Software Design, Modelling and Analysis in UML

Lecture 12: Core State Machines III

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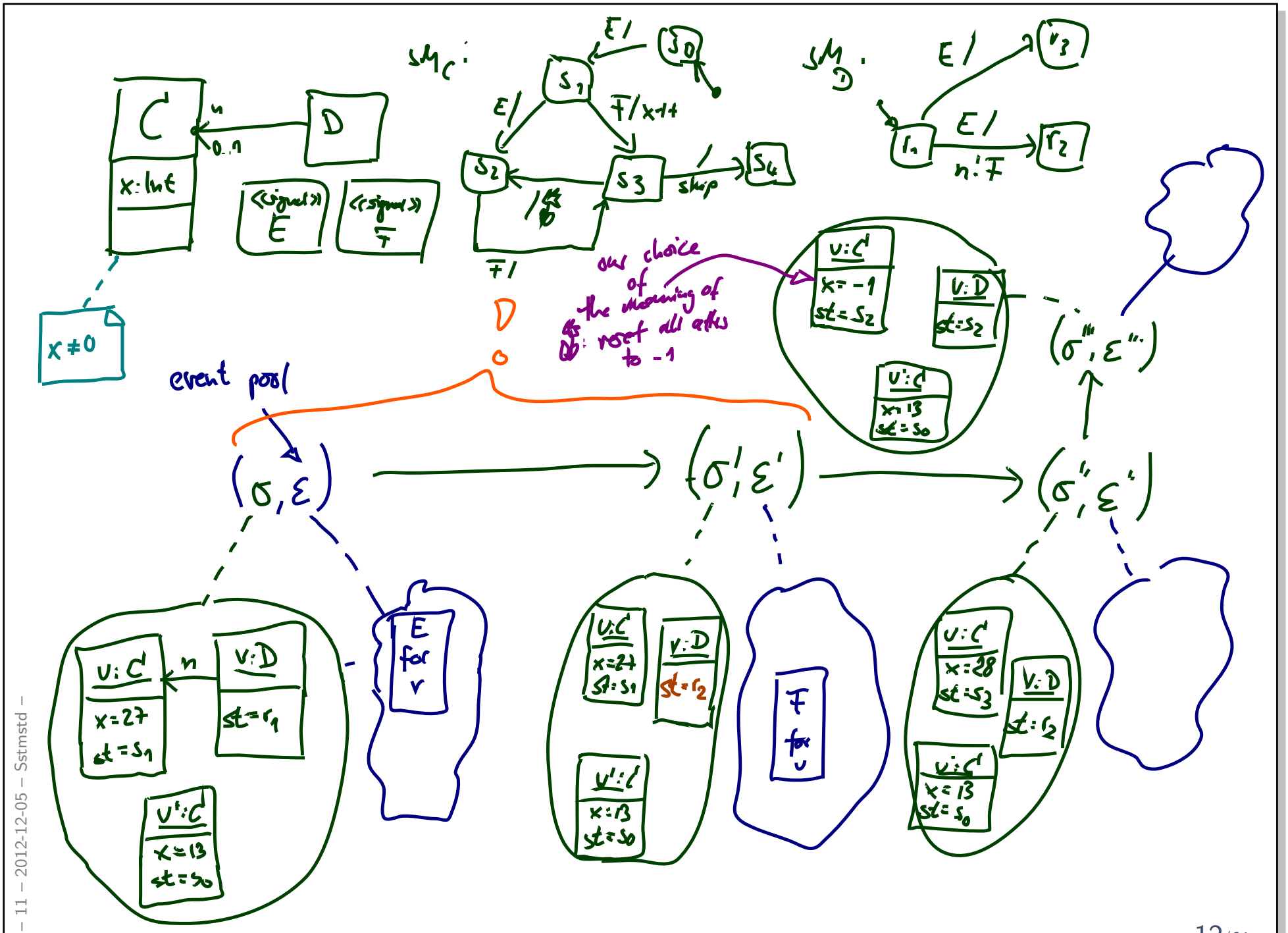
Contents & Goals

Last Lecture:

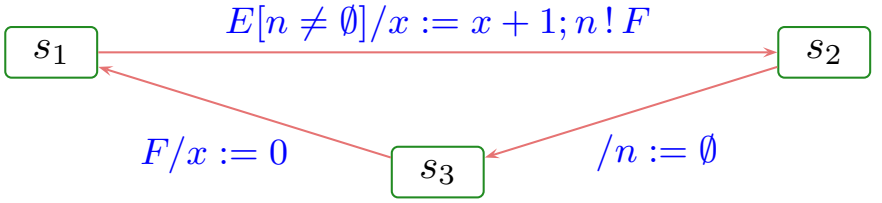
- The basic causality model
- Ether

This Lecture:

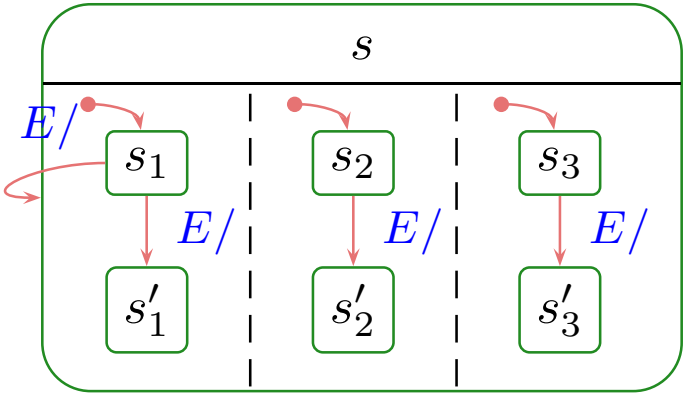
- **Educational Objectives:** Capabilities for following tasks/questions.
  - What does this State Machine mean? What happens if I inject this event?
  - Can you please model the following behaviour.
  - What is: Signal, Event, Ether, Transformer, Step, RTC.
- **Content:**
  - System Configuration, Transformer
  - Examples for transformer
  - Run-to-completion Step
  - Putting It All Together


C
x: Int
n
0..n
D
«signal» E
«signal» F
x≠0
SM_C :
S0
S1
S2
S3
S4
E /
F / x++
skip
F /
SM_D :
r1
r2
r3
n : F
D
our choice of the meaning of ◇: reset all attrs to -1
event pool
(σ, ε)
(σ', ε')
(σ'', ε'')
(σ''', ε''')
v: C'
x = -1
st = S2
v: D
st = S2
v': C'
x = 13
st = S0
v: C'
x = 27
st = S1
n
v: D
st = r1
v': C'
x = 13
st = S0
E for v
v: C'
x = 27
st = S1
v: D
st = r2
v': C'
x = 13
st = S0
F for v
v: C'
x = 28
st = S3
v: D
st = r2
v': C'
x = 13
st = S0

And?



- **...**:
  - We have to formally define what **event occurrence** is.
  - We have to define where events **are stored** – what the event pool is.
  - We have to explain how **transitions are chosen** – "matching".
  - We have to explain what the **effect of actions** is – on state and event pool.
  - We have to decide on the **granularity** — micro-steps, steps, run-to-completion steps (aka. super-steps)?
  - We have to formally define a notion of **stability** and RTC-step **completion**.
  - And then: hierarchical state machines.



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**.

