New Ways of Using Formal Models in Industry

Michael Leuschel

Overview

- Part 1: Overview of 25 years of history of B
  - taken from FMICS 2020 article with Michael Butler, Philipp Körner, Sebastian Krings, Thierry Lecomte, Luis-Fernando Mejia, Laurent Voisin entitled “The First Twenty-Five Years of Industrial Use of the B-Method”
- Part 2: Commandments and Lessons using B and building tools for B, Z, and other formal methods (mainly the tool ProB https://prob.hhu.de) inspired by Bowen, Hall, Hinchey

Part 1: History

Formal Methods

- Mathematical techniques to produce correct software and systems
- Highly recommended e.g. for SIL3/SIL4 railway applications (CENELEC)
- Some Benefits: Problems detected earlier and correction less costly, lower level testing (unit) not required as SW execution errors proven impossible

B Formal Method

Specification

Tool Support

Refinement

Origins of B

- Train protection system SACEM for Paris RER Line A
  - put into operation in 1988, sketch of the B-Method by Jean-Raymond Abrial
- 1989 project by Alstom, RATP, SNCF to develop tools and train engineers
- Paris Metro Line 14 contract won by Matra Transport (now Siemens Transportation Systems)
  - **1995**: B tools industrialised by Digilog (then Steria, now CLEARSY) leading to Atelier-B
  - ready by end 1998:110 kLOC B model,
    83% automatic proof, 86 kLOC Ada
  - Still in version 1.0, no single issue caused by software

B Logical Foundations

- Typed first-order **predicate logic** with equality
  - Well-Definedness Conditions to stay in two-valued logic
- **Arithmetic** over mathematical integers and implementable integers
- **Set theory**
  - Sets, Relations, Functions, Sequences
  - including higher-order functions
- B is simpler than its predecessor Z
- and provides structuring and refinement for proving and code generation

related state-based formal methods:
Z, TLA+, Alloy, VDM, ASM

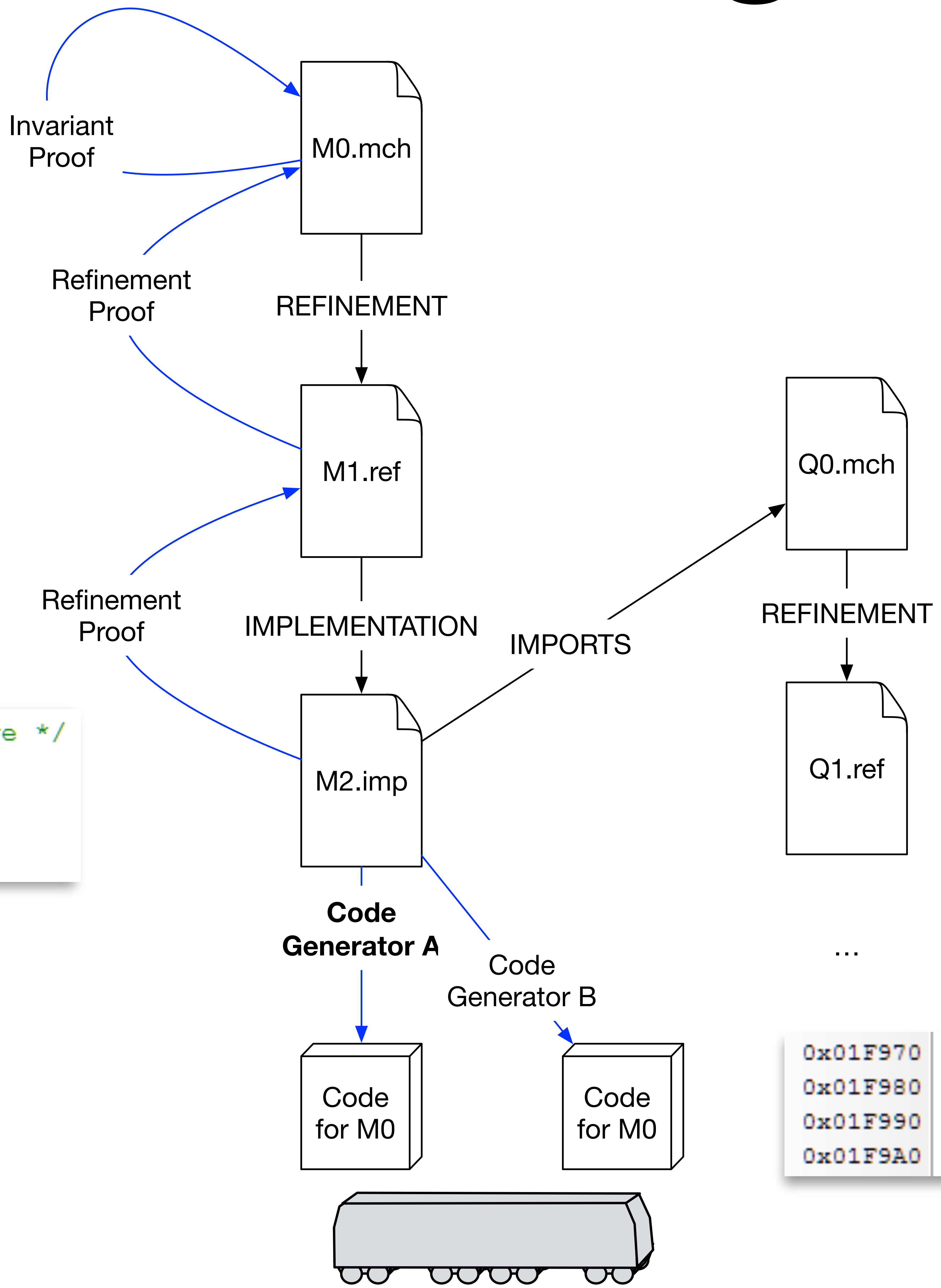
$$p \in \mathrm{dom}(a) \rightarrowtail \mathrm{dom}(a) \land \forall i \cdot (i \in 1..(\mathrm{size}(a)-1) \Rightarrow p(a(i)) < p(a(i+1)))$$

B Structuring

- Enables **decomposing** a specification
- Ensures that code generated for a B machine can be safely re-used
- Ensures **tractable proof** obligations
- Some key concepts:
  - VARIABLES vs CONSTANTS and associated INVARIANTS and PROPERTIES
  - OPERATIONS to modify variable values
  - Various B machine structuring mechanisms (INCLUDES, USES, SEES, …)
  - REFINEMENT and IMPLEMENTATION machines

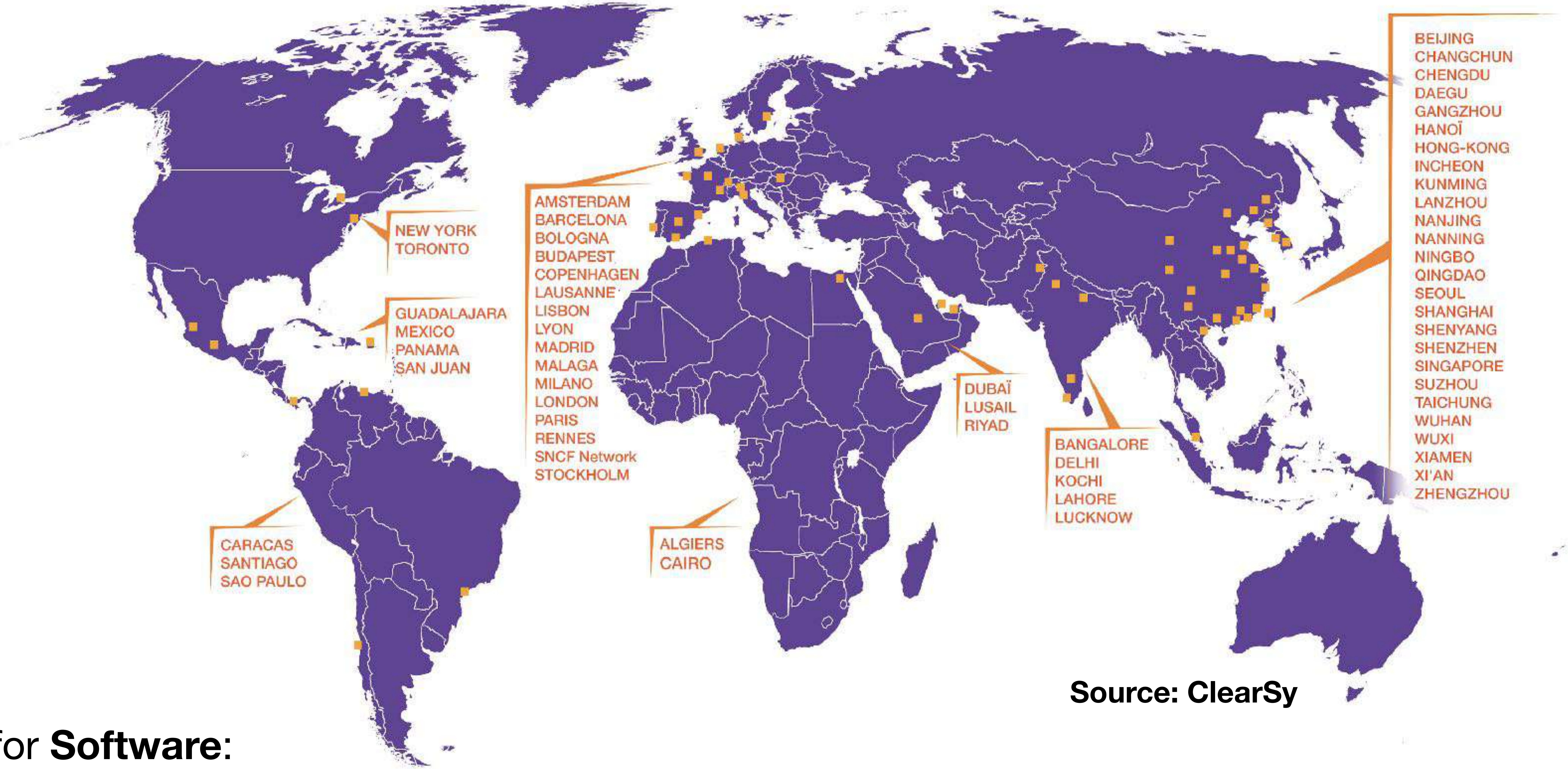
B Structuring

```
activation_sequence = /* Activation d'une séquence non active */
PRE ¬(sequences = sequences_actives) THEN
    ANY sequ WHERE
        sequ ∈ sequences - sequences_actives
    THEN
        sequences_actives := sequences_actives ∪ {sequ}
    END
END;
```




```
activation_sequence = /* Activation d'une séquence non active */
VAR sequ IN
    sequ <-- indexSequenceInactive;
    activeSequence(sequ)
END;
```

0x01F970	FFFF	8B4C	2440	89C5	8D7D	0C8B	4110	89CE
0x01F980	83C6	0C8D	1485	0000	0000	8D42	0883	F807
0x01F990	7617	F7C7	0400	0000	740F	8B41	0C8D	7D10
0x01F9A0	83C6	0489	450C	8D42	04FC	89C1	C1E9	02F3



Source: ClearSy

- B for **Software**:
  - about 30% of CBTC systems worldwide employ the B formal method
  - Urbalis 400, Alstom, over 100 metro lines worldwide, 25% of worldwide CBTC market

FM Success Story

One citation

- “Beyond the technological challenge of using such a complex formal method in an industrial context, it is now clear for us that building software using **B is not more expensive** than using conventional methods. Better, due to our experience in using this method, we can assert that using **B is cheaper when considering the whole development process** (from specification to validation and sometimes certification)”

- From: Didier Essamé, Daniel Dollé: B in Large-Scale Projects: The Canarsie Line CBTC Experience. In: LNCS Vol. 4355, Springer.

B for System Modelling

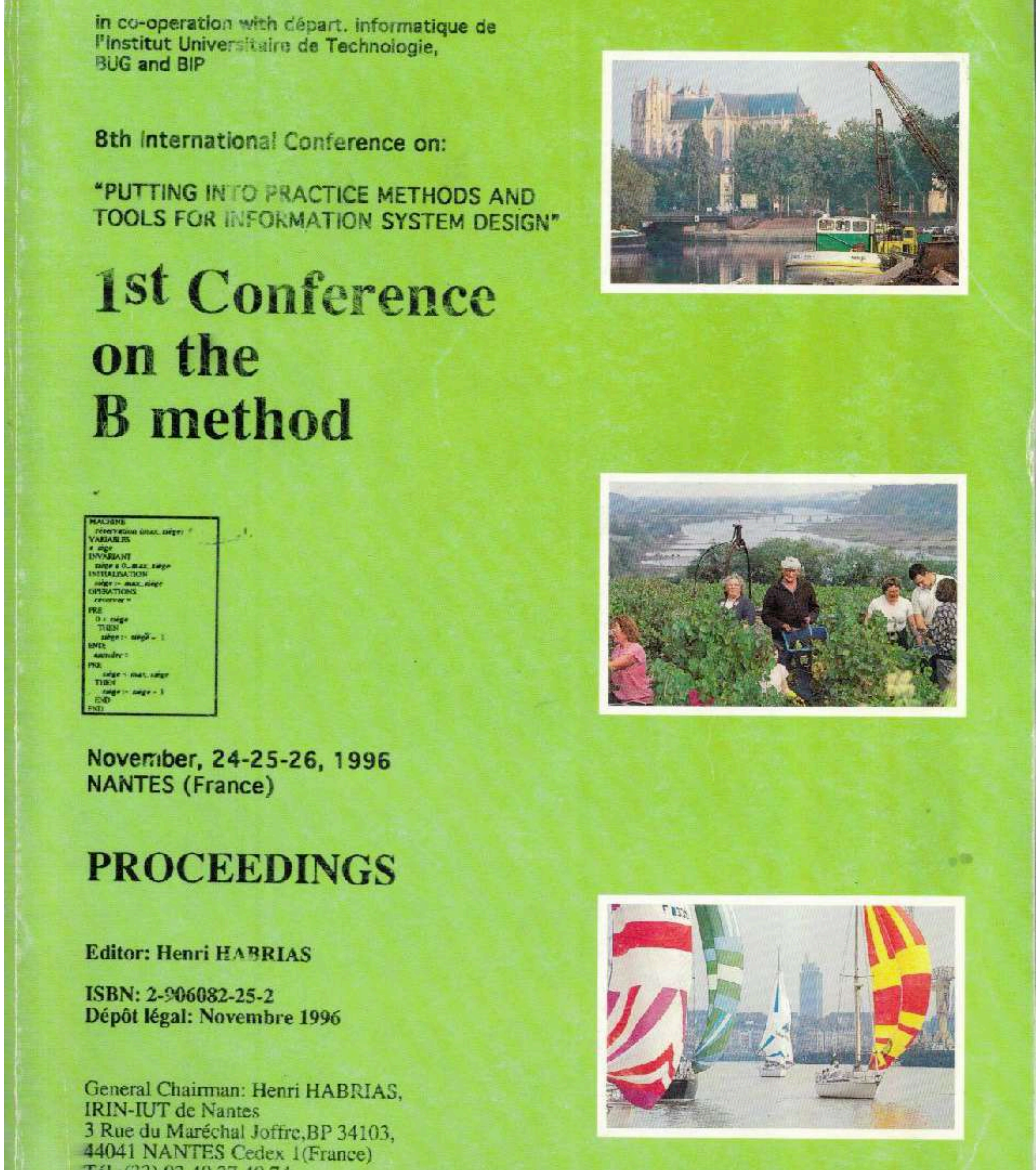
Event-B for System Modelling

- Analyse an entire system of components
- Ensure that together they ensure safety (and functionality)
- Talks about **events** rather than **operations**
- Refinement
  - used to structure reasoning, view a system at different levels of granularity
  - requires a more liberal view of refinement

First paper
on Event-B
already published
by Abrial in 1996

Session 6: Chairman, M. Frappier (Univ. de Sherbrooke, Canada)

10h15 *Extending B without Changing it (for Developing Distributed Systems)*
Invited speaker: Jean-Raymond Abrial (Consultant independant, Paris, F)


in co-operation with départ. informatique de l'Institut Universitaire de Technologie, BUG and BIP

8th International Conference on:

"PUTTING INTO PRACTICE METHODS AND TOOLS FOR INFORMATION SYSTEM DESIGN"

1st Conference on the B method

November, 24-25-26, 1996
NANTES (France)

