

ATELIER EVENT-B/RODIN

INTRODUCTION À LA MÉTHODE EVENT-B ET SES DIFFÉRENTS OUTILS

🎓 TAPAS-ANR meeting

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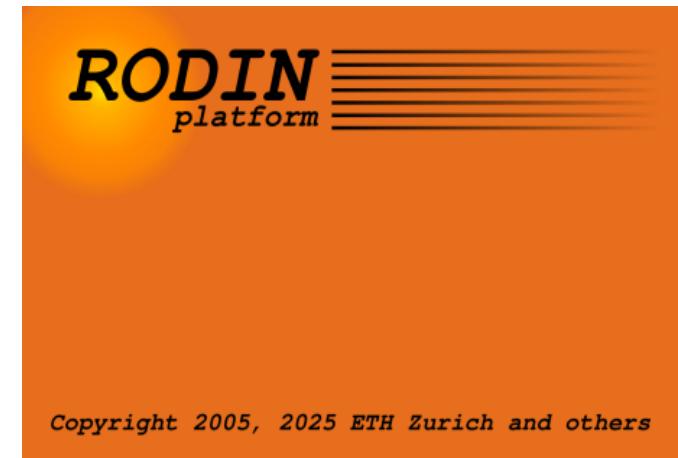
OUTLINE

- The Event-B method
- The Pro-B animator/model-checker
- The Theory plugin

[Back to the outline](#) - [Back to the begin](#)

THE RODIN PLATFORM

- The **Rodin** platform (an **Eclipse-based IDE**) is intended to support the construction and verification of **Event-B models**.
 - provides effective support for **refinement** and **mathematical proof**.
 - **plugins** for editing models, generating proof obligations, proving, animating, model-checking, code generating ...
- **Rodin Platform and Plug-in Installation:**
 - Requires **Java JRE** (version 17 or later) → www.oracle.com/fr/java/.
 - Download the Core → sourceforge.net/projects/rodin-b-sharp/.



RODIN ON MACS

Procedure to run the Intel version of Rodin on macs with Apple Silicon processors:

1. download [this JDK](#) (it's a Java 17 runtime for Intel)
2. install it by double-clicking it; the Java runtime is installed in
[`/Library/Java/JavaVirtualMachines/temurin-17.jre`](#)
3. find the downloaded [`Rodin.app`](#) and modify the file
[`Rodin.app/Contents/Eclipse/rodin.ini`](#)
 - add the next two lines just before the one with [`-vmargs`](#)

```
-vm
/Library/Java/JavaVirtualMachines/temurin-17.jre/Contents/Home/bin/java
```

4. as with all other Rodin releases for mac, one also needs to execute

```
$ xattr -rc Rodin.app
```



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THE RODIN PLATFORM

Required plugins for this tutorial :

menu : **Help -> Install New Software ...**

- the **Atelier B Provers plugin** from the **Atelier B Provers** Update site.

https://www.atelierb.eu/update_site/atelierb_provers

- the **ProB plugin** from the **ProB** Update site.

<https://stups.hhu-hosting.de/rodin/prob1/release/>

- the **Theory plugin** from the **Rodin Plug-ins (archive)** Update site.

<https://rodin-b-sharp.sourceforge.net/updates-archive>

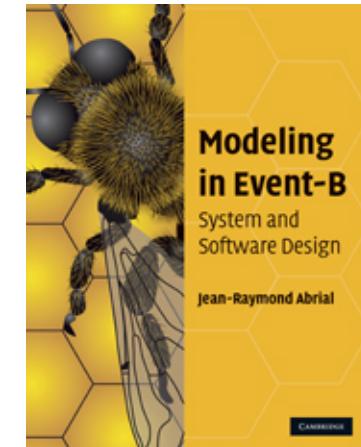
OUTLINE

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[Back to the outline](#) - [Back to the begin](#)

THE EVENT-B METHOD

- The **Event-B method** is an evolution of the **classical B method**.
 - modeling a system by a **set of events** instead of **operations**.
- The **Event-B method** is a **formal method** based on **first-order logic** and **set theory**.
- The **Event-B method** is based on :
 - the notions of pre-conditions and post-conditions (**Hoare**),
 - the **weakest pre-condition** (**Dijkstra**),
 - and the **calculus of substitution** (**Abrial**).
- The **Event-B method** is adapted to analyse **discrete systems**.
 - offers the possibility of modelling **discrete behaviors**.



THE EVENT-B METHOD

THE STATE OF A MODEL

- A discrete model is first made of a **state**
- The state is represented by some **constants** and **variables**
- Constants are linked by some **properties**
- Variables are linked by some **invariants**
- Properties and invariants are written using **set-theoretic expressions**

THE EVENT-B METHOD

THE EVENTS OF A MODEL (TRANSITIONS)

- A discrete model is also made of a number of events
- An event is made of a guard and an action
- The guard denotes the enabling condition of the event
- The action denotes the way the state is modified by the event
- Guards and actions are written using set-theoretic expressions

THE EVENT-B METHOD

A MODEL SCHEMATIC VIEW

CONTEXT ctx_1
EXTENDS ctx_2

SETS s
CONSTANTS c
AXIOMS
 $A(s, c)$
THEOREMS
 $T(s, c)$
END

MACHINE mch_1
REFINES mch_2
SEES ctx_i

VARIABLES v
INVARIANTS
 $I(s, c, v)$
THEOREMS
 $T(s, c, v)$
EVENTS
 $[events_list]$
END

event $\hat{=}$
any x
where
 $G(s, c, v, x)$
then
 $BA(s, c, v, x, v')$
end

THE EVENT-B METHOD

OPERATIONAL INTERPRETATION

```
Initialize;  
while (some events have true guards) {  
    Choose one such event;  
    Modify the state accordingly  
}
```

- An event execution is supposed to **take no time**
- Thus, **no two events can occur simultaneously**
- When all events have false guards, the **discrete system stops**
- When some events have true guards, **one of them** is chosen non-deterministically and **its action modifies the state**
- The previous phase is **repeated** (if possible)

THE EVENT-B METHOD

COMMENTS ON THE OPERATIONAL INTERPRETATION

- Stopping is not necessary: a discrete system may run for ever
- This interpretation is just given here for informal understanding
- The meaning of such a discrete system will be given by the proofs which can be performed on it

BUILDING LARGE COMPUTERIZED SYSTEMS

REFINEMENT

- Refinement allows us to build model *gradually*
- We shall build an *ordered sequence* of more precise models
- Each model is a *refinement* of the one preceding it
- A useful analogy: looking through a *microscope*
- *Spatial* as well as *temporal* extensions
- *Data refinement*



PURPOSE OF THIS LECTURE

- To present an **example of system development**
- Our approach → a series of **more and more accurate models**
- This approach is called **refinement**
- The models formalize the view of an **external observer**
- With each refinement **observer “zooms in”** to see more details

PURPOSE OF THIS LECTURE

- Each model will be analyzed and **proved to be correct**
- The **aim** is to obtain a system that will be **correct by construction**
- The **correctness criteria** are formulated as **proof obligations**
- **Proofs** will be performed by using the **sequent calculus**
- **Inference rules** used in the sequent calculus will be **reviewed**

THE EVENT-B METHOD

MODELS AND PROOF OBLIGATIONS

CONTEXT ctx_1
EXTENDS ctx_2

SETS s
CONSTANTS c
AXIOMS
 $A(s, c)$
THEOREMS
 $T(s, c)$
END

MACHINE mch_1
REFINES mch_2
SEES ctx_i

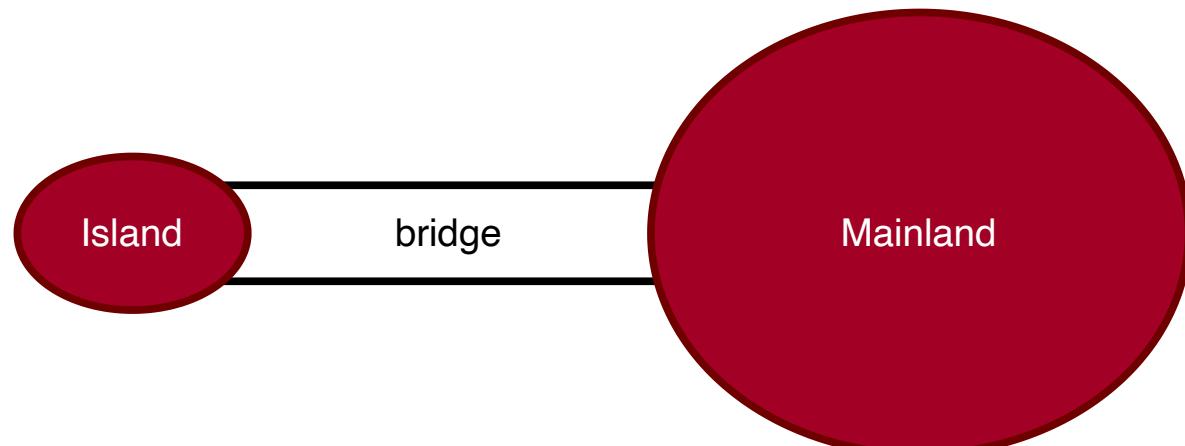
VARIABLES v
INVARIANTS
 $I(s, c, v)$
THEOREMS
 $T(s, c, v)$
EVENTS
 $[events_list]$
END

event $\hat{=}$
any x
where
 $G(s, c, v, x)$
then
 $BA(s, c, v, x, v')$
end

$$\begin{aligned} A(s, c) &\vdash T(s, c) \\ A(s, c) \wedge I(s, c, v) &\vdash T(s, c, v) \\ A(s, c) \wedge I(s, c, v) \wedge G(s, c, v, x) &\vdash \exists v'. BA(s, c, v, x, v') \\ A(s, c) \wedge I(s, c, v) \wedge G(s, c, v, x) \wedge BA(s, c, v, x, v') &\vdash I(s, c, v') \\ \dots \end{aligned}$$

A REQUIREMENTS DOCUMENT

- The function of this system is to **control cars** on a **narrow bridge**.
- This bridge is supposed to link the **mainland** to a small **island**.
- **FUN-1** → controlling cars on a bridge between the mainland and an island.
- **FUN-2** → the number of cars on the bridge and the island is limited.
- **FUN-3** → the bridge is one way or the other, not both at the same time.



