Software Design, Modelling and Analysis in UML

Lecture 10: Constructive Behaviour, State Machines Overview

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Contents & Goals

Last Lecture:

- Completed discussion of modelling **structure**.

This Lecture:

- **Educational Objectives:** Capabilities for following tasks/questions.
  - Discuss the style of this class diagram.
  - What's the difference between reflective and constructive descriptions of behaviour?
  - What's the purpose of a behavioural model?
  - What does this State Machine mean? What happens if I inject this event?
  - Can you please model the following behaviour.
- **Content:**
  - Purposes of Behavioural Models
  - Constructive vs. Reflective
  - UML Core State Machines (first half)

Modelling Behaviour

Stocktaking...

Have: Means to model the **structure** of the system.

- Class diagrams graphically, concisely describe sets of system states.
- OCL expressions logically state constraints/invariants on system states.

Want: Means to model **behaviour** of the system.

- Means to describe how system states **evolve over time**, that is, to describe sets of **sequences**

$$\sigma_0, \sigma_1, \dots \in \Sigma^\omega$$

of system states.

not real-time,
just counting steps here

What Can Be Purposes of Behavioural Models?

(We will discuss this in more detail in Lecture 22.)

Example: Pre-Image
(the UML model is supposed to be the blue-print for a software system).

A description of behaviour could serve the following purposes:

- **Require** Behaviour.

  “This sequence of inserting money and requesting and getting water must be possible.”
  (Otherwise the software for the vending machine is completely broken.)

- **Allow** Behaviour.

  “After (inserting money and choosing a drink), the drink is dispensed (if in stock).”
  (If the implementation insists on taking the money first, that’s a fair choice.)

- **Forbid** Behaviour.

  “This sequence of getting both, a water and all money back, must not be possible.” (Otherwise the software is broken.)

What Can Be Purposes of Behavioural Models?

(We will discuss this in more detail in Lecture 22.)

Example: Pre-Image **Image**

(the UML model is supposed to be the blue-print for a software system).

A description of behaviour could serve the following purposes:

- **Require** Behaviour. **"System definitely does this"**

  "This sequence of inserting money and requesting and getting water must be possible."

  (Otherwise the software for the vending machine is completely broken.)

- **Allow** Behaviour. **"System does subset of this"**

  "After (inserting money and choosing a drink), the drink is dispensed (if in stock)."

  (If the implementation insists on taking the money first, that's a fair choice.)

- **Forbid** Behaviour. **"System never does this"**

  "This sequence of getting both, a water and all money back, must not be possible." (Otherwise the software is broken.)

Note: the latter two are trivially satisfied by doing nothing...

Constructive vs. Reflective Descriptions

[Harel, 1997] proposes to distinguish constructive and reflective descriptions:

- "*A language is* **constructive** *if it contributes to the dynamic semantics of the model. That is, its constructs contain information needed in executing the model or in translating it into executable code.*"

  A constructive description tells **how** things are computed (which can then be desired or undesired).

- "*Other languages are* **reflective** *or* **assertive**, *and can be used by the system modeler to capture parts of the thinking that go into building the model – behavior included –, to derive and present views of the model, statically or during execution, or to set constraints on behavior in preparation for verification.*"

  A reflective description tells **what** shall or shall not be computed.

Note: No sharp boundaries!

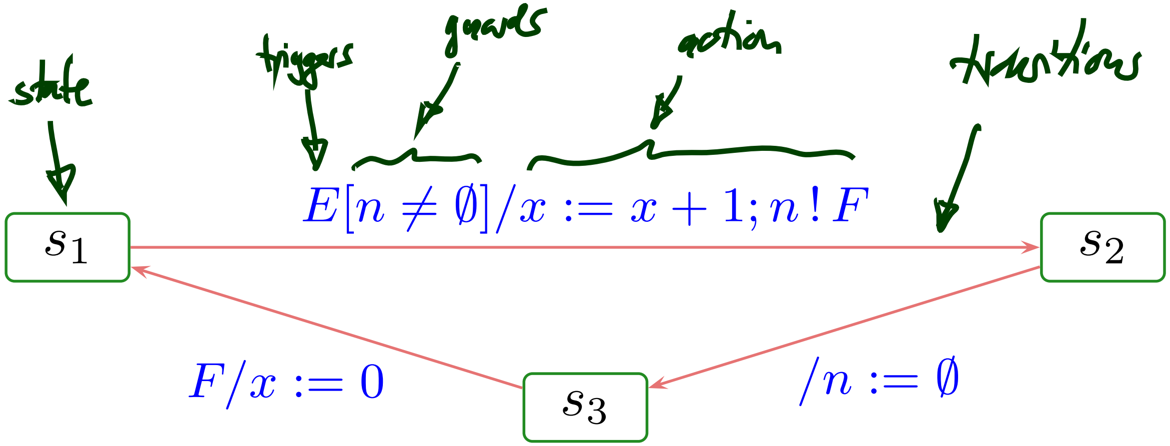
Constructive UML

UML provides two visual formalisms for constructive description of behaviours:

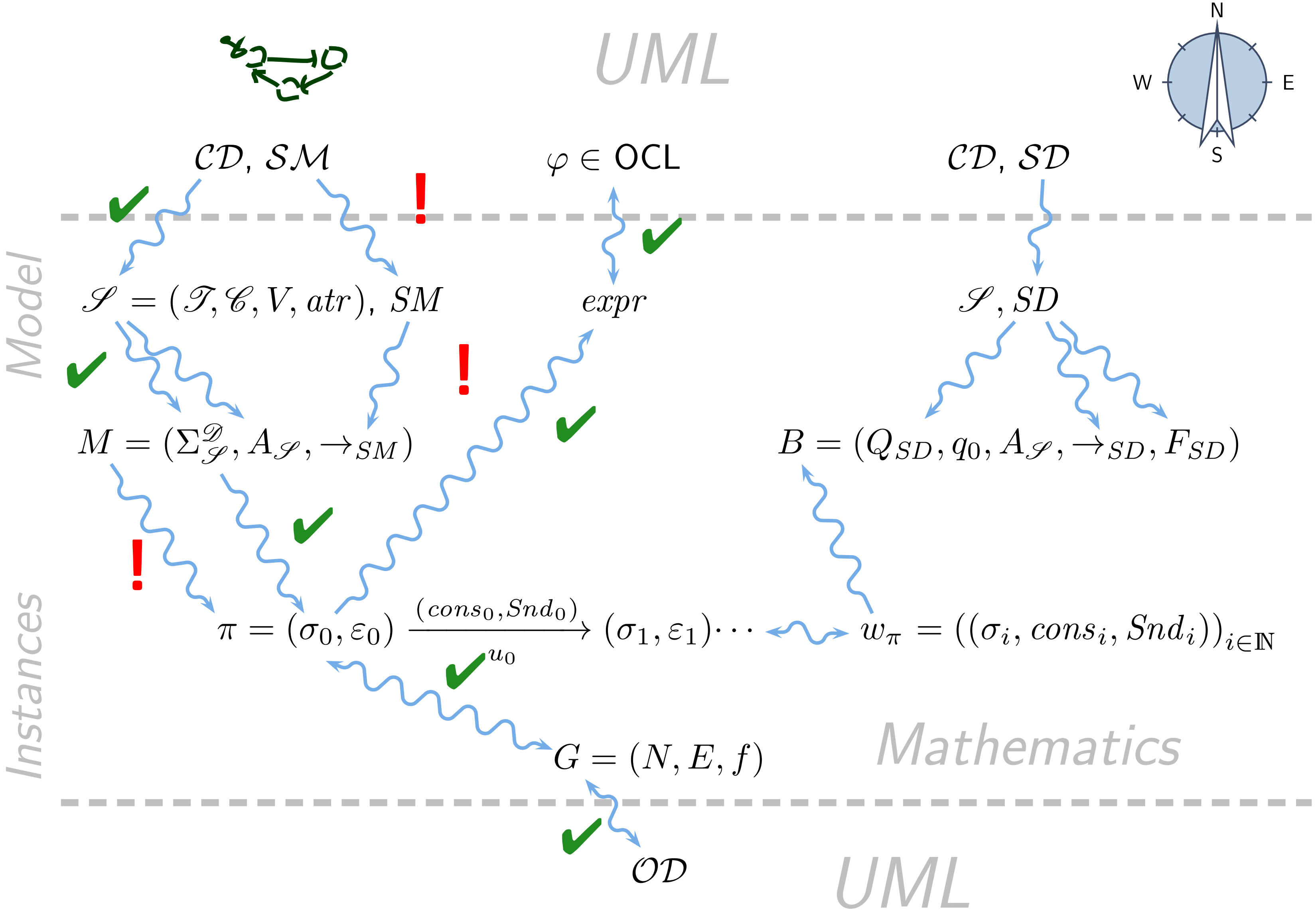
- **Activity Diagrams**
- **State-Machine Diagrams**

We (exemplary) focus on State-Machines because

- somehow “practice proven” (in different flavours),
- prevalent in embedded systems community,
- indicated useful by [Dobing and Parsons, 2006] survey, and
- Activity Diagram’s intuition changed (between UML 1.x and 2.x) from transition-system-like to petri-net-like...
- Example state machine:



Course Map



$\mathcal{CD}$, $\mathcal{SM}$

$\varphi \in$ OCL

$\mathcal{CD}$, $\mathcal{SD}$

$\mathscr{S} = (\mathscr{T}, \mathscr{C}, V, atr)$, SM

$expr$

$\mathscr{S}, SD$

$M = (\Sigma_{\mathscr{S}}^{\mathscr{D}}, A_{\mathscr{S}}, \to_{SM})$

$B = (Q_{SD}, q_0, A_{\mathscr{S}}, \to_{SD}, F_{SD})$

$\pi = (\sigma_0, \varepsilon_0) \xrightarrow[u_0]{(cons_0, Snd_0)} (\sigma_1, \varepsilon_1) \cdots$

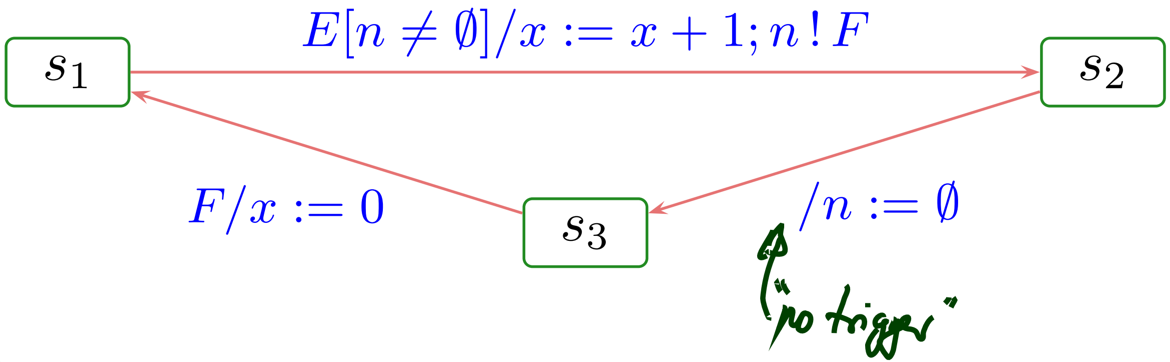
$w_\pi = ((\sigma_i, cons_i, Snd_i))_{i \in \mathbb{N}}$

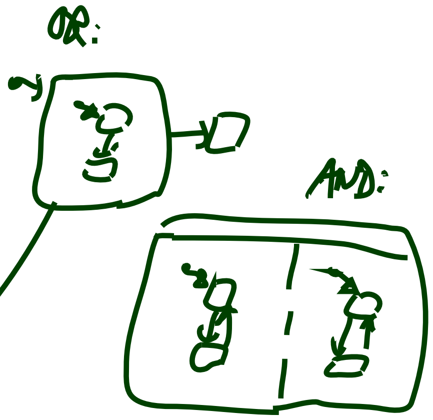
$G = (N, E, f)$

$\mathcal{OD}$

UML State Machines: Overview

UML State Machines





Brief History:

- Rooted in **Moore/Mealy machines**, Transition Systems
- [Harel, 1987]: **Statecharts** as a concise notation, introduces in particular hierarchical states.
- Manifest in tool **Statemate** [Harel et al., 1990] (simulation, code-generation); nowadays also in **Matlab/Simulink**, etc.
- From UML 1.x on: **State Machines** (in State Chart Diagrams) (not the official name, but understood: UML-Statecharts)
- Late 1990's: tool **Rhapsody** with code-generation for state machines.