PROCEEDINGS

Editor: Henri HABRIAS

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General Chairman: Henri HABRIAS,
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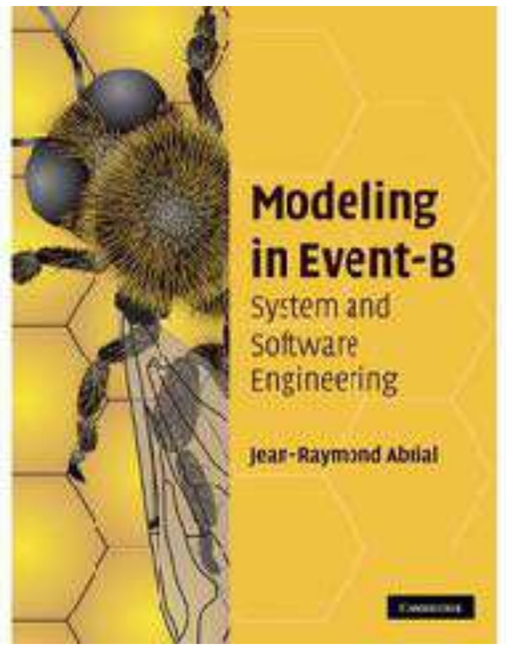
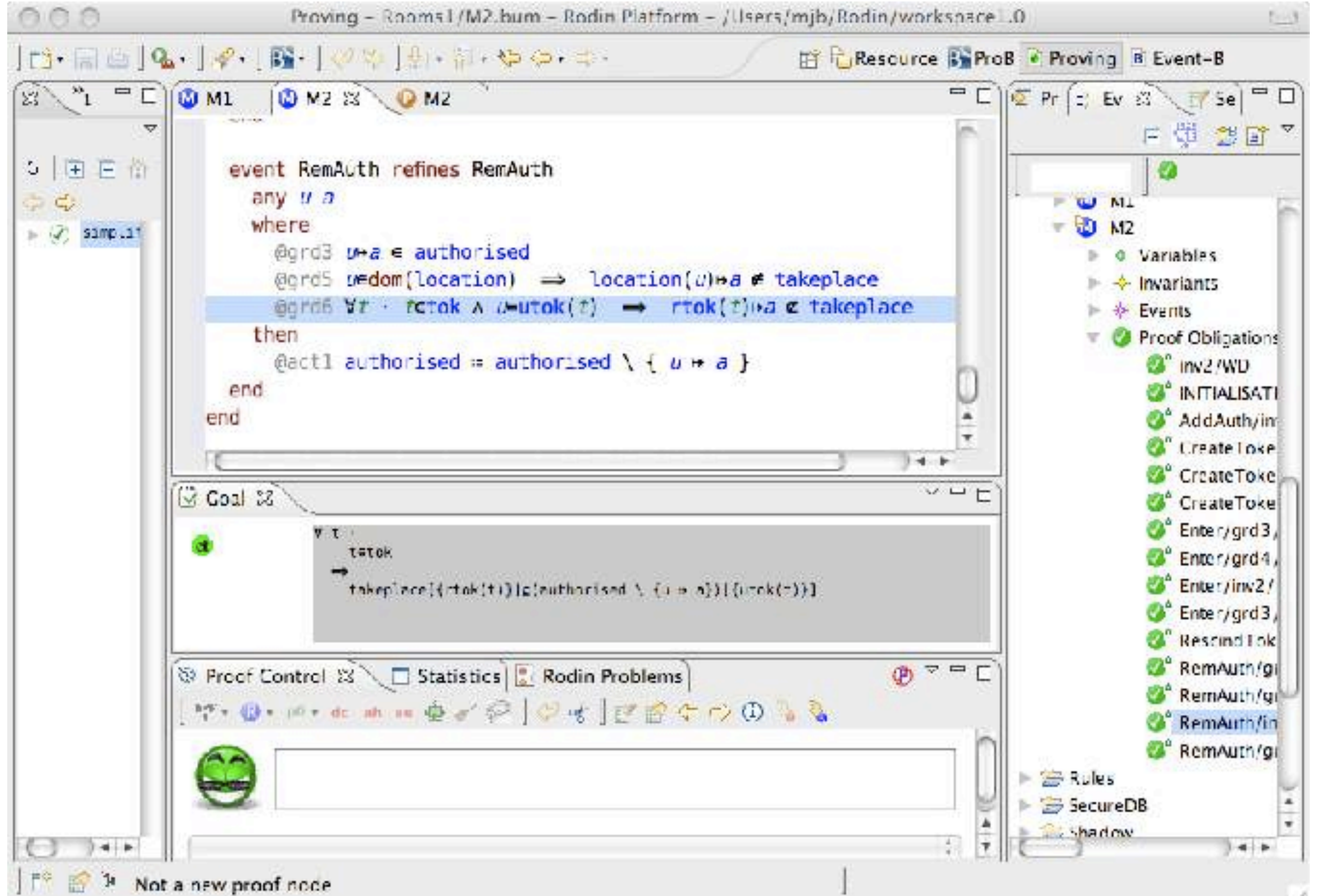
Foundations of Event-B



- Described in book “Modelling in Event-B” by Abrial (2010).
- Better proof automation thanks to simpler substitutions (aka statements) and proof obligations (witnesses, …)
- More expressive and flexible refinement
- Some changes to expressions and predicates
- Foundations realised in the Rodin platform



Tool Support for Event-B

- Rodin
  - Eclipse-based IDE for POG, proof, …
- Atelier B
  - also supports Event-B projects with POG and proof
- ProB
  - Multi-Level Animation, Visualization, Model Checking

CBTC models of ClearSy

- Thales Toronto installed CBTC system for NYC Subway Line 7
  - CBTC = Communication-based Train Control: automatic train control system using a combination of classical trackside train detection (TTD) and position reports sent by trains
  - ClearSy was asked to perform a **formal** verification of the **safety** of the system for Thales Toronto
    - from November 2010 until December 2012
    - ClearSy was using the Event-B along with the Atelier-B prover

http://www.tools.clearsy.com/resources/formal-proofs-for-the-nyct-line-7-modernization-project/

Summary of Results

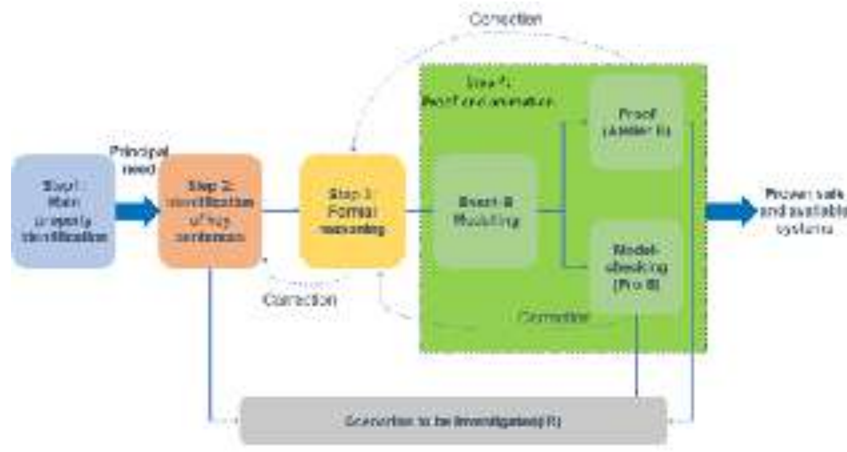
- CBTC system **safety** (no collision, no derailment, no overspeeding, correct tracking,…) **formally verified** with B and Atelier-B

- **Key properties** and knowledge extracted and put into the formal model

- Formal **model** was **reused** for NYCT I2S [Sabatier, RSSR16], similar analyses have since then been carried out (Octys CBTC by RATP [Comptier et al., RSSR17],…)

- Showed that a **large** industrial, safety-critical system could be effectively formally analysed and proven correct using Event-B

Alstom Zone Controller



- System analysis carried out in 2018 for a large software system (CBTC Zone Controller) by Alstom, ClearSy and University of Düsseldorf [Comptier et al., RSSR’19]
  - Software for this component generated using classical B
  - Analysis with Atelier B and ProB
  - Enabled to extract **key** safety **properties** which enable future evolution of the component

ETCS Hybrid Level 3

- Several formal methods case done of the ETCS Hybrid Level 3 (HL3) principles

- B Model and system developed by Thales and University of Düsseldorf

  - Identified over 50 issues in various versions of the HL3 specification

  - Formal model was used in **real-time** for field demonstration in December 2017 at ETCS National Integration Facility in Hitchin/UK, providing evidence that the HL3 principles are consistent and allow desired operational behaviour

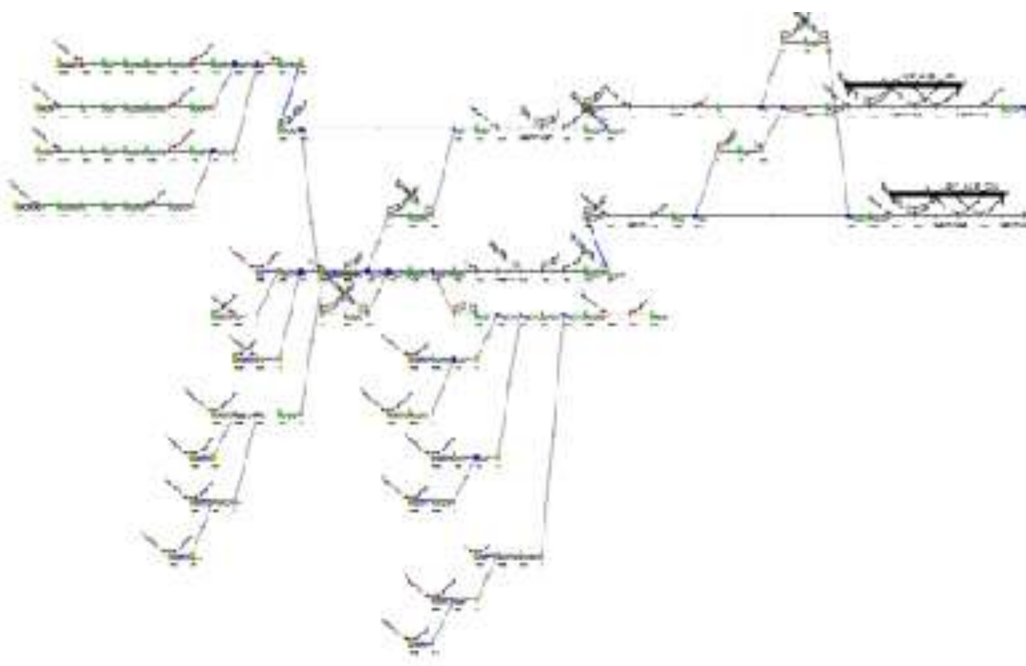
B for Data Validation

Data Validation

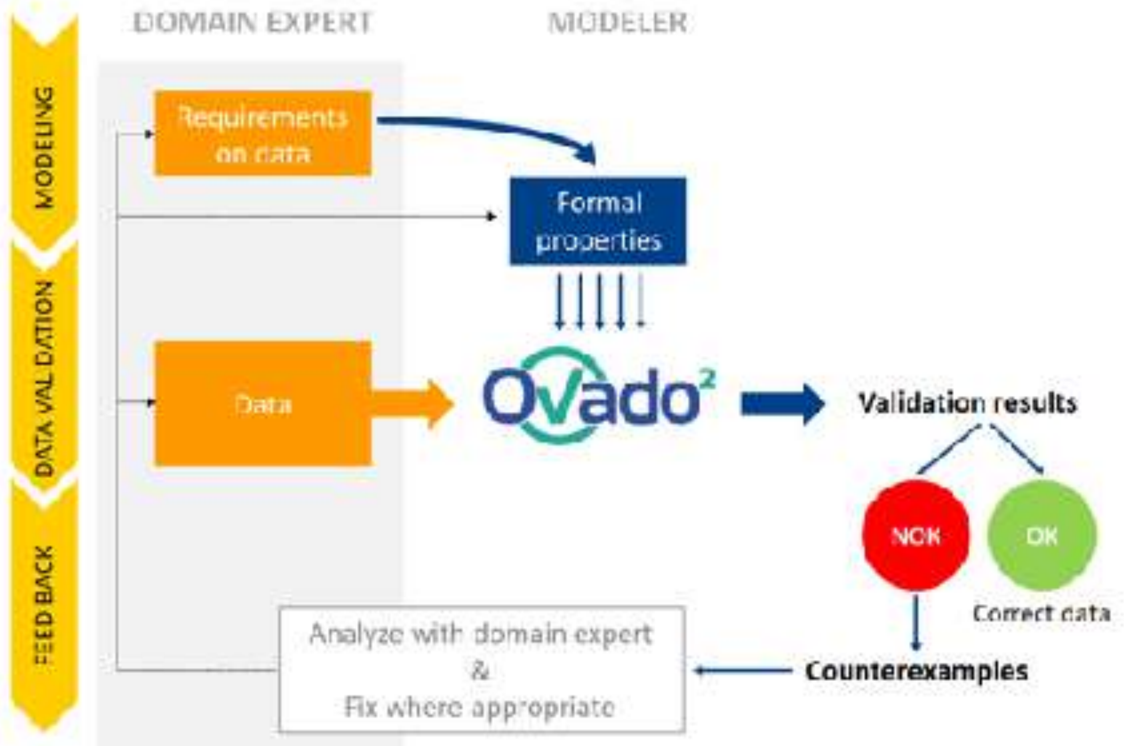
Name	ID	IP	Type	UpLink	DownLink	Length	GPS 1	GPS 2
Route_tx_001	243		R	Route_tx_005	Route_vx_002	345		
Route_vx_002	178		R	Route_vx_002	EndLine_000	178		
Switch_w_003	256	192.15.4.55	S	Route_vx_128	Route_tx_005	23		
Relay_s_004	12	192.15.4.10	Y				N 50.85 903	O 6.84 201
Route_tx_005	3		R	Route_tx_006	Route_vx_128	291		
Relay_s_001	55	192.15.4.125	Y					
Route_tx_006	22		R	EndLine_001	Route_vx_002	110		
Route_vx_128	177		R	Route_tx_006	Route_vx_002	145		
Switch_w_009	242	192.15.4.10	S	Route_vx_128	Route_tx_005	34		
EndLine_000	0		E		Route_vx_002	1		
EndLine_001	1		F	Route_vx_002		1		
Signal_xs_002	32	192.15.4.12	G	Route_vx_128		22		
Signal_xs_003	33	192.15.4.13	G	Route_tx_005		51		
Balise_b_001	301		B	Route_vx_128		0	N 50.85 933	O 6.84 508
Balise_b_002	302		B	Route_tx_005		0	N 50.86 123	O 6.84 550

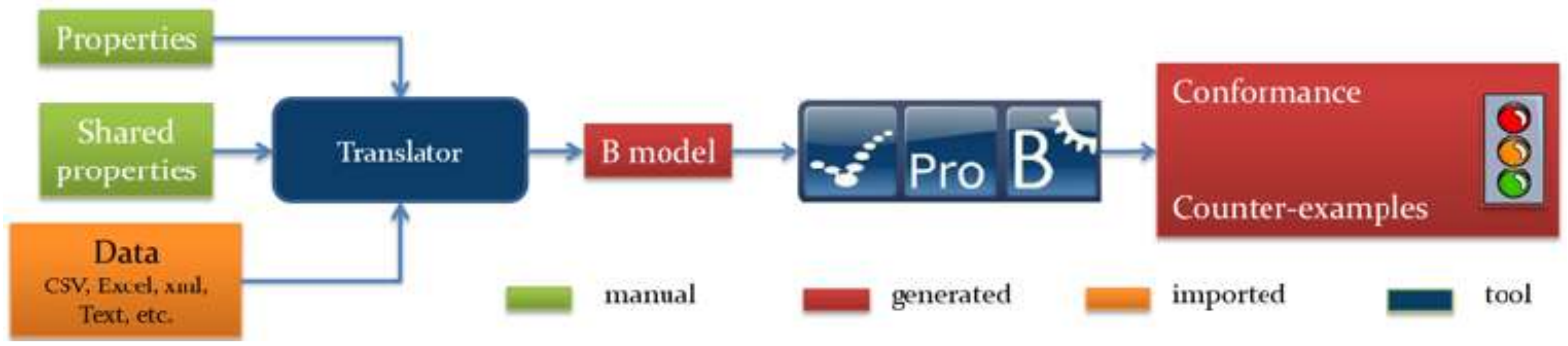
- What is the use of a formally proven software if some of its (non trivial) parameters are wrong ?
- Data Validation: Automatic check of large data sets against properties
- Properties : international standards, national regulations, manufacturer habits, customer requirements, safety assumptions made during development, …
  - E.g. metro line static data used by the automatic pilot (software) to drive safely

