# Journal First: Building Specifications in the Event-B Institution

Marie Farrell, Rosemary Monahan and James F. Power

CPS Seminar @ University of Southampton
June 29, 2023

# Building Specifications in the Event-B Institution

Logical Methods in Computer Science
Volume 18, Issue 4, 2022, pp. 4:1–4:55
https://lmcs.episciences.org/

Submitted Mar. 22, 2021
Published Nov. 09, 2022

## BUILDING SPECIFICATIONS IN THE EVENT-B INSTITUTION

MARIE FARRELL, ROSEMARY MONAHAN, AND JAMES F. POWER

Department of Computer Science and Hamilton Institute, Maynooth University, Ireland
*e-mail address*: marie.farrell@mu.ie

# Building Specifications in the Event-B Institution

Logical Methods in Computer Science
Volume 18, Issue 4, 2022, pp. 4:1–4:55
https://lmcs.episciences.org/

Submitted Mar. 22, 2021
Published Nov. 09, 2022

## BUILDING SPECIFICATIONS IN THE EVENT-B INSTITUTION

MARIE FARRELL, ROSEMARY MONAHAN, AND JAMES F. POWER

Department of Computer Science and Hamilton Institute, Maynooth University, Ireland
*e-mail address*: marie.farrell@mu.ie

marie.farrell@manchester.ac.uk

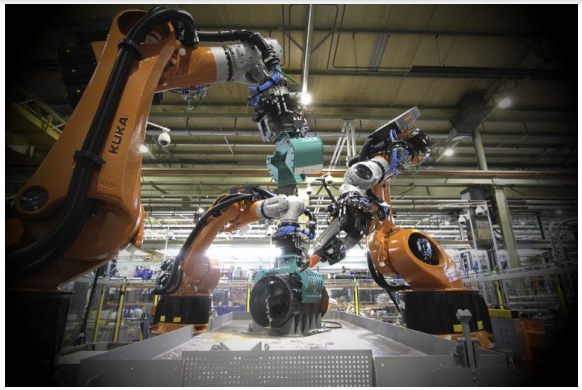
## Disclaimer:

There will be equations and commutative diagrams on these slides but I will only superficially explain them. All of the details and proofs are in the paper.

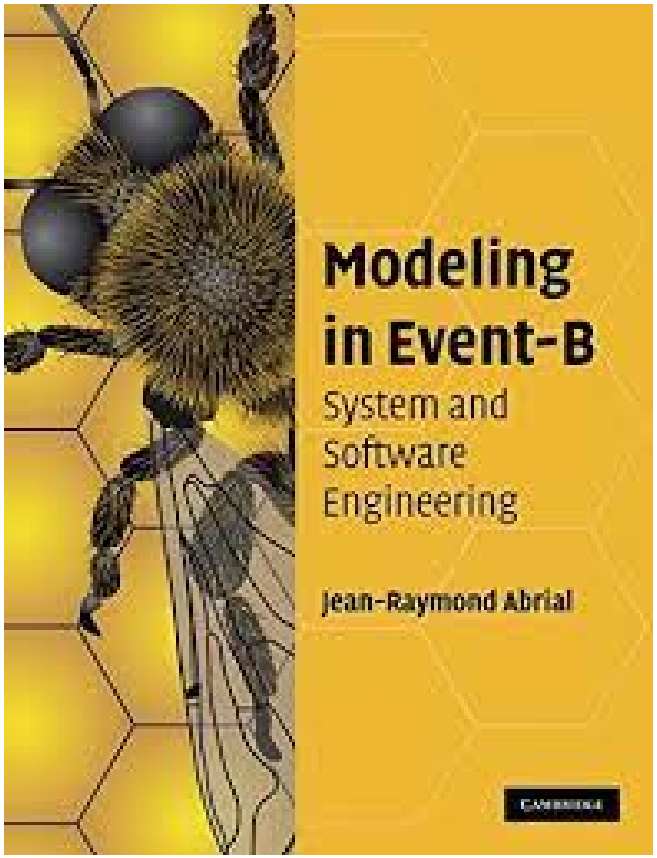
# Formal Methods for Critical Systems

## What if I told you?

I modelled and verified critical systems using a language with **no formal semantics**. Further, there is **no native support to make the code modular** in this language and **translations** to other languages are **not systematic**.






Modeling
in Event-B
System and
Software
Engineering
Jean-Raymond Abrial

# Think About It...

## Formal Semantics

- Proof obligations give a list of properties to prove for a given model.
- Not a semantics for the language itself.

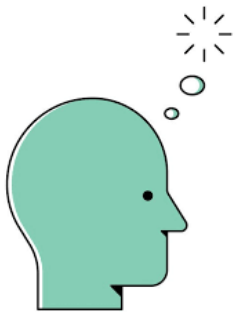
## Modularisation

- Lots of plugins but no direct language support.

## Interoperability

- Lots of plugins but no way of checking that the semantics is preserved.

# Forget everything that you know about Event-B!



# Building Specifications in the Event-B Institution

Logical Methods in Computer Science
Volume 18, Issue 4, 2022, pp. 4:1–4:55
https://lmcs.episciences.org/

Submitted Mar. 22, 2021
Published Nov. 09, 2022

## BUILDING SPECIFICATIONS IN THE EVENT-B INSTITUTION

MARIE FARRELL, ROSEMARY MONAHAN, AND JAMES F. POWER

Department of Computer Science and Hamilton Institute, Maynooth University, Ireland
*e-mail address*: marie.farrell@mu.ie

**Event-B?**

# Event-B Formal Specification Language

```
CONTEXT ctx
   EXTENDS ctx0
   SETS S
   CONSTANTS c
   AXIOMS
      A(s,c)
```

```
MACHINE m  REFINES m0
SEES ctx
  VARIABLES x
  INVARIANTS I(x)
  VARIANT n(x)
  EVENTS
    INITIALISATION, e1,...,en
```

```
Event ei ≙  status
   any p
   when G(x,p)
   with W(x,p)
   then BA(x,p,x')
end
```

# Building Specifications in the Event-B Institution

Logical Methods in Computer Science
Volume 18, Issue 4, 2022, pp. 4:1–4:55
https://lmcs.episciences.org/

Submitted Mar. 22, 2021
Published Nov. 09, 2022

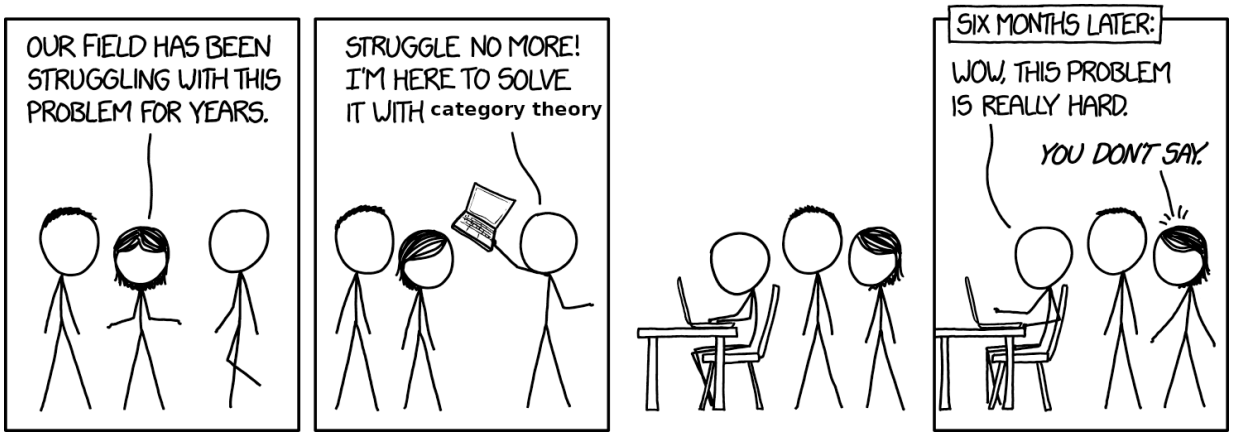
## BUILDING SPECIFICATIONS IN THE EVENT-B INSTITUTION

MARIE FARRELL, ROSEMARY MONAHAN, AND JAMES F. POWER

Department of Computer Science and Hamilton Institute, Maynooth University, Ireland
*e-mail address*: marie.farrell@mu.ie

**Institution?**

# Institutions: Some Maths



# An **institution** $\mathcal{INS}$ for a given formalism

Vocabulary: a category **Sign** whose objects are called signatures and whose arrows are called signature morphisms.

# An **institution** $\mathcal{INS}$ for a given formalism

Vocabulary: a category **Sign** whose objects are called signatures and whose arrows are called signature morphisms.

Syntax: a functor **Sen** : **Sign** $\to$ **Set** giving a set **Sen**$(\Sigma)$ of $\Sigma$-*sentences* for each signature $\Sigma$ and a function **Sen**$(\sigma)$ : **Sen**$(\Sigma) \to$ **Sen**$(\Sigma')$ for each signature morphism $\sigma : \Sigma \to \Sigma'$.

# An **institution** $\mathcal{INS}$ for a given formalism

Vocabulary: a category **Sign** whose objects are called signatures and whose arrows are called signature morphisms.

