Softwaretechnik / Software-Engineering

Lecture 12: Structural Software Modelling

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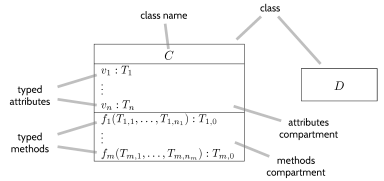
Topic Area Architecture & Design: Content

Content

Class Diagrams

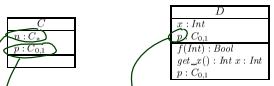
Class Diagrams: Concrete Syntax



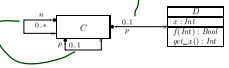
where

- $T_1, \ldots, T_{m,0} \in \mathscr{T} \cup \{C_{0,1}, C_* \mid C \text{ a class name}\}$
- $\mathscr{T}$ is a set of **basic types**, e.g. $Int, Bool, \ldots$.

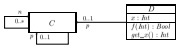
Concrete Syntax: Example



Alternative notation for $C_{0,1}$ and C_* typed attributes:



Alternative lazy notation for alternative notation:



And nothing else! This is the concrete syntax of class diagrams for the scope of the course.

Abstract Syntax: Object System Signature

Definition. An (Object System) Signature is a 6-tuple

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

where

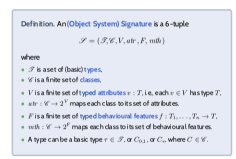
- $\mathscr{T}$ is a set of (basic) types,
- $\mathscr{C}$ is a finite set of classes,
- V is a finite set of typed attributes $v : T$, i.e., each $v \in V$ has type T,
- $atr : \mathscr{C} \to 2^V$ maps each class to its set of attributes.
- F is a finite set of typed behavioural features $f : T_1, \ldots, T_n \to T$,
- $mth : \mathscr{C} \to 2^F$ maps each class to its set of behavioural features.
- A type can be a basic type $\tau \in \mathscr{T}$, or $C_{0,1}$, or C_*, where $C \in \mathscr{C}$.

powerset of V

we will discuss these not so much

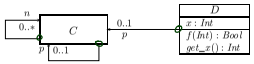
Note: Inspired by OCL 2.0 standard OMG (2006), Annex A.

Object System Signature Example



$$\mathscr{S}_0 = (\{Int, Bool\}, \{C, D\}, \{x : Int, p : C_{0,1}, n : C_*\}, \{C \mapsto \{p, n\}, D \mapsto \{p, x\}\}, \{f : Int \to Bool, get\_x : Int\}, \{C \mapsto \emptyset, D \mapsto \{f, get\_x\}\})$$

From Abstract to Concrete Syntax



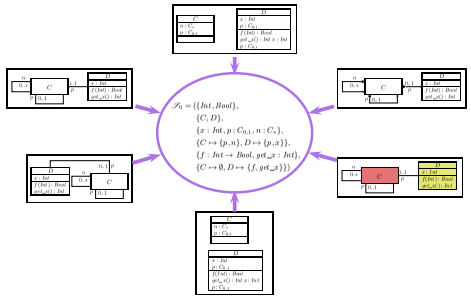
$$\mathscr{S} = (\mathscr{T}, \mathscr{C}, V, atr, F, mth)$$

- $\mathscr{T} = \{Int, Bool\}$,
- $\mathscr{C} = \{C, D\}$,
- $V = \{x : Int, p : C_{0,1}, n : C_*\}$,
- $atr = \{C \mapsto \{p, n\}, D \mapsto \{x, p\}\}$,
- $F = \{f : Int \to Bool, get\_x : Int\}$,
- $mth = \{C \mapsto \emptyset, D \mapsto \{f, get\_x\}\}$

$m : T_1, \ldots, T_n \to T$, $n \geq 0$
$m : \to T$ if $n = 0$
$m : T$ if $n = 0$ also ok

$mth(C) = \emptyset$
$mth(D) = \{f, get\_x\}$

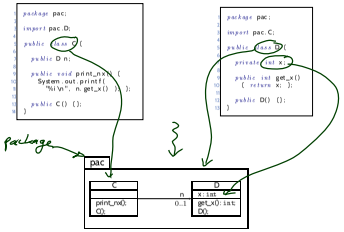
Once Again: Concrete vs. Abstract Syntax



Class Diagrams at Work

Visualisation of Implementation

- The class diagram syntax can be used to **visualise code**:
  provide rules which map (parts of) the code to class diagram elements.