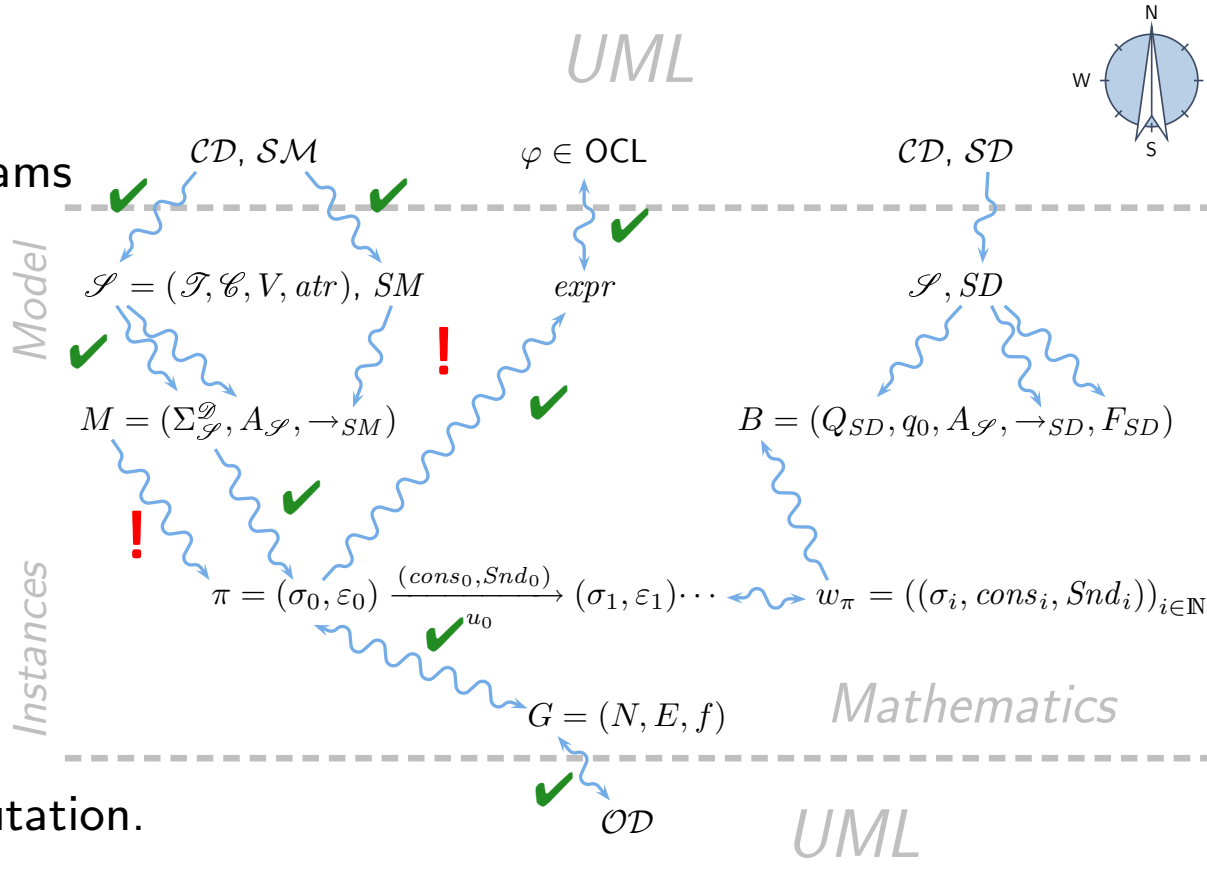
(viii) Def.: **Transformer**.

(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.



System Configuration, Ether, Transformer

Ether aka. Event Pool

Definition. Let $\mathscr{S} = (\mathscr{T}, \mathscr{C}, V, atr, \mathscr{E})$ be a signature with signals and $\mathscr{D}$ a structure.

We call a ~~structure~~ tuple $(Eth, ready, \oplus, \ominus, [\,\cdot\,])$ an ether over $\mathscr{S}$ and $\mathscr{D}$ if and only if it provides

- a **ready** operation which yields a set of events that are ready for a given object, i.e. for an event pool $\mathcal{E}$ and an object identity ν obtain a set of signal-instance identities

$$ready : Eth \times \mathscr{D}(\mathscr{C}) \to 2^{\mathscr{D}(\mathscr{E})}$$

- a operation to **insert** an event destined for a given object, i.e. $\mathcal{E}$ destination id ν event id ν obtain another event pool $\exists\, \mathcal{E}'$

$$\oplus : Eth \times \mathscr{D}(\mathscr{C}) \times \mathscr{D}(\mathscr{E}) \to Eth$$

- a operation to **remove** an event, i.e.

$$\ominus : Eth \times \mathscr{D}(\mathscr{E}) \to Eth$$

- an operation to clear the ether for a given object, i.e.

$$[\,\cdot\,] : Eth \times \mathscr{D}(\mathscr{C}) \to Eth.$$

Ether and [OMG, 2007b]

The standard distinguishes (among others)

- **SignalEvent** [OMG, 2007b, 450] and **Reception** [OMG, 2007b, 447].

On **SignalEvents**, it says

> *A signal event represents the receipt of an asynchronous signal instance. A signal event may, for example, cause a state machine to trigger a transition.* [OMG, 2007b, 449]
>
> [...]
>
> **Semantic Variation Points**
>
> *The means by which requests are transported to their target depend on the type of requesting action, the target, the properties of the communication medium, and numerous other factors.*
>
> *In some cases, this is instantaneous and completely reliable while in others it may involve transmission delays of variable duration, loss of requests, reordering, or duplication.*
>
> *(See also the discussion on page 421.)* [OMG, 2007b, 450]

Our **ether** is a general representation of the possible choices.

Often seen minimal requirement: order of sending **by one object** is preserved.
But: we'll later briefly discuss "discarding" of events.