Syntax: a functor **Sen** : **Sign** $\to$ **Set** giving a set **Sen**$(\Sigma)$ of $\Sigma$-*sentences* for each signature $\Sigma$ and a function **Sen**$(\sigma)$ : **Sen**$(\Sigma) \to$ **Sen**$(\Sigma')$ for each signature morphism $\sigma : \Sigma \to \Sigma'$.

Semantics: a functor **Mod** : **Sign**$^{op} \to$ **Cat** giving a category **Mod**$(\Sigma)$ of $\Sigma$-*models* for each signature $\Sigma$ and a functor **Mod**$(\sigma)$ : **Mod**$(\Sigma') \to$ **Mod**$(\Sigma)$ for each signature morphism $\sigma : \Sigma \to \Sigma'$.

# An **institution** $\mathcal{INS}$ for a given formalism

**Vocabulary:** a category **Sign** whose objects are called signatures and whose arrows are called signature morphisms.

**Syntax:** a functor $\mathbf{Sen} : \mathbf{Sign} \to \mathbf{Set}$ giving a set $\mathbf{Sen}(\Sigma)$ of $\Sigma$-*sentences* for each signature $\Sigma$ and a function $\mathbf{Sen}(\sigma) : \mathbf{Sen}(\Sigma) \to \mathbf{Sen}(\Sigma')$ for each signature morphism $\sigma : \Sigma \to \Sigma'$.

**Semantics:** a functor $\mathbf{Mod} : \mathbf{Sign}^{op} \to \mathbf{Cat}$ giving a category $\mathbf{Mod}(\Sigma)$ of $\Sigma$-*models* for each signature $\Sigma$ and a functor $\mathbf{Mod}(\sigma) : \mathbf{Mod}(\Sigma') \to \mathbf{Mod}(\Sigma)$ for each signature morphism $\sigma : \Sigma \to \Sigma'$.

**Satisfaction:** for every signature $\Sigma$, a satisfaction relation $\models_{\mathcal{INS},\Sigma}$ between $\Sigma$-models and $\Sigma$-sentences.
An institution must uphold the **satisfaction condition**: for any signature morphism $\sigma : \Sigma \to \Sigma'$ and translations $\mathbf{Mod}(\sigma)$ of models and $\mathbf{Sen}(\sigma)$ of sentences we have for any $\phi \in \mathbf{Sen}(\Sigma)$ and $M' \in |\, \mathbf{Mod}(\Sigma') \,|$.

$$M' \models_{\mathcal{INS},\Sigma'} \mathbf{Sen}(\sigma)(\phi) \quad \Leftrightarrow \quad \mathbf{Mod}(\sigma)(M') \models_{\mathcal{INS},\Sigma} \phi$$

$$\begin{array}{c} \Sigma_1 \\ \downarrow{\scriptstyle \sigma} \\ \Sigma_2 \end{array}$$

$$\begin{array}{ccc} \mathbf{Sen}(\Sigma_1) & \xrightarrow{\rho^{Sen}_{\Sigma_1}} & \mathbf{Sen}'(\rho^{Sign}(\Sigma_1)) \\ \downarrow{\scriptstyle \mathbf{Sen}(\sigma)} & & \downarrow{\scriptstyle \mathbf{Sen}'(\rho^{Sign}(\sigma))} \\ \mathbf{Sen}(\Sigma_2) & \xrightarrow[\rho^{Sen}_{\Sigma_2}]{} & \mathbf{Sen}'(\rho^{Sign}(\Sigma_2)) \end{array} \qquad \begin{array}{ccc} \mathbf{Mod}'(\rho^{Sign}(\Sigma_2)) & \xrightarrow{\rho^{Mod}_{\Sigma_2}} & \mathbf{Mod}(\Sigma_2) \\ \downarrow{\scriptstyle \mathbf{Mod}'(\rho^{Sign}(\sigma))} & & \downarrow{\scriptstyle \mathbf{Mod}(\sigma)} \\ \mathbf{Mod}'(\rho^{Sign}(\Sigma_2)) & \xrightarrow[\rho^{Mod}_{\Sigma_1}]{} & \mathbf{Mod}(\Sigma_1) \end{array}$$

*"truth is invariant under change of notation"*

# First-Order Predicate Logic with Equality ($\mathcal{FOPEQ}$)

Signatures: $\Sigma_{\mathcal{FOPEQ}} = \langle S, \Omega, \Pi \rangle$

- $S$ is a set of sort names
- $\Omega$ is a set of operation names
- $\Pi$ is a set of predicate names indexed by arity.

# First-Order Predicate Logic with Equality ($\mathcal{FOPEQ}$)

Signatures: $\Sigma_{\mathcal{FOPEQ}} = \langle S, \Omega, \Pi \rangle$

- $S$ is a set of sort names
- $\Omega$ is a set of operation names
- $\Pi$ is a set of predicate names indexed by arity.

Sentences: closed first-order formulae using $\wedge, \vee, \neg, \Rightarrow, \Leftrightarrow, \exists, \forall$ and the logical constants `true` and `false`.

# First-Order Predicate Logic with Equality ($\mathcal{FOPEQ}$)

**Signatures:** $\Sigma_{\mathcal{FOPEQ}} = \langle S, \Omega, \Pi \rangle$

- $S$ is a set of sort names
- $\Omega$ is a set of operation names
- $\Pi$ is a set of predicate names indexed by arity.

**Sentences:** closed first-order formulae using $\wedge, \vee, \neg, \Rightarrow, \Leftrightarrow, \exists, \forall$ and the logical constants `true` and `false`.

**Models:** consist of a carrier set $|A|_s$ for each sort name $s \in S$, a function $f_A : |A|_{s_1} \times \cdots \times |A|_{s_n} \to |A|_s$ for each operation name $f \in \Omega_{s_1 \ldots s_n, s}$ and a relation $p_A \subseteq |A|_{s_1} \times \cdots \times |A|_{s_n}$ for each predicate name $p \in \Pi_{s_1 \ldots s_n}$.

# First-Order Predicate Logic with Equality ($\mathcal{FOPEQ}$)

**Signatures:** $\Sigma_{\mathcal{FOPEQ}} = \langle S, \Omega, \Pi \rangle$

- $S$ is a set of sort names
- $\Omega$ is a set of operation names
- $\Pi$ is a set of predicate names indexed by arity.

**Sentences:** closed first-order formulae using $\wedge, \vee, \neg, \Rightarrow, \Leftrightarrow, \exists, \forall$ and the logical constants `true` and `false`.

**Models:** consist of a carrier set $|A|_s$ for each sort name $s \in S$, a function $f_A : |A|_{s_1} \times \cdots \times |A|_{s_n} \to |A|_s$ for each operation name $f \in \Omega_{s_1 \ldots s_n, s}$ and a relation $p_A \subseteq |A|_{s_1} \times \cdots \times |A|_{s_n}$ for each predicate name $p \in \Pi_{s_1 \ldots s_n}$.

**Satisfaction Relation:** usual satisfaction of first-order sentences by first-order structures.

# Building Specifications in the Event-B Institution

Logical Methods in Computer Science
Volume 18, Issue 4, 2022, pp. 4:1–4:55
https://lmcs.episciences.org/

