Efficient Synthesis of Method Call Sequences for Test Generation and Bounded Verification

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Outline

1. Background and motivation
2. Algorithm with a running example
3. Evaluation

Background

- Test Generation

```
? ?
void fun1(int x, int y) {
    int u = f(x);
    int v = g(y);
    ...
    if (u < v) {
        // ERROR!
    }
}
```

- Bounded Verification

A bounded input space

```
void fun2(int x, int y) {
    while (...) {
        x = f(x);
        y = g(y);
    }
    ...
    assert(x != y);
}
```

Background

- Test Generation
- Bounded Verification

```
Heap-based data structures: List, Stack, Tree, Graph, ...
```

```
void fun1(T o, int y) {
    T u = o.m1();
    int v = g(y);
    ...
    if (u.m2(v) < 0) {
        // ERROR!
    }
}
```

```
void fun2(T o, int y) {
    while (...) {
        o = o.m1();
        y = g(y);
    }
    ...
    assert(o.m2(y) != 0);
}
```

How to determine the existence of, and further construct, an input heap state that satisfies a given specification?

A Simple Java Class

```
class Node {
   private Node next;
   private int value;
   private Node(Node n, int v) {
      this.next = n;
      this.value = v;
   }

   public static Node create(int v, boolean b) {
      if (b == true)
         return new Node(null, v * 2);
      else return new Node(null, v * 2 + 1);
   }
   ...
```

fields

constructor

static factory method

```
   ...
   public Node getNext() {
      return this.next;
   }
   public int getValue() {
      return this.value;
   }
   public void addAfter(int v) {
      this.next = new Node(null, v);
   }
   public Node addBefore(int v) {
      return new Node(this, v);
   }
}
```

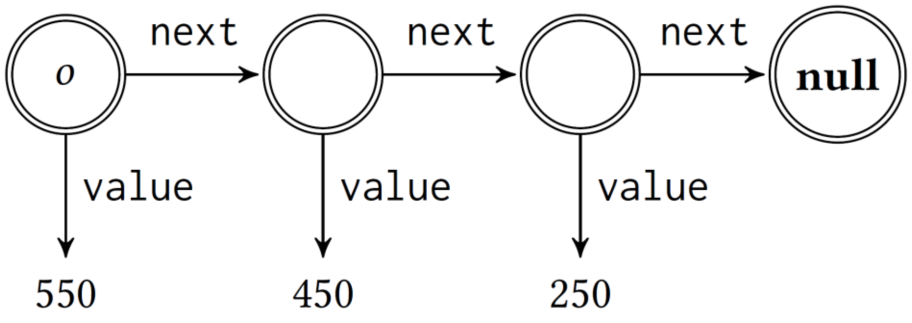
instance methods

A Simple Specification

```
class Node {
    private Node next;
    private int value;
    ...
}
```

```
boolean TEST(Node o) {
   return (o.value – o.next.value == 100) &&
      (o.next.value – o.next.next.value == 200) &&
      (o.value + o.next.next.value == 800);
}
```

A specification



A solution

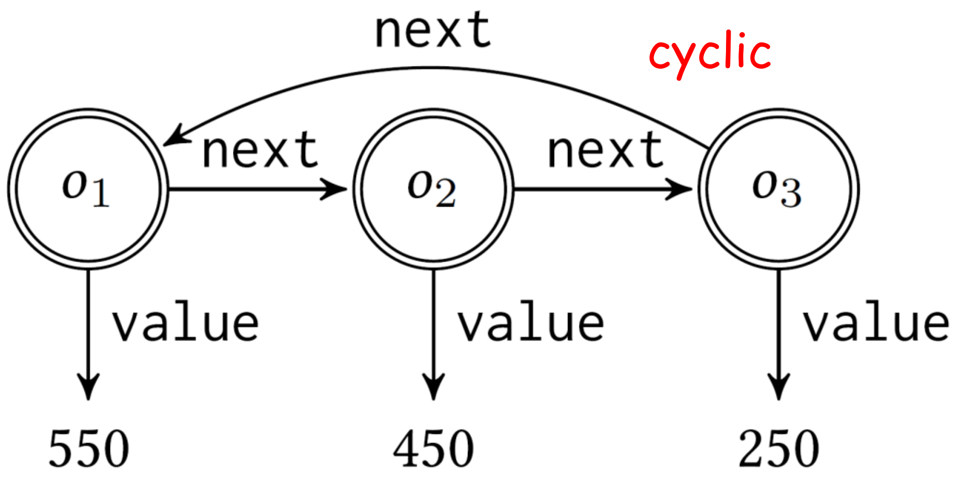
```
550 – 450 = 100
450 – 250 = 200
550 + 250 = 800
```

Existing Work

```
class Node {
    private Node next;
    private int value;
    ...
}
```

- Direct construction approaches
  - directly assign values to the fields of the heap objects
  - *Korat* [Boyapati et al. 2002], *JBSE* [Braione et al. 2015], ...

```
Node o1 = new Node(...);
Node o2 = new Node(...);
Node o3 = new Node(...);
o1.next = o2; o1.value = 550;
o2.next = o3; o2.value = 450;
o3.next = o1; o3.value = 250;
```



violate the accessibility rules

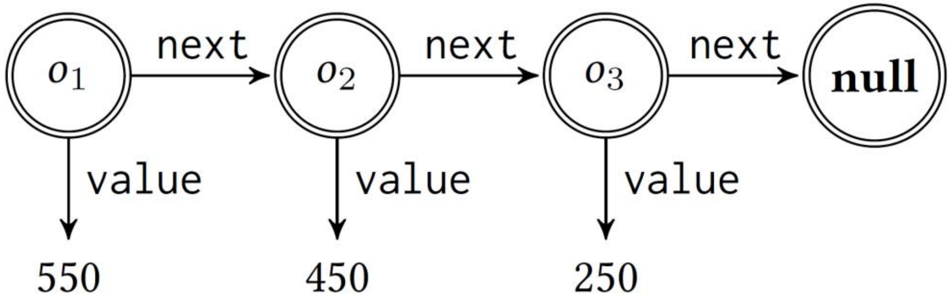
produce invalid/unreachable heap states

Existing Work

```
class Node {
    ...
    public static Node create(int v, boolean b);
    public Node addBefore(int v);
}
```

- Sequence generation approaches
  - synthesize and execute a sequence of calls to the public methods
  - *Seeker* [Thummalapenta et al. 2011], *SUSHI* [Braione et al. 2017], ...

```
Node o3 = Node.create(125, true);
Node o2 = o3.addBefore(450);
Node o1 = o2.addBefore(550);
```



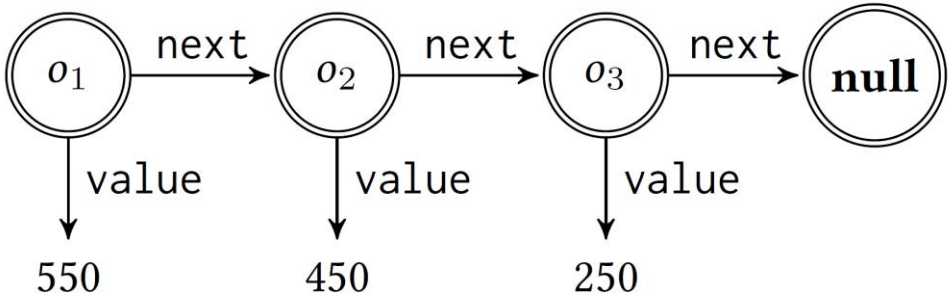
SUSHI, the previous state-of-the-art approach, fails to synthesize such a method call sequence within 10 hours

Existing Work

```
class Node {
   ...
   public static Node create(int v, boolean b);
   public Node addBefore(int v);
}
```

- Sequence generation approaches
  - synthesize and execute a sequence of calls to the public methods
  - *Seeker* [Thummalapenta et al. 2011], *SUSHI* [Braione et al. 2017], ...

```
Node o3 = Node.create(125, true);
Node o2 = o3.addBefore(450);
Node o1 = o2.addBefore(550);
```



Motivation & Contribution: developing an efficient synthesis algorithm for method call sequences

Outline

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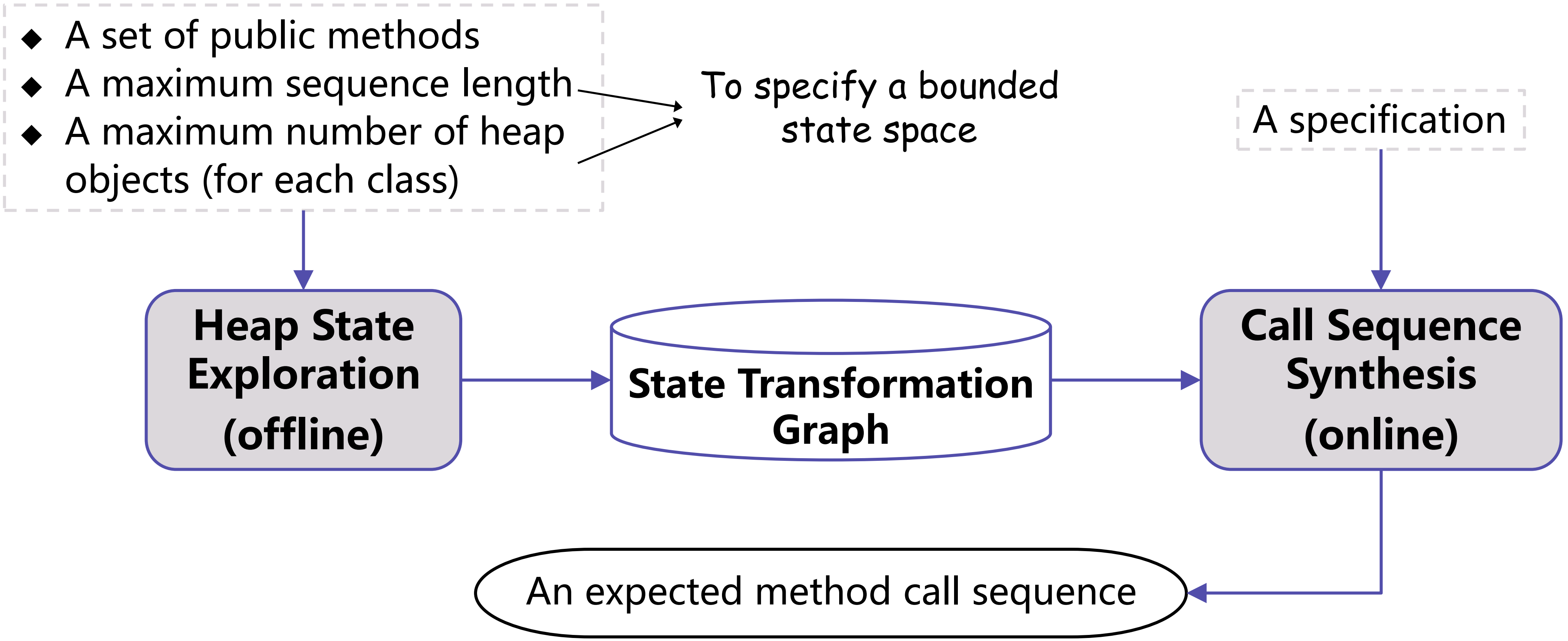
3. Evaluation

