Strategic Automated Software Testing in the Absence of Specifications

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Motivation

- How do we generate "useful" tests automatically?
  - With specifications, we can partition input space into subdomains and generate samples from these subdomains [Myers 79]
    - Korat [Boyapati et al. 02]: repOk (partitioning input space into valid and invalid subdomains)
    - AsmLT/SpecExplorer [MSR FSE]: abstract state machine

- How do we know the generated tests run incorrectly in the absence of uncaught exceptions?
  - With specifications, we know a fault is exposed when a postcondition is violated by a precondition-satisfying input.

- We know that specifications are often not written in practice

Our Strategic Approaches

- How do we generate "useful" tests automatically?
  - Detect and avoid redundant tests during/after test generation **[Xie, Marinov, and Notkin ASE 04]**
    - Based on inferred equivalence properties among object states
    - Detected redundant tests do not improve reliability
      – no changes in fault detection, structural coverage, confidence

- How do we know the program runs incorrectly in the absence of uncaught exceptions?
  - It is infeasible to inspect the execution of each single test
  - Select the most "valuable" subset of generated tests for inspection **[Xie and Notkin ASE 03]**
    - Based on inferred properties from existing (manual) tests
    - Select any test that violates one of these properties (deviation from "normal")

Overview

- Motivation
- Redundant-test detection based on object equivalence
- Test selection based on operational violations
- Conclusions

Example Code

[Henkel&Diwan 03]

```
public class IntStack {
  private int[] store;
  private int size;
  public IntStack() { … }
  public void push(int value) { … }
  public int pop() { … }
  public boolean isEmpty() { … }
  public boolean equals(Object o) { … }
}
```

Example Generated Tests

Test 1 (T1):

```
IntStack s1 =
    new IntStack();
s1.isEmpty();
s1.push(3);
s1.push(2);
s1.pop();
s1.push(5);
```

Test 2 (T2):

```
IntStack s2 =
    new IntStack();
s2.push(3);
s2.push(5);
```

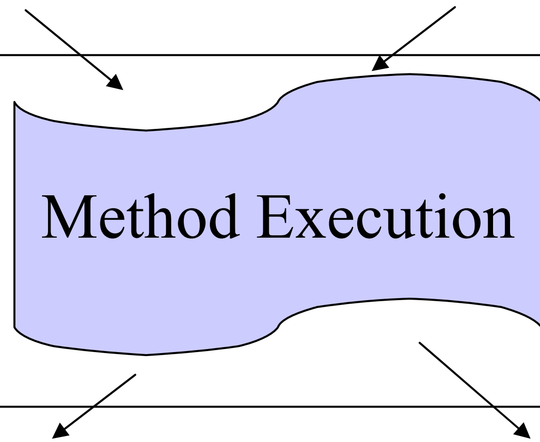
Test 3 (T3):

```
IntStack s3 =
    new IntStack();
s3.push(3);
s3.push(2);
s3.pop();
```

Same inputs ⇒ Same behavior

Assumption: deterministic method

Input = object state @entry + Method arguments



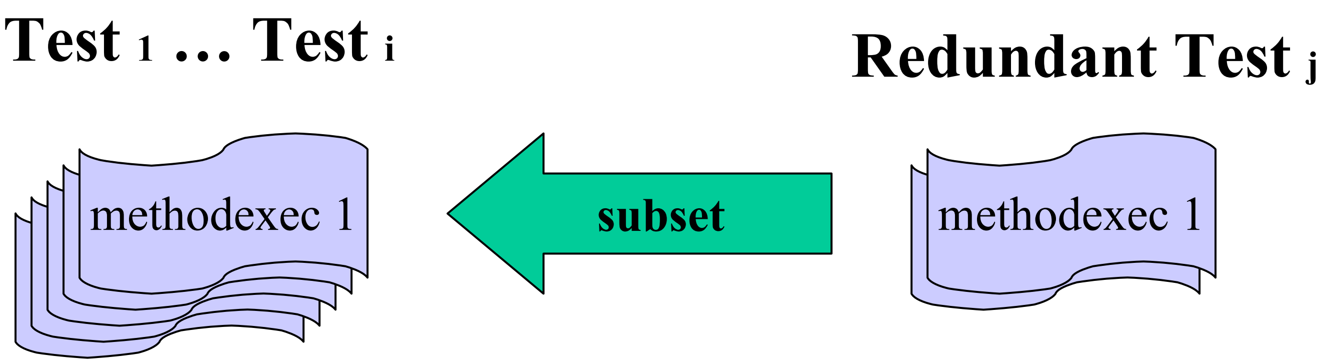
Output = object state @exit + Method return

