

Mutually Enhancing Test Generation and Specification Inference

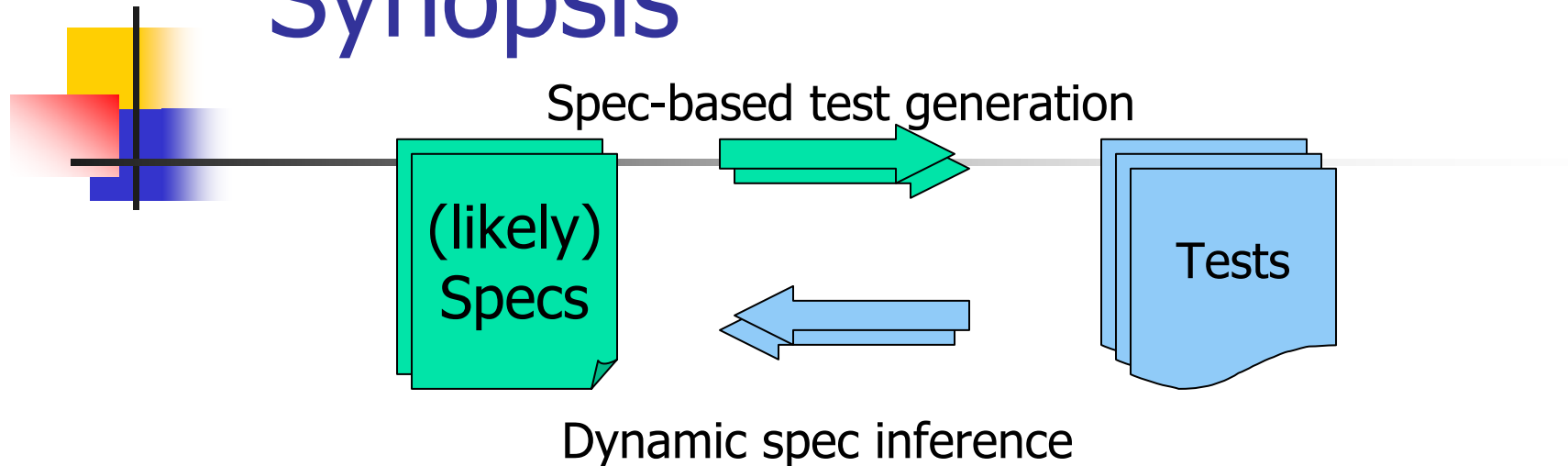
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August 15th, 2003

Foundations of Software Engineering, Microsoft Research

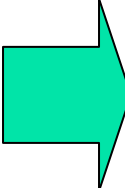
Synopsis



- Need specs for (many kinds of) test generation
- Need tests for dynamic spec inference
- We have applied feedback loop between these approaches that
 - aids in test generation (improving specs and helping in producing oracles)
 - aids in spec inference (improving the underlying test suites)



Outline

- 
- Background
 - Feedback Loop between Test Generation and Spec Inference
 - Axiomatic Spec Inference and Test Generation
 - Algebraic Spec Inference and Test Generation
 - Conclusion



Background – Test Generation

- White-Box Test Generation
 - Jtest [ParaSoft] ...
 - + Cover structural entities, e.g. statement, branch, path.
 - **Test oracle problem**
 - Rely on uncaught runtime exceptions
- Black-Box Test Generation
 - Korat [Boyapati et al.02], AsmL [Grieskamp et al. 02], Jtest...
 - + Use specs to guide test generation
 - + Use specs as test oracles
 - **Require *a priori* specs**