Workflow

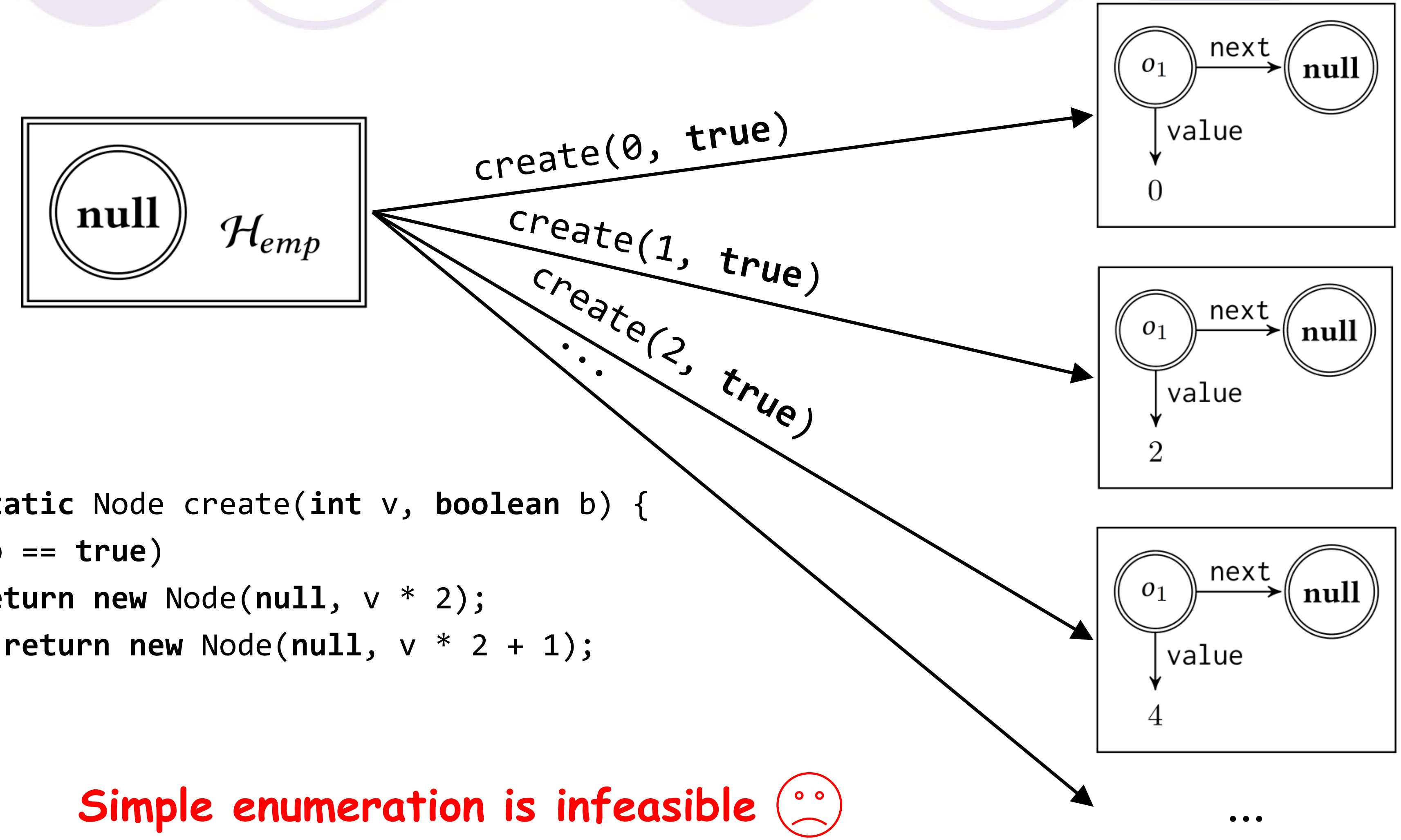


A set of public methods
A maximum sequence length
A maximum number of heap objects (for each class)
To specify a bounded state space
A specification
Heap State Exploration (offline)
State Transformation Graph
Call Sequence Synthesis (online)
An expected method call sequence

Heap State Exploration


```
class Node {
   ...
   public static Node create(int v, boolean b)
      { ... }
   public Node getNext() { ... }
   public int getValue() { ... }
   public void addAfter(int v) { ... }
   public Node addBefore(int v) { ... }
}
```

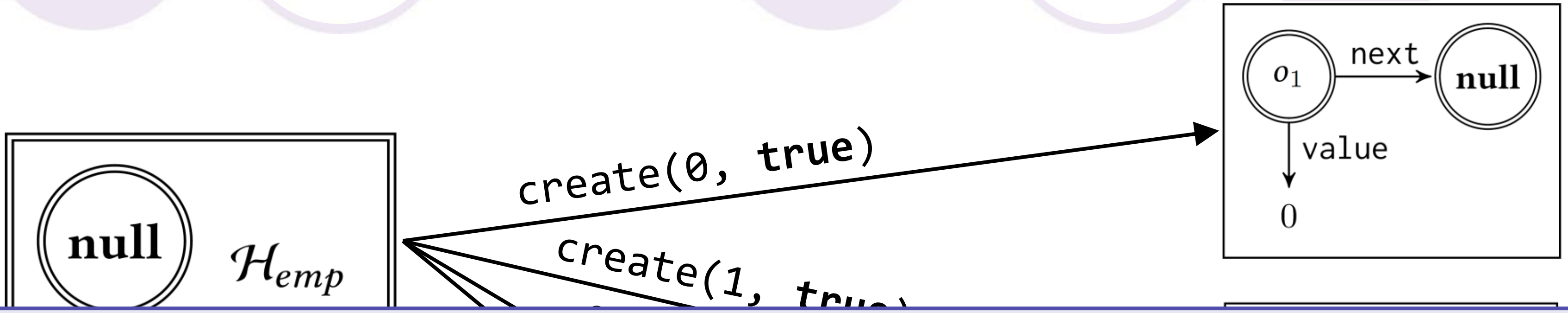
Heap State Exploration




```
public static Node create(int v, boolean b) {
    if (b == true)
       return new Node(null, v * 2);
    else return new Node(null, v * 2 + 1);
}
```

Simple enumeration is infeasible ☹

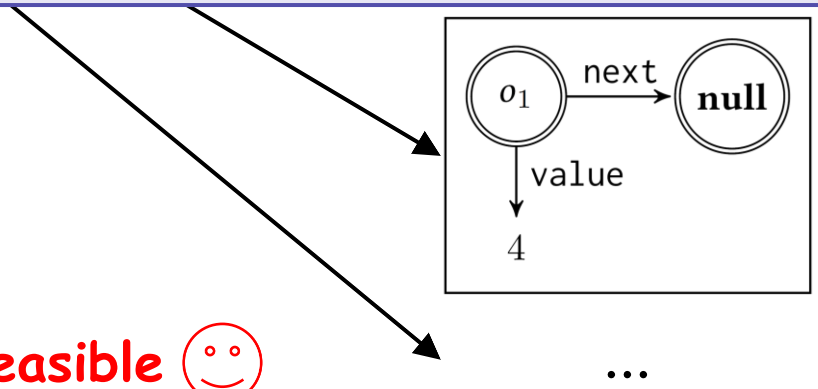
Heap State Exploration



A heap state = a heap structure (objects & references) + primitive values

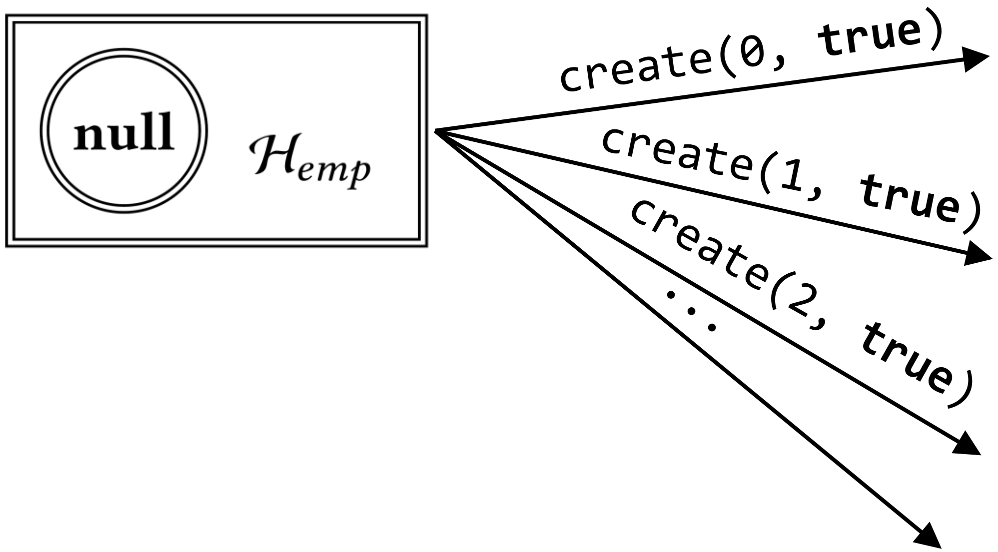
- The space of the former is relatively <u>small</u>, and can be enumerated.
- The space of the latter is large, but can be inferred using a <u>constraint solver</u>.

```
publi
    if (b == true)
        return new Node(null, v * 2);
    else return new Node(null, v * 2 + 1);
}
```

