Training Binary Classifiers as Data Structure Invariants

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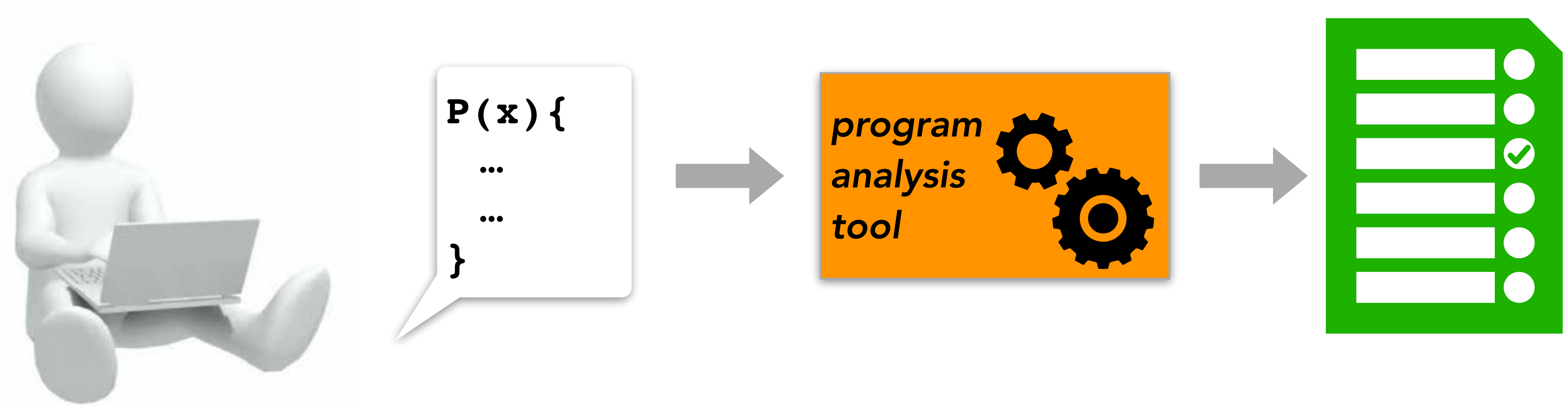
An Automated Analysis Scenario



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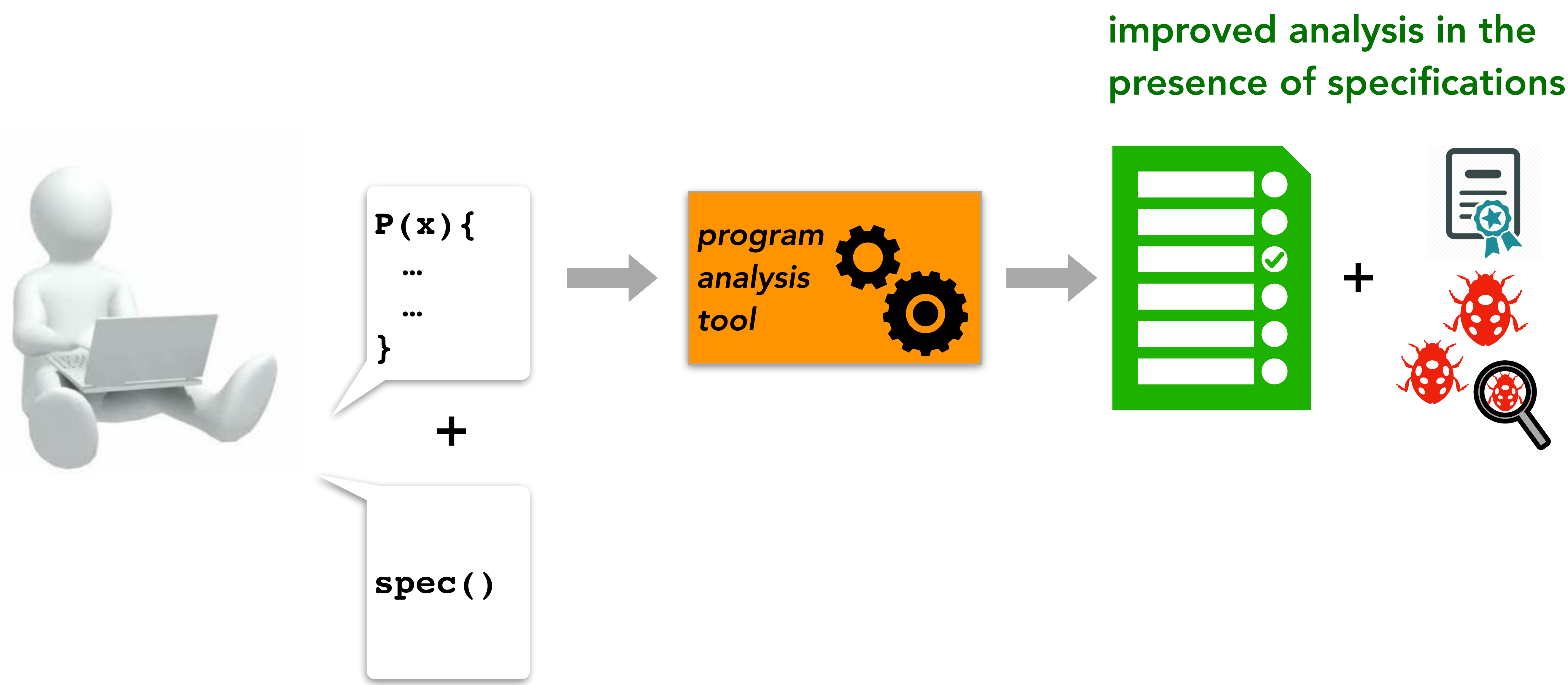

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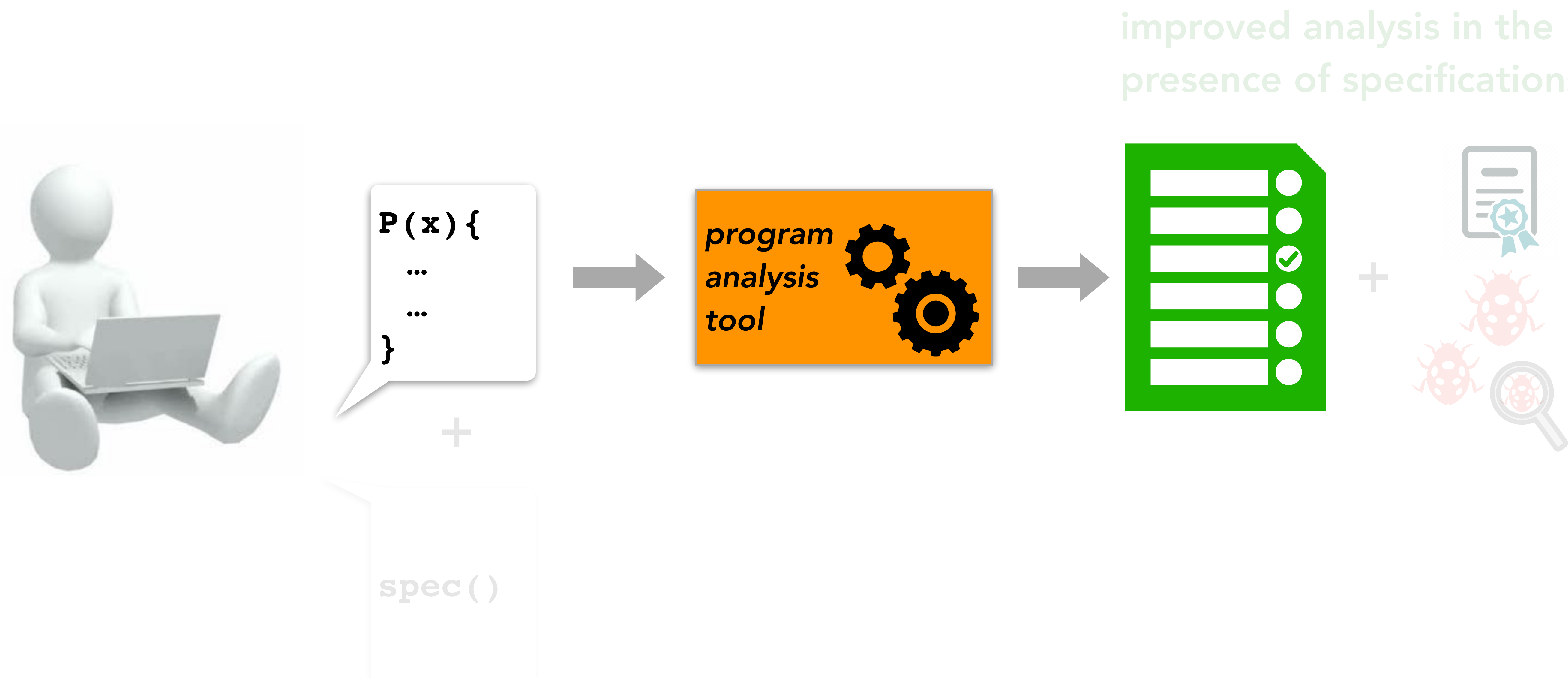
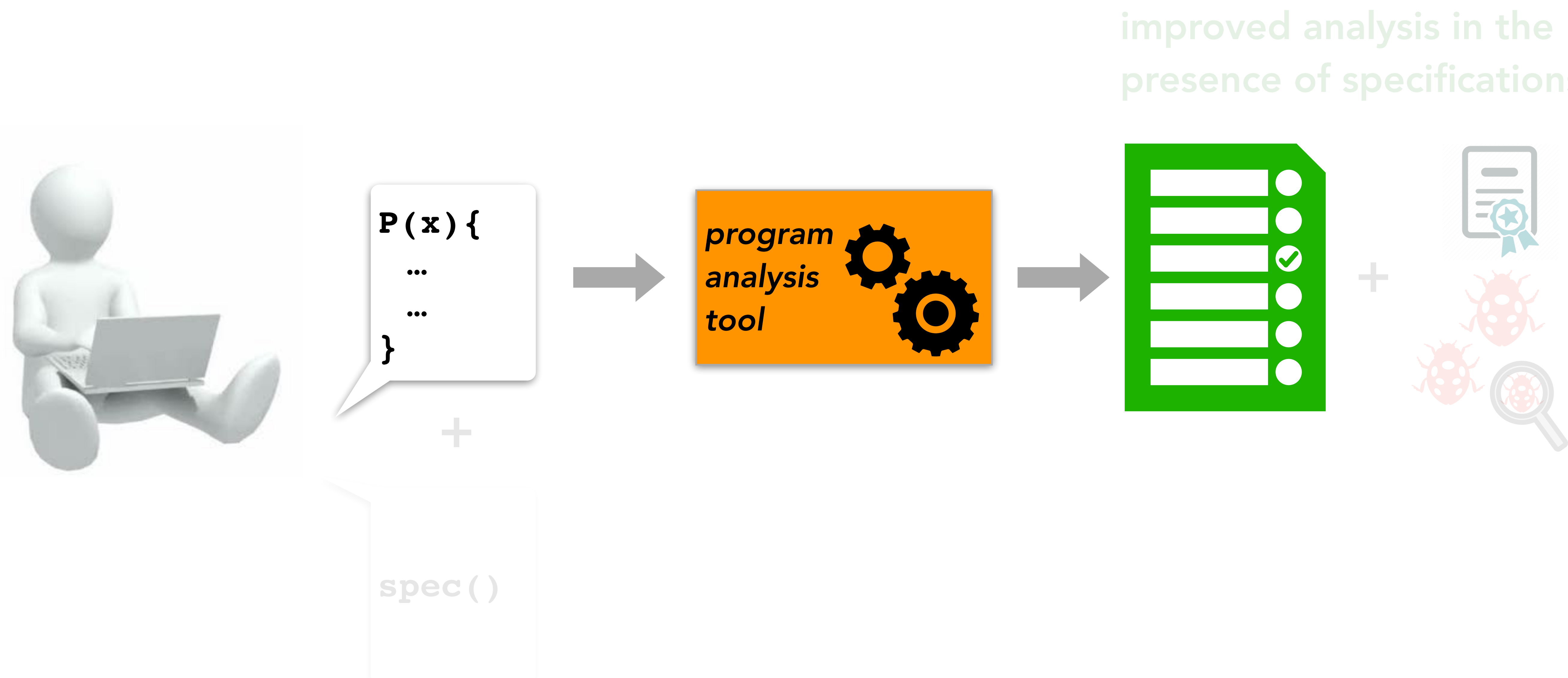


