Specifying Event/Data-based Systems

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Specifying Event/Data-based Systems

Event/Data-based systems

- behaviour controlled by events
- data states may change in reaction to events

Specification of event/data-based systems

- Model-oriented approaches (constructive specification)
  - Event-B, symbolic transition systems, CSP with data, UML behavioural/protocol state machines
- Property-oriented approaches (abstract specification)
  - modal (temporal, dynamic) logics, TLA
- Checking whether a concrete model satisfies certain abstract properties
- Refining abstract models to concrete implementations

Example: Specifying an ATM

Events $\{\mathsf{insertCard}, \mathsf{enterPIN}, \mathsf{ejectCard}\}$, data attributes $\{\mathsf{chk}\}$

Axiomatic specification using modal logic formulæ, like

- "Whenever a card has been inserted, a correct PIN can eventually be entered."
  - $\mathbf{AG}(\mathrm{done}(\mathsf{insertCard}) \to \mathbf{EF}(\mathrm{done}(\mathsf{enterPIN}) \land \mathsf{chk} = tt))$
  - $[\boldsymbol{E}^*; \mathsf{insertCard}]\langle \boldsymbol{E}^*; (\mathsf{enterPIN} /\!\!/ \mathsf{chk}' = tt)\rangle\mathrm{true}$
- "Whenever a correct PIN has been entered, the card can eventually be ejected."
  - $\mathbf{AG}(\mathsf{chk} = tt \to \mathbf{EF}\,\mathrm{enabled}(\mathsf{ejectCard}))$
  - $[\boldsymbol{E}^*; (\mathsf{enterPIN} /\!\!/ \mathsf{chk}' = tt)]\langle \boldsymbol{E}^*; \mathsf{ejectCard}\rangle\mathrm{true}$
- "A card cannot be ejected if it has not been inserted before."
  - $\neg\mathrm{enabled}(\mathsf{ejectCard})\ \mathbf{W}\ \mathrm{done}(\mathsf{insertCard})$
  - $[(-\mathsf{insertCard})^*; \mathsf{ejectCard}]\mathrm{false}$

Temporal Logic of Actions (1)

Leslie Lamport. Specifying Systems. Addison Wesley, 2002

- linear temporal logic for describing transition systems
- data from general set theory, no special notions of states or events

$$
\begin{aligned}
\mathit{InitATM} &\equiv \mathit{st} = \mathit{Card} \land \mathit{chk} \in \mathbb{B} \land \mathit{trls} \in \mathbb{N} \\
\mathit{InsertCard} &\equiv \mathit{st} = \mathit{Card} \land \mathit{chk}' = \mathit{ff} \land \mathit{trls}' = 0 \land \mathit{st}' = \mathit{PIN} \\
\mathit{EnterPIN}1 &\equiv \mathit{st} = \mathit{PIN} \land \mathit{trls} < 2 \land \mathit{chk}' = \mathit{ff} \land \mathit{trls}' = \mathit{trls} + 1 \land \mathit{st}' = \mathit{PIN} \\
\mathit{EnterPIN}2 &\equiv \mathit{st} = \mathit{PIN} \land \mathit{trls} = 2 \land \mathit{chk}' = \mathit{ff} \land \mathit{trls}' = \mathit{trls} + 1 \land \mathit{st}' = \mathit{Card} \\
\mathit{EnterPIN}3 &\equiv \mathit{st} = \mathit{PIN} \land \mathit{trls} \leq 2 \land \mathit{chk}' = \mathit{tt} \land \mathit{trls}' = \mathit{trls} + 1 \land \mathit{st}' = \mathit{Return} \\
\mathit{EnterPIN} &\equiv \mathit{EnterPIN}1 \lor \mathit{EnterPIN}2 \lor \mathit{EnterPIN}3 \\
\mathit{Cancel} &\equiv \mathit{st} = \mathit{PIN} \land \mathit{chk}' = \mathit{ff} \land \mathit{trls}' = \mathit{trls} \land \mathit{st} = \mathit{Return} \\
\mathit{EjectCard} &\equiv \mathit{st} = \mathit{Return} \land \mathit{chk}' = \mathit{chk} \land \mathit{trls}' = \mathit{trls} \land \mathit{st} = \mathit{Card} \\
\mathit{NextATM} &\equiv \mathit{InsertCard} \lor \mathit{EnterPIN} \lor \mathit{Cancel} \lor \mathit{EjectCard} \\
\mathit{ATM} &\equiv \mathit{InitATM} \land \Box[\mathit{NextATM}]_{\mathit{st},\mathit{chk},\mathit{trls}} \land \mathrm{WF}_{\mathit{st},\mathit{chk},\mathit{trls}}(\mathit{NextATM})
\end{aligned}
$$

Temporal Logic of Actions (2)