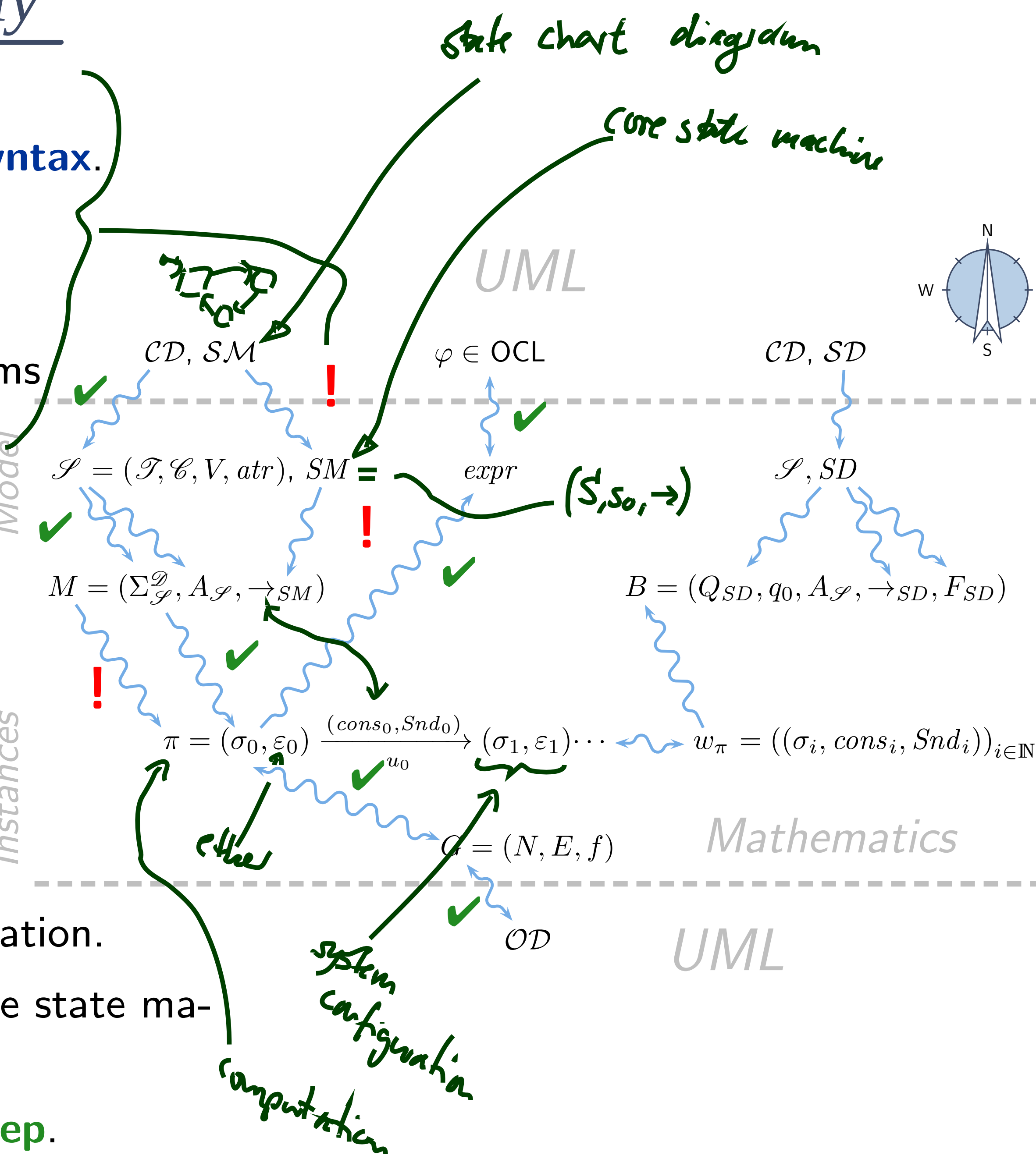
Note: there is a common core, but each dialect interprets some constructs subtly different [Crane and Dingel, 2007]. *(Would be too easy otherwise. . .)*

Roadmap: Chronologically

- (i) What do we (have to) cover?
  UML State Machine Diagrams **Syntax**.
- (ii) Def.: Signature with **signals**.
- (iii) Def.: **Core state machine**.
- (iv) Map UML State Machine Diagrams to core state machines.

