Automated Test-Input Generation

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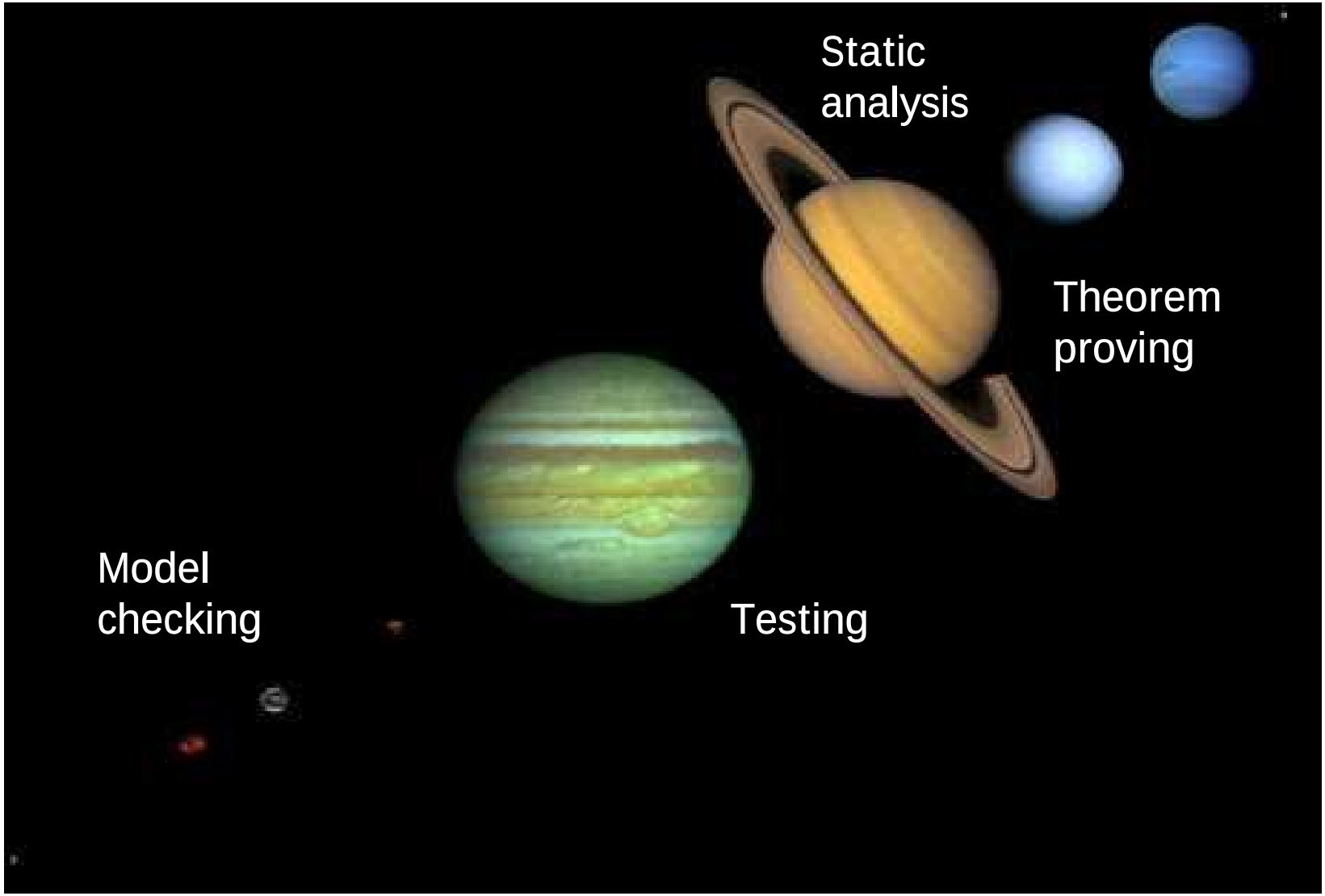
Why Automate Testing?

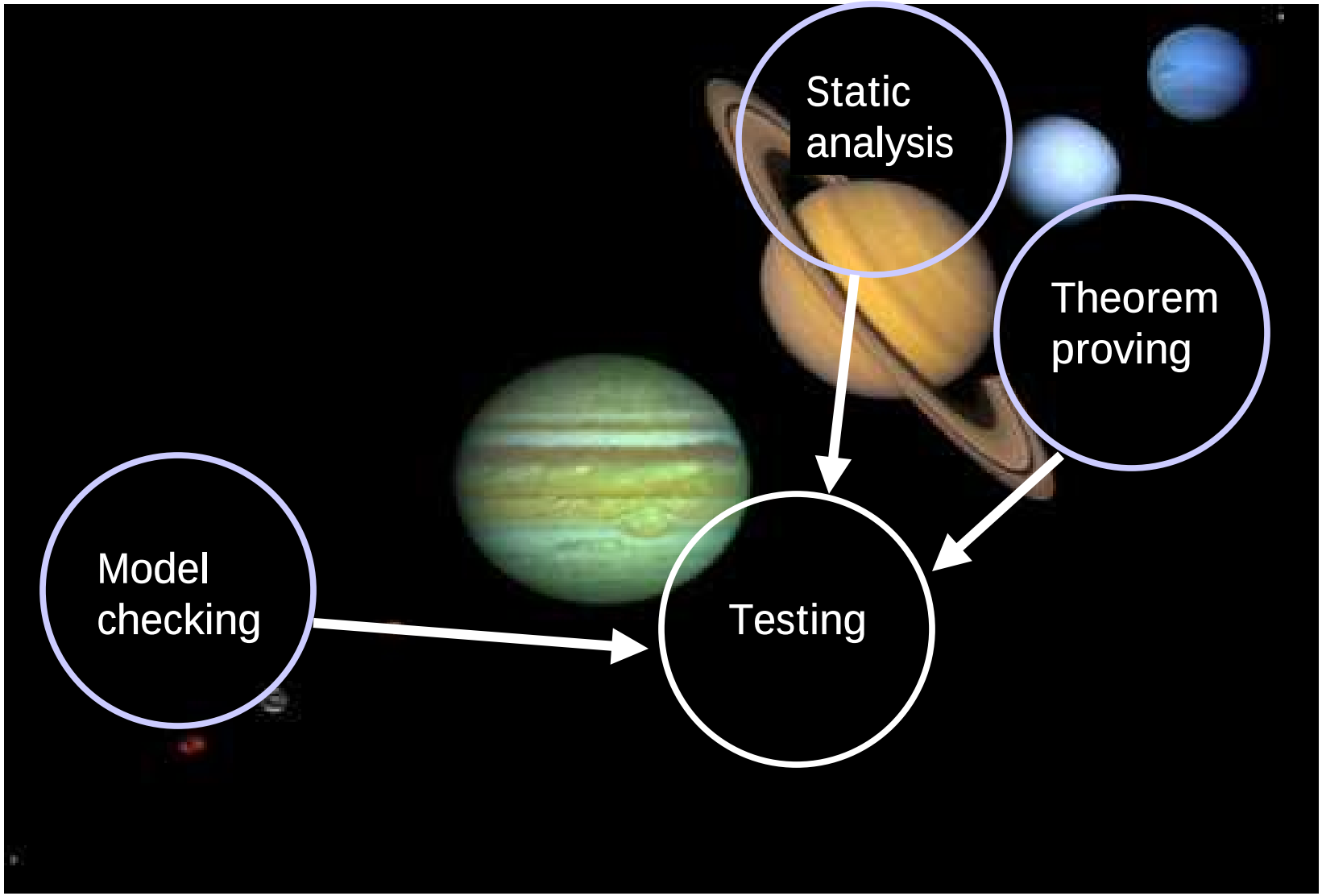
- Software testing is important
  - Software errors cost the U.S. economy about $59.5 billion each year (0.6% of the GDP) [NIST 02]
  - Improving testing infrastructure could save 1/3 cost
- Software testing is costly
  - Account for even half the total cost of software development [Beizer 90]
- Automated testing reduces manual testing effort
  - Test execution: JUnit framework
  - Test generation: Parasoft Jtest, Agitar Agitator, etc.
  - Test-behavior inspection: Agitar Agitator

Software Quality Assurance



Adapted from Doron Peled's slide

Software Quality Assurance



Adapted from Doron Peled's slide

Binary Search Tree Example

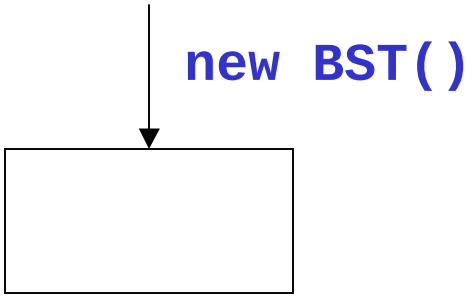
```
public class BST implements Set {
  static class Node {
    int val;
    Node left;
    Node right;
  }
  Node root;
  int size;
  public void insert (int value) { … }
  public void remove (int value) { … }
  public bool contains (int value) { … }
}
```

Approaches

- Method-sequence exploration
  - Parasoft Jtest 4.5 and others
- Specification-based state exploration
  - TestEra [Marinov&Khurshid ASE 01], Korat [Boyapati et al. ISSTA 02]
- Concrete-state exploration
  - Rostra [Xie et al. ASE 04], NASA JPF [Visser et al. ISSTA 04]
- Symbolic-state exploration
  - Symstra [Xie et al. TACAS 05]

Exploring Method Sequences

- Method arguments: **`insert(1), insert(2), insert(3), remove(1), remove(2), remove(3), contains(1)`**



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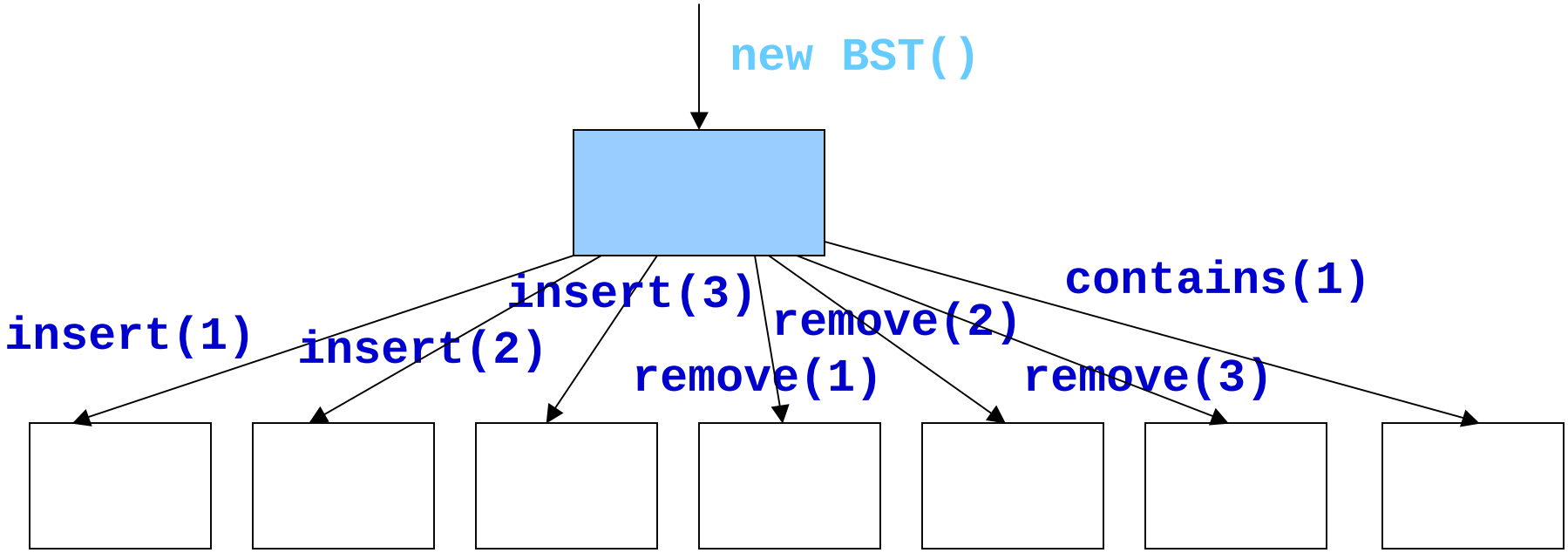

