Specification of Systems with Parameterised Events: An Institution-independent Approach

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Dedicated to Luis Soares Barbosa

on the occasion of his 60th birthday

Some Bits of History

- 2005: First meeting of Luis and Rolf in Macau (FACS Wsh., *Formal Aspects of Component Software*)

  Common research interest: Rigorous development of reactive component systems (formal models, logics, methods)

- 2010-2013: MONDRIAN project - *Foundations for architectural design* (Luis coordinator, Rolf external consultant)
- 2015: First common publication: *Refinement in hybridised institutions*, with A. Madeira and M. Martins, FAoC journal
- 2016-2022: Continuation of our common research, with Alexander Knapp joining

Luis' Habilitation 2016

Development of Reactive Component Systems

We are interested in a stepwise refinement methodology
$SP_0 \rightsquigarrow SP_1 \rightsquigarrow \cdots \rightsquigarrow SP_n$

For doing this we want a logic that is suitable for specifications of reactive component systems on various abstraction levels.

Our proposal: **Dynamic Logic with Binders** $\mathcal{D}^{\downarrow}$
[ICTAC 2016] with A. Madeira and M. Martins

$\mathcal{D}^{\downarrow}$-logic is suitable to express

- **abstract specifications** of requirements (safety, liveness, ...)
  - we take regular modalities from Dynamic Logic
- **constructive specifications** representing concrete processes
  - we take variables with binders from Hybrid Logic

Actions and Formulæ in $\mathcal{D}^{\downarrow}$-Logic

A **signature** is a finite set A of **atomic actions**.

Structured actions:

$$\alpha ::= a \in A \mid \alpha; \alpha \mid \alpha + \alpha \mid \alpha^*$$

Formulæ:

$$\varphi ::= \mathrm{true} \mid \neg\varphi \mid \varphi \vee \varphi \mid \langle\alpha\rangle\varphi$$

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and z a state variable.

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and z a state variable.

Usual abbreviations, like $[\alpha]\varphi = \neg\langle\alpha\rangle\neg\varphi$

Sentences are formulæ without free variables.

Semantics of $\mathcal{D}^{\downarrow}$-logic

Models are reachable LTS with initial state:

$$\mathcal{M} = (W, w_0, (\xrightarrow{a} \subseteq W \times W)_{a \in A})$$

Satisfaction relation:

For sentences φ, $\quad \mathcal{M} \models^{\mathcal{D}^{\downarrow}} \varphi$ if $\mathcal{M}, w_0 \models \varphi$

Satisfaction Relation in $\mathcal{D}^{\downarrow}$

For any A-model $\mathcal{M} = (W, w_0, \rightarrow)$, $w \in W$ and $v : Z \rightarrow W$,

- $\mathcal{M}, w, v \models \langle\alpha\rangle\varphi$ if
  there exists $w \xrightarrow{\alpha} w'$ such that $\mathcal{M}, w', v \models \varphi$,
- $\mathcal{M}, w, v \models z$ if $w = v(z)$,
- $\mathcal{M}, w, v \models \downarrow z.\, \varphi$ if $\mathcal{M}, w, v\{z \mapsto w\} \models \varphi$,
- $\mathcal{M}, w, v \models @_z\varphi$ if $\mathcal{M}, v(z), v \models \varphi$,
- ...

Abstract and Concrete Specifications in $\mathcal{D}^{\downarrow}$

Example: *Bounded Counter* with two actions *inc*, *reset*

Abstract requirements specification:

- It is always possible to reset the counter:
  $[(\mathit{inc} + \mathit{reset})^*]\langle \mathit{reset} \rangle\, \mathrm{true}$
- Whenever a reset has happened, two successive increments are possible:
  $[(\mathit{inc} + \mathit{reset})^*; \mathit{reset}]\langle \mathit{inc}; \mathit{inc} \rangle\, \mathrm{true}$
- Three increments in a row are never allowed:
  $[(\mathit{inc} + \mathit{reset})^*; \mathit{inc}; \mathit{inc}; \mathit{inc}]\, \mathrm{false}$

