Run-Time Assertion Checking and Monitoring Java Programs

Envisage Bertinoro Summer School June 2014

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Your Lecturers Today

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What This Talk Is All About

Formal Methods in Practice:

> *Theorie ist, wenn man alles weiss und nichts klappt.*
> *Praxis ist, wenn alles klappt und keiner weiss warum.*

What Fails In Practice: Run-Time Assertion Checking

Take for example JML (citing Peter Wong)

- Stability of tooling
- IDE support e.g. on-the-fly parsing and type checking, navigability between specifcations and source codes
- Maintainability of specification due to constant code change
- Error reporting and analysis

See also

Run-time checking of data- and protocol-oriented properties of Java programs: an industrial case study. *Stijn de Gouw, Frank S. de Boer, Peter Y. H. Wong and Einar Broch Johnsen. SAC 2013.*

Outline

Formal Specification: Assertions

Behavioral Abstraction

Run-time checking of data- and protocol-oriented properties

Tooling

What? Formal Specfification? Assertions?

Industrial Relevance

National Institute of Standards and Technology (NIST):

> *Software errors cost us approximately $60 billion per year in lost productivity, increased time to market costs, higher market transaction costs, etc. If allowed to continue unchecked this problem's costs may get much worse.*

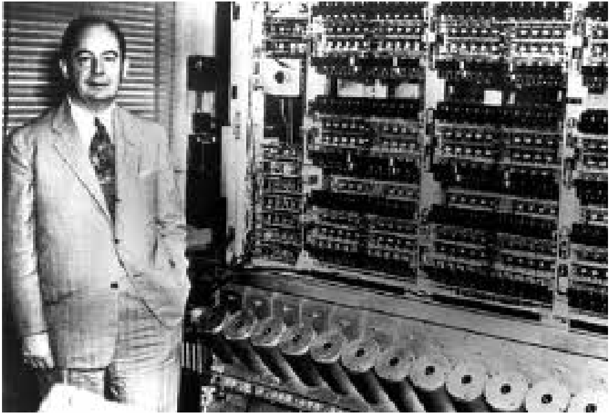
Managerial Misconceptions:

> *Software development is not an art, and programmers are not artists, despite any claims to the contrary.*
>
> *Management has come to believe the first and most important misconception: that it is impossible to ship software devoid of errors in a cost-effective way.*

What Makes Software Buggy?

An imperative program describes how a problem can be solved by a computer.

The Von Neumann Architecture of Imperative Programming



What The Hack Are You Doing?

What does the following program compute,
assuming that the initial value of x is greater than or equal to 0?

$y := 0; u := 0; v := 1;$
while $u + v \leq x$
do $y := y + 1;$
$\quad u := u + v;$
$\quad v := v + 2$
od

Debugging: Let it Flow

x	y	u	v
13	0	0	1
13	1	1	3
13	2	4	5
13	3	9	7
$\vdots$	$\vdots$	$\vdots$	$\vdots$

What's the relation between the values of x, y, u and v?

Robert Floyd Introduced Assertions For Program Specification in the Seventies

$$y^2 \leq x < (y+1)^2$$

Edsger Dijkstra Introduced Structured Programming

Debugging only shows that a program is incorrect.

Sir. Tony Hoare Developed a First Programming Logic

$$\{P\}S\{Q\}$$

Design by Contract

Caller = Client and Callee = Supplier
in
Method calls in object-oriented programs

Designer must formally specify for each method:

- What does it expect? (precondition)
- What does it guarantee?(postcondition)
- What does it maintain? (invariant)

Main idea:

Formal specification of contracts by assertions, i.e. logical formulas

Design by Contract in Practice

- Object-oriented programming language Eiffel introduced by the company Eiffel Software.
- The Java Modelling Language JML supports run-time assertion checking.
- Spec# is a formal language for API contracts developed and used by Microsoft.
- Object Constraint Language (OCL) for the specification of UML diagrams

Behavioral Abstraction (Information Hiding)

State of the Art (= state-based)

- Getters:

  Get_X

- Model variables (JML):

  public model instance JMLObjectBag elementsInQueue

Formal Semantics: Full Abstraction

Minimal information required for compositionality

That is,

smallest congruence containing operational equivalence:

$$S \equiv S' \text{if and only if } O(C[S]) = O(C[S']),$$

for every context $C[\cdot]$

Compositionality Java Programs

Two perspectives:

- Threads (stack: shared-variable concurrency)
- Classes (Objects) (monitor: message passing)

Compositionality Shared Variable Concurrency (Multi-threading)

Initial/final state semantics is not compositional:

$$O(x := x+1; x := x+1) = O(x := x+2)$$

but

$$O(x := x+1; x := x+1 \parallel x := 0) \neq O(x := x+2 \parallel x := 0)$$

We need reactive sequences:

$$R(x := x+1) = \{\langle \sigma, \sigma[x := \sigma(x)+1] \rangle \mid \sigma \in \Sigma\}$$

and

$$R(S_1 \parallel S_2) = R(S_1) \parallel R(S_2)$$

where $\parallel$ denotes interleaving.

