Automated Size Analysis for OCL

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Overview

- Target: Object Constraint Language
- Idea: Size Abstraction
- Method: Infinite State Model Checking
- Experiments: Verification of Java Card API Specifications
  - Reveal specification errors in 26 out the 150 methods
  - Propose fully verified OCL specifications

OCL

What is Object Constraint Language (OCL)?

- A specification language for describing constraints on object oriented models
- Developed at IBM and now part of the UML standard
- Used to describe precise constraints that cannot be presented in UML diagrams:
  - *class invariants* on attributes and associations
  - *pre and post conditions* of class methods

OCL

Why shall we care about OCL?

- UML/OCL is a widely adopted industry standard at the design stage
  - Object Management Group (OMG) standard
- Identifying design errors before the implementation stage is cost effective

There is a lack of automatic verification tools to check the correctness of OCL specifications!

OCL Collection

OCL allows collections of arbitrary types and this makes automatic verification difficult.

There are three basic collection types in OCL:

- A Set is a collection that contains instances of a valid OCL type but does not contain duplicate elements
- A Bag is like a Set, but it can contain duplicate elements
- A $Sequence$ is like a Bag but the elements are ordered

OCL Example

From OCL Specifications of Java Card API 2.1.1

Class Invariant:

```
self.thrownExceptions->isEmpty() implies (self.theAID->size() >= 5
and self.theAID->size() <= 16)
```

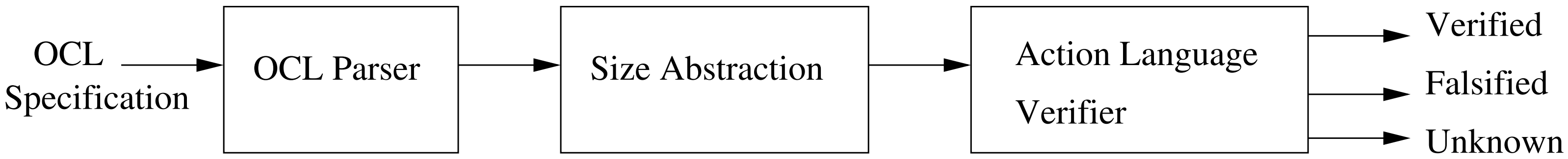
Method Specification:

```
context AID::equal(anObject: Set(Integer)): Boolean
  post: self.thrownExceptions = self.thrownExceptions@pre
       and (result = (anObject->asSequence = self.theAID))


context AID::getBytes(dest: Sequence(Integer), offset: Integer,
                       e: Integer): Integer
  post: ...
       self.theAID = dest->
       subSequence(offset, offset+self.theAID->size())
       ...
```

Size Analysis

OCL Size Analysis Framework:



Size Abstraction:

- Converts OCL expressions on collection types into arithmetic constraints on their sizes
  - Abstracts away the contents of the collections

Action Language Verifier (ALV):

- Composite model checking (BDD + Polyhedra + DFA)
- Infinite state verification using conservative approximation techniques (e.g., widening, bounded fixpoint computations)

Size Abstraction

Since we abstract away the contents, size constraints may not be precise.

For example, the size constraints generated for the expression o_1`->union(`o_2`)`:

- if o_1, o_2 are Set, then $max(o_1.v, o_2.v) \leq o.v \leq o_1.v + o_2.v$
- if o_1, o_2 are Bag or Seq, then $o.v = o_1.v + o_2.v$

where

- o denotes the collection that is the result of the expression (which is the union of o_1 and o_2)
- $o.v$, $o_1.v$, $o_2.v$ denote the sizes of the collections