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- It is always possible to reset the counter:
  $[(inc + reset)^*]\langle reset\rangle\, \mathrm{true}$
- Whenever a reset has happened, two successive increments are possible:
  $[(inc + reset)^*; reset]\langle inc; inc\rangle\, \mathrm{true}$
- Three increments in a row are never allowed:
  $[(inc + reset)^*; inc; inc; inc]\, \mathrm{false}$

Concrete specification:

- Whenever a reset has happened, the counter is in its initial state:
  $\downarrow z_0.[(inc + reset)^*; reset]\, z_0$

$\mathcal{D}^{\downarrow}$-Logic is an Institution

In: [Barbosa, Hennicker, Madeira, and Martins; TCS 2018]

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- The notion of an **institution** [Goguen and Burstall 83] captures the essential ingredients that a logical system should provide when being used in formal software development.
- Clear separation between syntax (**signatures** and **sentences**), semantics (mathematical **models**) and the relationship between the two in terms of **satisfaction relations** $M \models_{\Sigma} \varphi$.

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An **institution** consists of

- a category *Sig* of *signatures*,
- a *sentences* functor $\mathrm{Sen} : \mathit{Sig} \to \mathrm{Set}$,
- a *models* functor $\mathit{Mod} : \mathit{Sig}^{\mathrm{op}} \to \mathrm{Cat}$, and
- a family of **satisfaction relations** $\models_{\Sigma} \subseteq |\mathit{Mod}(\Sigma)| \times \mathrm{Sen}(\Sigma)$

such that the *satisfaction condition* holds, i.e.

for all $\sigma : \Sigma \to \Sigma'$ in *Sig*, $M' \in \mathit{Mod}(\Sigma')$, and $\varphi \in \mathit{Sen}(\Sigma)$

$$\mathit{Mod}(\sigma)(M') \models_{\Sigma} \varphi \iff M' \models_{\Sigma'} \mathrm{Sen}(\sigma)(\varphi)$$

Integrating Data: The Event/Data-Based Logic $\mathcal{E}^{\downarrow}$

Example: *Bounded Counter*

with two **data attributes** val : Nat, max : Nat

Abstract requirement:

Whenever the counter value is smaller than the upper bound an increment is possible:

$[(\mathit{inc} + \mathit{reset})^*](\mathsf{val} < \mathsf{max}) \rightarrow \langle \mathit{inc} /\!\!/ \mathsf{val}' = \mathsf{val} + 1 \rangle \mathrm{true}$

Syntactic Concepts of $\mathcal{E}^{\downarrow}$-Logic

An **event/data signature** $\Sigma = (E, \Delta)$ consists of a finite set E of **events** and a finite set Δ of **data attributes**.

Event/data actions:

$$\alpha ::= e /\!\!/ \psi_{2\Delta} \mid \alpha; \alpha \mid \alpha + \alpha \mid \alpha^*$$

where $e \in E$ and $\psi_{2\Delta}$ is a "2-data state formula", i.e. a data state formula over $\Delta \cup \Delta'$.

Σ-formulæ:

$$\varphi ::= \text{true} \mid \neg\varphi \mid \varphi \vee \varphi \mid \langle\alpha\rangle\varphi \mid z \mid \downarrow z.\, \varphi \mid @_z\varphi \mid \psi_\Delta$$

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We can turn $\mathcal{E}^{\downarrow}$-logic into an institution

In: [Hennicker, Knapp, Madeira; FAoC 2021]
Hybrid dynamic logic institutions for event/data-based systems

Integrating Event Parameters

Submitted for [Festschrift for Luis, 2022]

Example: *Bounded Counter*

Event with parameter: $\mathit{inc}(\mathsf{x})$ where x is a variable of type Nat.