General TLA system specification format

$$Init \land \Box[Next]_{\vec{v}} \land L$$

- $Init$ state predicate for initial states
- $Next$ disjunction of transition predicates (actions)
  - involving primed and unprimed variables
- tuple $\vec{v}$ of variables that can be changed by the system
  - $[A]_{v_1,\ldots,v_n} \equiv A \lor (v_1 = v_1' \land \ldots \land v_n = v_n')$
- L conjunction of action fairness conditions (weak, strong)

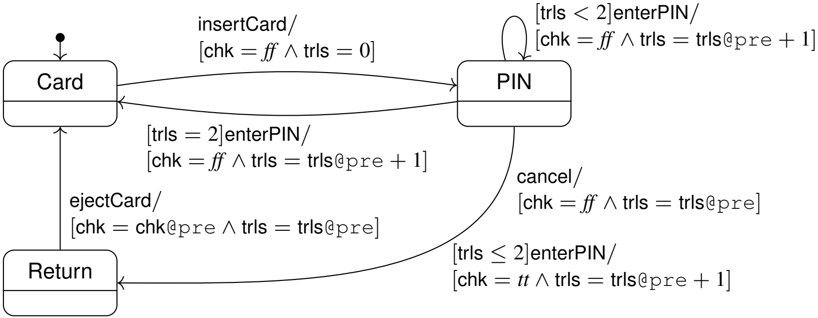
TLA stutter-invariant

- stuttering steps without changes to system variables
- parallel composition (mainly) by conjunction, trace refinement as implication
- property specifications in LTL

UML State Machines (1)

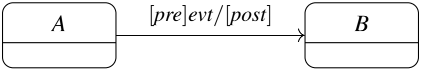
Object Managment Group. Unified Modeling Language 2.5.1.
formal/2017-12-05, 2017

- protocol and behaviour state machines (like Harel state charts)
- data from contextual static structure, dedicated support for (hierarchical) states and (signal, call, &c.) events

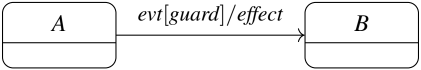


UML State Machines (2)

Protocol state machines for describing legal sequences of event occurrences



Behaviour state machines for operational specifications



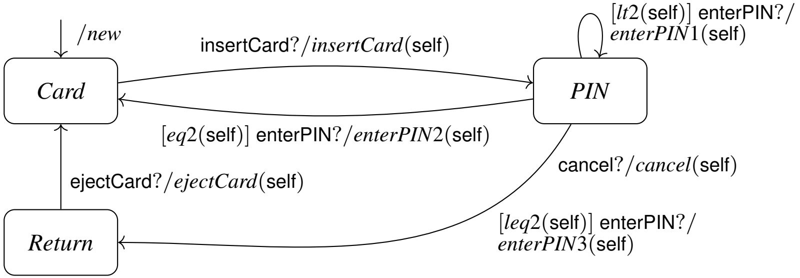
UML notorious for lack of semantics

- parallel composition "synchronously" by orthogonal regions (same machine), or "asynchronously" (different machines) via event queues
- refinement ("redefinition") rather unclear
- property specifications in OCL (`oclInState`)

Symbolic Transition Systems (1)

Pascal Poizat, Jean-Claude Royer. A Formal Architectural Description Language based on Symbolic Transition Systems and Modal Logic. J. Univ. Comp. Sci. 12(12), 2006, pp. 1741–1782

- symbolic analysis by unfolding
- data from underlying abstract data type, explicit states and events



$$insertCard(newATM(chk, trls)) = newATM(ff, 0)$$
$$lt2(newATM(chk, trls)) = trls < 2$$

Symbolic Transition Systems (2)

General form of transitions

$$T \subseteq S \times Tm(\Sigma_{Bool}, X) \times Evt(L) \times Tm(\Sigma_{Dt}, X) \times S$$

- source (control) state, guard term, event (input/output), action term, target (control) state
- Unfolding into symbolic state set S': if $v \in Tm(\Sigma_{Dt})$, $(s, v) \in S'$, $(s, g, e, a, t) \in T$, and $g(v){\downarrow}$, then $(t, a(v){\downarrow}) \in S'$
- initial semantics of abstract data type

Used for specifying software architectures

- parallel composition by synchronous product
- property specifications in modal logic over events with (control) state test $@s$ and state binding $\overset{@}{\exists}\, x \,.\, \varphi$

Communicating Sequential Processes (1)