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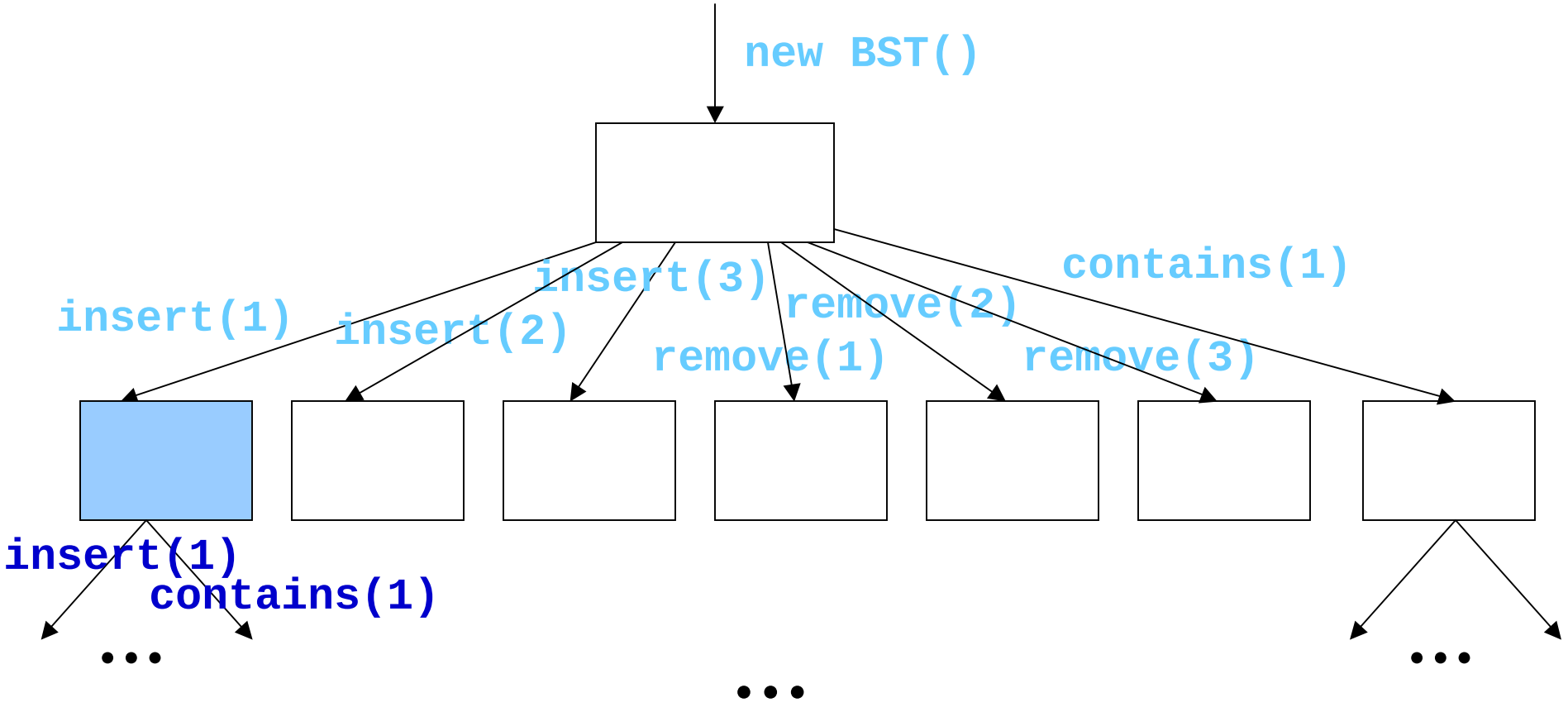
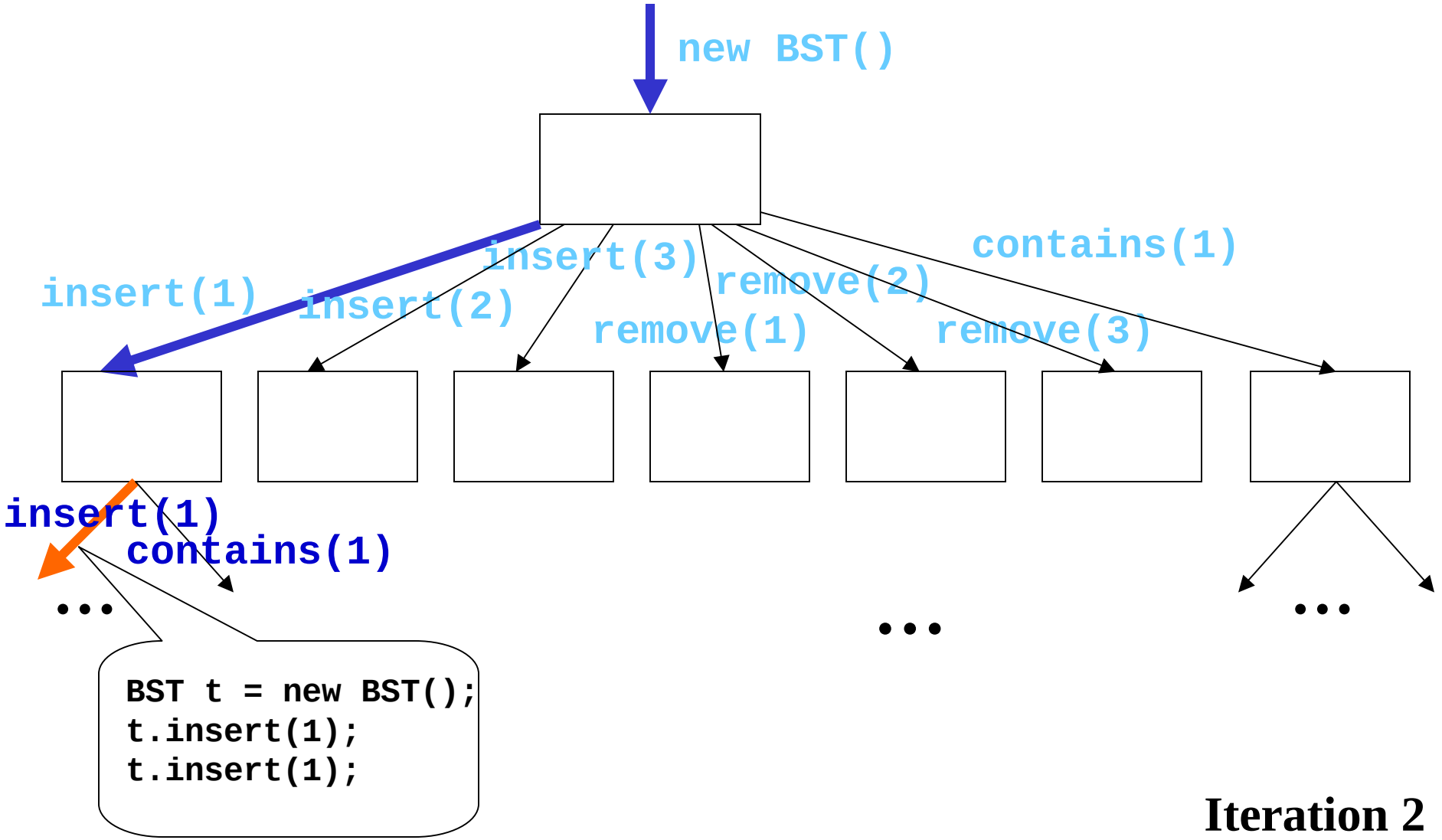


Generating Tests from Exploration

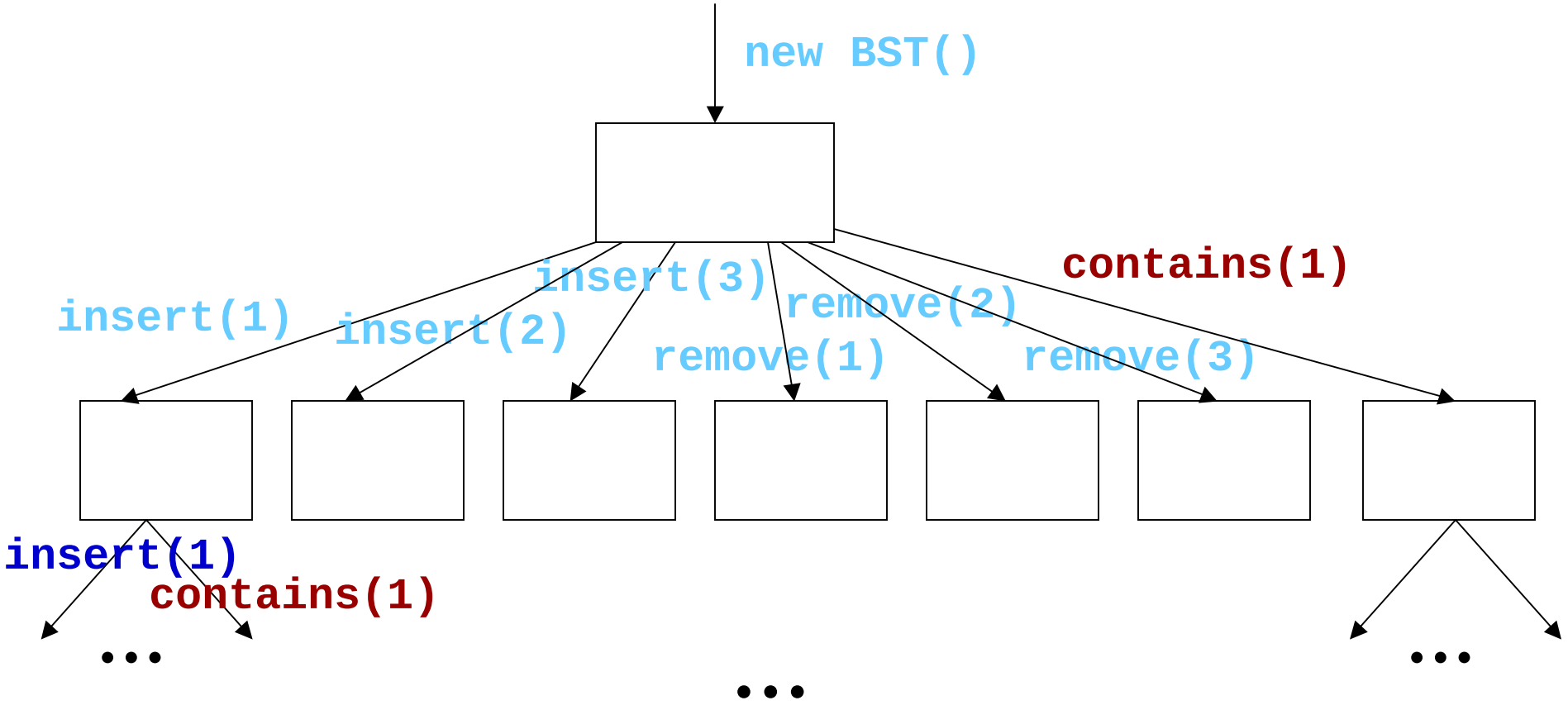
- Collect method sequence along the shortest path (constructor-call edge **à** each method-call edge)