Submitted Mar. 22, 2021
Published Nov. 09, 2022

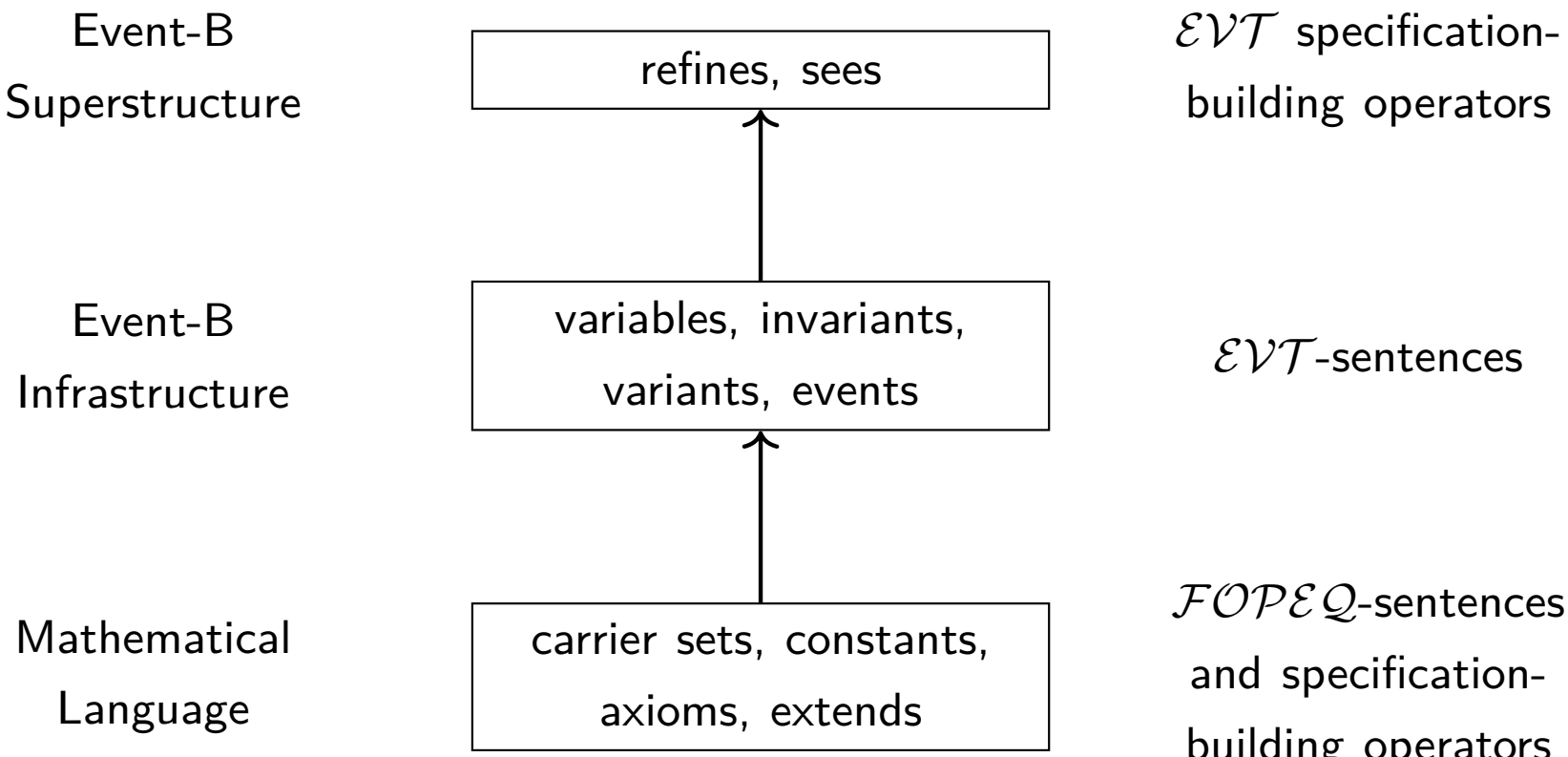
## BUILDING SPECIFICATIONS IN THE EVENT-B INSTITUTION

MARIE FARRELL, ROSEMARY MONAHAN, AND JAMES F. POWER

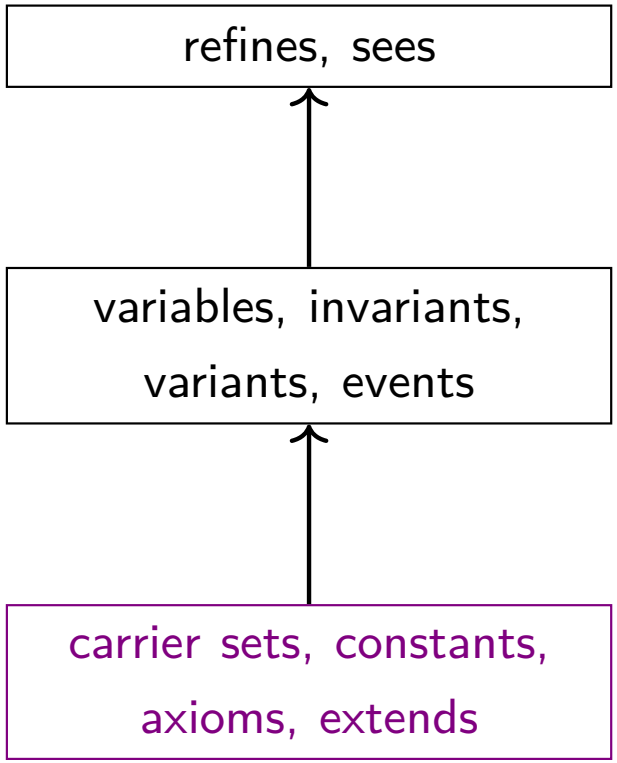
Department of Computer Science and Hamilton Institute, Maynooth University, Ireland
*e-mail address*: marie.farrell@mu.ie

**Event-B Institution?**

# The Three-Layer Model



# The Three-Layer Model



# The $\mathcal{FOPEQ}$ Interface

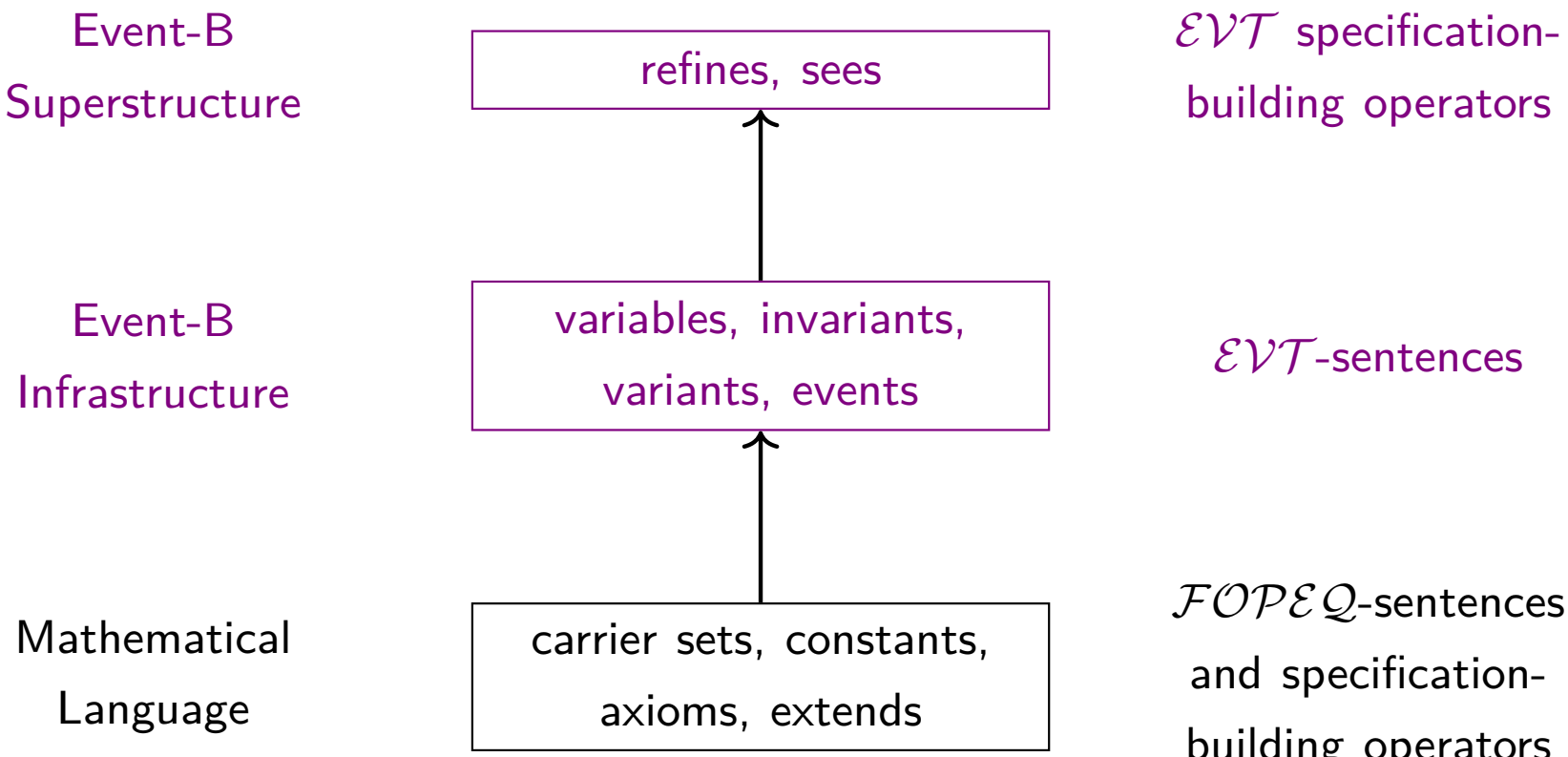
**$\mathcal{FOPEQ}$ Operations**

- $\texttt{F.and} : \Sigma\text{-}formula^* \to \Sigma\text{-}formula$
- $\texttt{F.lt} : \Sigma\text{-}term \times \Sigma\text{-}term \to \Sigma\text{-}formula$
- $\texttt{F.leq} : \Sigma\text{-}term \times \Sigma\text{-}term \to \Sigma\text{-}formula$
- $\texttt{F.exists} : VarName^* \times \Sigma\text{-}formula \to \Sigma\text{-}formula$
- $\texttt{F.}\iota : VarName^* \to \Sigma\text{-}formula \to \Sigma\text{-}formula$

**$\mathcal{FOPEQ}$ Functions**

- $\mathbb{P}_\Sigma : LabelledPred \to \Sigma\text{-}formula$
- $\mathbb{T}_\Sigma : Expression \to \Sigma\text{-}term$
- $\mathbb{M} : SetName^* \times ConstName^* \times LabelledPred^* \to |\mathbf{Sign}_{\mathcal{FOPEQ}}|$

# The Three-Layer Model



# What is $\mathcal{EVT}$?

# $\mathcal{EVT}$ - The Institution for Event-B (Vocabulary)

Signatures: $\Sigma_{\mathcal{EVT}} = \langle S, \Omega, \Pi, E, V \rangle$

- $S$, $\Omega$, $\Pi$ from $\mathcal{FOPEQ}$
- $E$ is a function from event names to their status.
- $V$ is a set of sort-indexed variable names.