System Configuration

Definition. Let $\mathscr{S}_0 = (\mathscr{T}_0, \mathscr{C}_0, V_0, atr_0, \mathscr{E})$ be a signature with signals, $\mathscr{D}_0$ a structure of $\mathscr{S}_0$, $(Eth, ready, \oplus, \ominus, [\,\cdot\,])$ an ether over $\mathscr{S}_0$ and $\mathscr{D}_0$. Furthermore assume there is one core state machine M_C per class $C \in \mathscr{C}$.

A system configuration over $\mathscr{S}_0$, $\mathscr{D}_0$, and Eth is a pair

$$(\sigma, \varepsilon) \in \Sigma^{\mathscr{D}}_{\mathscr{S}} \times Eth$$

where

- $\mathscr{S} = (\mathscr{T}_0 \,\dot\cup\, \{S_{M_C} \mid C \in \mathscr{C}\},\quad \mathscr{C}_0,$

  $V_0 \,\dot\cup\, \{\langle stable : Bool, -, \mathit{true}, \emptyset\rangle\}$

  $\dot\cup\, \{\langle st_C : S_{M_C}, +, s_0, \emptyset\rangle \mid C \in \mathscr{C}\}$

  $\dot\cup\, \{\langle params_E : E_{0,1}, +, \emptyset, \emptyset\rangle \mid E \in \mathscr{E}_0\},$

  $\{C \mapsto atr_0(C)$

  $\cup\, \{stable, st_C\} \cup \{params_E \mid E \in \mathscr{E}_0\} \mid C \in \mathscr{C}\},\quad \mathscr{E}_0)$

- $\mathscr{D} = \mathscr{D}_0 \,\dot\cup\, \{S_{M_C} \mapsto S(M_C) \mid C \in \mathscr{C}\}$, and
- $\sigma(u)(r) \cap \mathscr{D}(\mathscr{E}_0) = \emptyset$ for each $u \in \mathrm{dom}(\sigma)$ and $r \in V_{0_{a,r,*}}$

a type name for the set of states in C's state machine

if Bool ∉ $\mathscr{T}_0$ then add it here, and have $\mathscr{D}(Bool) = \mathbb{B}$

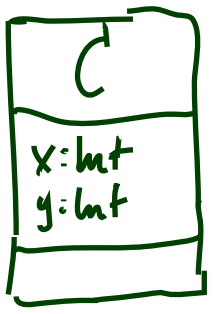
initial state of C's state machine

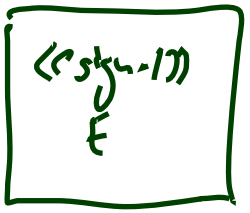
each object can refer to signal instances (at most one at a time) in order to access signal attributes

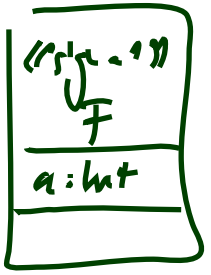
$\in 2^{\mathscr{D}(C)}$ if r:$C_{0,1}$ or r:C_*

states of state machine M_C of C

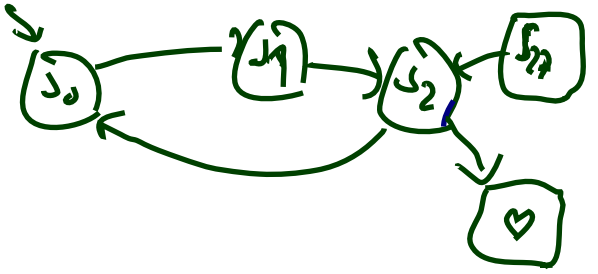
(e.g. r:$C_{a,r}$)







sm_C :



$\mathcal{D}_0(Int) = \mathbb{Z}$

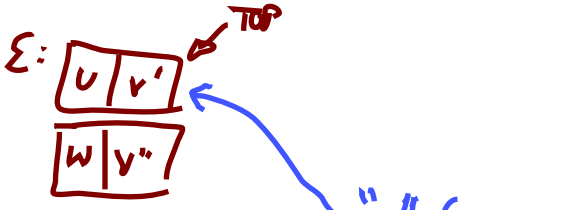
$$\varphi_0 = (\{Int\}, \{C, E, F\}, \{x:Int, y:Int, a:Int\}, \{C \mapsto \{x,y\}, E \mapsto \emptyset, F \mapsto \{a\}\}, \{E,F\})$$

$$\varphi = (\{Int, Bool, S_{sm_C}\}, \{C, E, F\}, \{x,y,a : Int, stable : Bool, st_C : S_{sm_C}, params_E : E_{0,1}, params_F : F_{0,1}\},$$
$$\{C \mapsto \{x,y,stable,st_C,params_E,params_F\}, E \mapsto \emptyset, F \mapsto \{a\}\}, \{E,F\})$$

