Formal Analysis of UML/OCL Models

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Abstract

In this talk, we present the theorem proving environment HOL-OCL. The HOL-OCL system is an interactive proof environment for UML/OCL specifications that is integrated in an MDE framework. HOL-OCL allows to reason over UML class models annotated with OCL specifications. Moreover, HOL-OCL provides several derived proof calculi that allow for formal derivations of validity of UML/OCL formulae. These formulae arise naturally when checking the consistency of class models, when formally refining abstract models to more concrete ones or when discharging side-conditions from model-transformations.

Outline

1. Introduction
2. OCL in an Industrial Context
3. HOL-OCL
4. Mechanized Support for Model Analysis Methods
5. Conclusion and Future Work

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The Situation Today

A Software Engineering Problem

- Software systems
  - are becoming more and more complex and
  - are used in safety and security critical applications.
- Formal methods are one way to increase their reliability.
- But, formal methods are hardly used by mainstream industry:
  - difficult to understand notation
  - lack of tool support
  - high costs
- Semi-formal methods, especially UML,
  - are widely used in industry, but
  - they lack support for formal methodologies.

Is OCL an Answer?

UML/OCL attracts the practitioners:

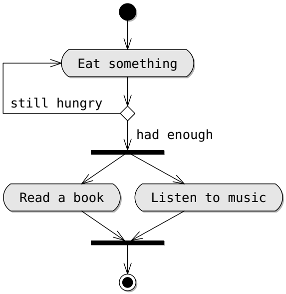
- is defined by the object-oriented community,
- has a "programming language face,"
- increasing tool support.

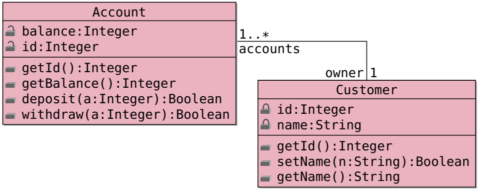
UML/OCL is attractive to researchers:

- defines a "core language" for object-oriented modeling,
- provides good target for object-oriented semantics research,
- offers the chance for bringing formal methods closer to industry.

The Unified Modeling Language (UML)

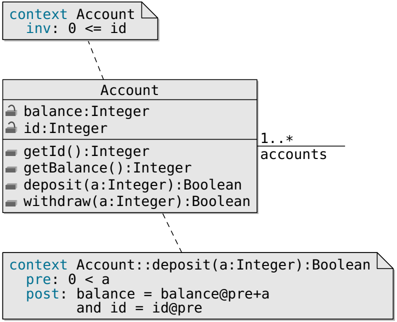
- Visual modeling language
- Object-oriented development
- Industrial tool support
- OMG standard
- Many diagram types, e. g.,
  - activity diagrams
  - **class diagrams**
  - …





The Object Constraint Language (OCL)

- Textual extension of the UML
- Allows for annotating UML diagrams
- In the context of class–diagrams:
  - invariants
  - preconditions
  - postconditions
- Can be used for other diagrams



OCL by Example

- Class invariants:

```
context Account inv: 0 <= id
```

- Operation specifications:

```
context Account::deposit(a:Integer):Boolean
pre: 0 < a
post: balance = balance@pre + a
```

- A "uniqueness" constraint for the class `Account`:

```
context Account inv:
    Account::allInstances()
      ->forAll(a1,a2 | a1.id = a2.id implies a1 = a2)
```

OCL context OCL keywords UML path expressions

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Metamodeling and OCL (Revised)

- OCL can also be used to extend the MOF meta model
- 2.0 has a MOF-based metamodel for its abstract syntax
- OCL can be used for expressing queries on model content, e. g.,
  - model transformation implementation
  - event filtering

Level	MOF terms	OCL
M3	meta-meta-model	OCL specification
M2	meta-model	OCL constrains DSL
M1	model	OCL constrains model
M0	object	N/A

Target Groups and Impact: a Rough Picture

Level	MOF terms	OCL
M3	1	standards developer
M2	10 . . . 100	**tool developer**
M1	1 000 . . . 10 000	application developer
M0	100 000 . . . 10 000 000	end user

Industrial OCL Suport: An Example

Modeling Infrastructure (MOIN) developed by SAP:

- platform for SAP's next generation of modeling tools
- rougly similar to Eclipse (i.e., EMF), but not based on EMF
- provides an OCL 2.0 type checker
- provides an efficient evaluation environment (impact analysis for model changes)