Iteration 2

Pruning State-Preserving Methods

- Method arguments: `insert(1), insert(2), insert(3), remove(1), remove(2), remove(3), contains(1)`



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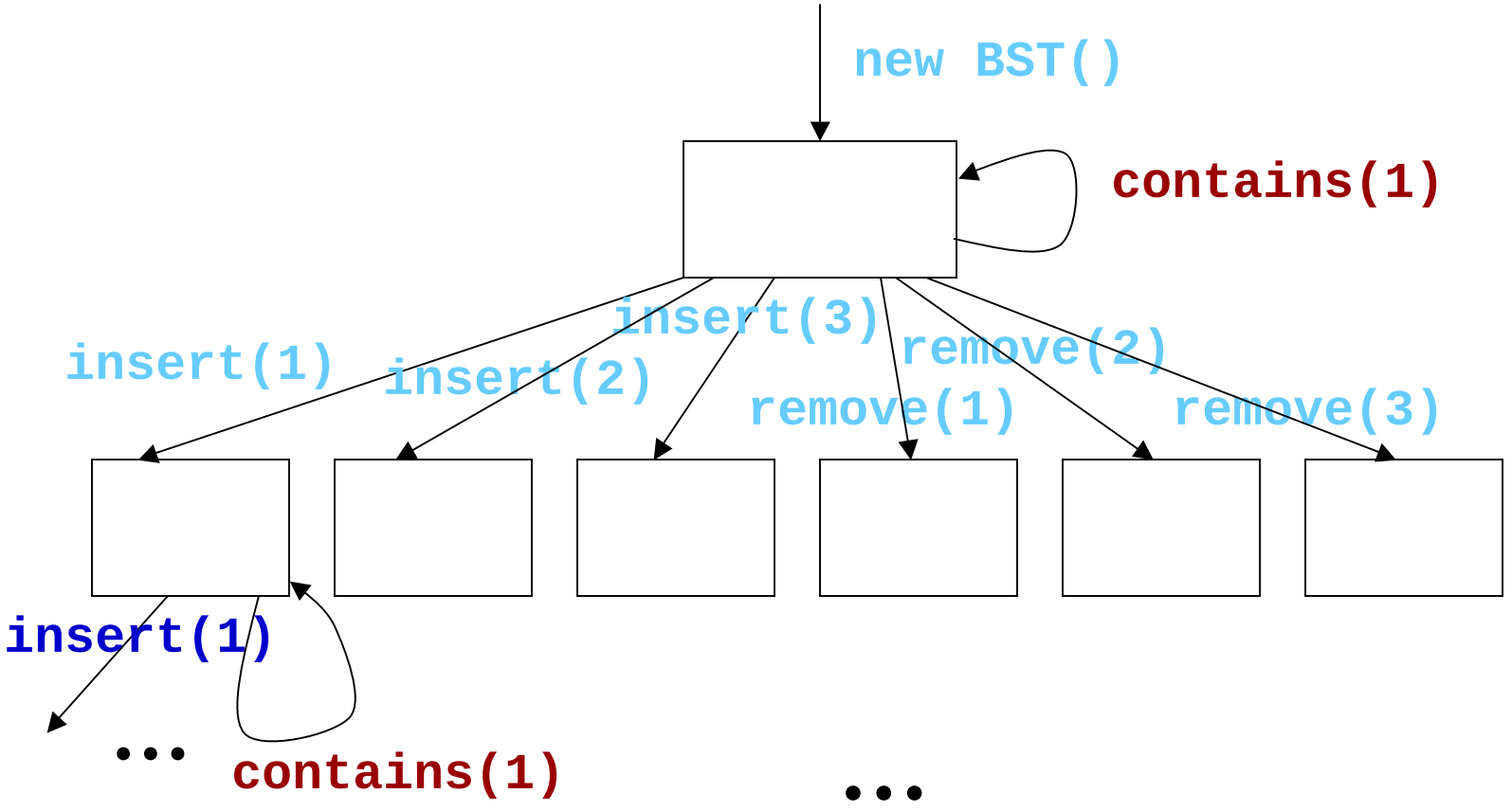
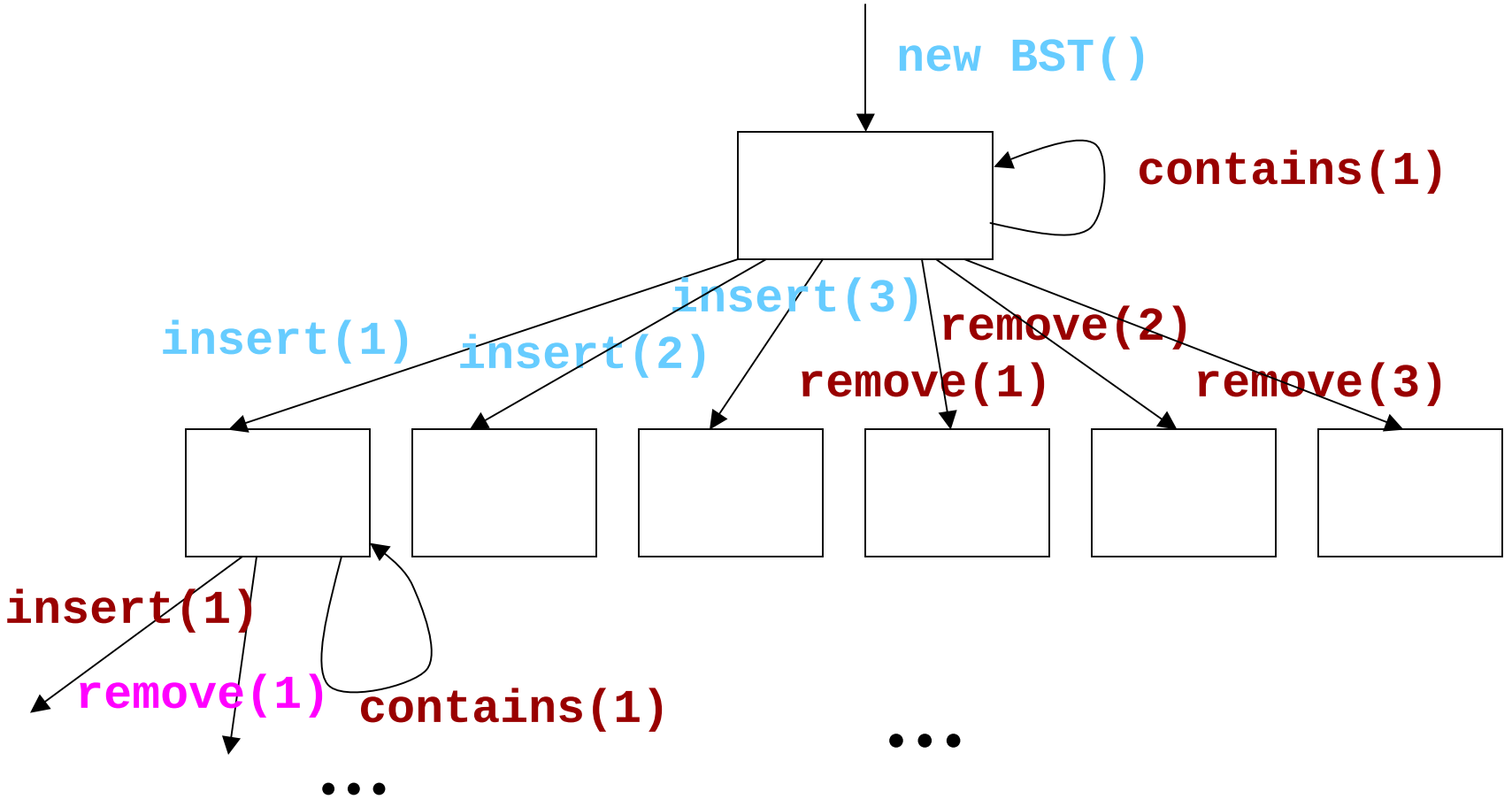


Observation

- Some method sequences lead receiver object states back to earlier explored states



Rationale

- Focus on each method execution individually

- When method executions are deterministic, unnecessary to test a method with the same inputs (same inputs ⇒ same behavior)
  - method inputs: incoming program states
    - receiver-object state: transitively-reachable-field values
    - arguments

Binary Search Tree Example

```
public class BST implements Set {
  //@ invariant       // class invariant for BST
  //@ repOk();
   Node root;
   int size;
   public void insert (int value) { … }
   public void remove (int value) { … }
   public bool contains (int value) { … }
}
```

- If receiver-object states are directly constructed, we need to have a way to know valid object states
  - defined by a Java predicate: **`repOK`**

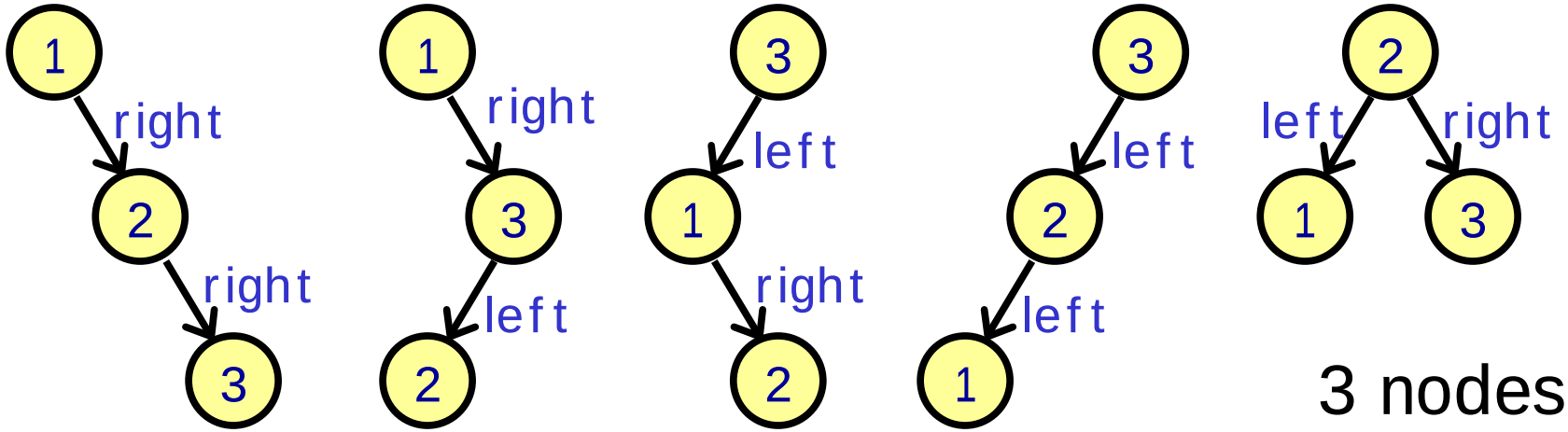
repOk (Class Invariant)

```
boolean repOk() {
  if (root == null) return size == 0;  // empty tree has size 0
  Set visited = new HashSet(); visited.add(root);
  List workList = new LinkedList(); workList.add(root);
  while (!workList.isEmpty()) {
    Node current = (Node)workList.removeFirst();
    if (current.left != null) {
      if (!visited.add(current.left)) return false; // acyclicity
      workList.add(current.left);
    }
    if (current.right != null) {
      if (!visited.add(current.right)) return false; // acyclicity
      workList.add(current.right);
    }
  }
  if (visited.size() != size) return false; // consistency of size
  if (!isOrdered(root)) return false;       // data is ordered
  return true;
}
```