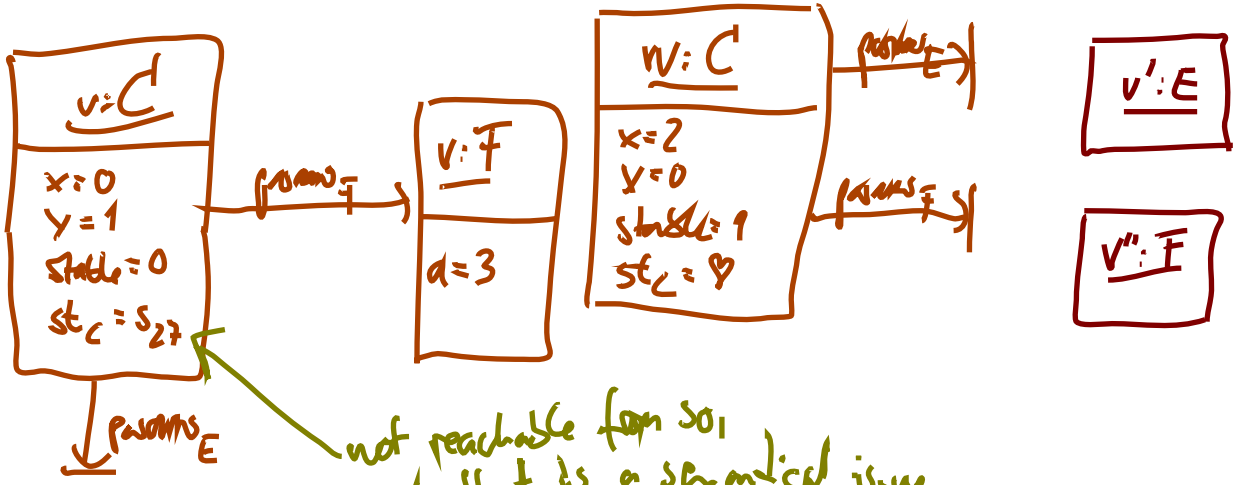
$\mathcal{D}(Int) = \mathcal{D}_0(Int)$

$\mathcal{D}(S_{sm_C}) = \{s_0, s_1, s_2, ♡, s_{27}\}$

if Eth is shared FIFO queue



σ :



System Configuration Step-by-Step

- We start with some signature with signals $\mathscr{S}_0 = (\mathscr{T}_0, \mathscr{C}_0, V_0, atr_0, \mathscr{E})$.
- A **system configuration** is a pair (σ, ε) which comprises a system state σ wrt. $\mathscr{S}$ (not wrt. $\mathscr{S}_0$).
- Such a **system state** σ wrt. $\mathscr{S}$ provides, for each object $u \in \mathrm{dom}(\sigma)$,
  - values for the **explicit attributes** in V_0,
  - values for a number of **implicit attributes**, namely
    - a **stability flag**, i.e. $\sigma(u)(stable)$ is a boolean value,
    - a **current (state machine) state**, i.e. $\sigma(u)(st)$ denotes one of the states of core state machine M_C,
    - a temporary association to access **event parameters** for each class, i.e. $\sigma(u)(params_E)$ is defined for each $E \in \mathscr{E}$.
- For convenience require: there is **no link to an event** except for $params_E$.

Stability

Definition.
Let (σ, ε) be a system configuration over some $\mathscr{S}_0$, $\mathscr{D}_0$, Eth.

We call an object $u \in \mathrm{dom}(\sigma) \cap \mathscr{D}(\mathscr{C}_0)$ stable in σ if and only if

$$\sigma(u)(stable) = \mathit{true}.$$

Events Are Instances of Signals

Definition. Let $\mathscr{D}_0$ be a structure of the signature with signals $\mathscr{S}_0 = (\mathscr{T}_0, \mathscr{C}_0, V_0, atr_0, \mathscr{E})$ and let $E \in \mathscr{E}_0$ be a **signal**.