At SAP, OCL is

- widely used for anotating meta-models (M2)
- used by Development Architects

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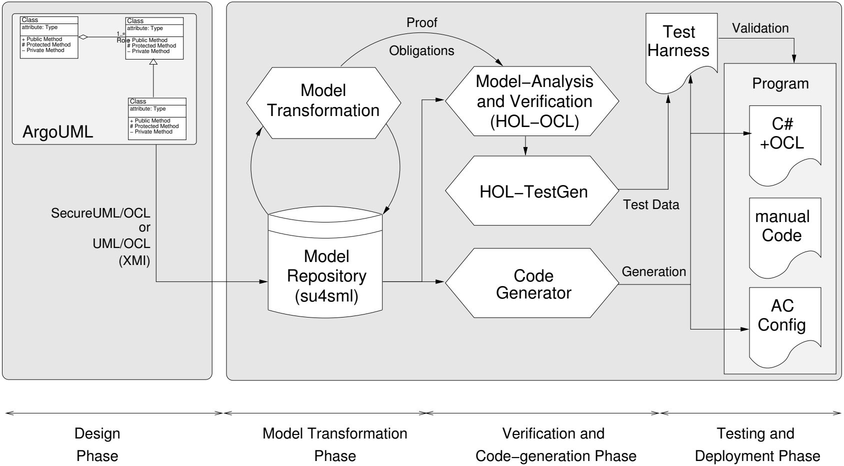
The HOL-OCL Vision:

Tool Supported Formal Methods for (Model-driven) Software Development



HOL-OCL

- HOL-OCL provides:
  - a formal, machine-checked semantics for OO specifications,
  - an interactive proof environment for OO specifications,
  - publicly available: `http://www.brucker.ch/projects/hol-ocl/`,
  - next (major) release planned in November 2008.
- HOL-OCL is integrated into a toolchain providing:
  - extended well-formedness checking,
  - proof-obligation generation,
  - methodology support for UML/OCL,
  - a transformation framework (including PO generation),
  - code generators,
  - support for SecureUML.

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Motivation

Observation:

- UML/OCL is a *generic* modeling language:
  - usually, only a sub-set of UML is used and
  - per se there is no standard UML-based development process.
- Successful use of UML usually comprises
  - a well-defined development process and
  - tools that integrate into the development process.

Conclusion:

- Formal methods for UML-based development should
  - support the local UML development methodologies and
  - integrate smoothly into the local toolchain.

A toolchain for formal methods should provide
tool-support for **methodologies**.

Well-formedness of Models

Well-formedness Checking

- Enforce **syntactical** restriction on (valid) UML/OCL models.
- Ensure a minimal quality of models.
- Can be easily supported by fully-automatic tools.

Example

- There should be at maximum five inheritance levels.
- The Specification of public operations may only refer to public class members.
- …

Proof Obligations for Models

Proof Obligation Generation

- Enforce **semantical** restriction on (valid) UML/OCL models.
- Build the basis for formal development methodologies.
- Require formal tools (theorem prover, model checker, etc).

Example

- Liskov's substitution principle.
- Model consistency
- Refinement.
- …

Proof Obligations: Liskov's Substitution Principle

Liskov substitution principle

Let $q(x)$ be a property provable about objects x of type T. Then $q(y)$ should be true for objects y of type S where S is a subtype of T.

For constraint languages, like OCL, this boils down to:

- *pre-conditions* of overridden methods must be *weaker*.
- *post-conditions* of overridden methods must be *stronger*.

Which can formally expressed as implication:

- Weakening the pre-condition:

$$op_{\text{pre}} \to op_{\text{pre}}^{\text{sub}}$$

- Weakening the pre-condition:

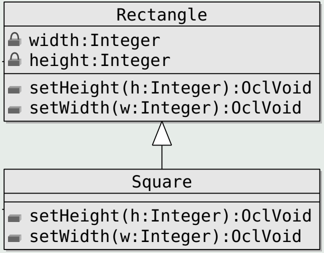
$$op_{\text{post}}^{\text{sub}} \to op_{\text{post}}$$

Proof Obligations: Liskov's Substitution Principle

Example

```
context Rectangle::setWidth(w:Integer):OclVoid
  pre: w >= 0
  post: self.width = w
```

```
context Square::setWidth(w:Integer):OclVoid
  pre: w >= 0
  post: self.width = w and self.height=w
```

