DySy: Dynamic Symbolic Execution for Invariant Inference

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Invariant Inference

```
Object top() {
  if(Empty)
    return null;
  return theArray[topOfStack];
}
```

Invariant Inference Tool

postcondition:	topOfStack = old topOfStack
class invariant:	theArray != null
class invariant:	topOfStack >= 0 && topOfStack < theArray.Length

Daikon

- First and most mature dynamic invariant inference tool

- Work flow
  - Instrumentation of all variables in scope of program
  - Execution of program
  - At each method entry / exit
    - Instantiation of invariant templates
    - Disqualification of inferred invariants which are refuted by an execution trace

- Invariant templates
  - Frequently used invariant patterns

Dynamic Invariant Inference – Problems

- Inferred invariants often
  - irrelevant
  - false
  - occasionally interesting but too simplistic
  - reflect the test suite

- Daikon's dubious invariants
  - theArray.getClass() != result.getClass()
  - topOfStack >> DEFAULT_CAPACITY == 0

DySy

- Solution proposed by authors
  - Invariant inference using dynamic symbolic execution

- Idea
  - Execute program symbolically in parallel to real execution
  - Record path condition
  - Use recorded path conditions to infer invariants

- DySy implements this idea

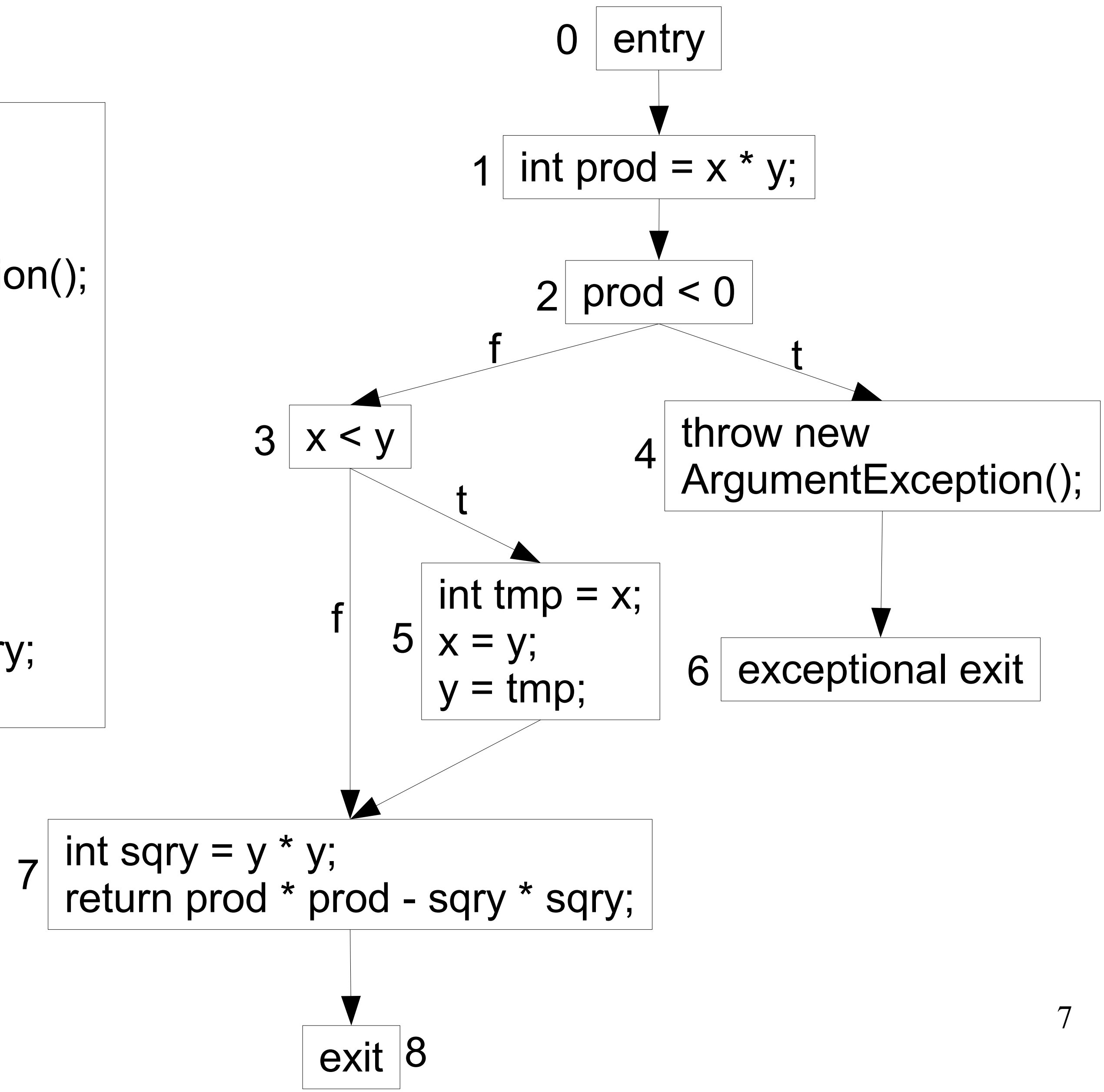
Symbolic Execution

- Replaces concrete inputs of a method with symbolic values

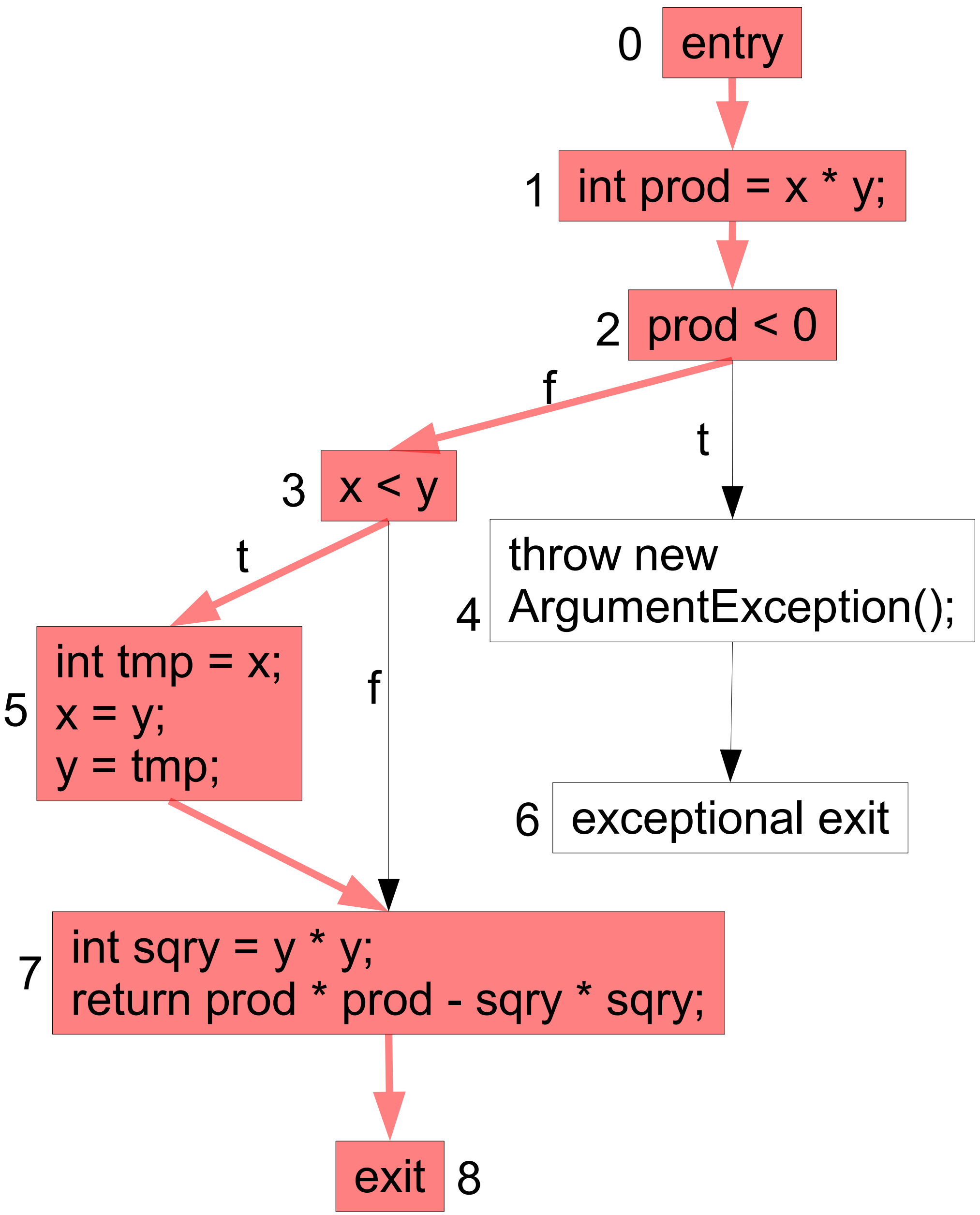
- Path condition
  - Accumulator of properties which the inputs must satisfy in order for an execution to follow the particular associated path
    - Explicit branches (control flow)
    - Implicit branches (exceptional behavior)