Size Constraints

OCL Expression	Type o, o_1, o_2	Size Constraint
o_1->including(e)	s, s	$o_1.v \leq o.v \leq o_1.v + 1 \wedge (o_1.v = 0 \Rightarrow o.v = 1) \wedge o_1.c$
	m, m	$o.v = o_1.v + 1 \wedge o_1.c$
o_1->append(e)	m, m	$o.v = o_1.v + 1 \wedge o_1.c$
o_1->excluding(e)	s, s	$max(0, o_1.v - 1) \leq o.v \leq o_1.v \wedge o_1.c$
	m, m	$max(0, o_1.v - 1) \leq o.v \leq o_1.v \wedge o_1.c$
o_1->union(o_2)	s, s, s	$max(o_1.v, o_2.v) \leq o.v \leq o_1.v + o_2.v \wedge o_1.c \wedge o_2.c$
	$m, s/m, m/s$	$o.v = o_1.v + o_2.v \wedge o_1.c \wedge o_2.c$
o_1->intersection(o_2)	$s, s/m, m/s$	$0 \leq o.v \leq min(o_1.v, o_2.v) \wedge o_1.c \wedge o_2.c$
	m, m, m	$0 \leq o.v \leq min(o_1.v, o_2.v) \wedge o_1.c \wedge o_2.c$
o_1-o_2	s, s, s	$max(0.o_1.v - o_2.v) \leq o.v \leq o_1.v \wedge o_1.c \wedge o_2.c$
o_1->subSequence(i_1, i_2)	m, m	$(o1.v \geq i_2 \geq i_1 \wedge o.v = i_2 - i_1 + 1) \wedge o_1.c$
o_1->at(i)	m, m	$(o_1.v \geq i \geq 0 \Rightarrow o.v = 1) \wedge o_1.c$
o_1->asSet	s, s	$o.v = o_1.v \wedge o_1.c$
	s, m	$((o_1.v > 0 \wedge 1 \leq o.v \leq o_1.v) \vee (o_1.v = o.v = 0)) \wedge o_1.c$

OCL Specification

```
context OwnerPIN::update(newpin: Sequence(Integer),
offset:Integer,length: Integer, e:Integer)

pre: newpin->notEmpty()
     and offset >= 0
     and offset+length <= newpin->size()
     and length >= 0
post:(
1:     thrownExceptions=thrownExceptions@pre
2:     and self.pin->subSequence(0,length)
          =newpin->subSequence(offset, offset+length)
      )or(
3:     thrownExceptions=thrownExceptions@pre->including(e)
4:     and length > self.maxPINSize
      )or(
5:     thrownExceptions=thrownExceptions@pre->including(e)
6:     and systemInstance->notEmpty()
      )
```

Size Constraints

```
newpin->notEmpty()
```

newpin.size > 0

```
self.pin->subSequence(0,length)
```

result.size = length - 0 + 1 and pin.size >= length and length >= 0

```
thrownExceptions = thrownExceptions@pre->including(e)
```

thrownExceptions.size = result.size and result.size = thrownExceptions@pre.size + 1

Action Language Abstraction

```
module updateMod()
  updateMod:
pre: newpin > 0 and offset >= 0 and length + offset <= newpin
        and length >= 0 and
post:(
1:    (thrownExceptions' = thrownExceptions
2:    and tmp8 = tmp9
      and tmp8 = length - 0 + 1 and pin' >= length and length >= 0
      and tmp9 = length + offset - offset + 1
      and newpin' >= length + offset and length + offset >= offset
      ) or (
3:    thrownExceptions' = tmp10 and tmp10 = thrownExceptions + 1
4:    and length > maxPINSize'
      ) or (
5:    thrownExceptions' = tmp11 and tmp11 = thrownExceptions + 1
6:    and systemInstance' > 0)
      ); endmodule
```

OCL Formalization

An OCL class specification is $C = (P, A, M)$, where

- P: a set of properties representing class invariants
- A: a set of attributes (fields of the class)
- M: a set of methods. For each $m \in M$,
    - $m.pre : A$ is pre condition
    - $m.post : A \times A@pre$ is post condition

We define the formal semantics of OCL as a transition system.