Andrew W. Roscoe. The Theory and Practice of Concurrency. Prentice Hall, 1998

- process algebra (like CCS, LOTOS, μCRL)
- data from set theory, process terms as states, labels as events

$$
\begin{aligned}
\mathsf{Card}(chk, trls) &= \mathsf{insertCard} \to \mathsf{PIN}(\mathit{ff}, 0) \\
\mathsf{PIN}(chk, trls) &= \quad (trls < 2 \;\&\; \mathsf{enterPIN} \to \quad \mathsf{PIN}(\mathit{ff}, trls + 1) \\
&\qquad\qquad\qquad\qquad\qquad\quad \sqcap \mathsf{Return}(tt, trls + 1)) \\
&\quad \Box\ (trls = 2 \;\&\; \mathsf{enterPIN} \to \quad \mathsf{Card}(\mathit{ff}, trls + 1) \\
&\qquad\qquad\qquad\qquad\qquad\quad \sqcap \mathsf{Return}(tt, trls + 1)) \\
&\quad \Box\ (\mathsf{cancel} \to \mathsf{Return}(\mathit{ff}, trls)) \\
\mathsf{Return}(chk, trls) &= \mathsf{ejectCard} \to \mathsf{Card}(chk, trls)
\end{aligned}
$$

$$
\mathsf{ATM} = \sqcap_{(chk, trls) \in \mathbb{B} \times \mathbb{N}} \mathsf{Card}(chk, trls)
$$

Communicating Sequential Processes (2)

Semantics based on traces, failures, and divergences

$$tr(a \rightarrow P) = \{\langle\rangle\} \cup \{\langle a\rangle \frown s \mid s \in tr(P)\}$$

$$tr(c \mathbin{\&} P) = \begin{cases} tr(P) & \text{if } c \text{ evaluates to true} \\ \{\langle\rangle\} & \text{otherwise} \end{cases}$$

$$tr(P \mathbin{\Box} Q) = tr(P) \cup tr(Q)$$

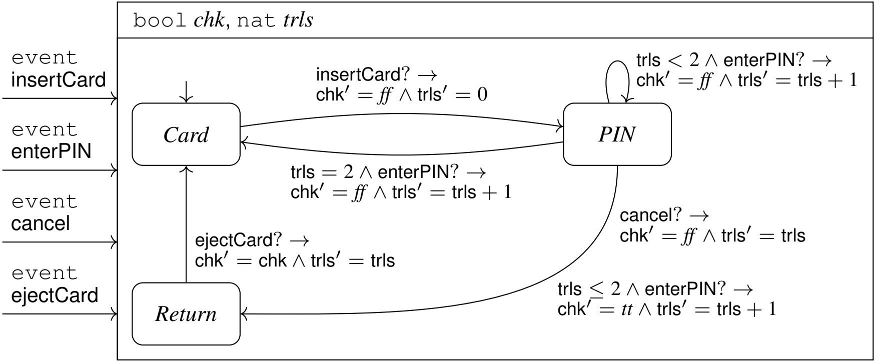
$$tr(P \sqcap Q) = tr(P) \cup tr(Q)$$

- (synchronous) parallel composition integral part of the language
- property specifications also given by CSP processes
- combination with algebraic specification language CASL for loose semantics of data

Synchronous Languages (1)

Rajeev Alur. Principles of Cyber-Physical Systems. MIT Press, 2015

- tick-based, synchronous execution (like Lustre, Esterel)
- events given by status of signals (present or absent)



Synchronous Languages (2)

Synchrony hypothesis

- Model of computation: In each tick, read inputs, compute, produce outputs
  - synchronous and instanteneous over all tasks
  - dependency checks over tasks
- Semantics: $s_1 \xrightarrow{i_1/o_1} s_2 \xrightarrow{i_2/o_2} \cdots$

Status (and values) of all signals form a single event

- parallel composition by task union
- asynchronous variant based on channels (similar to Promela)

Event-B (1)

Jean-Raymond Abrial. Modeling in Event-B. Cambridge University Press, 2010

- abstract state machine approach (like Z, B)
- events as transitions, state and data from set theory

$$
\begin{array}{l}
\textbf{invariant}\ st \in \{Card, PIN, Return\} \land chk \in \mathbb{B} \land tlrs \in \mathbb{N} \\
\quad \textbf{events}\ \mathsf{init}\ \widehat{=}\ \textbf{then}\ st := Card\ \textbf{end} \\
\qquad \mathsf{insertCard}\ \widehat{=}\ \textbf{when}\ st = Card\ \textbf{then}\ chk := \mathit{ff};\ trls := 0; st := PIN\ \textbf{end} \\
\qquad \mathsf{enterPIN}\ \widehat{=}\ \textbf{when}\ st = PIN\ \textbf{then}\ chk, trls, st :| \\
\qquad\qquad (trls < 2 \land chk' = \mathit{ff} \land trls' = trls + 1 \land st' = PIN) \lor \\
\qquad\qquad (trls = 2 \land chk' = \mathit{ff} \land trls' = trls + 1 \land st' = Card) \lor \\
\qquad\qquad (trls \leq 2 \land chk' = \mathit{tt} \land trls' = trls + 1 \land st' = Return) \\
\qquad\quad \textbf{end} \\
\qquad \mathsf{cancel}\ \widehat{=}\ \textbf{when}\ st = PIN\ \textbf{then}\ chk := \mathit{ff}; st := Return\ \textbf{end} \\
\qquad \mathsf{ejectCard}\ \widehat{=}\ \textbf{when}\ st = Return\ \textbf{then}\ st := Card\ \textbf{end}
\end{array}
$$

Event-B (2)