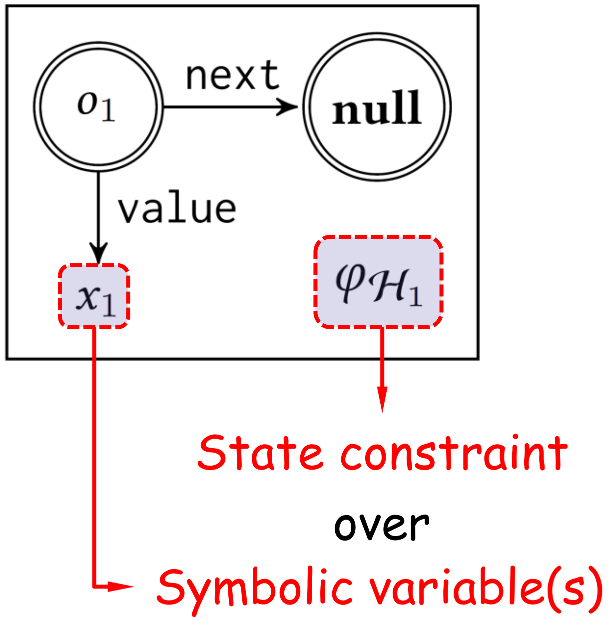


Enumeration of the heap structures is feasible ☺

State Abstraction

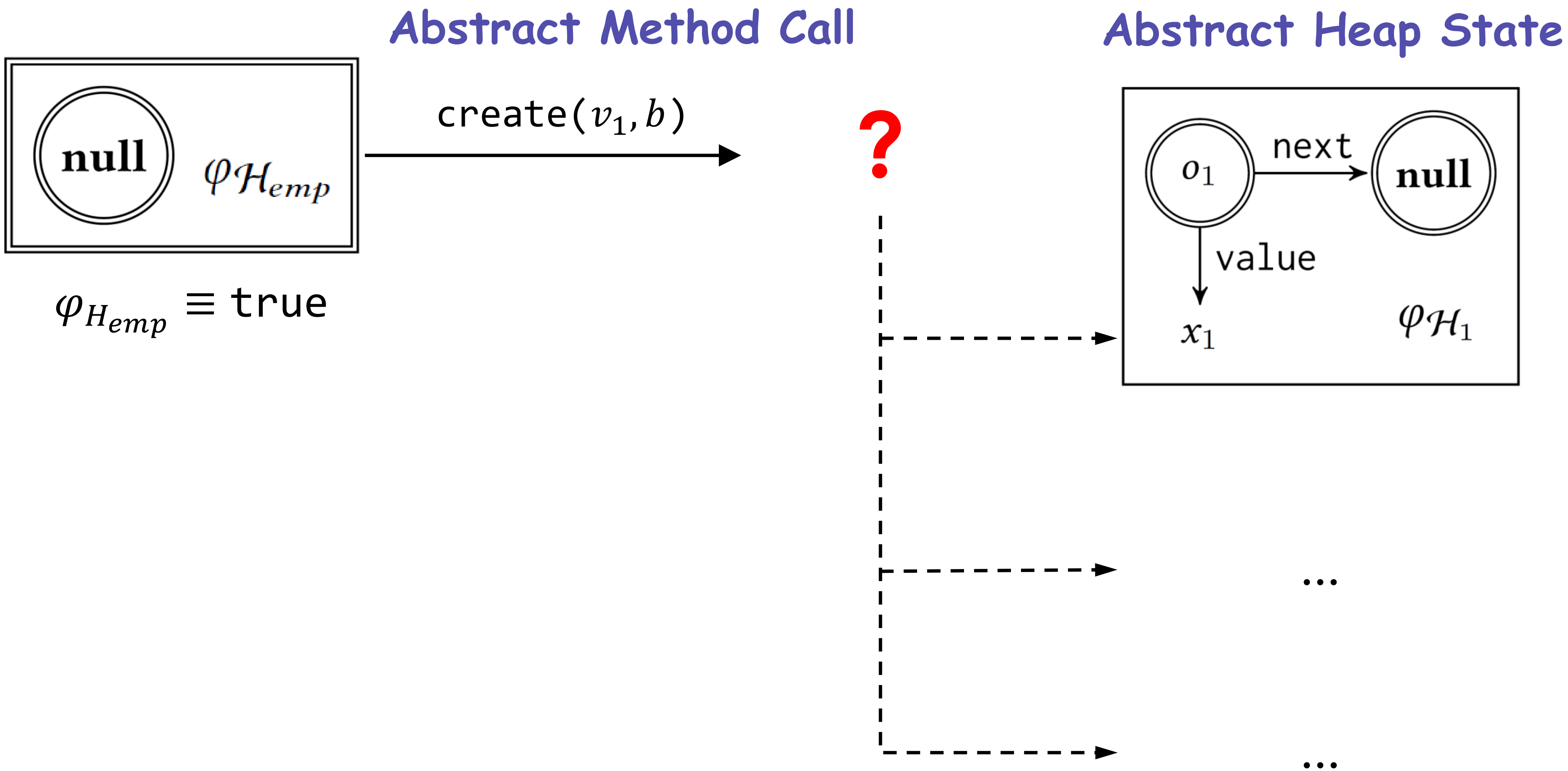


Abstract Heap State

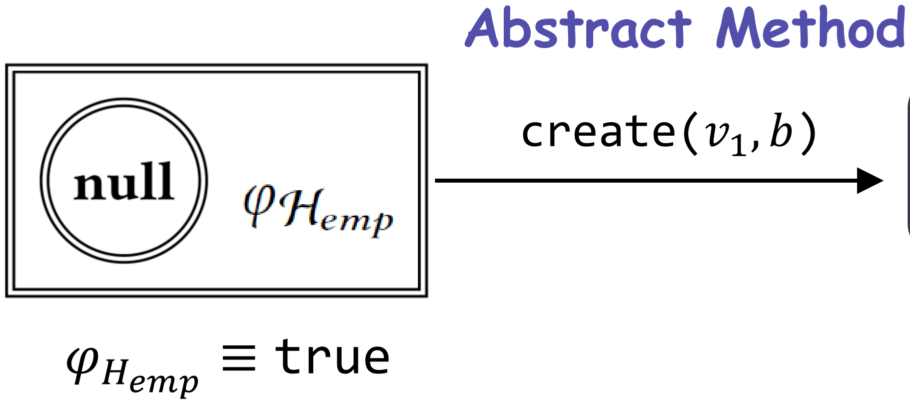


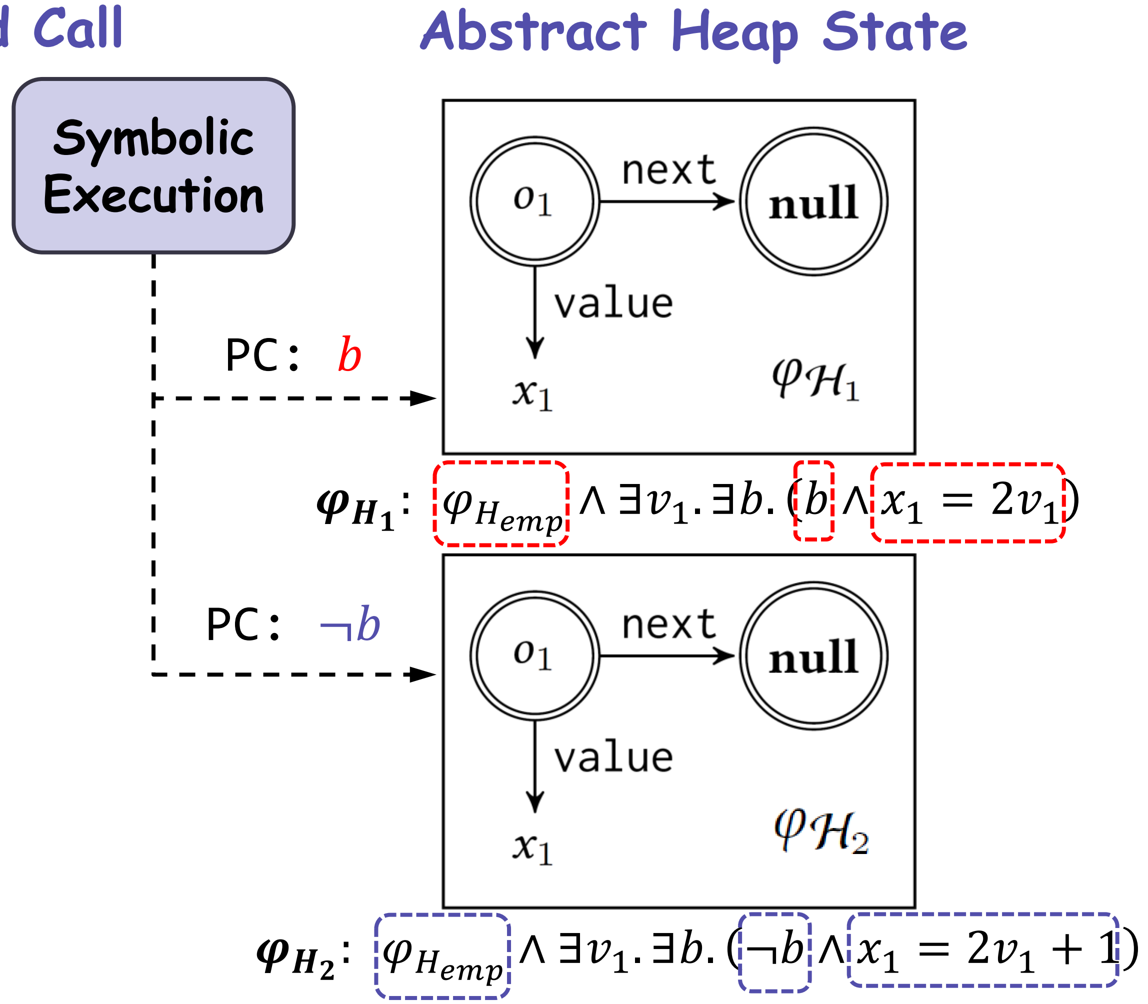
e.g., $\exists v_1 . \exists b . (b \wedge x_1 = 2v_1)$