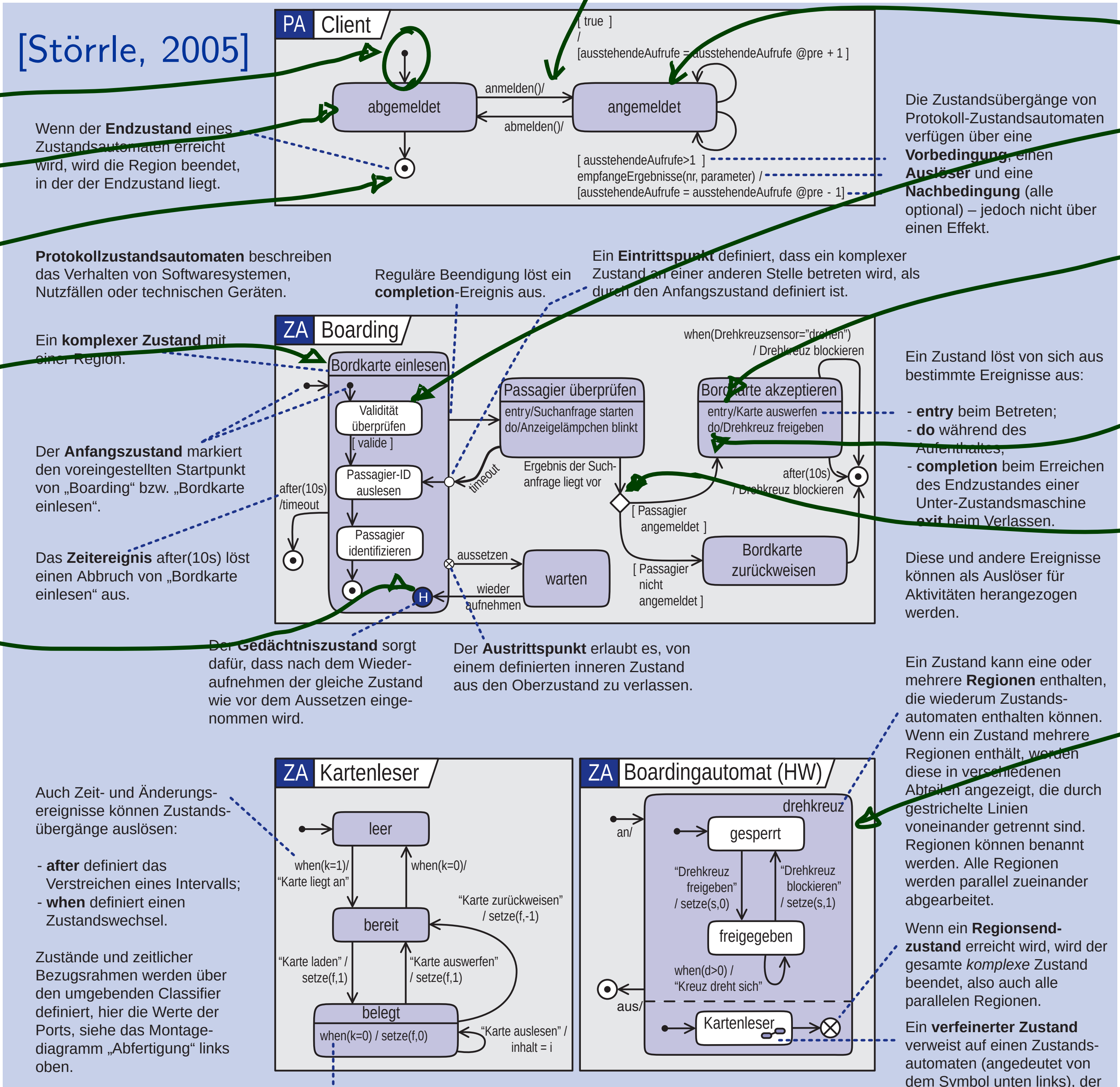
Semantics:
The Basic Causality Model

- (v) Def.: **Ether** (aka. event pool)
- (vi) Def.: **System configuration**.
- (vii) Def.: **Event**.
- (viii) Def.: **Transformer**.
- (ix) Def.: **Transition system**, computation.
- (x) Transition relation induced by core state machine.
- (xi) Def.: **step**, **run-to-completion step**.
- (xii) Later: Hierarchical state machines.



UML State Machines: Syntax

UML State-Machines: What do we have to cover?



[Störrle, 2005]

Wenn der Endzustand eines Zustandsautomaten erreicht wird, wird die Region beendet, in der der Endzustand liegt.

Protokollzustandsautomaten beschreiben das Verhalten von Softwaresystemen, Nutzfällen oder technischen Geräten.

Reguläre Beendigung löst ein **completion**-Ereignis aus.

Ein **Eintrittspunkt** definiert, dass ein komplexer Zustand an einer anderen Stelle betreten wird, als durch den Anfangszustand definiert ist.

Ein **komplexer Zustand** mit einer Region.

Der **Anfangszustand** markiert den voreingestellten Startpunkt von „Boarding“ bzw. „Bordkarte einlesen“.

Das **Zeitereignis** after(10s) löst einen Abbruch von „Bordkarte einlesen“ aus.

Der **Gedächtniszustand** sorgt dafür, dass nach dem Wieder-aufnehmen der gleiche Zustand wie vor dem Aussetzen einge-nommen wird.

Der **Austrittspunkt** erlaubt es, von einem definierten inneren Zustand aus den Oberzustand zu verlassen.

Auch Zeit- und Änderungs-ereignisse können Zustands-übergänge auslösen:

- **after** definiert das Verstreichen eines Intervalls;
- **when** definiert einen Zustandswechsel.

Zustände und zeitlicher Bezugsrahmen werden über den umgebenden Classifier definiert, hier die Werte der Ports, siehe das Montage-diagramm „Abfertigung“ links oben.

Die Zustandsübergänge von Protokoll-Zustandsautomaten verfügen über eine **Vorbedingung**, einen **Auslöser** und eine **Nachbedingung** (alle optional) – jedoch nicht über einen Effekt.

Ein Zustand löst von sich aus bestimmte Ereignisse aus:

- **entry** beim Betreten;
- **do** während des Aufenthaltes;
- **completion** beim Erreichen des Endzustandes einer Unter-Zustandsmaschine
- **exit** beim Verlassen.

Diese und andere Ereignisse können als Auslöser für Aktivitäten herangezogen werden.