B for Data Validation



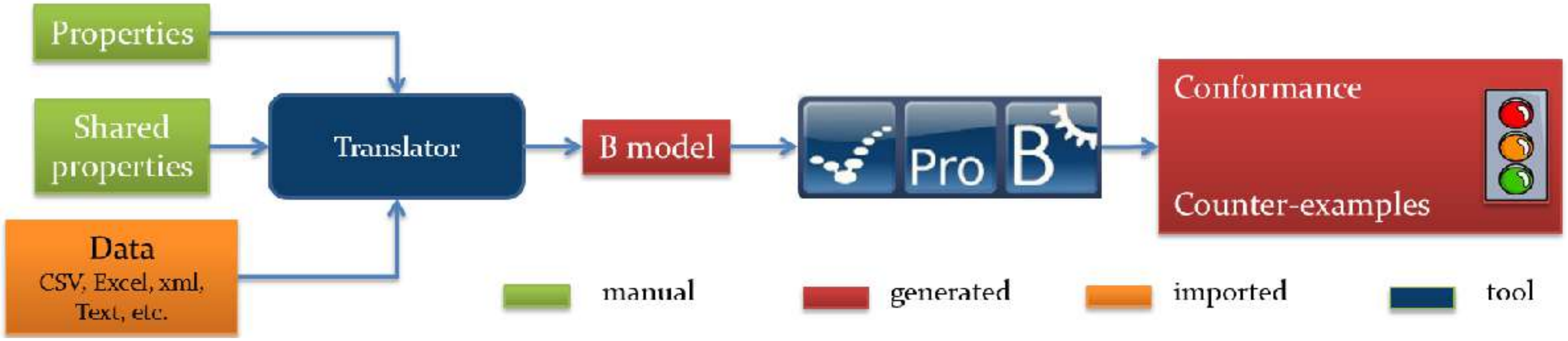
- Express properties in B: works well with graph-based properties or if software already developed with B
- Initial developments
  - OVADO for RATP, based on predicateB
  - ProB for Siemens in 2008/2009 within Deploy EU project





Aspects of Data Validation

- Focus on expressivity: B language extended (IF-THEN-ELSE, LET for expressions, external functions for string manipulation, regular expressions)
- Tool certification: Tool certified for T2 usage according to EN50128
  - extensive testing and validation and/or double chain
- Full automation, scale to large data values, provide user feedback

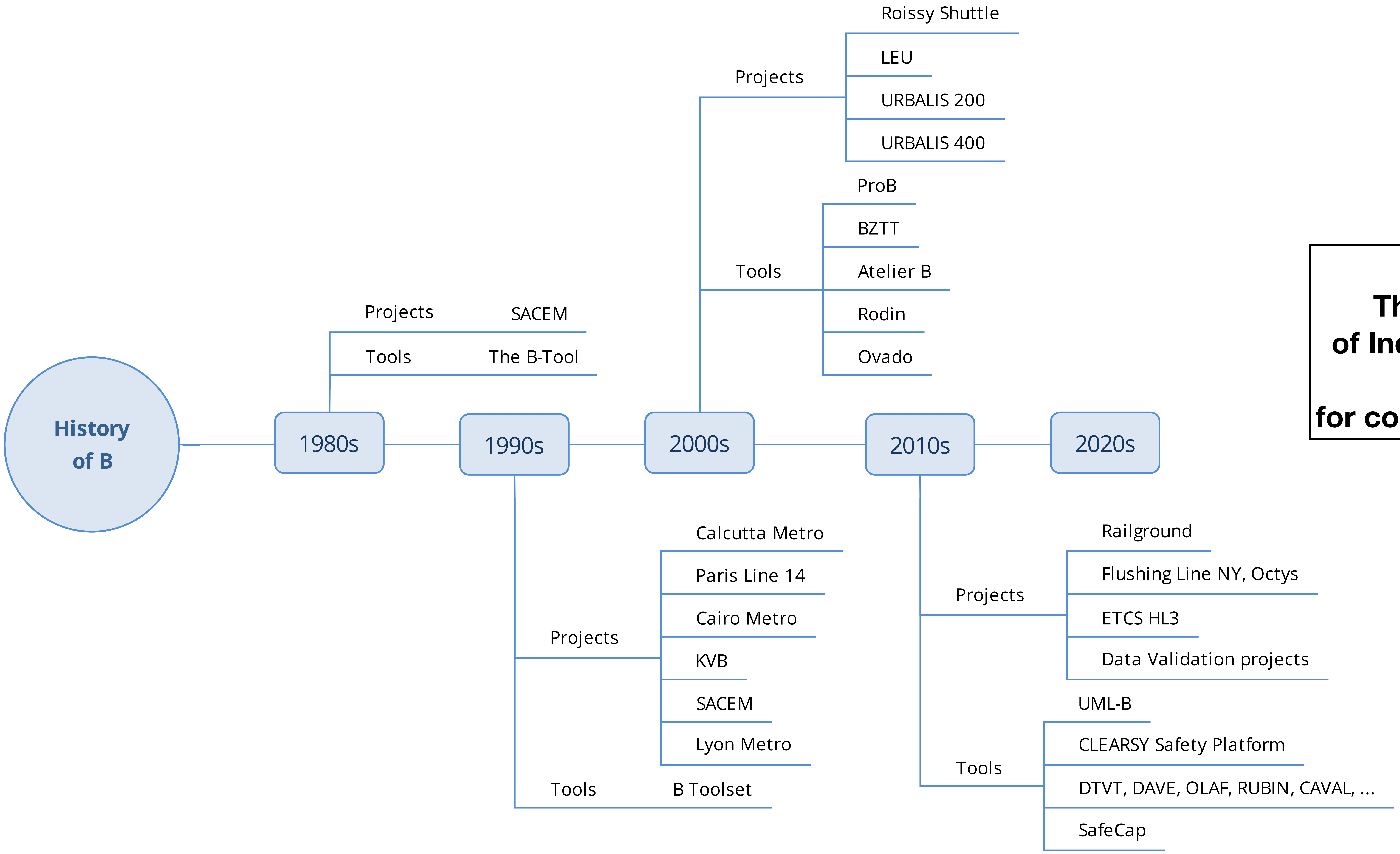


B for **Data Validation: Industrial Uses**

- Line 1 Paris, the second CDGVAL line LISA at the CDG airport in Paris, São Paulo line 4, ALGER line 1, Barcelona line 9, all by Siemens using **RDV** built-on top of **ProB**,
- more metro lines in Paris managed by RATP using **OVADO** which includes a tool developed called predicateB as first chain (development funded by CLEARSY and been maintained and evolved by Systerel for the last 15 years) and **ProB** as secondary tool chain
- Alstom for their URBALIS 400 CBTC system in 2014 using a tool based on **ProB** called **DTVT** developed by CLEARSY for various lines, e.g., in Mexico, Toronto, São Paulo and Panama
- Alstom and SNCF also applied data validation for ETCS-Level 1 software in 2018 using another tool developed by CLEARSY using **ProB**.
- Together with Systerel, Alstom conducted data validation of the Octys CBTC for RATP in 2017 using the **OVADO** tool.
- by Thales using a tool based on ProB called **Rubin** for checking engineering rules of their ETCS Radio Block Centre
- Other tools based on **ProB** were developed by CLEARSY such as **Dave** for General Electric or the latest generation tool called **Caval**.

FM Success Story

Reflections



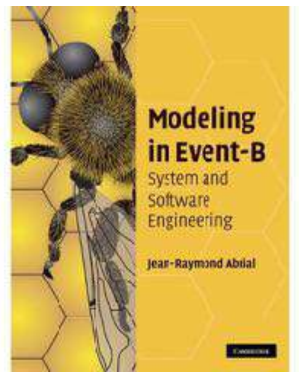
see FMICS'2020 article
The First Twenty-Five Years
of Industrial Use of the B-Method

for common success, fail factors,...

Summary: B and its Uses

- B for **software development** (classical B): refine specification until B0, apply code generators
  - Line 14 Paris, Alstom U400, …
  - FM success story, new potential for hardware (LCHIP)

- B for **system modelling** (Event-B): verify critical properties, understand why a system is correct
  - CBTC Flushing Line, NYCT I2S, Octys, Hybrid Level 3, …
  - Activities have increased in last years, potential for executable models



- B for **data validation**: express properties and B and check data (possibly using a double chain)
  - DTVT, Ovado, Dave, Olaf, Caval, Rubin, … for Line 1 Paris, Amsterdam, …
  - FM success story, widespread usage in railway industry

Part II : Commandments and Lessons

for a) using B and

for b) building tools for B, Z, and other formal methods

Inspiration

- Jonathan P. Bowen, Michael G. Hinchey:
  Ten Commandments Ten Years On: Lessons for ASM, B, Z and VSR-net. Rigorous Methods for Software Construction and Analysis 2009: 219-233

- Jonathan P. Bowen, Mike G. Hinchey:
  Ten Commandments of Formal Methods... Ten Years On. Conquering Complexity 2012: 237-251

- Jonathan P. Bowen, Michael G. Hinchey:
  Ten Commandments of Formal Methods. Computer 28(4): 56-63 (1995)

- Jonathan P. Bowen, Michael G. Hinchey:
  Seven More Myths of Formal Methods. IEEE Softw. 12(4): 34-41 (1995)

- Jonathan P. Bowen, Michael G. Hinchey:
  Seven More Myths of Formal Methods. FME 1994: 105-117

- Anthony Hall:
  Seven Myths of Formal Methods. IEEE Softw. 7(5): 11-19 (1990)

Thou Shalt Animate your Models

- ensures your assumptions are consistent (there is at least one model)
- allows to spot errors which are impossible to avoid using invariants and difficult to describe using temporal logic
- spots class of errors you haven’t thought of yet

“Every formal model (proven or not) which has not been animated contained errors”

Christophe Metayer, Systerel

(liberal translation from French based on verbal communication)

Earley Parsing Algorithm Model

earley_0
- inv2/WD
- INITIALISATION/inv1/INV
- INITIALISATION/inv2/INV
- selector/grd2/WD
- selector/grd4/WD
- selector/inv1/INV
- selector/inv2/INV
- predictor/grd2/WD
- predictor/grd3/WD
- predictor/inv1/INV
- predictor/inv2/INV
- completer/grd2/WD
- completer/grd4/WD
- completer/grd5/WD
- completer/inv1/INV
- completer/inv2/INV
- final/grd1/WD
- final/grd1/GRD

earley_1
- inv1/WD
- INITIALISATION/inv2/INV
- INITIALISATION/inv1/INV
- INITIALISATION/act2/SIM
- selector/grd1/WD
- selector/grd2/WD
- selector/grd4/WD
- selector/inv2/INV
- selector/inv1/INV
- selector/grd1/GRD
- selector/act1/WD
- predictor/grd1/WD
- predictor/grd2/WD
- predictor/grd3/WD
- predictor/inv2/INV
- predictor/inv1/INV
- predictor/grd1/GRD
- predictor/act1/WD
- completer/grd1/WD
- completer/grd2/WD
- completer/grd3/WD
- completer/grd4/WD
- completer/grd5/WD
- completer/inv2/INV
- completer/inv1/INV
- completer/grd1/GRD
- completer/grd3/GRD
- completer/act1/WD
- final/grd1/WD
- final/grd1/GRD

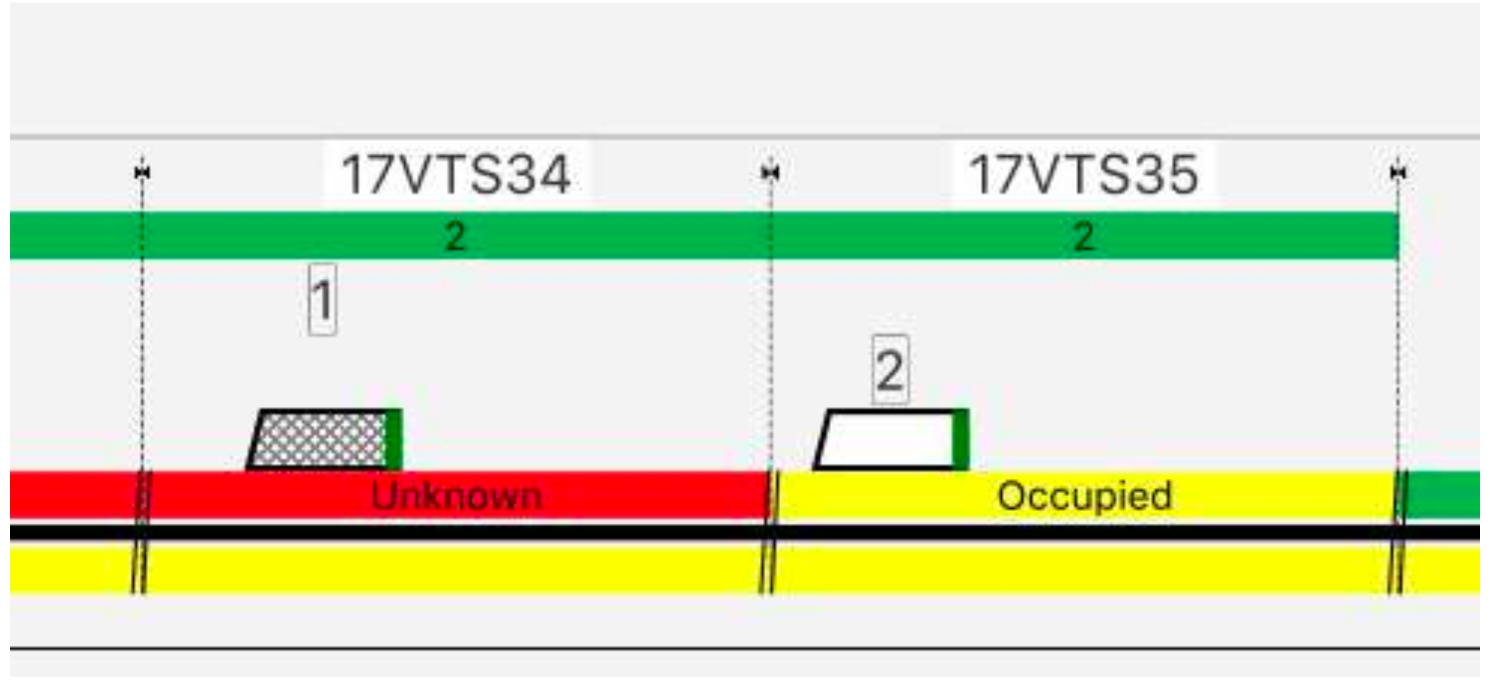
earley_2
- inv3/WD
- inv4/WD
- INITIALISATION/inv1/INV
- INITIALISATION/inv2/INV
- INITIALISATION/inv3/INV
- INITIALISATION/inv4/INV
- selector/grd1/WD
- selector/grd2/WD
- selector/grd4/WD
- selector/grd6/WD
- selector/inv1/INV
- selector/inv2/INV
- selector/inv3/INV
- selector/inv4/INV
- selector/grd5/GRD
- selector/grd1/GRD
- selector/act1/WD
- selector/act2/WD
- predictor/grd1/WD
- predictor/grd2/WD
- predictor/grd3/WD
- predictor/grd5/WD
- predictor/inv1/INV
- predictor/inv2/INV
- predictor/inv3/INV
- predictor/inv4/INV
- predictor/grd4/GRD
- predictor/grd1/GRD
- predictor/act1/WD
- predictor/act2/WD
- completer/grd1/WD
- completer/grd2/WD
- completer/grd3/WD
- completer/grd4/WD
- completer/grd5/WD
- completer/grd7/WD
- completer/inv1/INV
- completer/inv2/INV
- completer/inv3/INV
- completer/inv4/INV
- completer/grd6/GRD

