Distributed, Multi-threaded Verification of Java Programs

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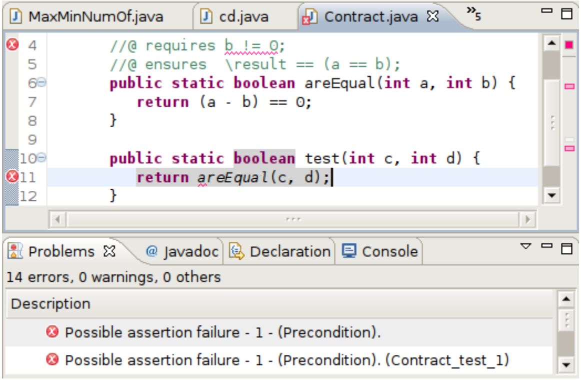
Extended Static Checking

- More than type checking
- Neither sound nor complete
- Able to detect many errors
  - contract violations
  - uncaught runtime exception
- fully automatic
- compiler-like interface

Example: A violated contract



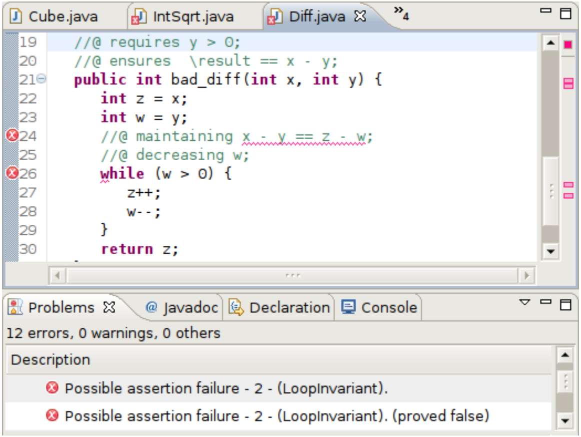
```
    //@ requires b != 0;
    //@ ensures  \result == (a == b);
    public static boolean areEqual(int a, int b) {
       return (a - b) == 0;
    }

    public static boolean test(int c, int d) {
       return areEqual(c, d);
    }
```

14 errors, 0 warnings, 0 others

Description
Possible assertion failure - 1 - (Precondition).
Possible assertion failure - 1 - (Precondition). (Contract_test_1)

Example: An invalid loop invariant



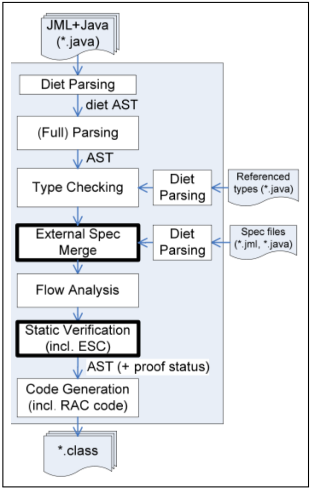
```
//@ requires y > 0;
//@ ensures  \result == x - y;
public int bad_diff(int x, int y) {
   int z = x;
   int w = y;
   //@ maintaining x - y == z - w;
   //@ decreasing w;
   while (w > 0) {
      z++;
      w--;
   }
   return z;
```

12 errors, 0 warnings, 0 others

Description
Possible assertion failure - 2 - (LoopInvariant).
Possible assertion failure - 2 - (LoopInvariant). (proved false)

JML4: An IVE for JML

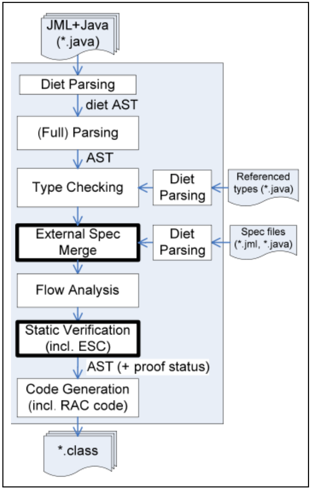
- Integrate support for JML into Eclipse
  - scanning, parsing, type checking, flow analysis, code generation
- Process inline & out-of-band JML
- Enhance non-null type system
- JML errors look like others
- Ensure hooks for RAC, ESC, FPV



Compiler phases

ESC4: ESC in JML4

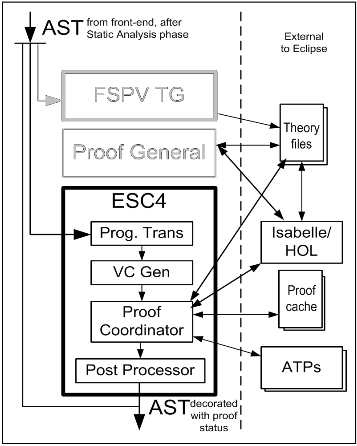
- Static analysis just before code generation
- Input is a "good" AST
- Multiple forms can be performed



Compiler phases

Overview of ESC4

- Converts AST to CFG (similar to GCs)
- Converts CFG to VC
- Uses a variety of strategies to discharge
- Reports unprovable assertions as problems
- Adds proof status to AST



Dataflow in ESC4

Generating VCs

AST converted to VC using techniques by Barnett & Leino

- Translate AST to an acyclic CFG
- Replace method calls with specs
- Remove side effects with DSA
- Produce single VC per method with wp

Discharging VCs

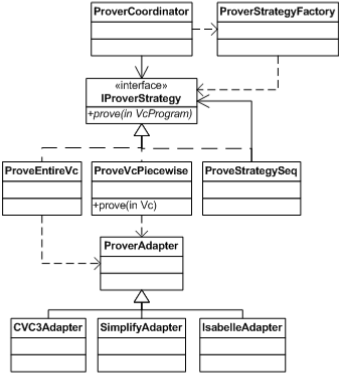
Configurable Proof Coordinator to discharge VCs

- Different prover strategies easily implemented
- First try to prove entire VC with Simplify
- If fails,
  - break into sub-VCs
  - try with Simplify, CVC3, and Isabelle/HOL[a]

[a] as an ATP!