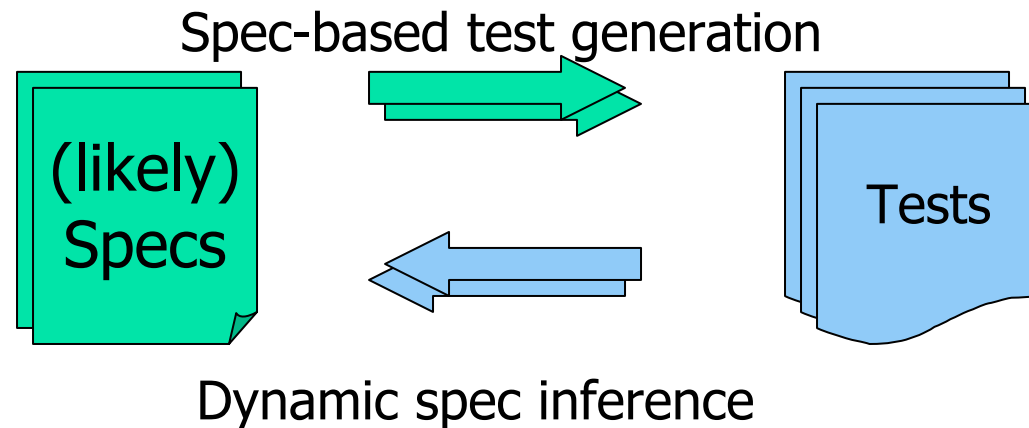


Background – Dynamic Spec Inference

- Axiomatic specification inference
 - Daikon [Ernst et al. 01]
- Algebraic specification inference
 - [Henkel & Diwan 03]
- Protocol specification inference
 - Strauss [Ammons et al. 02], Hastings [Whaley et al. 02]

Quality of analysis depends on quality of tests

Background – Circular Dependency

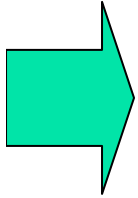


- Circular dependency: test generation and spec inference
- Win-win feedback loop:
 - Better spec \leftrightarrow better tests?