Transition System

The corresponding transition system is $\|C\| = (S, I, R)$, where S is the set of states, $I \subseteq S$ is the initial states, and R is the transition relation, and

- $S = dom(A_1) \times \ldots \times dom(A_n)$
- For all $p \in P$, $I \subseteq \|p\|$
- $R_m = \{(s_1, s_2) \mid s_1 \in \|m.pre\| \wedge (s_1, s_2) \in \|m.post\|\}$
  - $R = \bigcup_{m \in M} R_m$
  - Given a set of states $Q \subseteq S$, $R(Q) = \{s_2 \mid \exists s_1 \in Q \text{ , } (s_1, s_2) \in R\}$
  - R^* denotes the reflexive transitive closure of R, and $R^*(I)$ is the set of all reachable states in the transition system

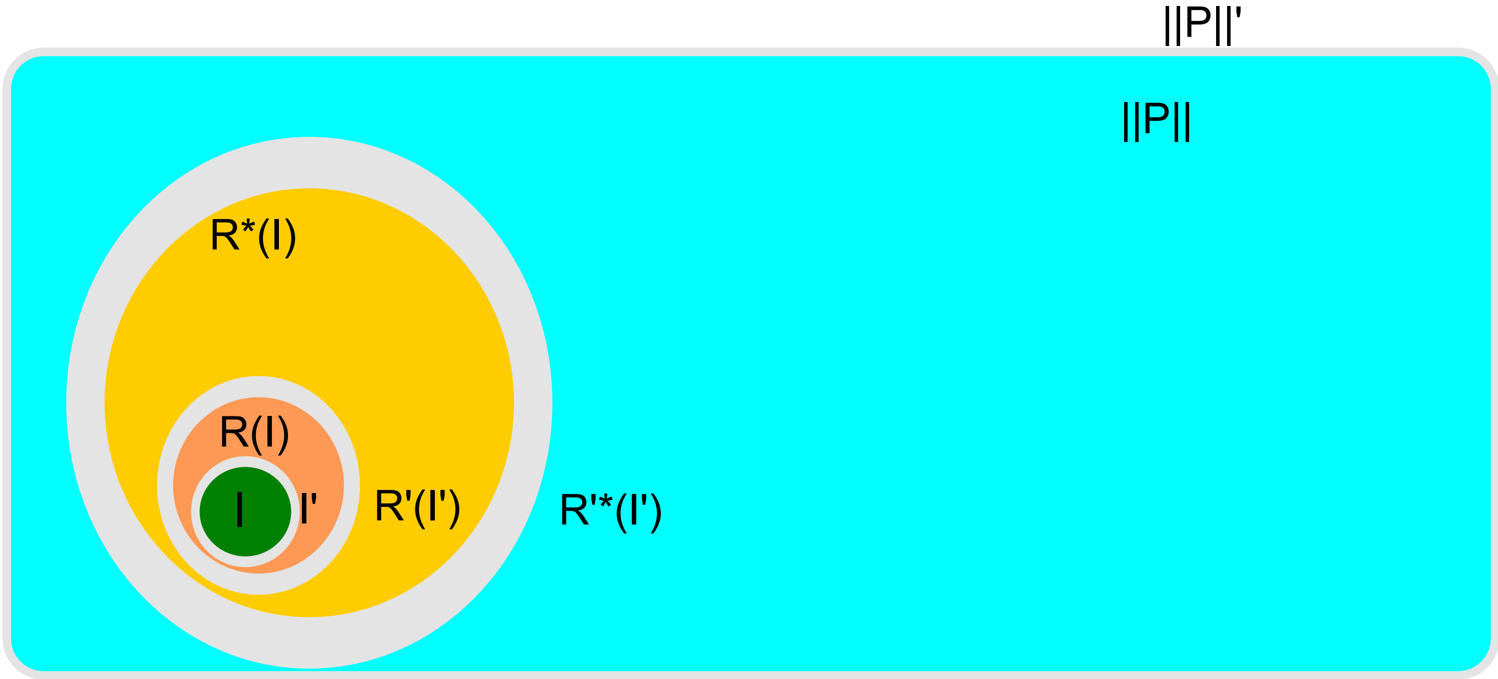
OCL Correctness

An OCL class specification is correct if and only if its class invariants are consistent with the pre and post conditions of its methods.