General event format

$$e \mathrel{\widehat{=}} \textbf{status}\ \sigma\ \textbf{when}\ G(\vec{v})\ \textbf{then}\ \vec{v} :\mid H(\vec{v}, \vec{v}')$$

- guard G, before-after predicate H (or assignments)
- status 'ordinary' or 'convergent' (internal: decreasing variant) or 'anticipated' (not increasing variant)

Focus on (data) refinement (proof obligations)

- traces based on weakest precondition semantics
- introducing new events by refining *skip*

- Parallel (de-)composition can be added (M. Butler 2009)
- Combination with CSP for explicit control (S. Schneider, H. Treharne 2010)

Specifying Event/Data-based Systems Revisited

Goals

- Common logical formalism for specifying event/data-based systems on various levels of abstraction
- Program development by stepwise refinement ("correct by construction")
  - from axiomatic to operational specifications
  - based on rigorous formal semantics

Approach — $\mathcal{E}^{\downarrow}$

- Integrate dynamic and hybrid logic features
  - Dynamic logic for abstract requirements (safety, liveness, ...)
  - Hybrid logic for concrete process structure
- Apply Sannella & Tarlecki's refinement methodology in the context of event/data-based systems

Rolf Hennicker, Alexandre Madeira. A. K. A Hybrid Dynamic Logic for Event/Data-based Systems. FASE 2019.

Syntax: Event/Data Actions and Formulæ (1)

Ed signature $\Sigma = (E, A)$ with events E and data attributes A

- data state $\omega \in \Omega(\Sigma) = A \to \mathcal{D}$
- state predicates $\varphi \in \Phi(\Sigma)$ with $\omega \models^{\mathcal{D}}_{A} \varphi$
- transition predicates $\psi \in \Psi(\Sigma)$ with $(\omega, \omega') \models^{\mathcal{D}}_{A} \psi$

Σ-ed actions $\lambda \in \Lambda(\Sigma)$

$$\lambda ::= e /\!\!/ \psi \mid \lambda_1 + \lambda_2 \mid \lambda_1 ; \lambda_2 \mid \lambda^*$$

- transition specification $e /\!\!/ \psi$ for event e and effect specification ψ
  - abbreviate $e_1 /\!\!/ \mathrm{true} + \ldots + e_k /\!\!/ \mathrm{true}$ by $\{e_1, \ldots, e_k\}$, $E(\Sigma)$ by $\boldsymbol{E}$, ...
- complex actions with "or" $+$, "sequence" $;$, and "iteration" *

Example: $\boldsymbol{E}^* ; \mathsf{enterPIN} /\!\!/ \mathsf{chk}' = tt$

"a finite sequence of events with arbitrary effects followed by event enterPIN such that afterwards attribute chk is tt"

Syntax: Event/Data Actions and Formulæ (2)

Σ-ed formulæ $\varrho \in \mathrm{Frm}^{\mathcal{E}\downarrow}(\Sigma)$

$$\varrho ::= \varphi \mid x \mid {\downarrow}x \,.\, \varrho \mid (@x)\varrho \mid \langle\lambda\rangle\varrho \mid [\lambda]\varrho \mid \mathrm{true} \mid \neg\varrho \mid \varrho_1 \vee \varrho_2$$

- state predicates φ
- control state variables $x \in X$
- hybrid logic "bind" ${\downarrow}x$ and "jump" $@x$
- dynamic logic "diamond" $\langle\lambda\rangle$ and "box" $[\lambda]$
- usual propositional connectives

Example: ${\downarrow}x_0 \,.\, [\boldsymbol{E}^*; (\mathsf{enterPIN} /\!\!/ \mathsf{chk}' = tt) + \mathsf{cancel}]\langle\boldsymbol{E}^*; \mathsf{ejectCard}\rangle x_0$

"Whenever a correct PIN has been entered or the transaction has been cancelled, the card can eventually be ejected and the ATM starts from the beginning."

Semantics: Event/Data Transition Systems

Σ-edts $M = (\Gamma, R, \Gamma_0) \in Edts^{\mathcal{E}\downarrow}(\Sigma)$

- configurations $\Gamma \subseteq C \times \Omega(\Sigma)$ of control states C and data states $\Omega(\Sigma)$
- transition relations $R \subseteq (R_e \subseteq \Gamma \times \Gamma)_{e \in E(\Sigma)}$
- initial configurations $\Gamma_0 \subseteq \{c_0\} \times \Omega_0$ with $\Omega_0 \subseteq \Omega(\Sigma)$
  - all configurations required to be reachable

Interpretation of Σ-ed actions over M as $(R_\lambda \subseteq \Gamma \times \Gamma)_{\lambda \in \Lambda(\Sigma)}$ defined by

- $R_{e/\!\!/\psi} = \{((c, \omega), (c', \omega')) \in R_e \mid (\omega, \omega') \models^{\mathcal{D}}_{A(\Sigma)} \psi\}$
- $R_{\lambda_1 + \lambda_2} = R_{\lambda_1} \cup R_{\lambda_2}$
- $R_{\lambda_1 ; \lambda_2} = R_{\lambda_1} ; R_{\lambda_2}$
- $R_{\lambda^*} = (R_\lambda)^*$

