A Tutorial on OpenJML

Leonidas Tsiopoulos

ITI8610 Software Assurance Course, Module III, Lecture 5 - 20/12/2017

Precursors to OpenJML

- JML was first used in an early *extended static checker* (ESC/Java) and was implemented in a set of tools called JML2.
- The second generation of ESC/Java, ESC/Java2, was made current with Java 1.4 and with the definition of JML.
- JML2 tools were based on hand-crafted compilers and the maintenance and update effort was overwhelming as Java evolved.
- A new approach was needed, one that built on an existing compiler to leverage further developments in that compiler but *allowed easy integration* with a Java IDE environment, and was *readily maintainable and extensible*.

OpenJML - Introduction

- OpenJML is an implementation of JML tools built by extending the OpenJDK Java tool set.

- OpenJDK has a readily extensible architecture, although it is quite amenable to extension since it has a complex compilation process with many components.

- The result is a suite of JML tools for **Java 8** that provides *static analysis*, *specification documentation*, and *runtime checking*, an API that is used for other tools, uses Eclipse as an IDE, and can be extended for further research.

- The main drawback is that in an Eclipse-integrated system, the Eclipse compiler is used (as is) for Java compilation and the OpenJML/OpenJDK compiler is used as a back-end tool for handling JML and verification tasks.

OpenJML command-line tool

- Ability to parse and type-check current JML
- Ability to perform static verification checks using back-end SMT solvers
- Ability to explore counterexamples (models) provided by the solver
- Partial implementation of JML-aware documentation generation
- Proof of concept implementation of runtime assertion checking
- JMLUnitNG has used OpenJML to create a test generation tool, using OpenJML's API to access the parsed specifications

Eclipse Java development environment OpenJML plug-in

- Ability to parse and type-check JML showing any errors or warnings as Eclipse problems, but with a custom icon and problem type
- Ability to check JML specifications against the Java code
  - Verification conditions are produced from the internal **ASTs** (Abstract Syntax Trees) and submitted to a back-end **Satisfiability Modulo Theories (SMT)** solver, and any proof failures are shown as Eclipse problems.
- Ability to use files with runtime checks along with Eclipse-compiled files
- Ability to explore specifications and counterexamples *within* the GUI
- Functionality integrated as Eclipse menus, commands, and editor windows

Exploring Counterexamples from Static Checking

- The Eclipse GUI enables exploring counterexamples produced by failed static checking much more effectively than previous JML tools.

- The Eclipse GUI for OpenJML interprets the counterexample information and relates it directly to the program as seen in the Eclipse editor windows.

- Previously, other tools created verification conditions, shipped them to a back-end solver, which produced counterexample information that was essentially a dump of the prover state and was notoriously difficult to debug.

OpenJML back-end SMT solvers – What is SMT?

- SMT solvers are useful for verification, proving the correctness of programs, software testing based on symbolic execution, and for program synthesis.

- Computer-aided verification of computer programs often uses SMT solvers.

- In computer science and mathematical logic, the **satisfiability modulo theories** (**SMT**) problem is a decision problem for logical formulas with respect to combinations of background theories expressed in classical *first-order logic with equality.*
  - Examples of theories: Real numbers, integers, theories of data structures like lists, arrays, bit-vectors, ...

SMT Instances

- An SMT instance is a *formula in first-order logic*, where some function and predicate symbols have additional interpretations, and SMT is the problem of determining whether such a formula is satisfiable.
- An SMT instance is a *generalization* of a *Boolean SAT instance* in which various sets of variables are replaced by predicates from corresponding underlying theories.
  - **Boolean SAT problem** is the problem of determining if there exists an interpretation that satisfies a given Boolean formula, i.e., it asks whether the variables of a given Boolean formula can be consistently replaced by the values TRUE or FALSE in such a way that the formula evaluates to TRUE.
    - E.g., "*a* AND NOT *b*" is satisfiable and "*a* AND NOT *a*" is unsatisfiable.
- SMT formulas provide a much richer modeling language than is possible with Boolean SAT formulas.

