# Reachability Analysis for Annotated Code

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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?

## Static Checking Example

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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;
}
```

# Is It Possible that Some Things Are not Checked?

## Code-Spec Inconsistency

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int withPre(int x) {
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  }
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}
```
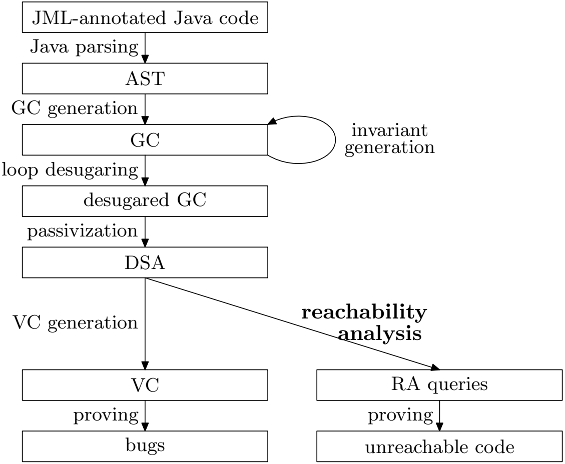

## Inconsistent Spec

```
/*@ 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



JML-annotated Java code

Java parsing

AST

GC generation

GC

invariant generation

loop desugaring

desugared GC

passivization

DSA

VC generation

**reachability analysis**

VC

RA queries

proving

bugs

proving

unreachable code

# 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

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

int useLibraryFunc() {
  int r = libraryFunc(11);
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```
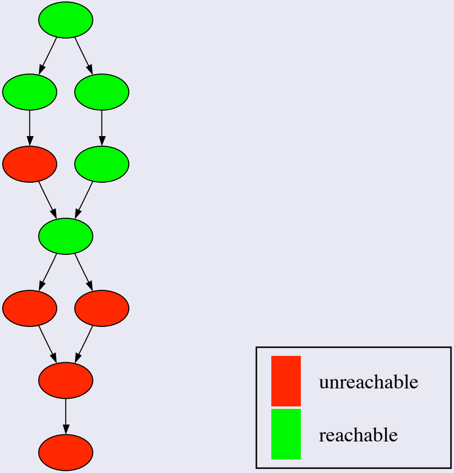

## useLibraryFunc as DSA

$$\begin{aligned}
C_1&: \quad \textbf{assert}\ 11 \geq 10;\\
C_2&: \quad \textbf{assume}\ r_1 = 11 \wedge r_1 < 10;\\
C_3&: \quad \textbf{assert}\ 0 \neq 0;\\
C_4&: \quad \textbf{assume}\ RES = 1/0
\end{aligned}$$

# 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

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

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

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### Call the Theorem Prover

for each node $n$,

ask the theorem prover if $\mathrm{pre}(n)$ is *unsatisfiable*

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2. most nodes are reachable
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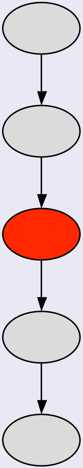
## Example of Propagation



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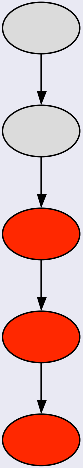

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|---|---|
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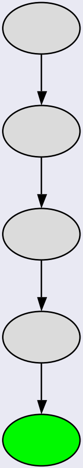

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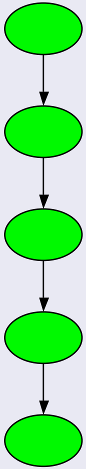


# Algorithm — Greedy Heuristic

1. Compute:
    1. $T$ — the immediate dominator tree of the nodes not known to be unreachable.
    2. $r$ — the root of $T$.
2. Choose an unlabeled node $x$ in $T$ with a maximal number of unlabeled dominators (greedy choice).
    1. Query the prover on $x$.
    2. Label $x$ *reachable*/*unreachable* accordingly and propagate.
    3. 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

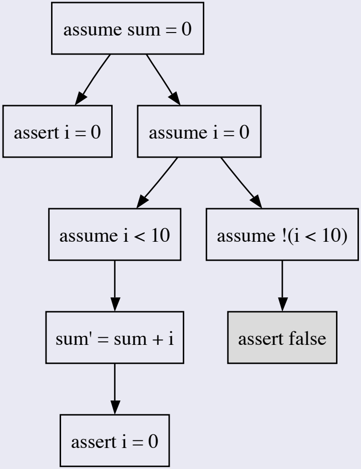
*The implementation is in the ESC/Java2's* `cvs` *head and can be enabled by the switch* `-era`.

# 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 $false$;
```