State Abstraction



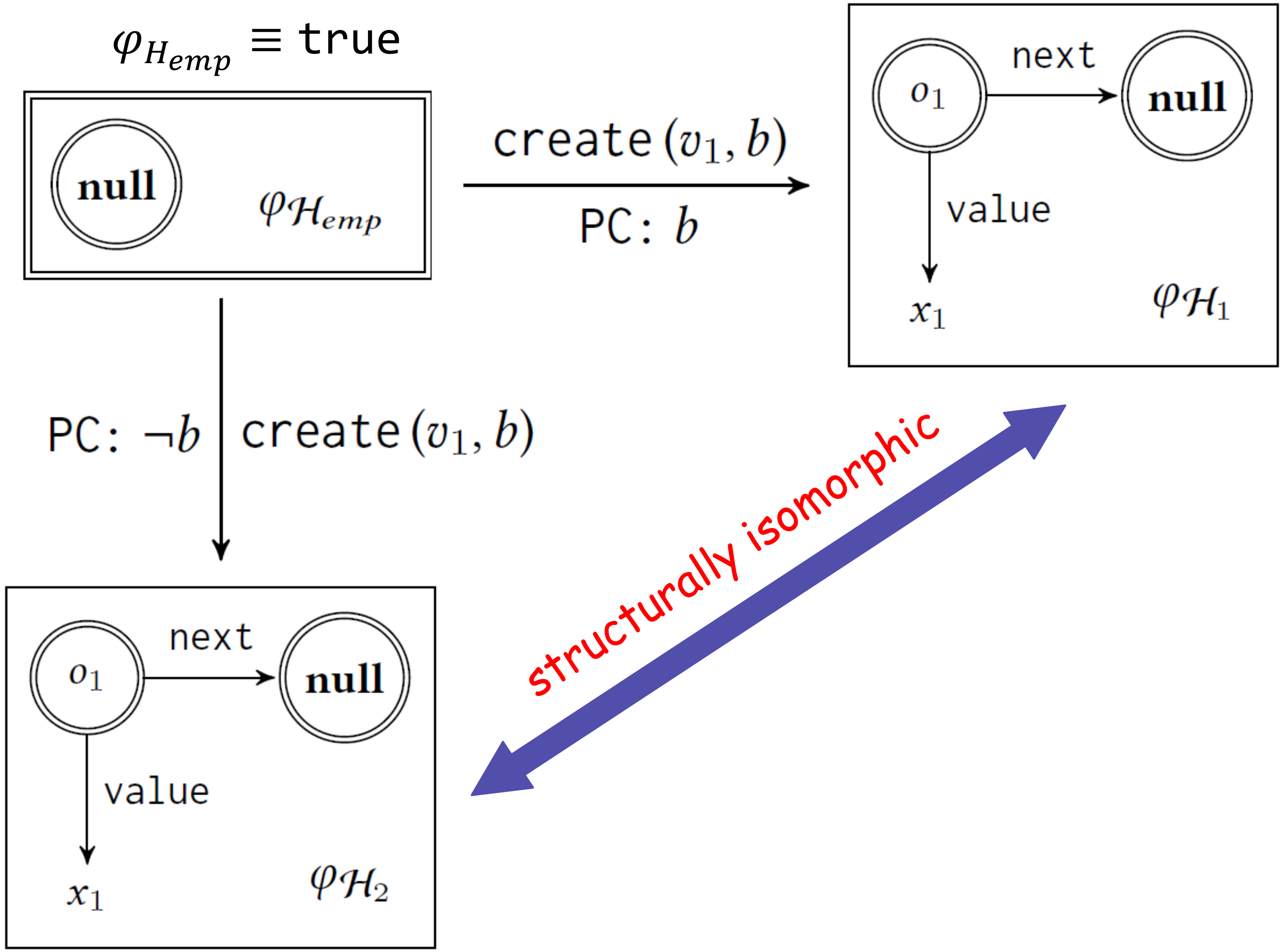
State Abstraction



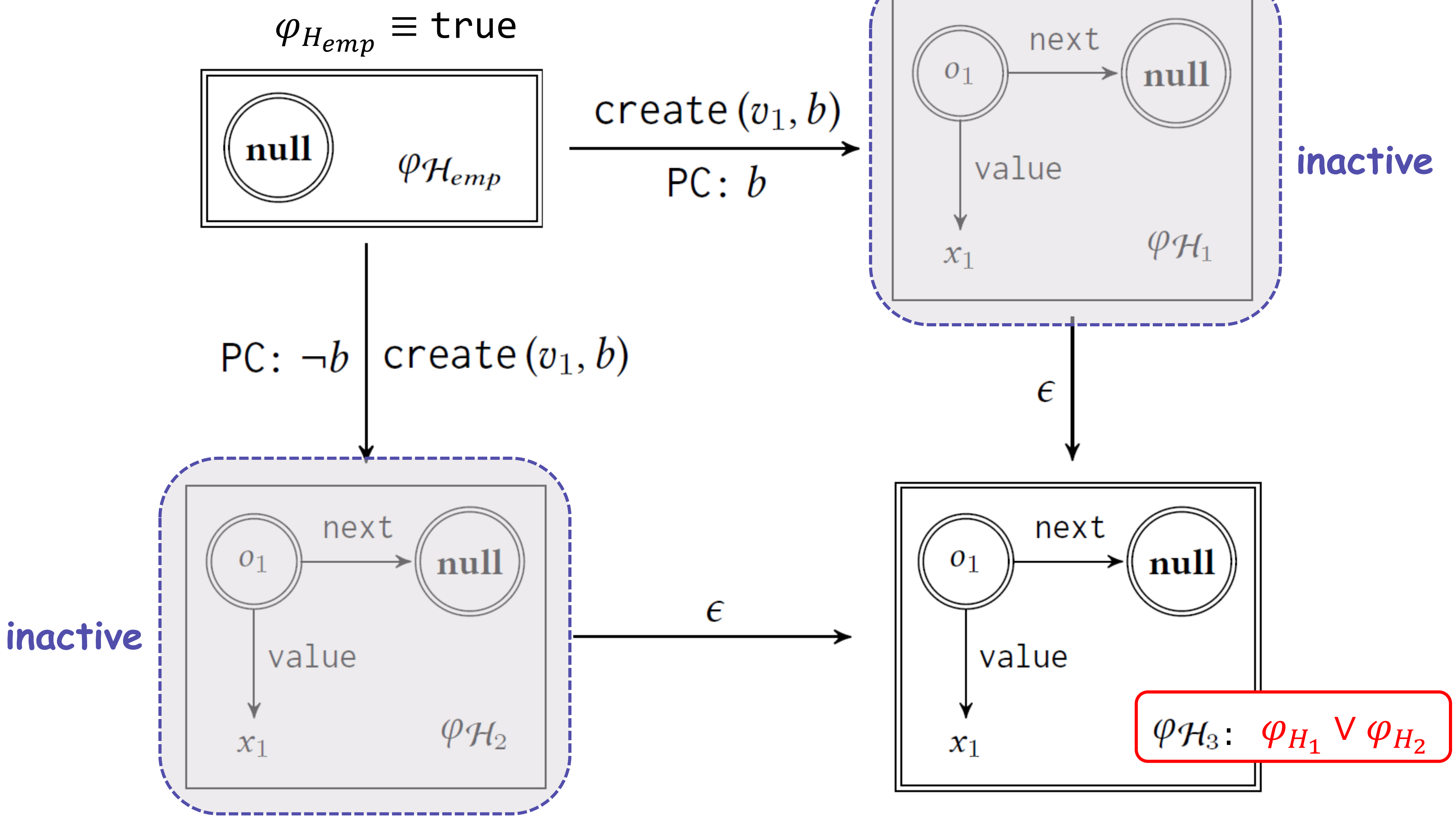



```
public static Node create(int v, boolean b) {
    if (b == true)
        return new Node(null, v * 2);
    else return new Node(null, v * 2 + 1);
}
```