Korat

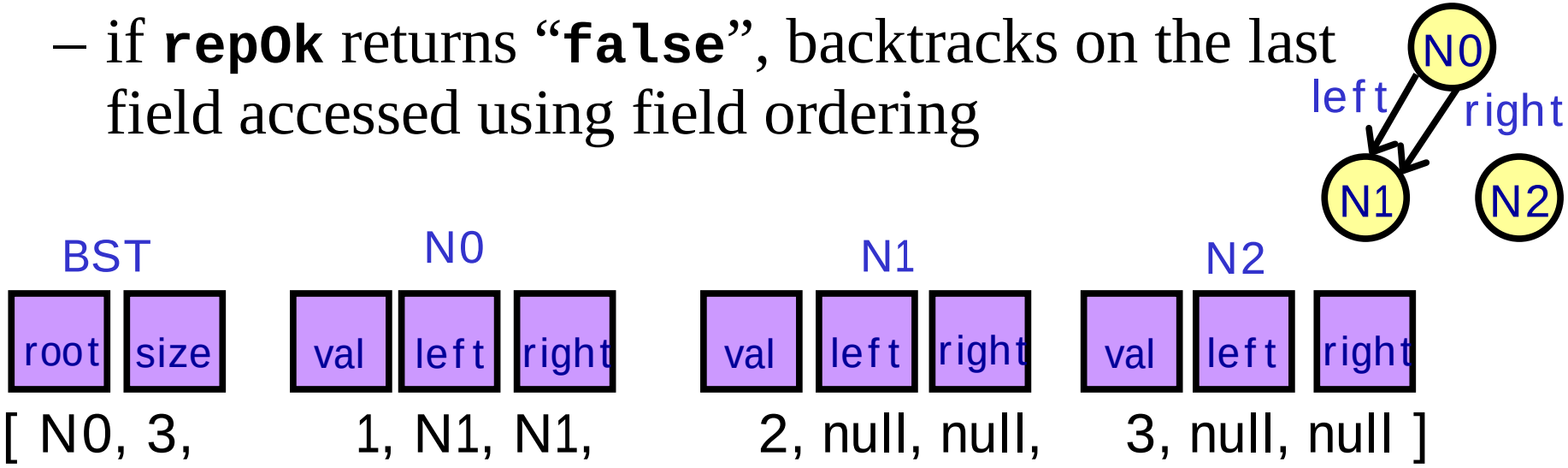
[Boyapati et al. ISSTA 02]

- Given predicate *p* and finitization *f*, generate all inputs for which *p* returns "*true*"
  - uses finitization to define input space
    - e.g., defines #nodes and what values can be on a BST node.
  - systematically explores valid input space
    - prunes input space using field accesses



Korat's Smart Search

- candidate is a vector of field domain indices
- for each candidate vector, Korat
  - creates corresponding structure
  - invokes **`repOk`** and monitors the execution
  - builds field ordering, i.e., list of fields ordered by time of first access
  - if **`repOk`** returns "**`true`**", outputs structure(s)
  - if **`repOk`** returns "**`false`**", backtracks on the last field accessed using field ordering



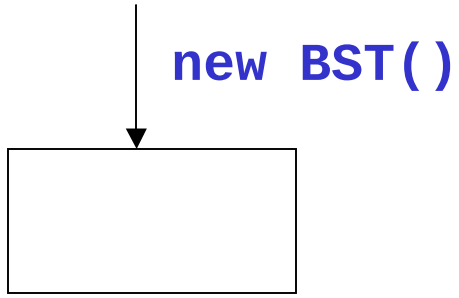
What if `repOK` is not there

- Then direct construction of valid object states seem impossible

- Solution: fall back to building valid object states with method sequences but in a smarter way
  - method-sequence exploration
    - assume a state-modifying method leads to a new object state
  - explicit-state exploration
    - inspect whether an object state is actually new (defined by transitively-reachable-field values)

Exploring Concrete States

- Method arguments: **`insert(1), insert(2), insert(3), remove(1), remove(2), remove(3)`**



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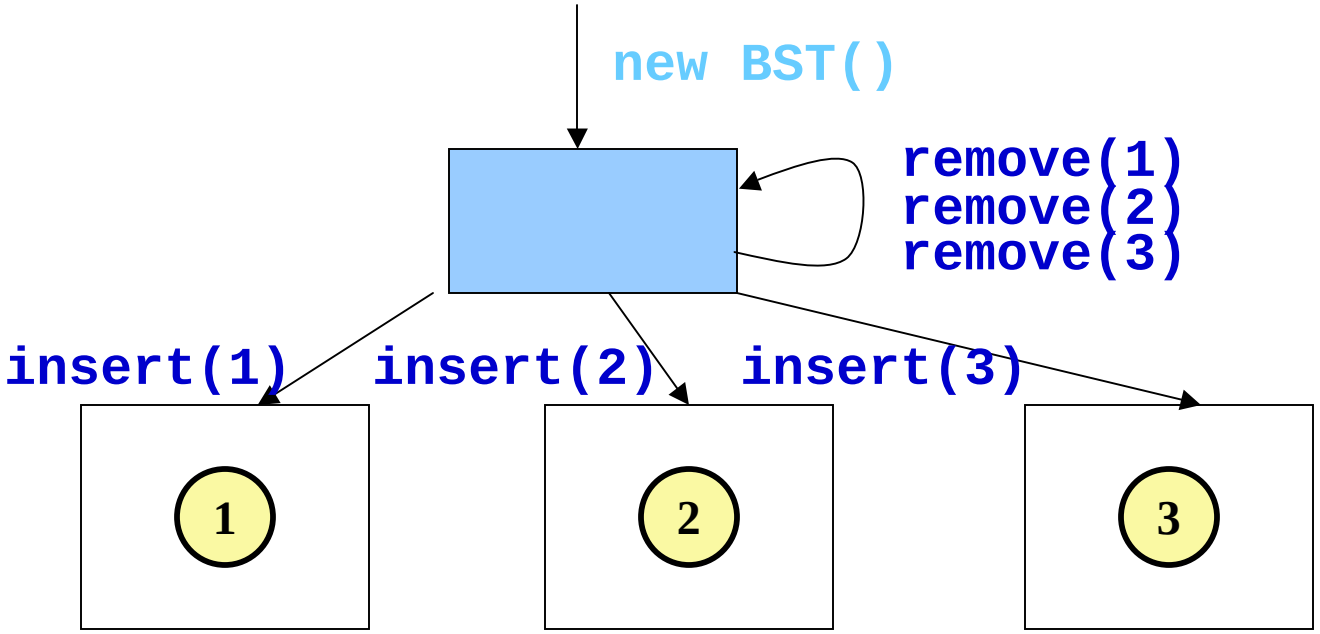

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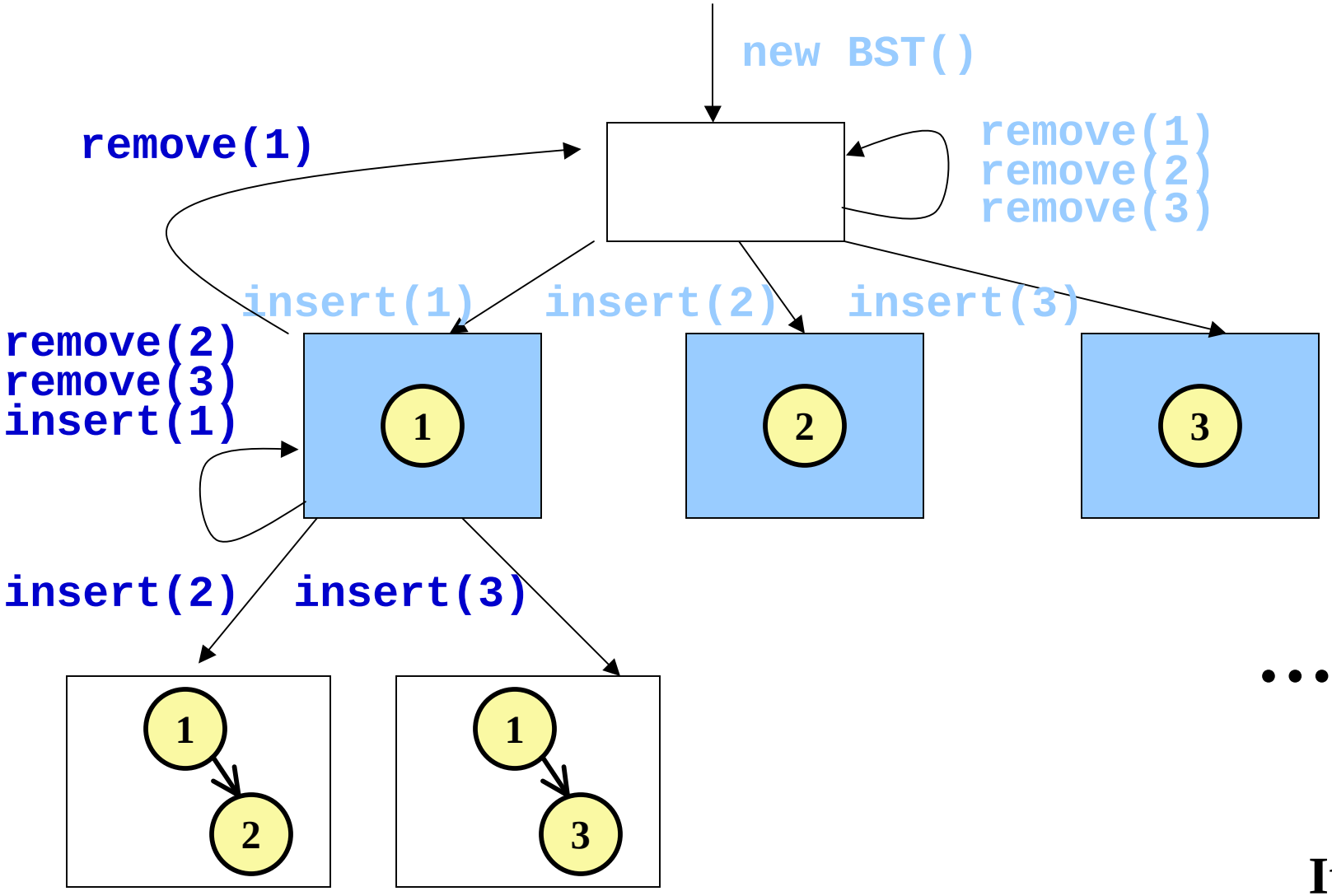
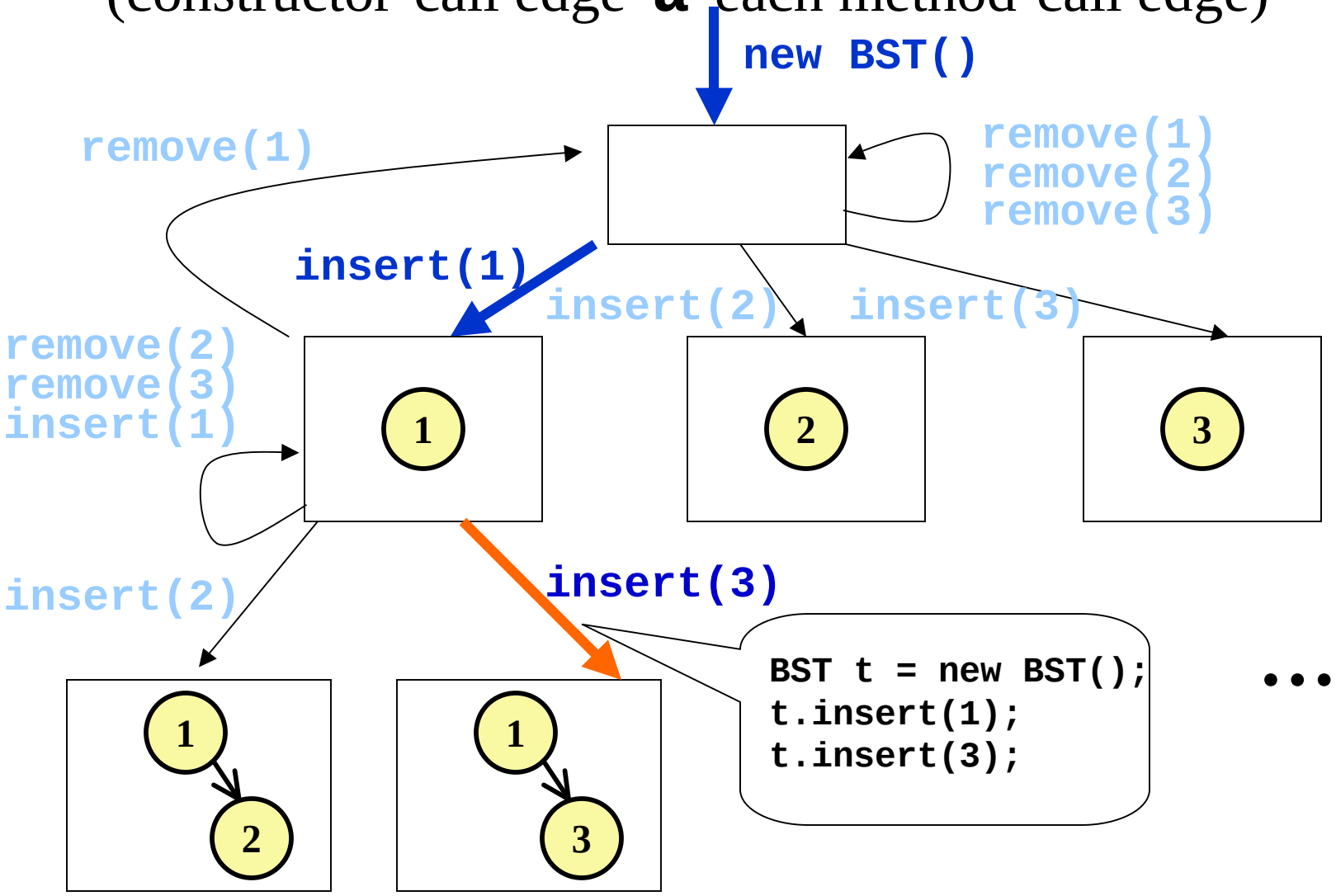


