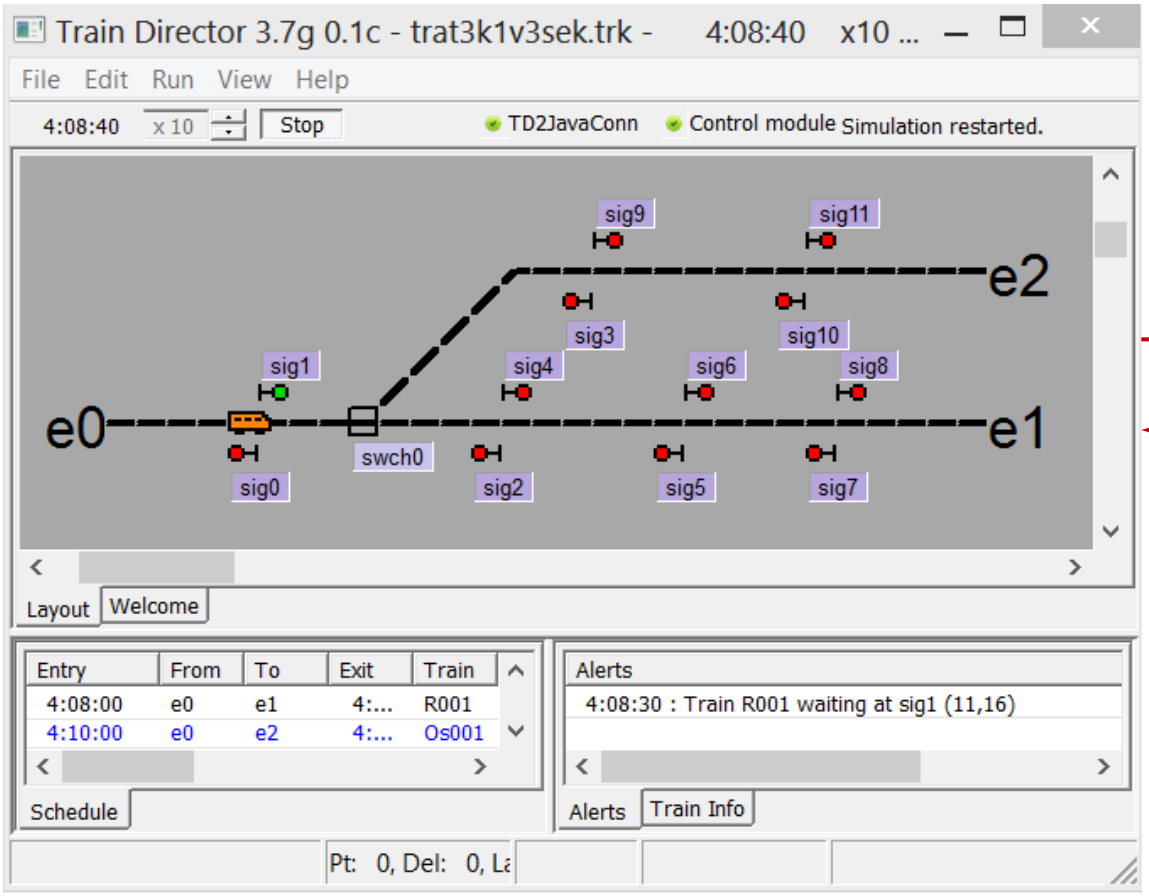
multiCommand
11 15 O

1←getSig(sig1)

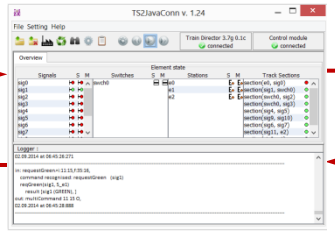
sigState=%int%
signalGreenState=1
sigIndex=SIGNALS