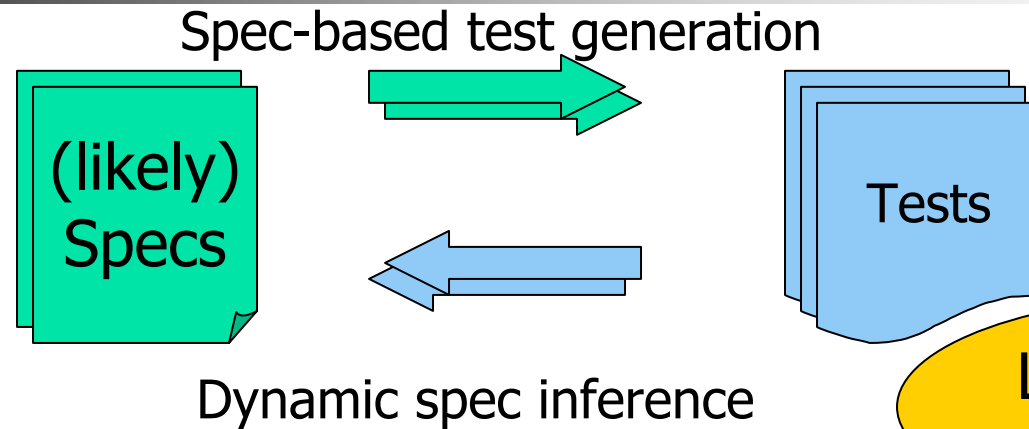


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Feedback Loop



- **Inferred Specs → Test Generation**

- Reduce the scope of analysis

Lack of Specs Problem

- **Generated Tests → Spec Inference**

- Verify/refine the inferred specs

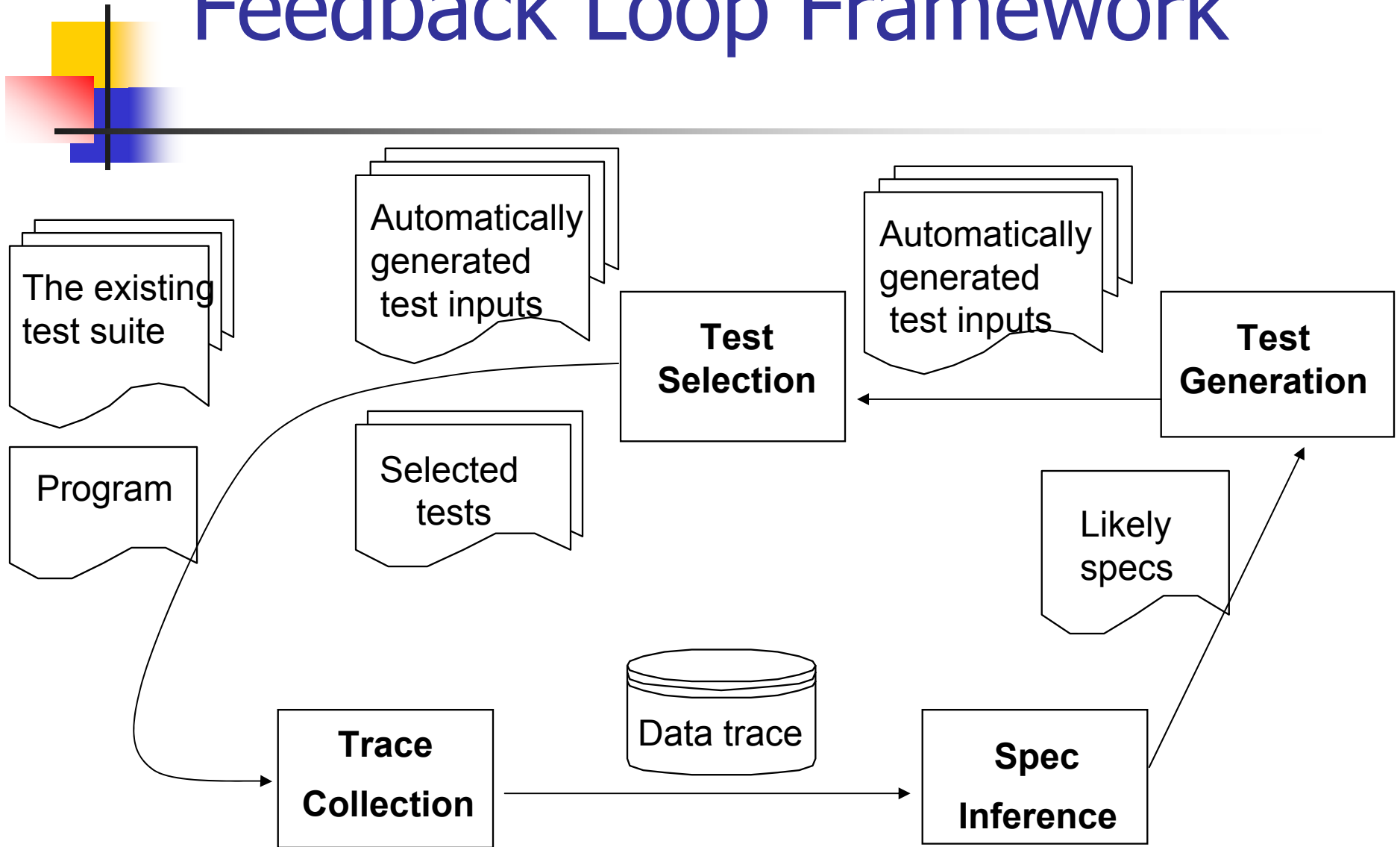
Insufficient Test Problem

- **Spec-Violating Tests → Test Selection**

- Inspection and test augmentation

Test Oracle Problem

Feedback Loop Framework





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Feedback Loop between Axiomatic Spec Inference and Test Generation

[ASE 03]

- Trace collection (Daikon Java front-end)
- Spec inference (Daikon)
- Test generation (Jtest)
- Test selection

- Iterations



Trace Collection & Axiomatic Spec Inference

- Trace collection
 - Method entry point: args, obj fields
 - Method exit point: return, updated args, obj fields
- Spec inference
 - Look for patterns and relationships among values, e.g. $x < a \wedge a < x < b \wedge y / a x \rightarrow b$
 - Preconditions, postconditions, and class invariants

Axiomatic Spec-Based Test Generation



- Black-box test generation based on Design by Contract (DbC) comments (Jtest)
 - Generates and executes test inputs
 - Ex: for a 11-method `uniqueBoundedStack` class with 47 LOC
 - Call length 1: 14 tests (63% statement cov.)
 - Call length 2: 96 tests (86% statement cov.)
 - Call length 3: 1745 tests (86% statement cov.)
 - Problem suppression for inputs violating the preconditions
 - Both preconditions and postconditions have impacts on test generation



Test Generation Issue: Over-Constrained Preconditions

- Too restrictive preconditions may leave (maybe important) legal inputs untested
- Solution: precondition guard removal

- New problem: allow illegal inputs
 - But only report postcondition-violating or exception-throwing illegal inputs
- Alternatives: precondition guard relaxation?