unfortunately, specifications
are sometimes unavailable

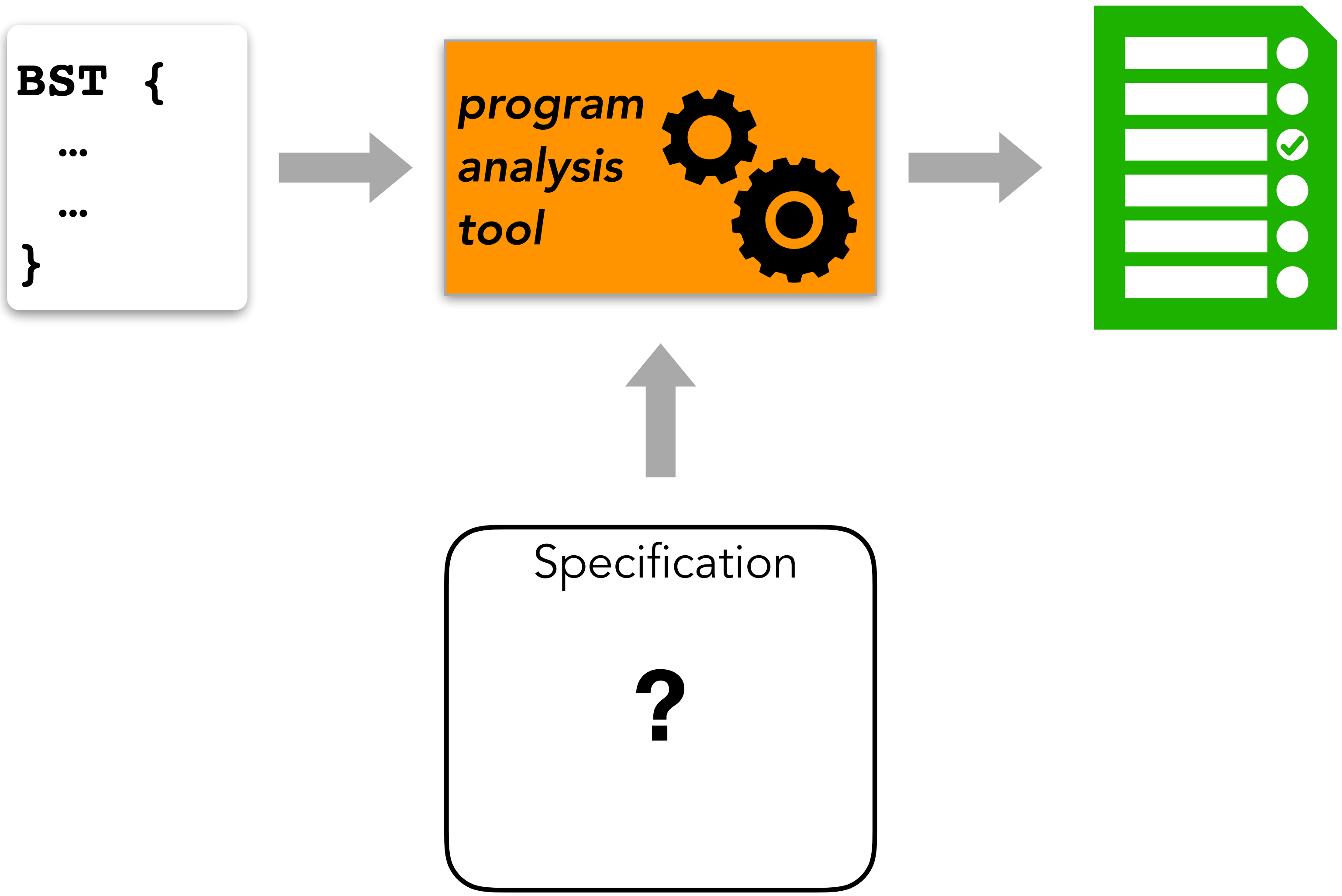
An Automated Analysis Scenario



unfortunately, specifications are sometimes unavailable

This emphasizes the relevance of the ***oracle problem***

Approaches to the Oracle Problem



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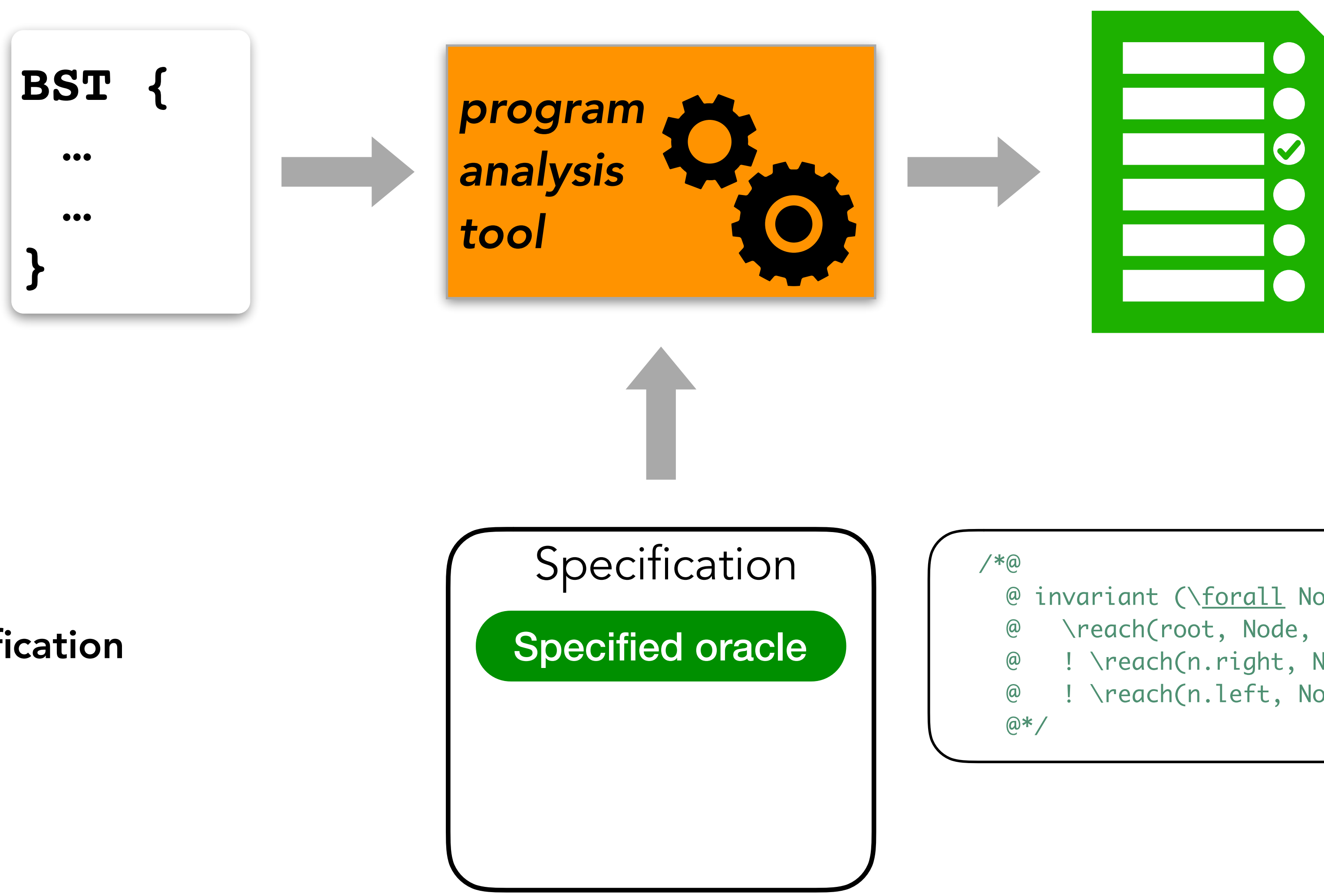
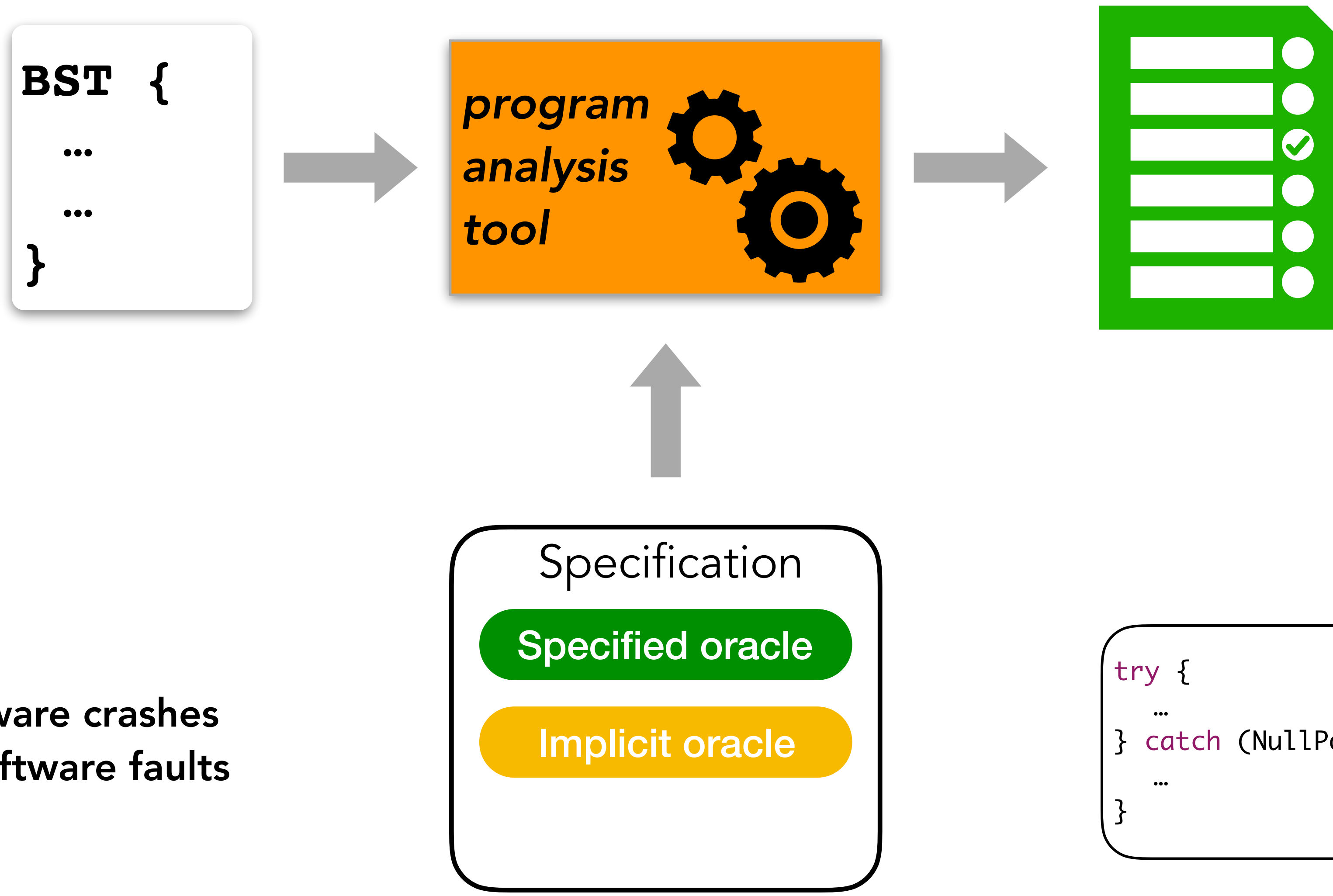


Manual specification

```
/*@
  @ invariant (\forall Node n;
  @   \reach(root, Node, left + right).has(n) implies
  @   ! \reach(n.right, Node, right + left).has(n) &&
  @   ! \reach(n.left, Node, left + right).has(n));
  @*/
```