Testing a method with the same inputs is unnecessary

We developed five techniques for representing and comparing object states

Redundant Tests Defined

- Equivalent method executions
  - the same method names, signatures, and input (equivalent object states @entry and arguments)
- Redundant test:
  - Each test produces a set of method executions
  - $Test_j$ is redundant for a test suite ($Test_1$ ... $Test_i$)
    - if the method executions produced by $Test_j$ is a subset of the method executions produced by $Test_1$ ... $Test_i$



Comparison with Traditional Definition

- Traditionally redundancy in tests was largely based on structural coverage
  - A test was redundant with respect to a set of other tests if it added no additional structural coverage (no statements, no edges, no paths, no def-use edges, etc.)
- Unlike our new definition, this structural-coverage-based definition is not safe.
  - A redundant test (in the traditional definition) can expose new faults

Five State-Representation Techniques

- Method-sequence representations
  - WholeSeq
    - The entire sequence
  - ModifyingSeq
    - Ignore methods that don't modify the state
- Concrete-state representations
  - WholeState
    - The full concrete state
  - MonitorEquals
    - Relevant parts of the concrete state
  - PairwiseEquals
    - **`equals()`** method used to compare pairs of states

WholeSeq Representation

Method sequences that create objects

Notation: methodName(entryState, methodArgs).state [Henkel&Diwan 03]

Test 1 (T1):

```
IntStack s1 =
   new IntStack();
s1.isEmpty();
s1.push(3);
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s1.push(5);
```

Test 3 (T3):

```
IntStack s3 =
   new IntStack();
s3.push(3);
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s3.pop();
```

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 s1.pop();
 s1.push(5);
```

```
Test 3 (T3):
 IntStack s3 =
    new IntStack();
 s3.push(3);
 s3.push(2);
 s3.pop();
```

<init>( ).state

WholeSeq Representation

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Test 3 (T3):

```
IntStack s3 =
   new IntStack();
s3.push(3);
s3.push(2);
s3.pop();
```

isEmpty(<init>( ).state).state

WholeSeq Representation

Method sequences that create objects

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 s1.isEmpty();
 s1.push(3);
 s1.push(2);
 s1.pop();
 s1.push(5);
```
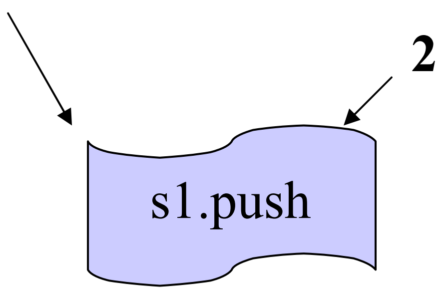

```
Test 3 (T3):
 IntStack s3 =
    new IntStack();
 s3.push(3);
 s3.push(2);
 s3.pop();
```

push(isEmpty(<init>( ).state).state, 3).state



WholeSeq Representation

Method sequences that create objects

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```
IntStack s1 =
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s1.isEmpty();
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s1.pop();
s1.push(5);
```
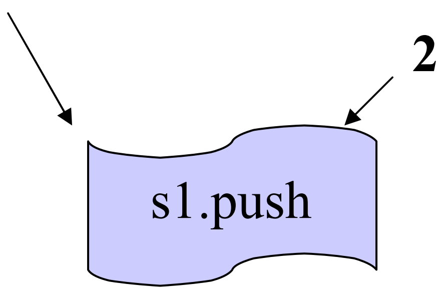
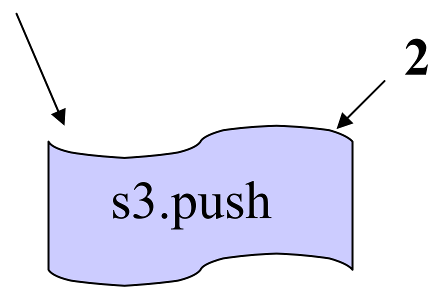

Test 3 (T3):