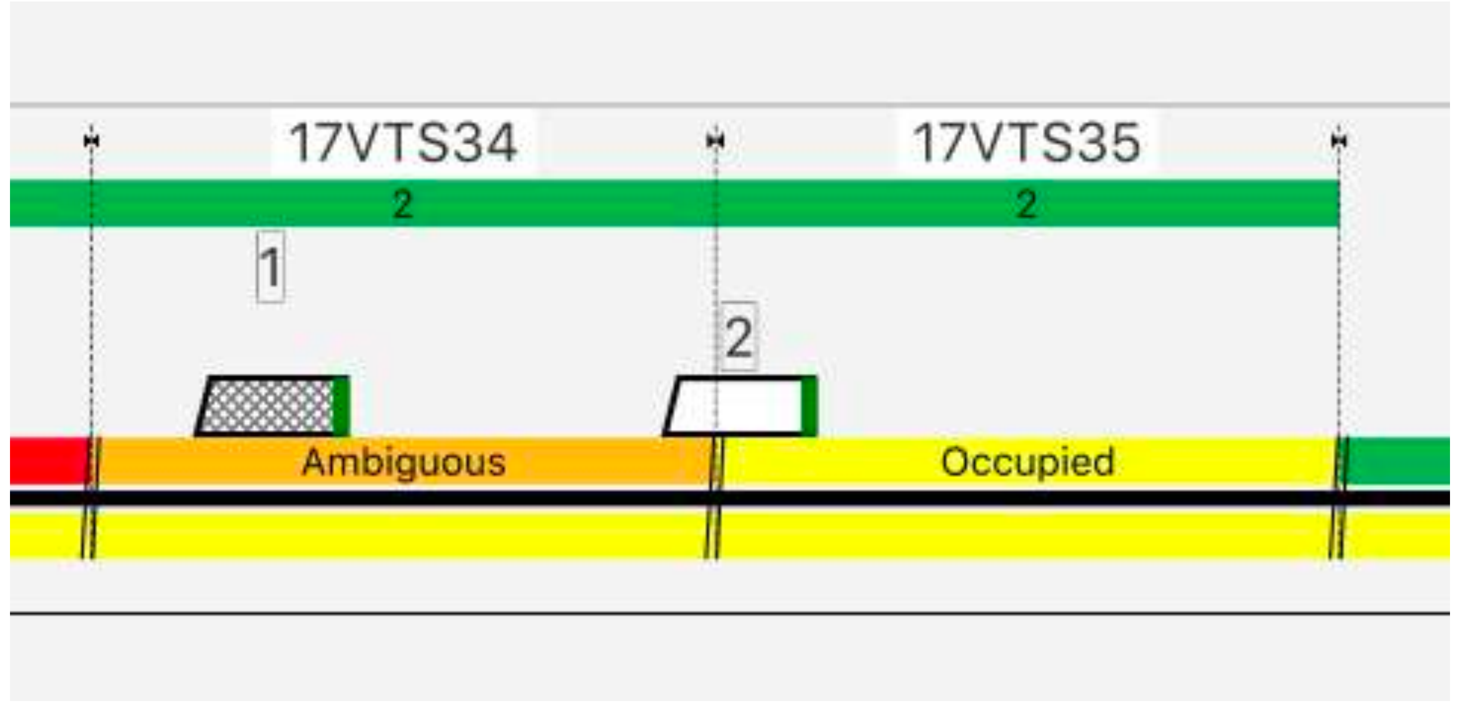
earley_3
- inv2/WD
- thm1/THM
- thm2/THM
- INITIALISATION/inv1/INV
- INITIALISATION/inv2/INV
- selector/grd5/WD
- selector/grd1/WD
- selector/grd2/WD
- selector/grd4/WD
- selector/grd6/WD
- selector/inv2/INV
- selector/grd5/GRD
- selector/grd1/GRD
- selector/grd3/GRD
- selector/grd4/GRD
- selector/grd6/GRD
- selector/act1/WD
- selector/act2/WD
- selector/act1/SIM
- selector/act2/SIM
- predictor/grd4/WD
- predictor/grd1/WD
- predictor/grd2/WD
- predictor/grd3/WD
- predictor/grd5/WD
- predictor/inv2/INV
- predictor/grd4/GRD
- predictor/grd1/GRD
- predictor/grd5/GRD
- predictor/act1/WD
- predictor/act2/WD
- predictor/act1/SIM
- predictor/act2/SIM
- move_predictor/grd1/WD
- move_predictor/grd2/WD
- move_predictor/grd3/WD
- move_predictor/grd5/WD
- move_predictor/grd4/WD
- move_predictor/inv2/INV
- completer/grd8/WD
- completer/grd1/WD

Fully proven,
but ProB found inconsistency
in the axioms (->>> instead of >->)
during animation

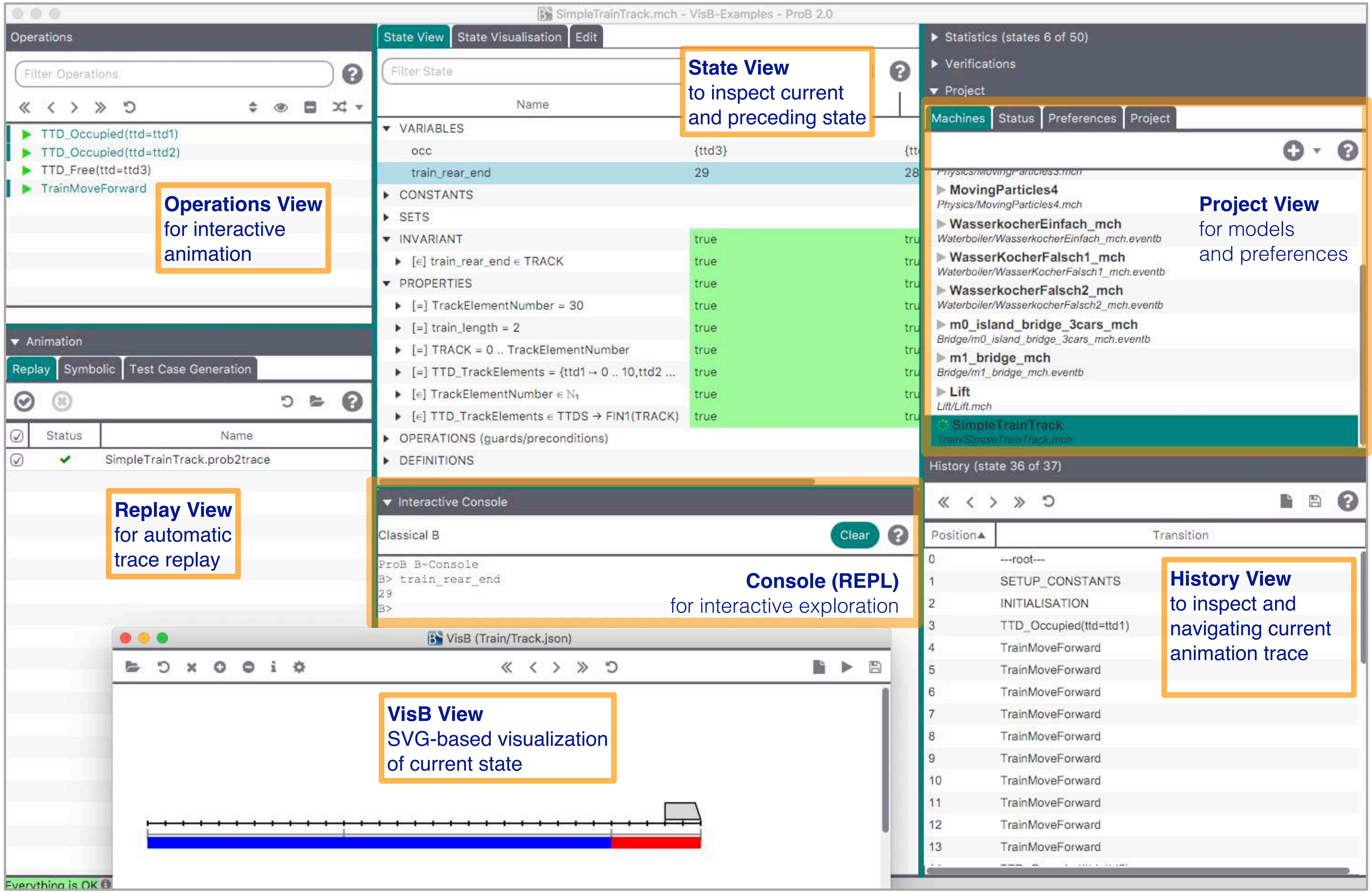
Thou Shalt Visualize 👁️

```
vss_left = {…,"17VTS33" |-> 140,"17VTS34" |-> 240,"17VTS34" |-> 340,…}
TTD_state = {TTD1|->free, TTD2|->occupied, TTD3|->occupied,…}
vss_state = {…,"17VTS33" |-> unknown,
                "17VTS34" |-> unknown, "17VTS35" |-> occupied,…}
…
Env_train_length = {train1|->30, train2|->30}
 Env_train_FP = {train1|->250, train2|->350}
…
registeredTrains = {train2}
train_reported_integrity = {train2|->confirmed_integrity}
```





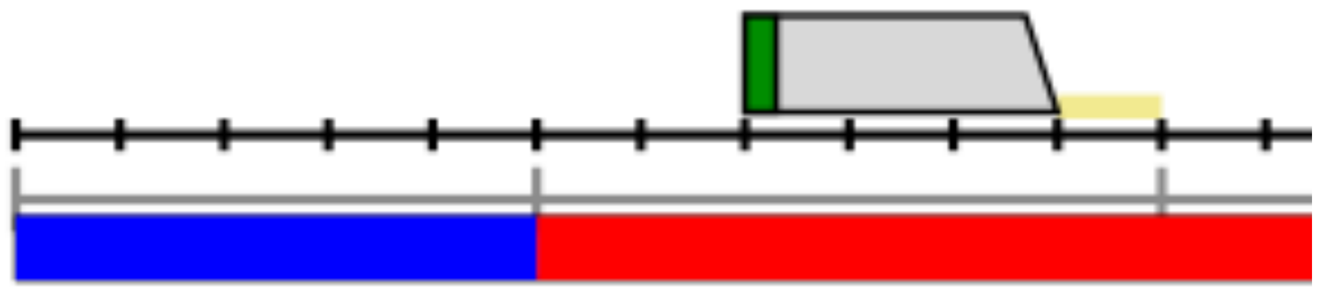
ProB2-UI Demo



https://prob.hhu.de

Simple Train Model

- Track is an interval 0..TrackElementNumber
- Track is divided into TTD (Trackside Train Detection) zones (e.g. implemented using track circuits or axle counters)
- Trains have positions train_rear_end(tr)..train_front_end(tr)
- Some trains have an MA (Movement Authority) extending beyond their front end

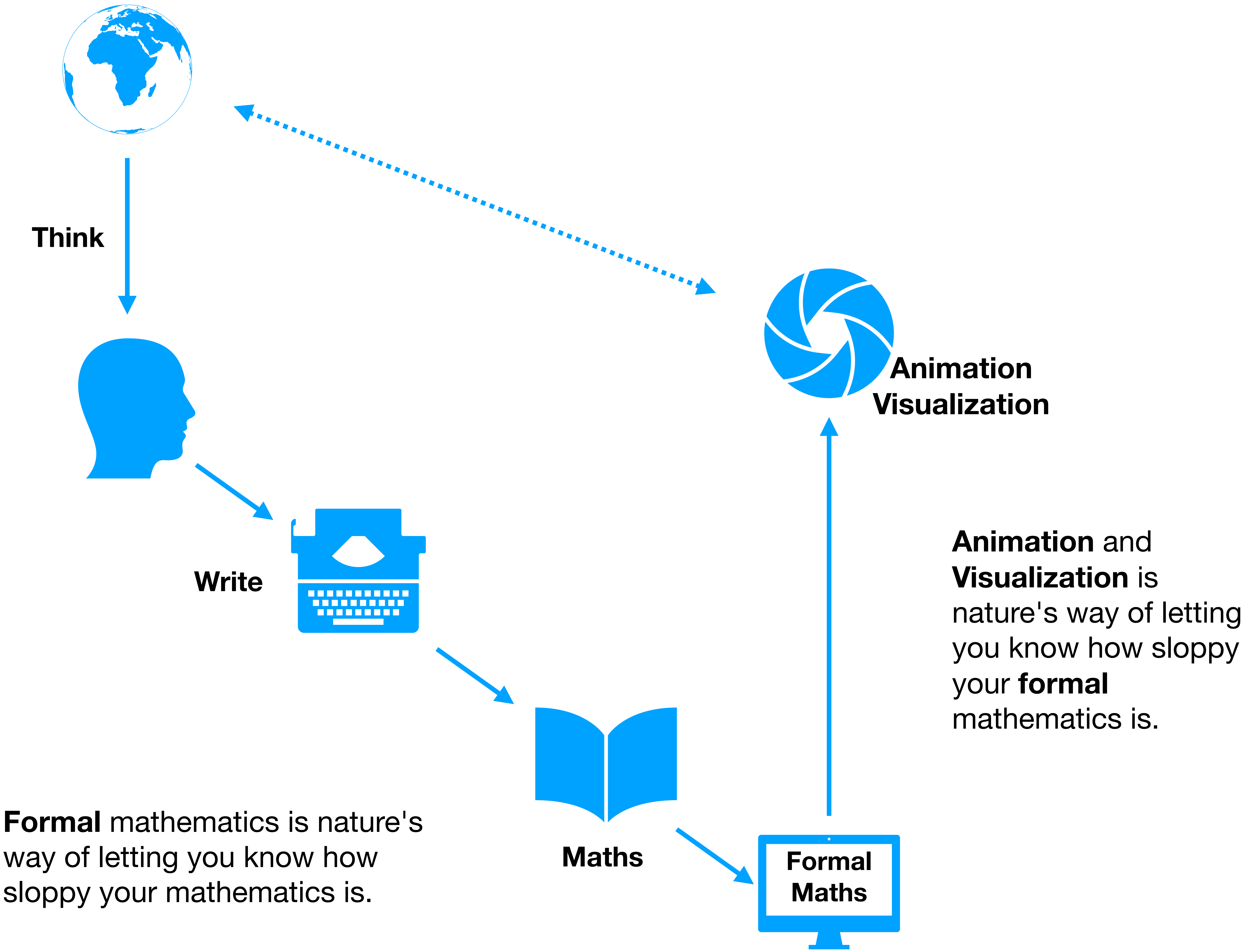


- Many things not modelled: delays, position reports, uncertainty of train image, train speed, braking curves, points, train integrity, …

Some Points

- Animation and Visualisation help me understand models others have written

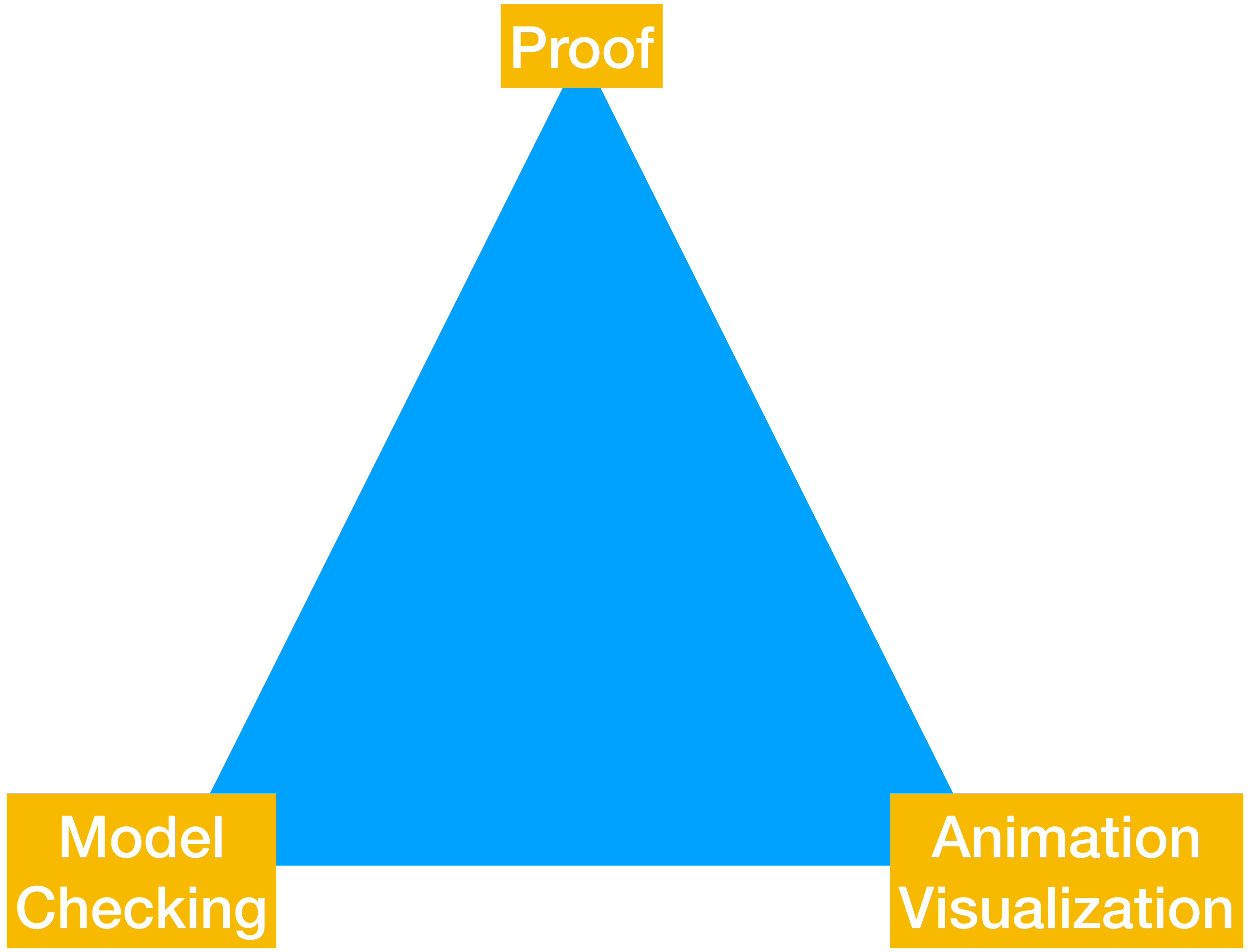
- also help make your model better understandable to other people, even domain experts not able to read your formal notation


Think
Write
Maths
Formal Maths
Animation Visualization
Animation and **Visualization** is nature's way of letting you know how sloppy your **formal** mathematics is.
Formal mathematics is nature's way of letting you know how sloppy your mathematics is.