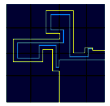


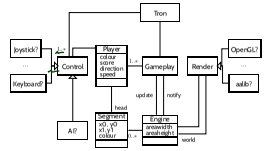
Visualisation of Implementation: (Useless) Example

- open favourite IDE,
- open favourite **project**,
- press "**generate class diagram**"
- **wait…wait…wait…**

- ca. 35 classes,
- ca. 5,000 LOC C#

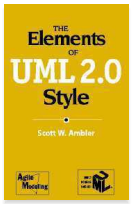
Visualisation of Implementation: (Useful) Example





- **Note**: a class **diagram** for visualisation may be partial.
  → show only the **most relevant** classes and attributes (for the given purpose).
- **Note**: a signature can be defined by **a set of** class diagrams.
  → use multiple class diagrams with **a manageable** number of classes for different purposes.
- A diagram is **a good diagram** if (and only if?) it serves its **purpose**!

Literature Recommendation



(Ambler, 2005)

A More Abstract Class Diagram Semantics

Object System Structure

Definition. A Object System **Structure** of signature

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

is a **domain function** $\mathscr{D}$ which assigns to each type a domain, i.e.

- $\tau \in \mathscr{T}$ is mapped to $\mathscr{D}(\tau)$.
- $C \in \mathscr{C}$ is mapped to an infinite set $\mathscr{D}(C)$ of **(object) identities**.
  - object identities of different classes are disjoint, i.e.
    $\forall C, D \in \mathscr{C} : C \neq D \rightarrow \mathscr{D}(C) \cap \mathscr{D}(D) = \emptyset$.
  - on object identities, (only) comparision for equality "$=$" is defined.
- C_* **and** $C_{0,1}$ for $C \in \mathscr{C}$ are mapped to $2^{\mathscr{D}(C)}$.

We use $\mathscr{D}(\mathscr{C})$ to denote $\bigcup_{C \in \mathscr{C}} \mathscr{D}(C)$; analogously $\mathscr{D}(\mathscr{C}_*)$.

Note: We identify **objects** and **object identities**,
because both uniquely determine each other (cf. OCL 2.0 standard).

Basic Object System Structure Example

Wanted: a structure for signature

$$\mathscr{S}_0 = (\{Int, Bool\}, \{C, D\}, \{x : Int, p : C_{0,1}, n : C_*\}, \{C \mapsto \{p, n\}, D \mapsto \{p, x\}\},$$
$$\{f : Int \to Bool, get\_x : Int\}, \{C \mapsto \emptyset, D \mapsto \{f, get\_x\}\})$$

A structure $\mathscr{D}$ maps

- $\tau \in \mathscr{T}$ to some $\mathscr{D}(\tau)$, $C \in \mathscr{C}$ to some identities $\mathscr{D}(C)$ (infinite, pairwise disjoint),
- C_* and $C_{0,1}$ for $C \in \mathscr{C}$ to $\mathscr{D}(C_{0,1}) = \mathscr{D}(C_*) = 2^{\mathscr{D}(C)}$.

$$\begin{aligned}
\mathscr{D}(Int) &= \mathbb{Z} \\
\mathscr{D}(C) &= \mathbb{N}^+ \times \{C\} \\
\mathscr{D}(D) &= \mathbb{N}^+ \times \{D\} \\
\mathscr{D}(C_{0,1}) = \mathscr{D}(C_*) &= 2^{\mathscr{D}(C)} \\
\mathscr{D}(D_{0,1}) = \mathscr{D}(D_*) &= 2^{\mathscr{D}(D)}
\end{aligned}$$

System State

Definition. Let $\mathscr{D}$ be a structure of $\mathscr{S} = (\mathscr{T}, \mathscr{C}, V, atr, F, mth)$.
A system state of $\mathscr{S}$ wrt. $\mathscr{D}$ is a type-consistent mapping

$$\sigma : \mathscr{D}(\mathscr{C}) \nrightarrow (V \nrightarrow (\mathscr{D}(\mathscr{T}) \cup \mathscr{D}(\mathscr{C}_*))).$$