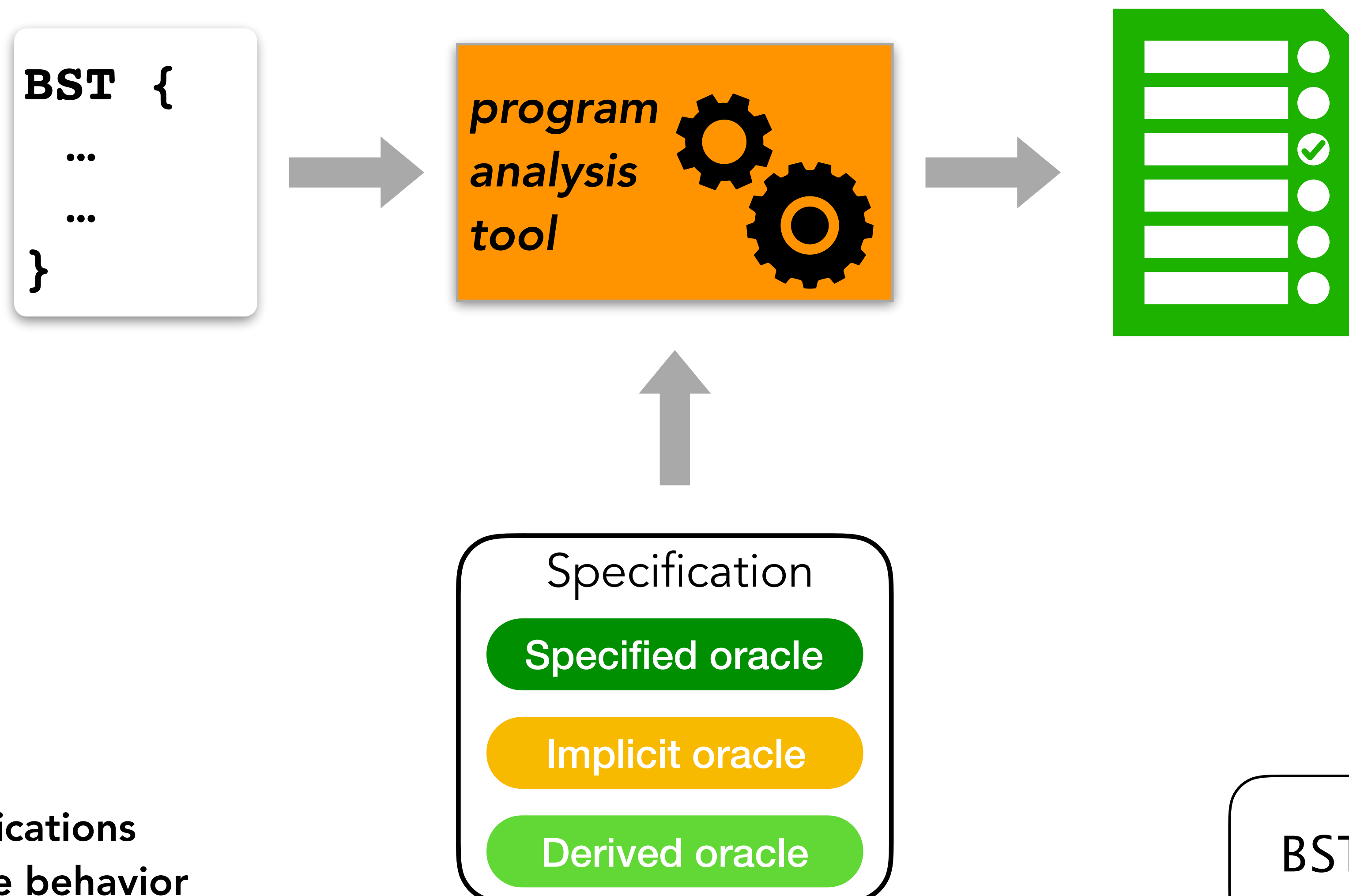
Approaches to the Oracle Problem



Analyze software crashes or general software faults

```
try {
   …
} catch (NullPointerException e) {
   …
}
```

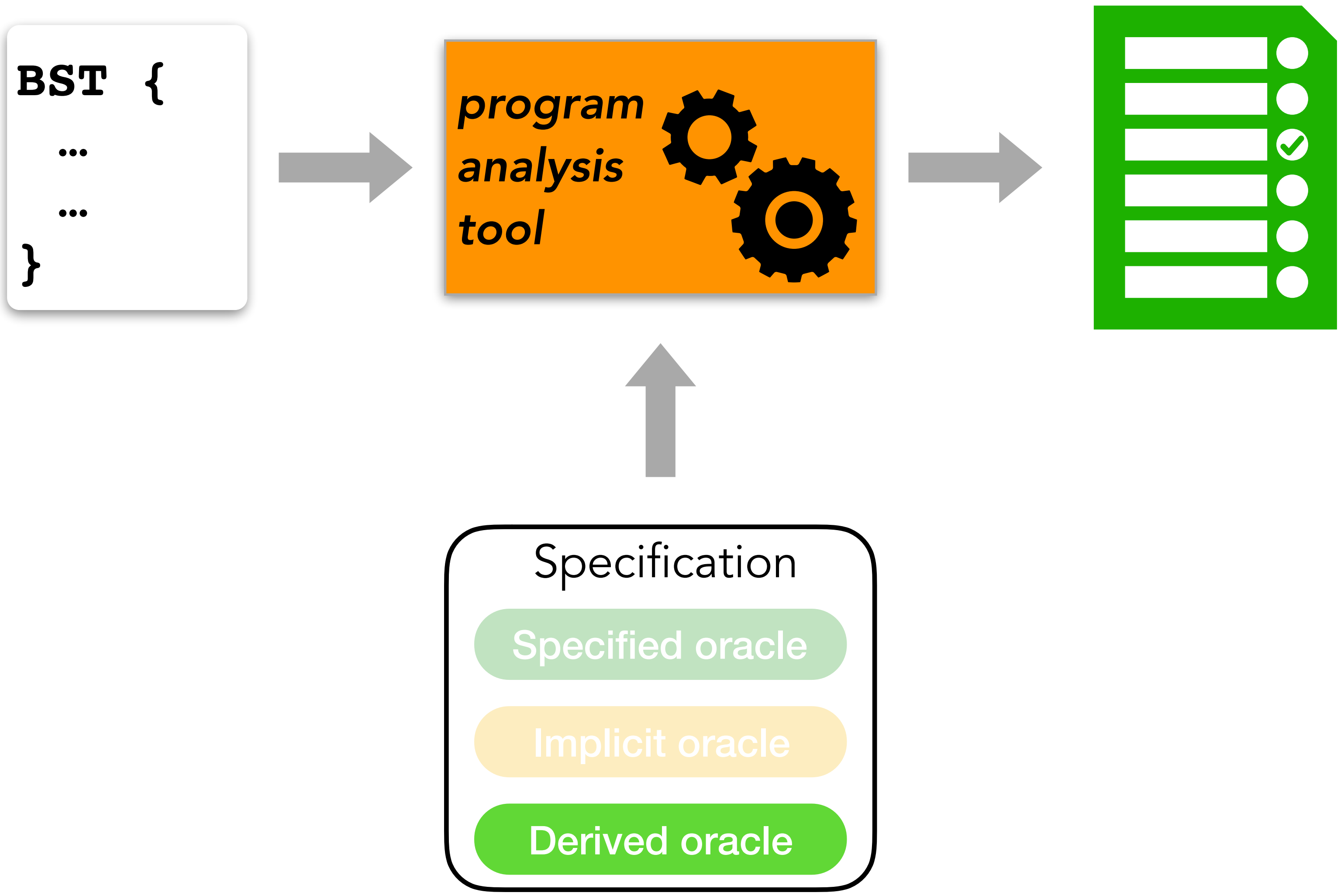
Approaches to the Oracle Problem



Derive specifications from software behavior

$\mathrm{BST} \equiv \mathrm{BST}'$

Approaches to the Oracle Problem



Invariants as Oracles

```
public class BST {

  public void BST() {

  }

  public void
  insert(…) {
    …
  }

  public void
  remove() {
    …
  }
  …
}
```

```
/*@
  @ invariant (\forall Node n;
  @   \reach(root, Node, left + right).has(n) implies
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  }

  public void
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    …
  }

  public void
  remove() {
    …
  }
  …
}
```
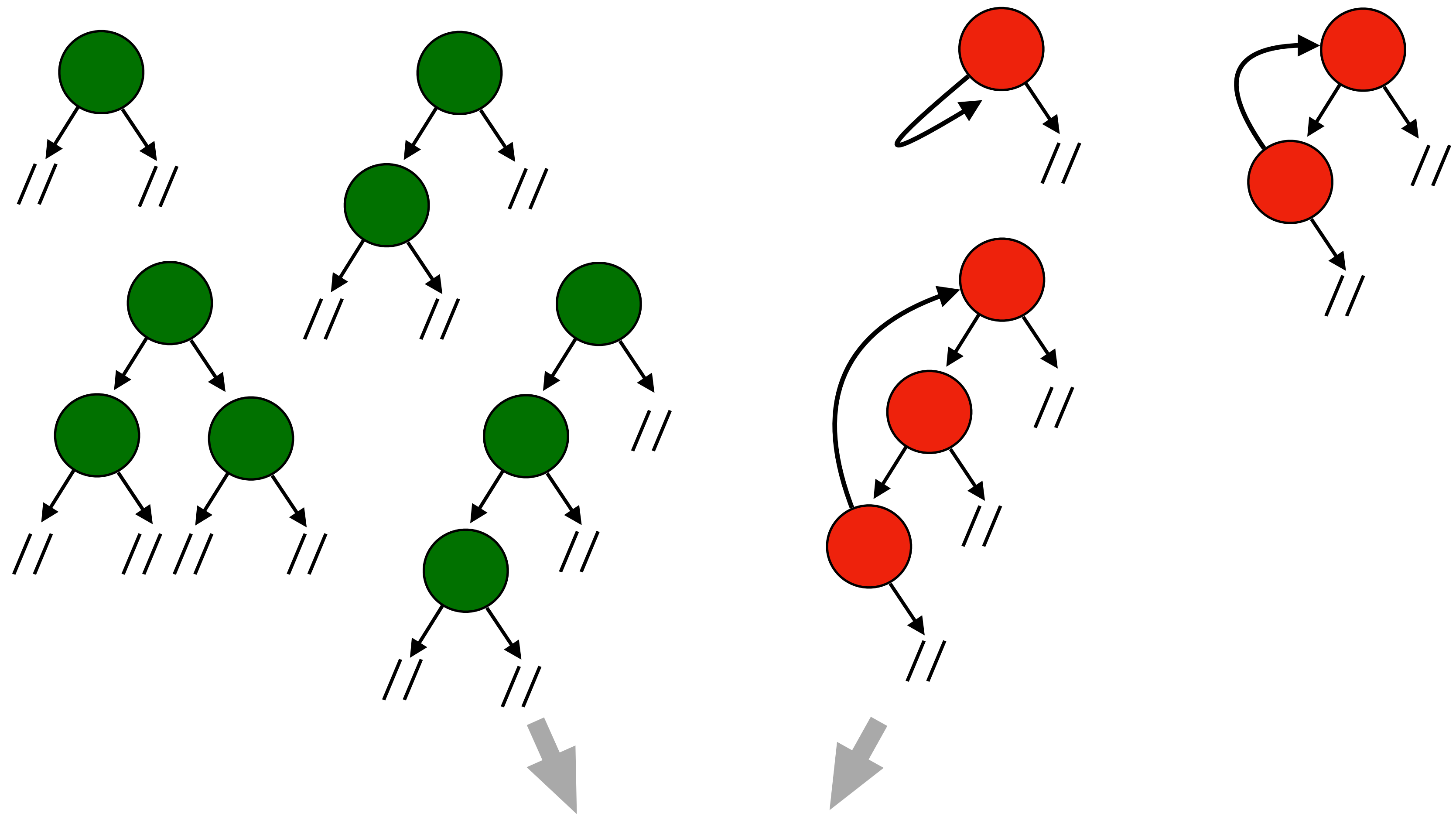

correct program states

incorrect program states




```
/*@
  @ invariant (\forall Node n;
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  @   ! \reach(n.right, Node, right + left).has(n) &&
  @   ! \reach(n.left, Node, left + right).has(n));
  @*/
```

