Advances in Programming Languages

APL8: ESC/Java2

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(including slides by Ian Stark and material adapted from ESC/Java2 tutorial by David Cok, Joe Kiniry and Erik Poll)

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Topic: Some Formal Verification

This is the last of three lectures about some techniques and tools for formal verification, specifically:

- Hoare logic
- JML: The Java Modeling Language
- ESC/Java2: The Extended Static Checker for Java

JML review

The *Java Modeling Language*, JML, combines model-based and contract approaches to specification.

Some design features:

The specification lives close to the code

Within the Java source, in *annotation comments* `/*@...@*/`

Uses Java syntax and expressions

Rather than a separate specification language.

Common language for many tools and analysis

Tools add their own extensions, and ignore those of others.

Web site: jmlspecs.org

ESC/Java2

> "The Extended Static Checker for Java version 2 (ESC/Java2) is a programming tool that attempts to find common run-time errors in JML-annotated Java programs by static analysis of the program code and its formal annotations."

http://kind.ucd.ie/products/opensource/ESCJava2

It is available both as a command-line tool and a plugin for the *Eclipse* development environment.

ESC/Java performs different kinds of check:

- checks based on types, flow of data, existing Java declarations;
- JML annotation checking that can be carried out directly;
- logical assertions that need an external proof tool.

These last ones are passed to the *Simplify* automated theorem prover.

Many different checks

ESC/Java2 checks for very many things. These include:

- Null pointer dereference
- Negative array index
- Array index too large
- Invalid type casts
- Array storage type mismatch
- Divide by zero
- Negative array size
- Unreachable code
- Deadlock in concurrent code
- Race condition
- Unchecked exception
- Object invariant broken
- Loop invariant broken
- Precondition not satisfied
- Postcondition not satisfied
- Assertion not satisfied

JML annotations and assertions can help with all of these.

Soundness and Completeness

As a practical tool ESC/Java makes some compromises: it is not perfect.

- Not complete: it may complain about a correct program.
- Not sound: it may approve an incorrect program.

However, it reliably checks straightforward specifications, and automatically points out many potential bugs.

In particular:

- Distinguishes between *errors* (definitely bad), *warnings* (could be bad) and *cautions* (can't be sure it's good).
- Sources of unsoundness and incompleteness are documented.

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. . . as we know, there are "known knowns"; there are things we know we know. We also know there are "known unknowns"; that is to say we know there are some things we do not know. But there are also "unknown unknowns" — the ones we don't know we don't know.

(Donald Rumsfeld, 2002)

History

ESC/Modula-3 DEC Systems Research Center (SRC) 1991–1996

ESC/Java Compaq SRC, then Hewlett-Packard 1997–2002

ESC/Java2 University of Nijmegen, University College Dublin 2004–

K. Rustan M. Leino. Extended Static Checking: A Ten-Year Perspective in *Informatics: 10 Years Back, 10 Years Ahead*. Lecture Notes in Computer Science 2000, Springer.

Demo

ESC/Java2 in Eclipse

Common specification idioms: non null

JML and ESC/Java2 introduce keywords for common specifications.

One of the most common specification requirements in Java is that objects be non-null. That's because one of the most common Java programming errors is NullPointerException.

```
//@ non_null
Object o;
```

Now every method invocation on o is known to not cause an exception, *but* every assignment to s must be checked to be non-null.

This is so important that it is about to enter the Java language as an official annotation @NonNull, to be exploited by ordinary compilers.

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> I call it my billion-dollar mistake. It was the invention of the null reference in 1965. [...] My goal was to ensure that all use of references should be absolutely safe, with checking performed automatically by the compiler. But I couldn't resist the temptation to put in a null reference
>
> (Tony Hoare, 2009)

Behavioural subtyping

Part of the object-oriented paradigm: an object in a subclass can **behave like** an object in a superclass.

Sometimes known as Liskov's *principle of substitutivity*:

> *properties that can be proved using the specification of an object's presumed type should hold even though the object is actually a subtype of that type* [Liskov and Wing, 1994]

This is captured by requiring, when A **extends** B

- each invariant in subclass A $\Longrightarrow$ an invariant in B.
- precondition for A.m $\Longleftarrow$ precondition for B.m
- postcondition for A.m $\Longrightarrow$ postcondition for B.m

Inherited specifications

Behavioural subtyping is ensured by *inherited specifications*. A child class automatically inherits the specification of its parent.

```
class Parent {
    //@ requires i >= 0;
    //@ ensures \result >= i;
    int m(int i){ ... }
}
class Child extends Parent {
    //@ also
    //@  requires i <= 0
    //@  ensures \result <= i;
    int m(int i){ ... }
}
```

Inherited specifications: a puzzle

The specification for Child is short for:

```
class Child extends Parent {
  /*@   requires i >= 0;
    @   ensures \result >= i;
    @ also
    @   requires i <= 0
    @   ensures \result <= i;
    @*/
  int m(int i){ ... }
}
```

What can the result of m(0) be?

Inherited specifications: the answer

This specification is equivalent to:

```
class Child extends Parent {
  /*@ requires i <= 0 || i >= 0;
    @ ensures i >= 0 ==> \result >= i;
    @ ensures i <= 0 ==> \result <= i;
    @*/
  int m(int i){ ... }
}
```

Inherited specifications: the answer

This specification is equivalent to:

```
class Child extends Parent {
  /*@ requires i <= 0 || i >= 0;
    @ ensures i >= 0 ==> \result >= i;
    @ ensures i <= 0 ==> \result <= i;
    @*/
  int m(int i){ ... }
}
```

- moral: take care specifying methods that may be overridden
- complex specifications may use a test

  `typeof(this)==\type(Parent)`

  to guard properties that are likely to change in child classes.

Methods leading to madness

Imperative programs can be very difficult to verify because of *reference escape* and *aliasing*.

```
class MyClass {
  int i;

  //@ modifies i;
  void m(MyClass o) {
    i = 3;
    o.i = 2; // ESC/Java2 gives a warning
}
```

Frame conditions

When verifying, we want to use *frame conditions* that say what stays the same when a method is executed.

Usually we want to assume that as much as possible is unchanged, but the conservative default in ESC/Java2 is:

```
//@ modifies \everything
```

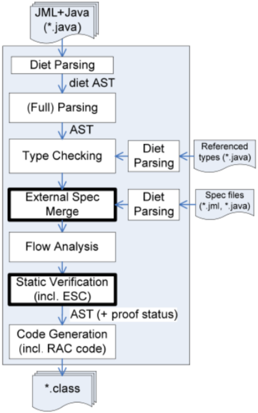
Another example where the functional paradigm is very useful:

```
//@ pure
public int getX() { return x; }
```

The **pure** annotation implies **modifies \nothing**.

JML4 and ESC4

- ESC/Java2 and other JML tools have an old-fashioned *batch mode* architecture
- **JML4** proposes an *Integrated Verification Environment*
- . . . integrated with Eclipse JDT
- . . . allowing multi-threaded verification, with per-method and per-class parallelism



JML4 compiler phases

from James et al, *Distributed, Multi-threaded Verification of Java Programs*, SAVCBS 2008.

Summary

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