We formalize this as follows:

Definition:
An OCL class specification $C = (P, A, M)$ *with the corresponding transition system* $\|C\| = (S, I, R)$ *is* ***correct****, if and only if, all the reachable states of the class satisfy all the class invariants, i.e., for all* $p \in P$, $R^*(I) \subseteq \|p\|$.

Reachability Analysis



- Concrete States: $I, R(I), R^*(I), ||P||$
- Abstract States (Over Approximation): $I', R'(I'), R'^*(I'), ||P||'$
- $R^*(I) \subseteq ||P||$, correct
- $R'^*(I') \subseteq ||P||'$, correct? We do not know.
- We use $\neg(||\neg P||)'$ as an under approximation of $||P||$.

Size Abstraction

Size abstraction satisfies the following properties:

$$
\begin{array}{llll}
\forall s \in S, & s \in I & \Rightarrow & abs(s) \in abs(I) \\
\forall s_1, s_2 \in S, & (s_1, s_2) \in R & \Rightarrow & (abs(s_1), abs(s_2)) \in abs(R) \\
\forall s \in S, \forall p \in P, & abs(s) \in \|\neg abs(\neg p)\| & \Rightarrow & s \in \|p\|
\end{array}
$$

Based on these properties, we can prove the following theorem:

Theorem:
Given a class specification C, if $abs(C)$ is correct, then C is correct.

Case Study: Java Card API

We applied our technique to verification of the Java Card Application Programming Interface (API) specifications.

- Java Card is a platform for developing applications that run on smart cards
- The OCL specifications of Java Card API 2.1.1 are given by [Larsson and Mostowski, ENTCS04].
- These include 31 classes and 150 methods in javacard.framework, javacard.security, javacard.framework.service, and javacardx.crypto packages.

Case Study: Java Card API

Almost any type of smart card can benefit from Java Card technology:

- Subscriber Identity Module (SIM) cards, used in cell phones on most wireless networks
- Financial cards supporting both online and offline transactions
- Government and health-care identity cards
- Smart tickets for mass transit

However, if there are errors in the Java Card API specifications, these applications may be vulnerable!