✓ return true

✘ return false

Invariants as Oracles

```
public class BST {

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  }

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    …
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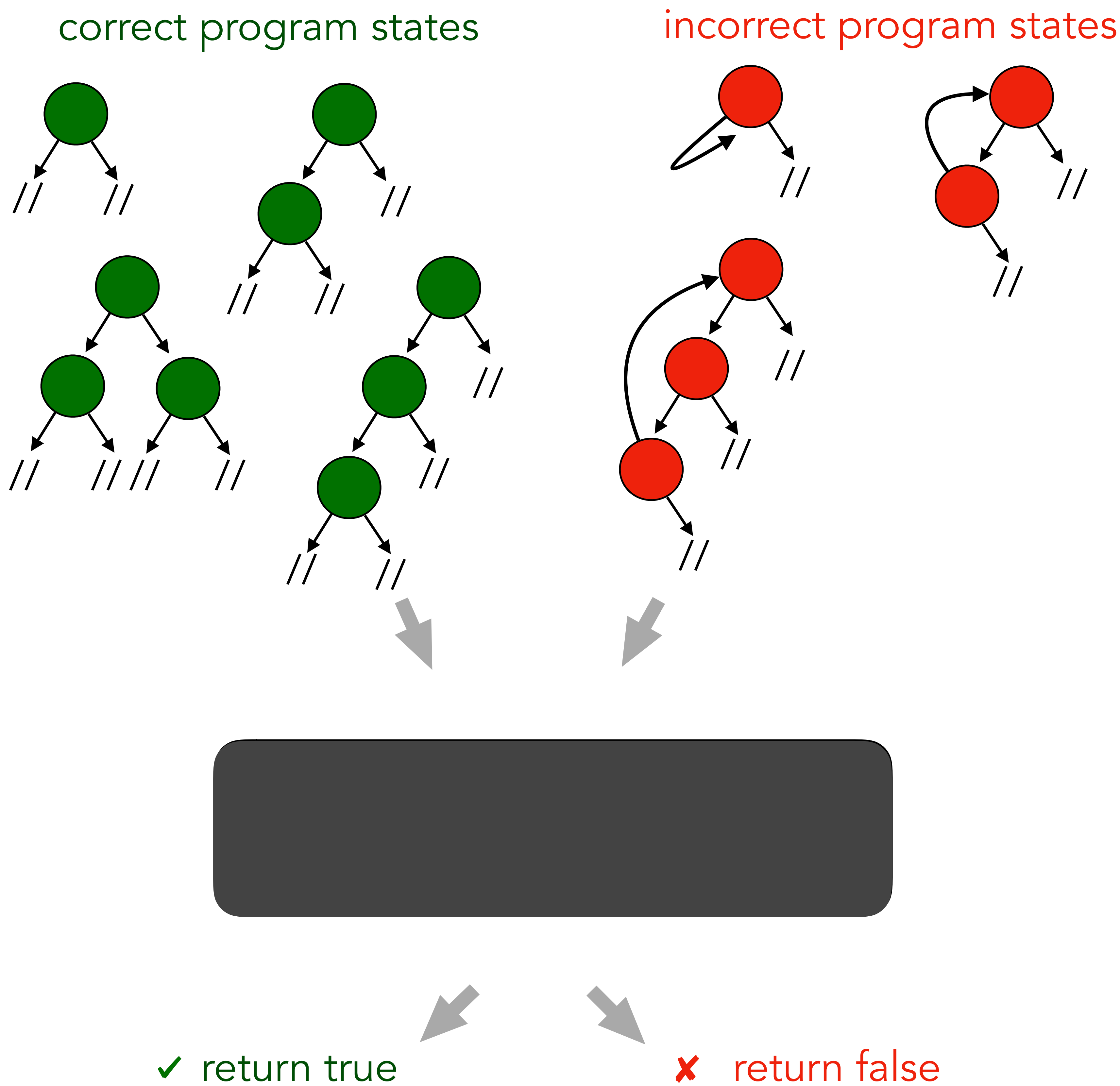

Invariants as Oracles

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  }

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    …
  }
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}
```
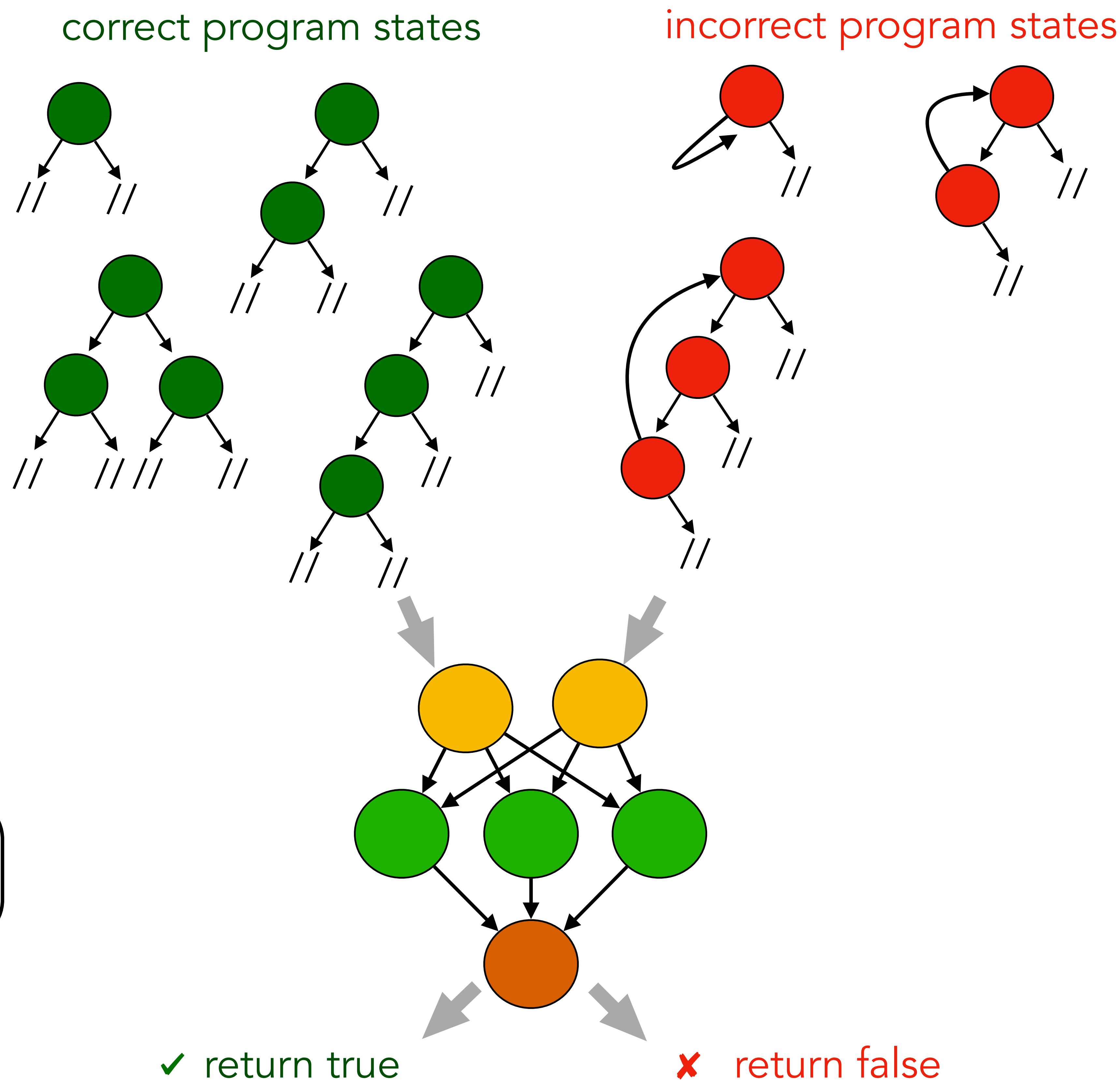
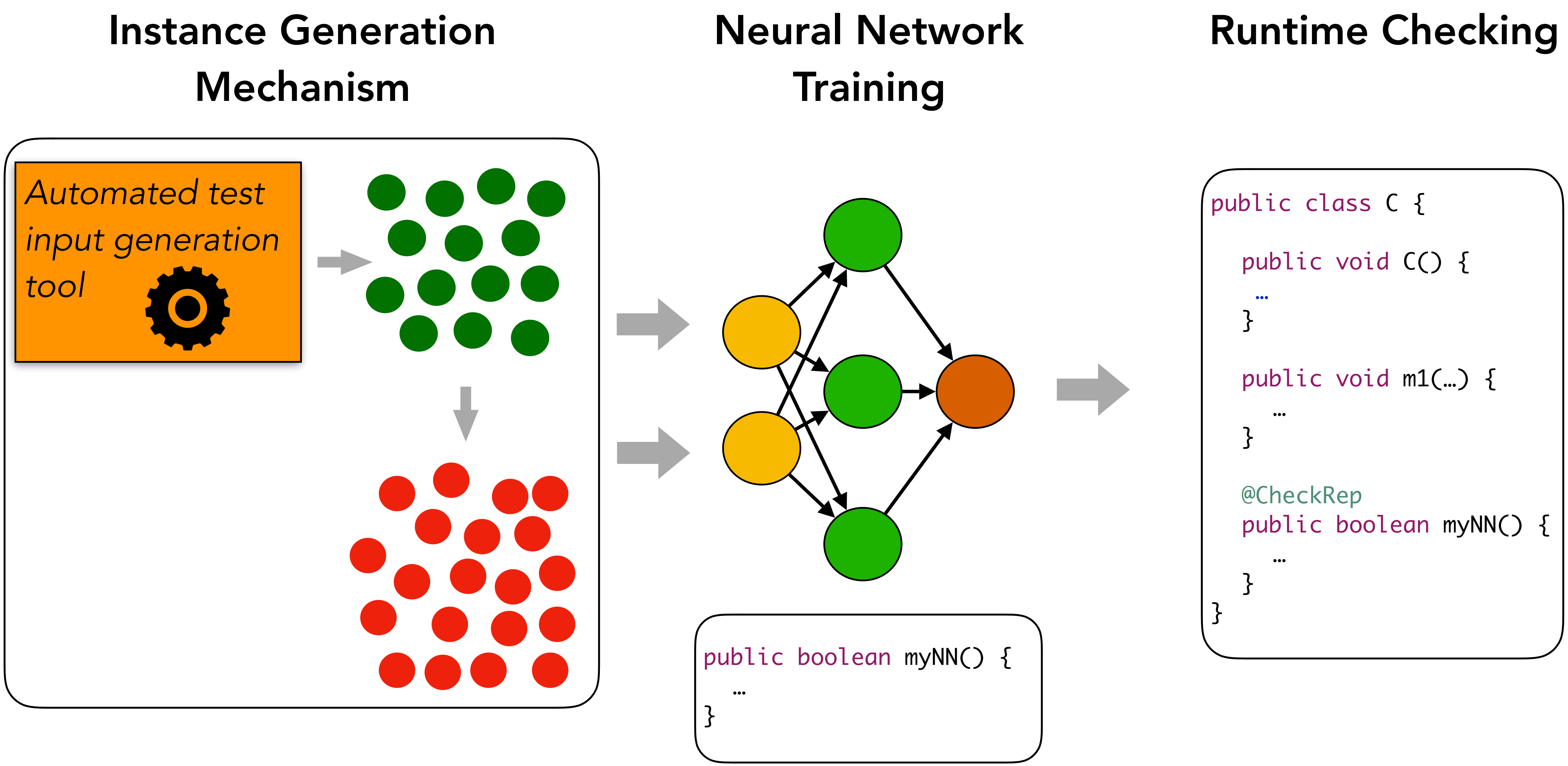



Train a machine learning classifier in order to be used as a test oracle

An Overview of the Approach



Instances Generation Mechanism

Positive instances: generated using assumed-correct building routines

```
public class C {

  public void C() {
     …
  }

  public void m1() {
     …
  }

  public void m2() {
     …
  }
  …
}
```