See

Reasoning about Recursive Processes in Shared-Variable Concurrency. F.S. de Boer. LNCS 5930, 2010.

Compositional Proof Theory for Communicating Sequential Processes (CSP)

From non-compositional:

Communication Assumptions $\{p\}c?x\{q\}$ and $\{p\}c!e\{q\}$

Cooperation Test

$$\left.\begin{array}{lll} \{p\} & c!e & \{q\} \\ \{p'\} & c?x & \{q'\} \end{array}\right\} \Rightarrow \{p \wedge p'\}x := e\{q \wedge q'\}$$

to compositional by means of histories (or traces)

Communication Axioms

$$\{\forall x.p[h\cdot(c,x)/h]\}c?x\{q\} \text{ and } \{p[h\cdot(c,e)/h]\}c!e\{q\}$$

Example:

$$\frac{\{[h]_c = \epsilon\}c?x\{[h]_c = (c,x)\} \ \{[h]_c = \epsilon\}c!0\{[h]_c = (c,0)\}}{\{[h]_c = \epsilon\}c?x \parallel c!0\{[h]_c = (c,x) \wedge [h]_c = (c,0)\}}$$

See

An assertion-based proof system for multithreaded Java by Abraham, de Boer, de Roever and Steffen, in TCS, Vol. 331, 2005.

A Short History of Histories

- Proofs of networks of processes by Misra and Chandy, in IEEE Transactions on Sofware Engineering, 1981.
- Formal justification of a proof system for CSP by K.R. Apt in J.ACM, Vol 30, 1983.
- A theory of communicating sequential processes, by Brookes, Hoare and Roscoe, in J. ACM, Vol. 31, 1984.
- Compositionality and concurrent networks: soundness and completeness of a proof system by Zwiers, de Roever and van Emde Boas, in LNCS, Vol. 194, 1985.
- Fully abstract trace semantics for a core Java language by Jeffrey and Rathke, in LNCS, Vol. 344, 2005.
- Object Connectivity and Full Abstraction for a Concurrent Calculus of Classes. Erika Ábrahám, Marcello M. Bonsangue, Frank S. de Boer, Martin Steffen: ICTAC 2004: 37-51

The Very Nature of Object-Orientation

Inherently Parallel (even If Sequential)

Run-Time Assertion Checking

Requires

- Executable assertions

But what we want (need badly) is

> *combining data- and protocol-oriented properties*

Main Idea

Grammars to specify protocols (= formal languages)

Main problem/challenge:

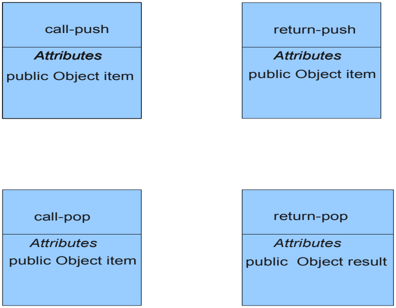
Integration grammars in assertion checking

that works in practice

Specifying Interfaces in Java: A Running Example

```
interface Stack {
  void push(Object item);
  Object pop();
}
```

The Modelling Framework: Messages



The Modelling Framework: Communication Views

Partial mappings from call and return events to tokens

Communication Views: An Example

```
view StackHistory {
  return void push(Object item) push,
  return Object pop() pop
}
```

General Properties of Communication Views

- Multiple views for interfaces
- Multiple views for classes/components (provided/required methods)
- User-defined event names
- Abstraction of irrelevant events
- Identifying different events
- Distinguishing different events using method signatures (method overloading)