Iteration 2

Generating Tests from Exploration

- Collect method sequence along the shortest path (constructor-call edge **à** each method-call edge)



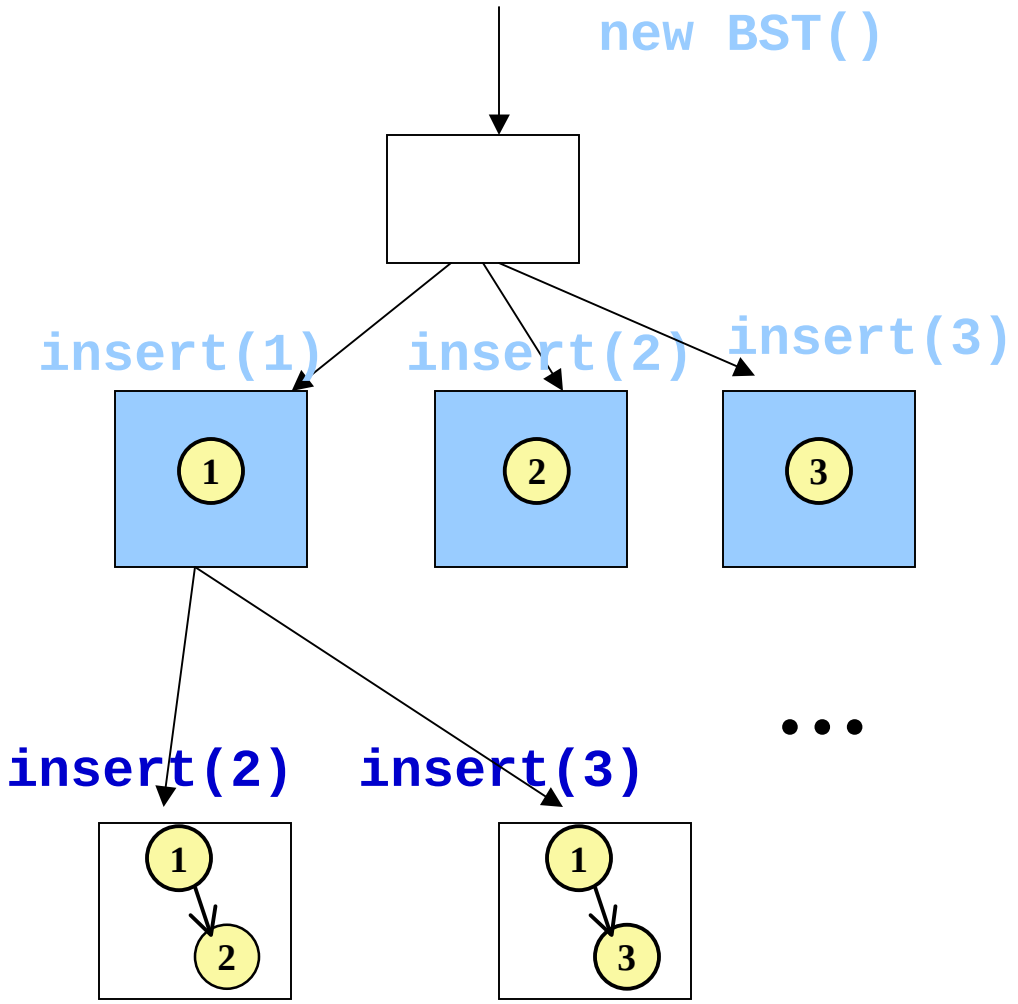
Improvement over Method-Sequence Exploration

- Industry standard tool adopting previous approach based on method sequences
  - Parasoft Jtest 4.5 www.parasoft.com
    - Generate tests with method-call lengths up to three
- Use Jtest to generate tests for 11 Java classes from various sources
  - most are complex data structures
- Apply Rostra on the Jtest-generated tests
  - 90% of generated tests are redundant, i.e., 90% tests contain no new method inputs

Issues of Concrete-State Exploration

- State explosion
  - need at least *N* different **`insert`** arguments to reach a BST with size *N*
  - run out of memory when *N* reaches 7
- Relevant-argument determination
  - assume a set of given relevant arguments
    - e.g., **`insert(1), insert(2), insert(3), etc.`**

Exploring Concrete States



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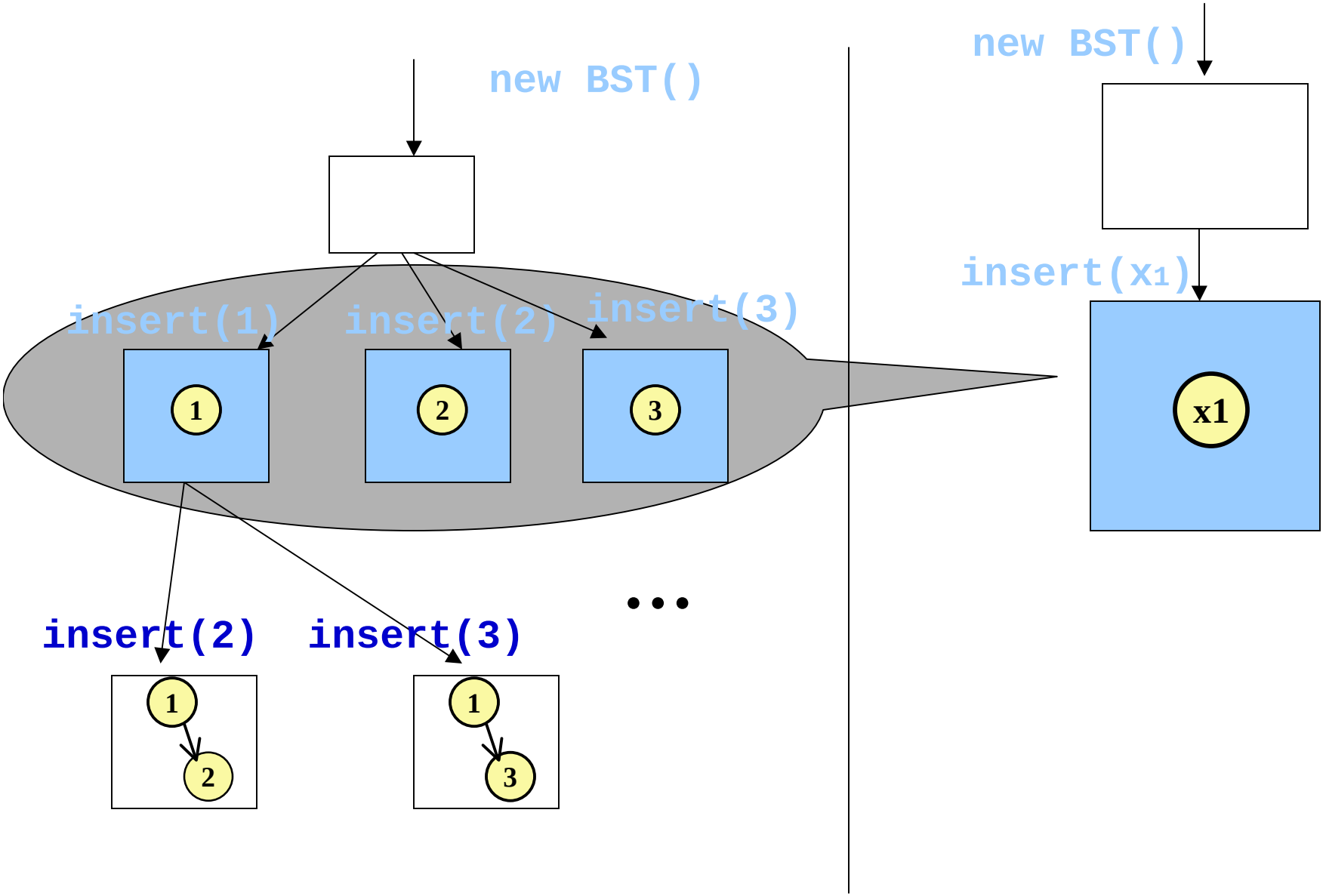
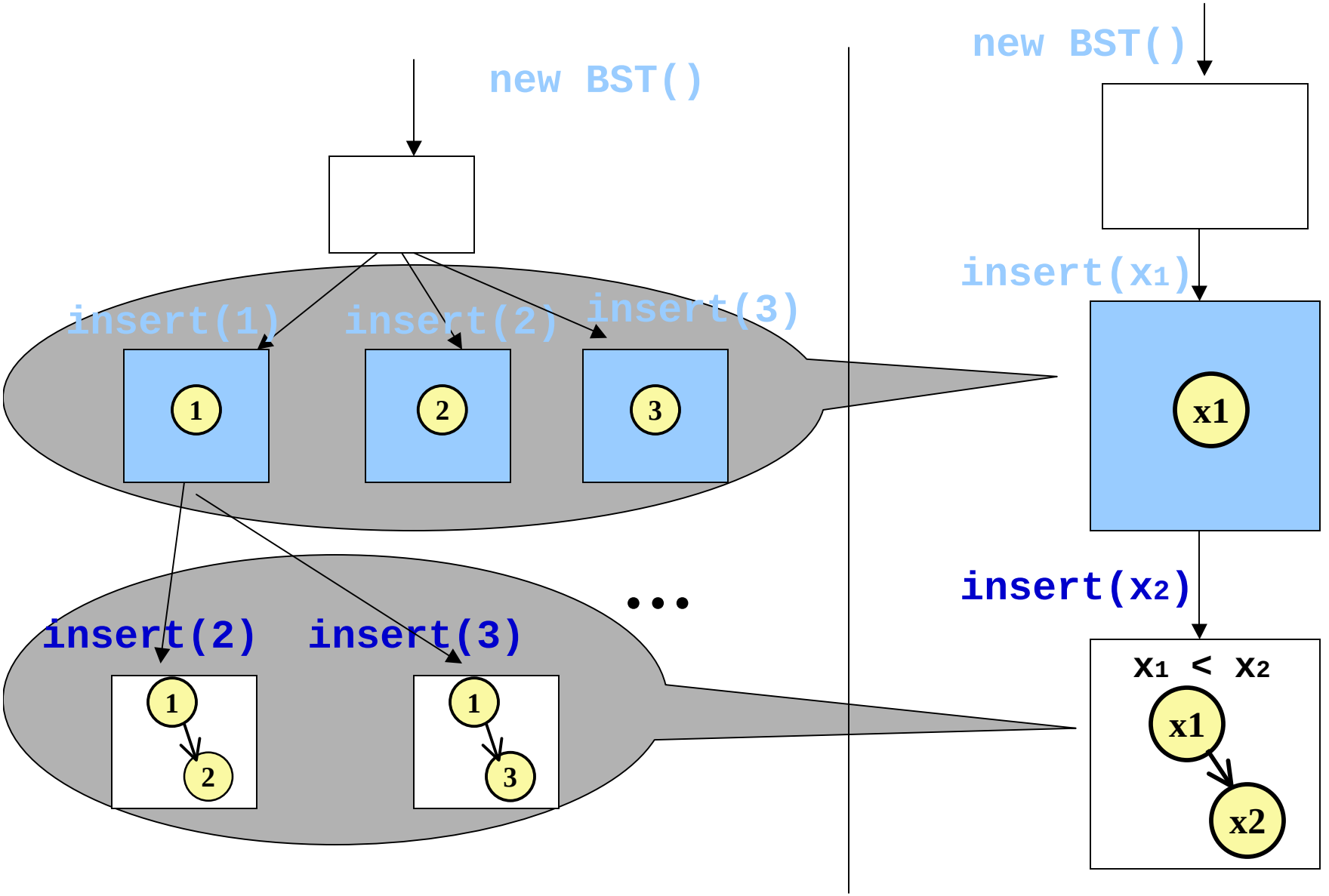
State Abstraction: Symbolic States