Let φ be: $\forall \mathsf{x}\,.\,(\mathsf{val} + \mathsf{x} \leq \mathsf{max} \rightarrow \langle \mathit{inc}(\mathsf{x}) /\!\!/ \mathsf{val}' = \mathsf{val} + \mathsf{x} \rangle \mathrm{true})$

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$$[(inc(x) + reset)^*]\varphi$$

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Our solution:

$$[(\mathit{inc}(\mathbf{any}\,\mathsf{x}) + \mathit{reset})^*]\varphi$$

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any x expresses a non-deterministic choice for the value of x

Structured Actions and Formulæ in $\mathcal{E}^{\downarrow}_{\mathrm{p}}$-Logic

An **event/data signature** $\Sigma = (E, \delta)$ consists of

- a finite set E of **parameterised events** $e(\textbf{any}\, X)$ where X is a finite list of variables and
- a **data signature morphism** $\delta : \Delta_0 \to \Delta$

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We assume given an arbitrary data institution which admits pushouts of signatures and amalgamations of models!

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$$\alpha ::= e(\textbf{any}\, X) /\!\!/ \psi_{2\delta}(Y) \mid \alpha ; \alpha \mid \alpha + \alpha \mid \alpha^*$$

where $\psi_{2\delta}(Y)$ is a "2-data state formula with variables in Y".

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The set of **Σ-formulæ** is given by

$$\varphi ::= \mathrm{true} \mid \neg\varphi \mid \varphi \vee \varphi \mid \langle\alpha\rangle\varphi \mid \psi_{\delta}(X) \mid \forall x \,.\, \varphi$$

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Our Solution Reconsidered

$$[(\mathit{inc}(\textbf{any}\,\mathsf{x}) + \mathit{reset})^*]\varphi$$

is

$$[(\mathit{inc}(\textbf{any}\,\mathsf{x}) + \mathit{reset})^*]$$
$$\forall \mathsf{x}\,.\,(\mathsf{val} + \mathsf{x} \leq \mathsf{max} \rightarrow \langle \mathit{inc}(\mathsf{x}) /\!\!/ \mathsf{val}' = \mathsf{val} + \mathsf{x}\rangle \mathrm{true})$$

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But $\mathit{inc}(\mathsf{x}) /\!\!/ \ldots$ is not syntactically correct.

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But $\mathit{inc}(\mathsf{x}) /\!\!/ \ldots$ is not syntactically correct.
Therefore we write

$$[(\mathit{inc}(\textbf{any}\,\mathsf{x}) + \mathit{reset})^*]$$
$$\forall \mathsf{x}\,.\,(\mathsf{val} + \mathsf{x} \leq \mathsf{max} \rightarrow \langle \mathit{inc}(\textbf{any}\,\mathsf{y}) /\!\!/ \mathsf{y} = \mathsf{x} \wedge \mathsf{val}' = \mathsf{val} + \mathsf{x}\rangle \mathrm{true})$$

Open Formulæ and Valuations (institution independent)

Let $\delta : \Delta_0 \to \Delta$ be a data signature morphism.

A **variable** over δ has a name, say x, and an associated type $\tau(x) : \Delta_0 \to \Delta_x$.

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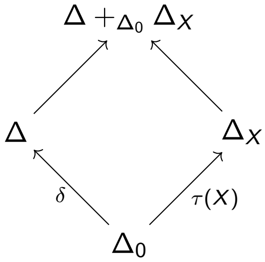
An **open δ-formula** is a pair, written $\varphi(X)$, such that X is a finite set of variable names and φ is a data sentence over the pushout signature

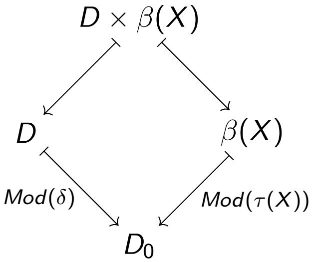


A **valuation** for the variables X is a function β which maps any $x \in X$ to a Δ_x-data model $\beta(x)$.