Ein Zustand kann eine oder mehrere **Regionen** enthalten, die wiederum Zustands-automaten enthalten können. Wenn ein Zustand mehrere Regionen enthält, werden diese in verschiedenen Abteilen angezeigt, die durch gestrichelte Linien voneinander getrennt sind. Regionen können benannt werden. Alle Regionen werden parallel zueinander abgearbeitet.

Wenn ein **Regionsend-zustand** erreicht wird, wird der gesamte *komplexe* Zustand beendet, also auch alle parallelen Regionen.

Ein **verfeinerter Zustand** verweist auf einen Zustands-automaten (angedeutet von dem Symbol unten links), der

transition

initial state

(necessary) state

final state (optional)

OR-state, nested state

history connector

basic state

entry action

do action

choice

AND-state, nested state

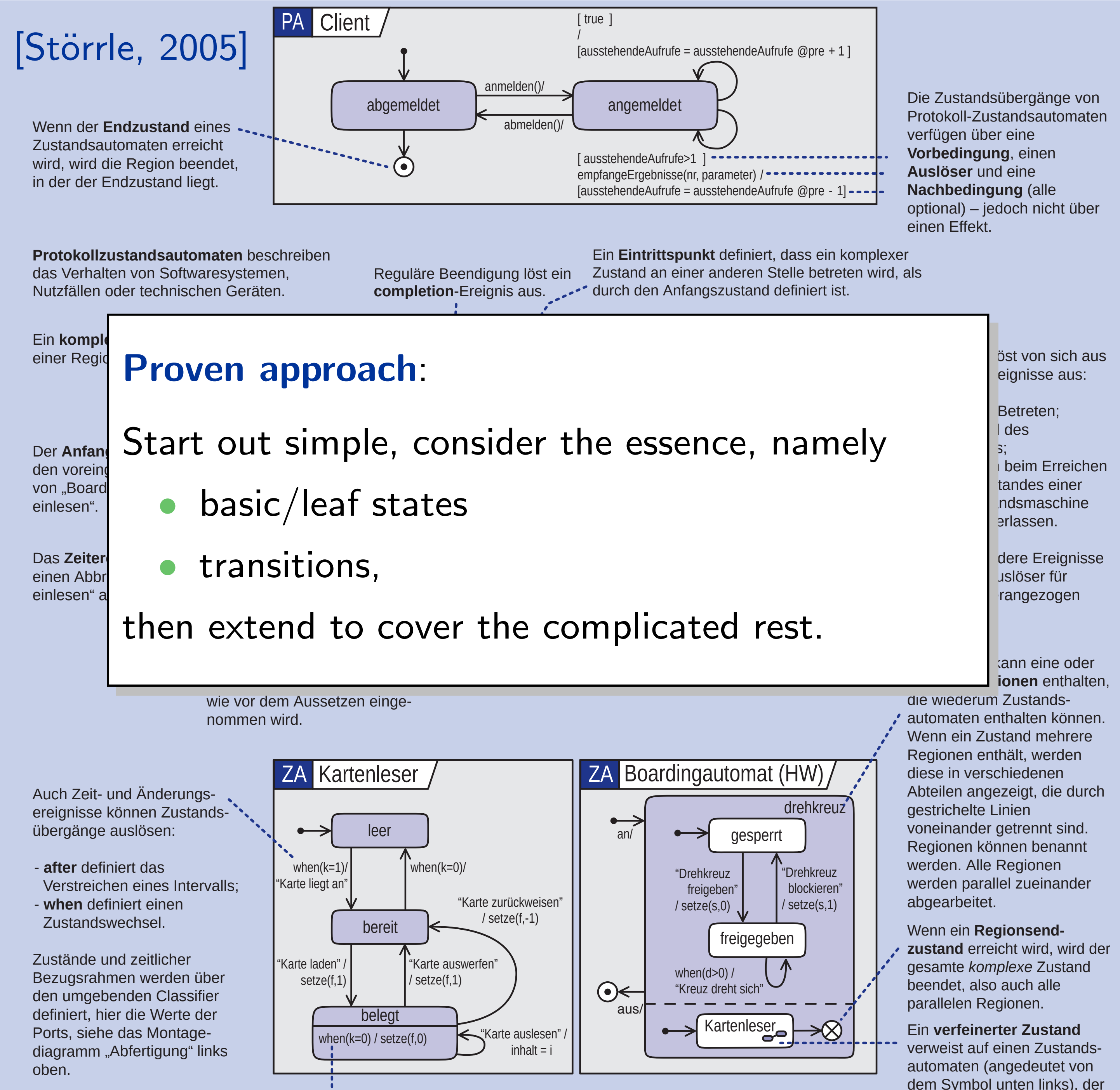
UML State-Machines: What do we have to cover?