I. Thou Shalt

Thou Shalt Not Abandon Thy Traditional Formal Proof Methods

- alternatively:
  Thou Shalt Use the Trinity of Methods



The Trinity of Methods

- I tend to use proof, model checking and animation together
    - **Proof**: solves the state explosion problem, provides key (inductive) properties and insights
    - **Model checking**: finds obvious problems, increases confidence that proof is feasible, checks liveness properties
    - **Animation**: validate scenarios (often part of the requirements), find inconsistencies, detect “surprising” and obvious errors quickly

Conflict of Interest

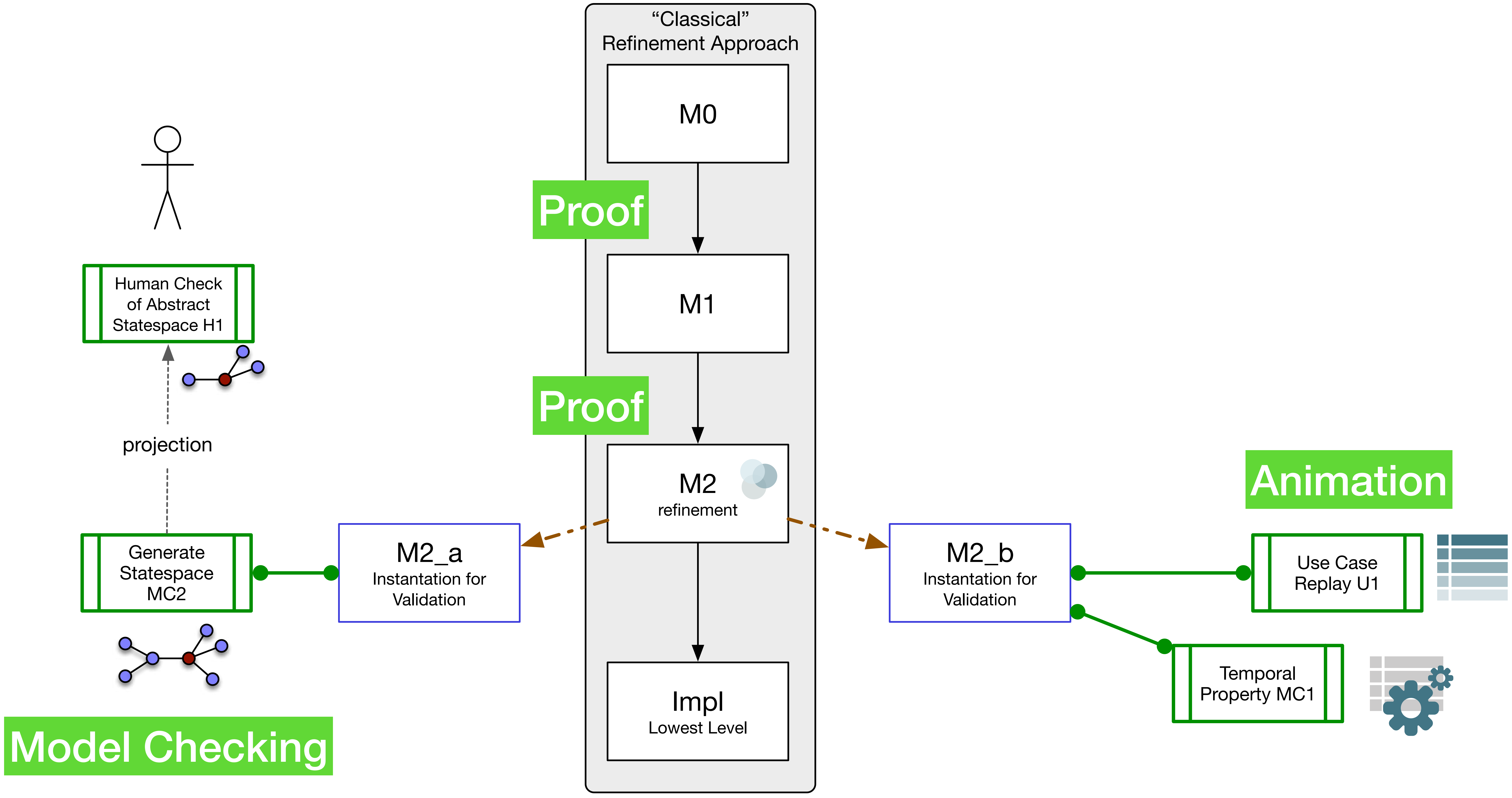
- Proof and animation have conflicting needs:
  - adding an axiomatic property for proof can make finding a valid model much harder

$\forall s \ . \ s \subseteq Track \Rightarrow P(s)$

  - adding concrete data and constructive definitions for animation can make proof harder and less general

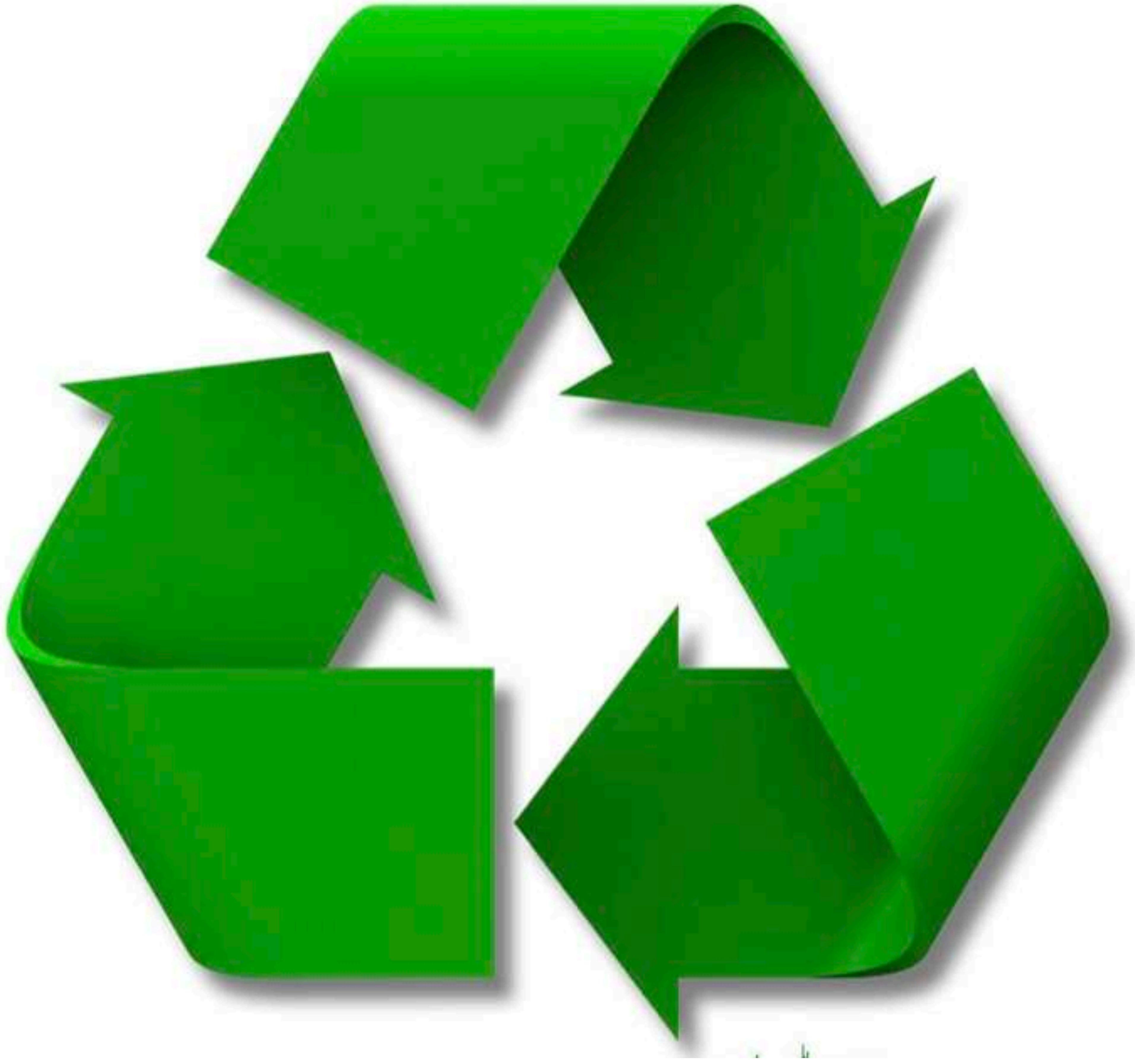
$f = \lambda x.x{\in}Train|front(x)..train\_ma(x)$

- Use refinement to create model checking and animation instances
- Annotate/isolate complex properties (@prob-ignore pragma)



“Classical”
Refinement Approach
M0
Proof
M1
Proof
M2
refinement
Impl
Lowest Level
Human Check
of Abstract
Statespace H1
projection
Generate
Statespace
MC2
Model Checking
M2_a
Instantation for
Validation
M2_b
Instantation for
Validation
Animation
Use Case
Replay U1
Temporal
Property MC1

Thou Shalt Reuse



Thou Shalt Reuse

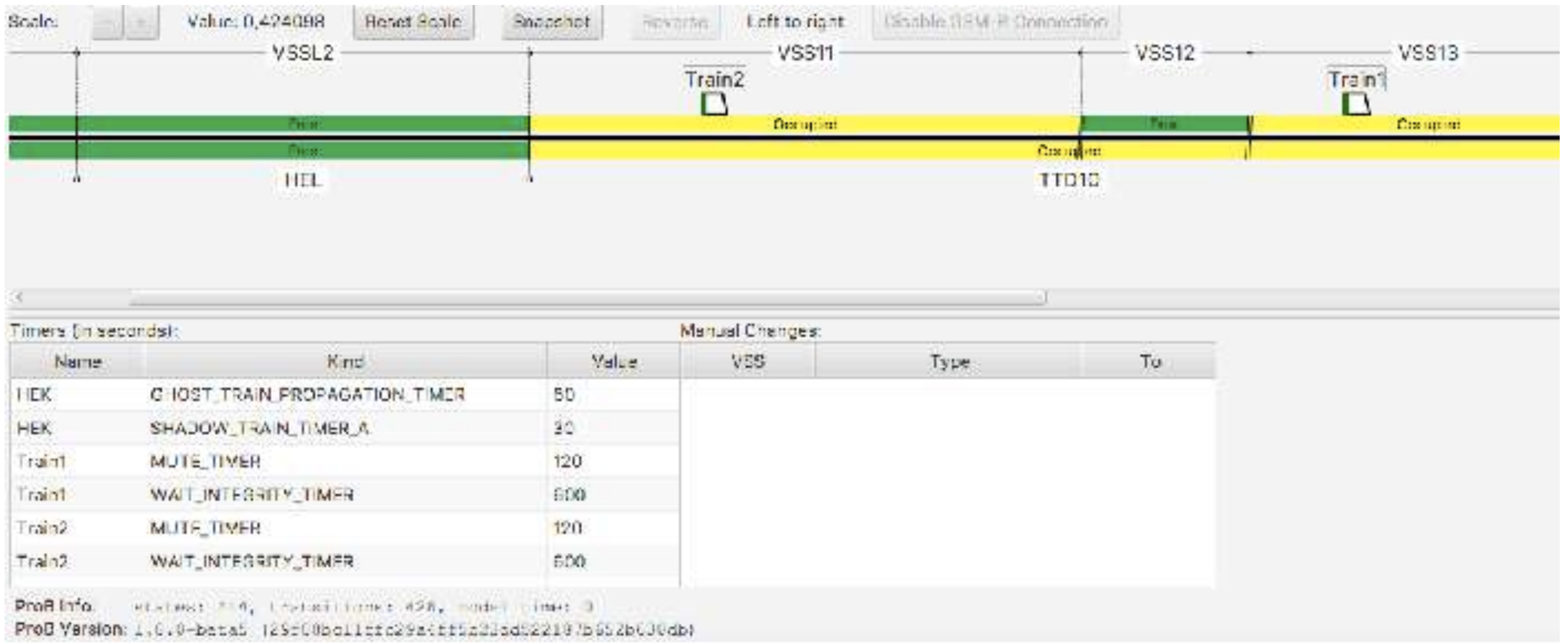
Ideas,
not Models

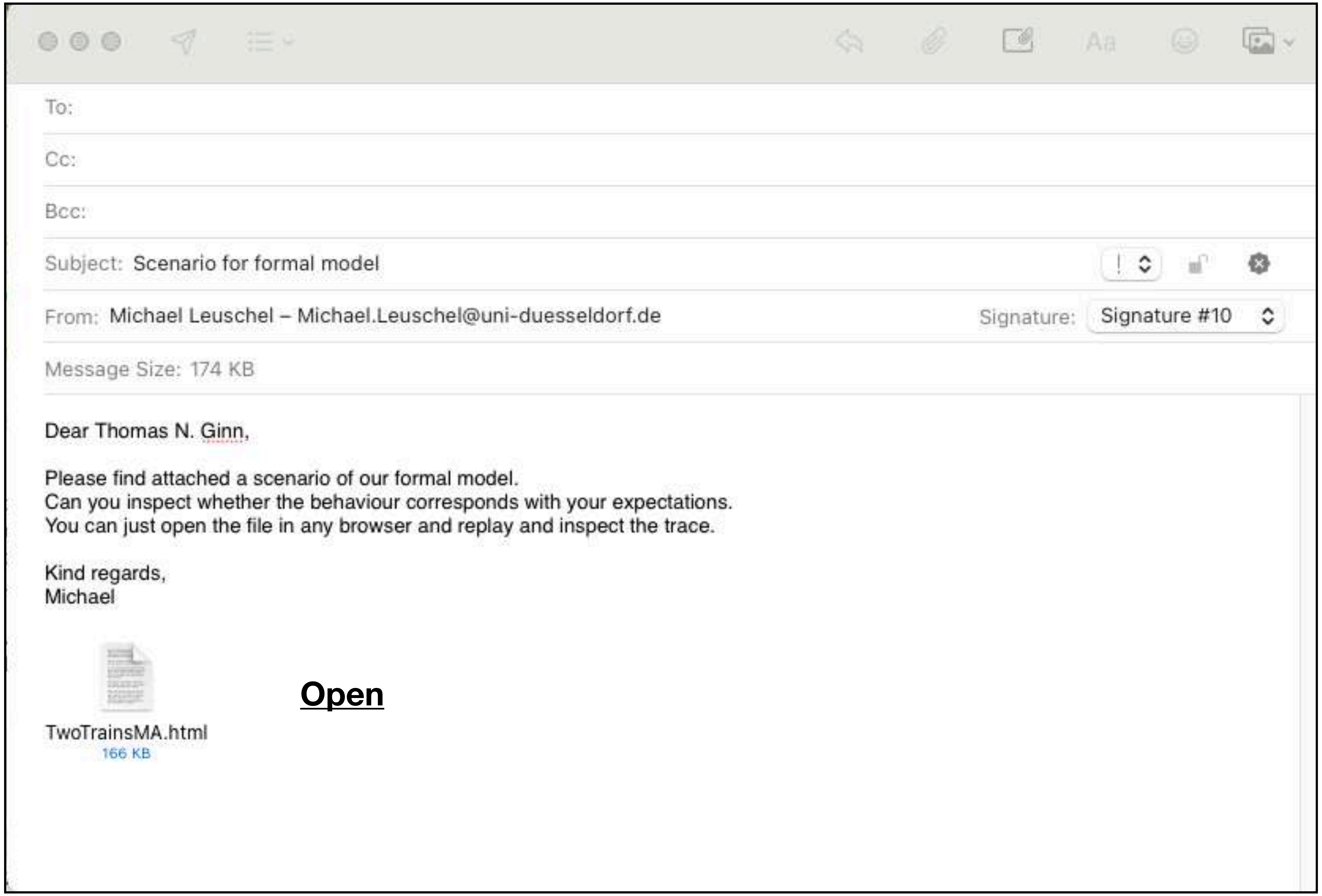
Thou Shalt Reuse Ideas, not Models

- When modelling:
  - Good idea to reuse: key concepts, ways to decompose a system, approach to ensure inductive proof is possible
  - Usually difficult to reuse formal models for modelling

Thou Shalt Use Models as Documentation

- Static Documentation
- Executable, interactive Documentation (HL3)





To:

Cc:

Bcc:

Subject: Scenario for formal model

From: Michael Leuschel – Michael.Leuschel@uni-duesseldorf.de

Signature: Signature #10

Message Size: 174 KB

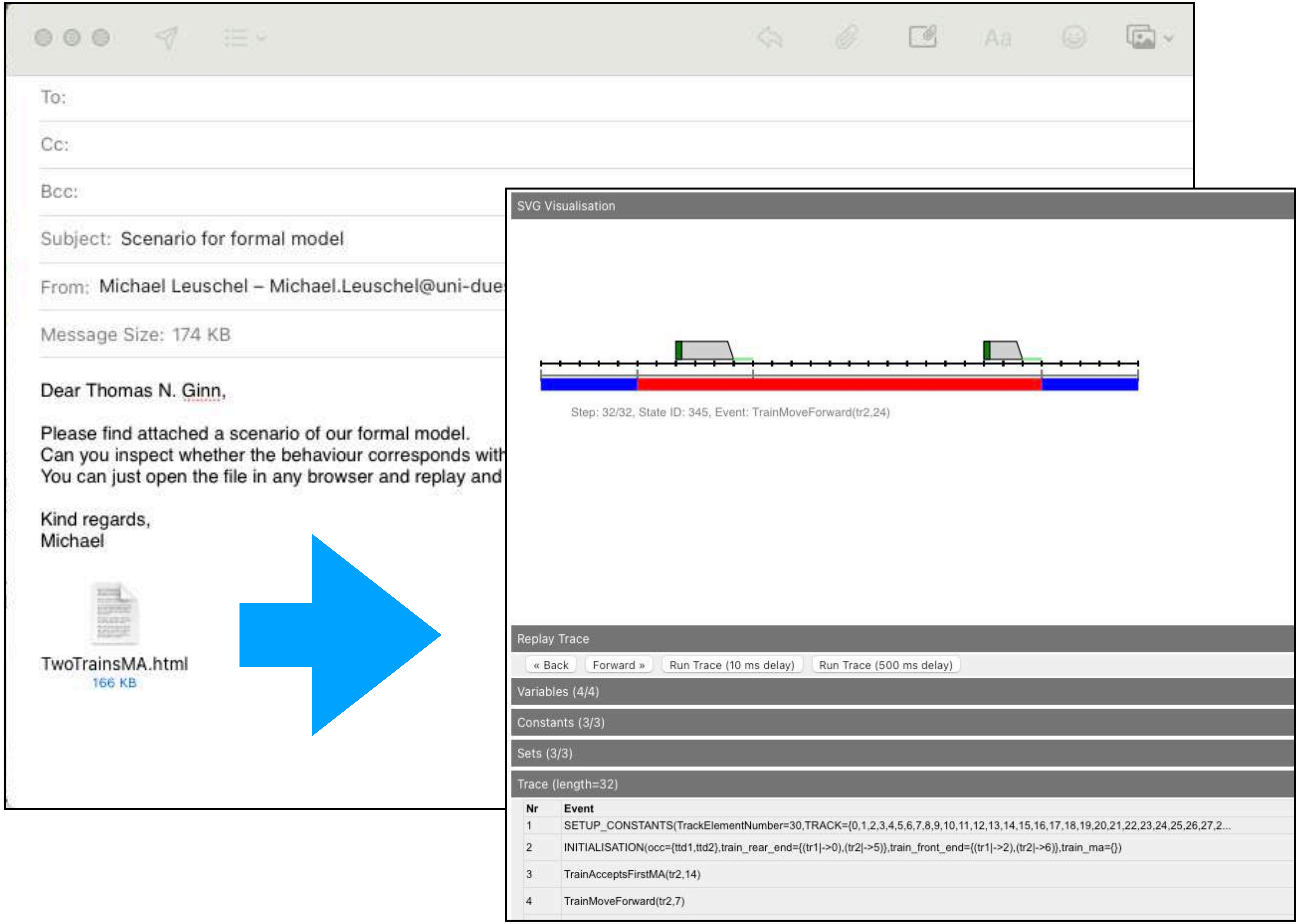
Dear Thomas N. Ginn,

Please find attached a scenario of our formal model.
Can you inspect whether the behaviour corresponds with your expectations.
You can just open the file in any browser and replay and inspect the trace.

Kind regards,
Michael

TwoTrainsMA.html
166 KB

Open



To:
Cc:
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Subject: Scenario for formal model
From: Michael Leuschel – Michael.Leuschel@uni-due
Message Size: 174 KB
Dear Thomas N. Ginn,
Please find attached a scenario of our formal model.
Can you inspect whether the behaviour corresponds with
You can just open the file in any browser and replay and
Kind regards,
Michael
TwoTrainsMA.html
166 KB
SVG Visualisation
Step: 32/32, State ID: 345, Event: TrainMoveForward(tr2,24)
Replay Trace
« Back
Forward »
Run Trace (10 ms delay)
Run Trace (500 ms delay)
Variables (4/4)
Constants (3/3)
Sets (3/3)
Trace (length=32)
Nr
Event
1
SETUP_CONSTANTS(TrackElementNumber=30,TRACK={0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,2...
2
INITIALISATION(occ={ttd1,ttd2},train_rear_end={(tr1|->0),(tr2|->5)},train_front_end={(tr1|->2),(tr2|->6)},train_ma={})
3
TrainAcceptsFirstMA(tr2,14)
4
TrainMoveForward(tr2,7)

ProB Jupyter Notebooks for Documentation

KISS PASSION Puzzle

A slightly more complicated puzzle (involving multiplication) is the KISS * KISS = PASSION problem.

In [3]:
```
    {K,P} ⊆ 1..9 ∧
    {I,S,A,O,N} ⊆ 0..9 ∧
    (1000∗K+100∗I+10∗S+S) ∗
    (1000∗K+100∗I+10∗S+S)
     =  1000000∗P+100000∗A+10000∗S+1000∗S+100∗I+10∗O+N ∧
    card({K, I, S, P, A, O, N}) = 7
```

Out[3]: *TRUE*

Solution:

- $P = 4$
- $A = 1$
- $S = 3$
- $I = 0$
- $K = 2$
- $N = 9$
- $O = 8$

ProB Jupyter Notebooks for Documentation

Mixing Functional Programming with Constraint Programming

In B we can also define (higher-order) functions and mix those with logical predicates.

In [12]:
```
1 f = λx.(x∈ℤ|x*x) ∧ res={x|f(x) = 100}
```

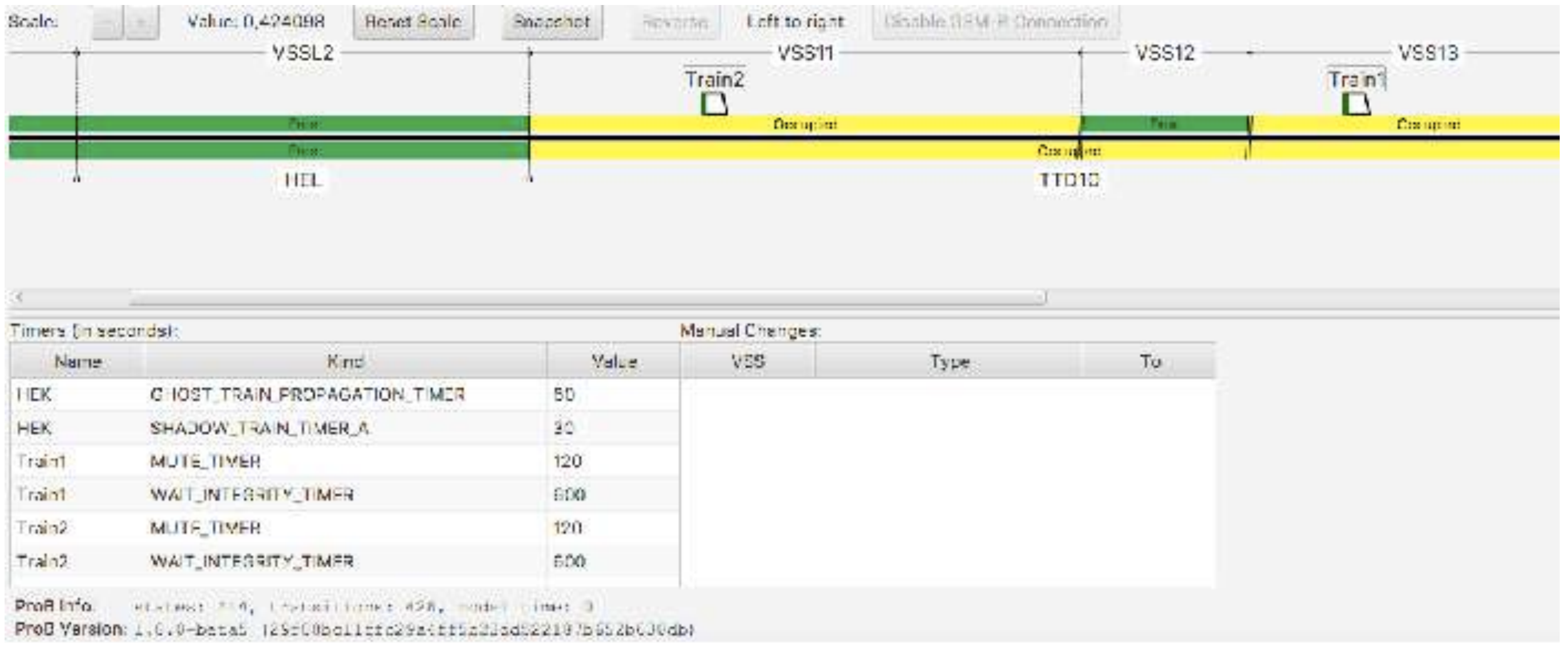
Out[12]: *TRUE*

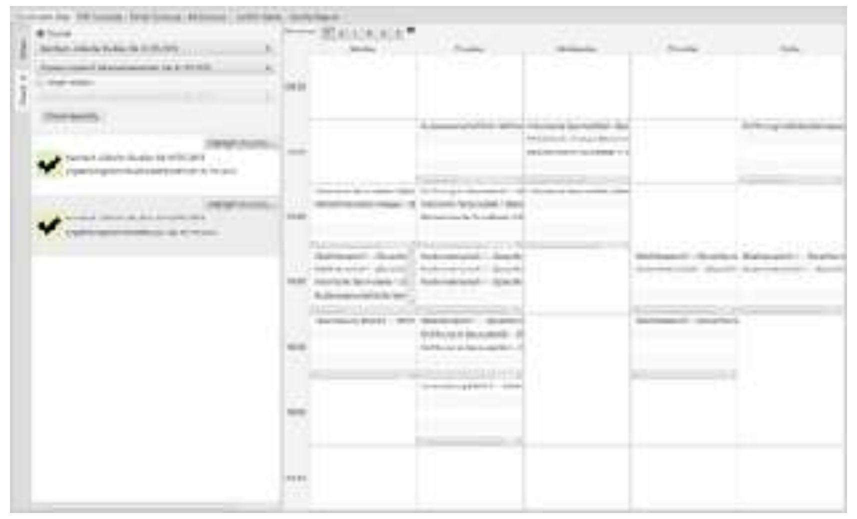
Solution:

- $res = \{-10, 10\}$
- $f = \lambda x \cdot (x \in INTEGER \mid x * x)$

Thou Shalt Use Execute your Models

- Oracle in Test Environment (Advance)
- Executable Prototype for early field tests (HL3)
- Long term: maybe formal models in the loop in the final product (Plues tool)





EU Project

first step (2014):
using B model in real
Alstom test environment

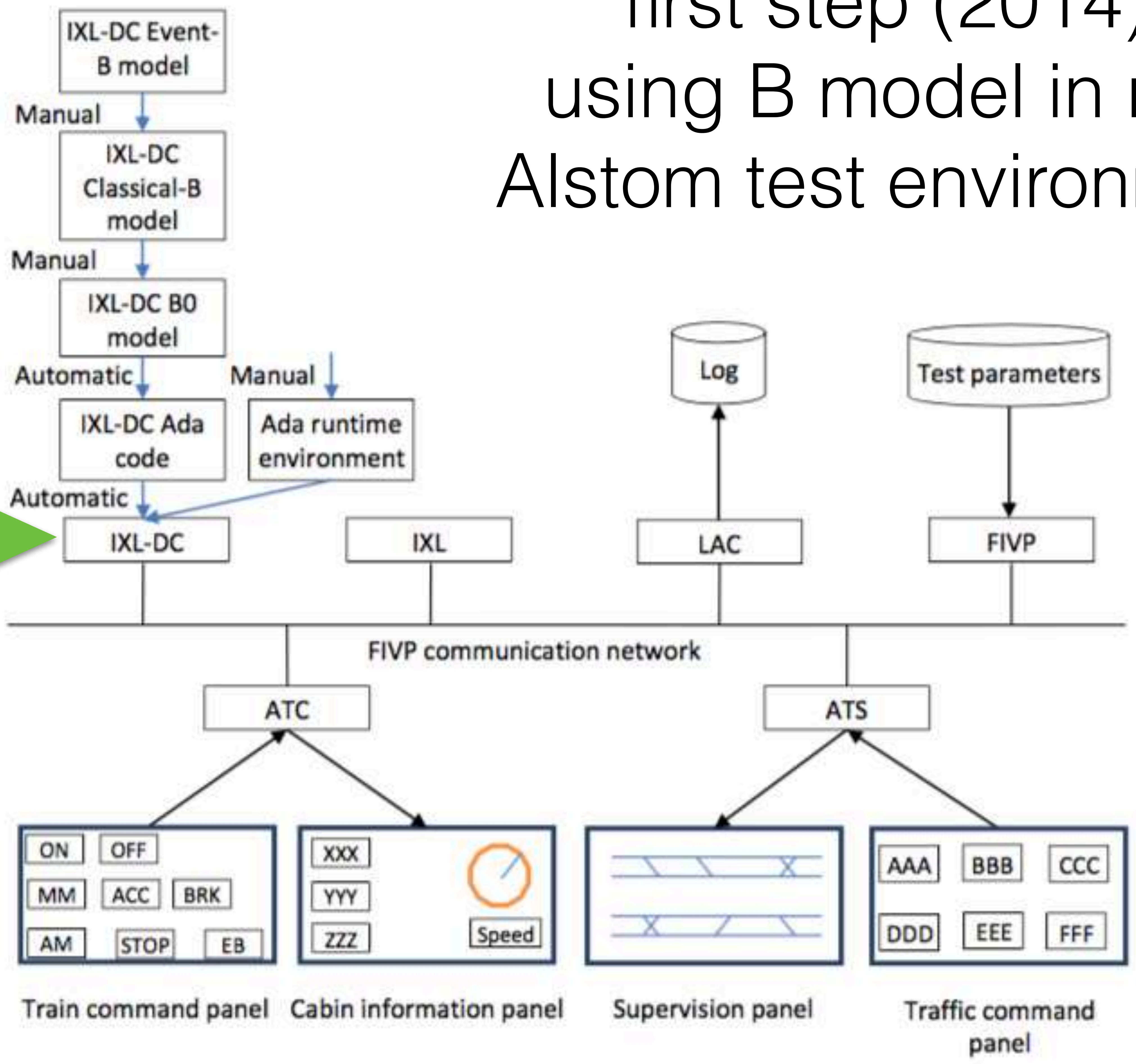


Figure 3.1. Envisioned IXL-DC code generation process and test environment architecture

http://www.advance-ict.eu Deliverable D1.3

Project for ProRail

- Field demonstration of the ETCS Hybrid Level 3 (HL3) principles
  - Demonstration by co-operation trackside (Thales, Siemens) and onboard (Alstom, Hitachi)
  - Demonstration line:
    ETCS National Integration Facility (ENIF) in Hitchin/UK

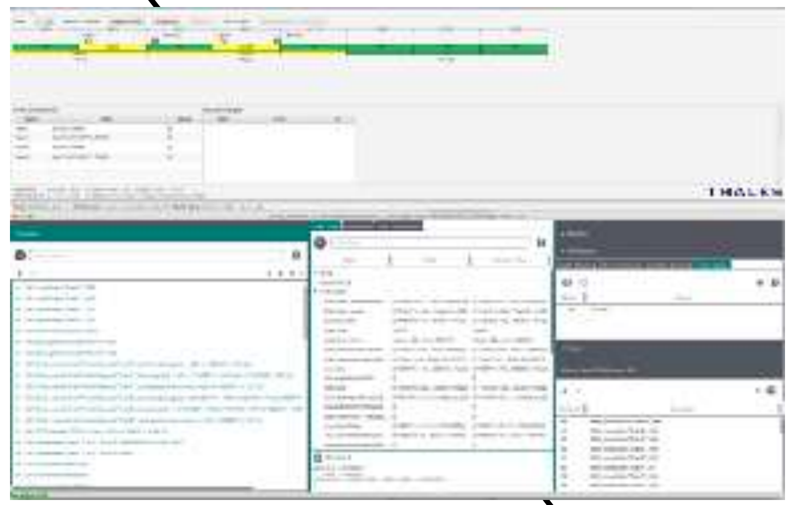
- There was insufficient time to model and code a prototype
- But there was sufficient time to embed the formal model at runtime