```
IntStack s3 =
   new IntStack();
s3.push(3);
s3.push(2);
s3.pop();
```

push(isEmpty(<init>( ).state).state, 3).state



push(<init>( ).state, 3).state



ModifyingSeq Representation

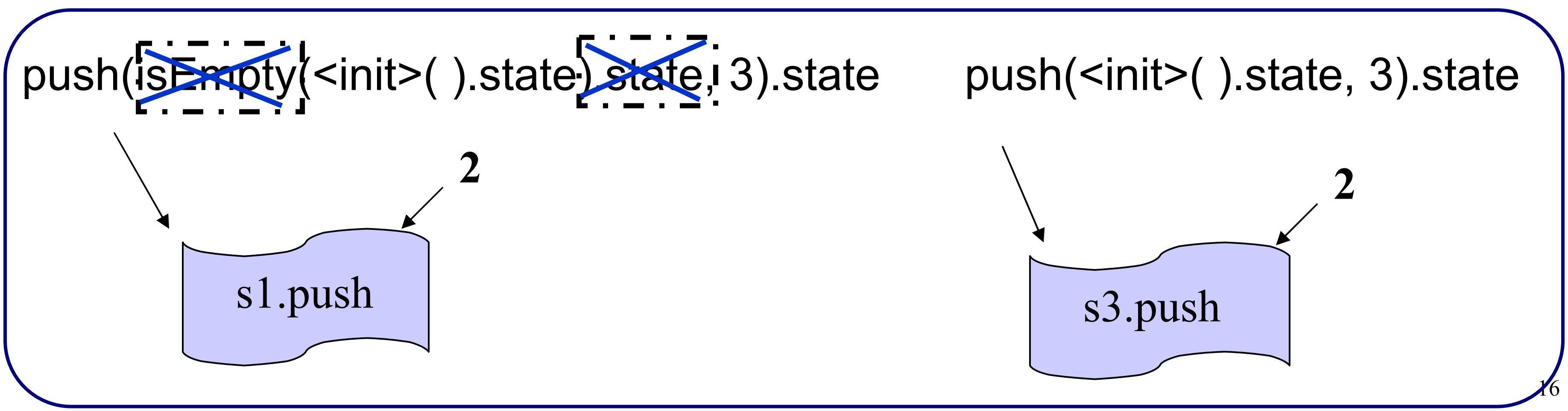
State-modifying method sequences that create objects

Test 1 (T1):

```
IntStack s1 =
   new IntStack();
s1.isEmpty();
s1.push(3);
s1.push(2);
s1.pop();
s1.push(5);
```

Test 3 (T3):

```
IntStack s3 =
   new IntStack();
s3.push(3);
s3.push(2);
s3.pop();
```



WholeState Representation

The entire concrete state reachable from the object

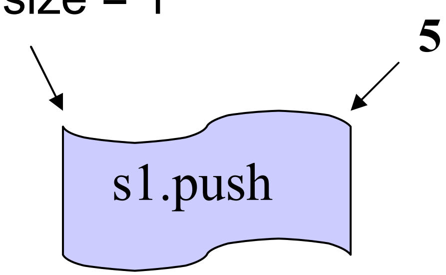
Test 1 (T1):

```
IntStack s1 =
   new IntStack();
s1.isEmpty();
s1.push(3);
s1.push(2);
s1.pop();
s1.push(5);
```

Test 2 (T2):

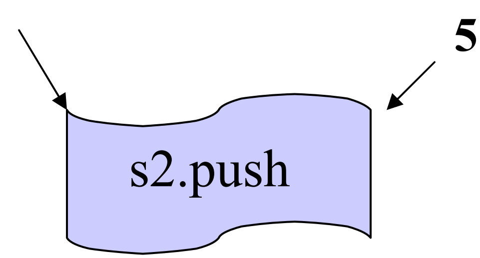
```
IntStack s2 =
   new IntStack();
s2.push(3);
s2.push(5);
```

store.length = 3
store[0] = 3
store[1] = 2
store[2] = 0
size = 1



Comparison by isomorphism

store.length = 3
store[0] = 3
store[1] = 0
store[2] = 0
size = 1



MonitorEquals Representation

The relevant part of the concrete state defined by *equals* (invoking obj.*equals*(obj) and monitor field accesses)

Test 1 (T1):

```
IntStack s1 =
   new IntStack();
s1.isEmpty();
s1.push(3);
s1.push(2);
s1.pop();
s1.push(5);
```

Test 2 (T2):