That is, for each $u \in \mathscr{D}(C), C \in \mathscr{C}$, if $u \in \mathrm{dom}(\sigma)$

- $\mathrm{dom}(\sigma(u)) = atr(C)$
- $\sigma(u)(v) \in \mathscr{D}(\tau)$ if $v : \tau, \tau \in \mathscr{T}$
- $\sigma(u)(v) \in \mathscr{D}(D_*)$ if $v : D_{0,1}$ or $v : D_*$ with $D \in \mathscr{C}$

We call $u \in \mathscr{D}(\mathscr{C})$ alive in σ if and only if $u \in \mathrm{dom}(\sigma)$.
We use $\Sigma^{\mathscr{D}}_{\mathscr{S}}$ to denote the set of all system states of $\mathscr{S}$ wrt. $\mathscr{D}$.

System State Examples

$$\mathscr{S}_0 = (\{Int, Bool\}, \{C, D\}, \{x : Int, p : C_{0,1}, n : C_*\}, \{C \mapsto \{p, n\}, D \mapsto \{p, x\}\},$$
$$\{f : Int \to Bool, get\_x : Int\}, \{C \mapsto \emptyset, D \mapsto \{f, get\_x\}\})$$

$$\mathscr{D}(Int) = \mathbb{Z}, \quad \mathscr{D}(C) = \{1_C, 2_C, 3_C, \ldots\}, \quad \mathscr{D}(D) = \{1_D, 2_D, 3_D, \ldots\}$$

A system state is a partial function $\sigma : \mathscr{D}(\mathscr{C}) \nrightarrow (V \nrightarrow (\mathscr{D}(\mathscr{T}) \cup \mathscr{D}(\mathscr{C}_*)))$ such that

- $\mathrm{dom}(\sigma(u)) = atr(C)$,
- $\sigma(u)(v) \in \mathscr{D}(\tau)$ if $v : \tau, \tau \in \mathscr{T}$,
- $\sigma(u)(v) \in \mathscr{D}(C_*)$ if $v : D_*$ or $v : D_{0,1}$ with $D \in \mathscr{C}$.

$$\sigma_1 = \emptyset$$

$$\sigma_2 = \{1_C \mapsto \{y \mapsto \text{rose}, p \mapsto \{5_C\}, n \mapsto \emptyset\},\ 5_C \mapsto \{y \mapsto \text{daisy}, p \mapsto \emptyset, n \mapsto \{1_C\}\},\ 4_D \mapsto \{x \mapsto 27, p \mapsto \{5_C\}\}\}$$

Content

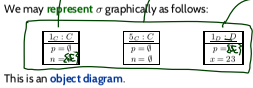
Object Diagrams

Object Diagrams

$$\mathscr{S}_0 = (\{Int, Bool\}, \{C, D\}, \{x : Int, p : C_{0,1}, n : C_*\}, \{C \mapsto \{p, n\}, D \mapsto \{p, x\}\},$$
$$\{f : Int \to Bool, get\_x : Int\}, \{C \mapsto \emptyset, D \mapsto \{f, get\_x\}\}), \qquad \mathscr{D}(Int) = \mathbb{Z}$$

$$\sigma = \{1_C \mapsto \{p \mapsto \emptyset, n \mapsto \{5_C\}\}, 5_C \mapsto \{p \mapsto \emptyset, n \mapsto \emptyset\}, 1_D \mapsto \{p \mapsto \{5_C\}, x \mapsto 23\}\}$$

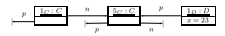
- We may represent σ graphically as follows:



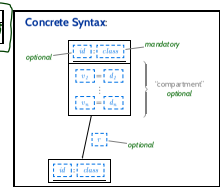
This is an **object diagram**.