# Signature Extraction

```
1 CONTEXT cd
2   CONSTANTS
3     d
4   AXIOMS
5     axm1: d ∈ ℕ
6     axm2: d > 0
7 END
```

```
1 MACHINE m0
2   SEES cd
3   VARIABLES
4     n
5   INVARIANTS
6     inv1: n ∈ ℕ
7     inv2: n ≤ d
8   EVENTS
9     Initialisation
10      then
11        act1: n := 0
12      Event ML_out ≙ ordinary
13       when
14         grd1: n < d
15       then
16         act1: n := n + 1
17    Event ML_in ≙ ordinary
18      when
19         grd1: n > 0
20      then
21         act1: n := n − 1
22 END
```

## Signature

$\Sigma_{\mathtt{m1}} = \langle\ S,\ \Omega,\ \Pi,\ E,\ V\ \rangle$

where

$S = \{\mathbb{N}\}$,

$\Omega = \{0 : \mathbb{N}, d : \mathbb{N}\}$,

$\Pi = \{> : \mathbb{N} \times \mathbb{N}\}$,

$E = \{(\mathtt{Init} \mapsto \mathtt{ordinary}),\ (\mathtt{ML\_in} \mapsto \mathtt{ordinary}),\ (\mathtt{ML\_out} \mapsto \mathtt{ordinary})\}$,

$V = \{\mathtt{n} : \mathbb{N}\}$

# $\mathcal{EVT}$ - The Institution for Event-B (Syntax)

## Sentences:

```
1  MACHINE m REFINES a SEES ctx
2    VARIABLES x̄
3    INVARIANTS I(x̄)
4    VARIANT n(x̄)
5    EVENTS
6    Initialisation ordinary
7      then  act-name: BA(x̄′)
       .
       .
8      .
9    Event e_i ≙  convergent
10     any p̄
11     when  guard-name: G(x̄, p̄)
12     with  witness-name: W(x̄, p̄)
13     then  act-name: BA(x̄, p̄, x̄′)
       .
       .
14     .
15 END
```

$$\{\langle e,\ I(\overline{x}) \ \wedge\ I(\overline{x\prime})\rangle \ \mid\ e \in dom(\Sigma.E)\}$$

$$\langle \mathtt{Init},\ BA(\overline{x}')\rangle$$

$$\langle \mathtt{e}_i,\ n(\overline{x\prime}) < n(\overline{x})\rangle$$

$$\langle \mathtt{e},\ \exists\, \overline{p} \cdot G(\overline{x},\overline{p}) \wedge W(\overline{x},\overline{p}) \wedge BA(\overline{x},\overline{p},\overline{x}')\rangle$$

# $\mathcal{EVT}$ - The Institution for Event-B (Semantics)

Models: $\langle A, L, R \rangle$

- $A$ is a $\Sigma_{\mathcal{FOPEQ}}$-model.
- $L \subseteq State_A$ provides the states after the `Init` event.
- $R.e \subseteq State_A \times State_A$.

```
1  Event e ≙
2    when  grd1: x < 2
3    then  act1: x := x + 1
4          act2: y := false
```

$$R_e = \left\{ \begin{array}{llll} \{x \mapsto 0, & y \mapsto \mathit{false}, & x' \mapsto 1, & y' \mapsto \mathit{false}\}, \\ \{x \mapsto 0, & y \mapsto \mathit{true}, & x' \mapsto 1, & y' \mapsto \mathit{false}\}, \\ \{x \mapsto 1, & y \mapsto \mathit{false}, & x' \mapsto 2, & y' \mapsto \mathit{false}\}, \\ \{x \mapsto 1, & y \mapsto \mathit{true}, & x' \mapsto 2, & y' \mapsto \mathit{false}\} \end{array} \right\}$$

# $\mathcal{EVT}$ - The Institution for Event-B (Satisfaction)

## Satisfaction:

1. For any $\mathcal{EVT}$-model $\langle A, L, R\rangle$ and $\mathcal{EVT}$-sentence $\langle e, \phi(\overline{x}, \overline{x\prime})\rangle$, where $e \neq \texttt{Init}$:

$$\langle A, L, R\rangle \models_{\Sigma} \langle e, \phi(\overline{x}, \overline{x}')\rangle \quad \Leftrightarrow \quad \forall \langle s, s'\rangle \in R.e{\cdot}A^{(s,s\prime)} \models_{\Sigma^{(V,V')}_{\mathcal{FOPEQ}}} \phi(\overline{x}, \overline{x}')$$

2. For $\mathcal{EVT}$-sentences of the form $\langle \texttt{Init}, \phi(\overline{x}')\rangle$:

$$\langle A, L, R\rangle \models_{\Sigma} \langle \texttt{Init}, \phi(\overline{x}')\rangle \quad \Leftrightarrow \quad \forall\, s' \in L \cdot A^{(s\prime)} \models_{\Sigma^{(V')}_{\mathcal{FOPEQ}}} \phi(\overline{x}')$$

# Building Specifications in the Event-B Institution

Logical Methods in Computer Science
Volume 18, Issue 4, 2022, pp. 4:1–4:55
https://lmcs.episciences.org/

Submitted Mar. 22, 2021
Published Nov. 09, 2022

## BUILDING SPECIFICATIONS IN THE EVENT-B INSTITUTION

MARIE FARRELL, ROSEMARY MONAHAN, AND JAMES F. POWER

Department of Computer Science and Hamilton Institute, Maynooth University, Ireland
*e-mail address*: marie.farrell@mu.ie

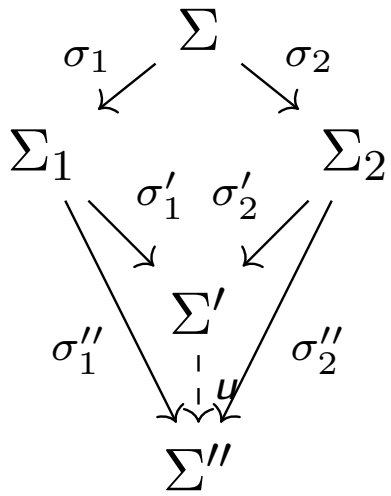
**Building Specifications?**

# Specification-Building Operators

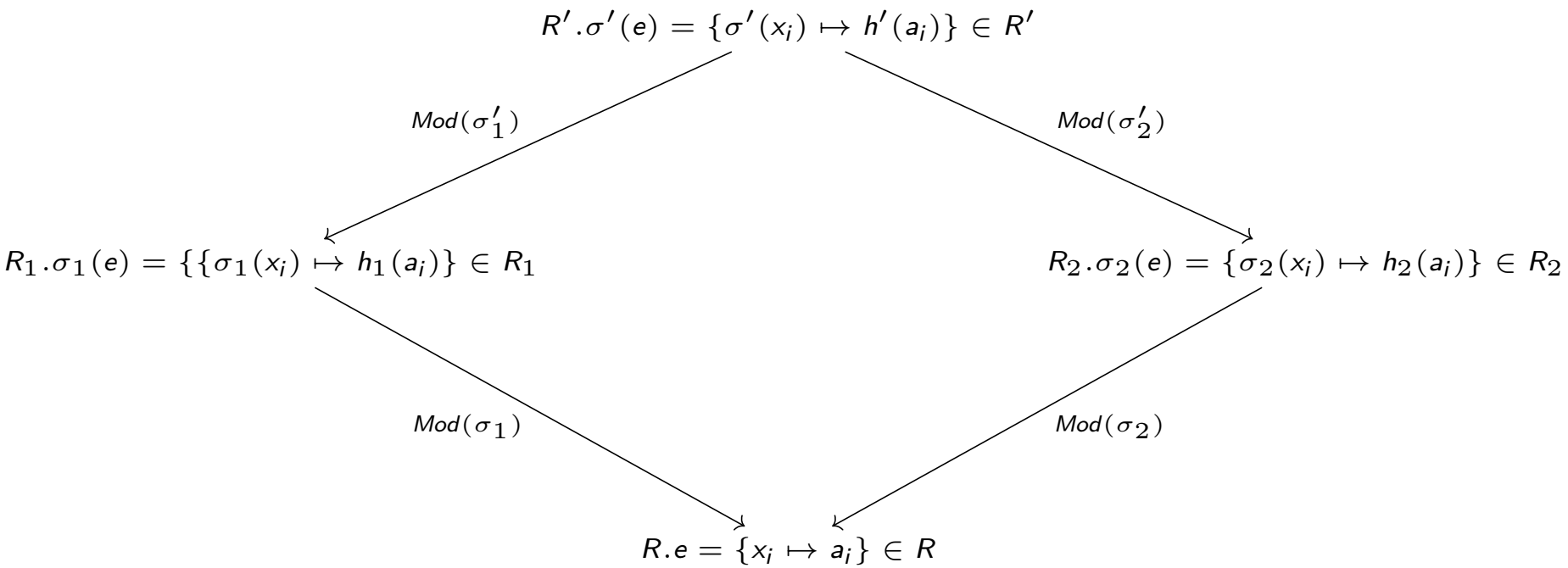
| Operation | Format | Description |
|---|---|---|
| Translation | $SP_1$ `with` $\sigma$ | Renames the signature components of $SP_1$ using the signature morphism $\sigma : \Sigma_{SP_1} \to \Sigma'$.<br>$Sig[SP_1 \texttt{ with } \sigma] = \Sigma'$<br>$Mod[SP_1 \texttt{ with } \sigma] = \{M' \in \lvert\mathbf{Mod}(\Sigma')\rvert \mid M'\rvert_\sigma \in Mod[SP_1]\}$. |
| Sum | $SP_1$ `and` $SP_2$ | Combines the specifications $SP_1$ and $SP_2$.<br>$SP_1 \texttt{ and } SP_2 = (SP_1 \texttt{ with } \iota) \cup (SP_2 \texttt{ with } \iota')$<br>where $Sig[SP_1] = \Sigma$, $Sig[SP_2] = \Sigma'$, $\iota : \Sigma \hookrightarrow \Sigma \cup \Sigma'$, $\iota' : \Sigma' \hookrightarrow \Sigma \cup \Sigma'$ |
| Enrichment | $SP_1$ `then` ... | Extends the specification $SP_1$ by adding new sentences after the `then` specification-building operator. This operator can be used to represent **superposition refinement** of Event-B specifications. |
| Hiding | $SP_1$ `hide via` $\sigma$ | Interprets a specification, $SP_1$, as one restricted to the signature components of another specified by the signature morphism $\sigma : \Sigma \to \Sigma_{SP_1}$.<br>$Sig[SP_1 \texttt{ hide via } \sigma] = \Sigma$<br>$Mod[SP_1 \texttt{ hide via } \sigma] = \{ M\rvert_\sigma \mid M \in Mod[SP_1]\}$. |