```
IntStack s2 =
   new IntStack();
s2.push(3);
s2.push(5);
```

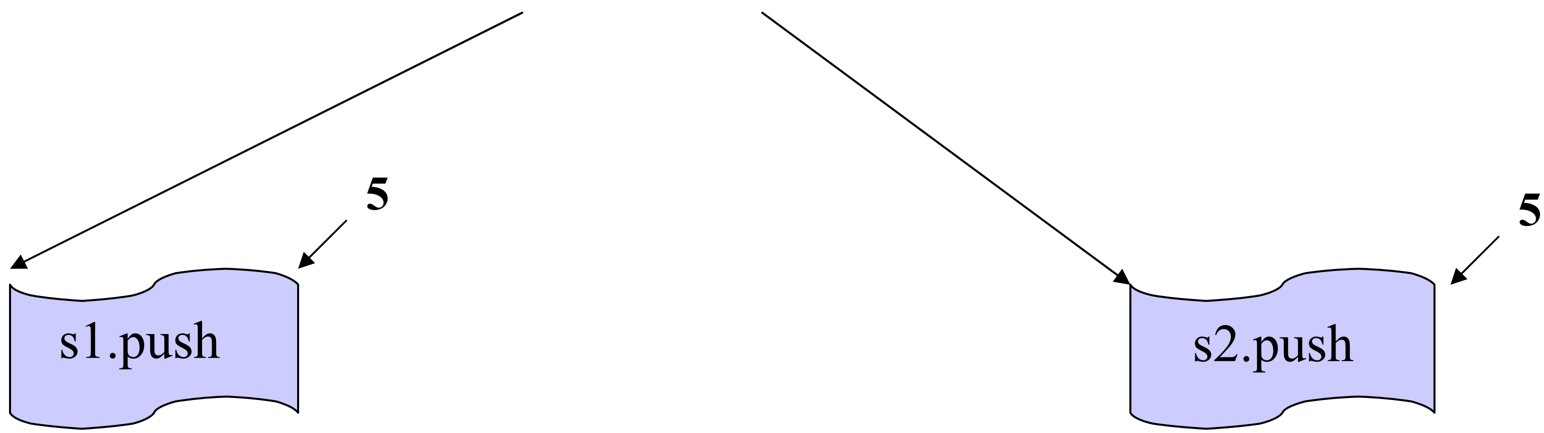
PairwiseEquals Representation

The results of *equals* invoked to compare pairs of states

```
Test 1 (T1):
 IntStack s1 =
    new IntStack();
 s1.isEmpty();
 s1.push(3);
 s1.push(2);
 s1.pop();
 s1.push(5);
```

```
Test 2 (T2):
 IntStack s2 =
    new IntStack();
 s2.push(3);
 s2.push(5);
```

```
s1.equals(s2) == true
```



Redundant-Test Detection

Test 1 (T1):

```
IntStack s1 =
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s1.isEmpty();
s1.push(3);
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s1.pop();
s1.push(5);
```

Test 3 (T3):

```
IntStack s3 =
   new IntStack();
s3.push(3);
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s3.pop();
```

Redundant-Test Detection

Test 1 (T1):

```
IntStack s1 =
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```

↔

Test 3 (T3):

```
IntStack s3 =
   new IntStack();
s3.push(3);
s3.push(2);
s3.pop();
```

Using last four techniques:

ModifyingSeq, WholeState, MonitorEquals, PairwiseEquals

Redundant-Test Detection

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Test 3 (T3):

```
IntStack s3 =
    new IntStack();
s3.push(3);
s3.push(2);
s3.pop();
```

Test 3 is redundant w.r.t Test 1

Using last four techniques:

ModifyingSeq, WholeState, MonitorEquals, PairwiseEquals

Detected Redundant Tests

Test 1 (T1):

```
IntStack s1 =
    new IntStack();
s1.isEmpty();
s1.push(3);
s1.push(2);
s1.pop();
s1.push(5);
```

Test 2 (T2):

```
IntStack s2 =
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s2.push(3);
s2.push(5);
```

Test 3 (T3):

```
IntStack s3 =
    new IntStack();
s3.push(3);
s3.push(2);
s3.pop();
```

technique	*detected redundant tests w.r.t. T1*
WholeSeq	
ModifyingSeq	T3
WholeState	T3
MonitorEquals	T3, T2
PairwiseEquals	T3, T2