Instances Generation Mechanism

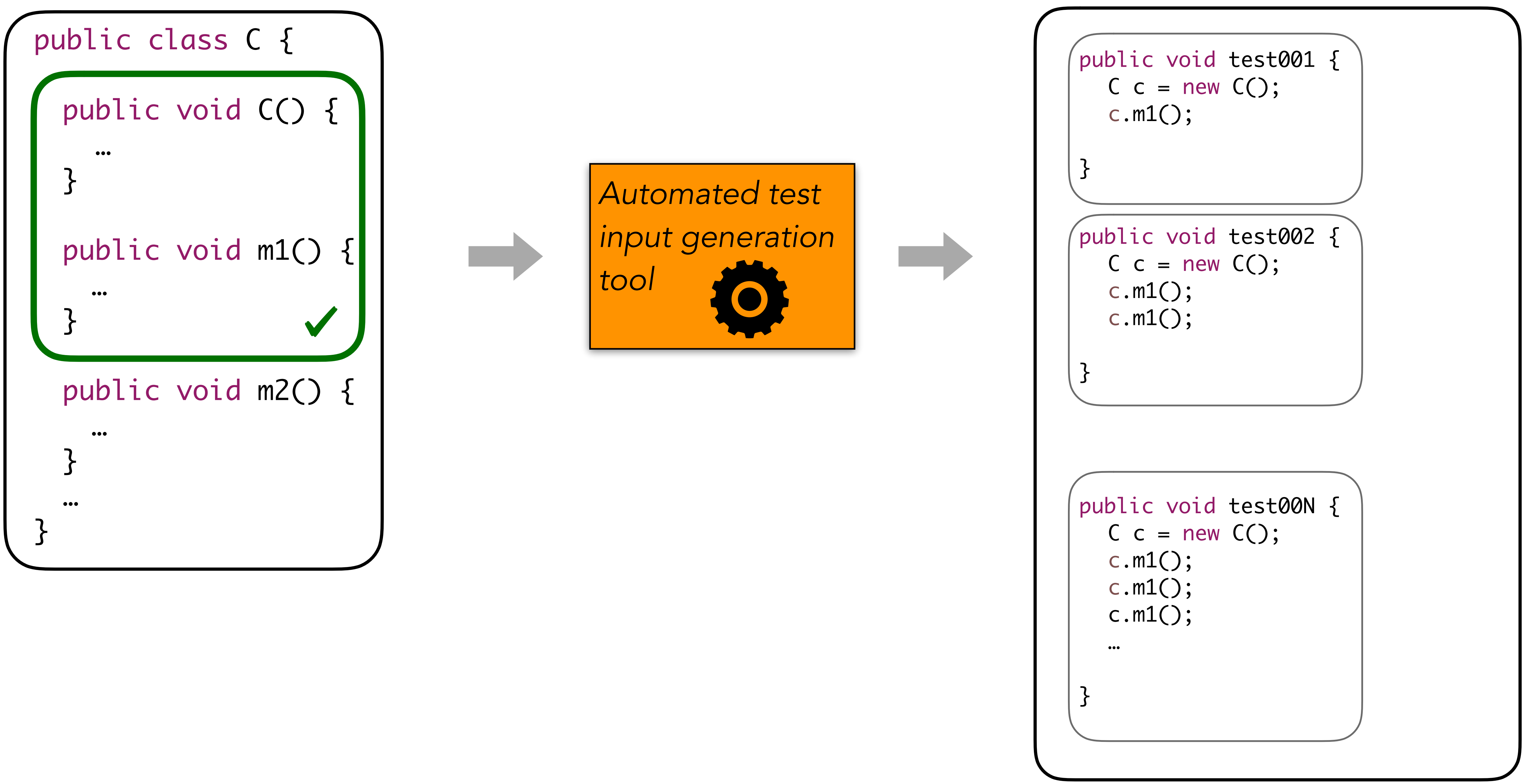
Positive instances: generated using assumed-correct building routines

Identification of assumed-correct builders

```
public class C {
  public void C() {
    …
  }

  public void m1() {
    …
  }
  public void m2() {
    …
  }
  …
}
```

Instances Generation Mechanism

Positive instances: generated using assumed-correct building routines



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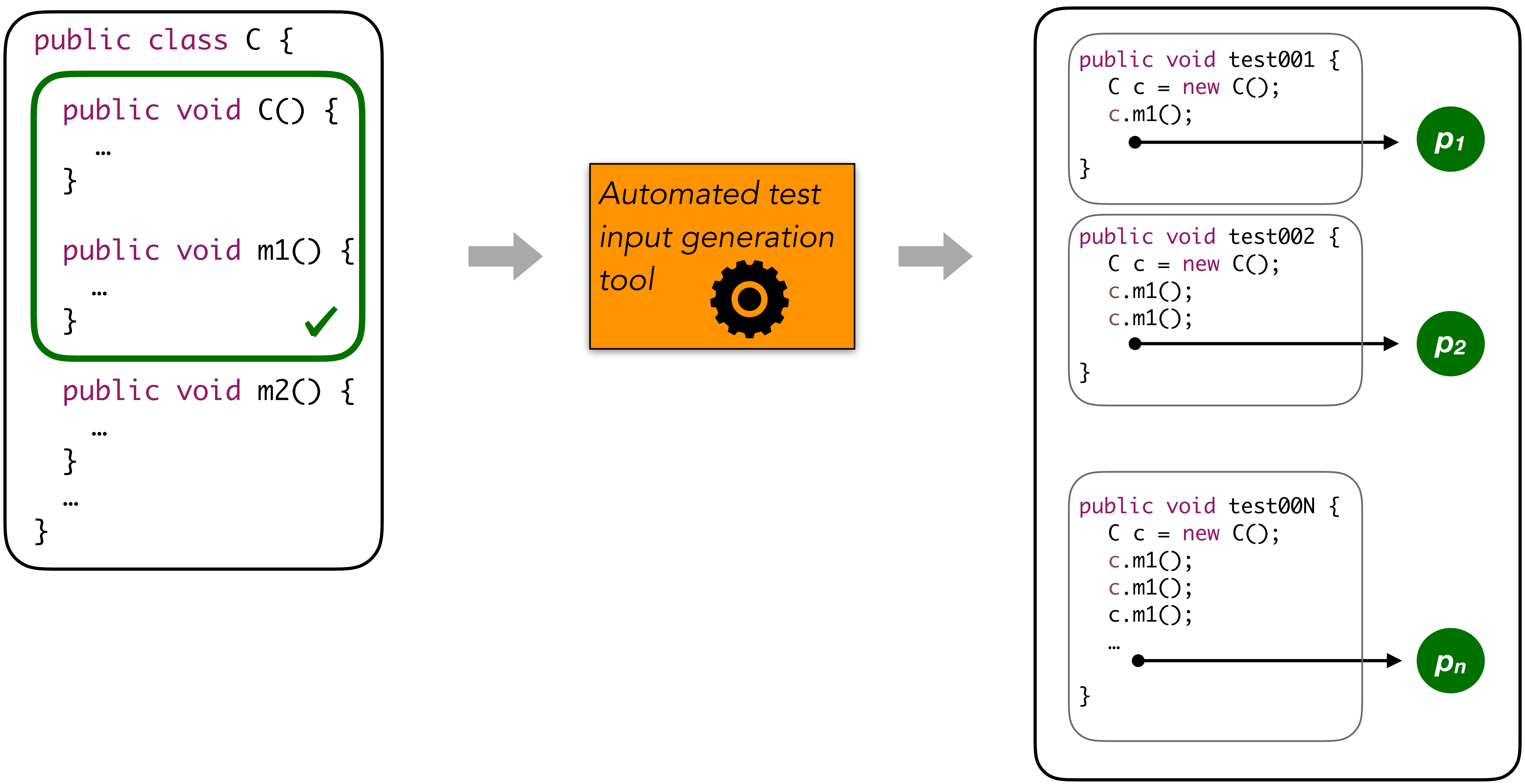

Negative instances: build a ***relational summary*** from valid instances, and mutate valid objects off the summary

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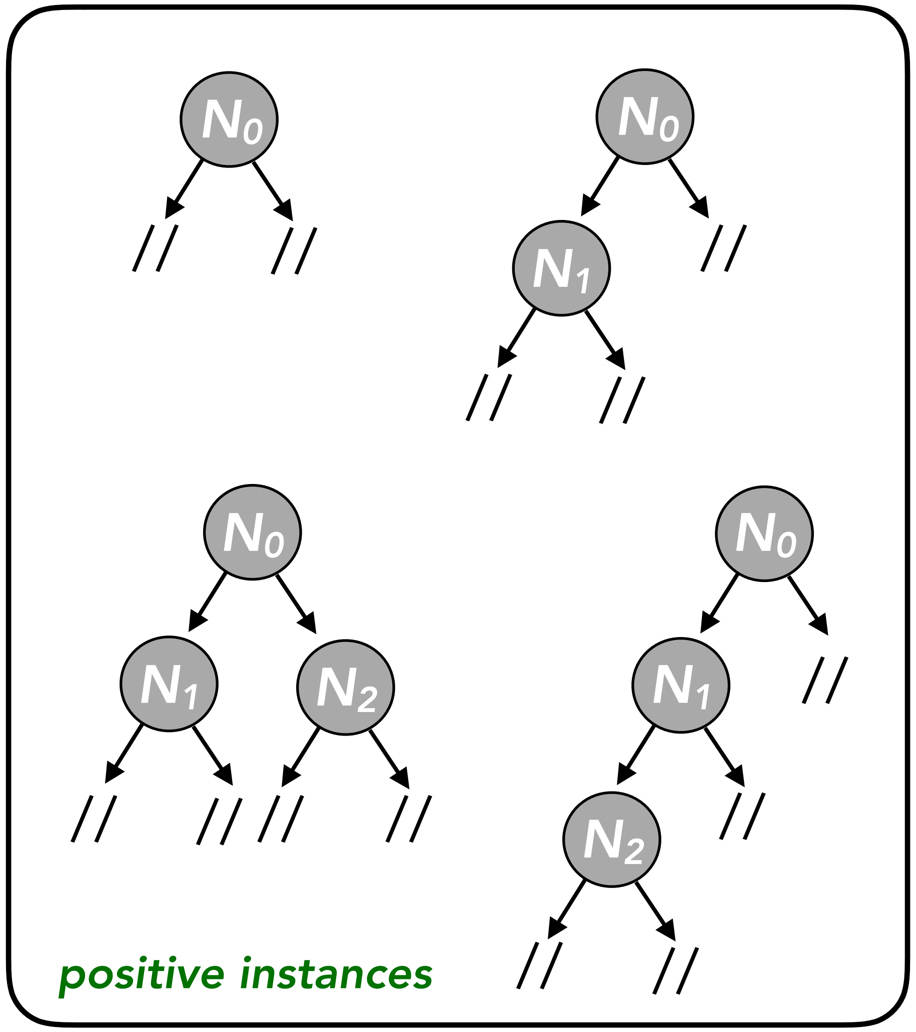