TD/TS2JC: How it works

Train Director



TS2JavaConn



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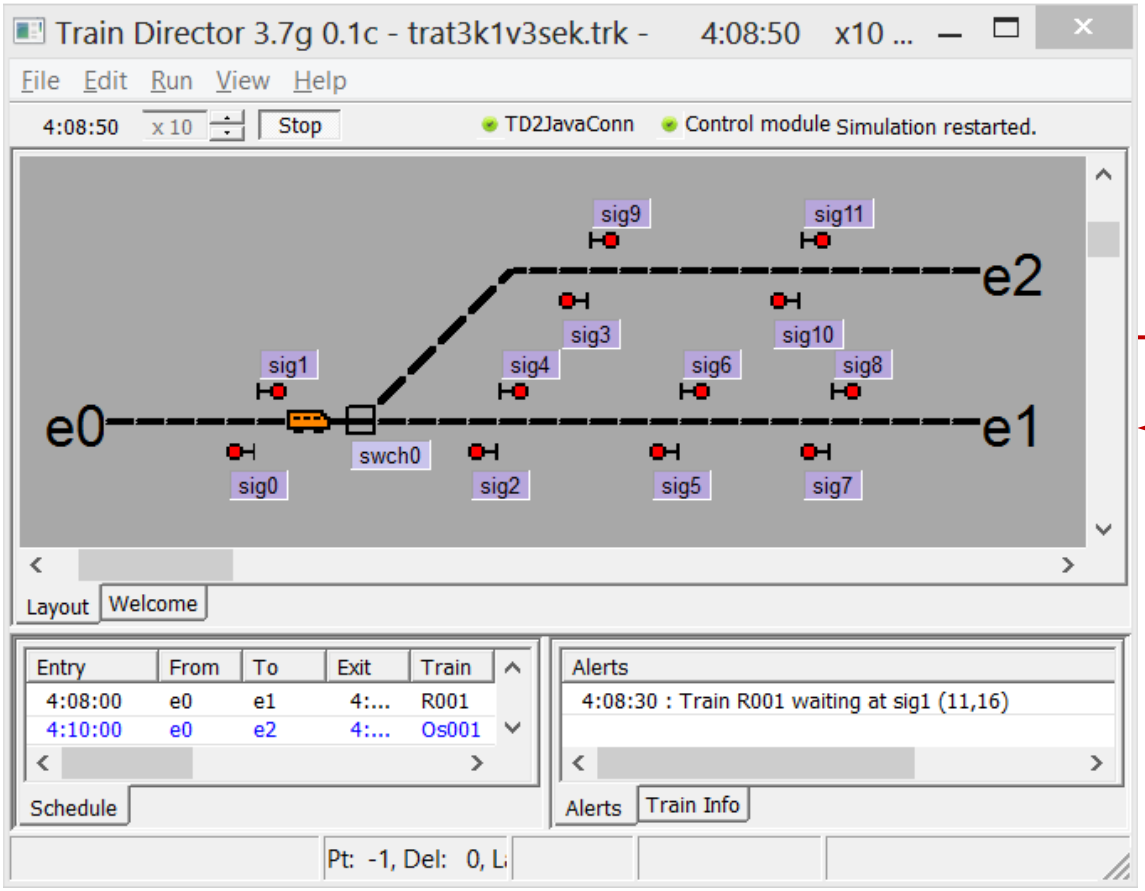
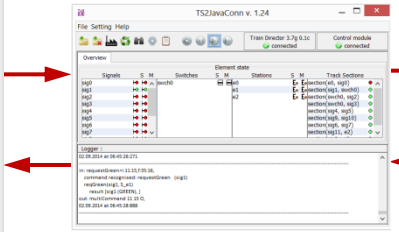
Cntrl3WayTrack();   }
…
```

TD/TS2JC: How it works

Train Director



TS2JavaConn



Control module

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…
 public Controller3way3secTr() {
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this.trD = new CntrlSimpleTrack(2);
this.trS = new CntrlSimpleTrack(3);
this.cntrl3waytrack = new
Cntrl3WayTrack();   }
…
```

More on TS2JavaConn / TD / OR

- Korečko, Š., Sorád, J. (2014). Using simulation games in teaching formal methods for software development. *Innovative Teaching Strategies and New Learning Paradigms in Computer Programming*, in Innovative Teaching Strategies and New Learning Paradigms in Computer Programming, R. Queirós, Ed., IGI Global, 2015, pp. 106–130.
  (draft version available **here**).

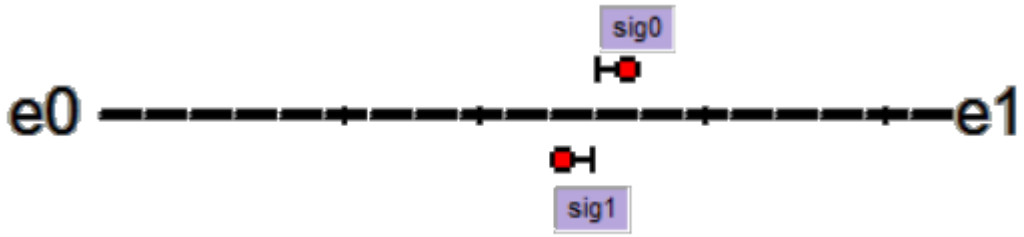
- Korečko, Š., Sorád, J., Dudláková, Z., Sobota, B. (2014, September). A toolset for support of teaching formal software development.
  In *International Conference on Software Engineering and Formal Methods* (pp. 278-283). Springer

- Korečko, Š., Sobota, B. (2017). Computer Games as Virtual Environments for Safety-Critical Software Validation. *Journal of Information and Organizational Sciences*, *41*(2), 197-212.