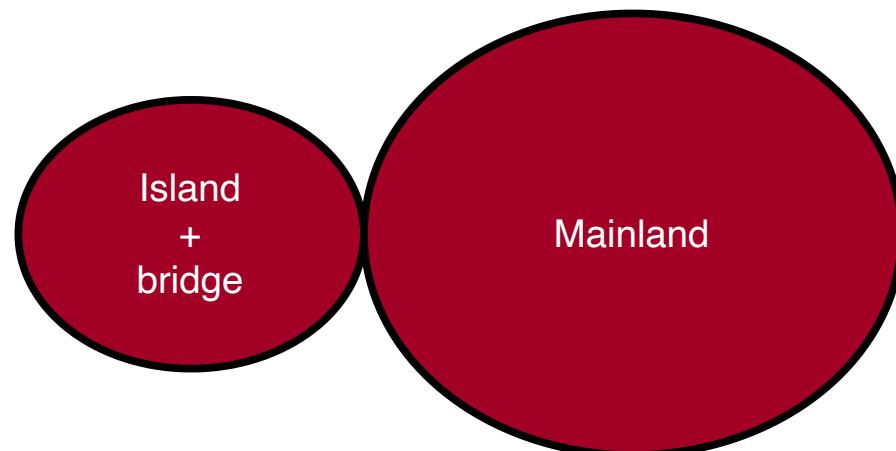
OUR REFINEMENT STRATEGY

- **Initial model** → Limiting the number of cars (**FUN-2**)
- **First refinement** → Introducing the one way bridge (**FUN-1, FUN-3**)

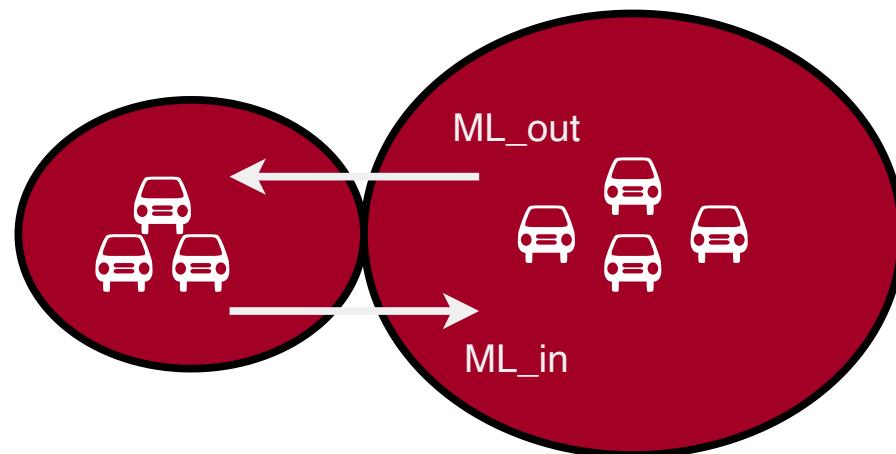
OUR REFINEMENT STRATEGY

- **Initial model** → Limiting the number of cars (**FUN-2**)
 - It is **very simple**
 - We do not even consider the bridge
 - We are just interested in the **pair “island-bridge”**
 - We are focusing **FUN-2** → limited number of cars on island-bridge
- **First refinement** → Introducing the one way bridge (**FUN-1, FUN-3**)

A SITUATION AS SEEN FROM THE SKY



TWO EVENTS THAT MAY BE OBSERVED



FORMALIZING THE STATE

- STATIC PART of the state → constant d with axiom axm0_1

CONSTANTS

d

AXIOMS

$\text{axm0_1}: d \in \mathbb{N}$

- d is the maximum number of cars allowed on the Island-Bridge
- axm0_1 states that d is a natural number
- Constant d is a member of the set $\mathbb{N} = \{0, 1, 2, \dots\}$

FORMALIZING THE STATE

- DYNAMIC PART of the state → variable n with invariants inv0_1 and inv0_2

VARIABLES

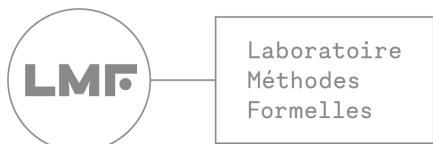
n

INVARIANTS

$\text{inv0_1}: n \in \mathbb{N}$

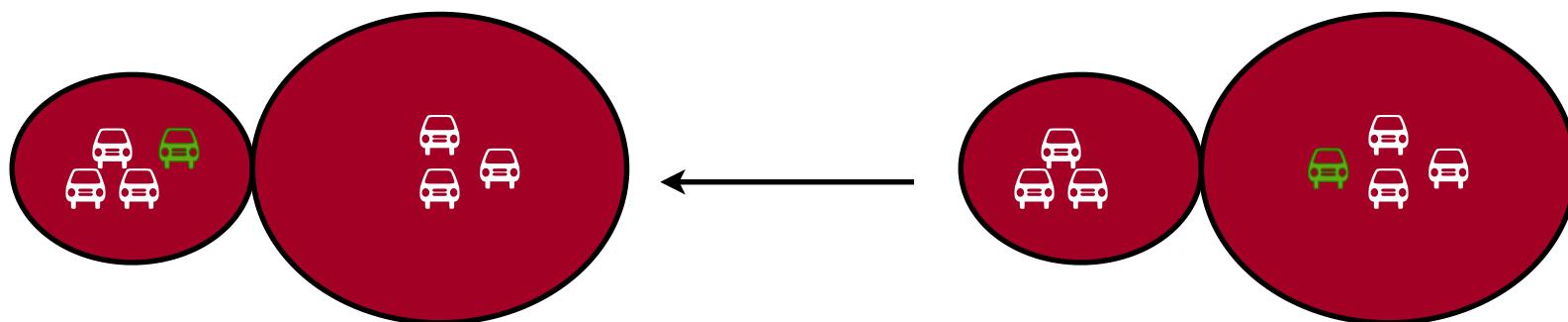
$\text{inv0_2}: n \leq d$

- n is the effective number of cars on the Island-Bridge
- n is a natural number (inv0_1)
- n is always smaller than or equal to d (inv0_2) → this is FUN 2



EVENT ML_out

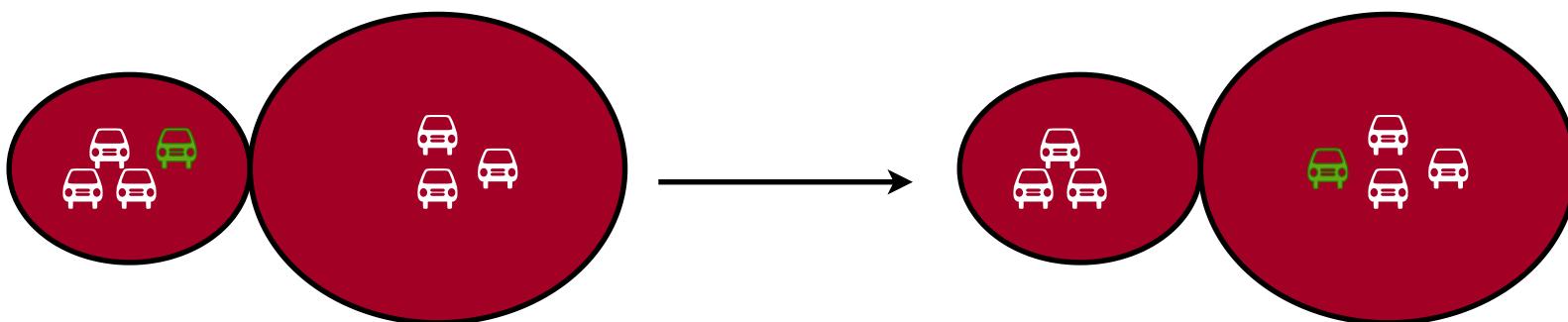
- This is the **first transition** (or event) that can be **observed**
- A car is leaving the mainland and entering the Island-Bridge



- The **number of cars** in the Island-Bridge is **incremented**

EVENT ML_in

- We can also observe a **second transition** (or event)
- A car leaving the Island-Bridge and re-entering the mainland



- The **number of cars** in the Island-Bridge is **decremented**

FORMALIZING THE TWO EVENTS (APPROXIMATION)

- An event is denoted by its **name** and its **action** (an assignment)
- Event **ML_out increments** the number of cars

```
ML_out ≡  
  then  
    act0_1: n := n + 1  
  end
```

- Event **ML_in decrements** the number of cars

```
ML_in ≡  
  then  
    act0_1: n := n - 1  
  end
```

WHY AN APPROXIMATION?

- These events are approximations for **two reasons**:
 1. They might be **insufficient** at this stage because **not consistent with the invariant**
 2. They might be **refined** (made more precise) later
- We have to perform a **proof** in order to **verify this consistency**.

INVARIANTS

- An invariant is a **constraint** on the allowed values of the variables
- An invariant **must hold on all reachable states** of a model
- To verify that this holds we must show that
 1. the invariant holds for **initial states**, and
 2. the invariant is **preserved by all events**
- We will formalize these two statements as **proof obligations (POs)**
- We need a **rigorous proof** showing that these POs indeed hold



BEFORE-AFTER PREDICATES

- To each event can be associated a **before-after predicate**
- It describes the **relation** between the **values** of the variable(s) **just before** and **just after** the event occurrence
- The **before-value** is denoted by the **variable name**, say n
- The **after-value** is denoted by the **primed variable name**, say n'

BEFORE-AFTER PREDICATES

EXAMPLE

► The events

```
ML_out ≡  
  then  
    act0_1: n := n + 1  
  end
```

```
ML_in ≡  
  then  
    act0_1: n := n - 1  
  end
```

► The corresponding before-after predicates

$$n' = n + 1$$

$$n' = n - 1$$

These representations are equivalent.

ABOUT THE SHAPE OF THE BEFORE-AFTER PREDICATES

- The before-after predicates we have shown are **very simple**

$$n' = n + 1$$

$$n' = n - 1$$

- The after-value n' is defined as a **function** of the before-value n
- This is because the corresponding events are **deterministic**
- We shall also consider some **non-deterministic** events

$$n' \in \{n + 1, n + 2\}$$

INTUITION ABOUT INVARIANT PRESERVATION

- Let us consider invariant `inv0_1`

$$n \in \mathbb{N}$$

- And let us consider event `ML_out` with before-after predicate

$$n' = n + 1$$

- Preservation of `inv0_1` means that we have (just after `ML_out`):

$$n' \in \mathbb{N} \quad \text{that is} \quad n + 1 \in \mathbb{N}$$

BEING MORE PRECISE

- Under hypothesis $n \in \mathbb{N}$ the conclusion $n + 1 \in \mathbb{N}$ holds
- This can be written as follows

$$n \in \mathbb{N} \quad \vdash \quad n + 1 \in \mathbb{N}$$

- This type of statement is called a **sequent**
- Sequent above → invariant preservation proof obligation for `inv0_1`

PROOF OBLIGATION

INVARIANT PRESERVATION

- We are given an **event** with **before-after predicate** $v' = E(c, v)$
- The following sequent expresses **preservation of invariant** $I_i(c, v)$

$$INV : A(c), I(c, v) \quad \vdash \quad I_i(c, E(c, v))$$

- It says $\rightarrow I_i(c, E(c, v))$ provable under hypotheses $A(c)$ and $I(c, v)$
- We have given the name ***INV*** to this proof obligation

VERTICAL LAYOUT OF PROOF OBLIGATIONS

- ➡ The proof obligation

$$INV : A(c), I(c, v) \vdash I_i(c, E(c, v))$$

- ➡ can be re-written vertically as follows

Axioms	$A(c)$
Invariants	$I(c, v)$
\vdash	\vdash
Modified Invariant	$I_i(c, E(c, v))$

BACK TO OUR EXAMPLE

- ⇒ We have two events

```
ML_out ≡  
  then  
    act0_1: n := n + 1  
  end
```

```
ML_in ≡  
  then  
    act0_1: n := n - 1  
  end
```

- ⇒ ... and two invariants

inv0_1: $n \in \mathbb{N}$

inv0_2: $n \leq d$

- ⇒ Thus, we need to prove four proof obligations

PROOF OBLIGATION FOR **ML_out** AND **inv0_1**

```
ML_out  $\hat{=}$ 
then
  act0_1:  $n := n + 1 \ // \ n' = n + 1$ 
end
```

