Testing, Debugging, Program Verification

Automated Test Case Generation, Part II

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Recap

Specification-/Model-Based Test Case Generation

Systematic test case generation from JML contracts:
Black Box guided by several Test Generation Principles

- Test states make precondition true, consistency with class invariant
- Disjunctive analysis of each clause in precondition
- Choose representative values from larger sets
- Generation principle for datatypes of unbound locations

Remaining Problems of ATCG

1. How to automate specification-based test generation?
2. Generated test cases bear no relation to implementation

Recap: Ideas Behind ATCG

Ideas common to systematic (automated) test case generation

- Formal analysis of specification and/or code yields enough information to produce test cases
- Systematic algorithms give certain coverage guarantees
- Post conditions and invariants can be turned into test oracles
- Mechanic reasoning technologies achieve automation:
  - constraint solving
  - logic-based deduction
  - symbolic execution
  - model finding

Automated Test Generation Methods

Methods derived from black box testing

The implementation is unknown. Test data generated from spec, randomly, etc.

Generate test cases by analyzing
formal specification or formal model of IUT (Implementation Under Test)

Methods derived from white box testing

The implementation is analyzed to generate test data.

Code-based test generation that uses symbolic execution of IUT.

Code-Based Test Generation

Generate test cases from symbolic execution of code of IUT

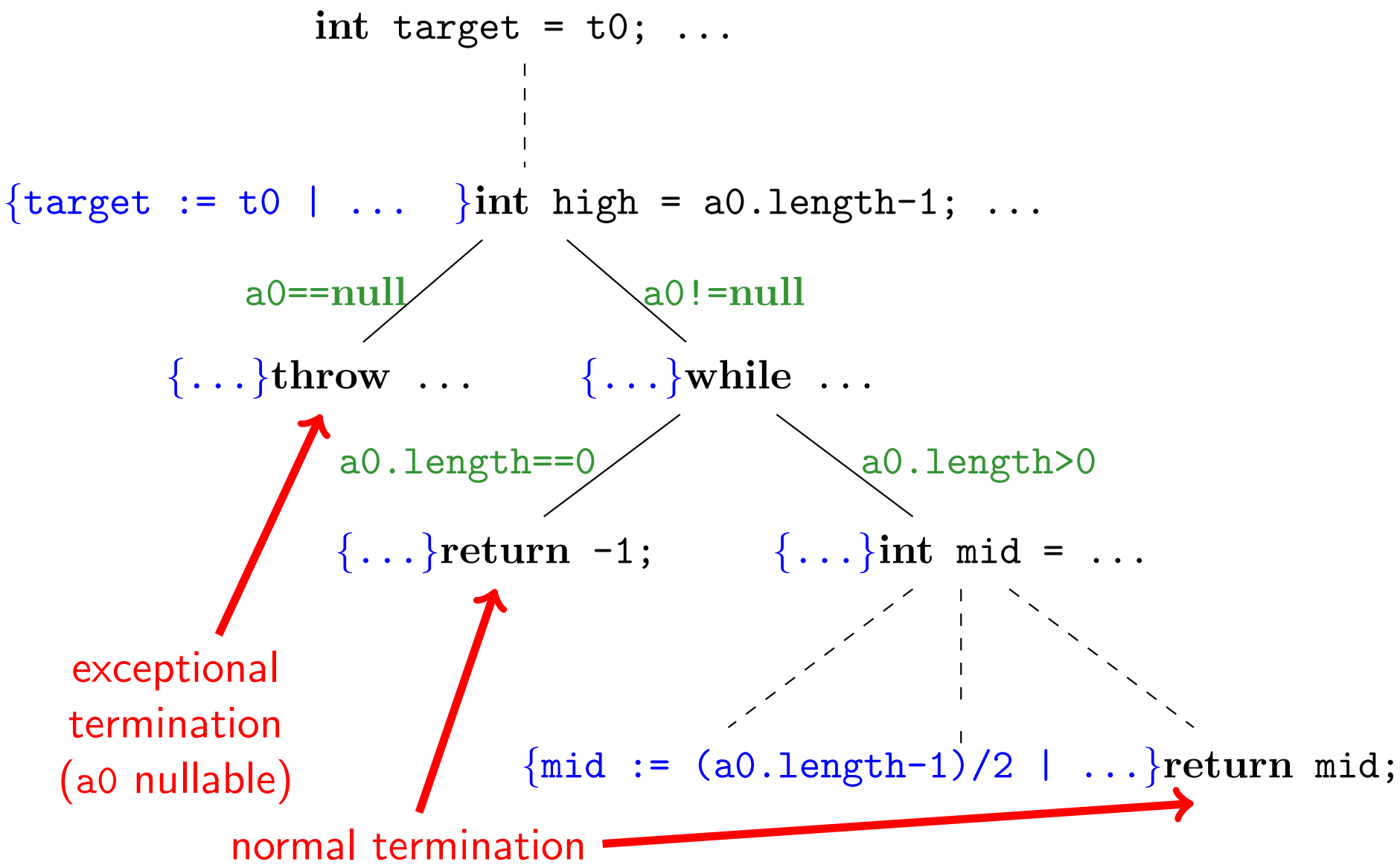
- White/glass box technology
- Current tools are research prototypes:
  Symstra, Java PathFinder, Korat, PEX, SpecExplorer, Kiasan, KeY
- Very dynamic development, nearly industrial strength
- JAVA, bytecode, .NET, C (via abstraction)
- No formal specification/system model required (but can help)