Test Selection

- Select tests violating at least one inferred postcondition.
- Inspect them:
 - illegal inputs:
 - Adding preconditions or defensive programming
 - legal inputs:
 - Fault exposure: bug fixing and regression test suite augmentation
 - Normal, but new feature exercising: regression test suite augmentation
- Complementary technique: Select tests exercising at least one new structural entity.

Specification Violation - Example

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

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

top: @post: [($result == -1) == (this.numberOfElements == 0)]
is violated by input:
uniqueBoundedStack THIS = new uniqueBoundedStack ();
THIS.push (-1);
int RETVAL = THIS.top ();
```




Iterations

- Iterates until reaching a fixed point (no violations)
- In the next iteration, spec inference is based on:
 - the existing test suite augmented by
 - new violating tests
 - all generated tests



Experiment – Subject Programs

Jtest method call length: 2

Programs	#Public Methods	#LOC	#Manual-tests	#Jtest-tests
UB-Stack (JUnit)	11	47	8	96
UB-Stack (JAX)	11	47	15	96
RatPoly-1	13	161	24	223
RatPoly-2	13	191	24	227
RatPolyStack-1	13	48	11	128
RatPolyStack-2	12	40	11	90
BinaryHeap	10	31	-	166
BinarySearchTree	16	50	-	147
DisjSets	4	11	-	24
QueueAr	7	27	-	120
StackAr	8	20	-	133
StackLi	9	21	-	99

Experiment – Results

With Preconds: basic tech

W/O Preconds: precondition removal tech

#SelT: #Selected tests

#FRT: #Fault-revealing tests

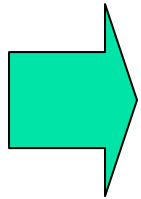
Programs	Iteration 1				Iteration 2				Iteration 3			
	With Preconds		W/O Preconds		With Preconds		W/O Preconds		With Preconds		W/O Preconds	
	#SelT	#FRT	#SelT	#FRT	#SelT	#FRT	#SelT	#FRT	#SelT	#FRT	#SelT	#FRT
UBS (JUnit)	1		15	5	2		6	1			1	
UBS (JAX)	3		25	9			4					
RatPoly-1	2	2	1	1								
RatPoly-2	1	1	1	1	1	1						
RatPolyStack-1			12	8			5	2			1	
RatPolyStack-2	1		10	7			2					
.....												
Median of #FRT/ #SelT	20%		68%		0%		17%		–		0%	

- #Selected tests are not too large (affordable to inspect)
- #Selected tests have high probability of exposing a fault or indicating a necessary precondition
- A couple of iterations are good enough



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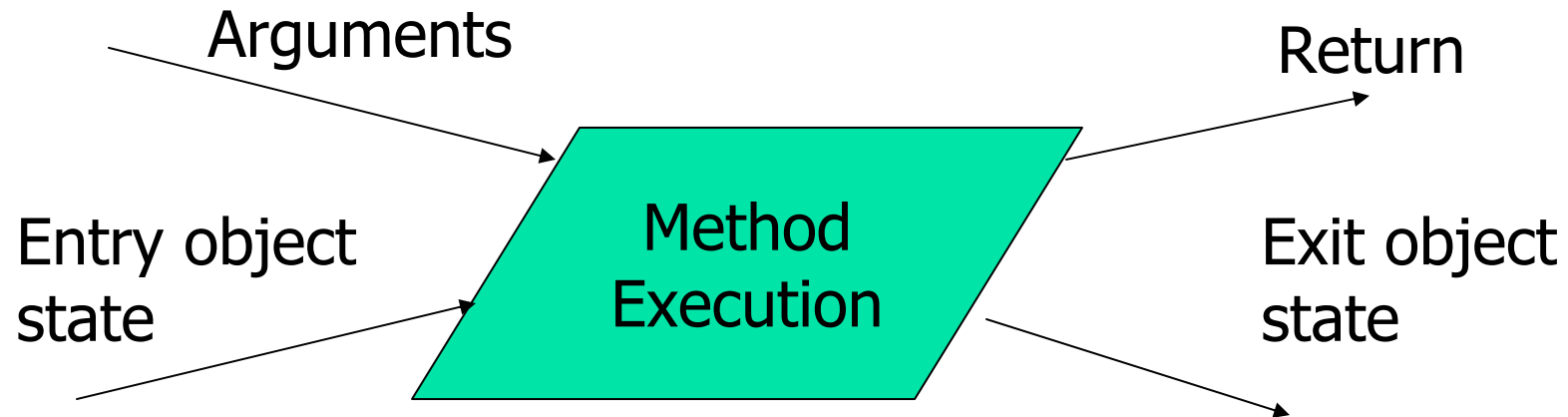
Feedback Loop between Algebraic Spec Inference and Test Generation

- Trace collection
- Spec inference
- Test generation
- Test selection

- Iterations

Trace Collection

- Object = data + operations



- Trace data:

- Method entry point: args, **entry object state**
- Method exit point: return, **exit object state**



Object State Collection - Challenges

- Simply outputting (all) object field values doesn't work
 - Which object fields of ancestor classes are relevant?
 - Which object fields of the current class are relevant?
 - How deep shall we track referencing object fields?



Object State Collection - Solution

- We developed a tracing front-end based on BCEL
- Require a pre-defined “equals” method
 - Instrument “*this.equals(this)*” at public method entry and exit points.
 - Collect the object field values accessed within “*this.equals(this)*”.
 - Sort these object field values by their field names and treat non-null reference field values as “Non-null”.
- **1389** (of 1745) Jtest-tests produce **12713** method executions, but only **63** distinct entry object states/args.

Object State Collection - Example

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

public boolean equals(uniqueBoundedStack s) {
    if (s.maxSize() != max)
        return false;
    if (s.getNumberOfElements() != numberOfElements)
        return false;
    int [] sElems = s.getArray();
    for (int j=0; j<numberOfElements; j++) {
        if ( elems[j] != sElems[j])
            return false;
    }
    return true;
}
```