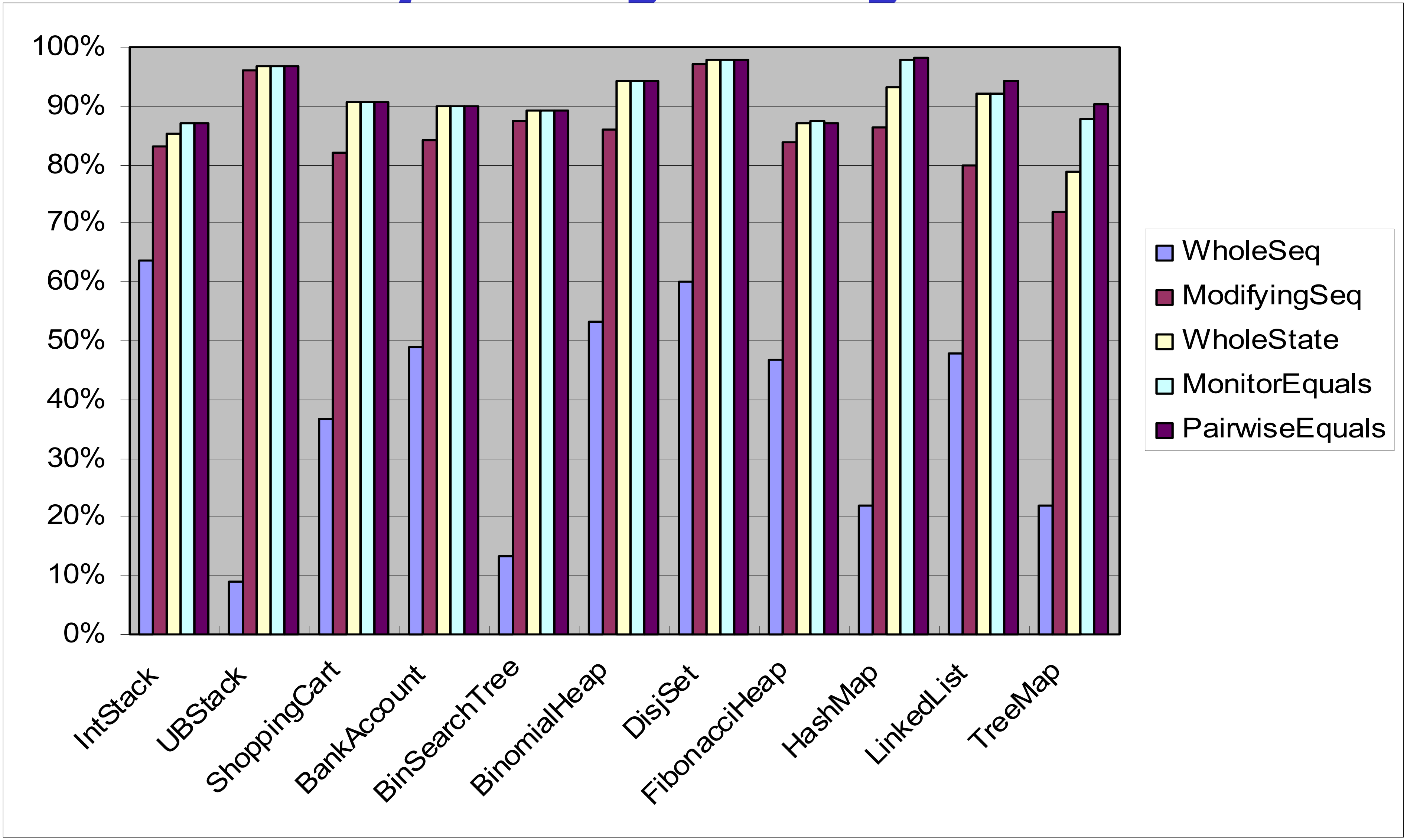
Experiment: Evaluated Test Generation Tools

- ParaSoft Jtest 4.5 (both black and white box testing)
  - A commercial Java testing tool
  - Generates tests with method-call lengths up to three
- JCrasher 0.2.7 (robustness testing)
  - An academic Java testing tool
  - Generates tests with method-call lengths of one
- Use them to generate tests for 11 subjects from a variety of sources
  - Most are complex data structures

Answered Two Questions

- How much do we benefit after applying Rostra on tests generated by Jtest and JCrasher?
  - The last three techniques detect around
    - **90%** redundant tests for Jtest-generated tests
    - **50%** on half subjects for JCrasher-generated tests.
  - Detected redundancy in increasing order for five techniques
- Does redundant-test removal decrease test suite quality?
  - The first three techniques preserve both branch cov and mutation killing capability
  - Two equals-based techniques have very small loss

Redundancy among Jtest-generated Tests



- **The last three techniques detect around 90% redundant tests**
- **Detected redundancy in increasing order for five techniques**

Overview

- Motivation
- Redundant-test detection based on object equivalence
- Test selection based on operational violations
- Conclusions

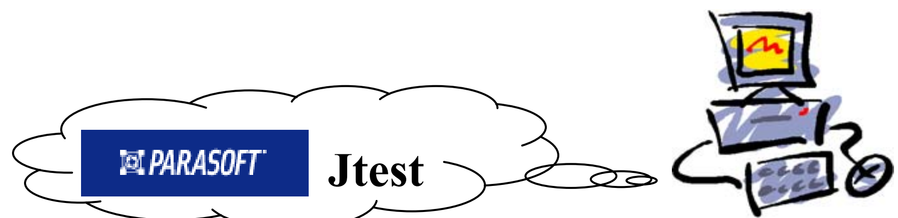
Operational Abstraction Generation
[Ernst et al. 01]

- Goal: determine properties true at runtime
  (e.g. in the form of Design by Contract)
- Tool: Daikon (dynamic invariant detector)
- Approach
  1. Run test suites on a program
  2. Observe computed values
  3. Generalize

