Lightweight Type-Like Hoare-Separation Specs for Java

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September 10, 2010

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Goals

Type systems are effective but not very precise, while program logics tend to be very precise, but undecidable.
This work goals are:

- Develop a lightweight specification language for Java, based on propositional logic;
- Extend the Java compiler, complementing type analysis with program correctness verification according to its specification.

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Outline

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Formal Specification and Verification

The process of software validation is a difficult problem, benefiting from the use of rigorous methods, preferably based on formalized mathematical techniques (e.g. logic):

- Improve specifications quality, removing ambiguities;
- Detect errors in advance;
- Correctness, equivalence, termination.

It is a research area for over 40 years and has seen a new impetus recently.

Hoare marked the 40th anniversary of his article writing a new article [Hoare 2009], which discusses the developments that have occurred since that time, and what might still happen.

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Formal Specification and Verification

The use of formal methods is not fully accepted by software developers:

- Complexity
- Cost

It is necessary to address formal methods using lightweight specifications.

Verification techniques grouped in:

- Static Verification
  - Theorem Proving
- Dynamic Verification
  - Code Coverage
  - Model Checking

This work focus is specification verification by static analysis, using theorem proving technique.

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Verification Techniques

- Hoare Logic
  - Flo67, Hoa69, Lam80
- Separation Logic
  - Rey02, OHRY01, PB05
- Weakest Precondition Calculus
  - Dij75, Rey02
- Dynamic Logic
  - Bec01, BK07
- Higher-order Logic
  - HJ00, JP01

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Our approach focus on Weakest Precondition Calculus and is inspired by Dual Intuitionistic Linear Logic and Separation Logic

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Dual Hoare-Separation Logic

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Languages with verification support

There are lots of tools that provide support for program verification:

- ESC/Java2
- JACK
- KRAKATOA
- LOOP
- jStar
- KeY
- Forge

Languages have also been designed with support for program verification:

- Gypsy
- Euclid
- Eiffel
- Spec#
- SPARK
- D

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Languages with verification support

- Require user intervention (e.g KRAKATOA);
- Don't satisfy correctness and/or completeness (e.g ESC/Java2, Forge);
- Coverage language limitations;
- Higher specification language expressiveness, but too complex.

Programmers:

- Have little knowledge in logic areas;
- Intend automatic processes, less complex and integrated into program development.

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Lightweight Type-Like Hoare-Separation Specs for Java

In our approach:

- Specification language similar to JML and Spec#'s but lightweight, based on monadic propositional logic and handles aliasing by separating pure from linear properties
  - No quantifiers
  - No reference to the value of an expression at its precondition (*old*)
- Verification based on weakest precondition calculus, executed directly from Java syntactic constructs
  - Verification Conditions proved using a SMT-Solver

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Expected Results

- Cover as much as possible the features of Java
- Integrate verification in the compile process
  - Approach the checks carried out by type systems to the fully formal logical checks.
- Perform verification automatically without user interaction

Dual Hoare-Separation Logic

$$
\begin{array}{lcll}
\psi & ::= & \phi + \varphi & \text{(Dual Formula)} \\
\varphi & ::= & \emptyset \mid \phi \mid \phi * \varphi & \text{(Linear Formula)} \\
\phi & ::= & & \text{(Classic Formula)} \\
 & & \bot & \text{(Bottom)} \\
 & \mid & \phi \; lc \; \phi & \text{(Binary Formula)} \\
 & \mid & \neg\phi & \text{(Negation)} \\
 & \mid & (\phi) & \text{(Parenthesized Formula)} \\
 & \mid & P(t_1, t_2, \cdots, t_n) & \text{(Predicate Symbols)} \\
lc & ::= & \vee \mid \wedge \mid \Rightarrow \mid \Leftrightarrow & \text{(Logical Connectives)} \\
t & ::= & & \text{(Terms)} \\
 & & c & \text{(Constants)} \\
 & \mid & x & \text{(Variables)} \\
 & \mid & f(t_1, t_2, \cdots, t_n) & \text{(Function Symbols)}
\end{array}
$$

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Dual Hoare-Separation Logic

ψ	$::=$	$\phi + \varphi$	(Dual Formula)
φ	$::=$	$\emptyset \mid \phi \mid \phi * \varphi$	(Linear Formula)
ϕ	$::=$		(Classic Formula)
		$\bot$	(Bottom)
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	$\mid$	$f(t_1, t_2, \cdots, t_n)$	(Function Symbols)