Prover back-end

- Prover Coordinator used to discharge VCs
  - gets strategy from a factory
  - factory governed by compiler options
- Adapters hide communication with provers
- Visitors to pretty print the VCs for ATPs
- VC proof-status cache persisted



ESC4's prover back-end

Benefits of multiple provers

Some enancements in ESC4 include

- Non-linear arithmetic
- Numeric quantifiers
- First-class quantifiers
- Full power of Isabelle/HOL

Using multiple provers comes at a price. . .
ESC is very useful, but CPU intensive

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Faster ESC

ESC is very useful, but CPU intensive

Multi-threaded VC Generation

- Analyze methods in parallel
- Analysis for a method is independent of that for any others

Distributed Discharging of VCs

- Use non-local resources to reduce time
- Easy to include new proof strategies in ESC4

Multi-threaded VC Generation

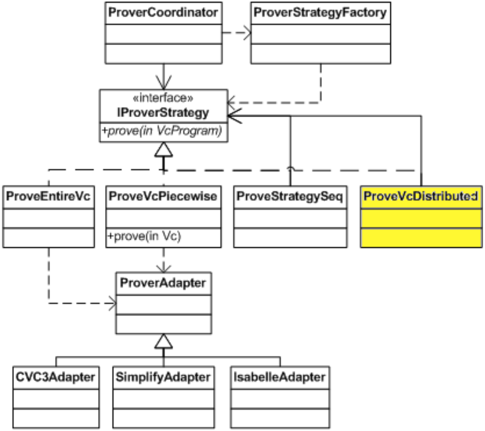
Process methods in parallel

- Package processing of method as work item
- Add it to a thread pool's task list
- Join point to wait until all finished

Process .java files in parallel

- Eclipse 3.4 JDT has concurrent compilation of source files
- ESC4 built atop JML4, which is built atop JDT
- Just have to make sure JML4 & ESC4 are thread safe

Distributed VC Processing



- Proof Coordinator made it easy
- Distributed strategy
  - sends pieces off to be verified
  - makes use of existing code to call provers

Deployment Scenarios

1. Prove whole VC remotely
   - Offloads work of Prover Coordinator for entire method
   - Sends VC to remote server processing
2. Prove sub-VCs remotely
   - Splits VC into sub-VCs & sends 'em off for remote discharging
   - Uses remote services to discharge the sub-VCs in parallel
3. Doubly Remote Prover Coordinator
   - Combines the two above
   - Remote Prover Coordinator
   - Sub-VCs discharged on remote services

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Validation - Setup

- 1 Java class with 51 methods $\rightsquigarrow$ 235 sub-VCs
- Doubly Remote Prover Coordinator local & remote
- ESC4 run on 2.4 GHz Pentium 4
- Remote Prover Coordinator on a 3.0 GHz Pentium 4
- Provers hosted on 2.4 GHz Quad-core Xeon processors.

Validation - Prover Invocations

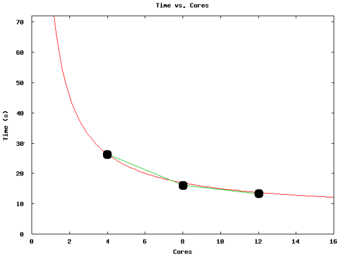
Prover	No. VCs	No. Proved	(%)
Simplify	235	193	82
CVC3	42	0	0
Negation[a]	42	23	55[b]
Isabelle	19	13	68
failed	6		

[a] Simplify used to prove the negation of the VC

[b] 80% of all false

Validation - Timing Results

No. servers	No. cores	Time (s) with Prover Coordinator local	Time (s) with Prover Coordinator remote
1	4	26.6	26.4
2	8	16.9	16.2
3	12	12.8	13.3



Running all locally took 72 s

Little difference between **remote** or **local** Prover Coordinator

$$t = 7.4 + \frac{76.0}{n}$$

Next Steps for ESC4

ESC4 is a quickly evolving research platform.

- It can do a few things that ESC/Java2 cannot.
- ESC/Java2 can do much more than it.

To close this gap

we continue to flesh out JML4 and ESC4
to more fully support Java and JML

Next Steps for ESC4

Easy performance gains

- improve interface to the theorem provers
- add load balancing
- caching of distributed proof results

Next Steps for ESC4

Further validation

- more case studies
- gather more timings

Conclusions

- ESC4 exploits several levels of parallelism
  - compilation unit & methods
  - sub-VCs
- using
  - local multi-threading
  - remote processing resources
- over 90% can be parallelized

Distributed, Multi-threaded Verification of Java Programs

Thank You!