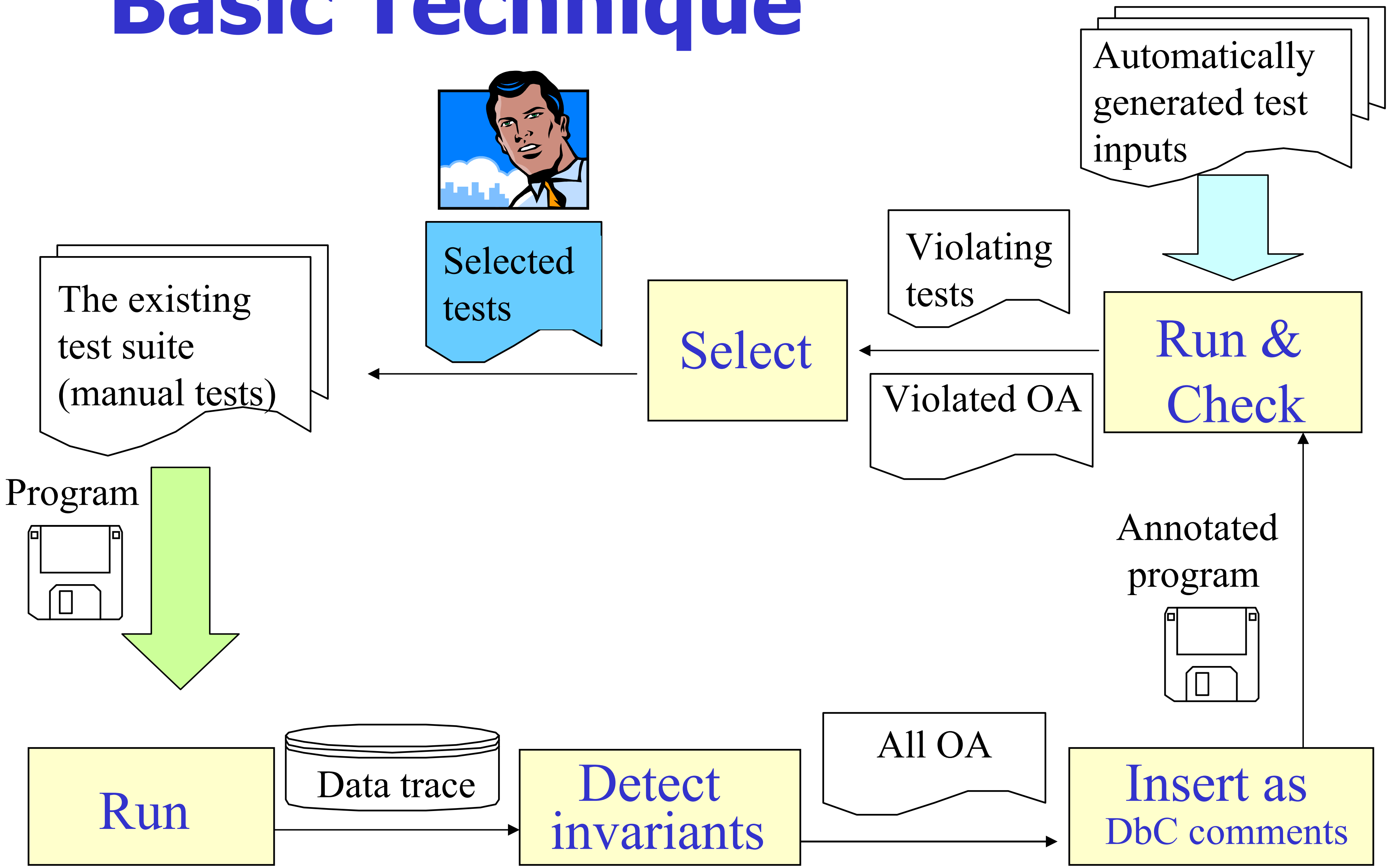
http://pag.lcs.mit.edu/daikon

Specification-Based Testing

- Goal: generate test inputs and test oracles from specifications
- Tool: ParaSoft Jtest (both black and white box testing)
- Approach:
  1. Annotate Design by Contract (DbC) [Meyer 97]
     - Preconditions/Postconditions/Class invariants
  2. Generate test inputs that
     - Satisfy preconditions
  3. Check if test executions
     - Satisfy postconditions/invariants