Axioms axm0_1	$d \in \mathbb{N}$
Invariant inv0_1	$n \in \mathbb{N}$
Invariant inv0_2	$n \leq d$
\vdash	\vdash
Modified Invariant inv0_1	$n + 1 \in \mathbb{N}$

This proof obligation is named **ML_out/inv0_1/INV**

PROOF OBLIGATION FOR **ML_out** AND **inv0_2**

```
ML_out  $\hat{=}$ 
then
  act0_1:  $n := n + 1 \ // \ n' = n + 1$ 
end
```

Axioms axm0_1	$d \in \mathbb{N}$
Invariant inv0_1	$n \in \mathbb{N}$
Invariant inv0_2	$n \leq d$
\vdash	\vdash
Modified Invariant inv0_2	$n + 1 \leq d$

This proof obligation is named **ML_out/inv0_2/INV**

PROOF OBLIGATION FOR ML_in AND inv0_1

```
ML_in  $\hat{=}$ 
      then
        act0_1: n := n - 1 // n' = n - 1
      end
```

Axioms axm0_1	$d \in \mathbb{N}$
Invariant inv0_1	$n \in \mathbb{N}$
Invariant inv0_2	$n \leq d$
\vdash	\vdash
Modified Invariant inv0_1	$n - 1 \in \mathbb{N}$

This proof obligation is named ML_in/inv0_1/INV

PROOF OBLIGATION FOR **ML_in** AND **inv0_2**

```
ML_in  $\hat{=}$ 
      then
        act0_1:  $n := n - 1 \ // \ n' = n - 1$ 
      end
```

Axioms axm0_1	$d \in \mathbb{N}$
Invariant inv0_1	$n \in \mathbb{N}$
Invariant inv0_2	$n \leq d$
\vdash	\vdash
Modified Invariant inv0_2	$n - 1 \leq d$

This proof obligation is named: **ML_in/inv0_2/INV**

SUMMARY OF PROOF OBLIGATIONS

ML_out/inv0_1/INV

$d \in \mathbb{N}$

$n \in \mathbb{N}$

$n \leq d$

\vdash

$n + 1 \in \mathbb{N}$

ML_in/inv0_1/INV

$d \in \mathbb{N}$

$n \in \mathbb{N}$

$n \leq d$

\vdash

$n - 1 \in \mathbb{N}$

ML_out/inv0_2/INV

$d \in \mathbb{N}$

$n \in \mathbb{N}$

$n \leq d$

\vdash

$n + 1 \leq d$

ML_in/inv0_2/INV

$d \in \mathbb{N}$

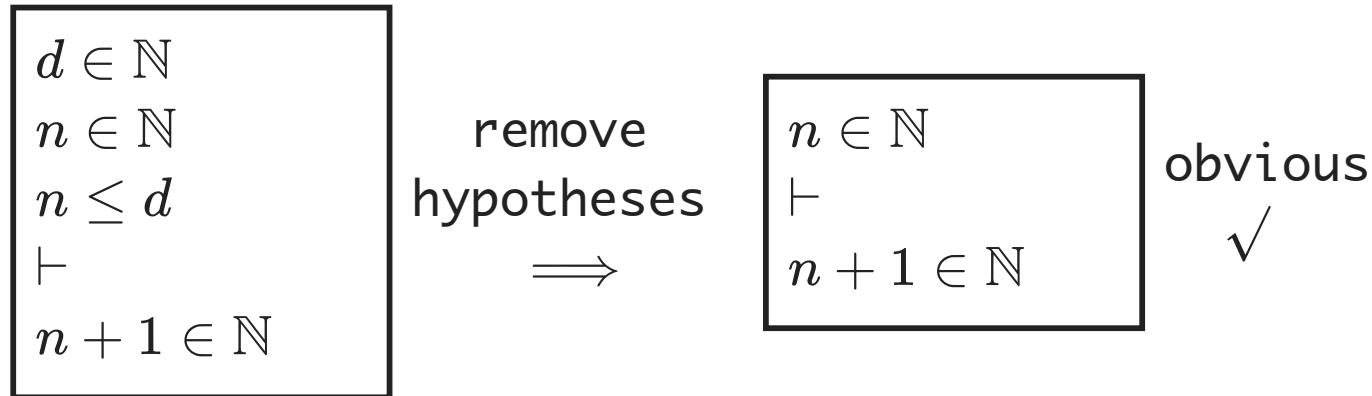
$n \in \mathbb{N}$

$n \leq d$

\vdash

$n - 1 \leq d$

INFORMAL PROOF OF $\text{ML_out}/\text{inv0_1}/\text{INV}$



- In the first step, we remove some irrelevant hypotheses
- In the second and final step, we accept the sequent as it is
- We have implicitly applied inference rules
- For rigorous reasoning we will make these rules explicit

INFERENCE RULES

MONOTONICITY OF HYPOTHESES

- The rule that removes hypotheses can be stated as follows:

$$\frac{H \vdash G}{H, H' \vdash G} \quad \text{MON}$$

- It expresses the **monotonicity** of the hypotheses

SOME ARITHMETIC INFERENCE RULES

THE SECOND PEANO AXIOM

$$\frac{}{n \in \mathbb{N} \vdash n + 1 \in \mathbb{N}} \text{P2}$$

$$\frac{}{0 < n \vdash n - 1 \in \mathbb{N}} \text{P2'}$$

MORE ARITHMETIC INFERENCE RULES

AXIOMS ABOUT ORDERING RELATIONS ON THE INTEGERS

$$\frac{}{n < m \quad \vdash \quad n + 1 \leq m} \quad \text{INC}$$

$$\frac{}{n \leq m \quad \vdash \quad n - 1 \leq m} \quad \text{DEC}$$

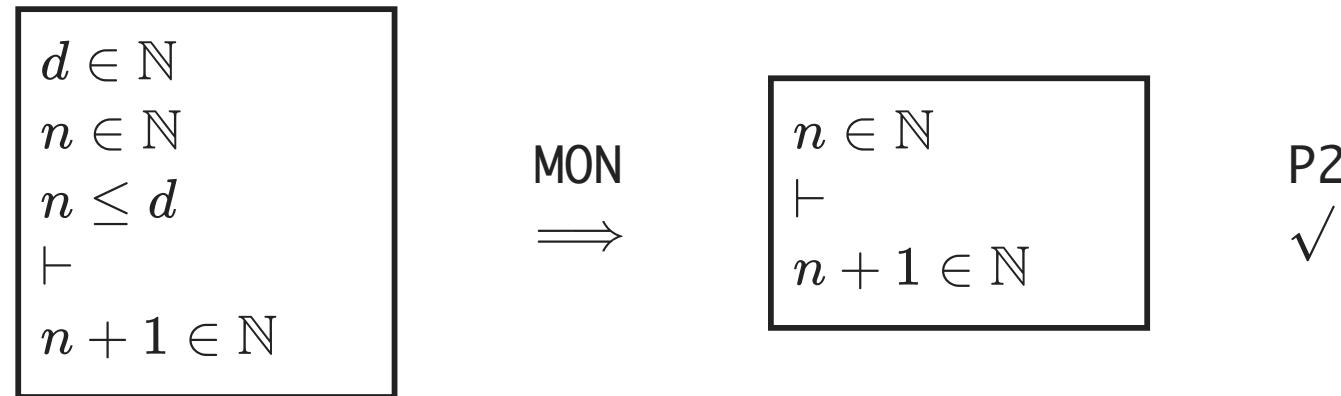
All inference rules implemented in Rodin are available [here](#)



PROOFS

- A **proof** is a **tree of sequents** with axioms at the leaves.
- The rules applied to the **leaves** are **axioms**.
- Each sequent is **labeled with** (name of) **proof rule** applied to it.
- The sequent at the root of the tree is called the **root sequent**.
- The **purpose** of a proof is to establish the **truth** of its root sequent.

A FORMAL PROOF OF $\text{ML_out}/\text{inv0_1}/\text{INV}$



Proof requires only application of two rules → **MON** and **P2**

A FAILED PROOF ATTEMPT

ML_out/inv0_2/INV

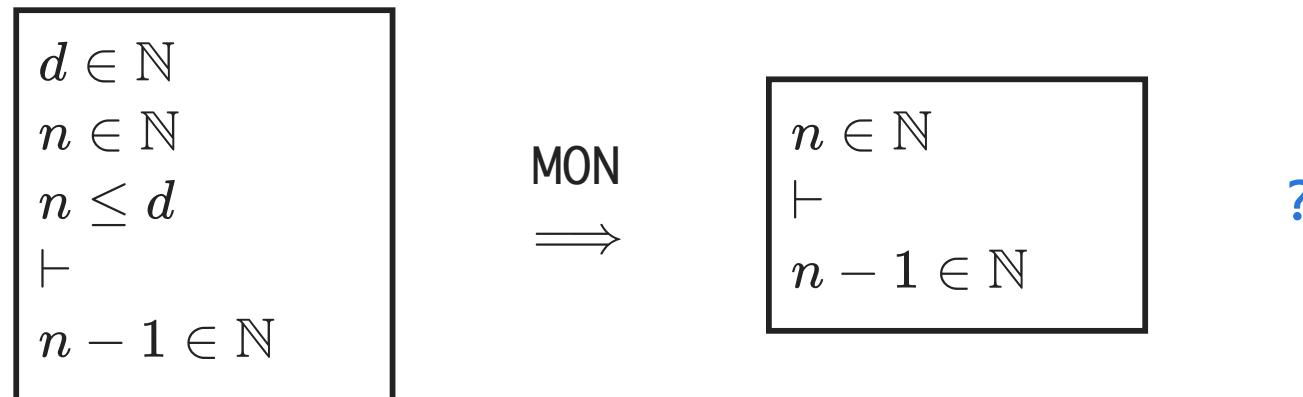
$$\boxed{\begin{array}{l} d \in \mathbb{N} \\ n \in \mathbb{N} \\ n \leq d \\ \vdash \\ n + 1 \leq d \end{array}} \xrightarrow{\text{MON}} \boxed{\begin{array}{l} n \leq d \\ \vdash \\ n + 1 \leq d \end{array}} ?$$

- We put a **?** to indicate that we have no rule to apply
- **The proof fails** → we cannot conclude with rule INC ($n < d$ needed)

$$\frac{}{n < m \quad \vdash \quad n + 1 \leq m} \text{INC}$$

A FAILED PROOF ATTEMPT

ML_in/inv0_1/INV



- **The proof fails** → we cannot conclude with rule P2' ($0 < n$ needed)

$$\frac{}{0 < n \quad \vdash \quad n - 1 \in \mathbb{N}} \text{P2'}$$

A FORMAL PROOF OF ML_in/inv0_2/INV

$$\frac{\boxed{\begin{array}{l} d \in \mathbb{N} \\ n \in \mathbb{N} \\ n \leq d \\ \vdash \\ n - 1 \leq d \end{array}} \quad \xrightarrow{\text{MON}} \quad \boxed{\begin{array}{l} n \leq d \\ \vdash \\ n - 1 \leq d \end{array}} \quad \checkmark}{n \leq m \quad \vdash \quad n - 1 \leq m} \quad \text{DEC}$$