- Alternative notation:

- Alternative non-standard notation:



Concrete Syntax:



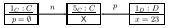
Special Case: Dangling Reference

Definition.
Let $\sigma \in \Sigma^{\mathscr{D}}_{\mathscr{S}}$ be a system state and $u \in \mathrm{dom}(\sigma)$ an alive object of class C in σ.
We say $r \in atr(C)$ is a dangling reference in u if and only if $r : C_{0,1}$ or $r : C_*$ and u refers to a non-alive object via v, i.e.

$$\sigma(u)(r) \not\subseteq \mathrm{dom}(\sigma).$$

Example:

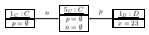
- $\sigma = \{1_C \mapsto \{p \mapsto \emptyset, n \mapsto \{5_C\}\}, 1_D \mapsto \{p \mapsto \{5_C\}, x \mapsto 23\}\}$ Sc ∉ dom(σ)
- Object diagram representation:



Partial vs. Complete Object Diagrams

- By now we discussed "**object diagram represents system state**":

$$\{1_C \mapsto \{p \mapsto \emptyset, n \mapsto \{5_C\}\}, \; 5_C \mapsto \{p \mapsto \emptyset, n \mapsto \emptyset\}, \; 1_D \mapsto \{p \mapsto \{5_C\}, x \mapsto 23\}\} \quad \rightsquigarrow$$



What about the other way round…?

- **Object diagrams** can be **partial**, e.g.

→ we may omit information.

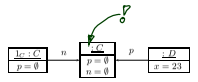
- Is the following object diagram **partial** or **complete**? (wrt. given signature $\mathscr{S}$)

- If an object diagram
  - has values for **all** attributes of **all** objects in the diagram, and
  - if we **say that** it is meant to be complete

  then we can **uniquely** reconstruct a system state σ.

Special Case: Anonymous Objects

If the object diagram



is considered as **complete**, then it denotes the set of all system states

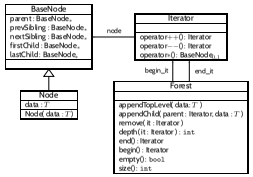
$$\{c_1 \mapsto \{p \mapsto \emptyset, n \mapsto \{c_2\}\}, c_2 \mapsto \{p \mapsto \emptyset, n \mapsto \emptyset\}, d \mapsto \{p \mapsto \{c_2\}, x \mapsto 23\}\}$$

where $c \in \mathscr{D}(C), \quad d \in \mathscr{D}(D), \quad c \neq 1_C$.

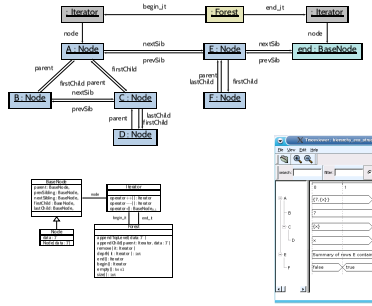
Intuition: different boxes represent different objects.

Object Diagrams at Work

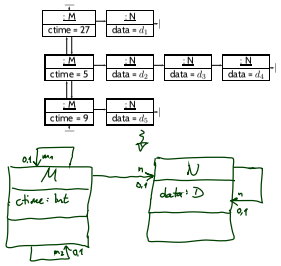
Example: Data Structure (Schumann et al., 2008)



Example: Illustrative Object Diagram (Schumann et al., 2008)



Object Diagrams for Analysis



Content

Towards Object Constraint Logic (OCL)
— "Proto-OCL" —

Constraints on System States

C
$x : Int$

- **Example**: for all C-instances, x should never have the value 27.

$$\forall\, c \in allInstances_C \bullet x(c) \neq 27$$

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$$\forall\, c \in allInstances_C \bullet x(c) \neq 27$$

- **Proto-OCL Syntax** wrt. signature $(\mathscr{T}, \mathscr{C}, V, atr, F, mth)$, c is a **logical variable**, $C \in \mathscr{C}$:

$$\begin{array}{rlll} F ::= & c & : \tau_C & \\ \mid & allInstances_C & : 2^{\tau_C}, \quad c \in \mathscr{C} & \\ \mid & v(F) & : \tau_C \to \tau_\perp, & \text{if } v : \tau \in atr(C), \ \tau \in \mathscr{T} \\ \mid & v(F) & : \tau_C \to \tau_D, & \text{if } v : D_{0,1} \in atr(C) \\ \mid & v(F) & : \tau_C \to 2^{\tau_D}, & \text{if } v : D_* \in atr(C) \\ \mid & f(F_1, \ldots, F_n) & : \tau_1 \times \cdots \times \tau_n \to \tau, & \text{if } f : \tau_1 \times \cdots \times \tau_n \to \tau \\ \mid & \forall\, c \in F_1 \bullet F_2 & : \tau_C \times 2^{\tau_C} \times \mathrm{B}_\perp \to \mathrm{B}_\perp & \end{array}$$