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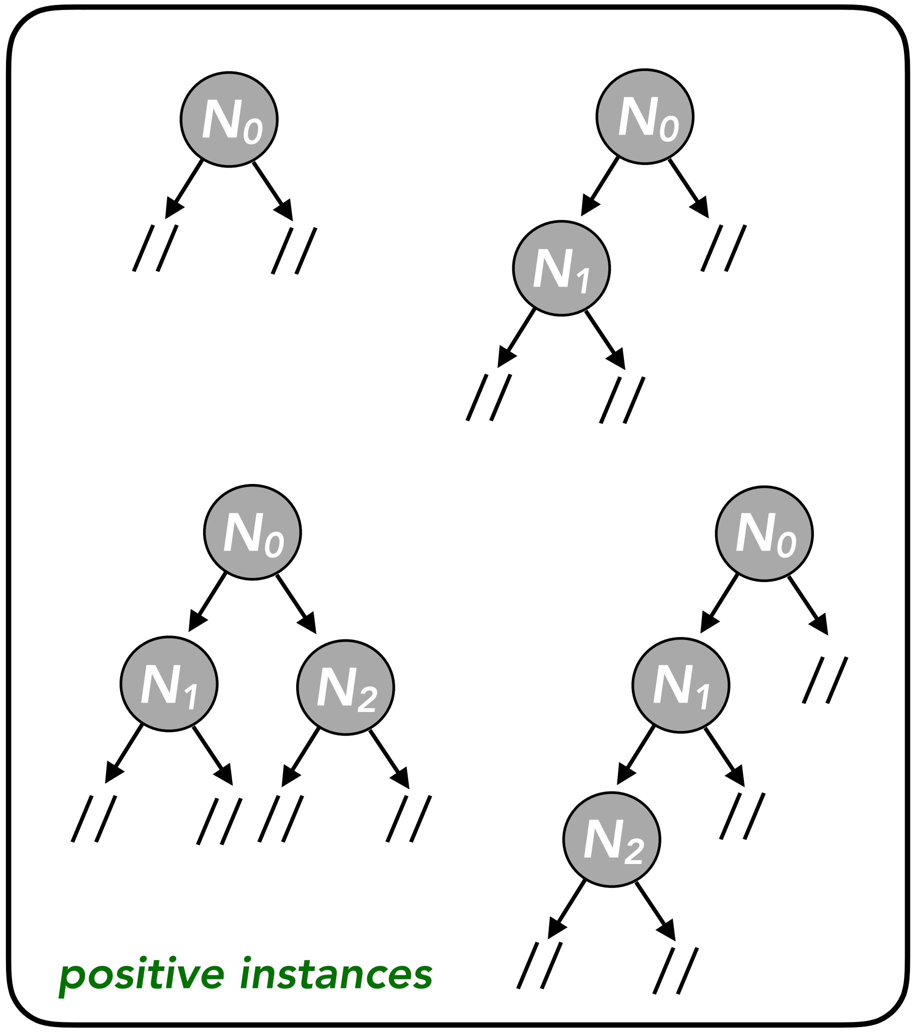
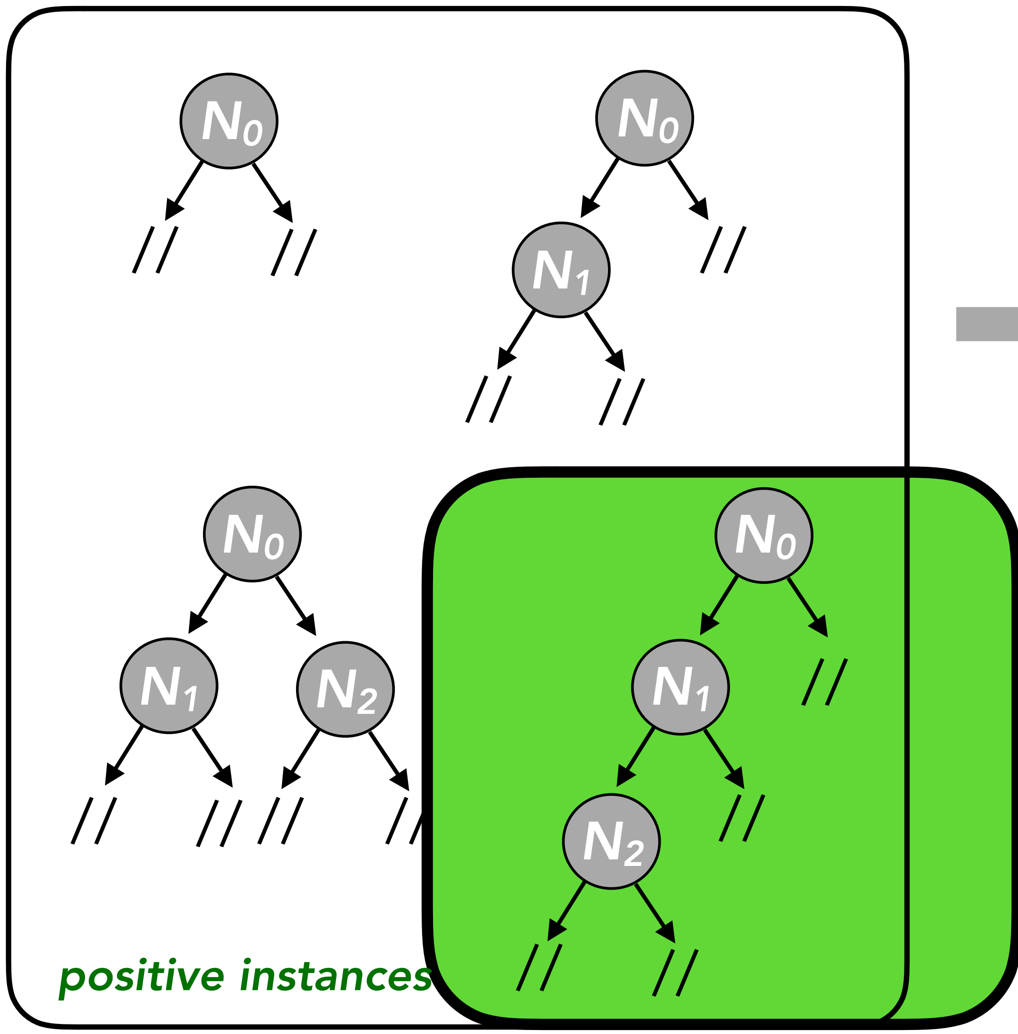


left	*null*	N_0	N_1	N_2
N_0				
N_1				
N_2				

right	*null*	N_0	N_1	N_2
N_0				
N_1				
N_2				

relational summary

Negative instances: build a ***relational summary*** from valid instances, and mutate valid objects off the summary

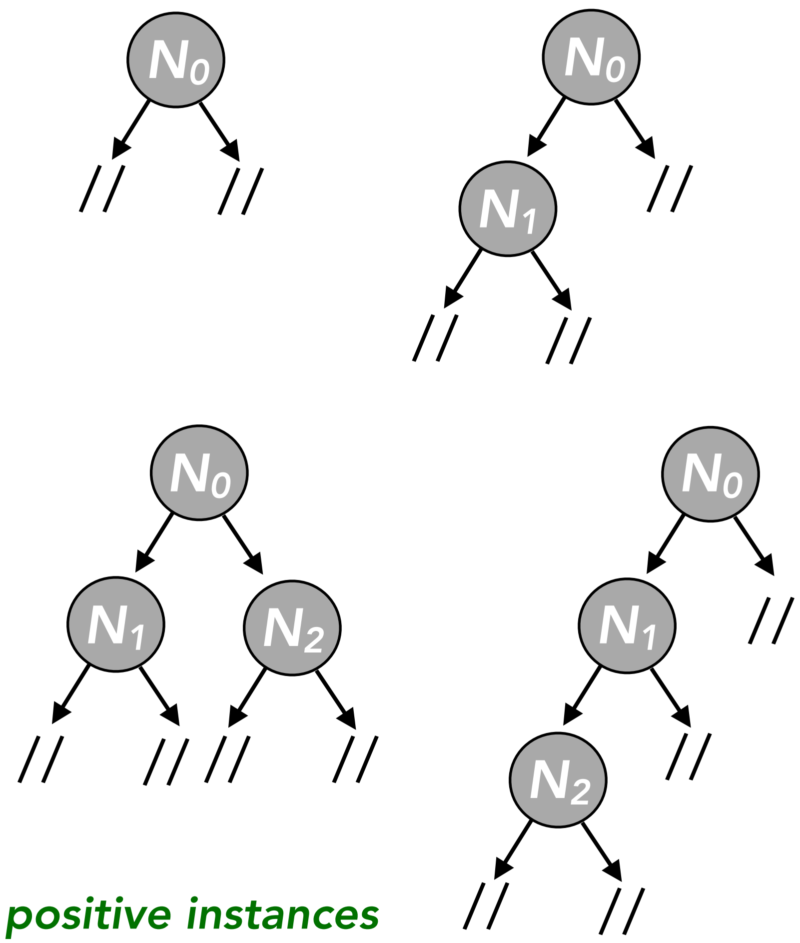


left	*null*	N_0	N_1	N_2
N_0	✓		✓	
N_1	✓			✓
N_2	✓			

right	*null*	N_0	N_1	N_2
N_0	✓			✓
N_1	✓			
N_2	✓			

relational summary

Negative instances: build a ***relational summary*** from valid instances, and mutate valid objects off the summary



positive instances

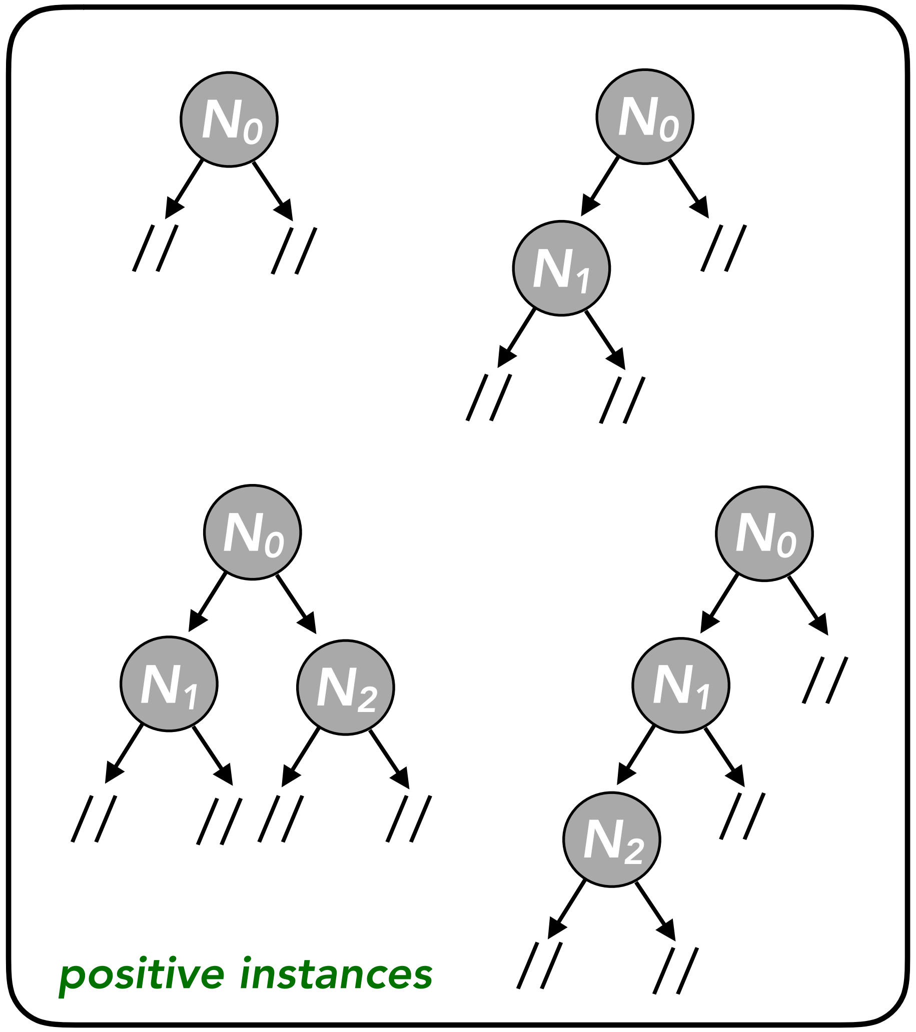
left	*null*	N_0	N_1	N_2
N_0	✓		✓	
N_1	✓			✓
N_2	✓			