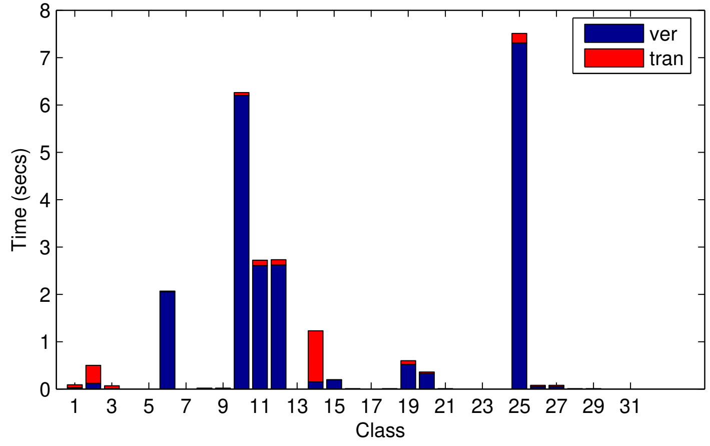
Identified Errors

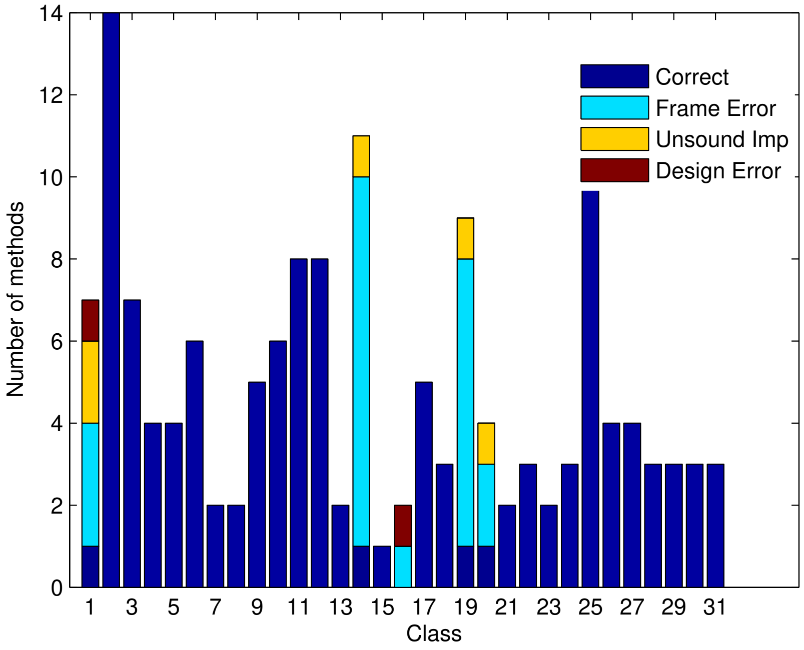
We identify the following types of errors in the OCL specifications of the Java Card API:

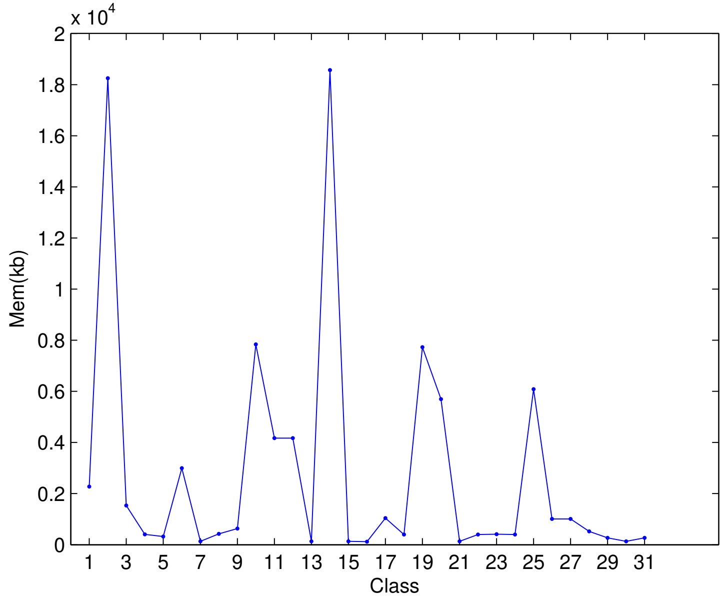
- Frame Error (FE):
  - missing frame constraints, such as a=a@pre
- Unsound Implication (UI):
  - In an implication structure, i.e., $\bigwedge_i b_i \rightarrow s_i$, if $\bigvee_i b_i$ is not universal, the undefined state ($\bigwedge_i \neg b_i$) is allowed to make unexpected transitions
- Design Error (DE):
  - missing pre
  - using an unrestricted parameter to define a restricted variable

Verification Results

All class specifications of Java Card API are either verified (26/31) or falsified (5/31) within 10 secs and 20MB.