Constraints on System States

C
$x : Int$

- **Example**: for all C-instances, x should never have the value 27.

$$\forall\, c \in allInstances_C \bullet x(c) \neq 27$$

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- The formula above in **prefix normal form**: $\forall\, c \in allInstances_C \bullet \neq (x(c), 27)$

Semantics

- **Proto-OCL Types:**
  - $\mathcal{I}[\![\tau_C]\!] = \mathcal{P}(C) \cup \{\bot\}, \quad \mathcal{I}[\![\tau_\bot]\!] = \mathcal{P}(\tau) \cup \{\bot\}, \quad \mathcal{I}[\![2^{\tau_C}]\!] = \mathcal{P}(C_\bot) \cup \{\bot\}$
  - $\mathcal{I}[\![\mathbb{B}_\bot]\!] = \{\mathit{true}, \mathit{false}\} \cup \{\bot\}, \quad \mathcal{I}[\![\mathbb{Z}_\bot]\!] = \mathbb{Z} \cup \{\bot\}$
- **Functions:**
  - We assume $f_\mathcal{I}$ given for each function symbol f ($\hookrightarrow$ in a minute).
- **Proto-OCL Semantics** (interpretation function):
  - $\mathcal{I}[\![c]\!](\sigma, \beta) = \beta(c)$ (assuming β is a type-consistent valuation of the logical variables).
  - $\mathcal{I}[\![allInstances_C]\!](\sigma, \beta) = \mathrm{dom}(\sigma) \cap \mathcal{P}(C)$.
  - $\mathcal{I}[\![v(F)]\!](\sigma, \beta) = \begin{cases} (\sigma\ (\mathcal{I}[\![F]\!](\sigma, \beta)))(v) & \text{, if } \mathcal{I}[\![F]\!](\sigma, \beta) \in \mathrm{dom}(\sigma) \\ \bot & \text{, otherwise} \end{cases}$ (if not $v : C_{0,1}$)
  - $\mathcal{I}[\![v(F)]\!](\sigma, \beta) = \begin{cases} \sigma(u')(v) & \text{, if } \mathcal{I}[\![F]\!](\sigma, \beta) = \{u'\} \subseteq \mathrm{dom}(\sigma) \\ \bot & \text{, otherwise} \end{cases}$ (if $v : C_{0,1}$)
  - $\mathcal{I}[\![f(F_1, \ldots, F_n)]\!](\sigma, \beta) = f_\mathcal{I}(\mathcal{I}[\![F_1]\!](\sigma, \beta), \ldots, \mathcal{I}[\![F_n]\!](\sigma, \beta))$.
  - $\mathcal{I}[\![\forall c \in F_1 \bullet F_2]\!](\sigma, \beta) = \begin{cases} \mathit{true} & \text{, if } \mathcal{I}[\![F_2]\!](\sigma, \beta[c := u]) = \mathit{true} \text{ for all } u \in \mathcal{I}[\![F_1]\!](\sigma, \beta) \\ \mathit{false} & \text{, if } \mathcal{I}[\![F_2]\!](\sigma, \beta[c := u]) = \mathit{false} \text{ for some } u \in \mathcal{I}[\![F_1]\!](\sigma, \beta) \\ \bot & \text{, otherwise} \end{cases}$

Semantics Cont'd

- Proto-OCL is a **three-valued** logic: a formula evaluates to *true*, *false*, or $\bot$.
- **Example:** $\wedge_\mathcal{I}(\cdot,\cdot) : \{\mathit{true}, \mathit{false}, \bot\} \times \{\mathit{true}, \mathit{false}, \bot\} \to \{\mathit{true}, \mathit{false}, \bot\}$ is defined as follows:

x_1	*true*	*true*	*true*	*false*	*false*	*false*	$\bot$	$\bot$	$\bot$
x_2	*true*	*false*	$\bot$	*true*	*false*	$\bot$	*true*	*false*	$\bot$
$\wedge_\mathcal{I}(x_1, x_2)$	*true*	*false*	$\bot$	*false*	*false*	*false*	$\bot$	*false*	$\bot$

We assume common logical connectives $\neg, \wedge, \vee, \ldots$ with canonical 3-valued interpretation.