Semantics: Event/Data Satisfaction Relation

Given Σ-edts M, valuation $v : X \to C(M)$, configuration $\gamma \in \Gamma(M)$

$M, v, \gamma \models^{\mathcal{E}\downarrow}_{\Sigma} \varphi$ iff $\omega(\gamma) \models^{\mathcal{D}}_{A(\Sigma)} \varphi$

$M, v, \gamma \models^{\mathcal{E}\downarrow}_{\Sigma} x$ iff $c(\gamma) = v(x)$

$M, v, \gamma \models^{\mathcal{E}\downarrow}_{\Sigma} {\downarrow} x \,.\, \varrho$ iff $M, v\{x \mapsto c(\gamma)\}, \gamma \models^{\mathcal{E}\downarrow}_{\Sigma} \varrho$

$M, v, \gamma \models^{\mathcal{E}\downarrow}_{\Sigma} (@x)\varrho$ iff $M, v, \gamma' \models^{\mathcal{E}\downarrow}_{\Sigma} \varrho$ for all $\gamma' \in \Gamma(M)$ with $c(\gamma') = v(x)$

$M, v, \gamma \models^{\mathcal{E}\downarrow}_{\Sigma} \langle\lambda\rangle\varrho$ iff $M, v, \gamma' \models^{\mathcal{E}\downarrow}_{\Sigma} \varrho$ for some $\gamma' \in \Gamma(M)$ with $(\gamma, \gamma') \in R(M)_{\lambda}$

$\ldots$

$M \models^{\mathcal{E}\downarrow}_{\Sigma} \varrho$ for Σ-ed sentences if $M, v, \gamma_0 \models^{\mathcal{E}\downarrow}_{\Sigma} \varrho$ for all $\gamma_0 \in \Gamma_0(M)$

Axiomatic Event/Data Specifications

Axiomatic ed specification $Sp = (\Sigma, Ax)$ over ed signature Σ

- set of Σ-ed sentences Ax as axioms

(Loose) semantics of Sp given by model class $\mathrm{Mod}(Sp)$ of edts

- $\mathrm{Mod}(Sp) = \{M \in \mathit{Edts}^{\mathcal{E}^\downarrow}(\Sigma) \mid M \models^{\mathcal{E}^\downarrow}_{\Sigma} Ax\}$

Example: Specification ATM_0 with $\Sigma_0 = (\{\mathsf{insertCard}, \ldots\}, \{\mathsf{chk}\})$ and Ax_0:

$$[\boldsymbol{E}^*; (\mathsf{enterPIN} /\!\!/ \mathsf{chk}' = \mathit{tt}) + \mathsf{cancel}]\langle \boldsymbol{E}^*; \mathsf{ejectCard}\rangle \mathrm{true}\ , \quad \ldots$$

Example: Specification ATM_1 with $\Sigma_1 = \Sigma_0$ and Ax_1:

$$\downarrow x_0\,.\,[\boldsymbol{E}^*; (\mathsf{enterPIN} /\!\!/ \mathsf{chk}' = \mathit{tt}) + \mathsf{cancel}]\langle \boldsymbol{E}^*; \mathsf{ejectCard}\rangle x_0$$

$$\downarrow x_0\,.\,\langle \mathsf{insertCard} /\!\!/ \mathsf{chk}' = \mathit{ff}\rangle \mathrm{true} \wedge [\mathsf{insertCard} /\!\!/ \neg(\mathsf{chk}' = \mathit{ff})]\mathrm{false} \wedge [-\mathsf{insertCard}]\mathrm{false}\ , \quad \ldots$$

Stepwise refinement in $\mathcal{E}^\downarrow$: $ATM_0 \rightsquigarrow ATM_1 \rightsquigarrow \ldots$

Refining $\mathcal{E}^{\downarrow}$-Specifications (1)

Simple refinement (or implementation) relation for specifications

$$Sp \rightsquigarrow Sp' \text{ if } \Sigma(Sp) = \Sigma(Sp') \text{ and } \mathrm{Mod}(Sp) \supseteq \mathrm{Mod}(Sp')$$

- no signature changes, no construction of an implementation

Constructor κ from $(\Sigma'_1, \ldots, \Sigma'_n)$ to Σ

- (total) function $\kappa : \mathit{Edts}^{\mathcal{E}^{\downarrow}}(\Sigma'_1) \times \ldots \times \mathit{Edts}^{\mathcal{E}^{\downarrow}}(\Sigma'_n) \to \mathit{Edts}^{\mathcal{E}^{\downarrow}}(\Sigma)$
- constructor composition by usual function composition