•stack =new uniqueBoundedStack()

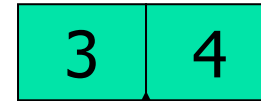
elems



↑
numberOfElements=0

•stack.push(3); stack.push(4); stack.pop();

elems



↑
numberOfElements=1

Exit state: (this.euqals(this))

elems = Non-null

elems[0] = 3

max = 2

numberOfElements = 1



Algebraic Spec Inference

- Compose method call pair from method executions
 - Method executions of *foo1* and *foo2* are composed as $foo2(foo1(S, arg1), arg2)$,
 - if $foo1.exit_state == foo2.entry_state$
- Look for equality patterns among args, return, entry state, exit state of either method in a pair
 - Based on axiom templates

Algebraic Spec Inference – Axiom Templates - I

- $foo2(foo1(S, arg1), arg2) = const$
 - $isEmpty(push(Stack, element)) == false$
- $foo2(foo1(S, arg1), arg2) = arg1 \text{ or } arg2$
 - $top(push(Stack, element)) == element$
- $foo2(foo1(S, arg1), arg2) = foo1(S, arg1)$
 - $equals(pop(uniqueBoundedStack()), uniqueBoundedStack())$
- $foo2(foo1(S, arg1), arg2) = S$
 - $equals(pop(push(Stack, element)), S)$
- $foo2(foo1(S, arg1), arg2) = foo1(foo2(S, arg2), arg1)$
 - $equals(push(push(Stack, element1), element2), push(push(Stack, element2), element1))$
- $foo1(S, arg1) = const$
 - $maxSize(Stack) == 2$
- $foo1(S, arg1) = S$
 - $equals(print(Stack), Stack)$