Iteration 2

State Abstraction: Symbolic States

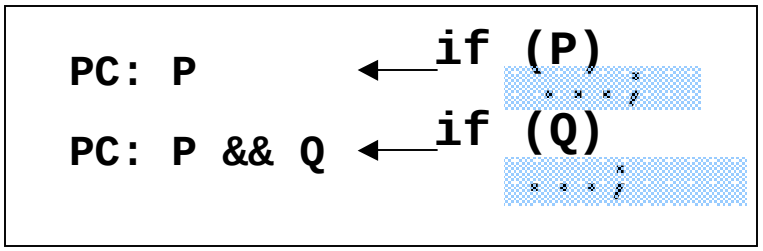


Iteration 2

Symbolic Execution

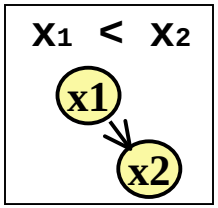
- Execute a method on symbolic input values
  - inputs: **`insert(SymbolicInt x)`**

- Explore paths of the method



- Build a path condition for each path
  - conjunct conditionals or their negations

- Produce symbolic states (<heap, path condition>)
  - e.g.,



Symbolic Execution Example

```
public void insert(SymbolicInt x) {
 if (root == null) {
   root = new Node(x);
 } else {
   Node t = root;
   while (true) {
    if (t.value < x) {
      //explore the right subtree
       ...

    } else if (t.value > x) {
      //explore the left subtree
       ...

    } else return;
  }
 }
 size++;
}
```

Exploring Symbolic States

```
public void insert(SymbolicInt x) {
 if (root == null) {
   root = new Node(x);
 } else {
   Node t = root;
   while (true) {
    if (t.value < x) {
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    } else return;
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}
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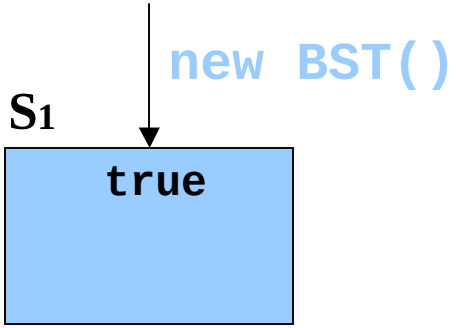

Exploring Symbolic States

```
public void insert(SymbolicInt x) {
 if (root == null) {
    root = new Node(x);
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    Node t = root;
    while (true) {
     if (t.value < x) {
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     } else if (t.value > x) {
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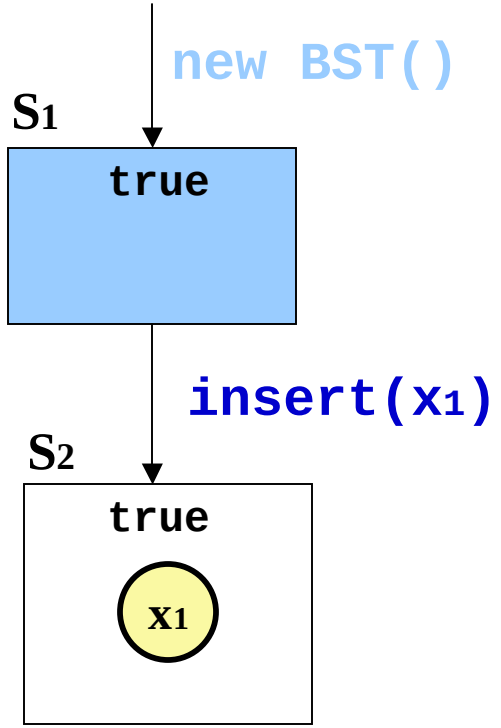
     } else return;
   }
 }
 size++;
}
```



Iteration 1

Exploring Symbolic States

```
public void insert(SymbolicInt x) {
 if (root == null) {
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 } else {
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   while (true) {
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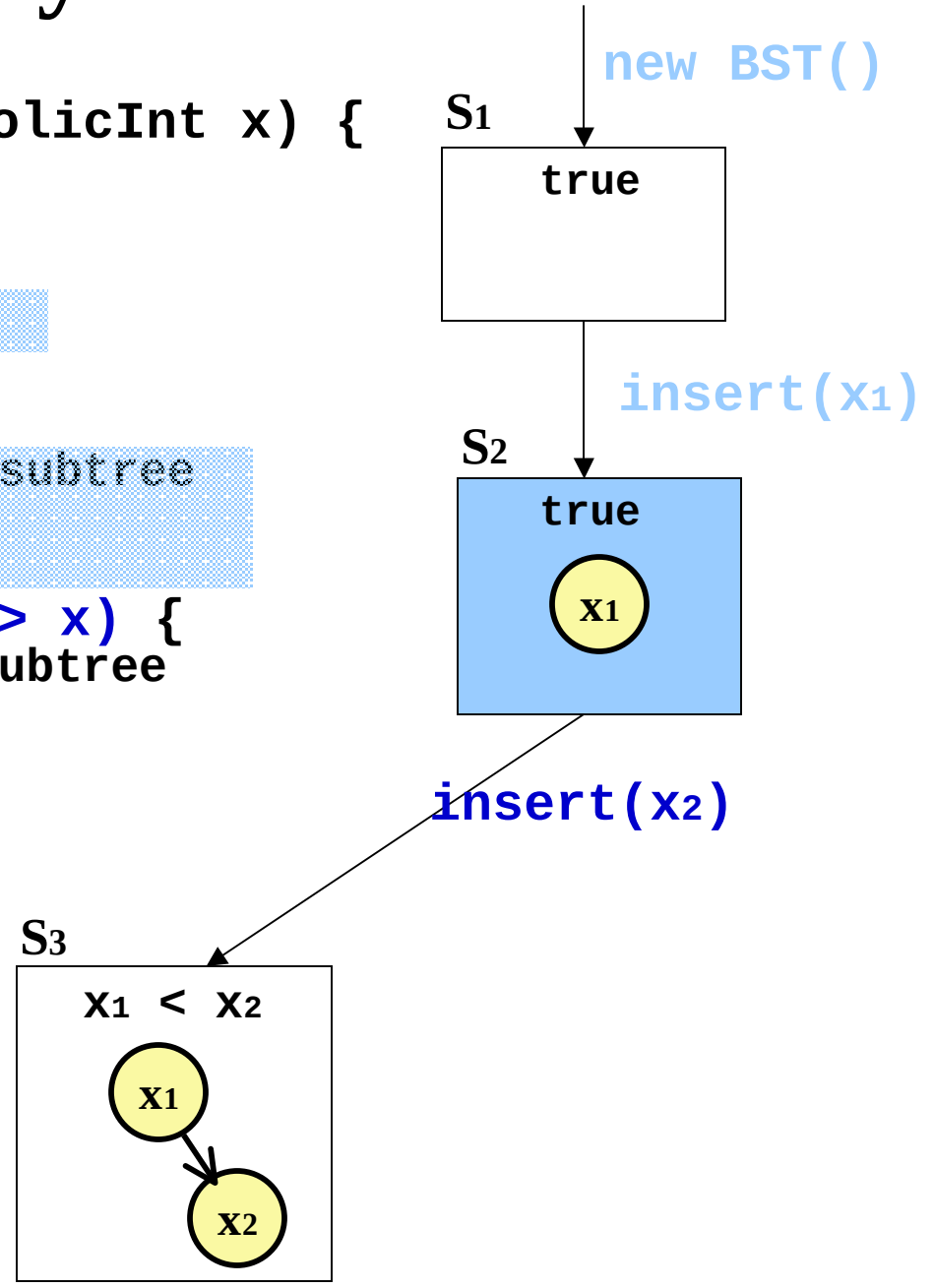
       ...
    } else return;
  }
 }
 size++;
}
```



Iteration 2

Exploring Symbolic States

```
public void insert(SymbolicInt x) {
 if (root == null) {
   root = new Node(x);
 } else {
   Node t = root;
   while (true) {
    if (t.value < x) {
      //explore the right subtree
       ...