Recap: What is Symbolic Execution?

Symbolic Execution

- State: a "symbolic" valuation of all variables (stack) and fields (heap)
  - Introduce new symbols (terms) to denote initial value of variables etc.
  - Each term represents a set of possible concrete values
- Execution tree: finite OR infinite tree of states
- States in the tree are annotated with next (sub-)statement to be executed (program counter)
- Branching state transitions are annotated with path conditions
- Each concrete execution path is an instance of some symbolic path through the tree
- Initial state given explicitly or by a symbolic precondition

Symbolic Execution Tree



Properties of Symbolic Execution

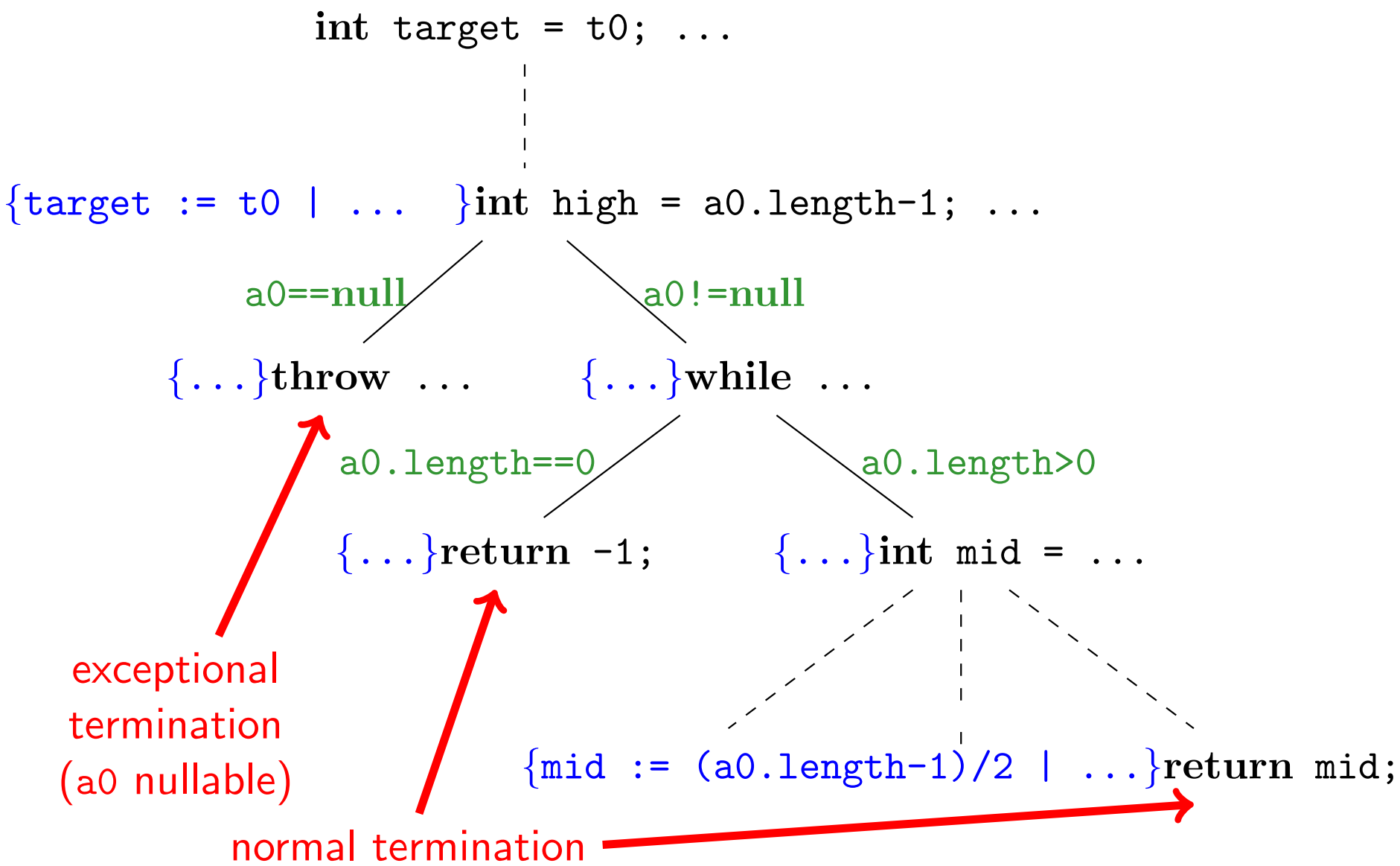
Important Conclusions

- One symbolic execution path corresponds to ∞ many test runs
- Programs with loops or recursion usually have ∞ many symbolic execution paths

Main Properties of Symbolic Execution

1. Even symbolic execution cannot cover all execution paths
2. But symbolic execution covers all execution paths up to finite depth

Symbolic Execution Tree: Binary Search



From Symbolic Execution to Test Cases