Proven approach:

Start out simple, consider the essence, namely

- basic/leaf states
- transitions,

then extend to cover the complicated rest.



[Störrle, 2005]

Wenn der **Endzustand** eines Zustandsautomaten erreicht wird, wird die Region beendet, in der der Endzustand liegt.

Die Zustandsübergänge von Protokoll-Zustandsautomaten verfügen über eine **Vorbedingung**, einen **Auslöser** und eine **Nachbedingung** (alle optional) – jedoch nicht über einen Effekt.

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Ein **komple**
einer Regio

öst von sich aus
eignisse aus:

Betreten;
des
s;
beim Erreichen
tandes einer
ndsmaschine
erlassen.

Der **Anfan**
den voreing
von „Board
einlesen“.

Das **Zeiter**
einen Abbr
einlesen“ a

dere Ereignisse
uslöser für
rangezogen

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wie vor dem Aussetzen eingenommen wird.

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Signature With Signals

Definition. A tuple

$$\mathscr{S} = (\mathscr{T}, \mathscr{C}, V, atr\xcancel{)}, \mathscr{E}) \quad \mathscr{E} \subseteq \mathscr{C} \text{ a set of signals,}$$

is called signature (with signals) if and only if

$$(\mathscr{T}, \mathscr{C} \xcancel{\dot{\cup} \mathscr{E}}, V, atr)$$

is a signature (as before).

Note: Thus conceptually, **a signal is a class** and can have attributes of plain type and associations.

Core State Machine

Definition.
A core state machine over signature $\mathscr{S} = (\mathscr{T}, \mathscr{C}, V, atr\cancel{)}, \mathscr{E})$ is a tuple

$$SM = (S, s_0, \rightarrow)$$

where

- S is a non-empty, finite set of **(basic) states**,
- $s_0 \in S$ is an **initial state**,
- and

source state

set of signals

destination state

$$\rightarrow \subseteq S \times \underbrace{(\mathscr{E} \,\dot{\cup}\, \{\_\})}_{\text{trigger}} \times \underbrace{Expr_{\mathscr{S}}}_{\text{guard}} \times \underbrace{Act_{\mathscr{S}}}_{\text{action}} \times S$$

disjoint union,
$\_ \notin \mathscr{E}$

is a labelled transition relation.

We assume a set $Expr_{\mathscr{S}}$ of boolean expressions over $\mathscr{S}$ (for instance OCL, may be something else) and a set $Act_{\mathscr{S}}$ of **actions**.

From UML to Core State Machines: By Example

UML state machine diagram $\mathcal{SM}$:

$$annot ::= \underbrace{[\langle event\rangle \overbrace{[\text{‘.’}\,\langle event\rangle]^*}^{\text{not considered in lecture}}]}_{\text{trigger}} \;\; \overbrace{[\,\text{‘[’}\,\langle guard\rangle\,\text{‘]’}\,]}^{\text{guard}} \;\; \overbrace{[\,\text{‘/’}[\langle action\rangle]\,]}^{\text{action}}$$

with

- $event \in \mathscr{E}$,
- $guard \in Expr_{\mathscr{S}}$ (default: *true*, assumed to be in $Expr_{\mathscr{S}}$)
- $action \in Act_{\mathscr{S}}$ (default: `skip`, assumed to be in $Act_{\mathscr{S}}$)

maps to

$$SM(\mathcal{SM}) = (\underbrace{\{s_1, s_2\}}_{S}, \underbrace{s_1}_{s_0}, \underbrace{(s_1, event, guard, action, s_2)}_{\rightarrow})$$

Annotations and Defaults in the Standard

Reconsider the syntax of transition annotations:

$$annot ::= \big[\langle event\rangle [\text{ `,' } \langle event\rangle]^*\big] \; [\text{ `[' } \langle guard\rangle \text{ `]' }] \; [\text{ `/' } [\langle action\rangle]]$$

and let's play a bit with the defaults:

the empty annotation → $\leadsto$ _, true, skip

$/ \leadsto$ _, true, skip

$E\ / \leadsto$ E, true, skip

$/\ act \leadsto$ _, true, act

$E\ /\ act \leadsto$ E, true, act

$E[gd]\ /\ act \leadsto$ E, gd, act

$act \in Act_{\mathscr{S}}$

$gd \in Expr_{\mathscr{S}}$

In the standard, the syntax is even more elaborate:

- $E(v)$ — when consuming E in object u, attribute v of u is assigned the corresponding attribute of E.
- $E(v : \tau)$ — similar, but v is a local variable, scope is the transition

Msg(x)/... $\leadsto$ Msg / x := params->x; ...

State-Machines belong to Classes, Are Executed by Objects

- In the following, we assume that a UML models consists of a set $\mathscr{CD}$ of class diagrams and a set $\mathscr{SM}$ of **state chart diagrams** (each comprising one **state machines** $\mathcal{SM}$).