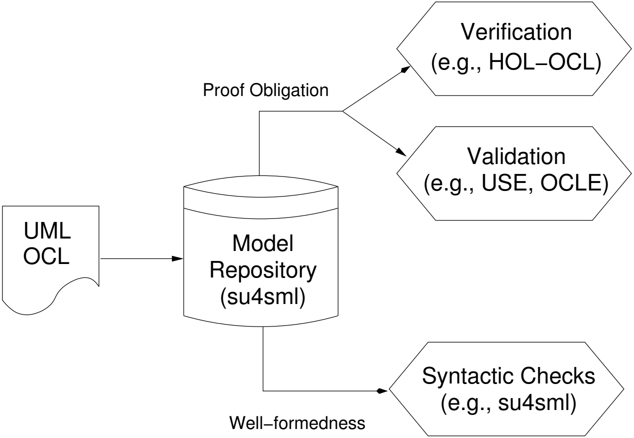


- Weakening the pre-condition:

$$(\texttt{w >= 0}) \rightarrow (\texttt{w >= 0})$$

- Strengthening the post-condition:

Well-formedness and Proof Obligations



Methodology

A tool-supported methodology should

- integrate into existing toolchains and processes,
- provide a unified approach, integrating ,
  - syntactic requirements (well-formedness checks),
  - generation of proof obligations,
  - means for **verification** (proving) or **validation**, and of course
- all phases should be supported by tools.

Example

A package-based object-oriented refinement methodology.

Refinement – Motivation

Support top-down development from an abstract model to a more concrete one.

- We start with an abstract transition system

$$sys_{\mathrm{abs}} = (\sigma_{\mathrm{abs}}, init_{\mathrm{abs}}, op_{\mathrm{abs}})$$

- We refine each abstract operation op_{abs} to a more concrete one: op_{conc}.
- Resulting in a more concrete transition system

$$sys_{\mathrm{conc}} = (\sigma_{\mathrm{conc}}, init_{\mathrm{conc}}, op_{\mathrm{conc}})$$

- Such refinements can be chained:

$$sys_1 \rightsquigarrow sys_2 \rightsquigarrow \cdots \rightsquigarrow sys_n$$

E.g., from an abstract model to one that supports code generation.

Refinement: Well-formedness

If package B refines a package A, then
one should be able to
substitute every usage of package A with package B.

1. The concrete package must provide at a corresponding public class for each public class of the abstract model.
2. For public attributes we require that their type and for public operations we require that the return type and their argument types are either basic datatypes or public classes.
3. For each public class of the abstract package, we require that the corresponding concrete class provides at least
   1. public attributes with the same name and
   2. public operations with the same name.
4. The types of corresponding abstract and concrete attributes and operations are compatible.

Refinement: Proof Obligtations – Consistency

A transition system is consistent if:

- The set of initial states is non-empty, i. e.,

$$\exists \sigma.\ \sigma \in \mathit{init}$$

- The state invariant is satisfiable, i. e., the conjunction of all invariants is invariant-consistent:

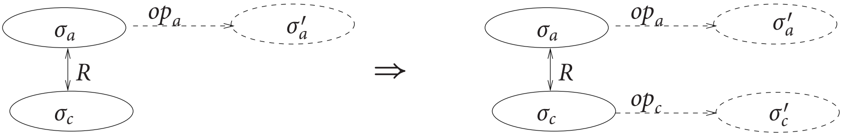
$$\exists \sigma.\ \sigma \models \mathit{inv}_1 \land \exists \sigma.\ \sigma \models \mathit{inv}_2 \land \cdots \land \exists \sigma.\ \sigma \models \mathit{inv}_n$$

- All operations op are implementable, i. e., for each satisfying pre-state there exists a satisfying post-state:

$$\forall\ \sigma_{\text{pre}} \in \Sigma, \mathit{self}, i_1, \ldots, i_n.\ \sigma_{\text{pre}} \models \text{pre}_{op} \longrightarrow \\ \exists\ \sigma_{\text{post}} \in \Sigma, \mathit{result}.\ (\sigma_{\text{pre}}, \sigma_{\text{post}}) \models \text{post}_{op}$$

Refinement: Proof Obligtations – Implements

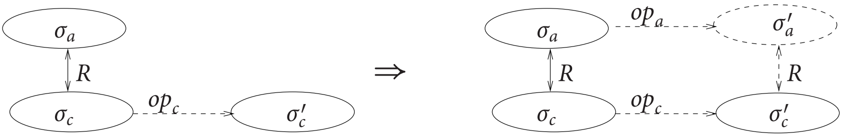
- Given an abstraction relation $R : \mathbb{P}(\sigma_{\text{abs}} \times \sigma_{\text{conc}})$ relating a concrete state S and an abstract states T.
- A forward refinement $S \sqsubseteq^{R}_{FS} T \equiv po_1(S, R, T) \wedge po_2(S, R, T)$ requires two proof obligations po_1 and po_2.
- **Preserve Implementability (po_1):**



$$po_1(S, R, T) \equiv \forall \sigma_a \in \text{pre}(S), \sigma_c \in V.\ (\sigma_a, \sigma_c) \in R \rightarrow \sigma_c \in \text{pre}(T)$$