Symbolic Execution – Example

```
int testme(int x, int y) {
  int prod = x * y;
  if(prod < 0) {
    throw new ArgumentException();
  }
  if(x < y) { // swap them
    int tmp = x;
    x = y;
    y = tmp;
  }
  int sqry = y * y;
  return prod * prod - sqry * sqry;
}
```



Symbolic Execution – Example



- Path
  - 0-1-2-3-5-7-8
- Initial state
  - x → X, y → Y
- Final state
  - result → X*Y*X*Y – X*X*X*X
- Path condition
  - !(X * Y < 0) && (X < Y)

DySy – Algorithm

- Step 1: Path condition & final state discovery
  - New interpreter instance for every method call
  - Interpreter evolves symbolic state according to all subsequently executed instructions
    - Detection of purity of method
    - Pure methods used as logical variables in path conditions
    - Recursion treated as logical variables as well
      - result == ((i <= 1) → 1) else i * fac(i-1)
  - Quadruple (method, pathCondition, result, finalState) recorded when method returns

DySy – Algorithm

- Step 2: Class invariant derivation
  - Computation of “class invariant candidates” of class *C*
    - Set of conjuncts *c* of all recorded path conditions of all methods of *C* where *c* only refers to the *this* argument
  - DySy checks which candidates are implied by all path conditions in the final states of all methods of *C*
    - Current implementation: DySy executes the test suite again and checks the candidates in the concrete final state of each call to a method of *C*
  - Class invariants used to simplify invariants of methods

DySy – Algorithm

- Step 3: Pre- and postcondition computation
  - Precondition of a method
    - Disjunction of its path conditions
  - Postcondition of a method
    - Conjunction of its path-specific postconditions
  - Path-specific post condition is an implication
    - Left hand side: path condition
    - Right hand side: Conjunction of equalities where each equality relates a logical variable to a term in the final state

DySy – Inference example

- Path conditions
  - !(x * y < 0) && (x < y)
  - !(x * y < 0) && !(x < y)
- Precondition
  - x * y >= 0
- Postcondition
  - result == (((x < y) → x*y*x*y – x*x*x*x)
    else (x*y*x*y - y*y*y*y)

```
int testme(int x, int y) {
  int prod = x * y;
  if(prod < 0) {
    throw new ArgumentException();
  }
  if(x < y) { // swap them
    int tmp = x;
    x = y;
    y = tmp;
  }
  int sqry = y * y;
  return prod * prod - sqry * sqry;
}
```

DySy – Loops

- Problem: enormous path conditions with straightforward symbolic execution

- *for* loops
  - Loop variables treated as symbolic values
  - Exit condition not recorded in path condition if loop body is entered
  - Symbolic conditions in loop body collapsed per-program-point with only the last value remembered

- Other kinds of loops are future work

DySy – Loop example

```
public int linSearch(int ele, int[] arr) {
   if(arr == null) {
      throw new ArgumentException();
   }
   for(int i = 0; i < arr.Length; i++) {
      if(ele == arr[i]) {
         return i;
      }
   }
   return -1;
}
```

- Postcondition (simplified)
  - !(ele == arr[$i]) → result == -1 || ele == arr[$i] → result == $i

DySy – Evaluation

- Comparison between DySy and Daikon using the StackAr benchmark
  - StackAr: Stack algebraic data type using an array
  - Benchmark used for case study in Daikon literature
  - Java implementation
  - Authors rewrote StackAr in C#

- Reference invariants hand-produced by human user

DySy – Results of evaluation

	Goal	Daikon		DySy	
		Strict	Relaxed	Strict	Relaxed
Total	27	19	27	20	25

Table 1 – Number of inferred reference invariants

- Strict count
  - Detection of deep object equality
  - Detection of full purity of method

- Relaxed count
  - Detection of reference equality

DySy – Results of evaluation

	Invariants		Unique subexpressions		
	Goal	Daikon	Goal	Daikon	DySy
Total	27	138	89	316	133

Table 2 – Total number of inferred invariants and unique subexpressions

- Performance
  - Daikon: 9 seconds
  - DySy: 28 seconds

DySy – Quote

“We believe that this technique represents
the future of dynamic invariant inference.”

DySy – Impact

- 35 citations (ACM Digital Library)
- Limited influence
- DySy not maintained anymore

DySy – Assessment

- As capable as Daikon but less verbose
- Many open issues
  - Ruling out invalid class invariant candidates inefficient
  - Large overhead due to symbolic execution
  - No support for loops except *for* loops
- Quality of invariants heavily depends on the test suite
- Proven to work well only for this particular stack