Basic Technique

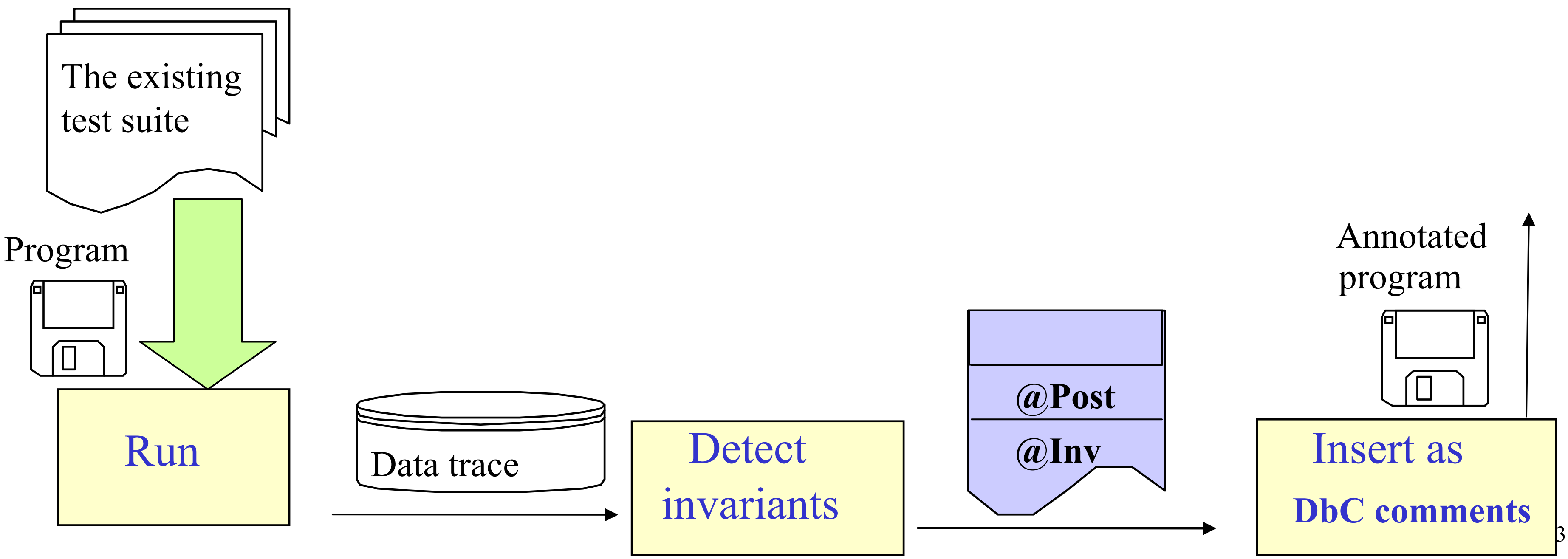


OA: Operational Abstractions

Precondition Removal Technique

- Overconstrained preconditions may leave (important) legal inputs unexercised

- Solution: precondition removal technique



Motivating Example [Stotts et al. 02]

```
public class uniqueBoundedStack {
  private int[] elems;
  private int numberOfElements;
  private int max;

  public uniqueBoundedStack() {
    numberOfElements = 0;
    max = 2;
    elems = new int[max];
  }

public int getNumberOfElements() {
    return numberOfElements;
  }
        ......
};
```

A manual test suite (15 tests)

Operational Violation Example

- Precondition Removal Technique

```
public int top(){
    if (numberOfElements < 1) {
      System.out.println("Empty Stack");
      return -1;
    } else {
      return elems[numberOfElements-1];
    }
}
```

```
@pre { for (int i = 0 ; i <= this.elems.length-1; i++)
      $assert ((this.elems[i] >= 0));   }
```

Daikon generates from manual test executions:

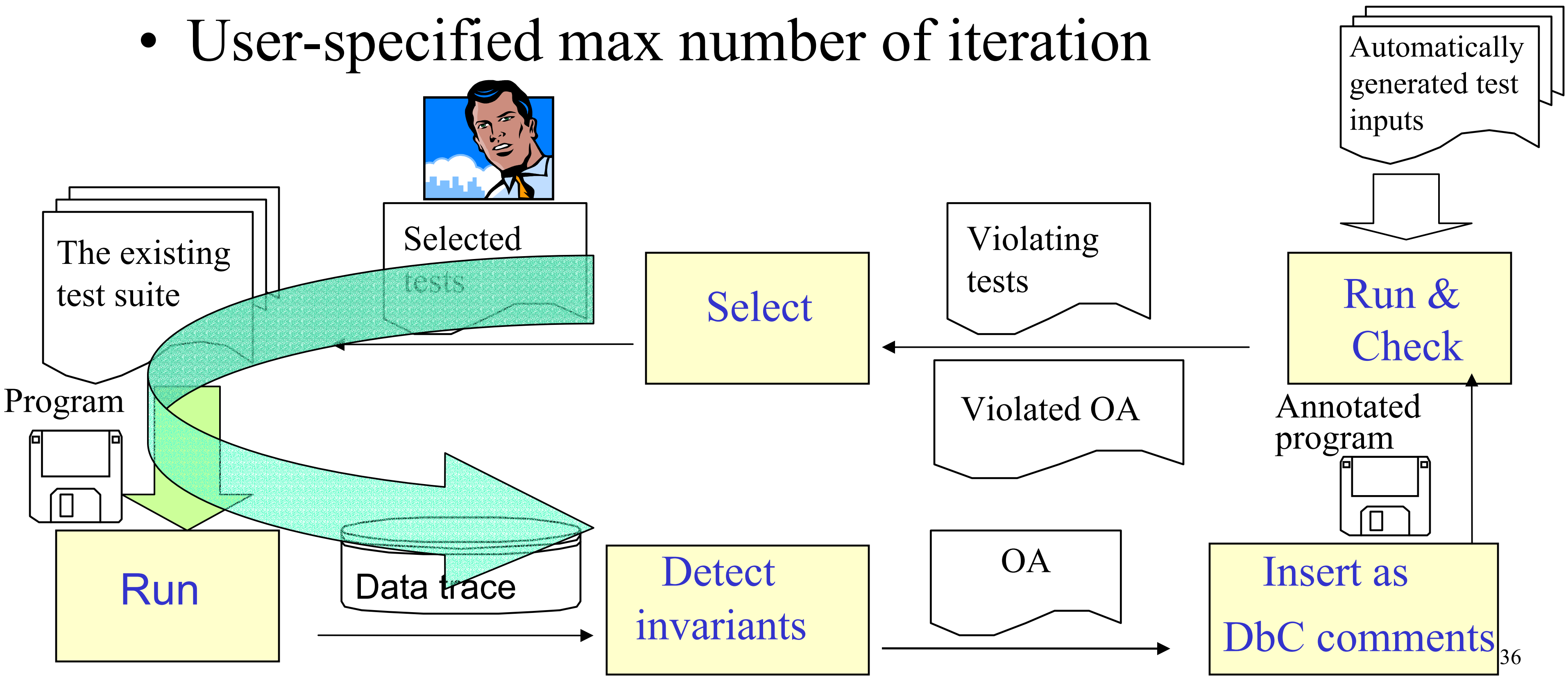
```
@post: [($result == -1) ⇔ (this.numberOfElements == 0)]
```

Jtest generates a violating test input:

```
uniqueBoundedStack THIS = new uniqueBoundedStack ();
THIS.push (-1);
int RETVAL = THIS.top ();
```

Iterations

- The existing tests augmented by selected tests are run to generate operational abstractions
- Iterates until
  - No operational violations
  - User-specified max number of iteration



Experiment: Subject Programs Studied

- **12** programs from assignments and texts (standard data structures)

- Accompanying manual test suites
  - ~**94**% branch coverage

Answered Questions

- Is the number of tests selected by our approach small enough?
  - if yes, affordable inspection effort
  - Range(0…25) Median(3)

- Do the selected tests by our approach have a high probability of exposing abnormal behavior?
  - if yes, select a good subset of generated tests
    - Iteration 1: **20%** (Basic) **68%** (Pre_Removal)
    - Iteration 2: **0%** (Basic) **17%** (Pre_Removal)

More Strategic Approaches-I

- How do we generate "useful" tests automatically?
  - Exhaustively exercise N arguments up to N method call length N
  - Breadth-first search of concrete-object state space: (limit: N = 6) [UW-CSE-04-01-05]
  - Breadth-first search of symbolic-object state space: (limit: N = 8) using symbolic execution to build up symbolic states [UW-CSE-04-10-02]
    - Longer method call length
    - Higher branch coverage
    - Generate representative arguments automatically

More Strategic Approaches - II

- How do we know the program runs incorrectly in the absence of uncaught exceptions?
  - **Test selection**: infer universal and common properties and identify common and special tests [OOPSLA Companion 04, UW-CSE-04-08-03]
  - **Test abstraction**: recover succinct object-state-transition information for inspection [ICFEM 04, SAVCBS 04]
  - **Regression testing**: detect behavior deviation of two versions by comparing value spectra (defined based on program states) [ICSM 04]

Conclusions

- Specifications can help automated software testing
  - However, specifications are often not written in practice
- Developed strategic approaches to enjoy some benefits of specification-based testing by using inferred program properties
  - Redundant test detection
  - Test generation
  - Test selection
  - Test abstraction
  - Regression testing

Questions?

http://www.cs.washington.edu/homes/taoxie/publications.htm