Verification and Testing with SMT Solvers

- For verification of programs a common technique is to translate *preconditions*, *postconditions*, *loop conditions*, and *assertions* into SMT formulas in order to determine if all properties can hold.

- Another important application of SMT solvers is *symbolic execution* for *analysis* and *testing* of programs.

OpenJML back-end SMT solvers

- OpenJML translates JML specifications into SMT-LIB format and passes the proof problems implied by the Java+JML program to back-end SMT solvers.

- OpenJML can use any SMT-LIBv2-compliant solver.
  - Z3, CVC4, Yices, ...
  - Simplify was the theorem prover of the *Extended Static Checkers* ESC/Java and still supported by OpenJML.

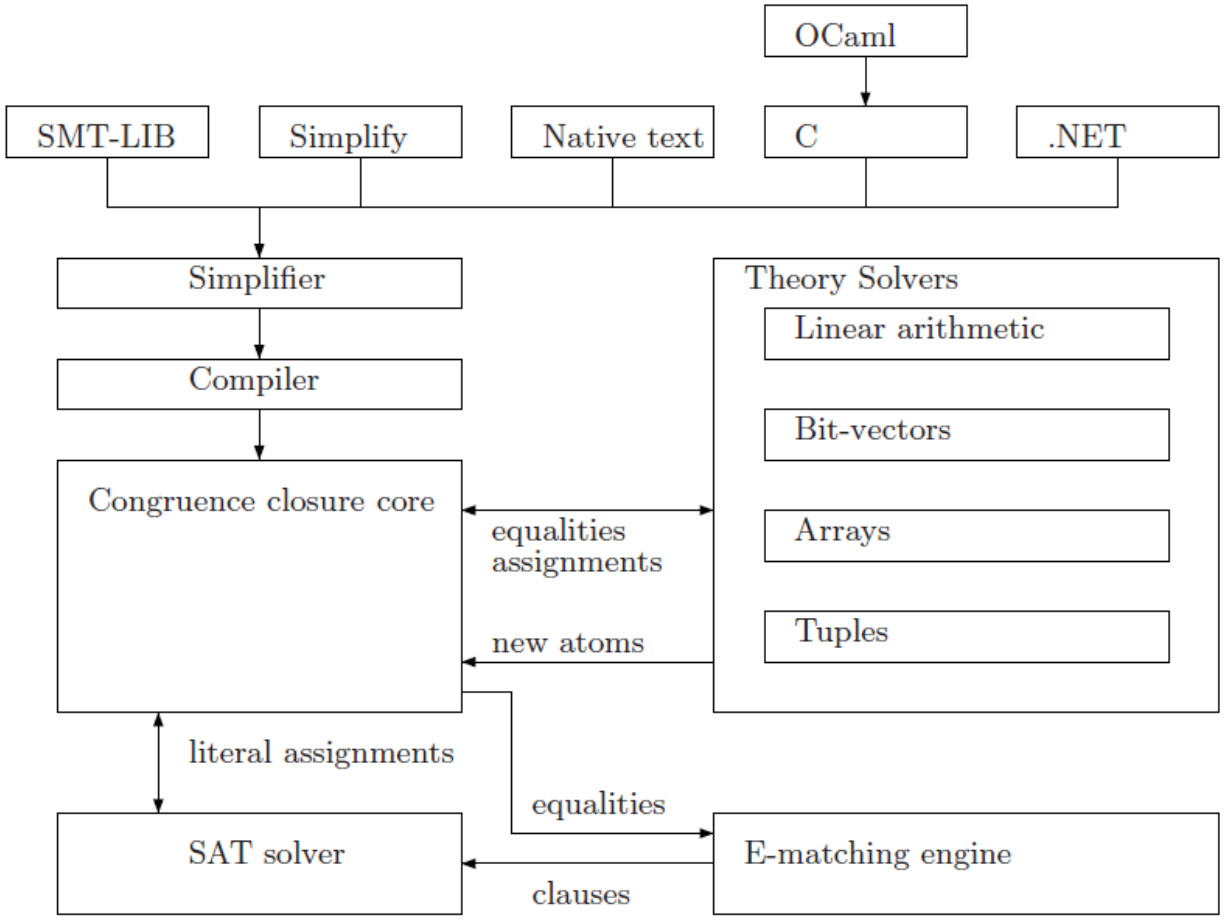
- Success in checking the consistency of the specifications and the code will depend on:
  - (a) the capability of the back-end SMT solver,
  - (b) the particular encoding of code + specifications into SMT by OpenJML, and
  - (c) the complexity and style in which the code and specifications are written.