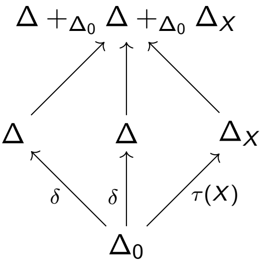
Satisfaction of Open Data Formulæ

For $\delta : \Delta_0 \to \Delta$ we assume a fixed Δ_0-model D_0 and we consider the class of Δ-models D whose reduct along δ is D_0.

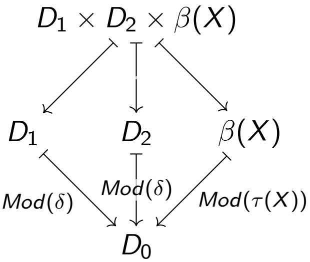
We define: $D, \beta \models_\delta \varphi(X)$ if $D \times \beta(X) \models_{\Delta +_{\Delta_0} \Delta_X} \varphi$



Dealing with Open 2-Data State Formulæ



(a) Colimit



(b) Limit

We define:

$$(D_1, D_2), \beta \models_{2\delta} \psi(X) \text{ if } D_1 \times D_2 \times \beta(X) \models_{\Delta +_{\Delta_0} \Delta +_{\Delta_0} \Delta_X} \psi$$

$$\text{e.g. } \psi(\{x\}) \equiv (\mathsf{val}' = \mathsf{val} + \mathsf{x})$$

Semantic Models in $\mathcal{E}_{\mathsf{p}}^{\downarrow}$

Let $\Sigma = (E, \delta : \Delta_0 \rightarrow \Delta)$ be an event/data signature.

A **configuration** is a pair $\gamma = (\mathit{ctrl}, \mathit{data})$ where *ctrl* is a **control state** and *data* is a **data state** formalised as a model over the data signature Δ (whose reduct along δ is D_0).

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A **Σ-model** is a labelled transition system $\mathcal{M} = (\Gamma, \gamma_0, \to)$ such that

- Γ is a *set of configurations*,
- $\gamma_0 \in \Gamma$ is the *initial configuration*,
- $\to$ is a family of *transition relations* $\xrightarrow{e(\beta_X)} \subseteq \Gamma \times \Gamma$, one for each event $e(\mathbf{any}\ X) \in E$ and each valuation β_X for X,
- all configurations in Γ are reachable from γ_0 via $\to$.

Satisfaction Relation in $\mathcal{E}_{\mathrm{p}}^{\downarrow}$

For any Σ-model $\mathcal{M}$, configuration $\gamma \in \Gamma$ and data variable valuation $\beta : \mathcal{X} \to \mathit{Mod}(\delta)$ "data models",

- $\mathcal{M}, \gamma, \beta \models \langle e(\textbf{any}\ X) /\!\!/ \psi_{2\delta}(Y)\rangle\varphi$ if

  there exists a valuation β_X for X and $\gamma \xrightarrow{e(\beta_X)} \gamma'$ such that $(\mathit{data}(\gamma), \mathit{data}(\gamma')), \beta\{X \mapsto \beta_X\} \models_{2\delta} \psi_{2\delta}(Y)$ and $\mathcal{M}, \gamma', \beta \models \varphi$,

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For sentences φ, $\mathcal{M} \models^{\mathcal{E}_{\mathrm{p}}^{\downarrow}} \varphi$ **if** $\mathcal{M}, \gamma_0 \models \varphi$

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$\mathcal{E}^{\downarrow}_{\mathrm{p}}$-logic is an institution!

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Related work: [Martins, Madeira, Diaconescu, Barbosa; CALCO 2011] *Hybridization of institutions*

Conclusion

Let us celebrate Luis!

With all our best wishes for
many further happy and successful years!