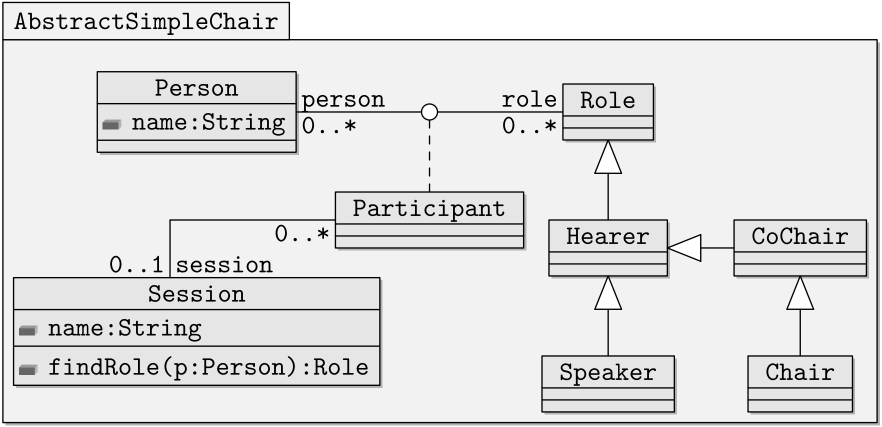
Refinement: Proof Obligtations – Refines

- Given an abstraction relation $R : \mathbb{P}(\sigma_{\text{abs}} \times \sigma_{\text{conc}})$ relating a concrete state S and an abstract states T.
- A forward refinement $S \sqsubseteq_{FS}^{R} T \equiv po_1(S, R, T) \wedge po_2(S, R, T)$ requires two proof obligations po_1 and po_2.
- **Refinement (po_2):**

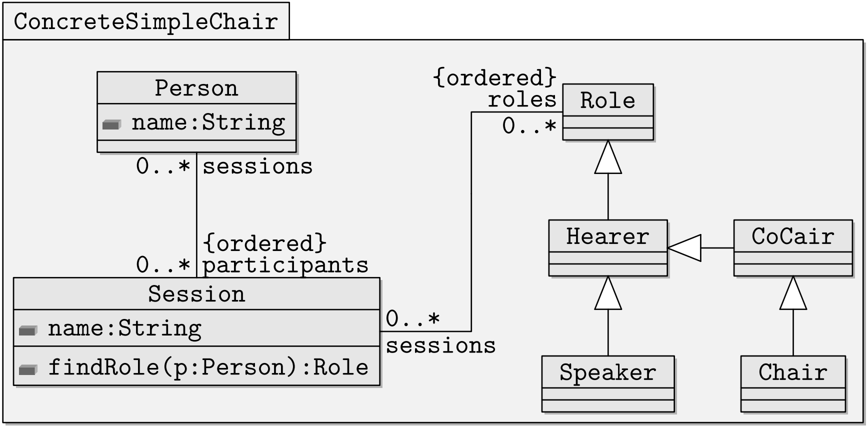


$$po_2(S, R, T) \equiv \forall \sigma_a \in \text{pre}(S), \sigma_c \in V.\ \sigma_{c'}.\ (\sigma_a, \sigma_c) \in R$$
$$\wedge\ (\sigma_c, \sigma_c') \vDash_M T \rightarrow \exists \sigma_a' \in V.\ (\sigma_a, \sigma_a') \vDash_M S \wedge (\sigma_{a'}, \sigma_{c'}) \in R$$

Refinement Example: Abstract Model



Refinement Example: Concrete Model



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Ongoing and Future Work

- Ongoing work includes improving the infrastructures for
  - well-formedness-checking,
  - proof-obligation generation (Liskov, Refinement,),
  - consistency checking,
  - Hoare-style program verification,
  - better proof automation in general.
- Future works could include the development for
  - integrating OCL validation tools, e.g., USE,
  - test-case generation (i.e., integrating HOL-TestGen),
  - supporting SecureUML.
  - ....

Thank you
for your attention!

Any questions or remarks?

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