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Assertions

D, I	::=	$CF + SLF$	(Dual Formula)
SLF	::=	$CF \mid CF * SLF$	(Sep. Formula)
CF	::=	**true** | **false** | $CF\ bop\ CF$ | **!** CF | $b : S$	(Classic Formula)
bop	::=	&& | || | => | <=>	(Logical Connectives)
b	::=	fn | **this** | **return** | pn	(Properties/States – Target)
S	::=	**true** | **false** | **pos** | **neg** | **zero** | **null** | sn	(Properties/States)

$pn \in$ parameter names
$fn \in$ field names
$sn \in$ state names

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Programs

program	::=	*classDecl**	(Program)
classDecl	::=	**class** *cn* { *classMember** }	(Class Declaration)
classMember	::=	...	(Class Member)
	|	*field*	(Instance Variable Declaration)
	|	*method*	(Method Declaration)
	|	*constructor*	(Constructor Declaration)
	|	*classSpec*	(Class Specification)
classSpec	::=		(Class Specification)
		define *sn*;	(Abstract Definition)
	|	**define** *sn* = *D*;	(Concrete Definition)
	|	**invariant** *D*;	(Class Invariant)
field	::=	*T fn* [= *E*]? ;	(Instance Variable Declaration)
method	::=	*modifier T mn*($\overline{arg}$) $\overline{spec}$ { *ST* }	(Method Declaration)
constructor	::=	*modifier cn*($\overline{arg}$) $\overline{spec}$ { *ST* }	(Constructor Declaration)
modifier	::=	**public** | **static** | ... | **pure**	(Modifiers)
spec	::=		(Procedure Specification)
		requires *D*	(Precondition)
	|	**ensures** *D*	(Postcondition)
ST	::=	...	(Statement)
	|	**assume** *D*	(Assume)
	|	**sassert** *D*	(Static Assert)

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Example (1)

```
1   public class File {
2       define open;
3
4       public File()
5           ensures + !open
6       {
7           assume + !open;
8       }
9
10      public void open()
11          requires + !open
12          ensures + open
13      {
14          assume + open;
15      }
16
17      public void write(int b)
18          requires + open
19          ensures + open
20      { }
21
22      public int read()
23          requires + open
24          ensures + open
25      { return 0; }
```

```
25      ...
26
27      public void close()
28          requires + open
29          ensures + !open
30      {
31          assume + !open;
32      }
33
34      public pure void nothing() {}
35
36      public static void main(
37              String[] args) {
38          File f = new File();
39          f.nothing();
40          f.open();
41          f.nothing();
42          f.nothing();
43          f.close();
44          f.nothing();
45          f.open();
46          //f.open(); // Wrong
47          f.close();
48          //f.close(); // Wrong
49      }
50  }
```

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Example (2)

```
1   public class Stack {
2
3       private Entry head;
4
5       class Entry {
6           public Entry(int x)
7               requires x:pos
8           { this(x, null); }
9
10          public Entry(int x, Entry n)
11              requires x:pos
12          {
13              this.x = x;
14              this.next = n;
15          }
16
17          private int x;
18          invariant x:pos;
19          private Entry next;
20
21          public Entry getNext()
22          { return next; }
23
24          public int getElement()
25              ensures return:pos
26          { return x; }
27      }
```

```
27      ...
28
29      public Stack()
30      { head = null; }
31
32      public void push(int i)
33          requires i:pos
34          ensures +!head:null
35      { head = new Entry(i, head); }
36
37      public int pop()
38          requires +!head:null
39          ensures return:pos
40      {
41          int res = head.getElement();
42          head = head.getNext();
43          return res;
44      }
45  }
```

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Verification Approach

Approach to program verification:

- Apply weakest precondition calculus to every method and constructor body;
- Rewrite properties and Java conditions in propositional logic predicates;
- Submit formulas to a SMT-Solver for validity proof.

WP Calculus

Weakest Precondition

Being P a program with postcondition R, then the weakest precondition is represented as:

$$wp(P, R)$$

$$[\texttt{while loop}]$$

$$\frac{(I \wedge \neg\varepsilon) \Rightarrow R \quad (I \wedge \varepsilon) \Rightarrow wp\,(ST, I)}{wp\left(\begin{array}{l}\textbf{while } (\varepsilon) \\ \quad \textbf{invariant } I \\ ST\end{array}, R\right) = I}$$