Code-Based Test Case Generation

1. Create symbolic execution tree for IUT until finite depth
2. For each terminating node (normal/exceptional) create test case:
   - **2.a** Let PC be path condition of executed branch
   - **2.b** Turn PC into quantifier-free first-order logic formula pc
   - **2.c** Find a f.o. model M for pc that validates it (use theorem prover)
   - **2.d** From M extract assignments for preamble of unit test case

Example (Code-Based Test Case Generation)

1. See previous slide
2. Choose right-most terminating path
   - **2.a** PC: `a0!=null && a0.length>0 && t0==a0[a0.length-1)/2]`
   - **2.b** $pc \equiv \neg a_0 = \text{null} \wedge \text{length}(a_0) > 0 \wedge t_0 = a_0[(\text{length}(a_0) - 1) \div 2]$
   - **2.c** $M(\text{length}(a_0)) = 2$, $M(a_0) = \{17, 42\}$, $M(t_0) = M(a_0[0]) = 17$
   - **2.d**
```
int target = 17; int[] array = {17,42};
```

Coverage, Code-Based

Code-based coverage criteria guaranteed by the resulting test suites depend on nodes/edges/paths covered in symbolic execution tree

All of finitely many feasible symbolic execution paths

Feasible Path Coverage — Rare to have (small) finite # of paths!