- **Example:** $+_\mathcal{I}(\cdot,\cdot) : (\mathbb{Z} \cup \{\bot\}) \times (\mathbb{Z} \cup \{\bot\}) \to \mathbb{Z} \cup \{\bot\}$

$$+_\mathcal{I}(x_1, x_2) = \begin{cases} x_1 + x_2 & \text{, if } x_1 \neq \bot \text{ and } x_2 \neq \bot \\ \bot & \text{, otherwise} \end{cases}$$

We assume common arithmetic operations $-, /, *, \ldots$
and relation symbols $>, <, \leq, \ldots$ with **monotone** 3-valued interpretation.

- And we assume the special unary function symbol $isUndefined$:

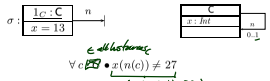
$$isUndefined_\mathcal{I}(x) = \begin{cases} \mathit{true} & \text{, if } x = \bot, \\ \mathit{false} & \text{, otherwise} \end{cases}$$

$isUndefined_\mathcal{I}$ is **definite**: it never yields $\bot$.

Example: Evaluate Formula for System State

- Recall **prefix notation:** $\forall\, c \in allInstances_C \bullet \neq(x(c), 27)$
  Note: $\neq$ is a binary function symbol, 27 is a 0-ary function symbol.
- **Example:**
  $\mathcal{I}[\![\forall c \in allInstances_C \bullet \neq(x(c), 27)]\!](\sigma, \emptyset) = \mathit{true}$, because…
  $\mathcal{I}[\![\neq(x(c), 27)]\!](\sigma, \beta), \quad \beta := \emptyset[c := 1_C] = \{c \mapsto 1_C\}$
  $= \neq_\mathcal{I}(\mathcal{I}[\![x(c)]\!](\sigma, \beta),\ \mathcal{I}[\![27]\!](\sigma, \beta))$
  $= \neq_\mathcal{I}(\sigma(\mathcal{I}[\![c]\!](\sigma, \beta))(x),\ 27_\mathcal{I})$
  $= \neq_\mathcal{I}(\sigma(\beta(c))(x),\ 27_\mathcal{I})$
  $= \neq_\mathcal{I}(\sigma(1_C)(x),\ 27_\mathcal{I})$
  $= \neq_\mathcal{I}(13,\ 27) = \mathit{true}$ …and 1_C is the only C-object in σ: $\mathcal{I}[\![allInstances_C]\!](\sigma, \emptyset) = \{1_C\}$.

More Interesting Example

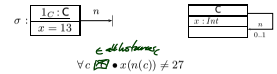


$\forall\, c \in allInstances_C \bullet x(n(c)) \neq 27$

- Similar to the previous slide, we need the value of

$$\sigma\,(\,\sigma(\mathcal{I}[\![c]\!](\sigma, \beta))(n)\,)(x)$$

More Interesting Example



$\forall\, c \in allInstances_C \bullet x(n(c)) \neq 27$

- Similar to the previous slide, we need the value of

$$\sigma\,(\,\sigma(\mathcal{I}[\![c]\!](\sigma, \beta))(n)\,)(x)$$

- $\mathcal{I}[\![c]\!](\sigma, \beta) = \beta(c) = 1_C$
- $\sigma(\mathcal{I}[\![c]\!](\sigma, \beta))(n) = \sigma(1_C)(n) = \emptyset$
- $\sigma\,(\,\sigma(\mathcal{I}[\![c]\!](\sigma, \beta))(n)\,)(x) = \bot$

by the following rule:

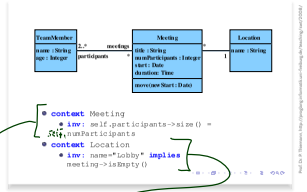
$$\mathcal{I}[\![v(F)]\!](\sigma, \beta) = \begin{cases} \sigma(u')(v) & \text{, if } \mathcal{I}[\![F]\!](\sigma, \beta) = \{u'\} \subseteq \mathrm{dom}(\sigma) \\ \bot & \text{, otherwise} \end{cases} \quad \text{(if } v : C_{0,1})$$

Object Constraint Language (OCL)

OCL is the same – just with less readable (?) syntax.