Our scenarios

EXAMPLES

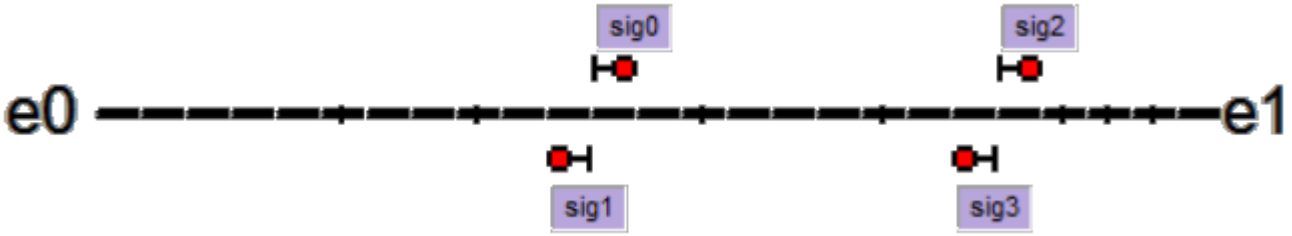
- route2sec and route2sec_deadlck




```
|-- e0_sig1 ------||- sig0_e1 --|
```

PRACTICE

- route3sec and route3sec_deadlck




```
|-- e0_sig1 -------||- sig0_sig3-||sig2_e1|
```

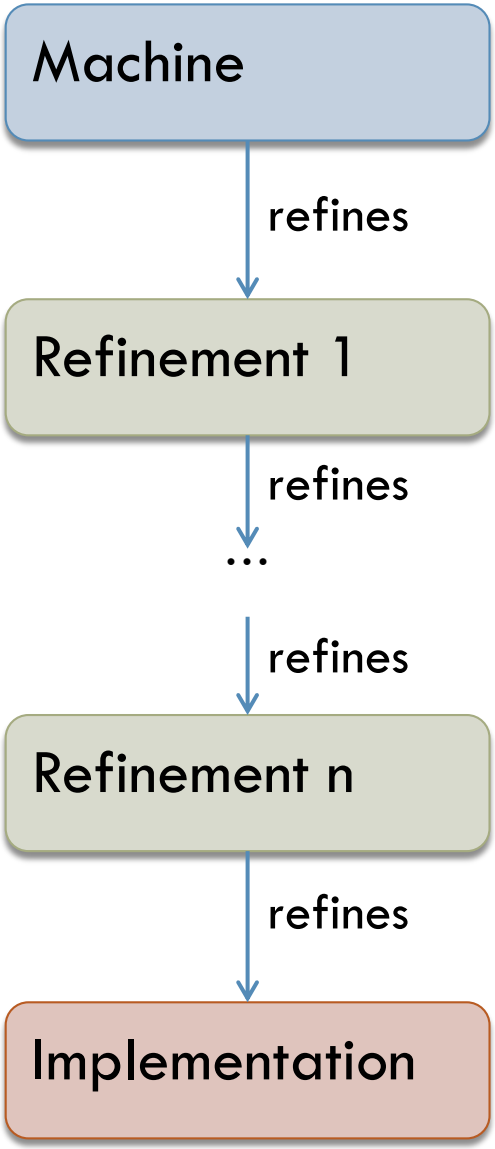
Formal Specification and Verification in B-Method

Development process

B-language

B-machine

Development in B-method



B-language

- Expressions and Predicates
  - mathematical notation
  - based on first-order logic and Zermelo-Fraenkel set theory
- Operations
  - Generalized Substitution Language (GSL)
  - based on E.W. Dijkstra's Guarded commands and Weakest Precondition Calculus
- Documentation supplied with Atelier-B
  - **B Language Reference** Manual
    - Detailed description
  - B Lanugage Keywords and Operators (**B Symbols**)
    - ASCII vs. mathematical notation

GS :: Syntax

GS	meaning of GS
skip	Empty GS (do nothing).
x := e	Assignment of value of expression e to variable x.
S_1 ; S_2	Sequential composition (do GS S_1, then GS S_2).
S_1 || S_2	Parallel composition (do S_1 and S_2 at once).
PRE E THEN S_1 END	If predicate E holds, do S_1. Otherwise, do anything.
SELECT E THEN S_1 END	If E holds, do S_1. Otherwise, do not execute.
IF E THEN S_1 ELSE S_2 END	If E holds, do S_1. Otherwise, do S_2.