WP Calculus

$$wp\,(x = k.mn(\overline{y}, \overline{z}), C + S) = I_c[this/k] \quad \Rightarrow \quad [\texttt{pure call - pm/pr/po}]$$

$$\left(\begin{array}{c} k \neq \texttt{null} \wedge Q_{mn_A}[this/k, \overline{p_1}/\overline{y}] \\ \wedge \\ \left(\left(\begin{array}{c} k \neq \texttt{null} \\ \wedge \\ R_{mn_A}[this/k, \overline{p_1}/\overline{y}, return/f] \end{array} \right) \Rightarrow C[x/f] \right) \end{array} \right)$$

$$+$$

$$\left(\left(\begin{array}{c} Q_{mn_B}[this/k, \overline{p_1}/\overline{y}, \overline{p_2}/\overline{z}] \\ \wedge \\ \left(R_{mn_B}[this/k, \overline{p_1}/\overline{y}, \overline{p_2}/\overline{z}, return/f] \Rightarrow S \downarrow \{k, x, \overline{z}\}[x/f] \right) \end{array} \right) \right)$$

$$*$$

$$S - \{k, x, \overline{z}\}$$

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WP Calculus

$$[\texttt{method call - lr/lo}]$$

$$\frac{S \downarrow \{\overline{z} \backslash x\} = \emptyset \qquad \texttt{true} + (k \neq \texttt{null} \wedge R_{mn_B}[this/k, \overline{p_1}/\overline{y}, return/f]) \Rightarrow S \downarrow \{k, x, \overline{z}\}[x/f]}{wp\,(x = k.mn(\overline{y}, \overline{z}), C + S) = I_c[this/k] \Rightarrow \left(\begin{array}{c} \left(\begin{array}{c} Q_{mn_A}[this/k, \overline{p_1}/\overline{y}] \\ \wedge \\ (R_{mn_A}[this/k, \overline{p_1}/\overline{y}] \Rightarrow C[x/f]) \end{array} \right) \\ + \\ \left(\begin{array}{c} k \neq \texttt{null} \\ \wedge \\ Q_{mn_B}[this/k, \overline{p_1}/\overline{y}, \overline{p_2}/\overline{z}] \\ * \\ S - \{k, x, \overline{z}\} \end{array} \right) \end{array} \right)}$$

Example

```
1  class Math {
2      public static pure int abs(int x)
3          ensures !return:neg
4      {
5          if (x > 0) return x;
6          else return -x;
7      }
8  }
```

Example

$$wp\left(\begin{array}{l}\textbf{if } (x > 0) \textbf{ return } x;\\ \textbf{else return } -x\end{array}, !\textbf{return} : \textbf{neg}\right) =$$

Example

$$wp\left(\begin{array}{l}\textbf{if } (x > 0) \textbf{ return } x;\\ \textbf{else return } -x\end{array}, !\textbf{return} : \textbf{neg}\right) =$$

[conditional]

$$wp\left(\begin{array}{l}\textbf{if } (\varepsilon)\ ST_1\\ \textbf{else } ST_2\end{array}, C + S\right) = \varepsilon \Rightarrow wp\,(ST_1, C + S) \wedge \neg\varepsilon \Rightarrow wp\,(ST_2, C + S)$$

Example

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$$= \begin{array}{c} >(x,0) \Rightarrow wp\Big(\textbf{return } x, \neg <(\textbf{return}, 0) + \emptyset\Big)\\ \wedge \\ \neg >(x,0) \Rightarrow wp\Big(\textbf{return } -x, \neg <(\textbf{return}, 0) + \emptyset\Big)\end{array} =$$

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Example

$$
\begin{array}{c}
> (x, 0) \Rightarrow wp\Big(\textbf{return } x, \neg < (\textbf{return}, 0) + \emptyset\Big) \\
= \qquad\qquad \wedge \qquad\qquad = \\
\neg > (x, 0) \Rightarrow wp\Big(\textbf{return } -x, \neg < (\textbf{return}, 0) + \emptyset\Big)
\end{array}
$$

Example

$$
\begin{array}{ccc}
 & > (x, 0) \Rightarrow wp\Big(\textbf{return } x, \neg < (\textbf{return}, 0) + \emptyset\Big) & \\
= & \wedge & = \\
 & \neg > (x, 0) \Rightarrow wp\Big(\textbf{return } -x, \neg < (\textbf{return}, 0) + \emptyset\Big) &
\end{array}
$$

[pure return]

$$wp\,(\textbf{return}\ \varepsilon, C + S) = R_{mn_{\boldsymbol{A}}}[\textbf{return}/\varepsilon] + R_{mn_{\boldsymbol{B}}}[\textbf{return}/\varepsilon]$$