REASONS FOR PROOF FAILURE

- We needed hypothesis $n < d$ to prove $\text{ML_out}/\text{inv0_2}/\text{INV}$
- We needed hypothesis $0 < n$ to prove $\text{ML_in}/\text{inv0_1}/\text{INV}$

$$\begin{aligned}\text{ML_out} \triangleq \\ \text{then} \\ \text{act0_1: } n := n + 1 \\ \text{end}\end{aligned}$$
$$\begin{aligned}\text{ML_in} \triangleq \\ \text{then} \\ \text{act0_1: } n := n - 1 \\ \text{end}\end{aligned}$$

- We are going to add $n < d$ as a guard to event ML_out
- We are going to add $0 < n$ as a guard to event ML_in

IMPROVING THE EVENTS

INTRODUCING GUARDS

```
ML_out ≡  
when  
  grd0_1: n < d  
then  
  act0_1: n := n + 1  
end
```

```
ML_in ≡  
when  
  grd0_1: 0 < n  
then  
  act0_1: n := n - 1  
end
```

- We are adding **guards** to the events
- The guard is the **necessary condition** for an event to *occur*

PROOF OBLIGATION

GENERAL INVARIANT PRESERVATION

- Given c with axioms $A(c)$ and v with invariants $I(c, v)$
- Given an event with guard $G(c, v)$ and b-a predicate $v' = E(c, v)$
- We modify the **Invariant Preservation PO** as follows:

Axioms

$A(c)$

Invariants

$I(c, v)$

Guard of the event

$G(c, v)$

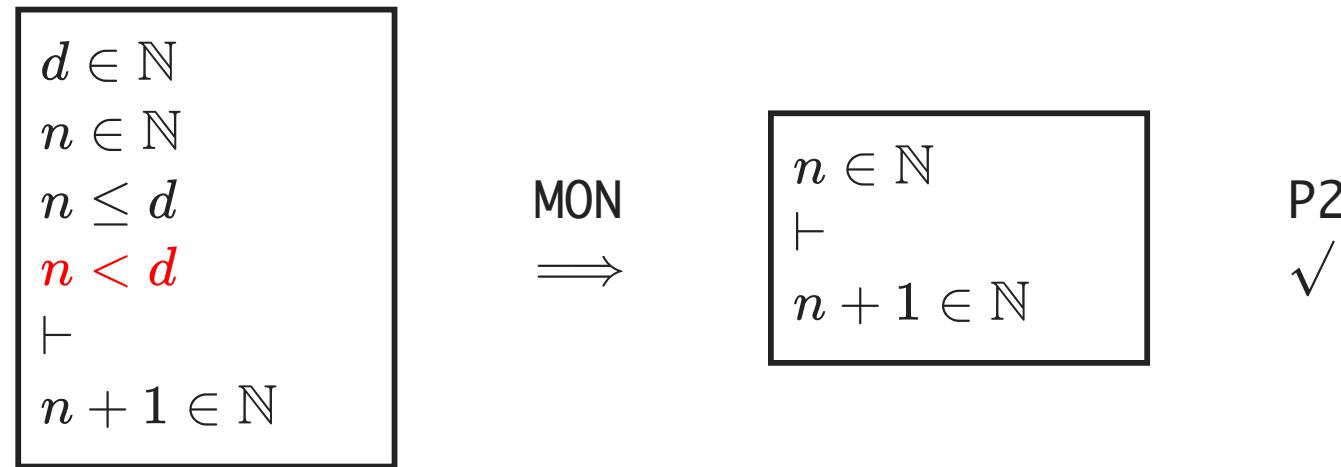
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Modified Invariant

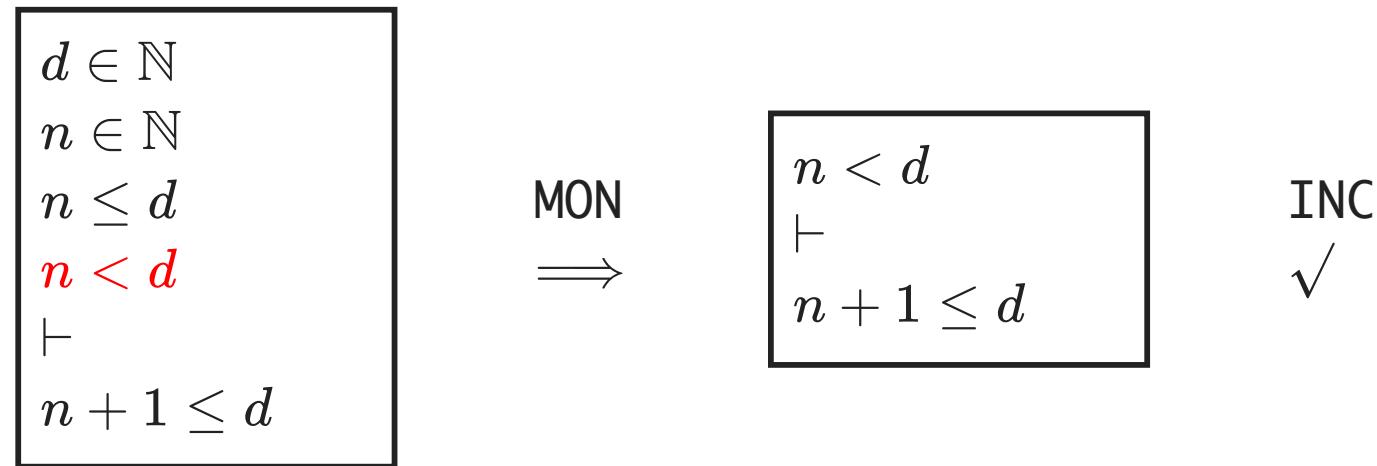
$I_i(c, E(c, v))$

A FORMAL PROOF OF $\text{ML_out}/\text{inv0_1}/\text{INV}$



Adding new assumptions to a sequent **does not affect its provability**

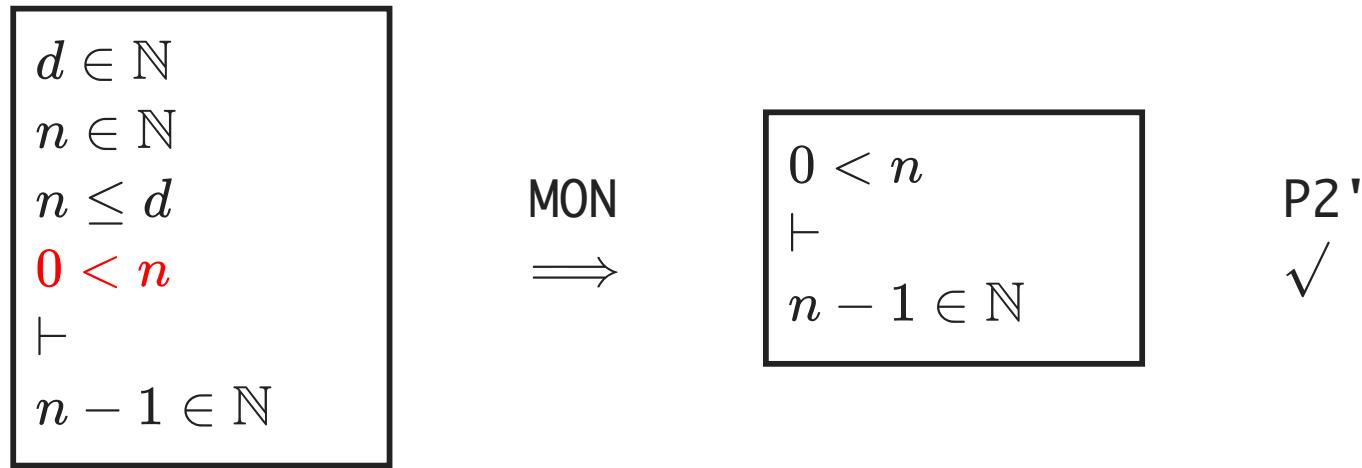
A FORMAL PROOF OF $\text{ML_out}/\text{inv0_2}/\text{INV}$



- Now we can conclude the proof using rule INC

$$\frac{}{n < m \quad \vdash \quad n + 1 \leq m} \text{INC}$$

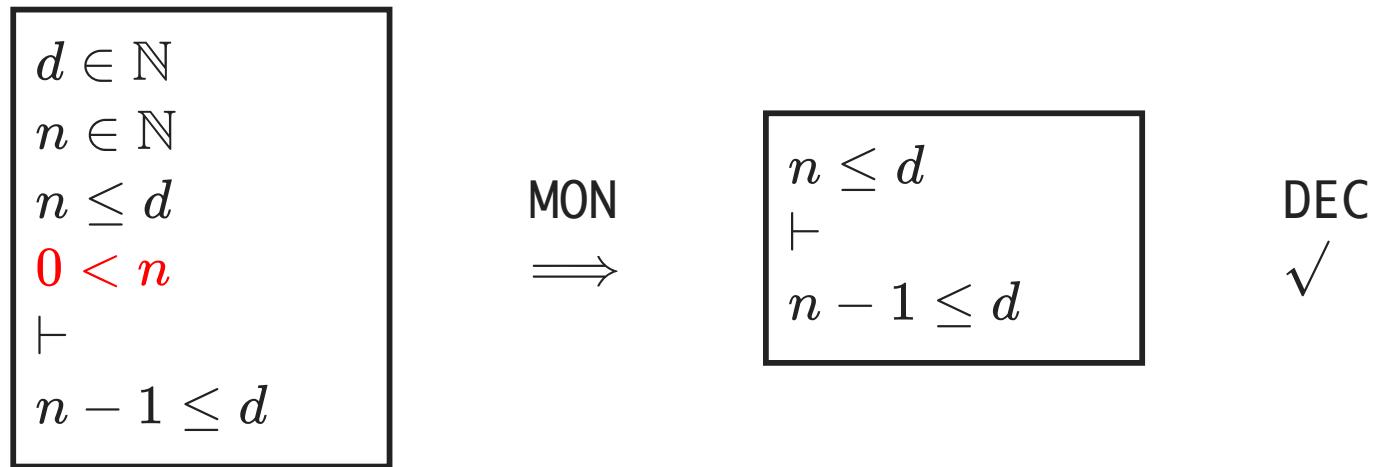
A FORMAL PROOF OF ML_in/inv0_1/INV



- Now we can conclude the proof using rule P2'

$$\frac{0 < n \quad \vdash \quad n - 1 \in \mathbb{N}}{\text{P2'}}$$

A FORMAL PROOF OF ML_in/inv0_2/INV



Again, the proof still works after the addition of a new assumption

RE-PROVING THE EVENTS NO PROOFS FAIL

ML_out/inv0_1/INV

$d \in \mathbb{N}$

$n \in \mathbb{N}$

$n \leq d$

$n < d$

\vdash

$n + 1 \in \mathbb{N}$

ML_in/inv0_1/INV

$d \in \mathbb{N}$

$n \in \mathbb{N}$

$n \leq d$

$0 < n$

\vdash

$n - 1 \in \mathbb{N}$

ML_out/inv0_2/INV

$d \in \mathbb{N}$

$n \in \mathbb{N}$

$n \leq d$

$n < d$

\vdash

$n + 1 \leq d$

ML_in/inv0_2/INV

$d \in \mathbb{N}$

$n \in \mathbb{N}$

$n \leq d$

$0 < n$

\vdash

$n - 1 \leq d$

INITIALISATION

- Our system must be **initialized** (with no car in the island-bridge)
- The initialisation event is **never guarded**
- It does **not mention any variable** on the right hand side of **$::=$**
- Its before-after predicate is just an **after predicate**