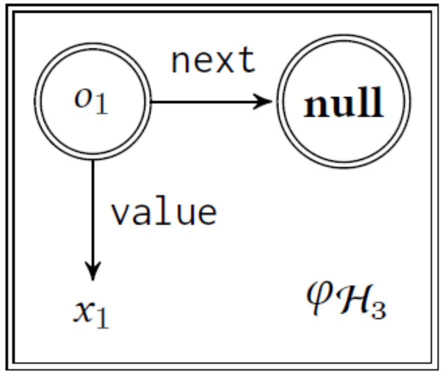
Structural Isomorphism



State Merging

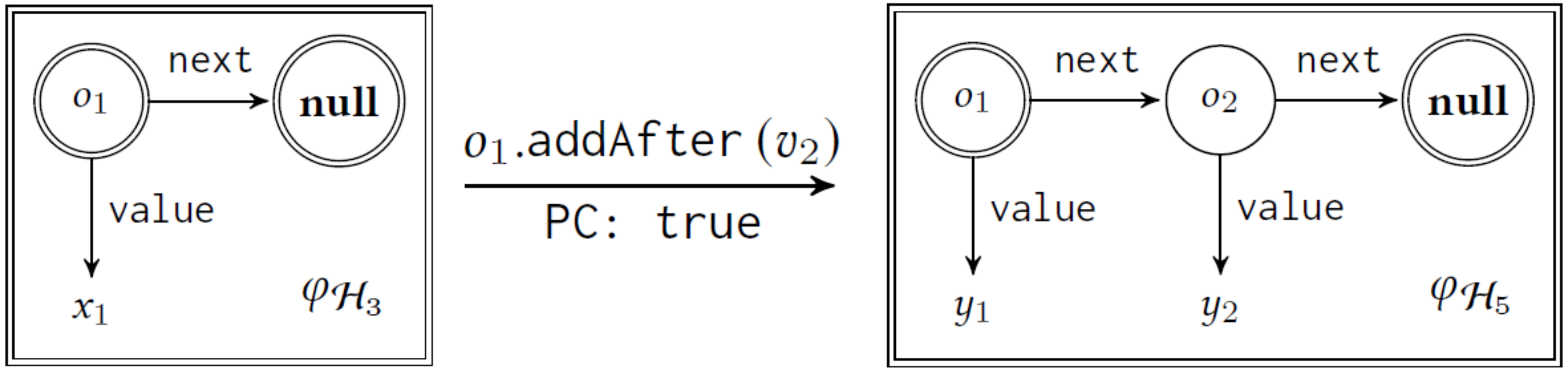


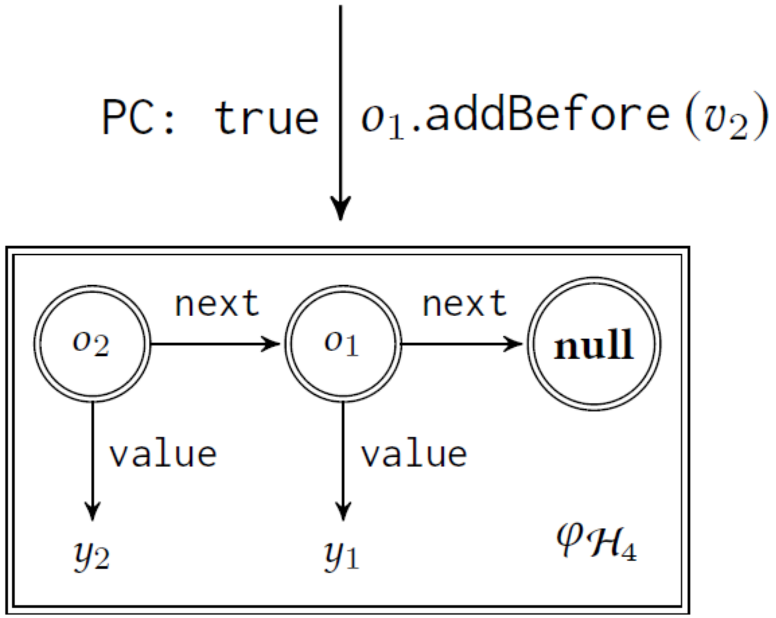
Heap State Exploration




```
public void addAfter(int v) {
   this.next = new Node(null, v);
}
public Node addBefore(int v) {
   return new Node(this, v);
}
```

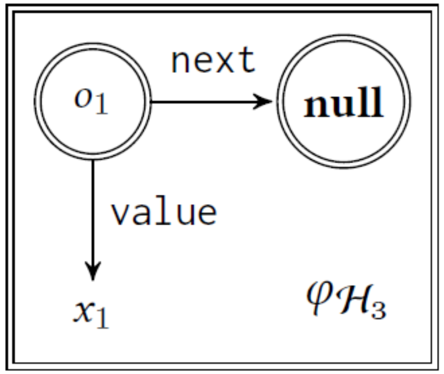
Heap State Exploration





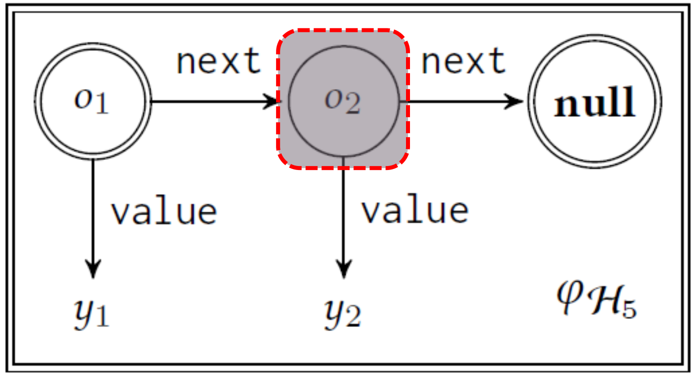

```java
public void addAfter(int v) {
   this.next = new Node(null, v);
}
public Node addBefore(int v) {
   return new Node(this, v);
}
```

Heap State Exploration



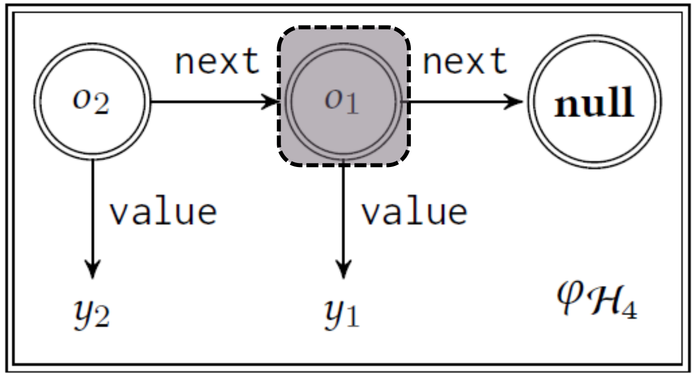
o_1.addAfter (v_2)

PC: true



not stack-accessible

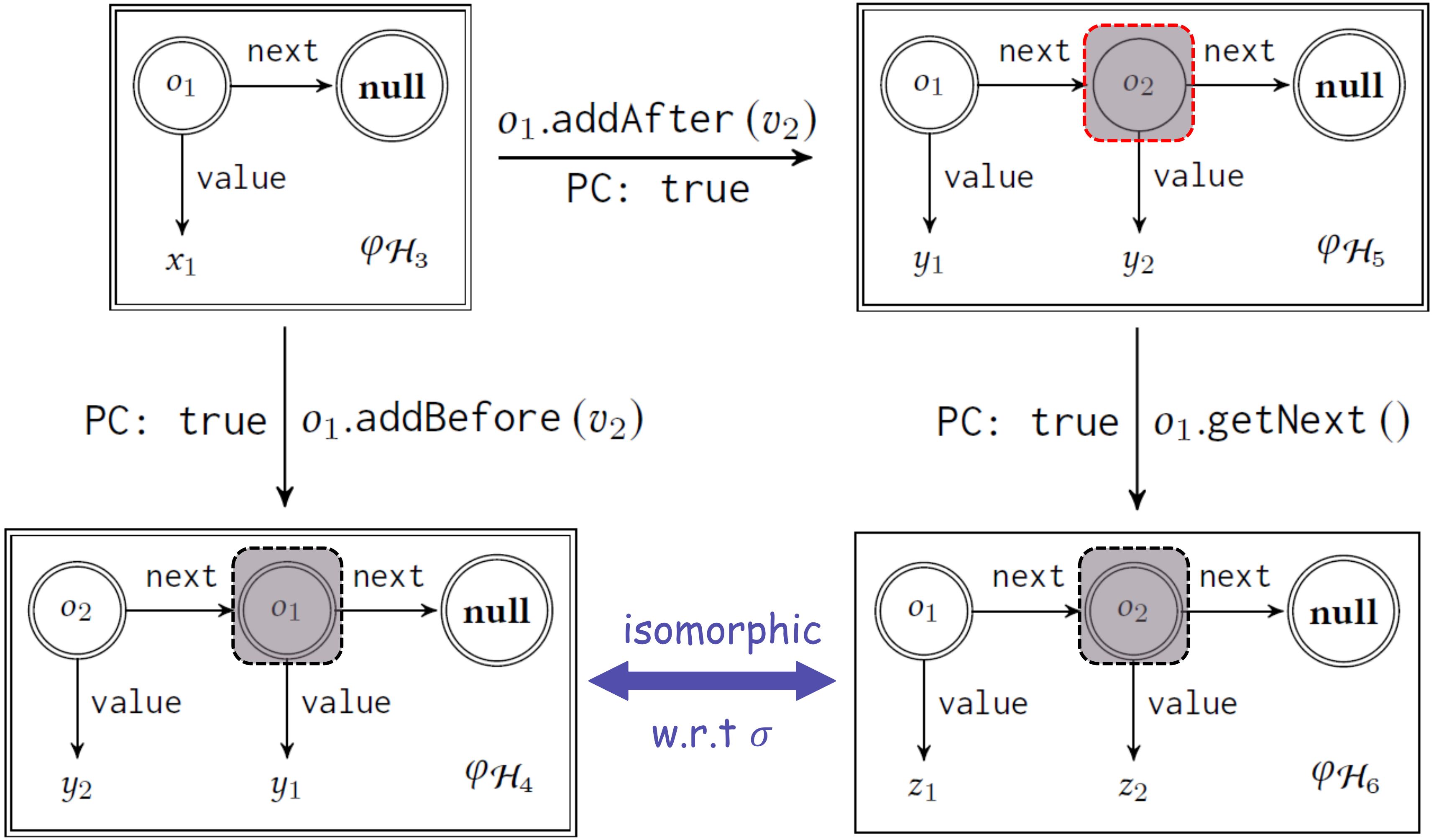
PC: true | o_1.addBefore (v_2)



stack-accessible

```
public void addAfter(int v) {
    this.next = new Node(null, v);
}
public Node addBefore(int v) {
    return new Node(this, v);
}
```

Heap State Exploration



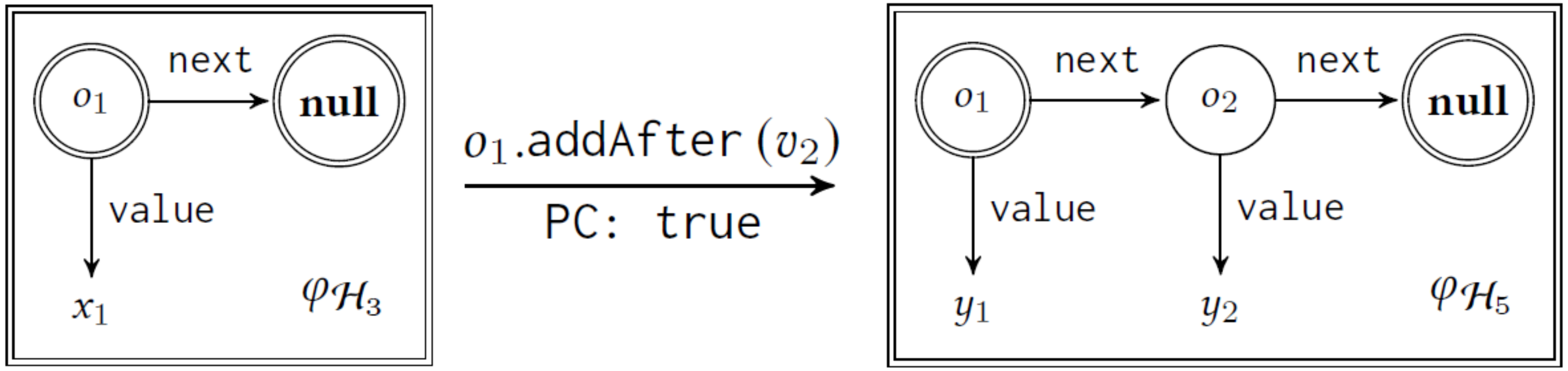
not stack-accessible

```
public Node getNext() {
    return this.next;
}
```