Natural Language Specification

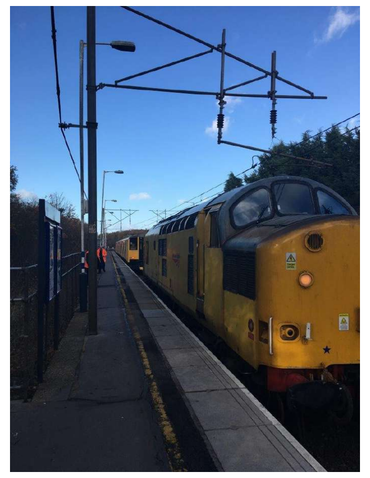
New System
New Feature

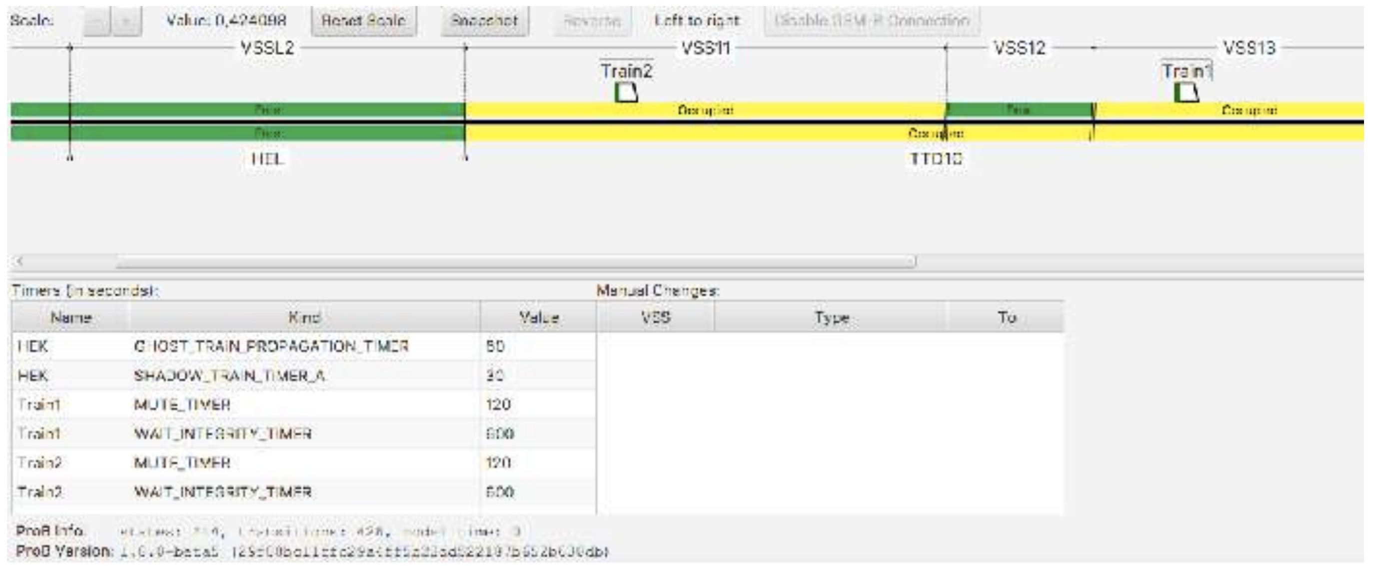
B

Formal Model



Testing, Debugging





Execution in real environment

ProRail Project Summary

- using model as demonstrator/prototype is feasible, there were a lot of technical issues, ProB was not one of them!
- animation/visualization can help understand and debug a given specification
- using a formal model allowed to quickly adapt the model as fixes for issues came along, several new requirements were integrated
  - log of formal model could be replayed step-by-step to analyse issues

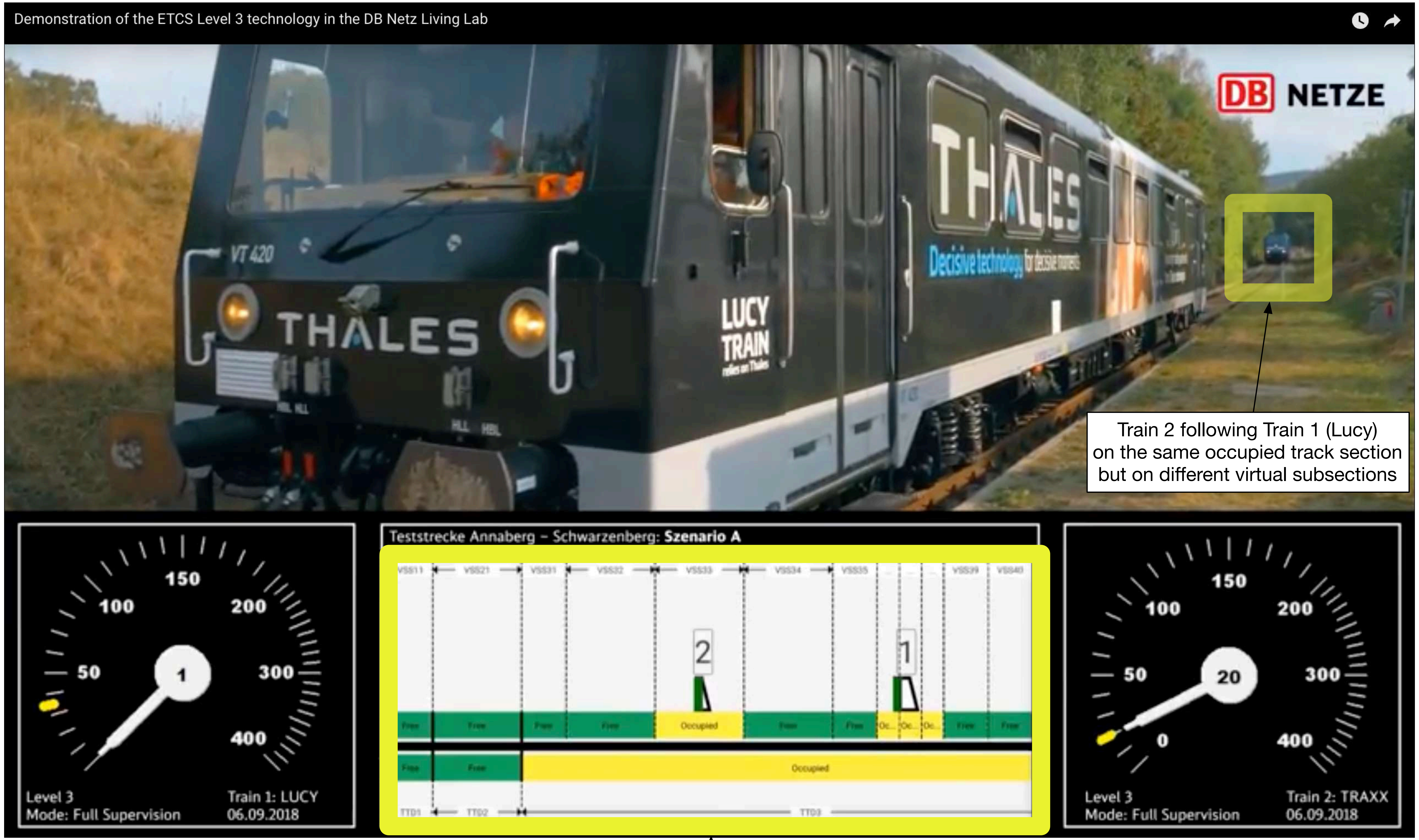
The use of formal methods in specification and demonstration of ERTMS Hybrid Level 3

Prepared on behalf of the International Technical Committee
by Maarten Bartholomeus, Bas Luttik, Tim Willemse,
Dominik Hansen, Michael Leuschel and Paul Hendriks

IRSE News
November 2019

https://www.youtube.com/watch?v=FjKnugbmrP4

ProB in Action : Formal Models in Realtime



Train 2 following Train 1 (Lucy)
on the same occupied track section
but on different virtual subsections

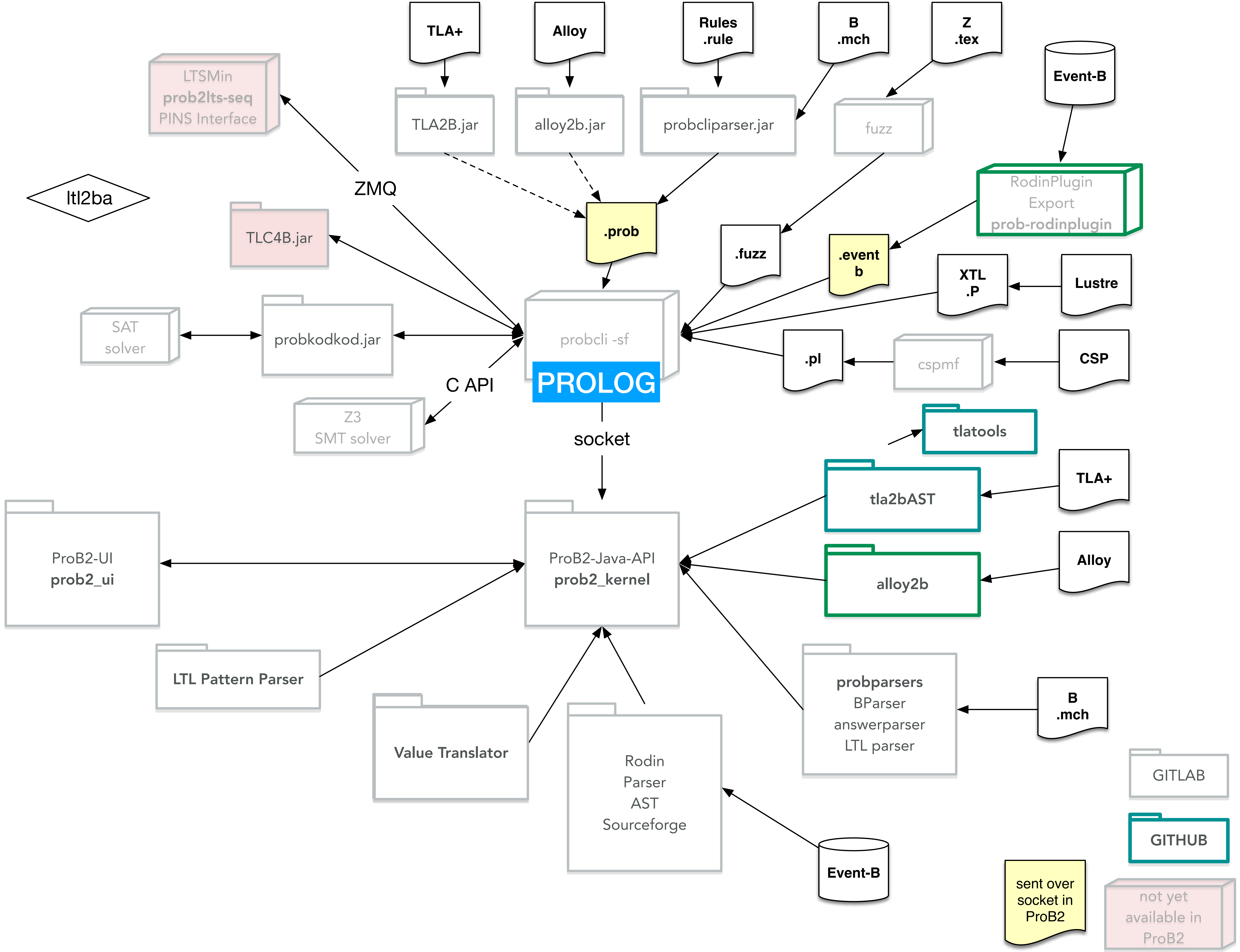
ProB running in real-time animating a
formal B model of the **Hybrid-Level 3** principles
developed by a team from the University of Düsseldorf and Thales with support from ClearSy

from modelling
to tools

Thou Shalt Choose an Appropriate Notation/ Programming Language for your Tool

- Prolog for type checking, rule-based theorem proving, constraint solving
- Java, Tcl/Tk, … for user interface
- C for LTL model checking
- …

The heart of ProB is written in Prolog



but other languages are used around it:
Java
C, C++
Tcl/Tk
Haskell

Hindley-Milner Type Inference

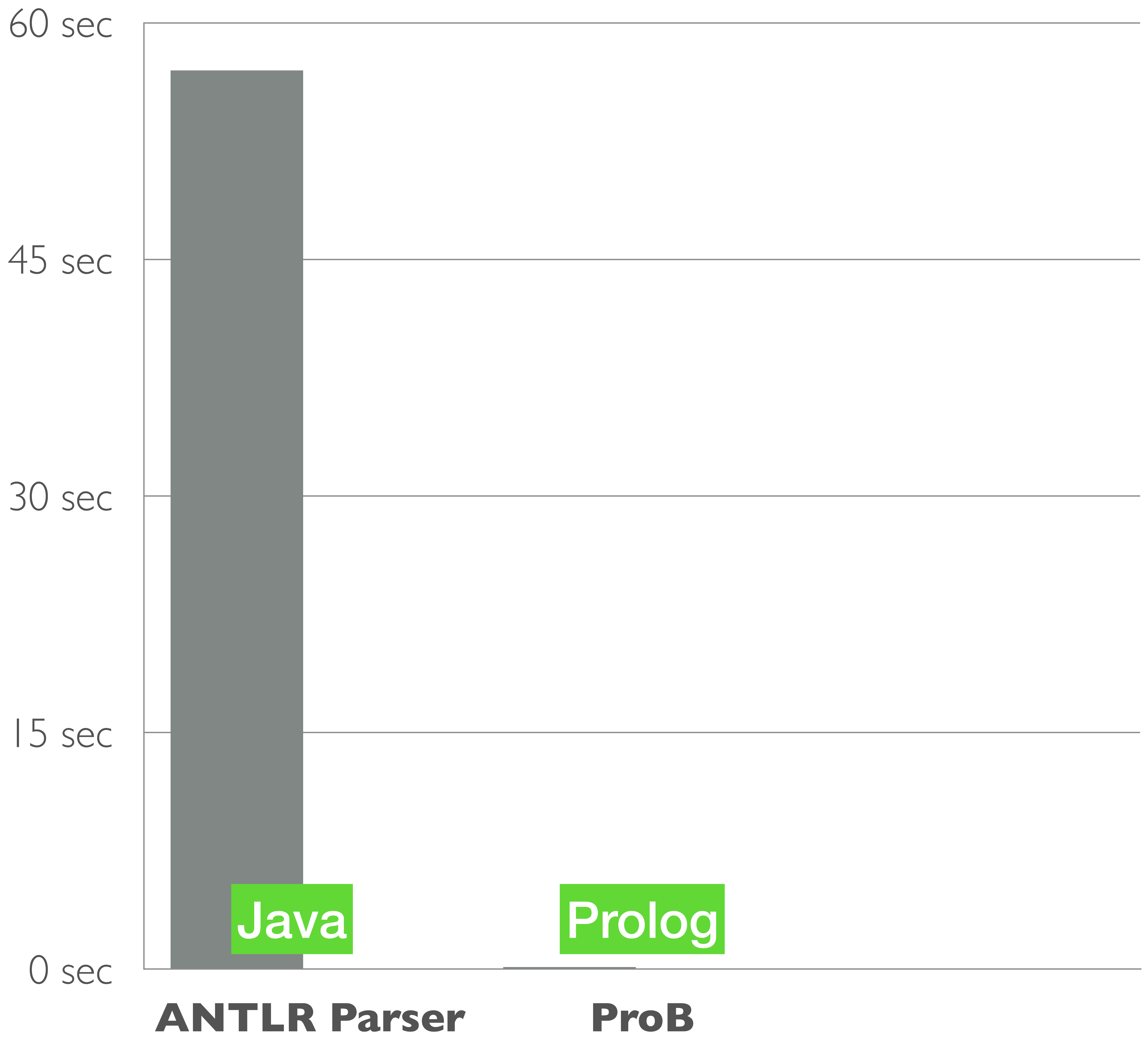
- Easy to encode in Prolog: one type inference rule is one Prolog clause
- More powerful than Atelier-B, …
- cf. VPT-2020 article
- Fast

```
type([],set(_)) --> !, [].
type(union(A,B),set(R)) --> !,type(A,set(R)), type(B,set(R)).
type(intersect(A,B),set(R)) --> !,type(A,set(R)), type(B,set(R)).
type(plus(A,B),integer) --> !,type(A,integer), type(B,integer).
type(in_set(A,B),predicate) --> !,type(A,TA), type(B,set(TA)).
type(gt(A,B),predicate) --> !,type(A,integer), type(B,integer).
type(and(A,B),predicate) --> !,type(A,predicate),type(B,predicate).
type(eq(A,B),predicate) --> !,type(A,TA),type(B,TA).
type(Nr,integer) --> {number(Nr)},!.
type([H|T],set(TH)) --> !,type(H,TH), type(T,set(TH)).
type(ID,TID) --> {identifier(ID)},\+ defined(id(ID,_)),!,
                 add((id(ID,TID))). % creates fresh variable
type(ID,TID) --> {identifier(ID)},defined(id(ID,TID)),!.
type(Expr,T,Env,_) :-
             format('Type error for ~w (expected: ~w, Env: ~w)~n',[Expr,T,Env]),fail.

defined(X,Env,Env) :- member(X,Env).
add(X,Env,[X|Env]).

identifier(ID) :- atom(ID), ID \= [].

type(Expr,Result) :- type(Expr,Result,[],Env), format('Typing env: ~w~n',[Env]).
```

$$\{z\} \cup \{x,y\} = u \wedge z > v$$

```
| ?- type(and(eq(union([z],[x,y]),u),gt(z,v)),R).
Typing env: [id(v,integer),id(u,set(integer)),id(y,integer),id(x,integer),id(z,integer)]
R = predicate ?
yes
```