    } else if (t.value > x) {
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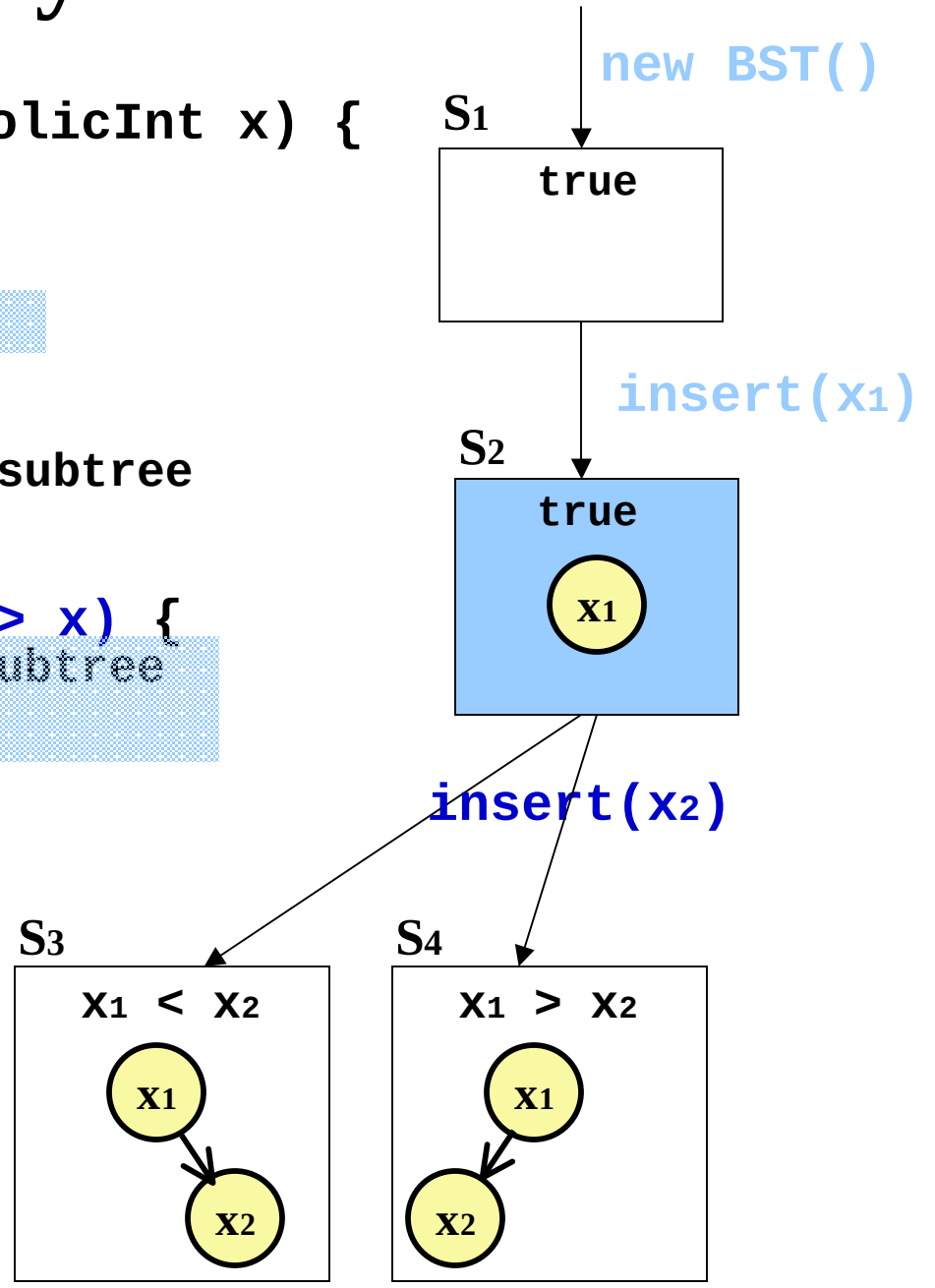
      ...

    } else return;
  }
 }
 size++;
}
```



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Exploring Symbolic States

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}
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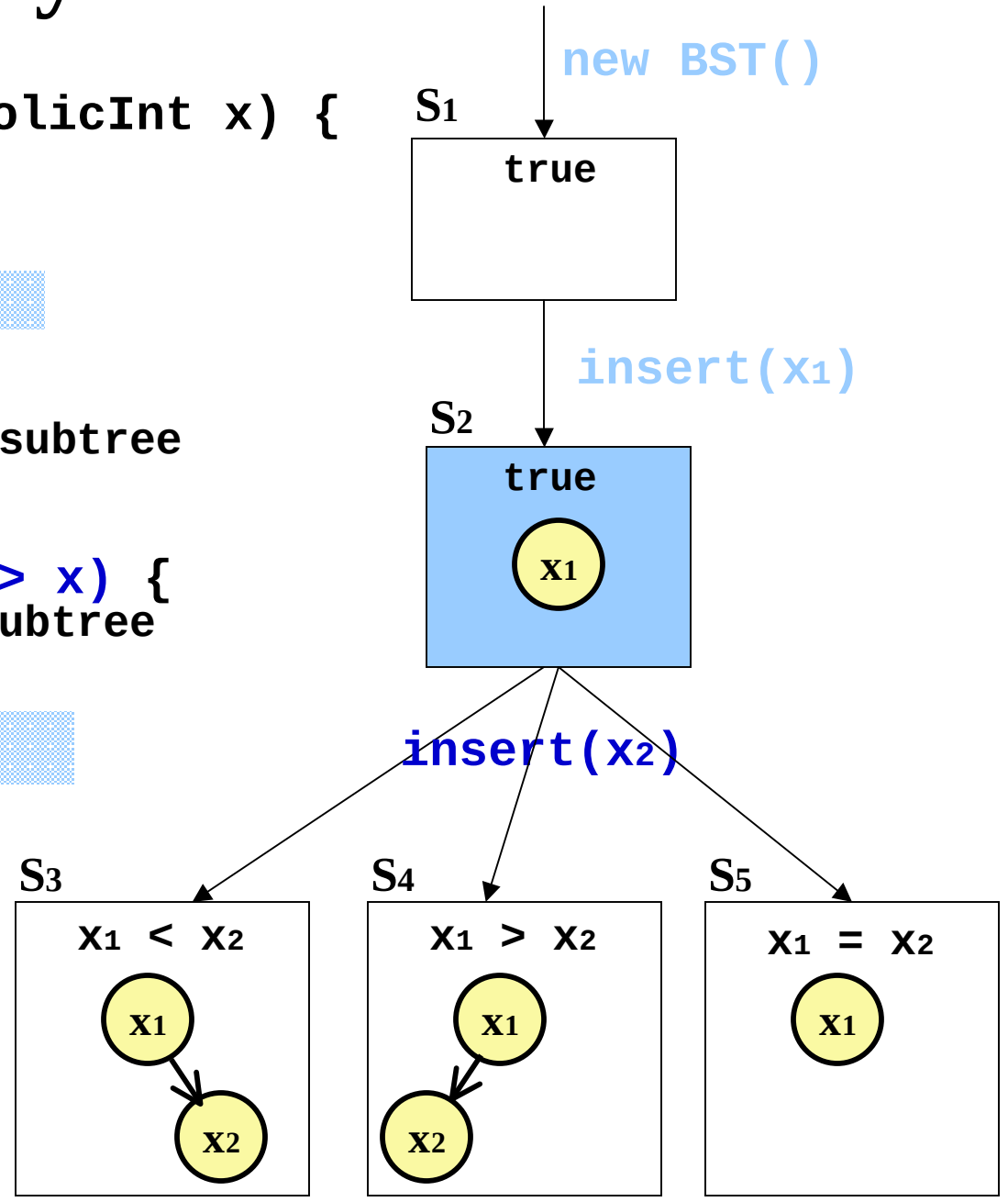


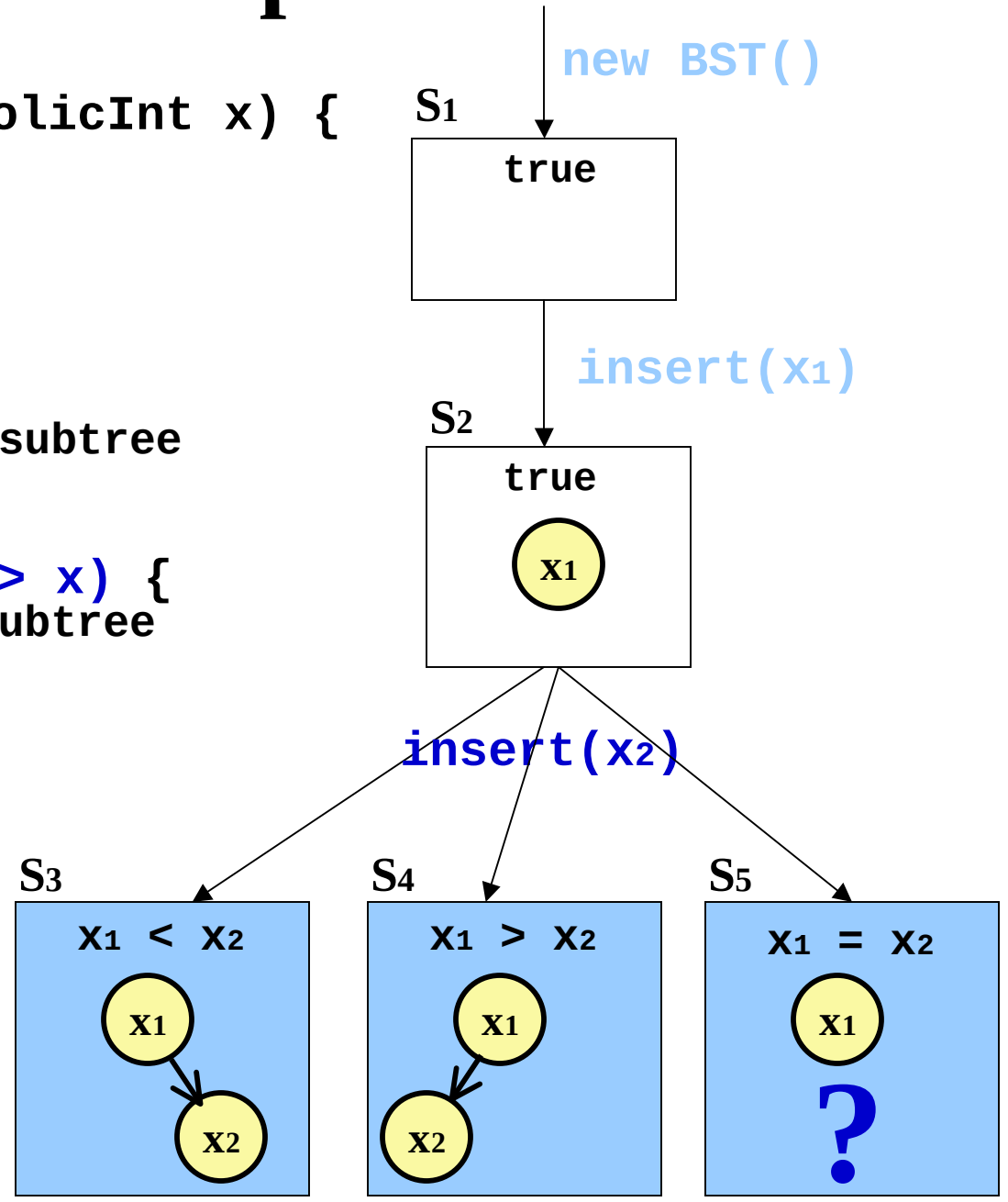
Iteration 2

Which States to Explore Next?

```
public void insert(SymbolicInt x) {
 if (root == null) {
   root = new Node(x);
 } else {
   Node t = root;
   while (true) {
    if (t.value < x) {
      //explore the right subtree
       ...

    } else if (t.value > x) {
      //explore the left subtree
       ...