(selected)

GS :: Semantics

[skip]P	= P
[x := e]P	= P[x:=e]
[PRE E THEN S END]P	= E & [S]P
[SELECT E THEN S END]P	= E => [S]P
[S_1 ; S_2]P	= [S_1][S_2]P
[IF E THEN S_1 ELSE S_2 END]P	= (E => [S_1]P) & (not(E) => [S_2]P)

(selected)

GS :: Semantics of Simultaneous Substitution

skip || T	= T	
x := E || y := F	= x, y := E, F	
(PRE P THEN S END) || T	= PRE P THEN S || T END	
(SELECT E THEN S END) || T	= SELECT E THEN S || T END	(*)
(IF E THEN S_1 ELSE S_2 END) || T	= IF E THEN S_1 || T ELSE S_2 || T END	(**)

(*) holds if S always terminates.
(*) holds if S_1 and S_2 always terminate.

(selected)

B-machine :: Syntax

```
MACHINE M(p)
CONSTRAINTS C
SETS St
CONSTANTS k
PROPERTIES Bh
VARIABLES v
DEFINITIONS D
INVARIANT I
INITIALISATION T
OPERATIONS
  y←op(x) =
   PRE P THEN S END
  …
END
```

- VARIABLES is ABSTRACT_VARIABLES
  - we can also have CONCRETE_VARIABLES
- CONSTANTS is CONCRETE_CONSTANTS
  - we can also have ABSTRACT_CONSTANTS

Example 1: B-machine route2sec

MACHINE route2sec

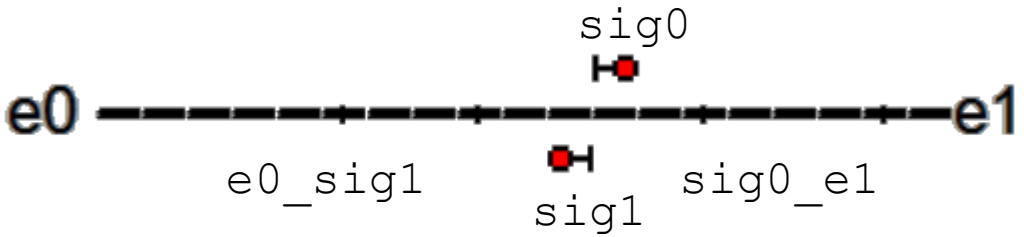
```
SETS
    PROP_SIGNAL={green, red};
    PROP_SECTION={free,occup}

CONCRETE_VARIABLES
    e0, e1, /*entry points*/
    sig0, sig1, /*signals*/
    e0_sig1, sig0_e1 /*track sections*/

INVARIANT
   e0:PROP_SIGNAL & e1:PROP_SIGNAL &
   ...
   & (e0=green => sig1=red)
   & (sig1=green => e0=red)
   & (e1=green => sig0=red)
   & (sig0=green => e1=red)
   & (e0=green   => e0_sig1=free)
   ...
```

```
INITIALISATION
    e0:=red || ... sig1:=red ||...
    e0_sig1:= free || sig0_e1:= free

OPERATIONS
    ss <-- getSig_sig0 = BEGIN ss:=sig0
END;
    ...
    reqGreen_e0 =
       IF sig1=red & e0_sig1=free
       THEN e0:=green END;
enterNI_e0_sig1 =
        BEGIN e0_sig1:=occup || e0:=red ||
        sig1:=red END;
     leaveNI_e0_sig1 =
        BEGIN e0_sig1:=free  END;
END
```



B-machine :: Proof Obligations

```
MACHINE M(p)
CONSTRAINTS C
SETS St
CONSTANTS k
PROPERTIES Bh
VARIABLES v
DEFINITIONS D
INVARIANT I
INITIALISATION T
OPERATIONS
  y←op(x) =
   PRE P THEN S END
  …
END
```

- Initialisation establishes the invariant
  - $(C \,\&\, Bh) \Rightarrow [T]\, I$
- Each operation preserves the invariant
  - $(C \,\&\, Bh \,\&\, I \,\&\, P) \Rightarrow [S]\, I$

(selected, simplified)

Example 2: Machine Verification

Invariant preservation by **reqGreen_e0**

MACHINE route2sec
...
CONCRETE_VARIABLES e0, sig1, e0_sig1 ...

INVARIANT
...
e0=green => e0_sig1=free
...
INITIALISATION
e0:=red || ... sig1:=red ||...