Algebraic Spec Inference – Axiom Templates - II

■ *Conditional axioms*

- $foo2(foo1(S, arg1), arg2) = ((arg1 == arg2)? RHS_true : RHS_false)$
- $foo2(foo1(S, arg1), arg2) = ((arg1 != arg2)? RHS_true : RHS_false)$
- $foo2(foo1(S, arg1), arg2) = ((foo3(S))? RHS_true : RHS_false)$

■ *Differencing axioms*

- $foo2(foo1(S, arg1), arg2) = RHS + const$



Algebraic Spec-Based Test Generation

- Parameter generation
 - Collect non-referencing parameter values exercised by existing tests
 - Collect method call traces from test class to handle referencing parameters
- Object state setup
 - Collect object states exercised by existing tests
- Method sequence generation
 - LHS and RHS of Inferred axioms
- Test code generation based on the Danish tool [Hughes & Stotts 96]



Test Selection

- Test selection
 - Axiom-violating tests
 - $LHS \neq RHS$ for axiom $LHS = RHS$
 - Minimum tests contributing to inference of a new axiom

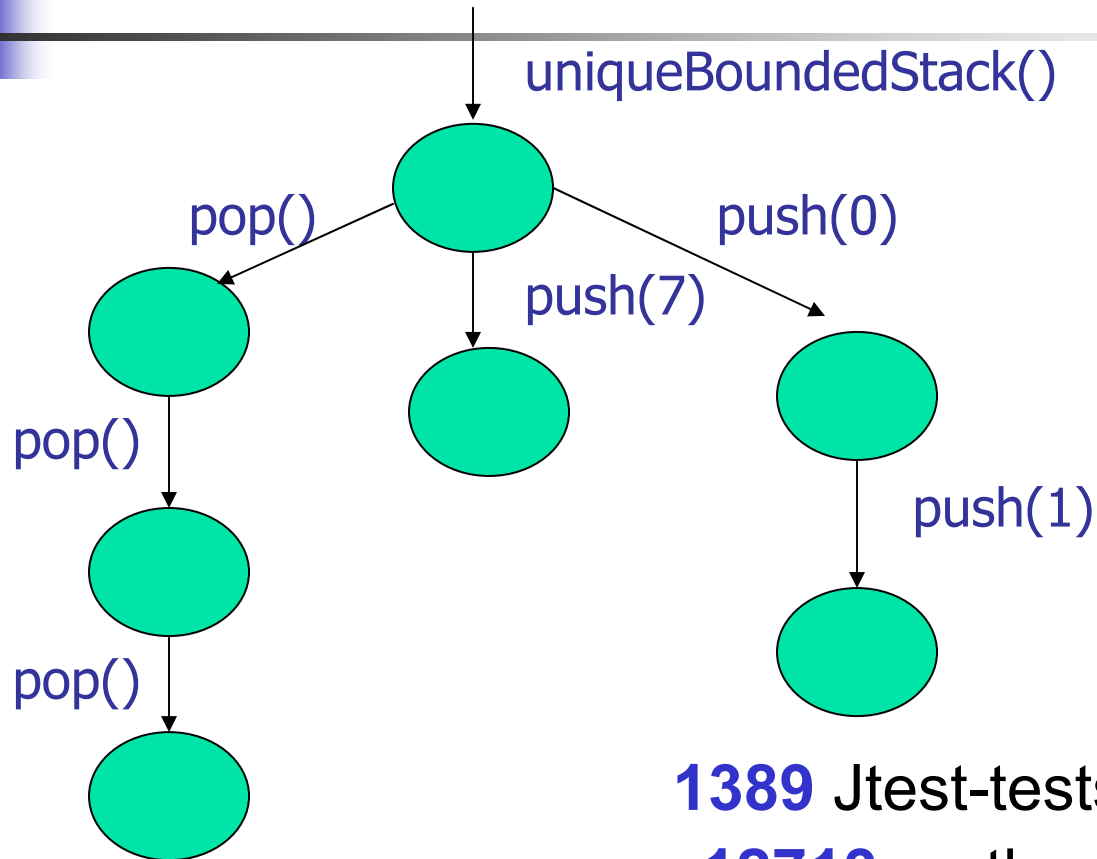
- Complementary technique: Select tests exercising at least one new structural entity.