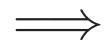
`init` $\hat{=}$

`begin`

`init0_1: n := 0`

`end`

After predicate



$n' = 0$

PROOF OBLIGATION INVARIANT ESTABLISHMENT

- Given c with axioms $A(c)$ and v with invariants $I(c, v)$
- Given an init event with after predicate $v' = K(c)$
- The Invariant Establishment PO is the following:

$$\begin{array}{ll} \text{Axioms} & A(c) \\ \vdash & \vdash \\ \text{Modified Invariant} & I_i(c, K(c)) \end{array}$$

APPLYING THE INVARIANT ESTABLISHMENT PO

$\alpha x m \theta_1$
 \vdash
Modified $\text{inv}_0 _ 1$

$d \in \mathbb{N}$
 \vdash
 $0 \in \mathbb{N}$

$\text{inv}_0 _ 1 / \text{INV}$

$\alpha x m \theta_1$
 \vdash
Modified $\text{inv}_0 _ 2$

$d \in \mathbb{N}$
 \vdash
 $0 \leq d$

$\text{inv}_0 _ 2 / \text{INV}$

MORE ARITHMETIC INFERENCE RULES

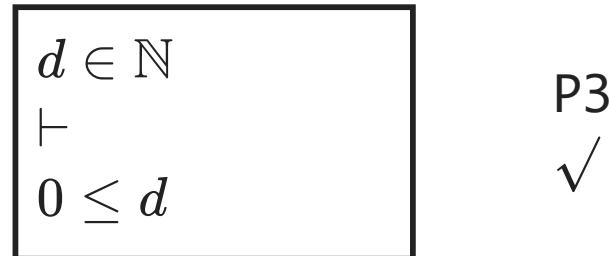
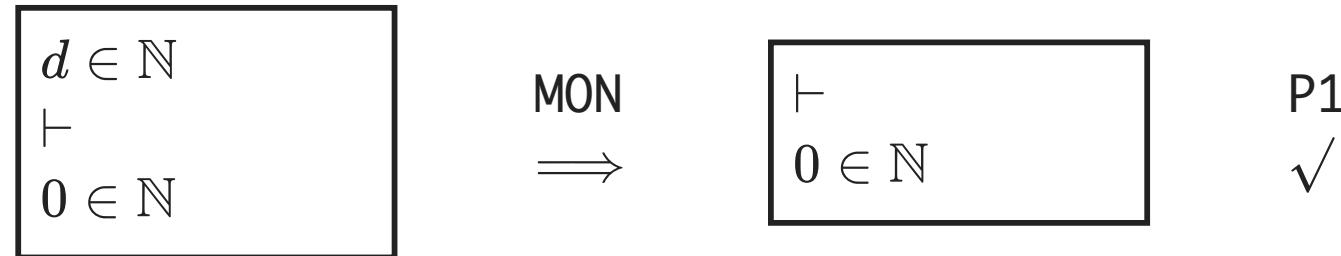
- First Peano Axiom

$$\frac{}{\vdash 0 \in \mathbb{N}} \quad P1$$

- Third Peano Axiom (slightly modified)

$$\frac{n \in \mathbb{N}}{n \in \mathbb{N} \quad \vdash 0 \leq n} \quad P3$$

PROOFS OF INVARIANT ESTABLISHMENT



A MISSING REQUIREMENT

- It is possible for the system to be blocked if both guards are false
- We do not want this to happen
- We figure out that one important requirement was missing
- **FUN-4** → Once started, the system should work for ever (**Deadlock Freedom**)

PROOF OBLIGATION

THE THEOREM PO RULE

- Given c with axioms $A(c)$ and v with invariants $I(c, v)$
- Given the theorem $Th(c, v)$
- Given the guards $G_1(c, v), \dots, G_m(c, v)$ of the events
- We have to prove the following:

$$\frac{\begin{array}{c} A(c) \\ I(c, v) \\ \vdash \\ Th(c, v) \end{array}}{\begin{array}{c} A(c) \\ I(c, v) \\ \vdash \\ G_1(c, v) \vee \dots \vee G_m(c, v) \end{array}}$$

APPLYING THE DEADLOCK FREEDOM PO

axm0_1

$d \in \mathbb{N}$

inv0_1

$n \in \mathbb{N}$

inv0_2

$n \leq d$

\vdash

\vdash

Disjunction of guards

$n < d \vee 0 < n$

- This cannot be proved with the inference rules we have so far
- $n \leq d$ can be replaced by $n = d \vee n < d$
- We continue our proof by a case analysis:
 - case 1: $n = d$
 - case 2: $n < d$

INFERENCE RULES FOR DISJUNCTION

- Proof by **case analysis**

$$\frac{H, P \vdash R \quad H, Q \vdash R}{H, P \vee Q \vdash R} \quad \text{OR_L}$$

- Choice for proving a **disjunctive goal**

$$\frac{H \vdash P}{H \vdash P \vee Q} \quad \text{OR_R1}$$

$$\frac{H \vdash Q}{H \vdash P \vee Q} \quad \text{OR_R2}$$

PROOF OF DEADLOCK FREEDOM

$$\begin{array}{l} d \in \mathbb{N} \\ n \in \mathbb{N} \\ n \leq d \\ \vdash \\ n < d \vee 0 < n \end{array}$$

MON
⇒

$$\begin{array}{l} n \leq d \\ \vdash \\ n < d \vee 0 < n \end{array}$$

OR_L
⇒

$$\begin{array}{l} n < d \\ \vdash \\ n < d \vee 0 < n \end{array}$$
$$\begin{array}{l} n = d \\ \vdash \\ n < d \vee 0 < n \end{array}$$
$$\begin{array}{l} n < d \\ \vdash \\ n < d \vee 0 < n \end{array}$$

OR_R1
⇒

$$\begin{array}{l} n < d \\ \vdash \\ n < d \end{array}$$

?
⇒

seems to be **obvious**


$$\begin{array}{l} n = d \\ \vdash \\ n < d \vee 0 < n \end{array}$$

?
⇒

can be (partially) solved
by **applying the equality**

MORE INFERENCE RULES

IDENTITY AND EQUALITY

- The **identity axiom** (conclusion holds by hypothesis)

$$\frac{}{P \vdash P} \text{ HYP}$$

- Rewriting an equality (**EQ_LR**) and reflexivity of equality (**EQL**)

$$\frac{H(F), E = F \vdash P(F)}{H(E), E = F \vdash P(E)} \text{ EQ_LR}$$

$$\frac{}{\vdash E = E} \text{ EQL}$$

PROOF OF DEADLOCK FREEDOM

$$\begin{array}{l} n < d \\ \vdash \\ n < d \vee 0 < n \end{array}$$

OR_R1
⇒

$$\begin{array}{l} n < d \\ \vdash \\ n < d \end{array}$$

HYP
✓

$$\begin{array}{l} n = d \\ \vdash \\ n < d \vee 0 < n \end{array}$$

EQ_LR
⇒

$$\begin{array}{l} \vdash \\ d < d \vee 0 < d \end{array}$$

OR_R2
⇒

$$\begin{array}{l} \vdash \\ 0 < d ? \end{array}$$

- We still have a problem → d must be positive!

ADDING THE FORGOTTEN AXIOM

- If $d = 0$, then no car can ever enter the Island-Bridge

CONSTANTS

d

AXIOMS

$\text{axm0_1}: d \in \mathbb{N}$

$\text{axm0_2}: 0 < d$

INITIAL MODEL CONCLUSION

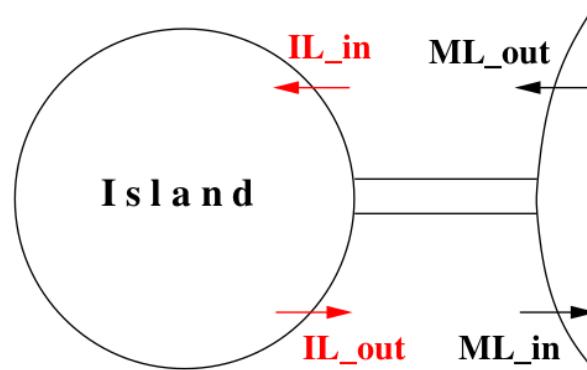
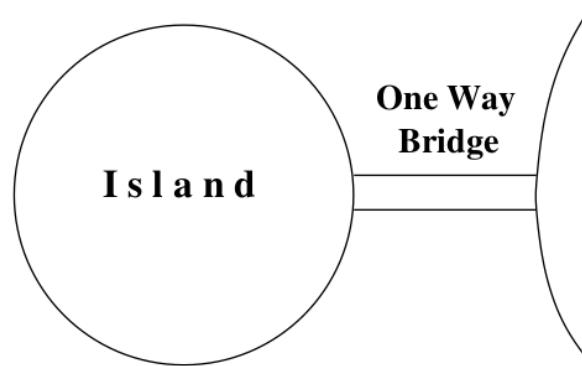
- Thanks to the proofs, we discovered 3 errors
- They were corrected by:
 - adding guards to both events
 - adding an axiom
- The interaction of modeling and proving is an essential element of Formal Methods with Proofs

OUR REFINEMENT STRATEGY

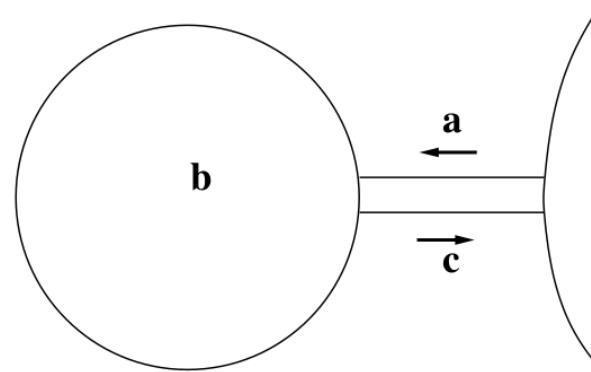
- **Initial model** → Limiting the number of cars (**FUN-2**)
- **First refinement** → Introducing the one way bridge (**FUN-1, FUN-3**)
 - Our **view** of the system gets **more accurate**
 - We introduce the **bridge** and **separate it from the island** (**FUN-1**)
 - We **refine** the state and the events
 - We also add **two new events** → **IL_in** and **IL_out**
 - We are focusing on **FUN-3** → one-way bridge

FIRST REFINEMENT

INTRODUCING A ONE-WAY BRIDGE



INTRODUCING THREE NEW VARIABLES



- a denotes the number of cars on bridge going to island
- b denotes the number of cars on island
- c denotes the number of cars on bridge going to mainland
- a , b , and c are the concrete variables
- They replace the abstract variable n

REFINING THE STATE

- Variables a , b , and c denote natural numbers

VARIABLES

$a \ b \ c$

INVARIANTS

`inv1_1:` $a \in \mathbb{N}$

`inv1_2:` $b \in \mathbb{N}$

`inv1_3:` $c \in \mathbb{N}$

REFINING THE STATE

INTRODUCING NEW INVARIANTS

- Relating the concrete state (a, b, c) to the abstract state (n)
INVARIANTS

...

inv1_4: $a + b + c = n$

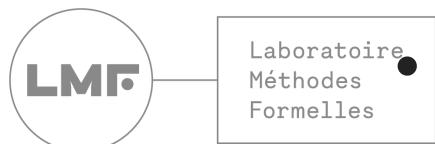
- Formalizing the new invariant → one way bridge (this is FUN-3)

INVARIANTS

...