# We Need Pushouts for Specification Building

Given two $\mathcal{EVT}$-signature morphisms $\sigma_1 : \Sigma \to \Sigma_1$ and $\sigma_2 : \Sigma \to \Sigma_2$ a pushout is a triple $(\Sigma', \sigma_1', \sigma_2')$ that satisfies the universal property: for all triples $(\Sigma'', \sigma_1'', \sigma_2'')$ there exists a unique morphism $u : \Sigma' \to \Sigma''$ such that the diagram below commutes.



# Institutions Must Preserve Amalgamation for Specification Building




...proofs are in the paper

# Building Specifications in the Event-B Institution

$\mathbb{B}$ : $\quad Machine \to Env \to |\mathbf{Spec}_{\mathcal{EVT}}|$ *#Build an $\mathcal{EVT}$ structured specification for one machine*

$$\mathbb{B}\ \left[\!\!\left[\begin{array}{l}\texttt{machine } m\\ \texttt{refines } a\\ \texttt{sees } ctx_1, \ldots, ctx_n\\ mbody\\ \texttt{end}\end{array}\right]\!\!\right]\ \xi\ =\ \left\langle\ \Sigma,\ \left[\begin{array}{l}\texttt{spec } [\![m]\!] \texttt{ over } \mathcal{EVT} =\\ \quad \textit{\# Include contexts using the comorphism } \rho:\\ \quad ([\![ctx_1]\!] \texttt{ and } \ldots \texttt{ and } [\![ctx_n]\!]) \texttt{ with } \rho\\ \quad \textit{\#Sentences from the refined machine (if any):}\\ \quad (\texttt{and } \mathbb{A}_\Sigma [\![mbody]\!] [\![a]\!] \xi)\\ \texttt{then}\\ \quad \mathbb{S}_\Sigma [\![mbody]\!]\end{array}\right]\ \right\rangle$$

*where* $\Sigma = \xi[\![m]\!]$.

$\mathbb{A}_\Sigma$ : $\quad MachineBody \to EventName \to Env \to |\ \mathbf{Spec}_{\mathcal{EVT}}\ |$

*#Extract any relevant specification from the refined (abstract) machine*

$$\mathbb{A}_\Sigma\ \left[\!\!\left[\begin{array}{l}\texttt{variables } v_1, \ldots, v_n\\ \texttt{invariants } i_1, \ldots, i_n\\ \texttt{theorems } t_1, \ldots, t_n\\ \texttt{variant } n\\ \texttt{events } e_{init},\ e_1, \ldots, e_n\end{array}\right]\!\!\right]\ [\![a]\!]\ \xi\ =\ \begin{array}{l}\mathbb{I}_\Sigma [\![i_1]\!] \texttt{ and } \ldots \texttt{ and } \mathbb{I}_\Sigma [\![i_n]\!]\\ \texttt{and } \mathbb{R}_\Sigma [\![e_1]\!] [\![a]\!] \xi \texttt{ and } \ldots \texttt{ and } \mathbb{R}_\Sigma [\![e_n]\!] [\![a]\!] \xi\\ \quad \textit{\#Conjoin sentences from each event definition}\end{array}$$

# Building Specifications in the Event-B Institution

$\mathbb{R}_\Sigma : \mathit{Event} \to \mathit{EventName} \to \mathit{Env} \to\mid \mathbf{Spec}_{\mathcal{EVT}} \mid$ *#Extract specification from one refined event*

$$\mathbb{R}_\Sigma \left[\!\!\left[ \begin{array}{l} \texttt{event } e_c \\ \texttt{status } s \\ \texttt{refines } e_1, \ldots, e_n \\ \mathit{ebody} \\ \texttt{end} \end{array} \right]\!\!\right] [\![a]\!]\ \xi\ =$$

$\texttt{let}$

$\quad \Sigma_a = \xi[\![a]\!]$, *#Signature of abstract machine*

$\quad$ *# Use $\Sigma_h$, $\sigma_h$ to select only refined events:*

$\quad \Sigma_h = \langle \Sigma_a.S,\ \Sigma_a.\Omega,\ \Sigma_a.\Pi,\ \{[\![e_1]\!], \ldots, [\![e_n]\!]\} \lhd \Sigma_a.E,\ \Sigma_a.V \rangle$,

$\quad \sigma_h : \Sigma_h \hookrightarrow \Sigma_a$,

$\quad$ *# Use $\sigma_m$ to reassign refined event sentences to $e_c$:*

$\quad \sigma_m : \Sigma_h \to \Sigma$

$$\quad \sigma_m = \left\langle \begin{array}{l} \Sigma_h.S \hookrightarrow \Sigma.S,\ \Sigma_h.\Omega \hookrightarrow \Sigma.\Omega, \Sigma_h.\Pi \hookrightarrow \Sigma.\Pi, \\ \Sigma_h.E \mapsto \{[\![e_c]\!]\} \lhd \Sigma.E, \\ \Sigma_h.V \hookrightarrow \Sigma.V \end{array} \right\rangle$$

$\texttt{in}$

$\quad ([\![a]\!]\ \texttt{hide via}\ \sigma_h)\ \texttt{with}\ \sigma_m.$

$\mathbb{I}_\Sigma : \mathit{LabelledPred} \to \mathit{Sen}_{\mathcal{EVT}}(\Sigma)$ *#Invariant sentences*

$\mathbb{I}_\Sigma\ [\![i]\!] = \{\langle [\![e]\!],\ \texttt{F.and}(\mathbb{P}_\Sigma [\![i]\!], \texttt{F.}\iota(\Sigma.V)(\mathbb{P}_\Sigma [\![i]\!]))\rangle \mid e \in \mathit{dom}(\Sigma.E)\}$

$\mathbb{V}_\Sigma : \mathit{Expression} \to \mathit{Sen}_{\mathcal{EVT}}(\Sigma)$ *#Variant can't increase for non-ord. events*

$$\mathbb{V}_\Sigma\ [\![n]\!] = \{\langle [\![e]\!],\ \texttt{F.lt}(\texttt{F.}\iota(\Sigma.V)(\mathbb{T}_\Sigma [\![n]\!]), \mathbb{T}_\Sigma [\![n]\!])\rangle \mid (e \mapsto \texttt{convergent}) \in \Sigma.E\} \cup \{\langle [\![e]\!],\ \texttt{F.leq}(\texttt{F.}\iota(\Sigma.V)(\mathbb{T}_\Sigma [\![n]\!]), \mathbb{T}_\Sigma [\![n]\!])\rangle \mid (e \mapsto \texttt{anticipated}) \in \Sigma.E\}$$