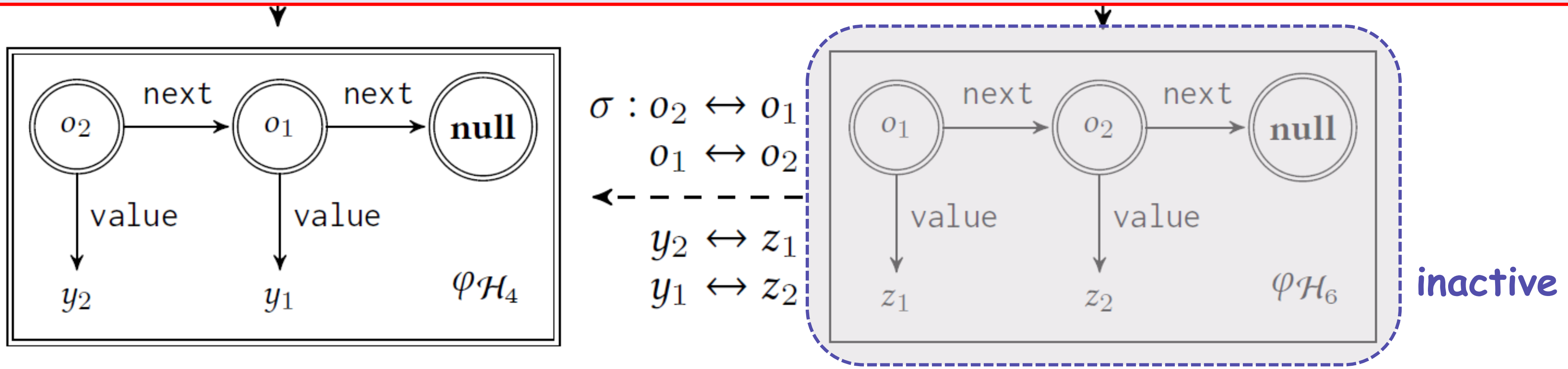
stack-accessible

stack-accessible

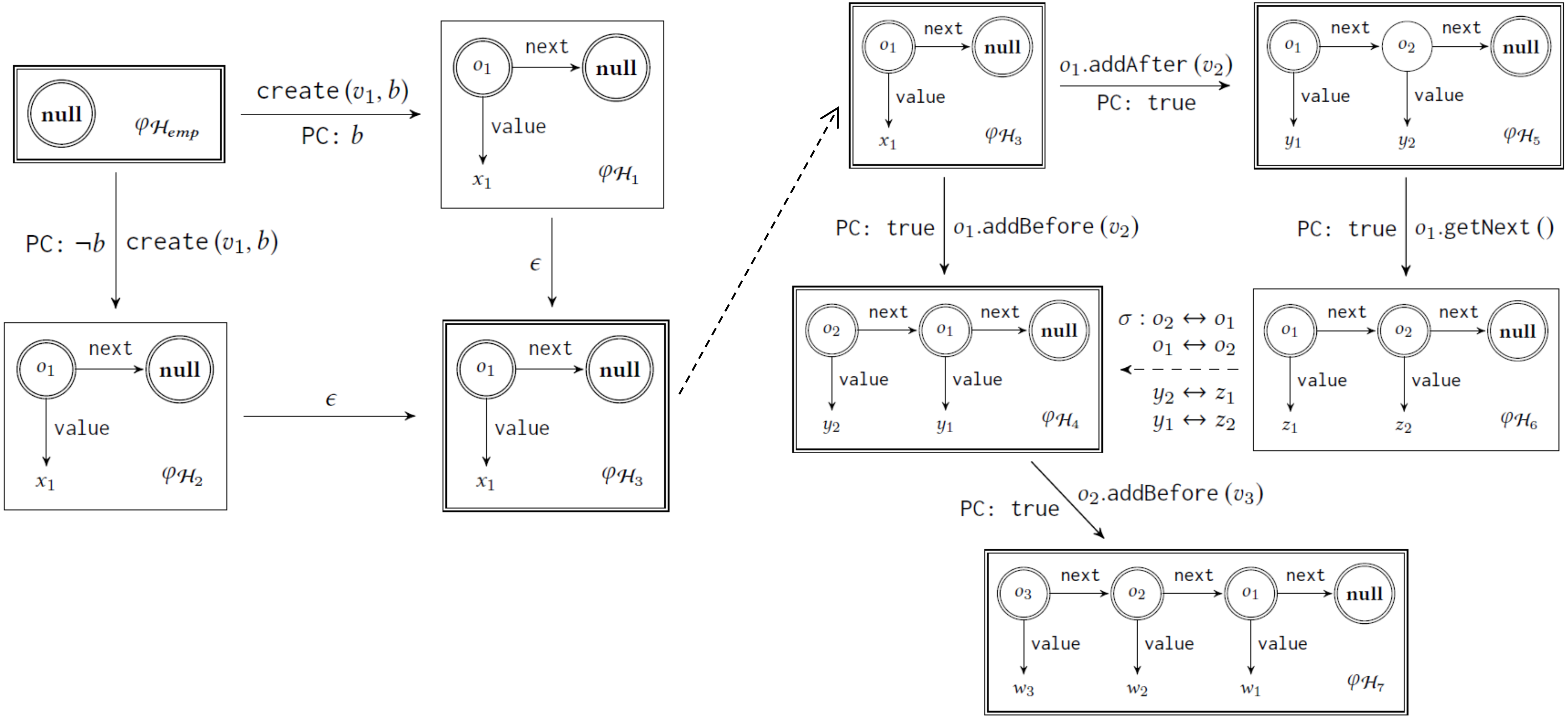
Heap State Exploration



All concrete heap states represented by H_6 are included in those represented by H_4!
(by checking $\varphi_{H_6} \rightarrow \varphi_{H_4}[y_2 \coloneqq z_1, y_1 \coloneqq z_2]$ holds for all z_1, z_2)