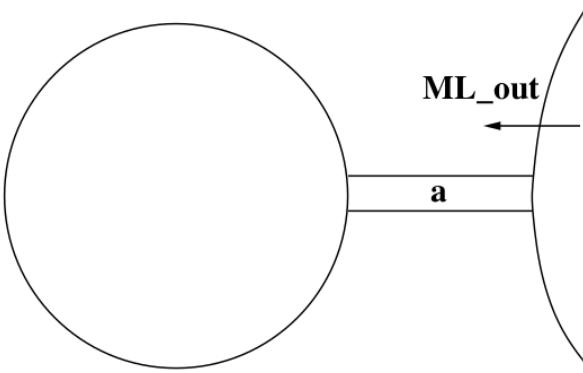
inv1_5: $a = 0 \vee c = 0$

- Invariants inv1_1 to inv1_5 are called the concrete invariants



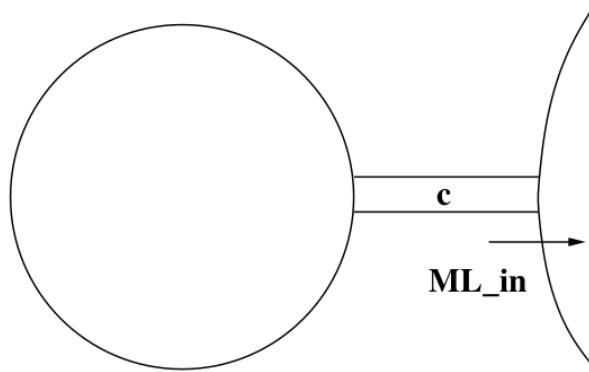
inv1_4 glues the abstract state, n , to the concrete state, a, b, c

PROPOSAL FOR REFINING EVENT **ML_out**



```
ML_out  $\hat{=}$ 
when
  grd1_1:  $a + b < d$ 
  grd1_2:  $c = 0$ 
then
  act1_1:  $a := a + 1$ 
end
```

PROPOSAL FOR REFINING EVENT **ML_in**



```
ML_in ≡  
when  
    grd1_1: 0 < c  
then  
    act1_1: c := c - 1  
end
```

BEFORE-AFTER PREDICATES

PRESERVED VARIABLES

ML_out $\hat{=}$

when

grd1_1: $a + b < d$

grd1_2: $c = 0$

then

act1_1: $a := a + 1$

end

ML_in $\hat{=}$

when

grd1_1: $0 < c$

then

act1_1: $c := c - 1$

end

Before-after predicates showing the unmodified variables

$$a' = a + 1 \wedge b' = b \wedge c' = c$$

$$a' = a \wedge b' = b \wedge c' = c - 1$$

INTUITION ABOUT REFINEMENT

- The concrete model behaves as specified by the abstract model (i.e., concrete model does not exhibit any new behaviors)
- To show this we have to prove that
 1. every concrete event is simulated by its abstract counterpart
(event refinement → following slides)
 2. to every concrete initial state corresponds an abstract one
(initial state refinement → later)
- We will make these two conditions more precise and formalize them as proof obligations.

INTUITION ABOUT REFINEMENT

```
ML_out  $\hat{=}$  //abstract  
when  
  grd0_1:  $n < d$   
then  
  act0_1:  $n := n + 1$   
end
```

```
ML_out  $\hat{=}$  //concrete  
when  
  grd1_1:  $a + b < d$   
  grd1_2:  $c = 0$   
then  
  act1_1:  $a := a + 1$   
end
```

- The concrete version is **not contradictory** with the abstract one
- When the **concrete version is enabled** then so is the abstract one
- **Executions** seem to be **compatible**



INTUITION ABOUT REFINEMENT

`ML_in $\hat{=}$ //abstract`

`when`

`grd0_1: 0 < n`

`then`

`act0_1: n := n - 1`

`end`

`ML_in $\hat{=}$ //concrete`

`when`

`grd1_1: 0 < c`

`then`

`act1_1: c := c - 1`

`end`

- Same remarks as in the previous slide
- But this has to be **confirmed by well-defined proof obligations**

PROOF OBLIGATIONS FOR REFINEMENT

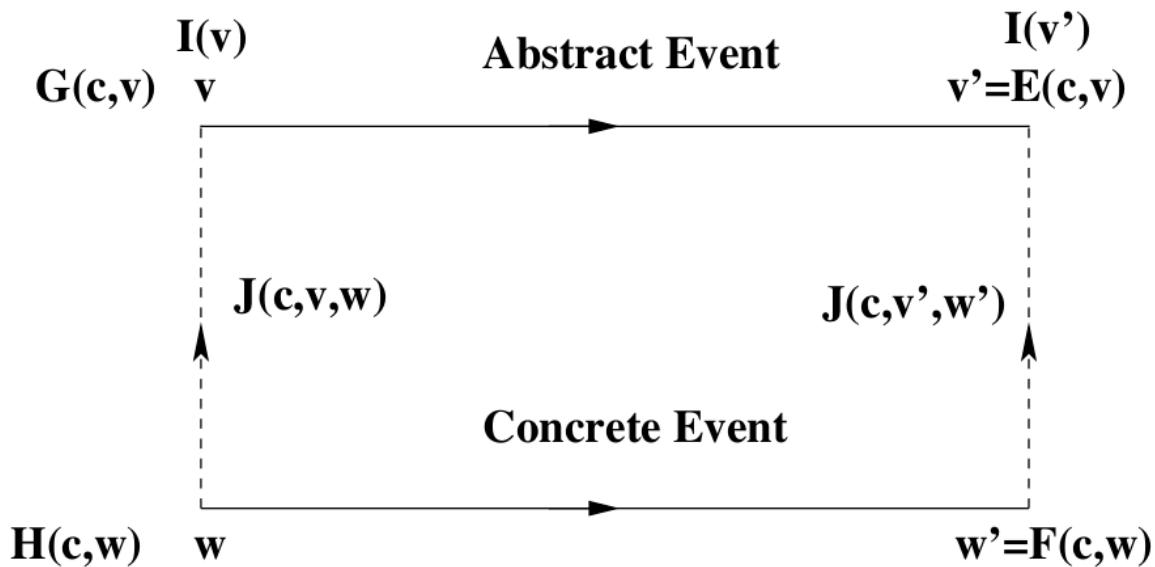
- The concrete guard is **stronger** than the abstract one
- Each concrete action is **compatible** with its abstract counterpart

PROVING CORRECT REFINEMENT

THE SITUATION

- Constants c with axioms $A(c)$
- Abstract variables v with abstract invariant $I(c, v)$
- Concrete variables w with concrete invariant $J(c, v, w)$
- Abstract event with guards $G(c, v) \rightarrow G_1(c, v), G_2(c, v), \dots$
- Abstract event with before-after predicate $v' = E(c, v)$
- Concrete event with guards $H(c, w)$ and b-a predicate $w' = F(c, w)$

PCORRECTNESS OF EVENT REFINEMENT



1. The concrete guard is **stronger** than the abstract one
([Guard Strengthening](#), following slides)
2. Each concrete action is **simulated by** its abstract counterpart
([Concrete Invariant Preservation](#), later)

PROOF OBLIGATION GUARD STRENGTHENING

Axioms

$A(c)$

Abstract Invariants

$I(c, v)$

Concrete Invariants

$J(c, v, w)$

GRD

Concrete Guard

$H(c, w)$

\vdash

\vdash

Abstract Guard

$G_i(c, v)$

APPLYING GUARD STRENGTHENING TO EVENT **ML_out**

PROOF OF **ML_out/GRD**

```
ML_out  $\hat{=}$  //abstract
when
  grd0_1:  $n < d$ 
then
  act0_1:  $n := n + 1$ 
end
```

```
ML_out  $\hat{=}$  //concrete
when
  grd1_1:  $a + b < d$ 
  grd1_2:  $c = 0$ 
then
  act1_1:  $a := a + 1$ 
end
```

APPLYING GUARD STRENGTHENING TO EVENT ML_out

PROOF OF $\text{ML_out}/\text{GRD}$

$d \in \mathbb{N}$
 $0 < d$
 $n \in \mathbb{N}$
 $n \leq d$
 $a \in \mathbb{N}$
 $b \in \mathbb{N}$
 $c \in \mathbb{N}$
 $a + b + c = n$
 $a = 0 \vee c = 0$
 $a + b < d$
 $c = 0$
 \vdash
 $n < d$

Laboratoire
Méthodes
Formelles

MON
 \implies

$a + b + c = n$
 $a + b < d$
 $c = 0$
 \vdash
 $n < d$

EQ_LR
 \implies

$a + b + 0 = n$
 $a + b < d$
 \vdash
 $n < d$

ARITH ...
 \implies

APPLYING GUARD STRENGTHENING TO EVENT **ML_out** PROOF OF **ML_out/GRD**

ARITH ...
 \implies

$$\boxed{\begin{array}{l} a + b = n \\ a + b < d \\ \vdash \\ n < d \end{array}}$$

EQ_LR
 \implies

$$\boxed{\begin{array}{l} n < d \\ \vdash \\ n < d \end{array}}$$

HYP
✓

APPLYING GUARD STRENGTHENING TO EVENT ML_in PROOF OF $\text{ML_in}/\text{GRD}$

```
ML_in  $\hat{=}$  //abstract
when
  grd0_1:  $0 < n$ 
then
  act0_1:  $n := n - 1$ 
end
```

```
ML_in  $\hat{=}$  //concrete
when
  grd1_1:  $0 < c$ 
then
  act1_1:  $c := c - 1$ 
end
```

APPLYING GUARD STRENGTHENING

TO EVENT ML_in

PROOF OF $\text{ML_in}/\text{GRD}$

$d \in \mathbb{N}$
 $0 < d$
 $n \in \mathbb{N}$
 $n \leq d$
 $a \in \mathbb{N}$
 $b \in \mathbb{N}$
 $c \in \mathbb{N}$
 $a + b + c = n$
 $a = 0 \vee c = 0$
 $a + b < d$
 $0 < c$
 \vdash
 0 < n

Laboratoire
Méthodes
Formelles

MON
 \Rightarrow

$b \in \mathbb{N}$
 $a + b + c = n$
 $a = 0 \vee c = 0$
 $0 < c$
 \vdash
 $0 < n$