right	*null*	N_0	N_1	N_2
N_0	✓			✓
N_1	✓			
N_2	✓			

relational summary

negative instances

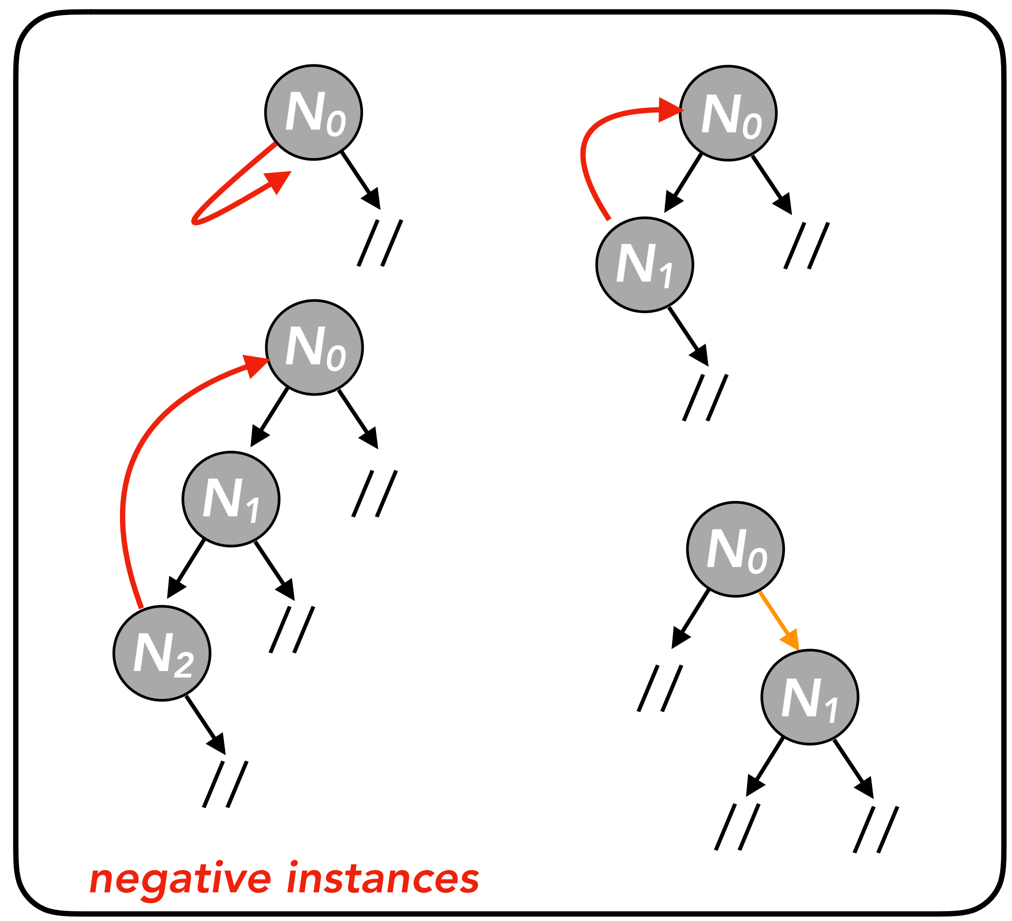
Negative instances: build a ***relational summary*** from valid instances, and mutate valid objects off the summary



left	null	N_0	N_1	N_2
N_0	✓	✗	✓	
N_1	✓	✗		✓
N_2	✓	✗		

right	null	N_0	N_1	N_2
N_0	✓		✗	✓
N_1	✓			
N_2	✓			

relational summary



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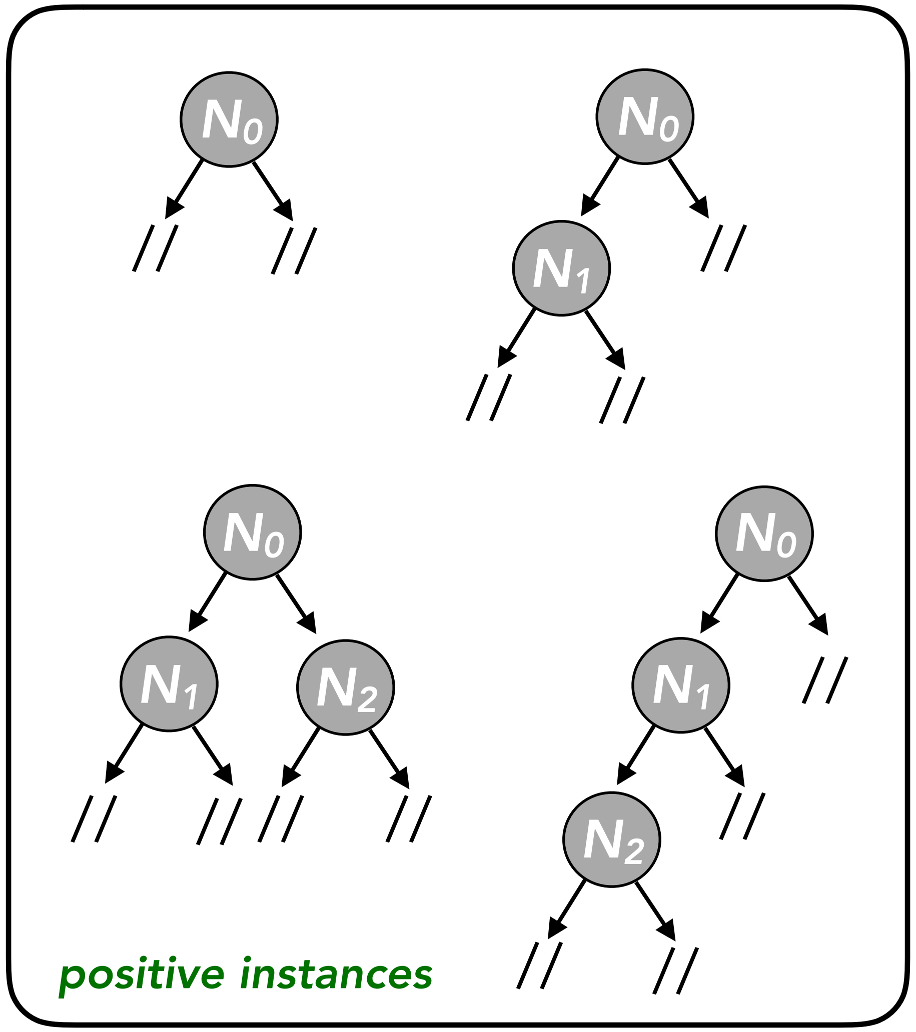
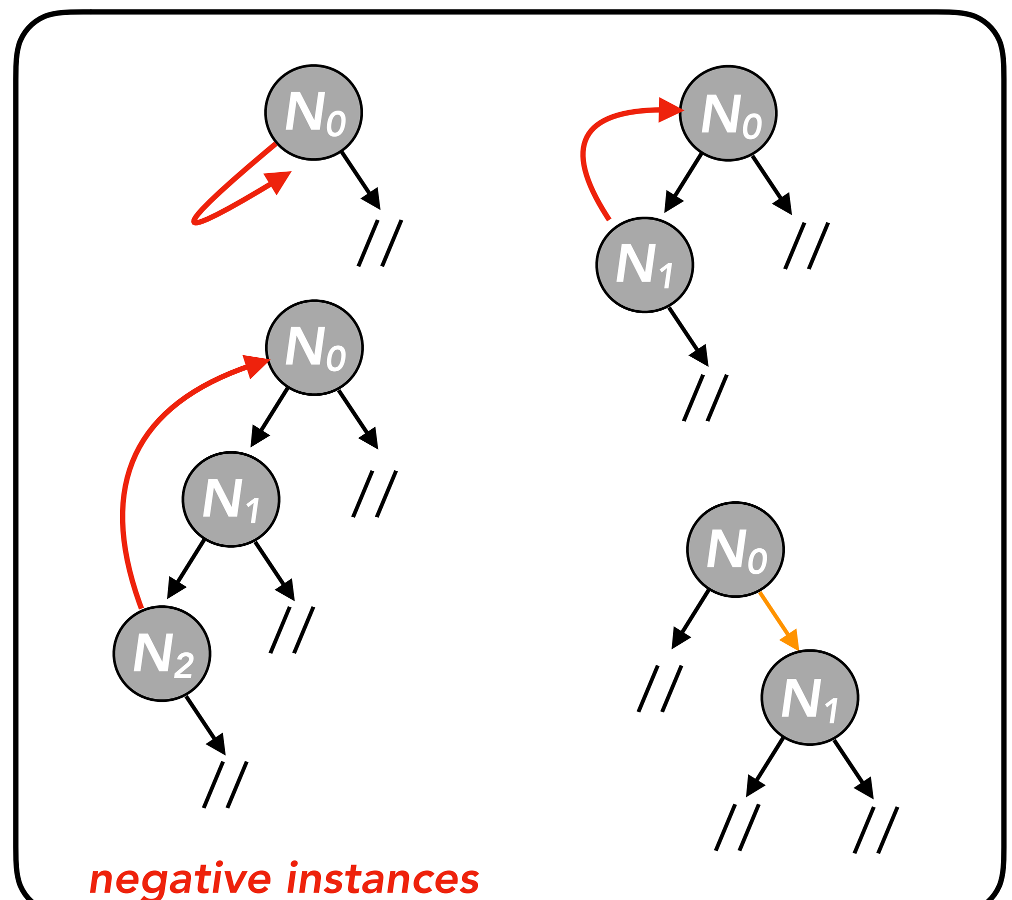


left	null	N_0	N_1	N_2
N_0	✓	✗	✓	
N_1	✓	✗		✓
N_2	✓	✗		

right	null	N_0	N_1	N_2
N_0	✓		✗	✓
N_1	✓			
N_2	✓			

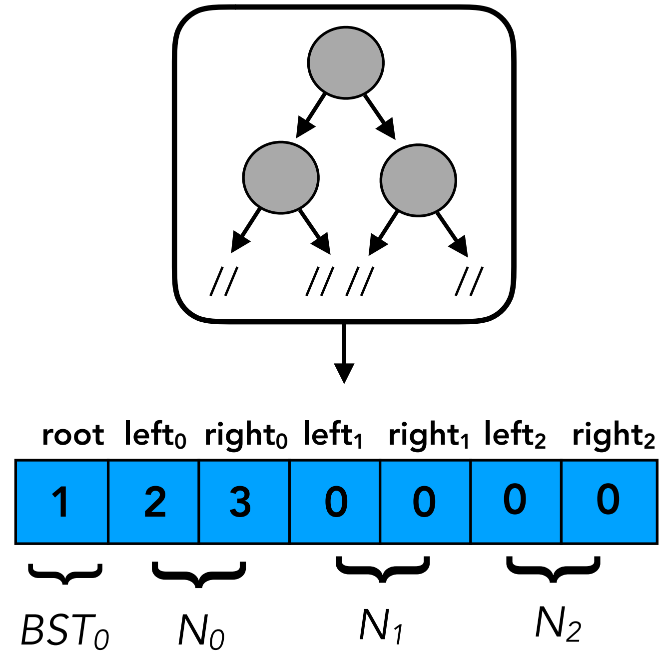
relational summary



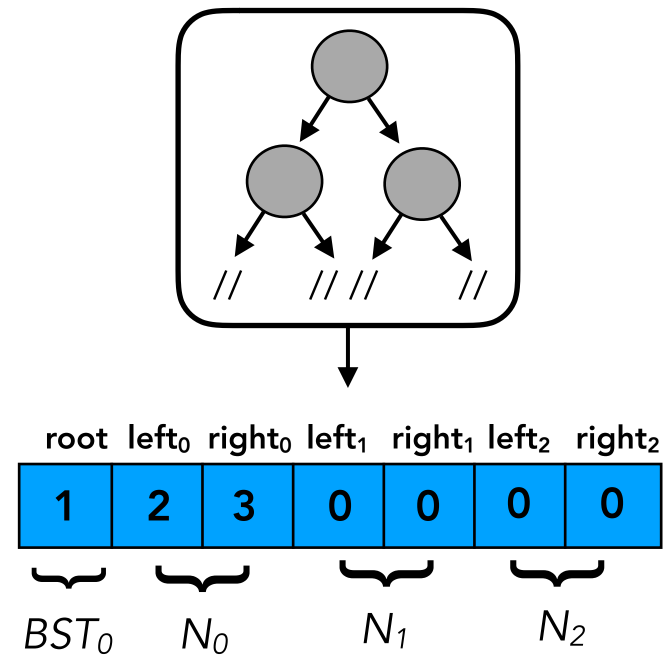
False negative instances may be generated