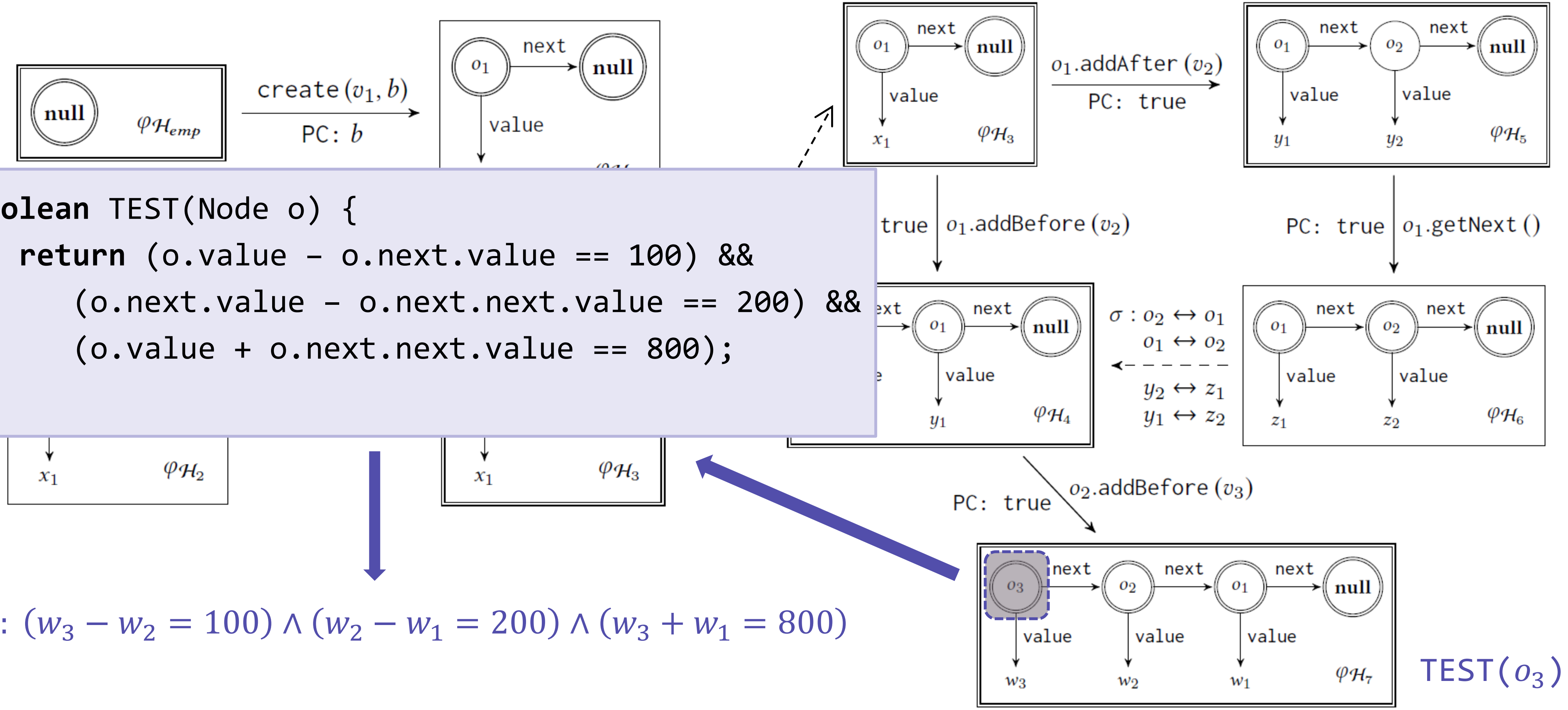


State Transformation Graph



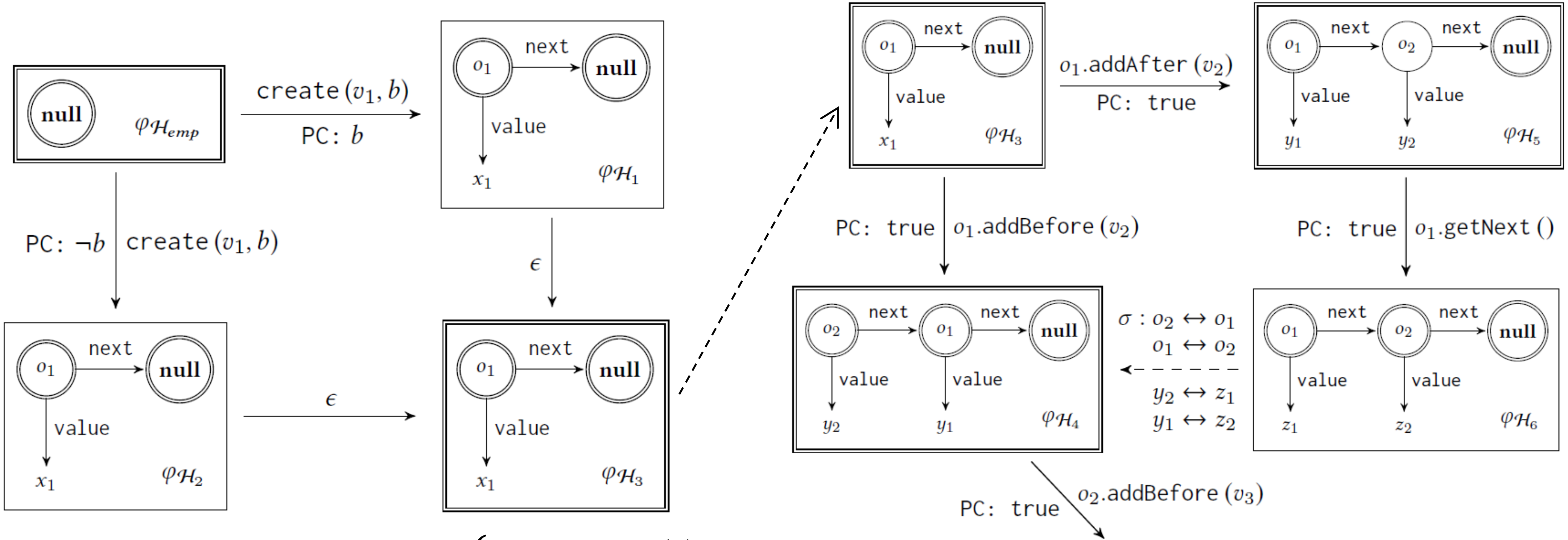
Call Sequence Synthesis

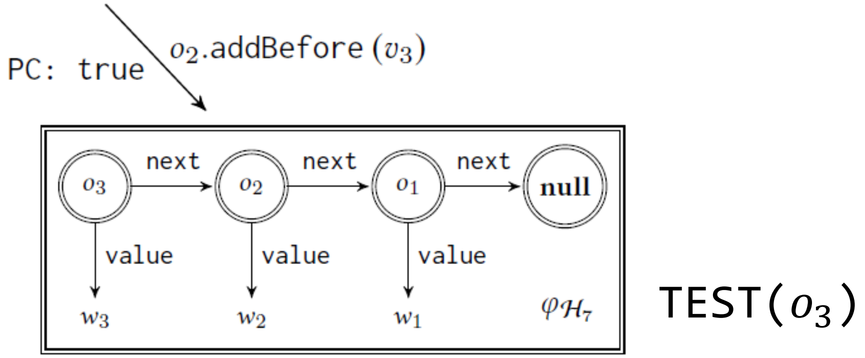
```
boolean TEST(Node o) {
   return (o.value – o.next.value == 100) &&
      (o.next.value – o.next.next.value == 200) &&
      (o.value + o.next.next.value == 800);
}
```



α: $(w_3 - w_2 = 100) \land (w_2 - w_1 = 200) \land (w_3 + w_1 = 800)$

Call Sequence Synthesis

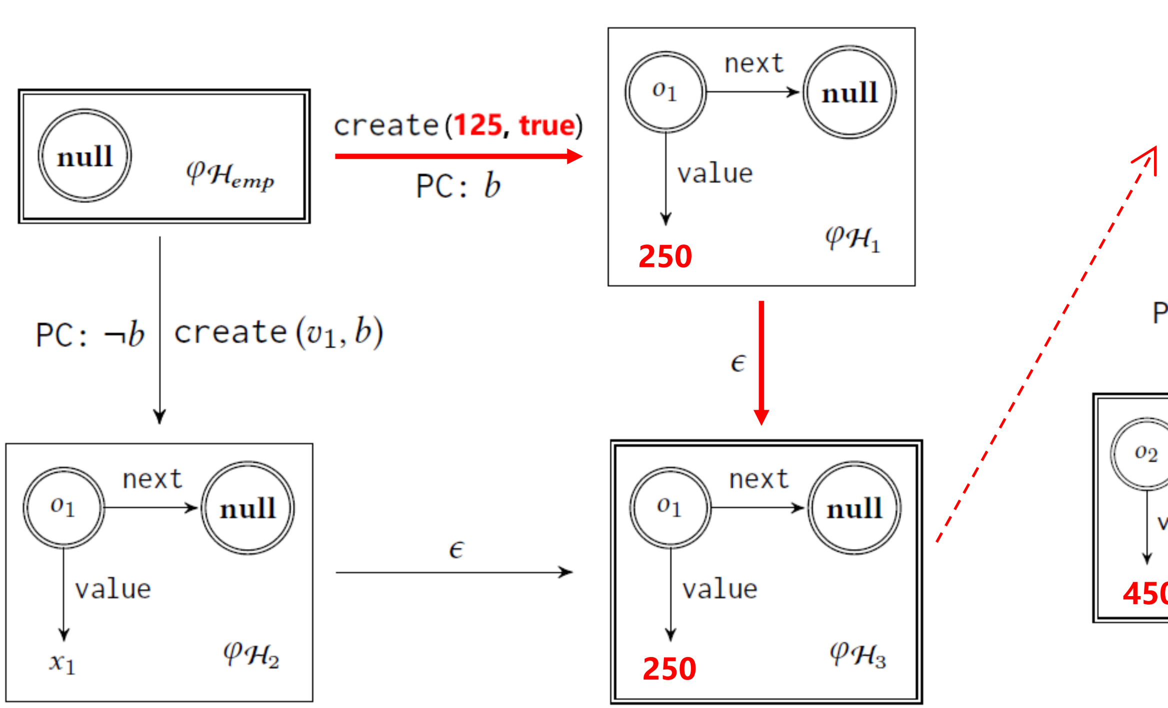


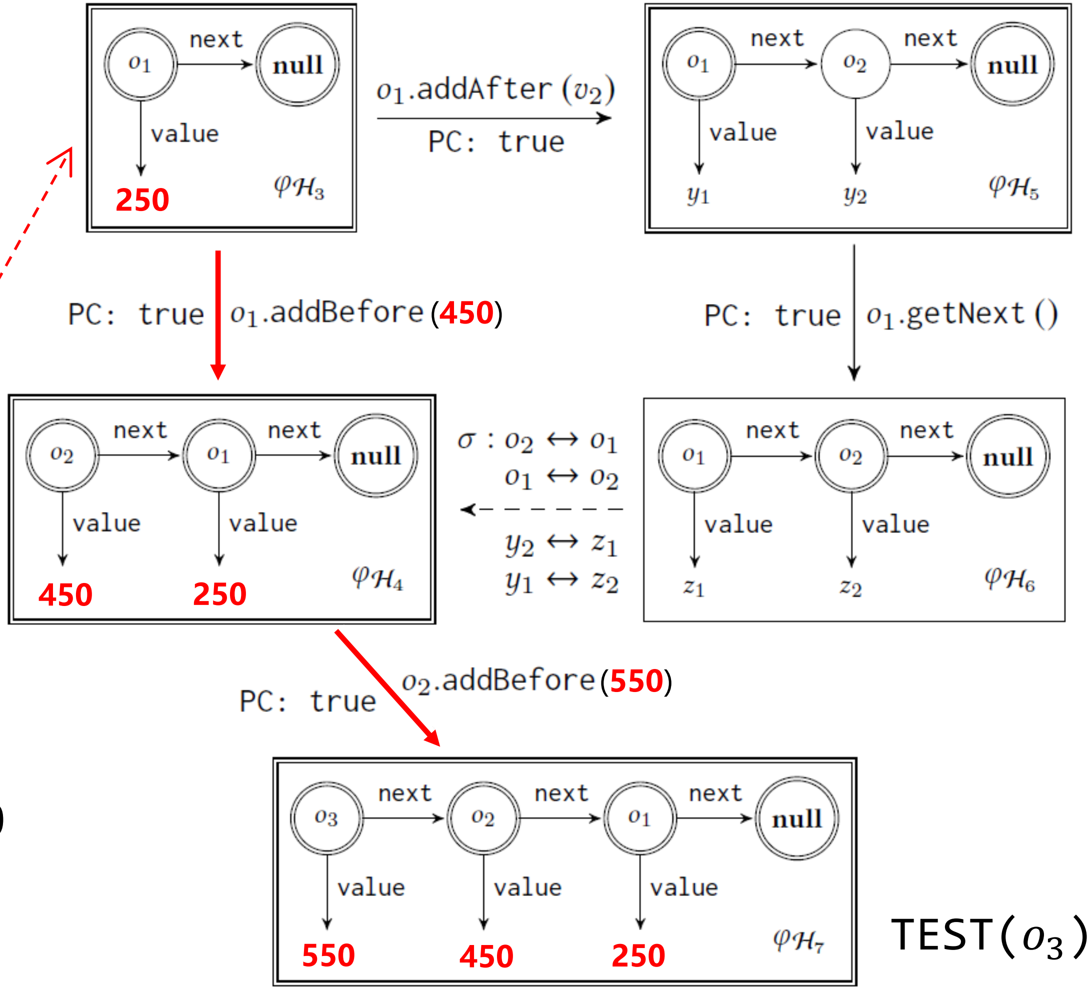


Solve $\varphi_{H_7} \wedge \alpha$ $\longrightarrow$

$$\begin{cases} w_3 = v_3 = 550 \\ w_2 = y_2 = v_2 = 450 \\ w_1 = y_1 = x_1 = 250 \\ v_1 = 125 \\ b = \text{true} \end{cases}$$