Each control-dependency in code occurs on some symbolic path

Feasible Branch Coverage — Achieved by unwinding loops often enough

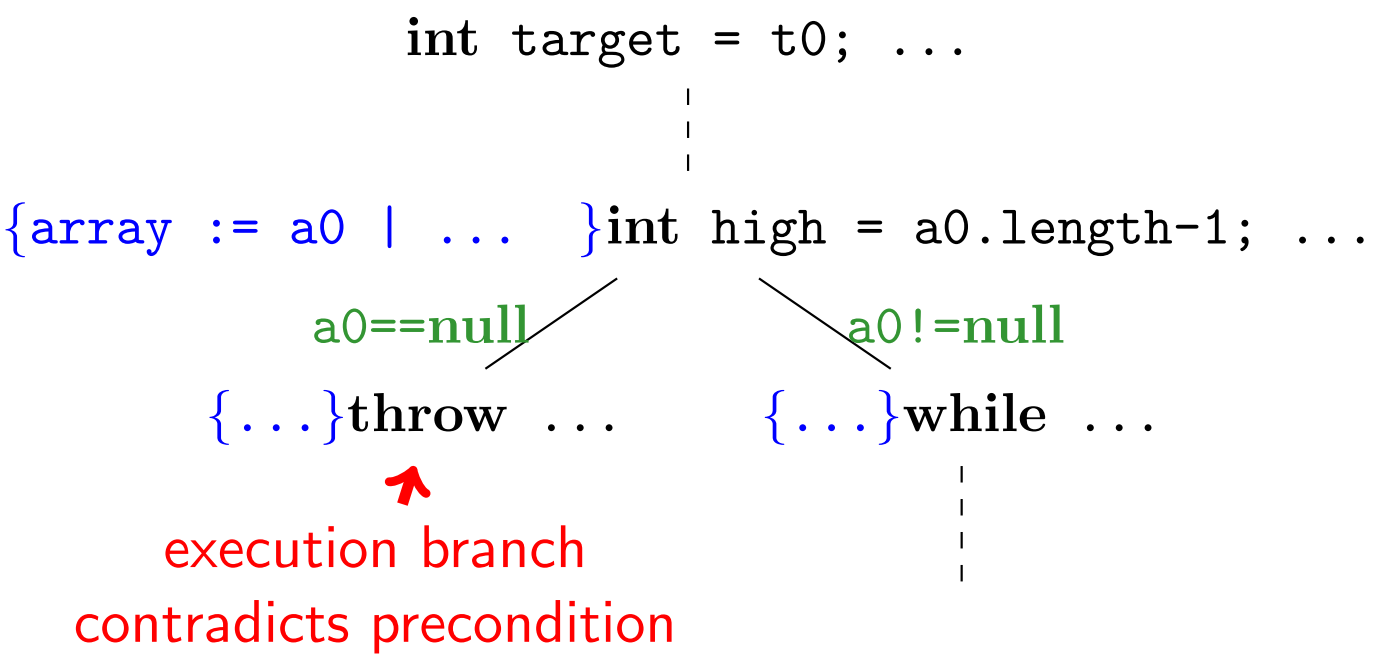
Each reachable statement occurs on some symbolic path

Reachable Statement Coverage — Achieved by unwinding each loop once

Preconditions: Pruning Infeasible Execution Paths

Example (Binary search with precondition (requires clause))

```
/*@ public normal_behavior
  @ requires array != null && ... ;
  @*/
int search(/*@ nullable @*/ int array[], int target) {..}
```



Postconditions: Synthesizing Test Oracle Code

Oracle Problem in Automated Testing

How to determine automatically whether a test run succeeded?

The "ensures" clause of a JML contract tells exactly that provided that "requires" clause is true for given test case

Guarded JML quantifiers as executable Java code

JML:

```
\forall int i; guard(i) ==> test(i)
```

Equivalent executable JAVA code:

```
for (int i = lowerBound; guard(i); i++) {
  if (!test(i)) { return false; }
} return true;
```

Combining Specification- and Code-Based ATCG

(Specification-Based) Test Generation Principle 1 (Relevance)

State at start of IUT execution must make required precondition true

(Specification-Based) Test Generation Principle 8 (Oracle)

Use "ensures" clauses of contracts (and class invariant) as test oracles

(Specification-Based) Test Generation Principle 3 (Clause Coverage)