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Example

$$
\begin{array}{c}
> (x, 0) \Rightarrow wp\Big(\textbf{return } x, \neg < (\textbf{return}, 0) + \emptyset\Big) \\
= \qquad\qquad \wedge \qquad\qquad = \\
\neg > (x, 0) \Rightarrow wp\Big(\textbf{return } -x, \neg < (\textbf{return}, 0) + \emptyset\Big)
\end{array}
$$

[pure return]

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$$
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> (x, 0) \Rightarrow \Big(\neg < (x, 0) + \emptyset\Big) \\
= \qquad\qquad \wedge \\
\neg > (x, 0) \Rightarrow \Big(\neg < (-x, 0) + \emptyset\Big)
\end{array}
\qquad \equiv \qquad
\begin{array}{c}
> (x, 0) \Rightarrow \neg < (x, 0) \\
\wedge \qquad\qquad + \emptyset \\
\neg > (x, 0) \Rightarrow \neg < (-x, 0)
\end{array}
$$

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Example

Recall that the absolute value of a number is well specified iff:

$$\{\ \}\ \textbf{int}\ \text{abs}(\textbf{int}\ x)\ \{\ !\textbf{return}{:}\text{neg}\ \}$$

Verification Condition Submitted to the SMT-Solver:

$$(\top + \emptyset) \Rightarrow \begin{pmatrix} > (x,0) \Rightarrow \neg < (x,0) \\ \wedge \\ \neg > (x,0) \Rightarrow \neg < (-x,0) \end{pmatrix} + \emptyset \equiv$$

$$\equiv (\top + \emptyset) \Rightarrow (\top + \emptyset) =$$

$$(\top \Rightarrow \top) + \emptyset = \top + \emptyset$$

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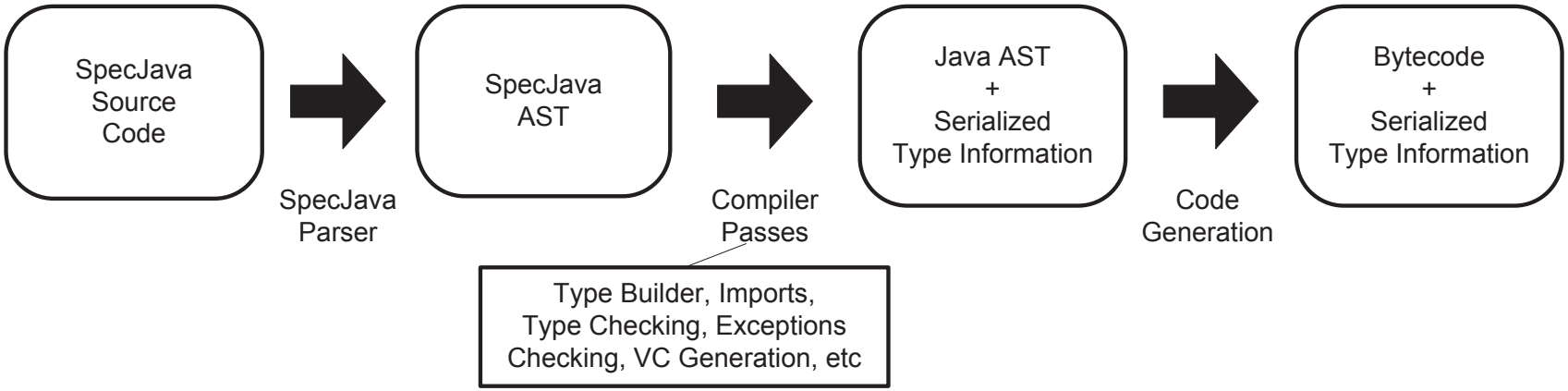
Implementation

The extension of the Java language is implemented using the Polyglot framework, which implements an extensible compiler for Java. [Nathaniel Nystrom, Michael Clarkson, and Andrew Myers]



`http://www.cs.cornell.edu/Projects/polyglot/`

`http://pessoa.fct.unl.pt/tiago.santos/tools/specjava.zip`

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Challenges

Some challenges of this work:

- Extend WP calculus for the Java language
- Solve aliasing problem
- Completely define the specification language and its integration in Polyglot
- Integrate SMT-Solver in Polyglot

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Future Work

- Dual Logic is new
  - Requires a theoretical study
- Extend WP Calculus
  - **break** statement
  - **continue** statement
  - Inheritance
- Extend Specification Support
  - Interface Specification
  - Core Java Specification
- Concurrency