Literature: (OMG, 2006; Warmer and Kleppe, 1999).

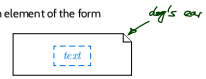
Examples *(from lecture "Softwaretechnik 2008")*



Putting It All Together

Where To Put OCL Constraints?

- **Notes**: A UML note is a diagram element of the form



$text$ can principally be everything, in particular comments and constraints.

Sometimes, content is explicitly classified for clarity:

- Conventions:

Modelling Structure with Class Diagrams

Definition. **Software** is a finite description S of a (possibly infinite) set $[\![S]\!]$ of (finite or infinite) computation paths of the form $\sigma_0 \xrightarrow{\alpha_1} \sigma_1 \xrightarrow{\alpha_2} \sigma_2 \cdots$ where

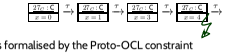
- $\sigma_i \in \Sigma, i \in \mathbb{N}_0$, is called **state** (or configuration), and
- $\alpha_i \in A, i \in \mathbb{N}_0$, is called **action** (or **event**).

The (possibly partial) function $[\![\cdot]\!] : S \mapsto [\![S]\!]$ is called **interpretation** of S.

- The set of **states** Σ could be the set of **system states** as defined by a class diagram, e.g.

$$\Sigma := \Sigma^{\mathscr{D}} \qquad \mathscr{S}: \boxed{\begin{array}{c} C \\ \hline a:\mathbb{N} \end{array}}$$

- A corresponding **computation path** of a software S could be



- If a requirement is formalised by the Proto-OCL constraint

$$F = \forall c \in allInstances_C \bullet x(c) < 4$$

then S **does not** satisfy the requirement.

Content

More General: Software vs. Proto-OCL

- Let $\mathscr{S}$ be an **object system signature** and $\mathscr{D}$ a **structure**.
- Let S be a **software** with
  - states $\Sigma \subseteq \Sigma^{\mathscr{D}}_{\mathscr{S}}$, and
  - **computation paths** $[\![S]\!]$.
- Let F be a Proto-OCL constraint over $\mathscr{S}$.
- We say $[\![S]\!]$ **satisfies** F, denoted by $[\![S]\!] \models F$, if and only if for all

$$\sigma_0 \xrightarrow{\alpha_1} \sigma_1 \xrightarrow{\alpha_2} \sigma_2 \cdots \in [\![S]\!]$$

and all $i \in \mathbb{N}_0$,

$$\mathcal{I}[\![F]\!](\sigma_i, \emptyset) = \textit{true}.$$

- We say $[\![S]\!]$ **does not satisfy** F, denoted by $[\![S]\!] \not\models F$, if and only if there exists $\sigma_0 \xrightarrow{\alpha_1} \sigma_1 \xrightarrow{\alpha_2} \sigma_2 \cdots \in [\![S]\!]$ and $i \in \mathbb{N}_0$, such that $\mathcal{I}[\![F]\!](\sigma_i, \emptyset) = \textit{false}$.
- **Note**: $\neg([\![S]\!] \not\models F)$ does not imply $[\![S]\!] \models F$.

Tell Them What You've Told Them...

- **Class Diagrams** can be used to **graphically**
  - visualise code,
  - define an **object system structure** $\mathscr{S}$.
- An **Object System** $\mathscr{S}$ (together with a structure $\mathscr{D}$)
  - defines a set of **system states** $\Sigma_{\mathscr{S}}^{\mathscr{D}}$.
- A **System State** $\sigma \in \Sigma_{\mathscr{S}}^{\mathscr{D}}$
  - can be **visualised** by an **object diagram**.
- **Proto-OCL** constraints can be evaluated on **system states**.
- A **software** over $\Sigma_{\mathscr{S}}^{\mathscr{D}}$ satisfies a Proto-OCL constraint F if and only if F evaluates to *true* in all system states of all the software's computation paths.

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