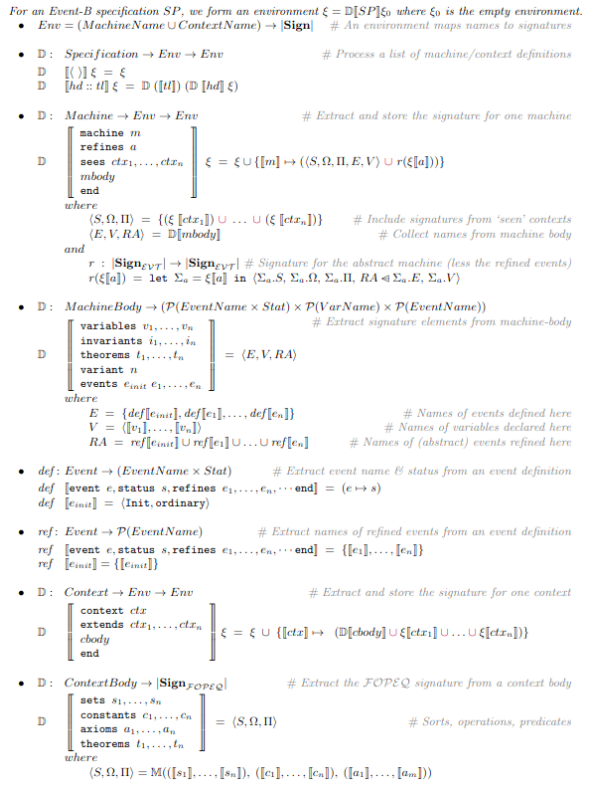
$\mathbb{E}_\Sigma : \mathit{InitEvent} \to \mathit{Sen}_{\mathcal{EVT}}(\Sigma)$ *#Initial event: get sentences from actions*

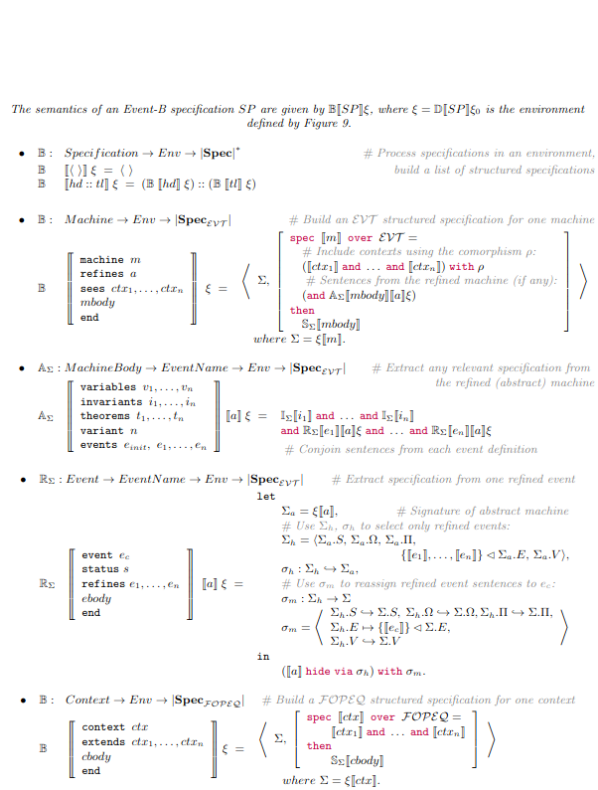
$$\mathbb{E}_\Sigma \left[\!\!\left[ \begin{array}{l} \texttt{event Initialisation} \\ \texttt{status ordinary} \\ \texttt{then } \mathit{act}_1, \ldots, \mathit{act}_n \\ \texttt{end} \end{array} \right]\!\!\right] = \{\langle \texttt{Init},\ BA \rangle\}$$

*where*

$BA = \texttt{F.and}(\mathbb{P}_\Sigma [\![\mathit{act}_1]\!], \ldots, \mathbb{P}_\Sigma [\![\mathit{act}_n]\!])$

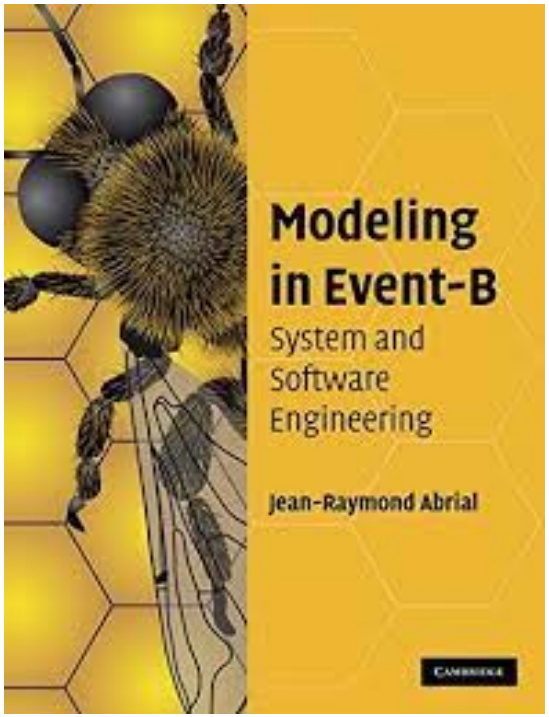
# Building Specifications in the Event-B Institution





...it's all in the paper.

# An Example: Cars On A Bridge



# An Example: Cars On A Bridge

```
CONTEXT cd
  CONSTANTS  d
  AXIOMS
     axm1: d ∈ ℕ
     axm2: d > 0
END
```

```
MACHINE m0
  SEES cd
  VARIABLES n
  INVARIANTS
     inv1: n ∈ ℕ
     inv2: n ≤ d
  EVENTS
    Initialisation
      then  act1: n := 0
     Event ML_out ≙ ordinary
      when  grd1: n < d
      then  act1: n := n + 1
    Event ML_in ≙ ordinary
      when  grd1: n > 0
      then  act1: n := n − 1
END
```

```
spec  CD =
  sort ℕ
  ops  d:ℕ
  .  d >  0
end
```

```
spec  M0 =
  CD
  then
    ops  n:ℕ
    .  n ≤ d
     EVENTS
      Initialisation
        thenAct  n := 0
      Event ML_out ≙ ordinary
        when n < d
        thenAct  n := n+1
      Event ML_in ≙ ordinary
        when n > 0
        thenAct  n := n-1
end
```

# An Example: Cars On A Bridge

```
spec  M1 =
  M0 and CD
    then
    ops  a:ℕ
         b:ℕ
         c:ℕ
    .  n = a + b + c
       a = 0  ∨  c = 0
    variant 2 * a + b
    EVENTS
      Initialisation
        thenAct  a := 0
                 b := 0
                 c := 0
      Event ML_out ≙ ordinary
        when a + b < d
             c = 0
        thenAct a := a+1
      Event IL_in ≙ convergent
        when  a > 0
        thenAct a := a-1
                b := b+1
      Event IL_out ≙ convergent
        when 0 < b
             a = 0
        thenAct b := b-1
                c := c+1
      Event ML_in ≙ ordinary
        when  c > 0
        thenAct  c := c-1
end
```

...more detail in the paper.

# So What?

# Modularisation via Specification Building

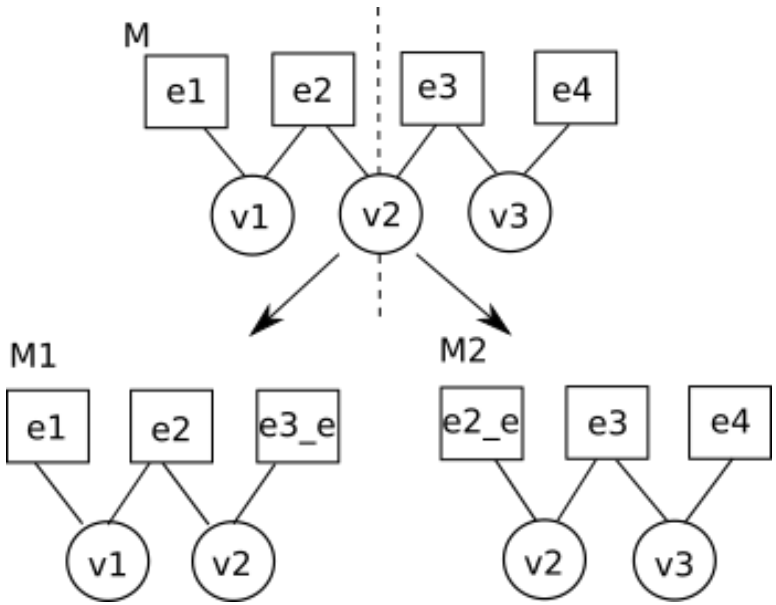
```
spec  DATAM0 =
  CD then
    ops n:ℕ
    . n ≤ d
      EVENTS
      Initialisation
        thenAct n := 0
end

spec  DATAM1 =
  DATAM0 then
    ops a, b, c : ℕ
    . n = a + b + c
      a = 0 ∨ c = 0
    variant 2*a+b
    EVENTS
      Initialisation
        thenAct  a := 0
                 b := 0
                 c := 0
end
```

```
spec  INOUT =
  ops v1, v2 : ℕ
  EVENTS
    Event out ≙ ordinary
      when v1 = 0
      thenAct v2 := v2 + 1
    Event in ≙ ordinary
      when v1 > 0
      thenAct v1 := v1 + 1
end

spec  M1 =
  DATAM1 and M0 and
  INOUT with {⟨out, ordinary⟩ ↦ ⟨ML_out, ordinary⟩,
              ⟨in, ordinary⟩ ↦ ⟨ML_in, ordinary⟩,
               v1 ↦ c, v2 ↦ a} and
  INOUT with {⟨out, ordinary⟩ ↦ ⟨IL_out, convergent⟩,
             ⟨in, ordinary⟩ ↦ ⟨IL_in, convergent⟩,
              v1 ↦ a, v2 ↦ c}
   then
     EVENTS
       Event ML_out ≙ ordinary
         when a + b < d
       Event IL_in ≙ convergent
         thenAct b:= b + 1
       Event IL_out ≙ convergent
         when 0 < b
         thenAct b := b + 1
end
```

# Modularisation via Specification Building: Shared Variable




```
1  spec  M1 =
2    (M hide via  σ1)
3      with {e3 ↦ e3_e}
4  end
5    where σ1 = {v1 ↦ v1, v2 ↦ v2,
6                e1 ↦ e1, e2 ↦ e2,
7                e3 ↦ e3}

8  spec  M2 =
9    (M hide via  σ2)
10     with {e2 ↦ e2_e}
11 end
12   where σ2 = {v2 ↦ v2, v3 ↦ v3,
13               e2 ↦ e2, e3 ↦ e3,
14               e4 ↦ e4}
```

...shared event and generic instantiation are covered in the paper.