- Furthermore, we assume ~~each~~ that each state machine $\mathcal{SM} \in \mathscr{SM}$ is **associated with a class** $C_{\mathcal{SM}} \in \mathscr{C}(\mathscr{S})$.

- For simplicity, we even assume a bijection, i.e. we assume that each class $C \in \mathscr{C}(\mathscr{S})$ has a state machine $\mathcal{SM}_C$ and that its class $C_{\mathcal{SM}_C}$ is C.

  If not explicitly given, then this one:

  maybe even better: ∅

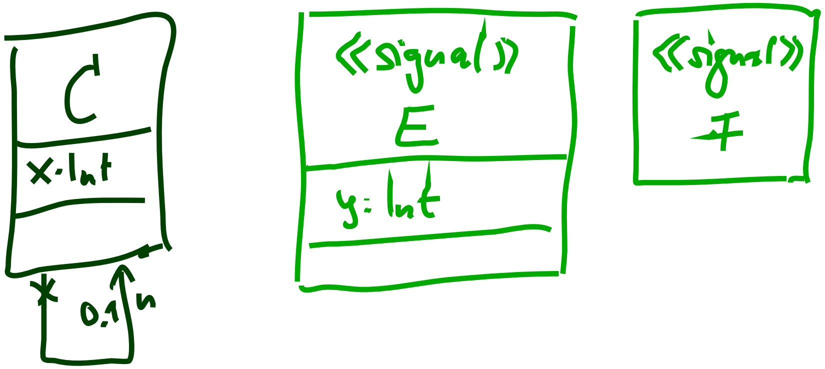
  $$\mathcal{SM}_0 := (\{s_0\}, s_0, \{(s_0, \_, \mathit{true}, \texttt{skip}, s_0)\}).$$

  We'll see later that, semantically, this choice does no harm.

- **Intuition 1**: $\mathcal{SM}_C$ describes the behaviour of **the instances** of class C.
  Intuition 2: Each instance of class C executes $\mathcal{SM}_C$. but with a local "program counter"!

Note: we don't consider **multiple state machines** per class.
Because later (when we have AND-states) we'll see that this case can be viewed as a single state machine with as many AND-states.

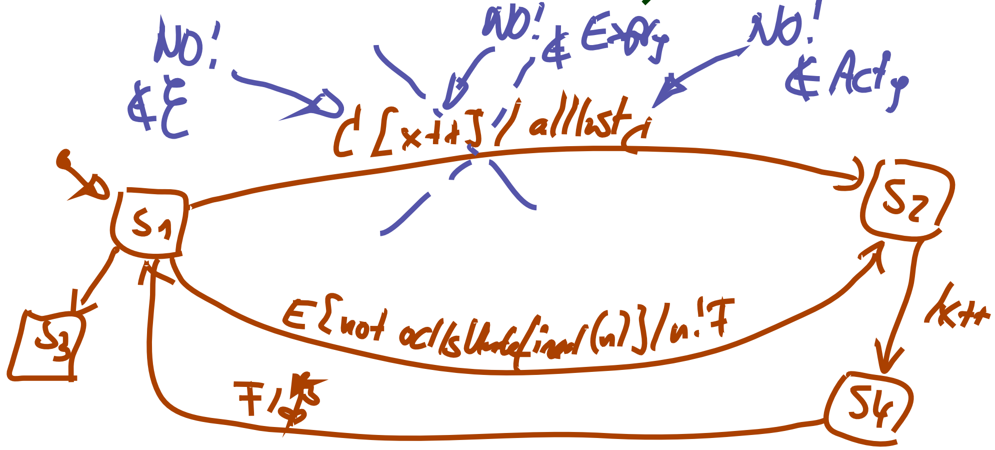
CD:



Expr$_{\mathscr{S}}$: OCL over $\mathscr{S}$

$Act_{\mathscr{S}} = \{skip, x{+}{+}, n!F, ↯\}$

UML



$$\mathscr{S} = \Big(\{Int\}, \{C, E, F\}, \{x : Int, n : C_{0,1}, y : Int\}, \{C \mapsto \{x, n\}, E \mapsto \{y\}, F \mapsto \emptyset\}, \underbrace{\{E, F\}}_{\mathscr{E}}\Big)$$

$$\begin{aligned} SM = \big(&\{s_1, s_2, s_3, s_4\}, s_1, \\ &\{(s_1, \_, true, skip, s_3), \\ &(s_1, E, \text{not oclIsUndefined}(n), n!F, s_2), \\ &(s_2, \_, true, x{+}{+}, s_4), \\ &(s_4, F, true, ↯, s_1)\}\big) \end{aligned}$$

MATH

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