$\langle Sp'_1, \ldots, Sp'_n \rangle$ constructor implementation via κ of Sp

- $Sp \rightsquigarrow_{\kappa} \langle Sp'_1, \ldots, Sp'_n \rangle$ if $\kappa(M'_1, \ldots, M'_n) \in \mathrm{Mod}(Sp)$ for all $M'_i \in \mathrm{Mod}(Sp'_i)$

(Sannella, Tarlecki 1988)

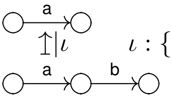
Refining $\mathcal{E}^{\downarrow}$-Specifications (2)

Refinement chain

$$Sp_1 \rightsquigarrow_{\kappa_1} Sp_2 \rightsquigarrow_{\kappa_2} \ldots \rightsquigarrow_{\kappa_{n-1}} Sp_n$$

Constructors for $\mathcal{E}^{\downarrow}$-specifications

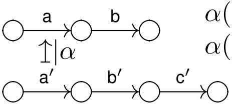
- relabelling κ_ρ
  - ρ-reduct of edts for a bijective ed signature morphism ρ
- restriction κ_ι
  - ι-reduct of edts for an injective ed signature morphism ι



$\iota : \{\mathsf{a}\} \hookrightarrow \{\mathsf{a}, \mathsf{b}\}$

- event refinement κ_α
  - α-reduct of edts for an ed signature morphism α to composite events

$$\theta ::= e \mid \theta + \theta \mid \theta ; \theta \mid \theta^*$$



$\alpha(\mathsf{a}) = \mathsf{a}'$
$\alpha(\mathsf{b}) = \mathsf{b}'; \mathsf{c}'$

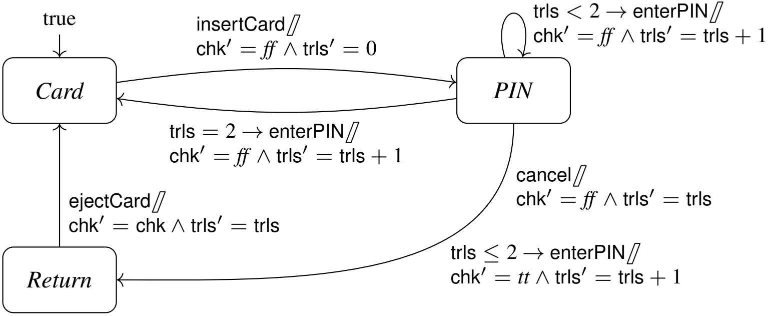
- parallel composition $\kappa_\otimes$
  - binary constructor: $Sp \rightsquigarrow_{\kappa_\otimes} \langle Sp'_1, Sp'_2 \rangle$
  - synchronous product of edts with composable signatures

Operational Event/Data Specifications (1)

More constructive specification style

- graphical representation (like STS, UML protocol state machines)
- can be faithfully expressed in $\mathcal{E}^{\downarrow}$

Example: Specification ATM_2 with $\Sigma_2 = (\{\text{insertCard}, \ldots\}, \{\text{chk}, \text{trls}\})$



Stepwise refinement in $\mathcal{E}^{\downarrow}$: $ATM_0 \rightsquigarrow ATM_1 \overset{?}{\rightsquigarrow} ATM_2$

Operational Event/Data Specifications (2)

Operational ed specification $O = (\Sigma, C, T, (c_0, \varphi_0))$ over ed signature Σ

- control states C
- transition relation specification $T \subseteq C \times \Phi(\Sigma) \times E(\Sigma) \times \Psi(\Sigma) \times C$
  - separate precondition in $\Phi(\Sigma)$ and transition predicate in $\Psi(\Sigma)$
- initial control state $c_0 \in C$, initial state predicate $\varphi_0 \in \Phi(\Sigma)$
  - all control states syntactically reachable from c_0

(Loose) semantics of O given by model class of edts with $M \in \mathrm{Mod}(O)$ if

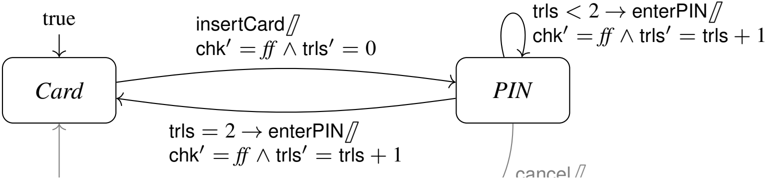
- $R(M)$ only shows transitions allowed by T
  - for all $((c, \omega), (c', \omega')) \in R(M)_e$ there is a $(c, \varphi, e, \psi, c') \in T$ with $\omega \models^{\mathcal{D}}_{A(\Sigma)} \varphi$ and $(\omega, \omega') \models^{\mathcal{D}}_{A(\Sigma)} \psi$
- $R(M)$ realises T for satisfied preconditions
  - for all $(c, \varphi, e, \psi, c') \in T$ and $\omega \models^{\mathcal{D}}_{A(\Sigma)} \varphi$, there is a $((c, \omega), (c', \omega')) \in R(M)_e$ with $(\omega, \omega') \models^{\mathcal{D}}_{A(\Sigma)} \psi$