Details for Falsified Classes

AID class:

Method	Err.	R	trans+ver.	Mem
AID	None	V	0.02+0.09s	2523k
equal	(FE)	V	0s+0s	299k
equals	UI	F	0.02s+0.02	610k
getBytes	DE	F	0.02s+0.02s	676k
getPartialBytes	(FE)	V	0.01s+0.02s	418k
partialEquals	UI	F	0.02s+0.01s	545k
RIDEquals	(FE)	V	0s+0s	324k

KeyEncryption Class:

Method	Err.	R	trans+ver.	Mem
getKeyCipherMod	(FE)	V	0s+0s	115k
setKeyCipherMod	DE	F	0s+0s	123k

JCSystem Class:

Method	Err.	R	trans+ver.	Mem
abortTransaction	None	V	0s+0.01s	266k
beginTransaction	(FE)	V	0s+0.06s	266k
commitTransaction	(FE)	V	0s+0.01s	266k
getAppletSharable-ObjectInterface	UI	F	0.06s+0.03s	815k
getTransactionDepth	(FE)	V	0s+0s	270k
isTransient	(FE)	V	0s+0.01s	270k
lookupAID	(FE)	V	0.03s+0.07s	1028k
MakeTransientBooleanArray	(FE)	V	0.09s+1.61s	1147k
MakeTransientByteArray	(FE)	V	0.06s+1.73s	1487k
MakeTransientObjectArray	(FE)	V	0.06s+1.72s	1495k
MakeTransientShortArray	(FE)	V	0.07s+1.72s	950k

OwnerPin/Pin Class:

Method	Err.	R	trans+ver.	Mem
getValidatedFlag	(FE)	V	0s+0.01s	385k
setValidatedFlag	(FE)	V	0.01s+0s	381k
OwnerPIN	(FE)	V	0.01s+0.05s	590k
update	(FE)	V	0.02s+0.7s	782k
resetAndUnblock	(FE)	V	0s+0.01s	381k
getTriesRemaining	(FE)	V	0.01s+0s	385k
isValidated	(FE)	V	0.01s+0s	381k
reset	None	V	0.01s+0s	381k
check	UI	F	0.03s+0.06s	877k

Example Errors

Class Invariant:

```
self.thrownExceptions->isEmpty() implies (self.theAID->size() >= 5
and self.theAID->size() <= 16)
```

Method Specification:

```
context AID::equal(anObject: Set(Integer)): Boolean
  post: self.thrownExceptions = self.thrownExceptions@pre
        and (result = (anObject->asSequence= self.theAID))
```

To fix: Add **self.theAID=self.theAID@pre**

```
context AID::getBytes(dest: Sequence(Integer), offset: Integer,
                         e: Integer): Integer
  post: ...
        self.theAID = dest->
        subSequence(offset, offset+self.theAID->size())
    ...
```

To fix: Change to self.theAID = dest->subSequence(offset, offset+**self.theAID@pre->size**())

Pros and Cons

Our size analysis tool

- Is more automated than tools that use theorem proving
    - KeY Tool [Ahrendt et al. SSM05]
- Provides stronger guarantees than simulation
    - USE, OCLE [Gogolla, Bohling, Richters, UML03]

  or bounded verification
    - Alloy [Jackson, ACM TOSEM02]

No free lunch!! We focus on size properties rather than providing a general verification framework.

Size Does Matter

Analyzing size properties is important and promising for several reasons:

- No extra specification effort needed from the software developers
- Violation of size properties is the cause of security vulnerabilities such as buffer overflows
- Effective automated verification can be achieved for size properties

Related Work

Size Analysis:

- Size Types [Hughes, Pareto, Sabry, POPL96], [Chin et al., ICSE05]
- C String Static Verifyer [Dor, Rodeh, Sagiv, PLDI03, SAS01]

Specification and Verification of Java Card API:

- KeY Tool [Mostowski, Verify07]
- VerifiCard [Berg, Jacobs, Poll, TACAS01]

Conclusion

- We proposed a novel size abstraction and analysis for object-oriented models
- We conducted a case study on OCL specifications of Java Card API
- The experiments indicate our abstraction is precise enough to verify/falsify target systems, while coarse enough to perform efficient infinite state model checking

Thank you for your attention

Questions?

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