Anecdotal Evidence:
Typechecking 8000 Line B specification



Semantic Translation Rules: Alloy2B

- Translator of Alloy [Jackson] to B
  - Adaptation of formal semantics of Alloy by simply using B syntax
  - Rules can be translated to Prolog clauses
- First version was written in Kotlin (JVM),
  then switched to Prolog as error prone and tedious to encode rules

$$E[\![p + q]\!]i \;\widehat{=}\; E[\![p]\!]i \cup E[\![q]\!]i$$

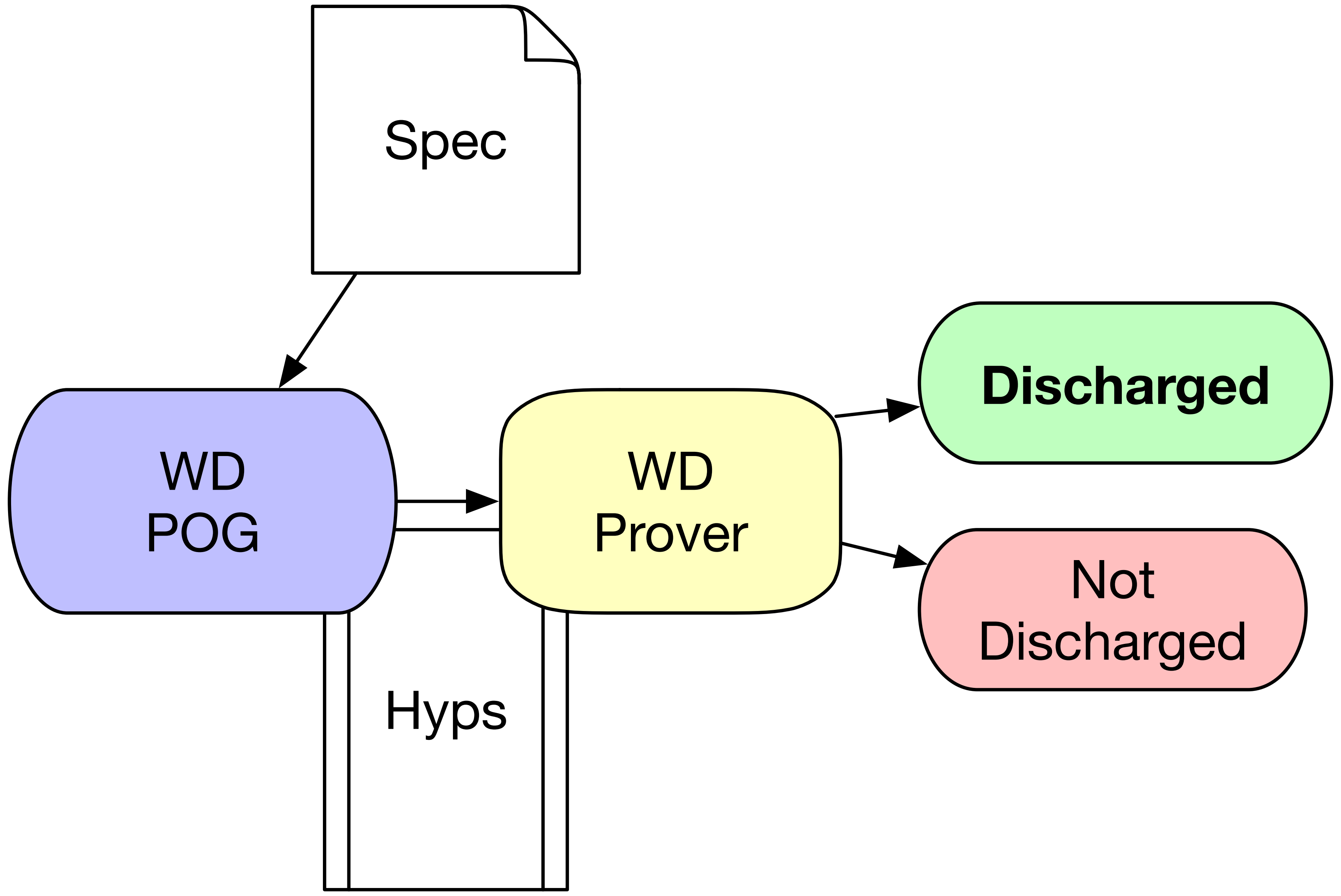
$$E[\![p \;\&\; q]\!]i \;\widehat{=}\; E[\![p]\!]i \cap E[\![q]\!]i$$

$$E[\![p \text{ - } q]\!]i \;\widehat{=}\; E[\![p]\!]i \setminus E[\![q]\!]i$$

```
translate_binary_e_p(Binary, TBinary) :-
    Binary =.. [Op,P,Q,_,POS],
    alloy_to_b_binary_operator(Op, BOp),
    translate_e_p(P, TP),
    translate_e_p(Q, TQ),
    translate_pos(POS, BPOS),
    TBinary =.. [BOp,BPOS,TP,TQ].

alloy_to_b_binary_operator(plus, union).
alloy_to_b_binary_operator(intersection, intersection).
alloy_to_b_binary_operator(minus, set_subtraction).
alloy_to_b_binary_operator(implication, implication).
alloy_to_b_binary_operator(iff, equivalence).
…
```

Prolog Theorem Prover for Proving Well-Definedness

- WD Prover [iFM’2020] to prove absence of division by zero, undefined function applications, cardinality of infinite sets, …
- Shared Hypothesis stack
  - pop via **Prolog backtracking**
  - Only **logarithmic** accesses to Hypotheses
  - Efficient **rule-based prover** using **Prolog unification**



Patterns for Lookups	
$finite(A)$	$A \in B$
$A = B$	$A \neq B$
$A \leq B$	$A \geq B$
$A \subseteq B$	$A \supseteq B$

WD Prover

One WD Prover Rule

“The range of a function is finite if the function is finite.”

```
check_finite(range(A),Hyp,ran(PT))  :- !,
                              check_finite(A,Hyp,PT)
```

Prolog

In Java:
82 lines of code
(9 lines are copyright notice)
The Prolog code is also very flexible:
it can be used for finding proofs
but also for re-playing or
checking proofs if the proof tree argument is provided

Rodin

```
/*******************************************************************************
 * Copyright (c) 2007, 2014 ETH Zurich and others.
 * All rights reserved. This program and the accompanying materials
 * are made available under the terms of the Eclipse Public License v
 * which accompanies this distribution, and is available at
 * http://www.eclipse.org/legal/epl-v10.html
 *
 * Contributors:
 *     ETH Zurich - initial API and implementation
 *******************************************************************************/
package org.eventb.internal.core.seqprover.eventbExtensions;

import org.eventb.core.ast.Expression;
import org.eventb.core.ast.FormulaFactory;
import org.eventb.core.ast.Predicate;
import org.eventb.core.ast.SimplePredicate;
import org.eventb.core.ast.UnaryExpression;
import org.eventb.core.seqprover.IProofMonitor;
import org.eventb.core.seqprover.IProverSequent;
import org.eventb.core.seqprover.IReasonerInput;
import org.eventb.core.seqprover.IReasonerOutput;
import org.eventb.core.seqprover.ProverFactory;
import org.eventb.core.seqprover.ProverRule;
import org.eventb.core.seqprover.SequentProver;
import org.eventb.core.seqprover.IProofRule.IAntecedent;
import org.eventb.core.seqprover.eventbExtensions.Lib;
import org.eventb.core.seqprover.reasonerInputs.EmptyInputReasoner;

public class FiniteRan extends EmptyInputReasoner {

	public static final String REASONER_ID = SequentProver.PLUGIN_ID + ".finiteRan";

	@Override
	public String getReasonerID() {
		return REASONER_ID;
	}

	@ProverRule("FIN_REL_RAN_R")
	protected IAntecedent[] getAntecedents(IProverSequent seq) {
		Predicate goal = seq.goal();

		// goal should have the form finite(ran(r))
		if (!Lib.isFinite(goal))
			return null;
		SimplePredicate sPred = (SimplePredicate) goal;
		if (!Lib.isRan(sPred.getExpression()))
			return null;

		// There will be 1 antecidents
		IAntecedent[] antecidents = new IAntecedent[1];

		UnaryExpression expression = (UnaryExpression) sPred.getExpression();

		Expression r = expression.getChild();

		final FormulaFactory ff = seq.getFormulaFactory();
		// finite(r)
		Predicate newGoal = ff.makeSimplePredicate(Predicate.KFINITE, r, null);
		antecidents[0] = ProverFactory.makeAntecedent(newGoal);

		return antecidents;
	}

	protected String getDisplayName() {
		return "finite of range of a relation";
	}

	@Override
	public IReasonerOutput apply(IProverSequent seq, IReasonerInput input,
			IProofMonitor pm) {
		IAntecedent[] antecidents = getAntecedents(seq);
		if (antecidents == null)
			return ProverFactory.reasonerFailure(this, input,
					"Inference " + getReasonerID()
							+ " is not applicable");

		// Generate the successful reasoner output
		return ProverFactory.makeProofRule(this, input, seq.goal(),
				getDisplayName(), antecidents);
```

Java

https://sourceforge.net/p/rodin-b-sharp/rodincore/ci/master/tree/org.eventb.core.seqprover/src/org/eventb/internal/core/seqprover/eventbExtensions/FiniteRan.java

WD Prover

```prolog
check_finite(range(A),Hyp,ran(PT)) :- !,
                  check_finite(A,Hyp,PT)
```

Prolog

```java
public class FiniteRan extends EmptyInputReasoner {

    public static final String REASONER_ID = SequentProver.PLUGIN_

    @Override
    public String getReasonerID() {
        return REASONER_ID;
    }

    @ProverRule("FIN_REL_RAN_R")
    protected IAntecedent[] getAntecedents(IProverSequent seq) {
        Predicate goal = seq.goal();

        // goal should have the form finite(ran(r))
        if (!Lib.isFinite(goal))
            return null;
        SimplePredicate sPred = (SimplePredicate) goal;
        if (!Lib.isRan(sPred.getExpression()))
            return null;

        // There will be 1 antecidents
        IAntecedent[] antecidents = new IAntecedent[1];

        UnaryExpression expression = (UnaryExpression) sPred.getEx

        Expression r = expression.getChild();

        final FormulaFactory ff = seq.getFormulaFactory();
        // finite(r)
        Predicate newGoal = ff.makeSimplePredicate(Predicate.KFINI
        antecidents[0] = ProverFactory.makeAntecedent(newGoal);
```

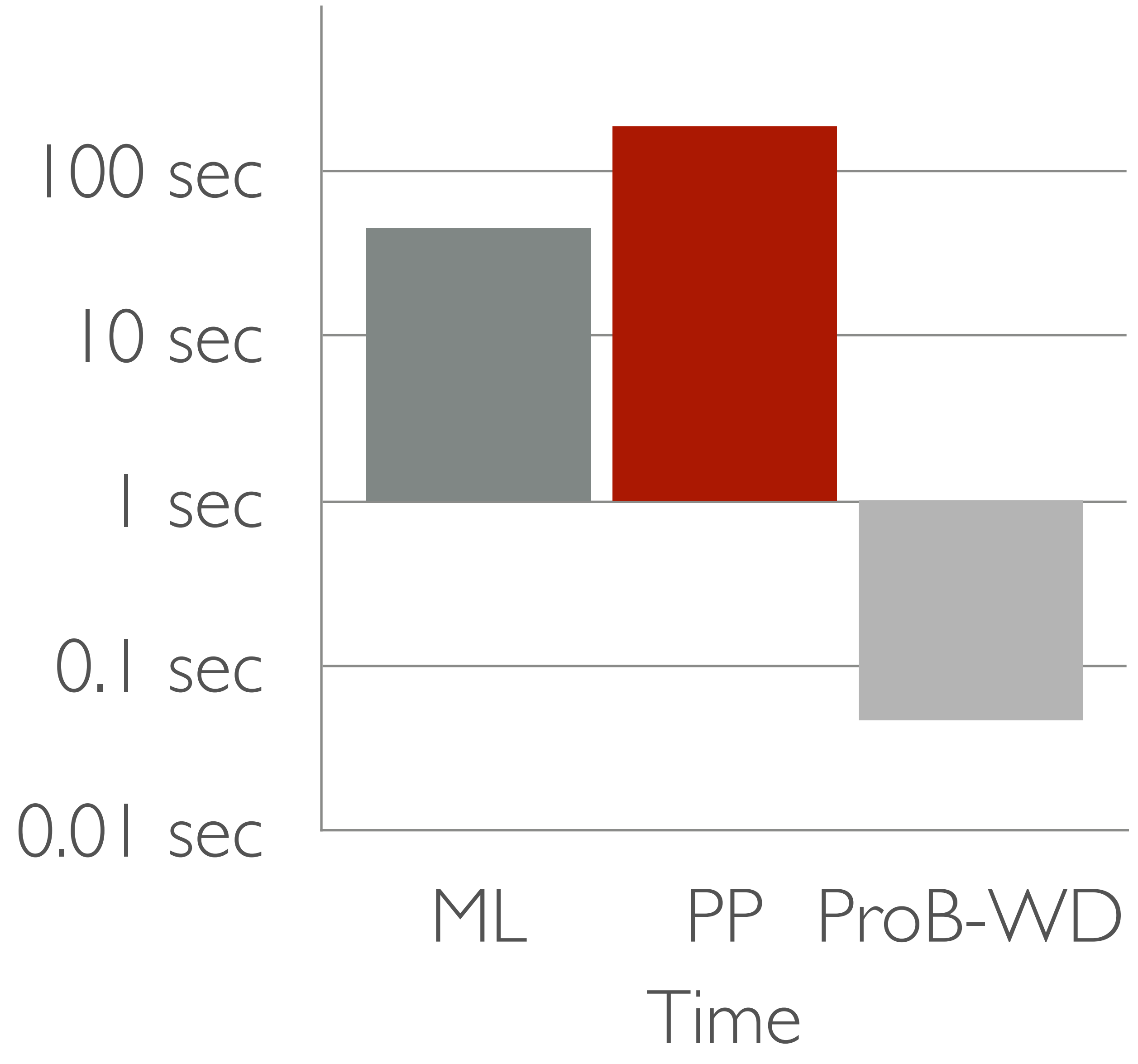
Java

WD Prover

Biased Benchmarks

- Test Atelier-B provers ML, PP and Z3 on 413 POs from ProB regression tests

- **Biased**, but shows that our prover is **fast** and can prove POs not proven by existing provers (in default settings)



Prover	Proved	Unproved	Ctrl-C	Min.	Max.	Total	w/o Min.
ProB-WD	413	0	0	0.000 sec	0.006 sec	0.047 sec	0.047 sec
ML	190	223	0	0.260 sec	18.725 sec	152.633 sec	45.253 sec
PP	230	165		0.092 sec	49.144 sec	222.940 sec	186.600 sec
			18			1017.406 sec	-
Z3	9	14	0	0.007 sec	2.520 sec	crash	-

A few more commandments

- Thou Shalt Honour Text and Command-Line Interfaces:
  - Text and command-line tools are not dead yet
- Thou Shalt Think Twice before Redeveloping your Tool from Scratch
  - Redeveloping a tool or even a UI from scratch is hard and will take longer than you think

- Thou Shalt Obtain User Feedback and User Your Own Tool
  - make it easy for users to provide feedback; use your tool yourself

Summary: Thou Shalt

I. Thou Shalt

1. Animate Your Models
2. Visualize Your Models
3. Reuse Ideas, not Models
4. Not Abandon Thy Traditional Formal Proof Methods
5. Use Models as Documentation
6. Execute Your Models

II. Thou Shalt

7. Choose an Appropriate Notation/Programming Language for Your Tool
8. Honour Text and Command-Line Interfaces
9. Think Twice before Redeveloping your Tool from Scratch
10. Obtain User Feedback and User Your Own Tool

Outlook: New Projects

- IVOIRE (with Univ. Linz)
  - Automate Validation in a Refinement-based Development Process
- KI-LOK
  - Certifying Railway Systems with AI

Formal Methods in Industry

- Formal methods in general and **B** in particular can be used to verify/validate:
  - **code** of individual components
  - **systems** consisting of components (algorithms, design,…)
  - **configurations** of components
- Formal methods have become much more useful thanks to **progress** in proof, constraint solving (SAT, SMT, CLP), visualization
  - tools can find errors which no human could ever find
  - tools can guarantee the absence of certain errors
  - tools can help visualize and understand very complex systems, behaviours and interactions

Danny De Schreye
Maurice Bruynooghe
Bart Demoen
Marc Denecker
Bern Martens
Wim Vanhoof

Robert Glück
Neil D. Jones
Jesper Jørgensen
Torben Mogensen

Fabio Fioravanti
Alberto Pettorossi
Maurizio Proietti
Emanuele De Angelis

John Gallagher
Manual Hermenegildo
German Puebla
Josep Silva
Salvador Tamarit
German Vidal

Kostis Sagonas
and many more

Thank you very much

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Philipp Körner
Sebastian Krings
Lukas Ladenberger
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Thierry Massart
Daniel Plagge

Antonia Pütz
Mireille Samia
Joshua Schmidt
David Schneider
Corinna Spermann
Sebastian Stock
Yumiko Takahashi
Edd Turner
Michelle Werth
Dennis Winter
Fabian Vu

Alstom (Fernando Mejia,...)
ClearSy (Thierry Lecomte,...)
Siemens
Systerel
Thales (Nader Nayeri, Georg Hemzal,...)