OpenJML Z3 back-end SMT solver

- Supported theories: empty theory, linear arithmetic, nonlinear arithmetic, bit-vectors, arrays, datatypes, quantifiers, strings
- Advanced algorithms for quantifier instantiation and theory combination.
- Z3 integrates a DPLL-based SAT solver, a core theory solver for equalities and uninterpreted functions, *satellite solvers* and an engine for quantifiers.

To get started:

https://rise4fun.com/z3/tutorial/guide



OpenJML CVC4 back-end SMT solver

- CVC4 works with a version of first-order logic with ***polymorphic*** types.
  - http://cvc4.cs.stanford.edu/web/

- Several built-in base theories: rational and integer linear arithmetic, arrays, tuples, records, inductive data types, bit-vectors, strings, and equality over uninterpreted function symbols (“empty theory”).

- Support for quantifiers through heuristic instantiation.

- CVC4 is fundamentally similar to other modern SMT solvers like Z3: it is a DPLL solver, with a SAT solver at its core and a delegation path to different decision procedure implementations, each in charge of solving formulas in some background theory.

OpenJML and Simplify theorem prover

- Simplify is a theorem prover for program checking developed at HP Labs.
- Simplify is the proof engine of the *Extended Static Checkers* ESC/Java.
- The goal of ESC is to prove, at compile-time, the absence of certain run-time errors, such as out-of-bounds array accesses and unhandled exceptions.
- The ESC approach first processes source code with a verification condition generator, which produces first-order formulas asserting the *absence* of the targeted errors, and then submits those verification conditions to the theorem prover.

OpenJML and Simplify theorem prover (cont.)

- Simplify's input is an arbitrary first-order formula, including quantifiers.
- Simplify handles propositional connectives by *backtracking search* and includes complete decision procedures for the supported theories (untyped first-order logic with function symbols and equality, arithmetic, maps, partial orders, ...).

- To test whether a formula is satisfiable, Simplify performs a backtracking search, guided by the propositional structure of the formula, attempting to find a satisfying assignment of truth values to atomic formulas that makes the formula *true*.

OpenJML Yices 2 back-end SMT solver

- Yices 2[1] is an SMT solver that decides the satisfiability of formulas containing uninterpreted function symbols with equality, real and integer arithmetic, bit-vectors, scalar types, and tuples.

- Both linear and nonlinear arithmetic is supported.

- Yices 2 includes a congruence-closure algorithm inspired by Simplify's E-graph and used an approach for theory combination based on the Nelson-Oppen method (also used in Simplify and other SMT solvers) complemented with lazy generation of interface equalities.

[1] http://yices.csl.sri.com/

OpenJML and Testing

- **JMLUnitNG**[1] is an automated unit test generation tool for JML-annotated Java code, including code using Java 1.5+ features such as generics, enumerated types, and enhanced for loops.
- JML assertions are used as *test oracles*.
- Tests can be generated for OpenJML RAC.
- Testing a class (or set of classes) with JMLUnitNG involves:
  1. Generating the test classes
  2. Compile the classes under test with OpenJML
  3. Compile the generated (test) classes with a regular Java compiler
  4. Run the tests.

[1] http://insttech.secretninjaformalmethods.org/software/jmlunitng/