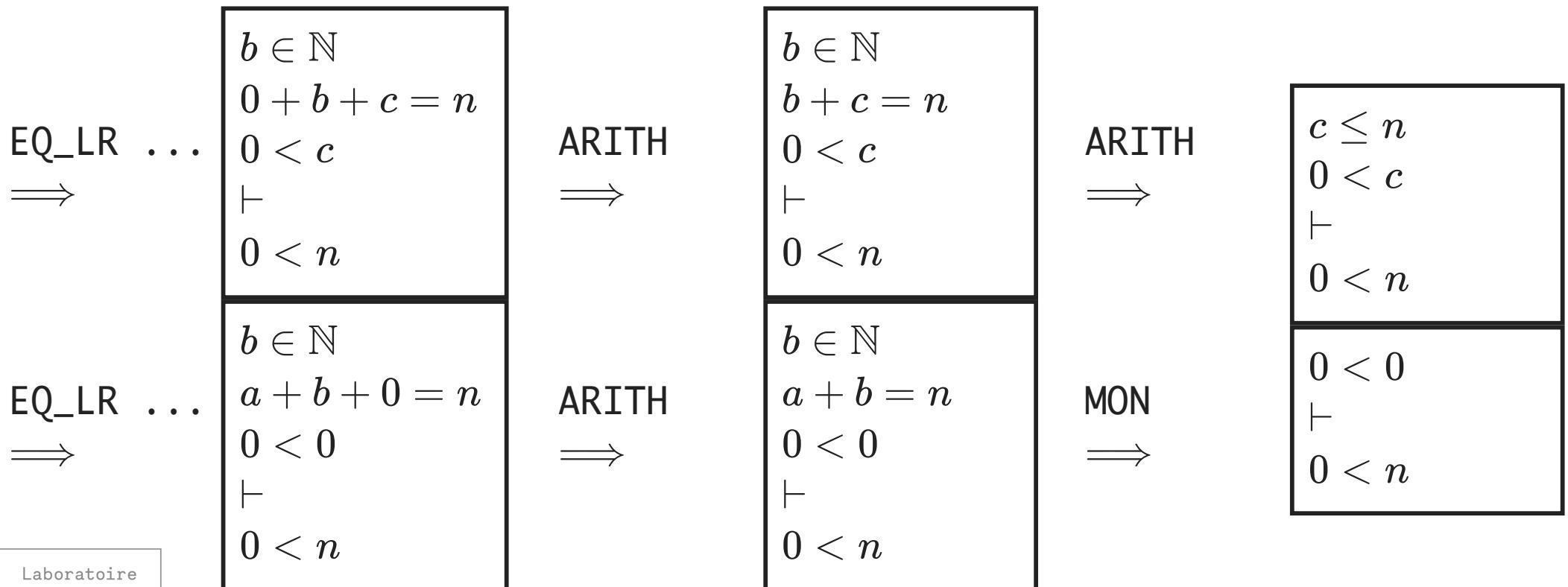
OR_L
 \Rightarrow

$b \in \mathbb{N}$
 $a + b + c = n$
 $a = 0$
 $0 < c$
 \vdash
 $0 < n$

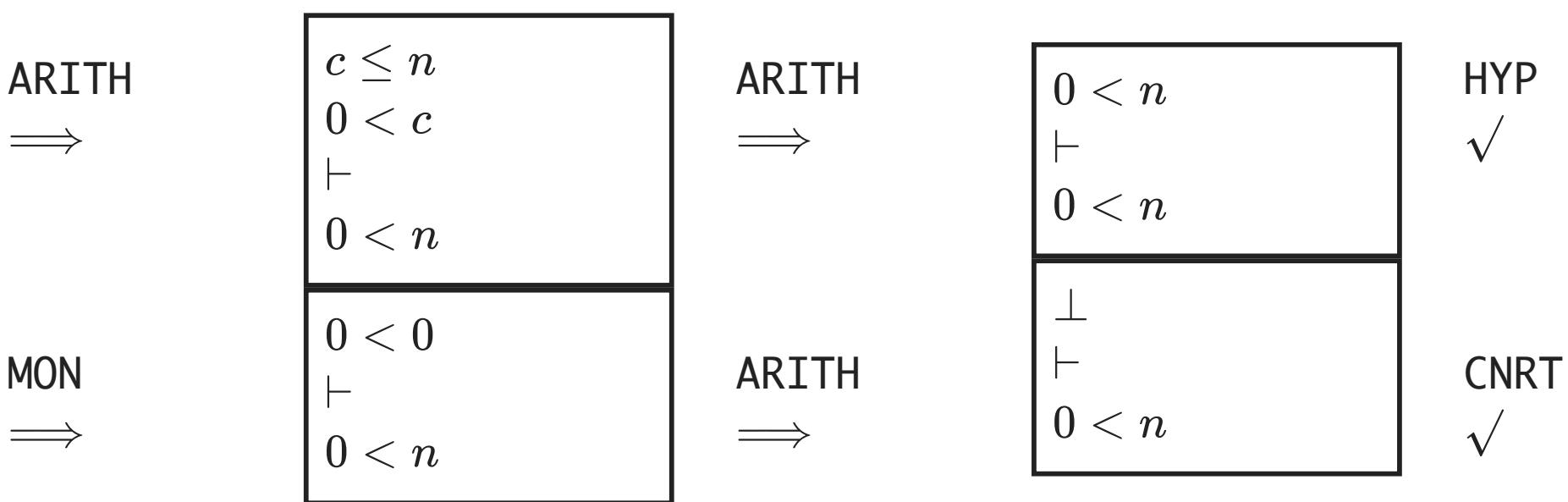
$b \in \mathbb{N}$
 $a + b + c = n$
 $c = 0$
 $0 < c$
 \vdash
 $0 < n$

EQ_LR ...
 \Rightarrow
EQ_LR ...
 \Rightarrow

APPLYING GUARD STRENGTHENING TO EVENT **ML_in** PROOF OF **ML_in/GRD**



APPLYING GUARD STRENGTHENING TO EVENT ML_in PROOF OF $\text{ML_in}/\text{GRD}$



- In the previous proof, we have used an additional inference rule
- It says that a false hypothesis entails any goal $\perp \vdash P$ **CNTR**



PROOF OBLIGATION

INVARIANT REFINEMENT

Axioms

$A(c)$

Abstract Invariants

$I(c, v)$

Concrete Invariants

$J(c, v, w)$

INV

Concrete Guard

$H(c, w)$

\vdash

\vdash

Modified Concrete Invariant

$J_j(c, E(c, v), F(c, w))$

APPLYING INVARIANT REFINEMENT TO EVENT ML_out

PROOF OF $\text{ML_out}/\text{inv1_4}/\text{INV}$

```
ML_out  $\hat{=}$  //abstract
when
  grd0_1:  $n < d$ 
then
  act0_1:  $n := n + 1$ 
end
```

```
ML_out  $\hat{=}$  //concrete
when
  grd1_1:  $a + b < d$ 
  grd1_2:  $c = 0$ 
then
  act1_1:  $a := a + 1$ 
end
```

APPLYING INVARIANT REFINEMENT TO EVENT **ML_out**

PROOF OF **ML_out/inv1_4/INV**

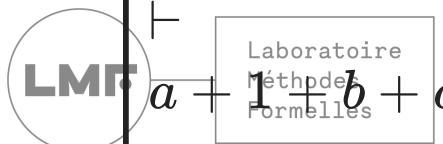
$d \in \mathbb{N}$
 $0 < d$
 $n \in \mathbb{N}$
 $n \leq d$
 $a \in \mathbb{N}$
 $b \in \mathbb{N}$
 $c \in \mathbb{N}$
 $a + b + c = n$
 $a = 0 \vee c = 0$
 $a + b < d$
 $c = 0$
 $\vdash a + b + c = n + 1$

MON
 \implies

$$\boxed{\begin{array}{l} a + b + c = n \\ + \\ a + 1 + b + c = n + 1 \end{array}}$$

ARITH
 \implies

$$\boxed{\begin{array}{l} a + b + c = n \\ + \\ a + b + c + 1 = n + 1 \end{array}}$$



APPLYING INVARIANT REFINEMENT TO EVENT **ML_out**

PROOF OF **ML_out/inv1_4/INV**

$$\boxed{\begin{array}{l} a + b + c = n \\ \vdash \\ a + b + c + 1 = n + 1 \end{array}}$$

EQ_LR
 \implies

$$\boxed{\begin{array}{l} \vdash \\ n + 1 = n + 1 \end{array}}$$

EQL
 \checkmark

REFINING THE INITIALIZATION

EVENT **init**

- Concrete initialization

EVENTS

INITIALISATION $\hat{=}$

$$a := 0$$

$$b := 0$$

$$c := 0$$

- Corresponding after predicate

$$a' = 0 \wedge b' = 0 \wedge c' = 0$$

PROOF OBLIGATION INITIALIZATION REFINEMENT

- Constants c with axioms $A(c)$
- Concrete invariant $J(c, v, w)$
- Abstract initialization with after predicate $v' = K(c)$
- Concrete initialization with after predicate $w' = L(c)$

$$\frac{\begin{array}{c} \text{Axioms} \\ \vdash \\ \text{Modified concrete invariants} \end{array}}{\begin{array}{c} A(c) \\ \vdash \\ J_j(c, K(c), L(c)) \end{array}} \quad \text{INV}$$

PROOF OBLIGATION

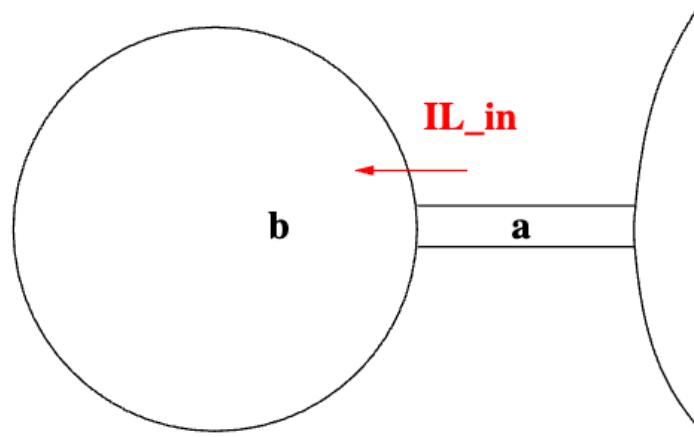
INITIALIZATION REFINEMENT

$$\begin{array}{l} d \in \mathbb{N} \\ 0 < d \\ \vdash \\ 0 + 0 + 0 = 0 \\ (a + b + c = n) \end{array}$$
$$\begin{array}{l} d \in \mathbb{N} \\ 0 < d \\ \vdash \\ 0 = 0 \vee 0 = 0 \\ (a = 0 \vee c = 0) \end{array}$$


ADDING NEW EVENTS

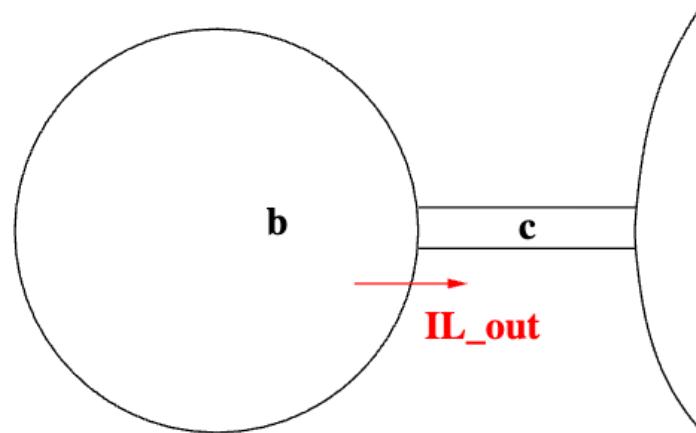
- new events add transitions that have **no abstract counterpart**
- can be seen as a kind of **internal steps** (w.r.t. abstract model)
- can only be seen by an **observer** who is "*zooming in*"
- **temporal refinement**: refined model has a finer time granularity

NEW EVENT **IL_in**



```
IL_in ≡  
when  
  grd1_1: 0 < a  
then  
  act1_1: a := a - 1  
  act1_2: b := b + 1  
end
```

NEW EVENT IL_out



```
IL_out ≡  
when  
    grd1_1: 0 < b  
    grd1_2: a = 0  
then  
    act1_1: b := b - 1  
    act1_2: c := c + 1  
end
```

BEFORE-AFTER PREDICATES

IL_in $\hat{=}$

when

grd1_1: $0 < a$

then

act1_1: $a := a - 1$

act1_2: $b := b + 1$

end

IL_out $\hat{=}$

when

grd1_1: $0 < b$

grd1_2: $a = 0$

then

act1_1: $b := b - 1$

act1_2: $c := c + 1$

end

$$\begin{aligned} a' &= a - 1 \wedge b' = b + 1 \wedge c' = c \\ a' &= a \wedge b' = b - 1 \wedge c' = c + 1 \end{aligned}$$

THE EMPTY ASSIGNMENT `skip`

- The before-after predicate of `skip` in the [initial model](#)

$$n' = n$$

- The before-after predicate of `skip` in the [first refinement](#)

$$a' = a \wedge b' = b \wedge c' = c$$

- The guard of the `skip` event is `true`.