Expressiveness of $\mathcal{E}^{\downarrow}$

Theorem For every operational ed specification O with finitely many control states there is an ed sentence ϱ_O such that

$$M \in \mathrm{Mod}(O) \iff M \models^{\mathcal{E}^{\downarrow}}_{\Sigma(O)} \varrho_O$$

Example



$$\begin{aligned}
&{\downarrow}\mathit{Card}\,.\,\langle \mathsf{insertCard}/\!\!/\mathsf{chk}' = \mathit{ff} \land \mathsf{trls}' = 0\rangle\\
&{\downarrow}\mathit{PIN}\,.\,(@\mathit{Card})[\mathsf{insertCard}/\!\!/\mathsf{chk}' = \mathit{ff} \land \mathsf{trls}' = 0]\mathit{PIN} \land\\
&\qquad\qquad\qquad [\mathsf{insertCard}/\!\!/\mathsf{chk}' = \mathit{tt} \lor \mathsf{trls}' \neq 0]\mathrm{false} \land\\
&\qquad\qquad\qquad [\{\mathsf{enterPIN}, \mathsf{cancel}, \mathsf{ejectCard}\}]\mathrm{false} \land \ldots
\end{aligned}$$

ATM-Example: Refinement in $\mathcal{E}^{\downarrow}$ (1)

Refinement chain for ATM specification

$$ATM_0 \rightsquigarrow ATM_1 \rightsquigarrow_{\kappa_\iota} ATM_2 \rightsquigarrow_{\kappa_\otimes;\kappa_\alpha} \langle ATM_3, CC \rangle$$

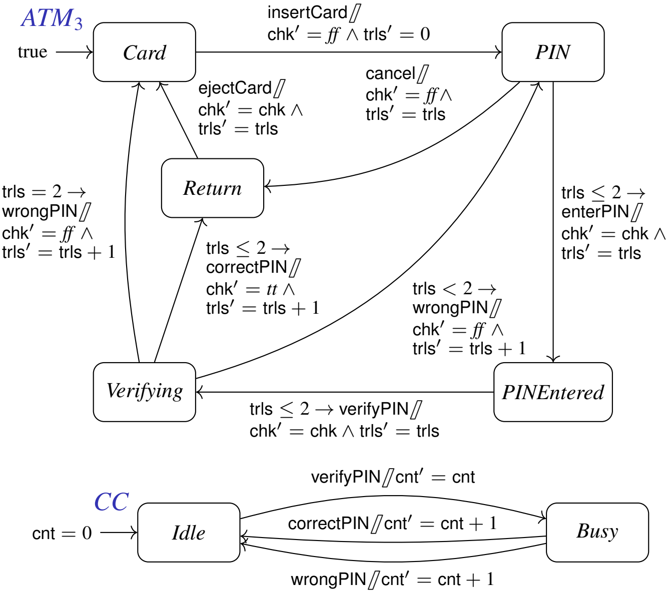
For $ATM_1 \rightsquigarrow_{\kappa_\iota} ATM_2$

- restriction constructor with $\iota : \Sigma_1 \hookrightarrow \Sigma_2$ injective

For $ATM_2 \rightsquigarrow_{\kappa_\otimes;\kappa_\alpha} \langle ATM_3, CC \rangle$

- event refinement constructor κ_α
- parallel composition constructor $\kappa_\otimes$ to two components

ATM-Example: Components



ATM-Example: Refinement in $\mathcal{E}^{\downarrow}$ (2)

Refinement chain for ATM specification

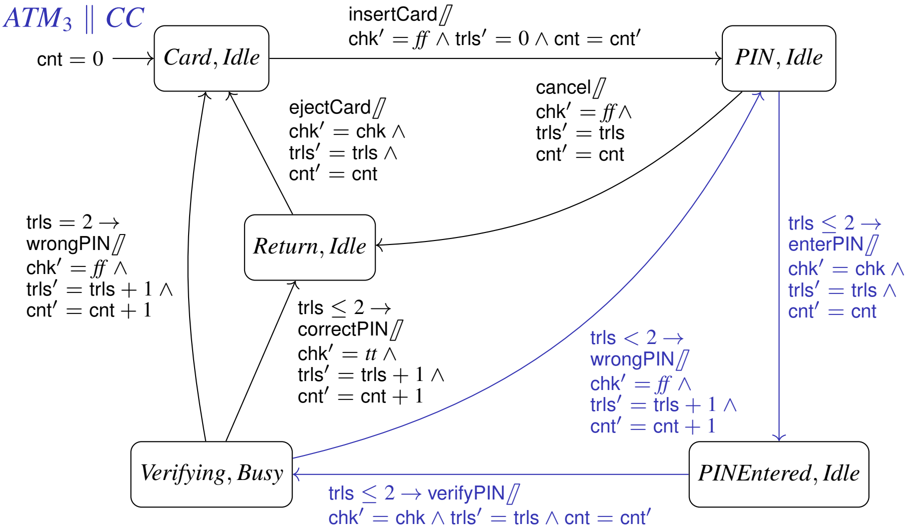
$$ATM_0 \rightsquigarrow ATM_1 \rightsquigarrow_{\kappa_\iota} ATM_2 \rightsquigarrow_{\kappa_\otimes;\kappa_\alpha} \langle ATM_3, CC \rangle$$

