Reachability Analysis for Annotated Code

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SAVCBS '07

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IST-15905

Why Annotated Code?

Static Checking Example

```
//@ ensures \result >= a;
//@ ensures \result >= b;
int max(int a, int b) {
  if (b > a)
    return b;
  else
    return b;
}
```

Why Annotated Code?

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```

Is It Possible that Some Things Are not Checked?

Code-Spec Inconsistency

```
/*@ requires x > 10;
  @ ensures \result == 1;*/
int withPre(int x) {
  if (x < 10) {
    // not checked
    return 2;
  }
  return 1;
}
```

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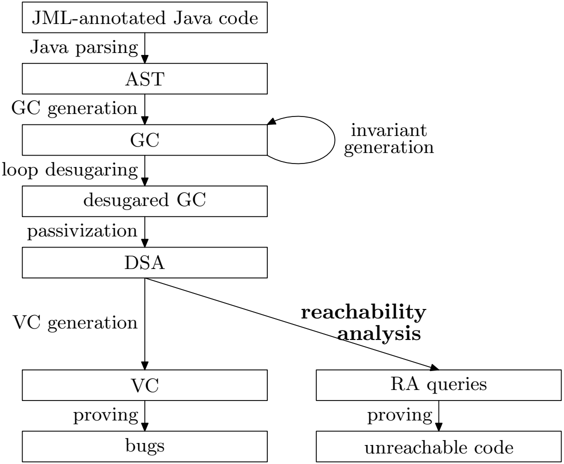
  }
  return 1;
}
```

Inconsistent Spec

```
/*@ requires i >= 10;
  @ ensures \result == i;
  @ ensures \result < 10;*/
int libraryFunc(int i);

int useLibraryFunc() {
  int r = libraryFunc(11);
  return 1/0; //not checked
}
```

ESC/Java2 Architecture



Input Language

Dynamic Single Assignment (DSA)

$$cmd := \textbf{assume}\ f \mid \textbf{assert}\ f \mid cmd \mathbin{[\!]} cmd \mid cmd\ ;\ cmd$$

where f is a first-order logic predicate on the program variables

Inconsistent Spec

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/*@ requires i >= 10;
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int useLibraryFunc() {
  int r = libraryFunc(11);
  return 1/0;  // not checked
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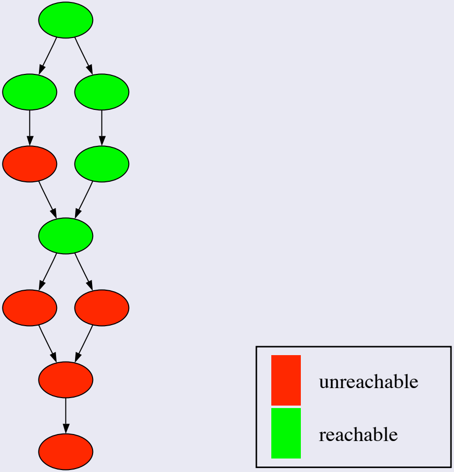
```

useLibraryFunc as DSA

C_1: **assert** $11 \geq 10$;
C_2: **assume** $r_1 = 11 \land r_1 < 10$;
C_3: **assert** $0 \neq 0$;
C_4: **assume** $RES = 1/0$

Reachability Propagation in Control Flow Graph

Code is unreachable if all paths leading to it block:



Computing Unreachable Code

Construct a *control flow graph* from DSA

- directed acyclic (DAG)
- nodes are labeled with commands:

$$\mathcal{L} : \mathrm{Nodes} \to \{\textbf{assume}\, f, \textbf{assert}\, f\}$$

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Compute *preconditions* and *postconditions* for nodes

$$\mathrm{post}(n) \equiv \mathrm{SP}(\mathrm{pre}(n), \mathcal{L}(n)) = \mathrm{pre}(n) \wedge f$$

$$\mathrm{pre}(n) \equiv \begin{cases} \mathit{true} & \text{if } n \text{ is an entry node} \\ \bigvee_{p \in \mathrm{parents}(n)} \mathrm{post}(p) & \text{otherwise} \end{cases}$$

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Call the Theorem Prover

for each node n,
ask the theorem prover if $\text{pre}(n)$ is *unsatisfiable*

Can We Do Better?