Call Sequence Synthesis

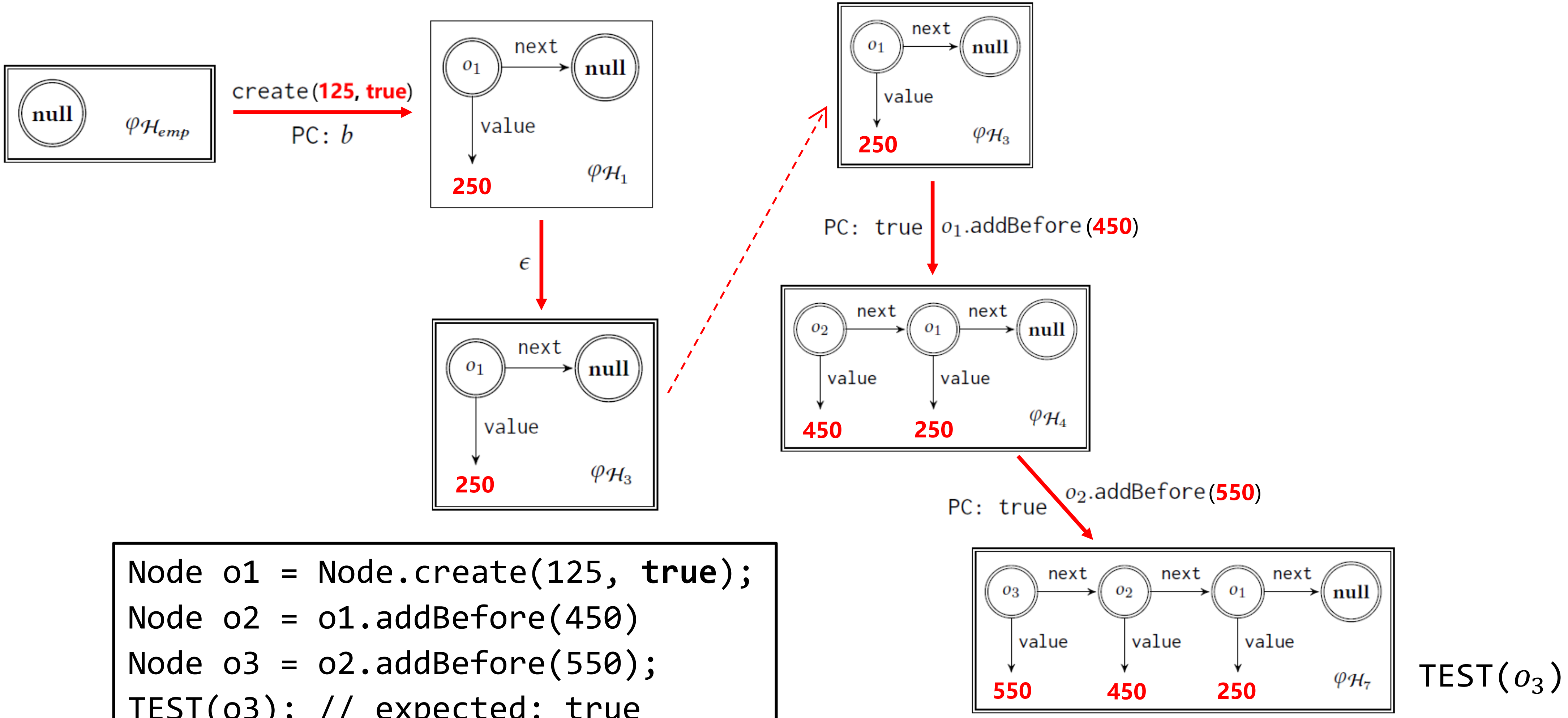




Solve $\varphi_{H_7} \wedge \alpha$ $\longrightarrow$

$$\begin{cases} w_3 = v_3 = 550 \\ w_2 = y_2 = v_2 = 450 \\ w_1 = y_1 = x_1 = 250 \\ v_1 = 125 \\ b = \text{true} \end{cases}$$

Call Sequence Synthesis




```
Node o1 = Node.create(125, true);
Node o2 = o1.addBefore(450)
Node o3 = o2.addBefore(550);
TEST(o3); // expected: true
```

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1. Background and motivation
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Evaluation Setup

- **Implentation**: A prototype named `MSeqSynth`
  - Symbolic Execution Engine: `JBSE`
  - Constraint Solver: `Z3`

- **Subject programs**: 14 data structure classes implemented in Java, including
  - 4 classes from SUSHI's experiments,
  - 6 classes from the Sireum/Kiasan's examples,
  - 2 classes from Software-artifact Infrastructure Repository (SIR),
  - 2 classes from the JavaScan website **(containing programming tutorials with examples)**

benchmarks used in previous publications

RQ1: Effectiveness on Test Generation

- **Baseline**: SUSHI (= a path selector + a search algorithm)

	Subject	$\|\mathcal{M}\|$	B_{all}	MSeqSynth T_{all}	MSeqSynth $T_{explore}$	MSeqSynth N_{solve}	MSeqSynth N_{fail}	MSeqSynth T_{solve}	MSeqSynth T_{fail}	MSeqSynth B_{cov}	SUSHI T_{all}	SUSHI N_{solve}	SUSHI N_{fail}	SUSHI T_{solve}	SUSHI T_{fail}	SUSHI B_{cov}
SUSHI	Avl	7	59	51.5	30	15	0	0.02	-	59	120.8	15	0	6	-	59
	RBT	10	191	399.4	300	34	0	0.22	-	**191**	3600*	30	14	35.1	175.5	162
	DList	38	136	486	328	49	0	0.05	-	**136**	3600*	41	16	11.9	>180	111
	CList	7	80	147	62	11	43	0.02	1.42	78	500.7	11	2	19.3	129.2	**80**
Kiasan	Avl	7	55	64.1	36	15	203	0.01	<0.01	**55**	3600*	10	20	5.6	>180	29
	RBT	10	180	438.7	295	35	983	0.08	0.04	**175**	3600*	20	21	16.2	>180	101
	BST	8	51	68.2	49	14	0	0.01	-	51	100.1	14	0	5.6	-	51
	AATree	8	58	3600*	1800*	16	563	0.02	2.95	**56**	3600*	12	18	5.6	>180	40
	Leftist	7	31	339.1	317	10	5	0.01	0.73	31	1000	10	5	5.5	>180	31
	Stack	8	17	28.3	12	10	0	0.01	-	17	67	10	0	5.5	-	17
SIR	DList	22	81	206	151	33	3	0.03	0.01	81	1018	33	3	8.4	>180	81
	SList	13	41	199.2	167	13	1	0.01	<0.01	41	302.7	13	1	5.5	>180	41
JavaScan	Skew	6	25	43.2	29	8	0	0.01	-	25	54.6	8	0	5.5	-	25
	Binom	9	114	3600*	1298	16	1419	0.05	0.02	**98**	3600*	14	16	5.6	>180	85

The total branches covered by MSeqSynth (1094) is 20% more than those covered by SUSHI (913).

RQ1: Effectiveness on Test Generation

- **Baseline**: SUSHI (= a path selector + a search algorithm)

				MSeqSynth							SUSHI					
	Subject	$\lvert\mathcal{M}\rvert$	B_{all}	T_{all}	$T_{explore}$	N_{solve}	N_{fail}	T_{solve}	T_{fail}	B_{cov}	T_{all}	N_{solve}	N_{fail}	T_{solve}	T_{fail}	B_{cov}
SUSHI	Avl	7	59	51.5	30	15	0	0.02	-	59	120.8	15	0	6	-	59
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	BST	8	51	68.2	49	14	0	0.01	-	51	100.1	14	0	5.6	-	51
	AATree	8	58	3600*	1800*	16	563	0.02	2.95	**56**	3600*	12	18	5.6	>180	40
	Leftist	7	31	339.1	317	10	5	0.01	0.73	31	1000	10	5	5.5	>180	31
	Stack	8	17	28.3	12	10	0	0.01	-	17	67	10	0	5.5	-	17
SIR	DList	22	81	206	151	33	3	0.03	0.01	81	1018	33	3	8.4	>180	81
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	Binom	9	114	3600*	1298	16	1419	0.05	0.02	**98**	3600*	14	16	5.6	>180	85

The total elapsed time of MSeqSynth (9671s) is 61% less than that of SUSHI (24764s).

RQ2: Effectiveness on Bounded Verification

- **Baseline**: a constructed baseline $\texttt{SE}_{\texttt{seq}}$ (based on the symbolic executor `JPF`)

Subject	Property	maxL = 7 T_{synth}	maxL = 7 T_{SE}	maxL = 8 T_{synth}	maxL = 8 T_{SE}
`Avl`	`balanced`	60.5	258	66.8	N/A
	`ordered`	31.1	260	39.5	N/A
	`wellFormed`	44.4	255	52.2	N/A
`BST`	`ordered`	39.1	1743	61.1	N/A
`AATree`	`ordered`	790.8	1630	N/A	N/A
	`wellLevel`	775.7	890	N/A	N/A
	`wellFormed`	1162	1637	N/A	N/A

MSeqSynth can verify heap-based programs and properties more efficiently than the baseline.

Summary

Thank you!

- Contribution: developing an efficient synthesis algorithm for method call sequences
- An offline procedure for exploring reachable heap states
  - Based on (isomorphic) state abstraction and state merging
- An online procedure for synthesizing method call sequences
  - Combining enumerative techniques and symbolic techniques
- Evaluation results show that our algorithm performs efficiently in both test generation tasks and bounded verification tasks.