Let $atr(E) = \{v_1, \ldots, v_n\}$. We call

$$e = (E, \{v_1 \mapsto d_1, \ldots, v_n \mapsto d_n\}),$$

or shorter (if mapping is clear from context)

$$(E, (d_1, \ldots, d_n)) \text{ or } (E, \vec{d}),$$

an event (or an instance) of signal E (if type-consistent).

We use $Evs(\mathscr{E}_0, \mathscr{D}_0)$ to denote the set of all events of all signals in $\mathscr{S}_0$ wrt. $\mathscr{D}_0$.

As we always try to maximize confusion...:

- By our existing naming convention, $u \in \mathscr{D}(E)$ is also called **instance** of the (signal) class E in system configuration (σ, ε) if $u \in \mathrm{dom}(\sigma)$.
- The corresponding event is then $(E, \sigma(u))$.

Signals? Events...? Ether...?!

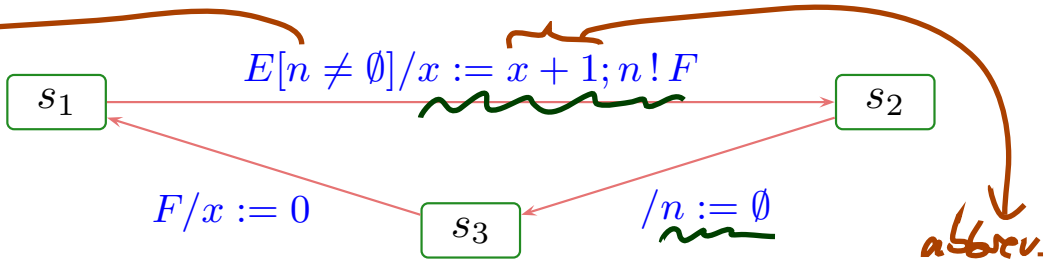
The idea is the following:

- **Signals** are **types** (classes).
- **Instances of signals** (in the standard sense) are kept in the **system state** component σ of system configurations (σ, ε).
- **Identities** of signal instances are kept in the **ether**.
- Each signal instance is in particular an **event** — somehow "a recording that this signal occurred" (without caring for its identity)
- The main difference between **signal instance** and **event**:

  Events don't have an identity.

- Why is this useful? In particular for **reflective** descriptions of behaviour, we are typically not interested in the identity of a signal instance, but only whether it is an "E" or "F", and which parameters it carries.

Where are we?



- **Wanted**: a labelled transition relation

$$(\sigma, \varepsilon) \xrightarrow{(cons, Snd)} (\sigma', \varepsilon')$$

  on system configuration, labelled with the **consumed** and **sent** events, (σ', ε') being the result (or effect) of **one object** u_x taking a transition of **its** state machine from the current state mach. state $\sigma(u_x)(st_C)$.

- **Have**: system configuration (σ, ε) comprising current state machine state and stability flag for each object, and the ether.

- **Plan**:
  (i) Introduce **transformer** as the semantics of action annotions.
  Intuitively, (σ', ε') is the effect of applying the transformer of the taken transition.
  (ii) Explain how to choose transitions depending on ε and when to stop taking transitions — the **run-to-completion "algorithm"**.

Transformer

Definition.
Let $\Sigma^{\mathscr{D}}_{\mathscr{S}}$ the set of system configurations over some $\mathscr{S}_0$, $\mathscr{D}_0$, Eth.

We call a relation

$$t \subseteq \mathscr{D}(\mathscr{C}) \times (\Sigma^{\mathscr{D}}_{\mathscr{S}} \times Eth) \times (\Sigma^{\mathscr{D}}_{\mathscr{S}} \times Eth)$$

a (system configuration) **transformer**.

- In the following, we assume that each application of a transformer t to some system configuration (σ, ε) for object u_x is associated with a set of **observations**

$$Obs_t[u_x](\sigma,\varepsilon) \in 2^{\mathscr{D}(\mathscr{C}) \times (\mathscr{D}(\mathscr{E}) \times Evs(\mathscr{E} \,\dot\cup\, \{*,+\},\mathscr{D}) \times \mathscr{D}(\mathscr{C}))}.$$

- An observation $(u_{src}, u_e, (E, \vec{d}), u_{dst}) \in Obs_t[u_x](\sigma,\varepsilon)$ represents the information that, as a "side effect" of u_x executing t, an event (!) $(E, \vec{d})$ has been sent from u_{src} to u_{dst}.