Iterations

- Iterations stop until reaching fixed point or terminating conditions are satisfied, e.g. `size = max_size`
- Not all possible method pairs can be composed
 - In the first iteration, dummy axioms are generated
- Grow parameters
 - When the return of a method is the same type as a parameter
- Grow object states
 - Construct object state tree, only new object states are added to the tree

Object State Tree Growth - Example

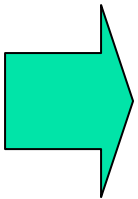


- 1389** Jtest-tests produces
- **12713** method executions
 - **63** distinct entry object states/args
 - **7** distinct object states!!

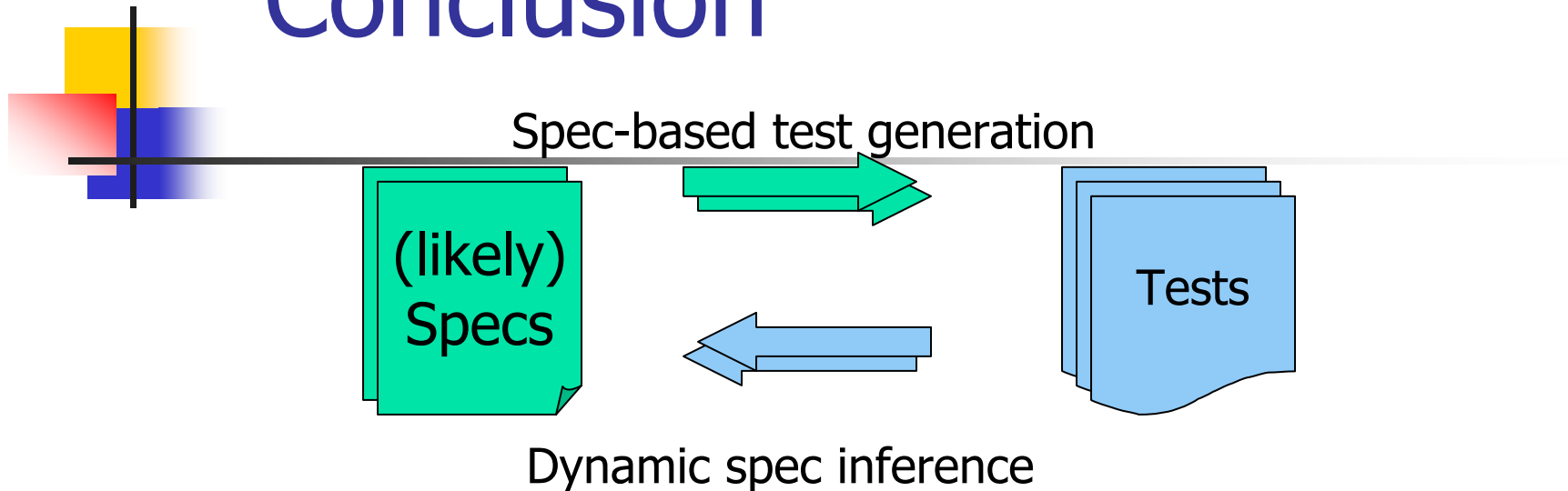


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Conclusion



- Feedback loop between test generation and spec inference
 - Axiomatic specs (integration of Daikon and Jtest)
 - Algebraic specs
- Aids in test generation (improving specs and helping in producing oracles)
- Aids in spec inference (improving the underlying test suites)



Questions?



Object State Collection - Complications

- “equals” may call other public methods
 - Keep track of call depth
- Object field’s object fields might be accessed
 - Tracked objects include “*this*”, referencing object fields transitively accessed from “*this*”.
 - Collect an object field value if its object is tracked
- More
 - Array element’s order doesn’t matter – access count heuristics
 - “equals(C obj)” method contains shortcut (if this == obj return true) – replace “return true” with nop