OPERATIONS
...
reqGreen_e0 =
IF sig1=red & e0_sig1=free
THEN e0:=green END;

(demonstrated only for the shown part of the invariant)

Example 2: Machine Verification

Invariant preservation by **reqGreen_e0**

(e0=green => e0_sig1=free) =>
[IF sig1=red & e0_sig1=free
THEN e0:=green END]
(e0=green => e0_sig1=free)

(C & Bh & I & P) =>[S] I

(I & P) =>[S] I

MACHINE route2sec
...
CONCRETE_VARIABLES e0, sig1, e0_sig1 ...

INVARIANT
...
e0=green => e0_sig1=free
...
INITIALISATION
e0:=red || ... sig1:=red ||...

OPERATIONS
...
reqGreen_e0 =
IF sig1=red & e0_sig1=free
THEN e0:=green END;

(demonstrated only for the shown part of the invariant)

Example 2: Machine Verification

Invariant preservation by **reqGreen_e0**

(e0=green => e0_sig1=free) =>
[IF sig1=red & e0_sig1=free
THEN e0:=green END]
(e0=green => e0_sig1=free)

(e0=green => e0_sig1=free) =>(
((sig1=red & e0_sig1=free) =>
[e0:=green] (e0=green => e0_sig1=free))
&
((not(sig1=red & e0_sig1=free) =>
[skip] (e0=green => e0_sig1=free))
)

MACHINE route2sec
...
CONCRETE_VARIABLES e0, sig1, e0_sig1 ...

INVARIANT
...
e0=green => e0_sig1=free
...
INITIALISATION
e0:=red || ... sig1:=red ||...

OPERATIONS
...
reqGreen_e0 =
IF sig1=red & e0_sig1=free
THEN e0:=green END;

[IF E THEN S1 ELSE S2 END]P=
(E => [S1]P) & (not(E) => [S2]P)

(demonstrated only for the shown part of the invariant)

Example 2: Machine Verification

Invariant preservation by **reqGreen_e0**

(e0=green => e0_sig1=free) =>
[IF sig1=red & e0_sig1=free
THEN e0:=green END]
(e0=green => e0_sig1=free)

(e0=green => e0_sig1=free) =>(
((sig1=red & e0_sig1=free) =>
[e0:=green] (e0=green => e0_sig1=free))
&
((not(sig1=red & e0_sig1=free) =>
[skip] (e0=green => e0_sig1=free))
)

[x := e]P = P[x:=e]
[skip]P = P

(e0=green => e0_sig1=free) =>(
((sig1=red & e0_sig1=free) =>
(green =green => e0_sig1=free))
&
((not(sig1=red & e0_sig1=free) =>
(e0=green => e0_sig1=free))
)

(demonstrated only for the shown part of the invariant)

Example 2: Machine Verification

Invariant preservation by **reqGreen_e0**

```
( a => (b & c)) <=> ((a =>b) & (a =>c))
(true => b) <=> b
(a => (b=>c)) <=>(( a & b) =>c)
```

```
(e0=green  => e0_sig1=free) =>(
 ((sig1=red & e0_sig1=free) =>
  [ e0:=green ] (e0=green   => e0_sig1=free))
 &
 ((not(sig1=red & e0_sig1=free) =>
  [skip] (e0=green   => e0_sig1=free))
)
```

```
(e0=green  => e0_sig1=free) =>(
 ((sig1=red & e0_sig1=free) =>
  (green =green   => e0_sig1=free))
 &
 ((not(sig1=red & e0_sig1=free) =>
  (e0=green   => e0_sig1=free))
)
```

```
( (e0=green  => e0_sig1=free) =>
   ((sig1=red & e0_sig1=free) =>
    (e0_sig1=free))
)
&
( ((e0=green  => e0_sig1=free) &
  not(sig1=red & e0_sig1=free)) =>
    (e0=green   => e0_sig1=free)
)
```

(demonstrated only for the shown part of the invariant)

Example 2: Machine Verification

Invariant preservation by **reqGreen_e0**

```
( (e0=green  => e0_sig1=free) =>
    true
)
&
true
```

(a & b) =>b

```
( (e0=green  => e0_sig1=free) =>
   ((sig1=red & e0_sig1=free) =>
    (e0_sig1=free))
)
&
( ((e0=green  => e0_sig1=free) &
  not(sig1=red & e0_sig1=free)) =>
    (e0=green   => e0_sig1=free)
)
```