For each disjunct D of precondition in DNF create a test case whose initial state makes D true and as many other disjuncts as possible false

(Code-Based) Test Generation Principle (Statement Coverage)

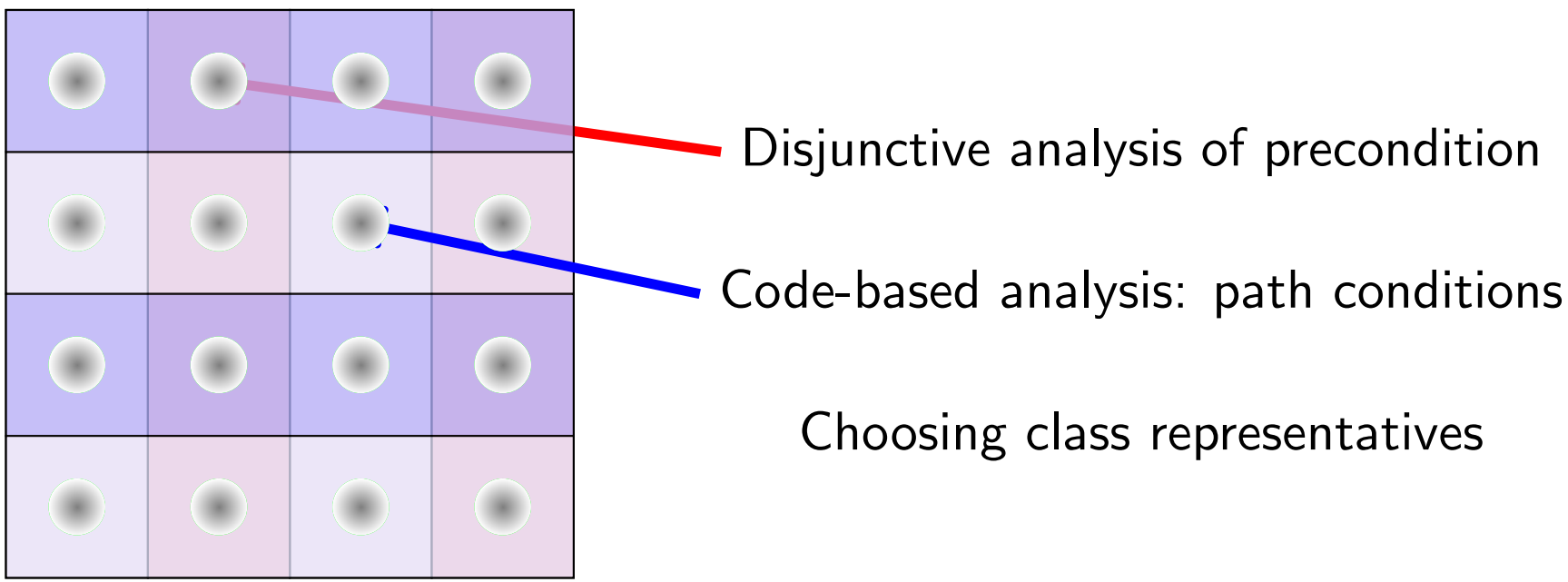
Create test case for each terminating node in symbolic execution tree — Unwind each loop at least once