REFINEMENT PROOF OBLIGATIONS FOR NEW EVENTS

- A new event must refine an implicit event, made of a skip action
 - Guard strengthening is trivial
 - Need to prove invariant refinement
- The new events must not diverge
 - To prove this we have to exhibit a variant
 - The variant yields a natural number (could be more complex)
 - Each new event must decrease this variant

EVENT IL_in REFINES skip

```
IL_in ^=
  when
    grd1_1: 0 < a
  then
    act1_1: a := a - 1
    act1_2: b := b + 1
  end
```

PROOF OF IL_in/inv1_4/INV

$d \in \mathbb{N}$
 $0 < d$
 $n \in \mathbb{N}$
 $n \leq d$
 $a \in \mathbb{N}$
 $b \in \mathbb{N}$
 $c \in \mathbb{N}$
 $a + b + c = n$
 $a = 0 \vee c = 0$
 $0 < a$
 \vdash
 $a - 1 + b + 1 + c = n$

MON
⇒

$a + b + c = n$
 \vdash
 $a - 1 + b + 1 + c = n$

ARITH
⇒

$a + b + c = n$
 \vdash
 $a + b + c = n$

HYP
✓



PROOF OBLIGATION

CONVERGENCE OF NEW EVENTS

- Axioms $A(c)$, invariants $I(c, v)$, concrete invariant $J(c, v, w)$
- New event with guard $H(c, w)$
- Variant $V(c, w)$

Axioms

$A(c)$

Abstract Invariants

$I(c, v)$

Concrete Invariants

$J(c, v, w)$

NAT

Concrete Guard

$H(c, w)$

\vdash

\vdash

Variant $\in \mathbb{N}$

$V(c, w) \in \mathbb{N}$

PROOF OBLIGATION

CONVERGENCE OF NEW EVENTS

- Axioms $A(c)$, invariants $I(c, v)$, concrete invariant $J(c, v, w)$
- New event with guard $H(c, w)$ and b-a predicate $w' = F(c, w)$
- Variant $V(c, w)$

Axioms

$$A(c)$$

Abstract Invariants

$$I(c, v)$$

Concrete Invariants

$$J(c, v, w)$$

Concrete Guard

$$H(c, w)$$

\vdash

Modified Var < Var

\vdash

$$V(c, F(c, w)) < V(c, w)$$

VAR

PROPOSED VARIANT

Weighted sum of a and b

VARIANT

variant_1: $2 \times a + b$

DECREASING OF THE VARIANT BY EVENT IL_in

```
IL_in  $\hat{=}$ 
when
  grd1_1:  $0 < a$ 
then
  act1_1:  $a := a - 1$ 
  act1_2:  $b := b + 1$ 
end
```

$$\begin{aligned}d &\in \mathbb{N} \\0 &< d \\n &\in \mathbb{N} \\n &\leq d \\a &\in \mathbb{N} \\b &\in \mathbb{N} \\c &\in \mathbb{N} \\a + b + c &= n \\a = 0 \vee c = 0 \\0 &< a \\\vdash \\2 \times (a - 1) + (b + 1) &< 2 \times a + b\end{aligned}$$



DECREASING OF THE VARIANT BY EVENT **IL_out**

```
IL_out  $\hat{=}$ 
when
  grd1_1:  $0 < b$ 
  grd1_2:  $a = 0$ 
then
  act1_1:  $b := b - 1$ 
  act1_2:  $c := c + 1$ 
end
```

$$\begin{aligned} d &\in \mathbb{N} \\ 0 &< d \\ n &\in \mathbb{N} \\ n &\leq d \\ a &\in \mathbb{N} \\ b &\in \mathbb{N} \\ c &\in \mathbb{N} \\ a + b + c &= n \\ a = 0 \vee c = 0 \\ 0 &< a \\ \vdash \\ 2 \times a + (b - 1) &< 2 \times a + b \end{aligned}$$



SUPERPOSITION (NOT COVERED IN THIS TUTORIAL)

Abstract_Event $\hat{=}$
when
 $G(c, u, v)$
then
 $u := E(c, u, v)$
 $v := M(c, u, v)$
end

Concrete_Event $\hat{=}$
when
 $H(c, v, w)$
then
 $v := N(c, v, w)$
 $w := F(c, v, w)$
end

Axioms
Abstract Invariants
Concrete Invariants
Concrete Guard
 \vdash
Same actions in common variables

$A(c)$
 $I(c, v)$
 $J(c, v, w)$
 $H(c, w)$
 \vdash
 $M(c, u, v) = N(c, v, w)$

SIM



OUTLINE

- The Event-B method
- The Pro-B animator/model-checker
- The Theory plugin

[Back to the outline](#) - [Back to the begin](#)

THE PROB ANIMATOR AND MODEL CHECKER

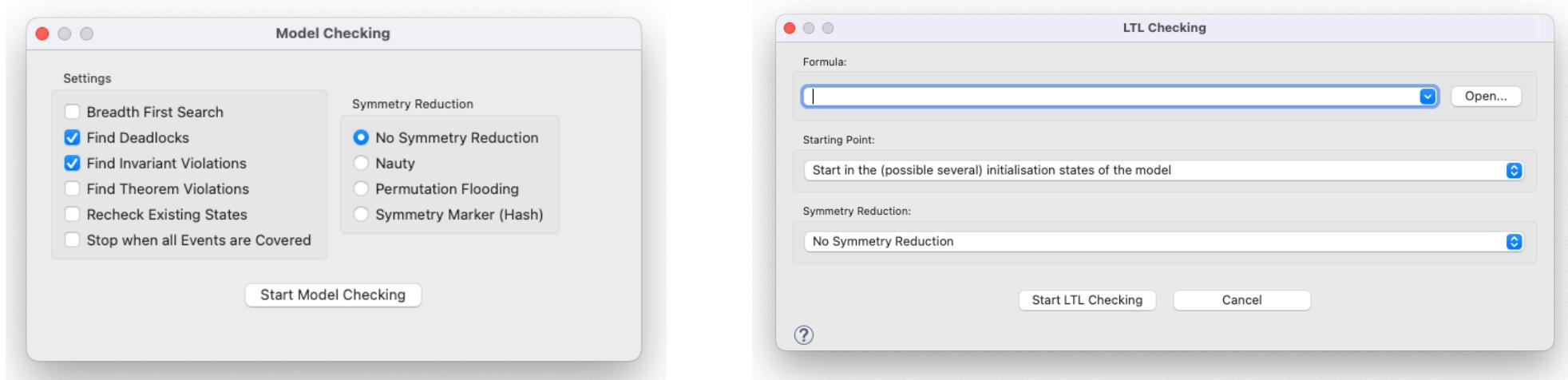
- ProB is an animator, constraint solver and model checker for the Event-B Method.
- ProB's animation features allow developers to control and validate the behavior of their specifications.
- Animation features are useful for infinite state machines, not for verification, but for debugging and testing.

[ProB main web page](#)

MODEL-CHECKING WITH PROB

- The **ProB plugin** allows **automatic verification** of the consistency of **Event-B** machines through **animation** and **model checking**.
- For exhaustive model verification, the given sets must be **limited to finite sets**.
 - ⇒ allows ProB to browse through the reachable states of the machine.
- The **ProB plugin** graphically displays **a counterexample** when it discovers **a property violation**.

THE PROB PLUGIN



- [Tutorial Rodin First Step](#)
- [Tutorial First Model Checking](#)
- [LTL/CTL Model Checking](#)

OUTLINE

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[Back to the outline](#) - [Back to the begin](#)

THE EVENT-B METHOD

THE THEORY PLUGIN

- Theory Plug-in provides capabilities to extend the Event-B mathematical language and the Rodin proving infrastructure.
- An Event-B theory can contain :
 - new datatype definitions,
 - new polymorphic operator definitions,
 - axiomatic definitions,
 - theorems,
 - associated rewrite and inference rules.

THEORY thy_1

IMPORT thy_2

DATATYPES

DT_1, \dots, DT_n

OPERATORS

OP_{11}, \dots, OP_{1n}

AXIOMATIC DEFINITIONS

operators

OP_{21}, \dots, OP_{2n}

axioms

A

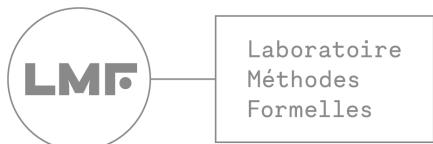
THEOREMS

T

PROOF RULES

PR

END



- Michael J. Butler and Issam Maamria.
Practical theory extension in Event-B. Theories of Programming and Formal Methods. 2013.
- Thai Son Hoang, Laurent Voisin, Asieh Salehi, Michael J. Butler, Toby Wilkinson, and Nicolas Beauger.
Theory plug-in for Rodin 3.x. CoRR, abs/1701.08625, 2017.

THE EVENT-B METHOD

THE THEORY PLUGIN

THEORY thy_1
IMPORT thy_2

DATATYPES

DT_1, \dots, DT_n

OPERATORS

OP_{11}, \dots, OP_{1n}

AXIOMATIC DEFINITIONS

operators

OP_{21}, \dots, OP_{2n}

axioms

A

THEOREMS

T

PROOF RULES

PR

END

CONTEXT ctx_1
EXTENDS ctx_2

SETS s

CONSTANTS c

AXIOMS

$A(s, c)$

THEOREMS

$T(s, c)$

END

MACHINE mch_1
REFINES mch_2
SEES ctx_i

VARIABLES v

INVARIANTS

$I(s, c, v)$

THEOREMS

$T(s, c, v)$

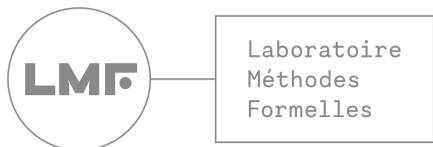
EVENTS

$[events_list]$

END

THE EVENT-B METHOD THE THEORY PLUGIN

DEMO



THANK YOU

Une grande partie de cette présentation a été réalisée en utilisant le livre
[Modeling in Event-B: System and Software Engineering](#)

[PDF version of the slides](#)

[Back to the begin](#) - [Back to the outline](#)