# What About Refinement?

# What About Refinement?

... we can do that too!

# Refinement

1. Signatures are the same:

$$SP_A \sqsubseteq SP_C \quad \Leftrightarrow \quad Mod(SP_C) \subseteq Mod(SP_A)$$

2. Signatures are different:

$$SP_A \sqsubseteq SP_C \quad \Leftrightarrow \quad Mod(\sigma)(SP_C) \subseteq Mod(SP_A)$$

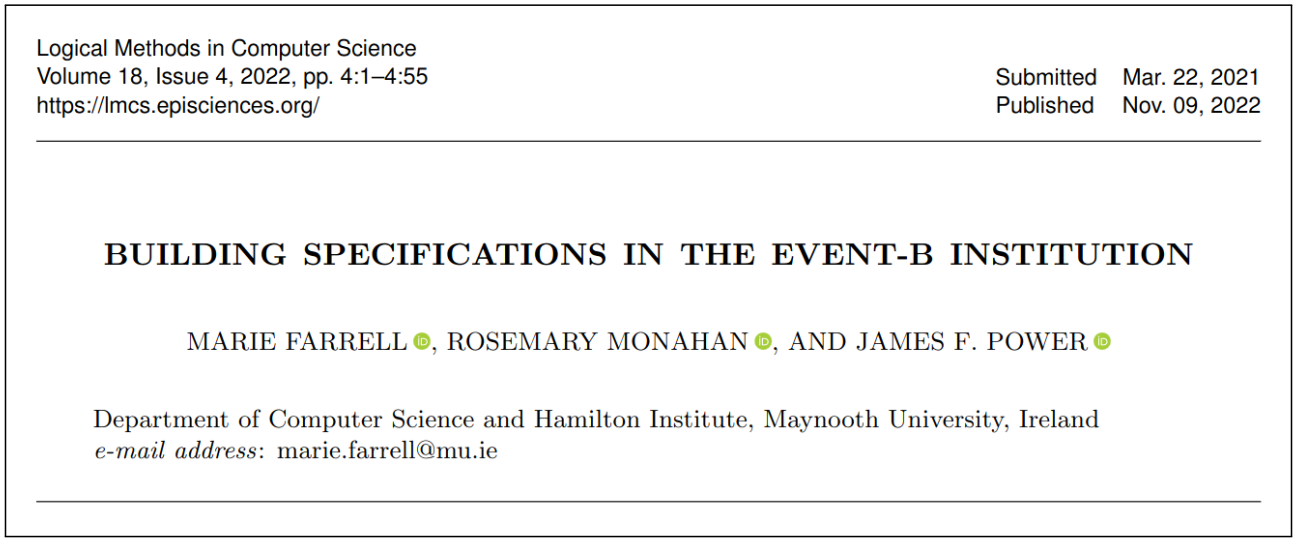
```
1 refinement REF0 : M0 to M1 =
2    ML_in ↦ ML_in, ML_out ↦ ML_out
3 end

4 refinement REF1A : M1 to M2 =
5    ML_in  ↦ ML_in, ML_out ↦ ML_out1,  IL_in  ↦ IL_in, IL_out ↦ IL_out1
6 end

7 refinement REF1B : M1 to M2 =
8    ML_in ↦ ML_in, ML_out ↦ ML_out2, IL_in ↦ IL_in, IL_out ↦ IL_out2
9 end
```

..other interesting refinement examples are in the paper.

# Building Specifications in the Event-B Institution



Logical Methods in Computer Science
Volume 18, Issue 4, 2022, pp. 4:1–4:55
https://lmcs.episciences.org/

Submitted Mar. 22, 2021
Published Nov. 09, 2022

**BUILDING SPECIFICATIONS IN THE EVENT-B INSTITUTION**

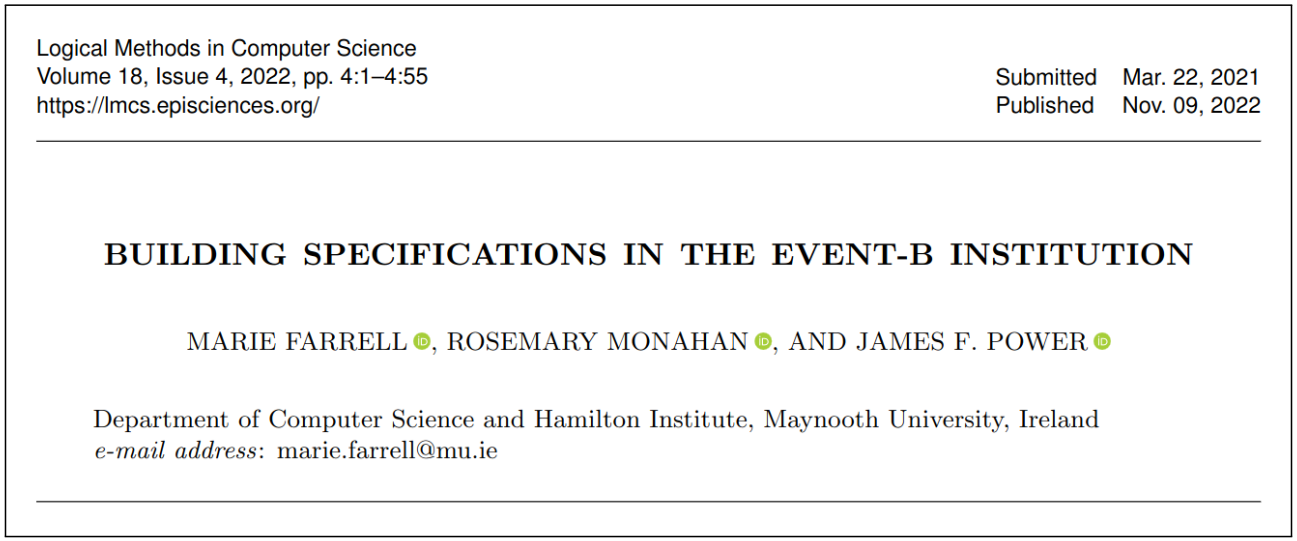
MARIE FARRELL, ROSEMARY MONAHAN, AND JAMES F. POWER

Department of Computer Science and Hamilton Institute, Maynooth University, Ireland
*e-mail address*: marie.farrell@mu.ie

Our Contributions:

1. A formal (translational) **semantics** for Event-B using the EB2EVT tool.

# Building Specifications in the Event-B Institution



Logical Methods in Computer Science
Volume 18, Issue 4, 2022, pp. 4:1–4:55
https://lmcs.episciences.org/

Submitted Mar. 22, 2021
Published Nov. 09, 2022

BUILDING SPECIFICATIONS IN THE EVENT-B INSTITUTION

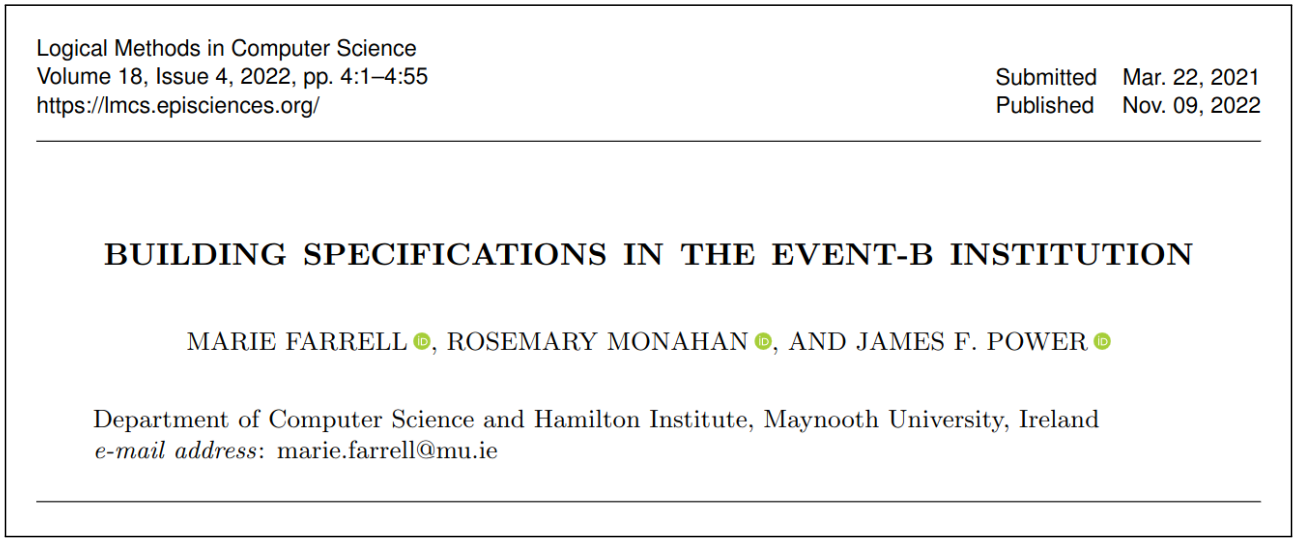
MARIE FARRELL, ROSEMARY MONAHAN, AND JAMES F. POWER

Department of Computer Science and Hamilton Institute, Maynooth University, Ireland
*e-mail address*: marie.farrell@mu.ie

Our Contributions:

1. A formal (translational) **semantics** for Event-B using the EB2EVT tool.
2. A standard approach to **modularisation** using specification-building operators.