  Special cases: creation/destruction.

Why Transformers?

- **Recall** the (simplified) syntax of transition annotations:

$$annot ::= [\quad \langle event \rangle \quad [\ \text{`['}\ \langle guard \rangle\ \text{`]'}\ ]\quad [\ \text{`/'}\ \langle action \rangle]\quad]$$

- **Clear**: $\langle event \rangle$ is from $\mathscr{E}$ of the corresponding signature.
- **But:** What are $\langle guard \rangle$ and $\langle action \rangle$?
  - UML can be viewed as being **parameterized** in **expression language** (providing $\langle guard \rangle$) and **action language** (providing $\langle action \rangle$).
  - **Examples**:
    - **Expression Language**:
      - OCL
      - Java, C++, . . . expressions
      - . . .
    - **Action Language**:
      - UML Action Semantics, "Executable UML"
      - Java, C++, . . . statements (plus some event send action)
      - . . .

In the following, we consider:

$$Act_{\mathcal{Y}} ::= \{skip\}$$
$$\cup \{update(expr_1, v, expr_2) \mid expr_1, expr_2 \in OCLExpr_{\mathcal{Y}}, v \in V\}$$
$$\cup \{send(expr_1, E, expr_2) \mid expr_1, expr_2 \in OCLExpr_{\mathcal{Y}}, E \in \mathcal{E}\}$$
$$\cup \{create(C, expr, v) \mid expr \in OCLExpr_{\mathcal{Y}}, C \in \mathcal{C}, v \in V\}$$
$$\cup \{destroy(expr) \mid expr \in OCLExpr_{\mathcal{Y}}\}$$

$Expr_{\mathcal{Y}}$: OCL expressions over $\mathcal{Y}$

Transformers as Abstract Actions!

In the following, we assume that we're **given**

- an **expression language** $Expr$ for guards, and
- an **action language** Act for actions,

and that we're **given**

- a **semantics** for boolean expressions in form of a partial function

$$I[\![\cdot]\!](\cdot,\cdot) : Expr \to ((\Sigma^{\mathscr{D}}_{\mathscr{S}} \times (\{\text{this}\} \to \mathscr{D}(\mathscr{C}))) \nrightarrow \mathbb{B})$$

  which evaluates expressions in a given system configuration,

  Assuming I to be partial is a way to treat "undefined" during runtime. If I is not defined (for instance because of dangling-reference navigation or division-by-zero), we want to go to a designated "error" system configuration.

- a **transformer** for each action: for each $act \in Act$, we assume to have

$$t_{act} \subseteq \mathscr{D}(\mathscr{C}) \times (\Sigma^{\mathscr{D}}_{\mathscr{S}} \times Eth) \times (\Sigma^{\mathscr{D}}_{\mathscr{S}} \times Eth)$$

Expression/Action Language Examples

We can make the assumptions from the previous slide because **instances exist**:

- for OCL, we have the OCL semantics from Lecture 03. Simply remove the pre-images which map to "$\perp$".
- for Java, the operational semantics of the SWT lecture uniquely defines transformers for sequences of Java statements.

We distinguish the following kinds of transformers:

- **skip**: do nothing — recall: this is the default action
- **send**: modifies ε — interesting, because state machines are built around sending/consuming events
- **create**/**destroy**: modify domain of σ — not specific to state machines, but let's discuss them here as we're at it
- **update**: modify own or other objects' local state — boring

Transformer Examples: Presentation

abstract syntax **concrete syntax**

op

intuitive semantics

...

well-typedness

...

semantics

object "execution" action of op

$$((\sigma, \varepsilon), (\sigma', \varepsilon')) \in t_{\mathsf{op}}[u_x] \text{ iff } \ldots$$

or

$$t_{\mathsf{op}}[u_x](\sigma, \varepsilon) = \{(\sigma', \varepsilon')\} \text{ where } \ldots$$

observables

$Obs_{\mathsf{op}}[u_x] = \{\ldots\}$, not a relation, depends on choice

(error) conditions

Not defined if ...