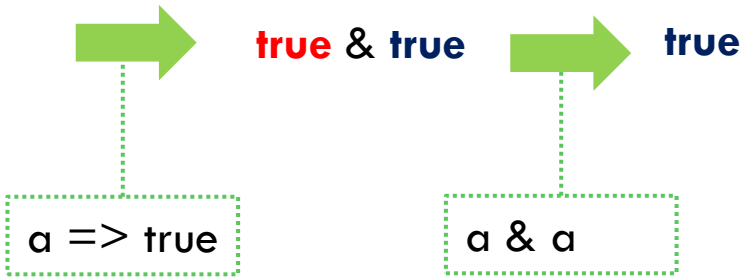
```
(e0=green  => e0_sig1=free) =>(
 ((sig1=red & e0_sig1=free) =>
  (green =green   => e0_sig1=free))
 &
 ((not(sig1=red & e0_sig1=free) =>
  (e0=green   => e0_sig1=free))
)
```

(demonstrated only for the shown part of the invariant)

Example 2: Machine Verification

Invariant preservation by **reqGreen_e0**

```
( (e0=green  => e0_sig1=free) =>
    true
)
&
true
```




```
( (e0=green  => e0_sig1=free) =>
   ((sig1=red & e0_sig1=free) =>
    (e0_sig1=free))
)
&
( ((e0=green  => e0_sig1=free) &
  not(sig1=red & e0_sig1=free)) =>
    (e0=green   => e0_sig1=free)
)
```

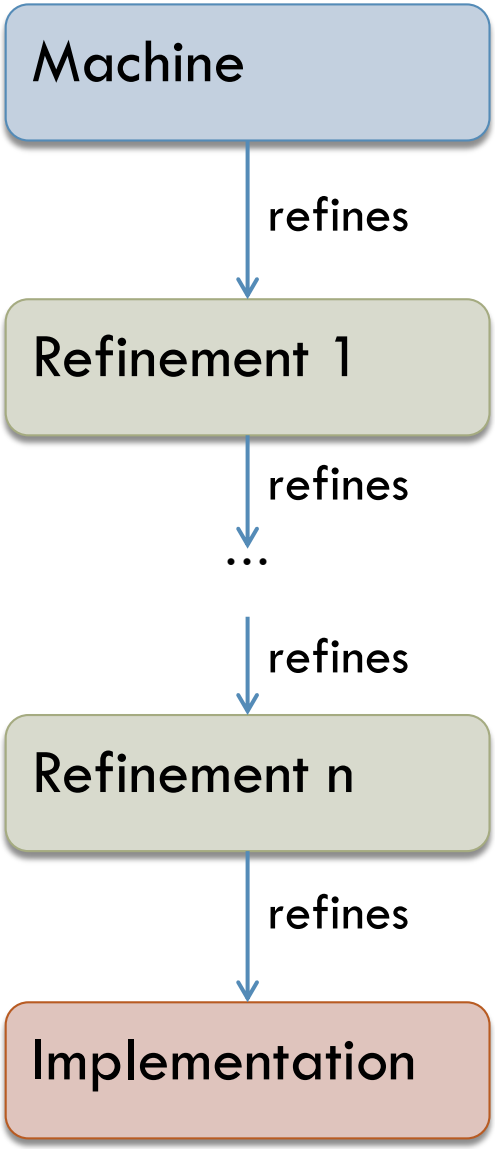
```
(e0=green  => e0_sig1=free) =>(
 ((sig1=red & e0_sig1=free) =>
  (green =green   => e0_sig1=free))
 &
 ((not(sig1=red & e0_sig1=free) =>
  (e0=green   => e0_sig1=free))
)
```

(demonstrated only for the shown part of the invariant)

Verified Refinement

- Implementation
- GS allowed in components
- Refinement proof obligations

From machine to Implementation



From machine to Implementation

```
MACHINE M(p)
CONSTRAINTS C
SETS St
CONSTANTS k
PROPERTIES Bh
VARIABLES v
DEFINITIONS D
INVARIANT I
INITIALISATION T
OPERATIONS
  y←op(x) =
   PRE P THEN S END
  …
END
```