# Building Specifications in the Event-B Institution



Logical Methods in Computer Science
Volume 18, Issue 4, 2022, pp. 4:1–4:55
https://lmcs.episciences.org/

Submitted Mar. 22, 2021
Published Nov. 09, 2022

BUILDING SPECIFICATIONS IN THE EVENT-B INSTITUTION

MARIE FARRELL, ROSEMARY MONAHAN, AND JAMES F. POWER

Department of Computer Science and Hamilton Institute, Maynooth University, Ireland
*e-mail address*: marie.farrell@mu.ie

Our Contributions:

1. A formal (translational) **semantics** for Event-B using the EB2EVT tool.
2. A standard approach to **modularisation** using specification-building operators.
3. An explication of Event-B **refinement** in the context of the EVT institution.

# Conclusions and Future Work

- Provide access to stronger, more general modularisation for Event-B without the need to modify the formalism itself.

# Conclusions and Future Work

- Provide access to stronger, more general modularisation for Event-B without the need to modify the formalism itself.
- Demonstrated how such modulrisation capabilities can be added to a formal specification language using the theory of institutions.

# Conclusions and Future Work

- Provide access to stronger, more general modularisation for Event-B without the need to modify the formalism itself.
- Demonstrated how such modulrisation capabilities can be added to a formal specification language using the theory of institutions.
- Future work: examine how this approach can be applied to other similar formal languages.

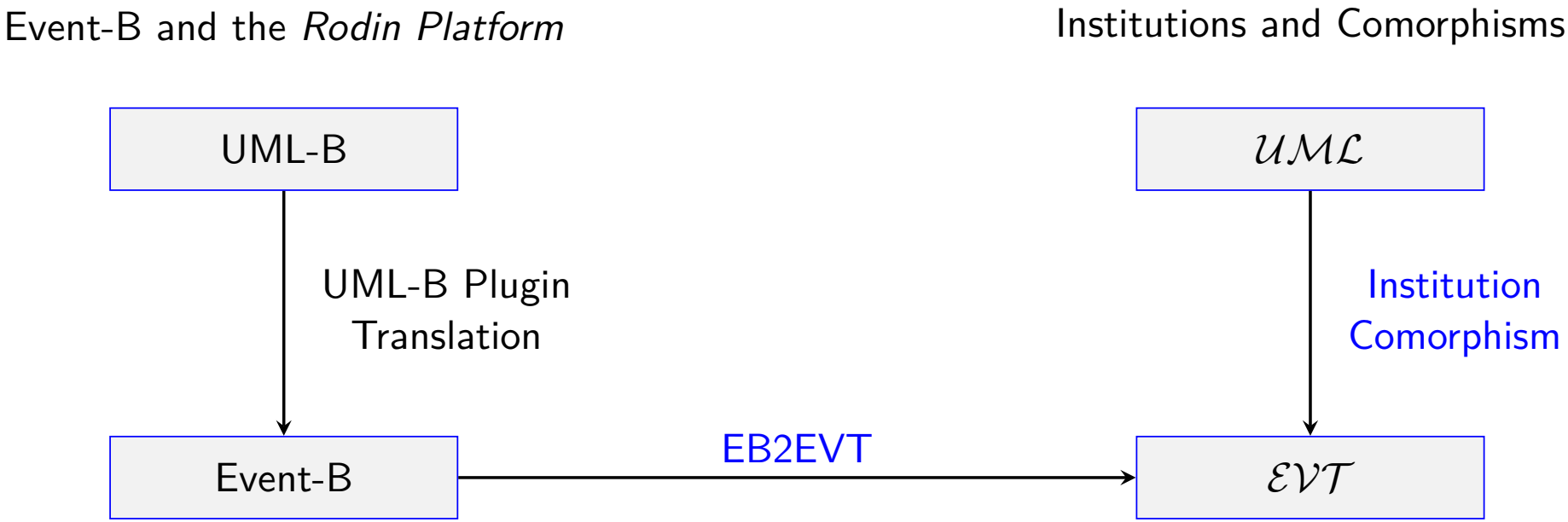
# Conclusions and Future Work

- Provide access to stronger, more general modularisation for Event-B without the need to modify the formalism itself.
- Demonstrated how such modulrisation capabilities can be added to a formal specification language using the theory of institutions.
- Future work: examine how this approach can be applied to other similar formal languages.
- Future Work: incorporate our semantics specification-building operators into Rodin using EB4EB and Theory Plugin.

# Conclusions and Future Work

- Provide access to stronger, more general modularisation for Event-B without the need to modify the formalism itself.
- Demonstrated how such modulrisation capabilities can be added to a formal specification language using the theory of institutions.
- Future work: examine how this approach can be applied to other similar formal languages.
- Future Work: incorporate our semantics specification-building operators into Rodin using EB4EB and Theory Plugin.
- Future Work: define institution morphisms to enable interoperability with other formalisms.

# Not in the paper...



# Connecting Institutions: Institution Comorphism

An institution comorphism $\rho : \mathbf{INS} \to \mathbf{INS}'$ is composed of:

- A functor $\rho^{Sign} : \mathbf{Sign} \to \mathbf{Sign}'$.
- A natural transformation $\rho^{Sen} : \mathbf{Sen} \to \rho^{Sign}; \mathbf{Sen}'$, that is, for each $\Sigma \in |\mathbf{Sign}|$, a function $\rho^{Sen}_{\Sigma} : \mathbf{Sen}(\Sigma) \to \mathbf{Sen}'(\rho^{Sign}(\Sigma))$.
- A natural transformation $\rho^{Mod} : (\rho^{Sign})^{op}; \mathbf{Mod}' \to \mathbf{Mod}$, that is, for each $\Sigma \in |\mathbf{Sign}|$, a functor $\rho^{Mod}_{\Sigma} : \mathbf{Mod}'(\rho^{Sign}(\Sigma)) \to \mathbf{Mod}(\Sigma)$.

An institution comorphism must ensure that for any signature $\Sigma \in |\mathbf{Sign}|$, the translations $\rho^{Sen}_{\Sigma}$ of sentences and $\rho^{Mod}_{\Sigma}$ of models preserve the satisfaction relation, that is, for any $\psi \in \mathbf{Sen}(\Sigma)$ and $M' \in |\mathbf{Mod}(\rho^{Sign}(\Sigma))|$:

$$\rho^{Mod}_{\Sigma}(M') \models_{\Sigma} \psi \quad \Leftrightarrow \quad M' \models'_{\rho^{Sign}(\Sigma)} \rho^{Sen}_{\Sigma}(\psi)$$

Logical Methods in Computer Science
Volume 18, Issue 4, 2022, pp. 4:1–4:55
https://lmcs.episciences.org/

Submitted Mar. 22, 2021
Published Nov. 09, 2022

**BUILDING SPECIFICATIONS IN THE EVENT-B INSTITUTION**

MARIE FARRELL, ROSEMARY MONAHAN, AND JAMES F. POWER

Department of Computer Science and Hamilton Institute, Maynooth University, Ireland
*e-mail address*: marie.farrell@mu.ie

# Questions?

marie.farrell@manchester.ac.uk

FM AS
Formal Methods
for
Autonomous Systems

5TH WORKSHOP ON

# FORMAL METHODS FOR AUTONOMOUS SYSTEMS

**Important Dates:**

- Submission: *17th of August 2023* (AOE)
- Notification: *15th of September 2023*
- Final Version due: *20th of October 2023*
- Workshop: *15th and 16th of November 2023*, hybrid format, at iFM 2023

**Submission Information:**

- Vision Papers and Research Previews: *6 pgs EPTCS*
- Regular Papers and Experience Reports: *15 pgs EPTCS*

**Topics of Interest include:**

- Applicable, tool-supported Formal Methods that are suited to Autonomous Systems,
- Runtime Verification or other formal approaches to deal with the gap between models/simulations and the real world
- Verification against safety assurance arguments or standards documents,
- Case Studies that identify challenges when applying formal methods to autonomous systems

https://fmasworkshop.github.io/FMAS2023/