Hybrid Coverage

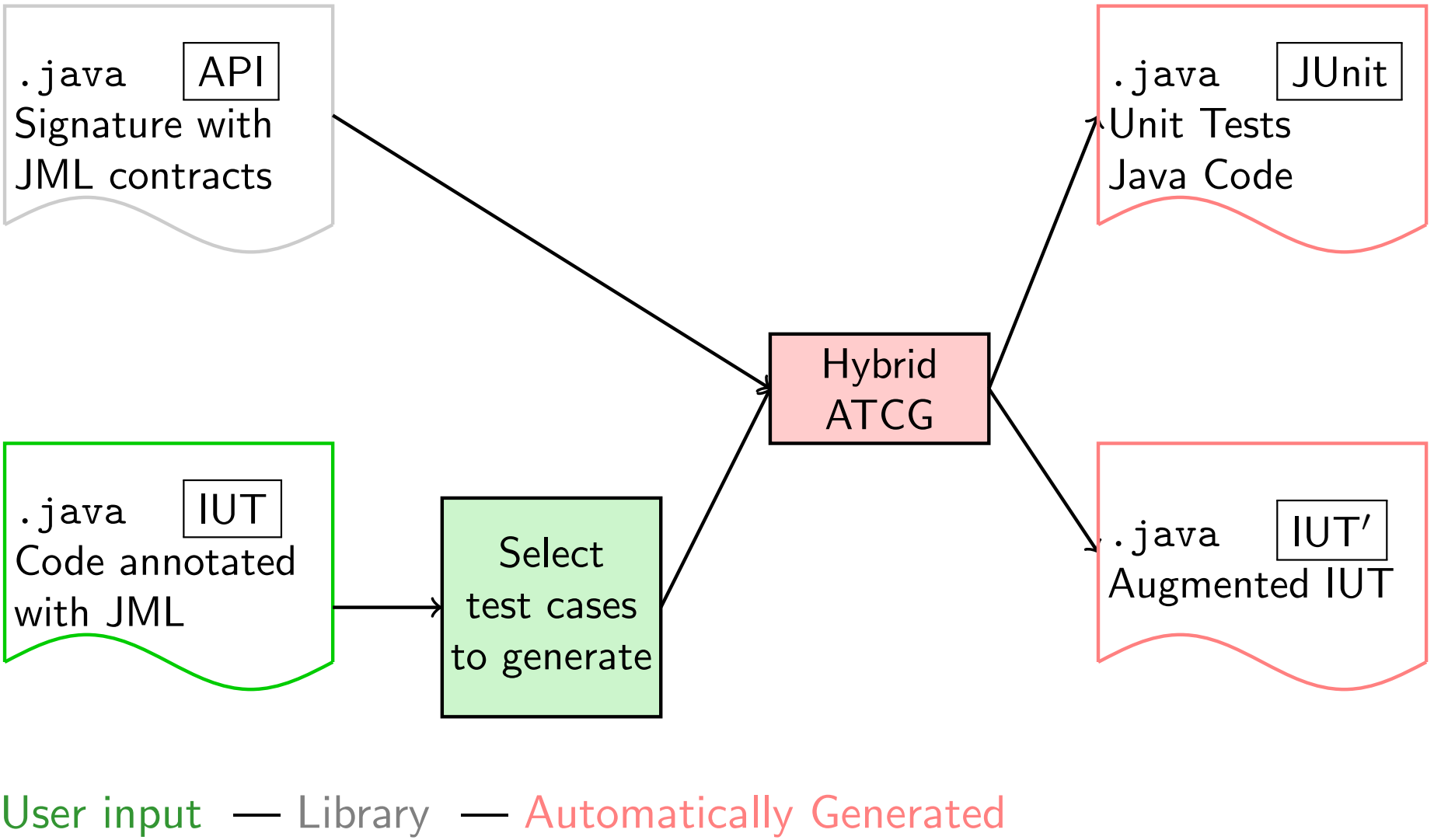
(Hybrid) Test Generation Principle

Create true/false test cases for each disjunct of precondition in DNF
AND
Create test case for each terminating node in symbolic execution tree

Resulting test cases fulfill logic- and code-based coverage criteria



Hybrid Test Case Generation: Overview



User input — Library — Automatically Generated

Summary

- Black box vs White box testing
- Black box testing $\sim$ Specification-/Model-based Test Generation
- White box testing $\sim$ Code-based Test Generation
- Systematic test case generation from JAVA code guided by Symbolic Execution
- Symbolic Execution:
  Path Condition + Symbolic State + Program Counter
- Test cases are models of path conditions in terminating paths
- Coverage criteria, feasible branch coverage
- Postconditions of contract and invariants provide test oracle
- Combine Specification-based and Code-based Test Generation