refines

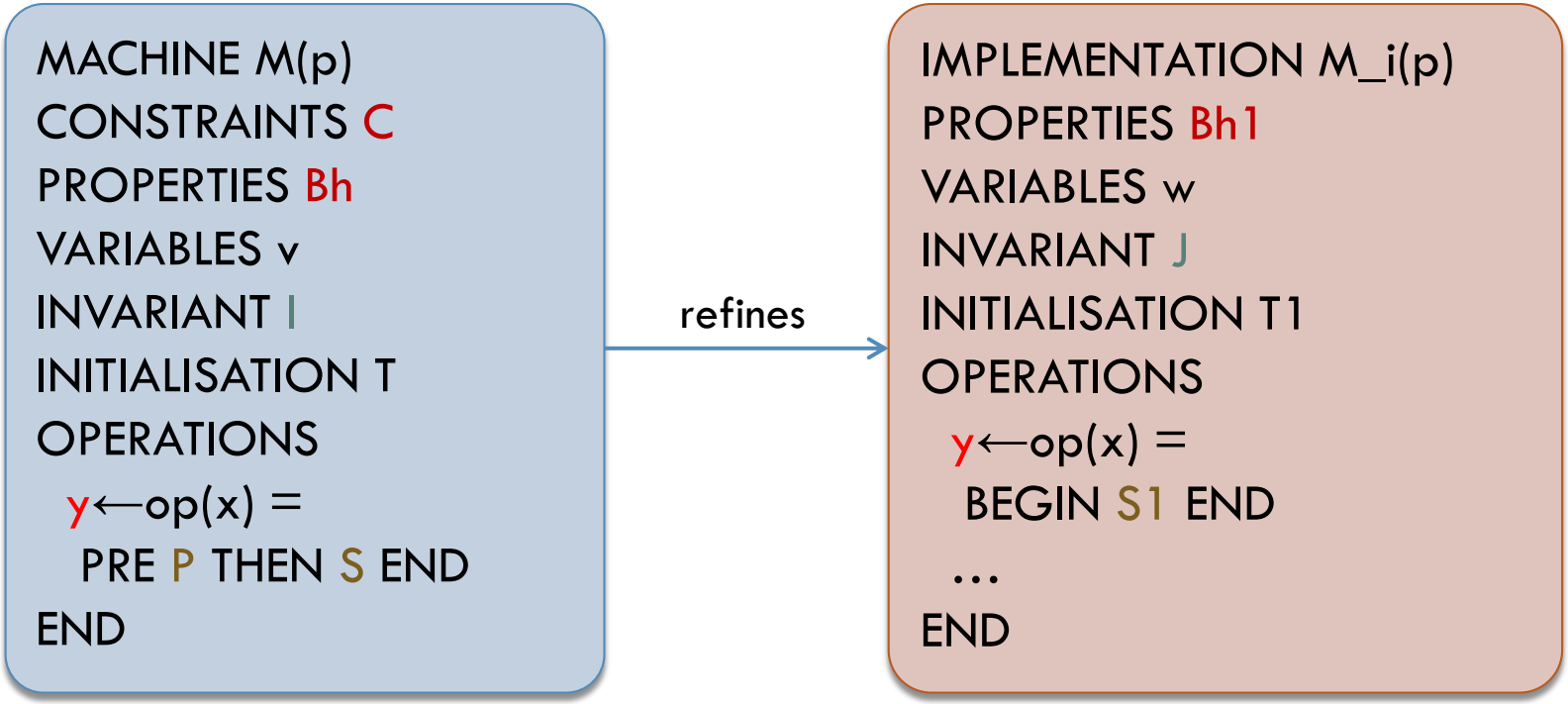
```
IMPLEMENTATION M_i(p)
REFINES M
SETS St1
CONCRETE_CONSTANTS k1
VALUES Vk1
PROPERTIES Bh1
VARIABLES w
DEFINITIONS D1
INVARIANT J
INITIALISATION T1
OPERATIONS
  y←op(x) =
   BEGIN S1 END
  …
END
```

GS in components

GS	Machine	Refinement	Implementation
skip	yes	yes	yes
x := e	yes	yes	yes
S_1 ; S_2	no	yes	yes
S_1 || S_2	yes	yes	no
PRE E THEN S_1 END	yes	yes	no
SELECT E THEN S_1 END	yes	yes	no
IF E THEN S_1 ELSE S_2 END	yes	yes	yes
WHILE E DO S … END	no	no	yes

(selected)

Refinement Proof Obligations



- Initialisation establishes the invariant
  - (C & Bh & Bh1) =>[T1] (not([T] not(J)))
- Each operation preserves the invariant
  - (C & Bh & Bh1 & I & J & P) =>[S1'](not([S] not(J ∧ y'=y)))

(selected, simplified)

Example 3: Machine Refinement

`route2sec.mch` **refines to** `route2sec_i.imp`.

MACHINE route2sec

SETS
PROP_SIGNAL={green, red};
PROP_SECTION={free,occup}

CONCRETE_VARIABLES
e0, e1, ...

INVARIANT
e0:PROP_SIGNAL & e1:PROP_SIGNAL &
...
INITIALISATION
e0:=red || ... sig1:=red ||...

OPERATIONS
ss <-- getSig_sig0 = BEGIN ss:=sig0
END;
...
reqGreen_e0 =
IF sig1=red & e0_sig1=free
THEN e0:=green END;

refines

IMPLEMENTATION route2sec_i

REFINES route2sec

INITIALISATION
e0:=red ; ... sig1:=red ; ...