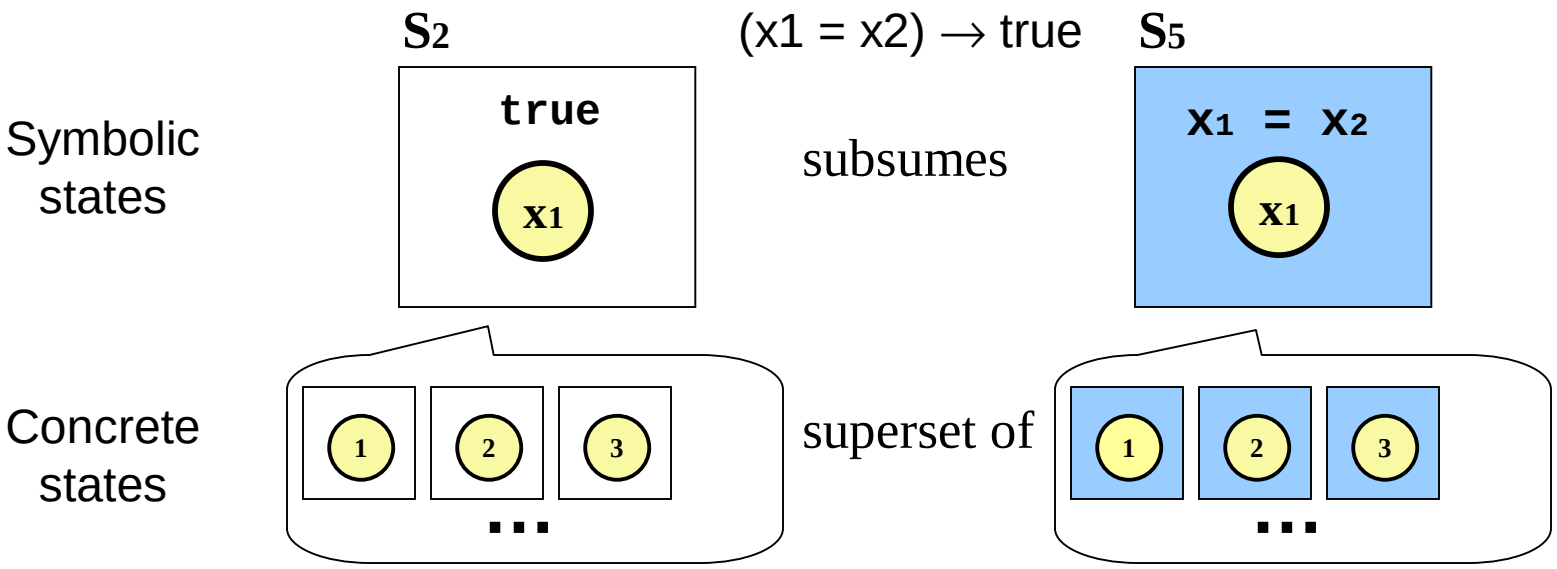
    } else return;
  }
 }
 size++;
}
```



Iteration 3

Symbolic State Subsumption

- Symbolic state S_2:<H_2, c_2> subsumes S_5:<H_5, c_5>
  - Heaps H2 and H5 are isomorphic
  - Path condition $c_5 \rightarrow c_2$ [checked using CVC Lite, Omega]
- If S_2 has been explored, S_5 is pruned.
  - Still guarantee path coverage within a method



Pruning Symbolic State

```
public void insert(SymbolicInt x) {
 if (root == null) {
   root = new Node(x);
 } else {
   Node t = root;
   while (true) {
    if (t.value < x) {
      //explore the right subtree
       ...

    } else if (t.value > x) {
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       ...

    } else return;
  }
 }
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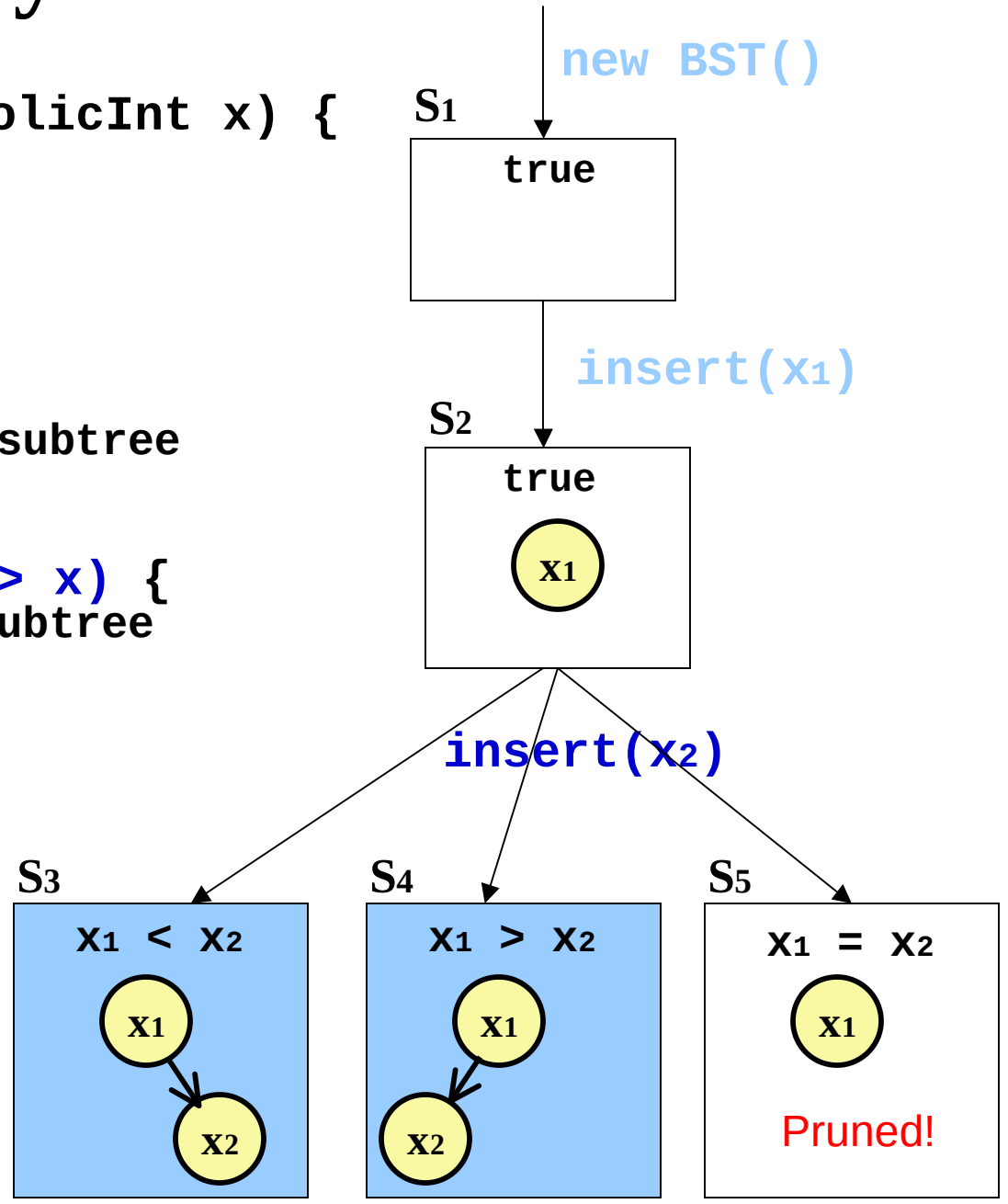
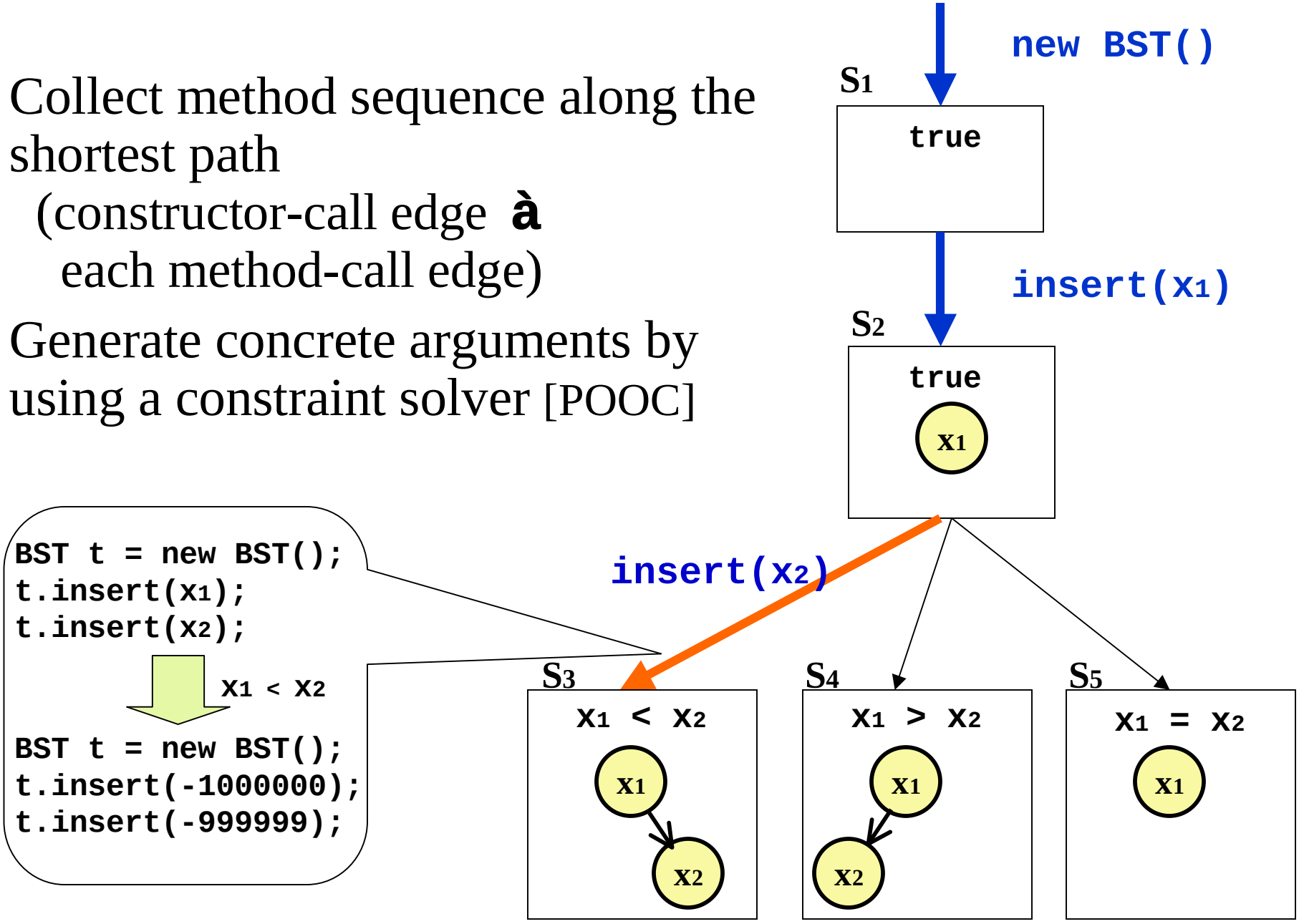
}
```



Iteration 3

Generating Tests from Exploration

- Collect method sequence along the shortest path
  (constructor-call edge **à** each method-call edge)
- Generate concrete arguments by using a constraint solver [POOC]



Improvement over Concrete-State Exploration

- Focus on the key methods (e.g., `add`, `remove`)
- Generate tests up to 8 iterations
  - Concrete-State vs. Symstra
- Measure #states, time, and branch coverage

- Experimental results show Symstra effectively
  - reduces the state space for exploration
  - reduces the time for achieving branch coverage

Statistics of Some Programs

class	N	Concrete-State			Symstra		
		Time (sec)	#states	%cov (branch)	Time (sec)	#states	%cov (branch)
BinarySearchTree	6	23	731	100	29	197	100
	7	Out of Memory			137	626	100
	8				318	1458	100
BinomialHeap	6	51	3036	84	3	7	84
	7	Out of Memory			4	8	90
	8				9	9	91
LinkedList	6	412	9331	100	0.6	7	100
	7	Out of Memory			0.8	8	100
	8				1	9	100
TreeMap	6	12	185	83	8	28	83
	7	42	537	84	19	59	84
	8	Out of Memory			63	111	84

Summary

- Method-sequence exploration
  - Parasoft Jtest 4.5 and others
- Specification-based state exploration
  - TestEra [Marinov&Khurshid ASE 01], Korat [Boyapati et al. ISSTA 02]
- Concrete-state exploration
  - Rostra [Xie et al. ASE 04], NASA JPF [Visser et al. ISSTA 04]
- Symbolic-state exploration
  - Symstra [Xie et al. TACAS 05]
- More recently: concolic-state exploration
  - DART [Godefroid et al. PLDI 05], EGT [Cadar&Engler SPIN 05], CUTE [Sen et al. FSE 05]

Questions?