The Modelling Framework: Attribute Grammars

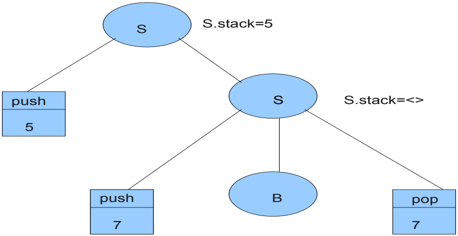
```
class EList extends List {
public EList append(Object element)
public EList append(EList list) }

Elist stack
```

$$
\begin{array}{lcll}
\mathsf{S} & ::= & \mathsf{push}\ S_1 & \mathsf{stack} = S_1\mathsf{.stack.append(push.item)} \\
 & | & S_1\ S_2 & \mathsf{stack} = S_2\mathsf{.stack.append(}S_1\mathsf{.Stack)} \\
 & | & \mathsf{B} & \mathsf{stack} = \mathsf{new\ EList()} \\
\mathsf{B} & ::= & \mathsf{push}\ \ \mathsf{B\ pop} & \\
 & | & \epsilon &
\end{array}
$$

Example

Parse tree of sequence of tokens

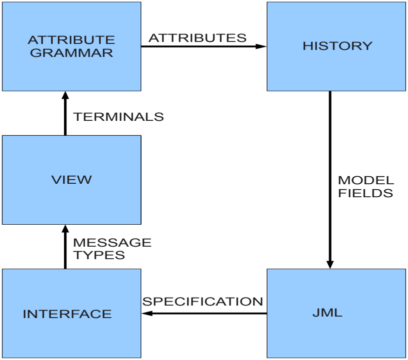
$$\text{push}(5)\ \text{push}(7)\ \text{pop}(7)$$



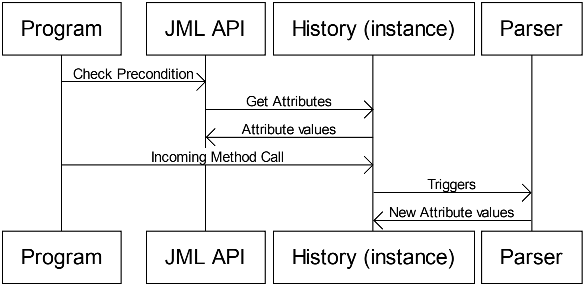
The Modelling Framework: Interface Specifications

```
interface Stack {
//@ public model instance StackHistory history;

//@ ensures history.stack() ==
        \old(history.stack()).append(item);
void push(Object item);

//@ requires history.stack().size != 0;
//@ ensures history.stack() = \old(history.stack()).tail();
//@ ensures \result == \old(history.stack()).head();
Object pop()
```

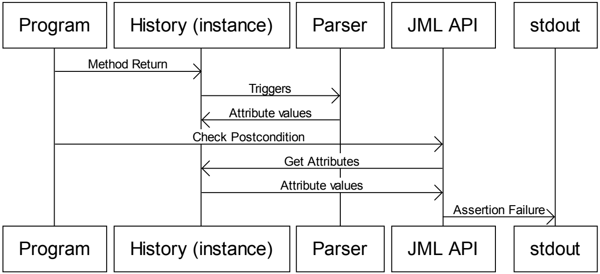
The Modelling Framework: Summary



Run-Time Assertion Checking: Method Invocation



Run-Time Assertion Checking: Method Return



Attribute Grammars as Behavioral Types

Another Example: Specifying the BufferedReader class

```
Class BufferedReader {
  BufferedReader(Reader in);
  void close();
  String readLine();
  ...
}
```

Communication View:

```
view BufferedReaderHistory {
  new(Reader in) open,
  call String readLine() read,
  call void close() close
}
```

Extended Attribute Grammar modeling the behavior of a BufferedReader

- BufferedReader can only be read when opened and before closed.
- BufferedReader can only be closed by the object that opened it:

$$
\begin{array}{llll}
\text{S} & ::= & \text{open } C & \text{assert open.caller} \mathrel{!}= \text{null} \\
 & & & ==> \text{open.caller} == C\text{.caller;} \\
 & | & \epsilon & \\
\text{C} & ::= & \text{read } C_1 & C\text{.caller} = C_1\text{.caller;} \\
 & | & \text{close } S & C\text{.caller} = \text{close.caller;} \\
 & | & \epsilon & C\text{.caller} = \text{null;}
\end{array}
$$

Summarizing

Attribute grammars provide a *systematic* approach for specifying histories which

- allows a *declarative* expression of complex properties of histories and
- seamlessly combines specification of
  - *protocol oriented properties* (grammar)
  - *data-oriented properties* (attributes)

  into a single formalism.