OPERATIONS
ss <-- getSig_sig0 = BEGIN ss:=sig0
END;
...
reqGreen_e0 =
IF sig1=red & e0_sig1=free
THEN e0:=green END;

Practice

Downloads

Abstract Specification

Refinement

Code generation

Deployment

Downloads

- Tutorial package
  - http://hron.fei.tuke.sk/~korecko/cefp19/cefp19BmethodPack.zip
- Atelier B
  - http://www.atelierb.eu/en/download/
- Java JDK
  - http://www.oracle.com/technetwork/java/javase/downloads/index.html
- TS2JavaConn/TrainDirector Toolset
  - http://hron.fei.tuke.sk/~korecko/FMInGamesExp/resources/allInOneTDTS2J.zip

T.0: Set up Atelier B

1. Unpack the tutorial package to `C:/VSD`
   - http://hron.fei.tuke.sk/~korecko/cefp19/cefp19BmethodPack.zip
2. Run Atelier B
   - Don't mind the warning displayed
3. Create a new workspace
   - *Name*: `cefp19`
   - ***Workspace database directory*: `C:/VSD/bdb`**
4. Set the *Default project directory* to `C:/VSD/Bprojects`

T.1: Atelier B project for route2sec

1. Run Atelier B.
2. Create a new project called `route2sec`.
   - type: software development
3. In *Project – Properties – software development* set *Generator* to *Legacy*.
4. To the project, add the components
   - `C:/VSD/Bprojects/route2sec.mch` and
   - `C:/VSD/Bprojects/route2sec_i.imp`
5. Check and prove both components.

T.2: From .imp to .java with BKPICompiler

1. Run BKPICompiler
   - `C:/VSD/BKPICompiler/BKPIcompiler.jar`
2. Right click on `route2sec` and choose *Generate Java code*
3. Delete `MainClass.java`
4. Compile `route2sec.java`
   - Just run `compile.bat`
   - Alternatively, you can use an online compiler
     - e.g. https://www.compilejava.net/

T.3: route2sec in TD/TS2JC

1. Run *Train Director*
   - `C:/VSD/TrainDirector/traindir3.exe`
   - If it doesn't show up, , go to is *Properties* and set it to run in the *Windows 7 compatibility mode*

1. In Train Director, open the file `C:/VSD/scenarios/route2sec.trk`

2. Run *TS2JavaConn*
   - `C:/VSD/TS2JavaConn/TS2JavaConn.jar`

3. In TS2JavaConn, load the module `C:/VSD/Bprojects/route2sec/java/route2sec.class`

4. Start the simulation (in TD or TS2JC).

T.4: Machine Specification for route3sec

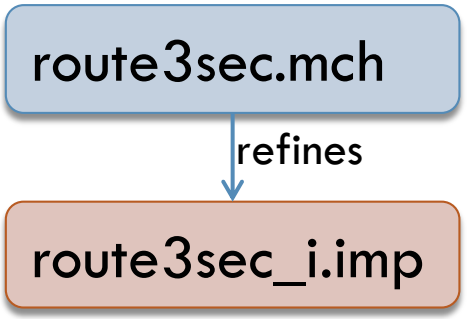
1. In Atelier B, create a new project called `route3sec` and add `route3sec.mch` to it.
   - In the same way as route2sec (T.1)
2. Finish `route3sec.mch` according to the TODO comments inside it.
3. Prove `route3sec.mch`.

route3sec.mch

T.5: route3sec Machine Refinement

1. In the project `route3sec` in Atelier B, create a new implementation component called `route3sec_i.imp`
2. Write code to `route3sec_i.imp`.
   - Hint: copy the code from `route3sec.mch` and modify it.
3. Verify `route3sec_i.imp`.
4. Translate `route3sec` to Java with the BKPI Compiler
5. Compile `route3sec.java`
6. Try the compiled module with TD/TS2JC
   - TD scenario is `C:/VSD/scenarios/route3sec.trk`

(In the same way as route2sec (T.2, T.3)



T.6 (optional): Deadlock Free route3sec

1. Specify and verify a deadlock free version of the previous controller for the scenario `route3sec_deadlck`.
   - Don't forget to add additional safety properties

2. Refine it to an implementation and verify the implementation.

3. Compile the implementation with BKPI Compiler and try with TrainDirector/TS2JavaConn

Thanks … and fill in the questionnaire

- Thank you for your participation.
  - I hope you enjoyed it.

- Please, fill in the questionnaire
  - https://drive.google.com/open?id=19jpdtR0PS-Mkq1x5_U1EfVaPGZivjNyBq4t0FVcpWHQ