Observations

1. reachability information can be propagated
2. most nodes are reachable
3. most nodes dominate some other node

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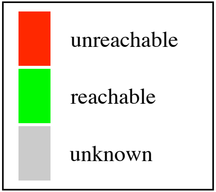
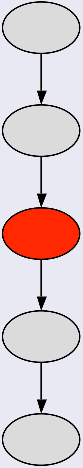


Example of Propagation



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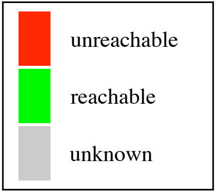

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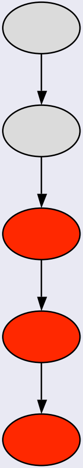

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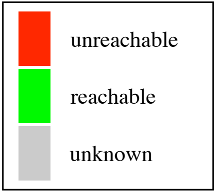

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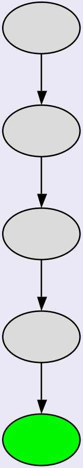

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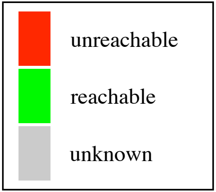

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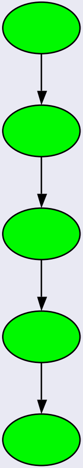


Algorithm — Greedy Heuristic

1. Compute:
   i. T — the immediate dominator tree of the nodes not known to be unreachable.
   ii. r — the root of T.
2. Choose an unlabeled node x in T with a maximal number of unlabeled dominators (greedy choice).
   i. Query the prover on x.
   ii. Label x *reachable*/*unreachable* accordingly and propagate.
   iii. If x is reachable then *go to* step 1.
3. By using binary search find the unreachable node on the path from r to x that is closest to r (the 'broken link' in chains). Label and propagate accordingly.
4. Repeat from step 1 while there are unlabeled nodes.

Case Study

Where

- ESC/Java2's front-end (`javafe`)
- 1890 methods
- running time 9 hours where reachability analysis took 34.8%

The Most Interesting Problems

- uncovered 5 inconsistencies in the JDK specifications
    - including a problem in treating of the *informal comment* `ensures \result <=> (* is upper-case *)`
- deficiencies of the checker (e.g., in *loop unrolling*)
- catching an undeclared exception
- most common: an error hiding subsequent code
- in some cases we don't know why the code is unreachable

Conclusions and Future Work

- unreachable code is a problem in practice, nevertheless,
- finding the exact source of unreachability is difficult, thus,
- in our future work we want to explore how we can provide more helpful feedback to the user

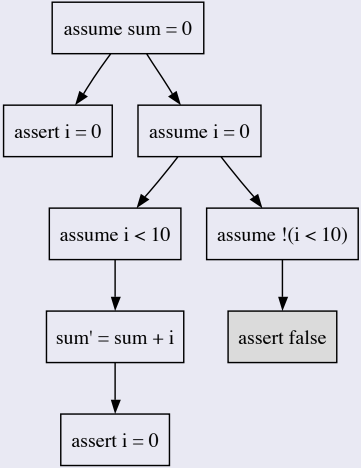
The implementation is in the ESC/Java2's `cvs` *head and can be enabled by the switch* `-era`.

Example with a Loop

Infinite Loop

```
int j = 0;
int sum = 0;
//@ loop_invariant i == 0;
for (int i = 0; i < 10; j++)
  sum += i;
//@ assert false;
```

DSA Control Flow Graph



Loop Unrolling

Loop Unrolled Twice

if C **then** B;
if C **then** B;
if C **then assume** *false*;