Transformer: Skip

abstract syntax

`skip`

concrete syntax

skip

intuitive semantics

do nothing

well-typedness

./.

semantics

$$t[u_x](\sigma, \varepsilon) = \{(\sigma, \varepsilon)\}$$

"if u_x executes skip on (σ,ε), this results in (σ,ε)"

observables

$$Obs_{\texttt{skip}}[u_x](\sigma, \varepsilon) = \emptyset$$

(error) conditions

Transformer: Update

abstract syntax

$\texttt{update}(expr_1, v, expr_2)$

concrete syntax

$expr_1.v := expr_2$ (also: this.v := expr2)

intuitive semantics

Update attribute v in the object denoted by $expr_1$ to the value denoted by $expr_2$.

well-typedness

$expr_1 : \tau_C$ and $v : \tau \in atr(C)$; $expr_2 : \tau$;
$expr_1, expr_2$ obey visibility and navigability

semantics

$$t_{\texttt{update}(expr_1,v,expr_2)}[u_x](\sigma,\varepsilon) = \{(\sigma',\varepsilon)\}$$

where $\sigma' = \sigma[u \mapsto \sigma(u)[v \mapsto I[\![expr_2]\!](\sigma,\beta)]]$ with
$u = I[\![expr_1]\!](\sigma,\beta)$, $\beta = \{\text{this} \mapsto u_x\}$.

observables

$$Obs_{\texttt{update}(expr_1,v,expr_2)}[u_x] = \emptyset$$

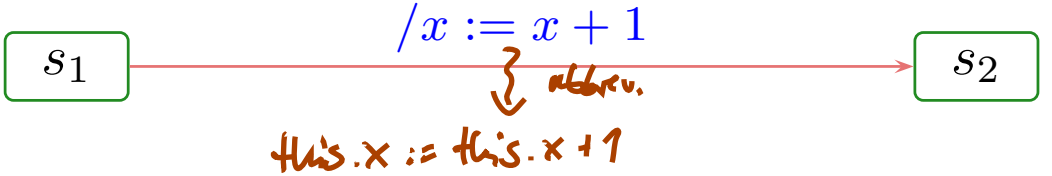
(error) conditions

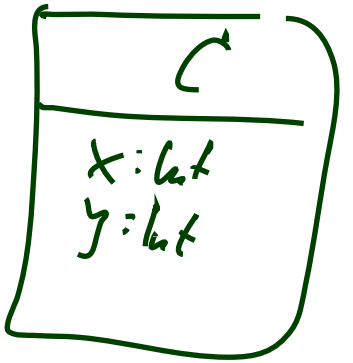
Not defined if $I[\![expr_1]\!](\sigma,\beta)$ or $I[\![expr_2]\!](\sigma,\beta)$ not defined.

ie. $t_{update(\ldots)}[u_x](\sigma,\varepsilon) \neq \emptyset$

Update Transformer Example

$\mathcal{SM}_C$:





$$\texttt{update}(expr_1, v, expr_2)$$

$$t_{\texttt{update}(expr_1,v,expr_2)}[u_x](\sigma,\varepsilon) = (\sigma[u \mapsto \sigma(u)[v \mapsto I[\![expr_2]\!](\sigma,\beta)]],\varepsilon),$$
$$u = I[\![expr_1]\!](\sigma,\beta)$$

σ:

$u_1 : C$
$x = 4$
$y = 0$

$u_x = u_1$

$t_{upd}[u_1](\sigma,\varepsilon) =$

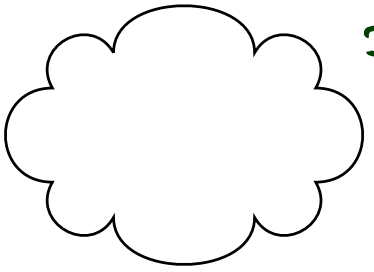
$(\sigma[u_1 \mapsto \sigma(u_1)[x \mapsto I[\![\text{this.x}]\!](\sigma,\{\text{this} \mapsto u_1\})+1]], \varepsilon)$

$=:\beta$ $=5$

$u_1 : C$
$x = 5$
$y = 0$

$:\sigma'$

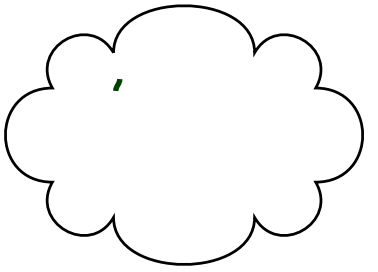
ε:



$I[\![\text{this.x}]\!](\sigma,\beta) + I[\![1]\!](\sigma,\beta)$

$=4$ $=1$

$=5$



$:\varepsilon'$

References

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