Replace $ATM_2 \rightsquigarrow_{\kappa_\otimes;\kappa_\alpha} \langle ATM_3, CC \rangle$ by

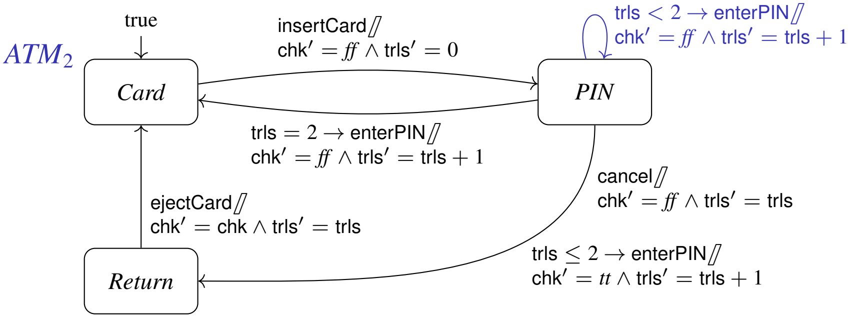
$$ATM_2 \rightsquigarrow_{\kappa_\alpha} ATM_3 \parallel CC \rightsquigarrow_{\kappa_\otimes} \langle ATM_3, CC \rangle$$

- syntactic parallel composition of operational ed specifications

ATM-Example: Syntactic Parallel Composition



ATM-Example: Event Refinement



$ATM_2 \rightsquigarrow_{\kappa_\alpha} ATM_3 \parallel CC$

- $\{\mathsf{chk}, \mathsf{trls}\} \subseteq \{\mathsf{chk}, \mathsf{trls}, \mathsf{cnt}\}$
- $\alpha(\mathsf{enterPIN}) = (\mathsf{enterPIN}; \mathsf{verifyPIN}; (\mathsf{correctPIN} + \mathsf{wrongPIN}))$

ATM-Example: Refinement in $\mathcal{E}^{\downarrow}$ (3)

$$ATM_0 \rightsquigarrow ATM_1 \overset{\kappa_\iota}{\rightsquigarrow} ATM_2 \overset{\kappa_\otimes ; \kappa_\alpha}{\rightsquigarrow} \langle ATM_3, CC \rangle$$

$$ATM_2 \overset{\kappa_\alpha}{\rightsquigarrow} ATM_3 \parallel CC \overset{\kappa_\otimes}{\rightsquigarrow} \langle ATM_3, CC \rangle$$

Proposition Let O_1, O_2 be operational ed specifications with composable signatures. Then

$$\mathrm{Mod}(O_1) \otimes \mathrm{Mod}(O_2) \subseteq \mathrm{Mod}(O_1 \parallel O_2)$$

(Converse inclusion does not hold.)

Theorem Let Sp be an (axiomatic or operational) ed specification, O_1, O_2 operational ed specifications with composable signatures, and κ a constructor from $\Sigma(O_1) \otimes \Sigma(O_2)$ to $\Sigma(Sp)$. Then

if $Sp \rightsquigarrow_\kappa O_1 \parallel O_2$, then $Sp \rightsquigarrow_{\kappa_\otimes ; \kappa} \langle O_1, O_2 \rangle$

Further Developments

Institutional formulation of $\mathcal{E}^{\downarrow}$

- institution $\mathcal{E}^{\downarrow}(\vec{\mathcal{D}})$ over an underlying data institution $\mathcal{D}$
- change of data institution (like propositional to first-order logic) as further refinement step

Rolf Hennicker, A. K., Alexandre Madeira. Hybrid Dynamic Logic Institutions for Event/Data-based Systems. Formal Aspect. Comp., 2021.

Encoding of (simple) UML state machines

- Parameterised events
- Theoroidal institution comorphism to CASL for theorem proving

Tobias Rosenberger, Saddek Bensalem, A. K., Markus Roggenbach. Institution-based Encoding and Verification of Simple UML State Machines in CASL/SPASS. WADT 2020.

Conclusions and Future Work

Specifying event/data-based systems in $\mathcal{E}^{\downarrow}$

- Expressive logic through combination of dynamic and hybrid features
- Support for both abstract requirements specifications and concrete implementations
- Support for stepwise refinement through constructor implementations

- Integrate other formalisms into $\mathcal{E}^{\downarrow}$-development process
  - TLA; similar to operational specifications: Event-B, UML state machines
  - communication compatibility for input/output
- Beyond bisimulation invariance for hybrid-free sentences
- Proof system for $\mathcal{E}^{\downarrow}$, including data states