Vector Representation and Network Architecture

Vector representation using the Korat approach



Vector Representation and Network Architecture



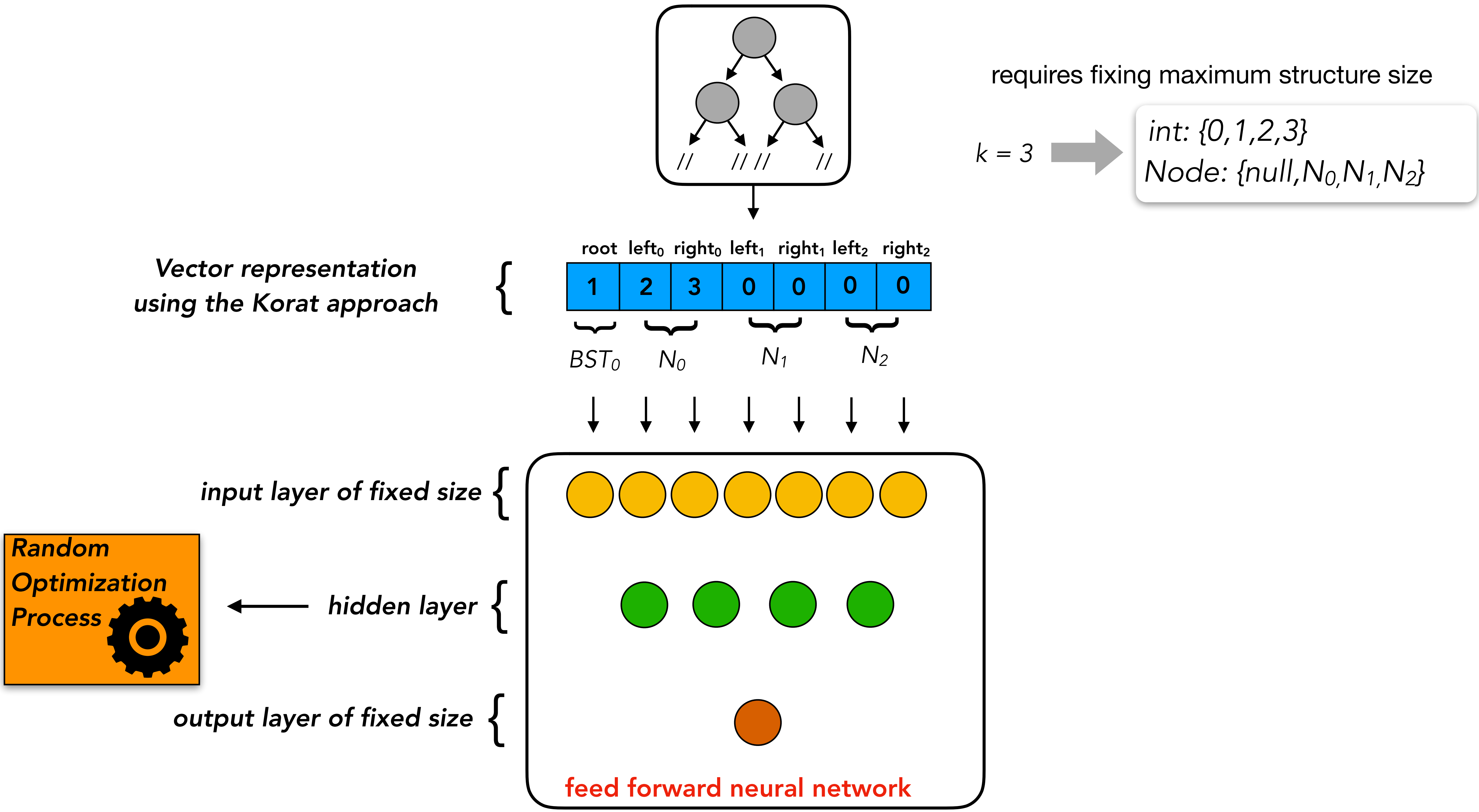
requires fixing maximum structure size

k = 3

int: {0,1,2,3}
Node: {null,N_0,N_1,N_2}

Vector representation using the Korat approach

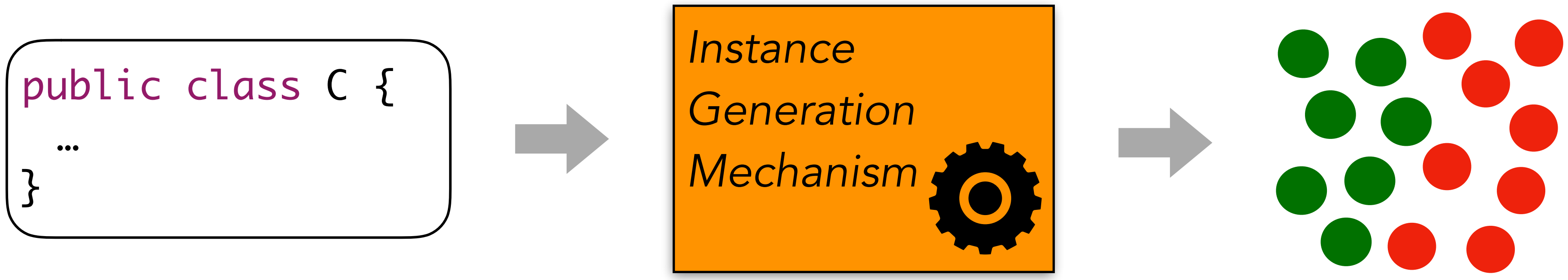
Vector Representation and Network Architecture



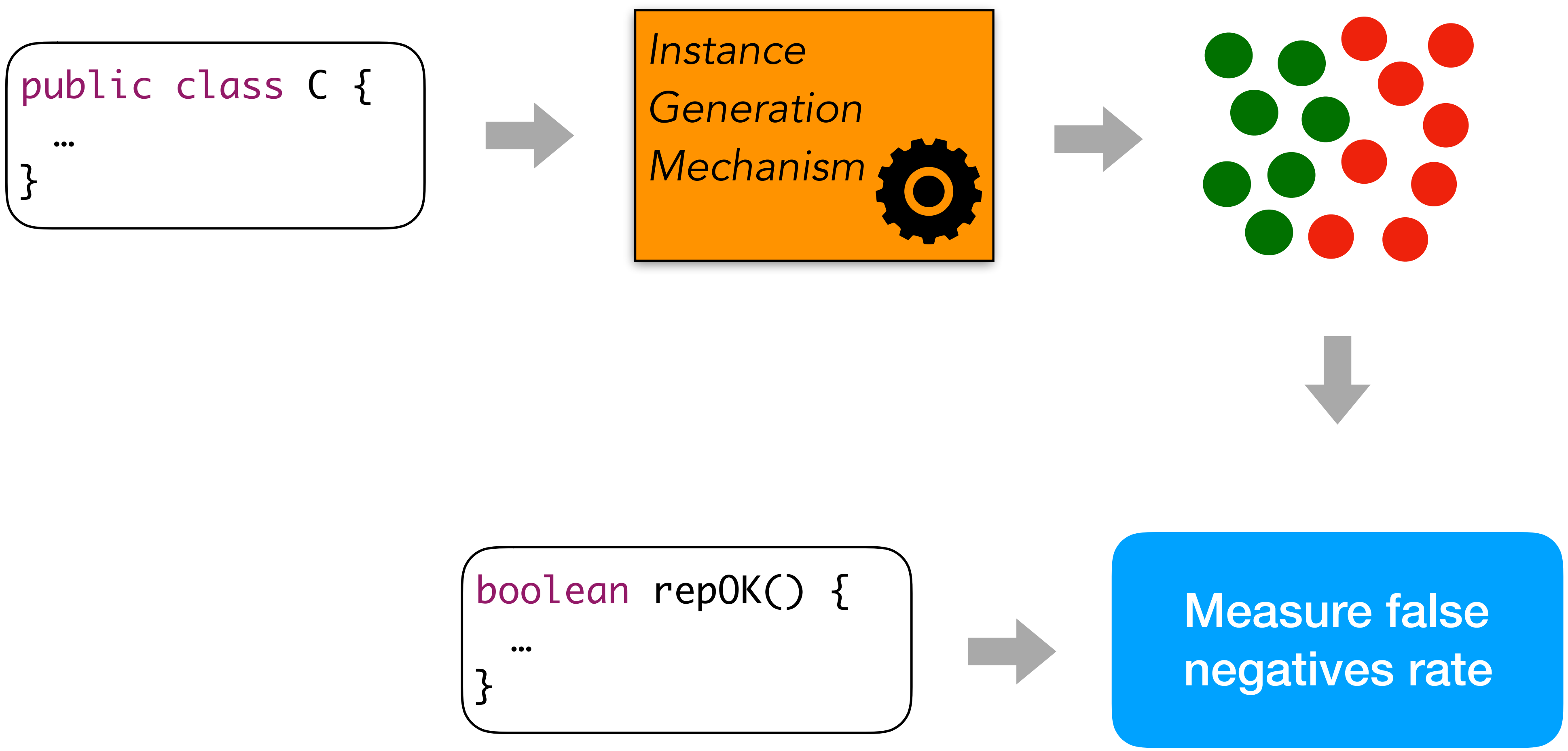
Evaluation

- ***RQ1: is the mechanism for negative instance generation effective?***
- ***RQ2: are neural networks precise in classifying valid/invalid data structure objects?***
- ***RQ3: can automated analysis be improved by the use of NN invariants?***

RQ1: Measure of False Negatives Rate



RQ1: Measure of False Negatives Rate



RQ1: Measure of False Negatives Rate

Singly Sorted List

bound	negative instances	false negatives rate
3	75	6,67 %
4	455	4,18 %
5	2418	2,81 %
6	10306	2,32 %
7	33949	2,24 %
8	83131	2,36 %

Binary Search Tree

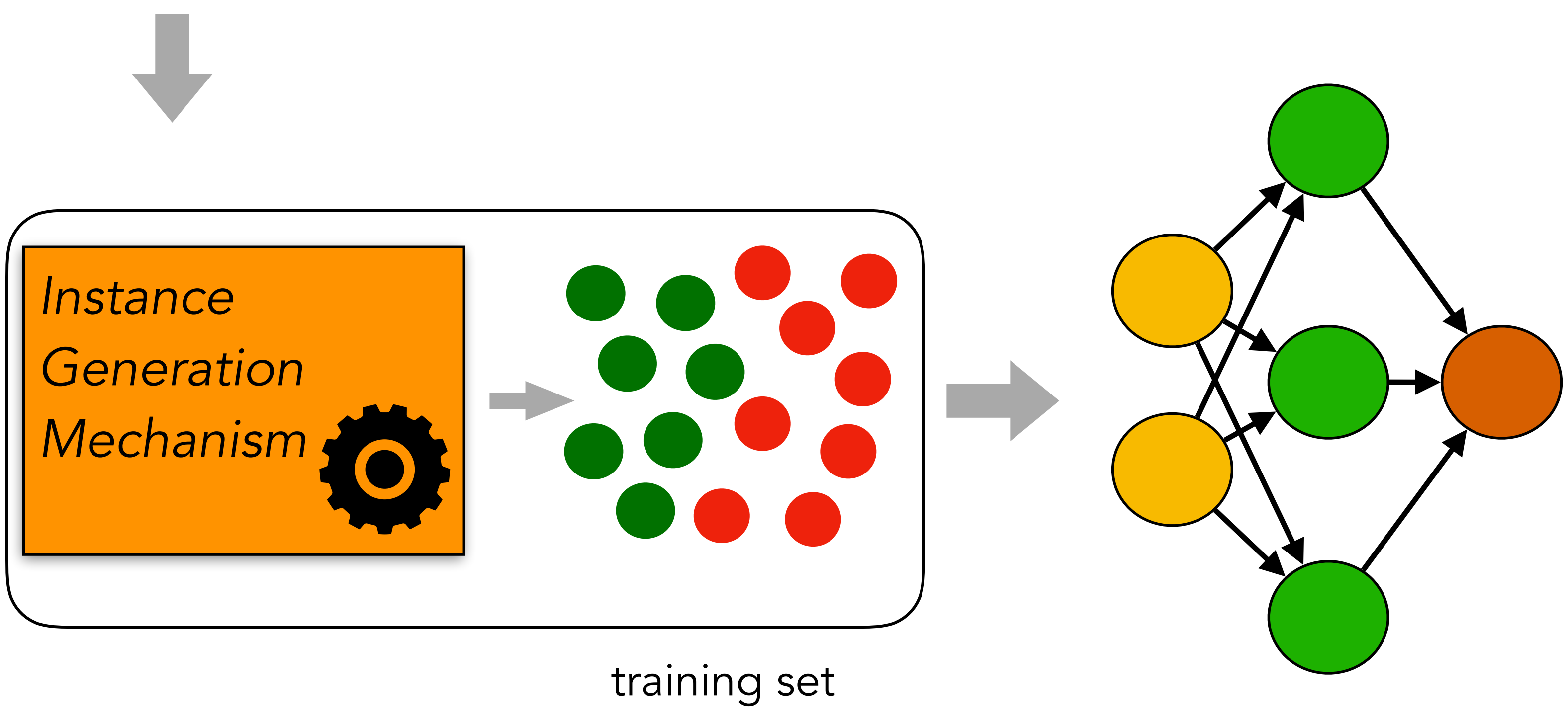
bound	negative instances	false negatives rate
3	200	4,50 %
4	1098	3,19 %
5	5089	0,26 %
6	18445	1,98 %
7	50808	1,65 %
8	106663	1,59 %

Red Black Tree

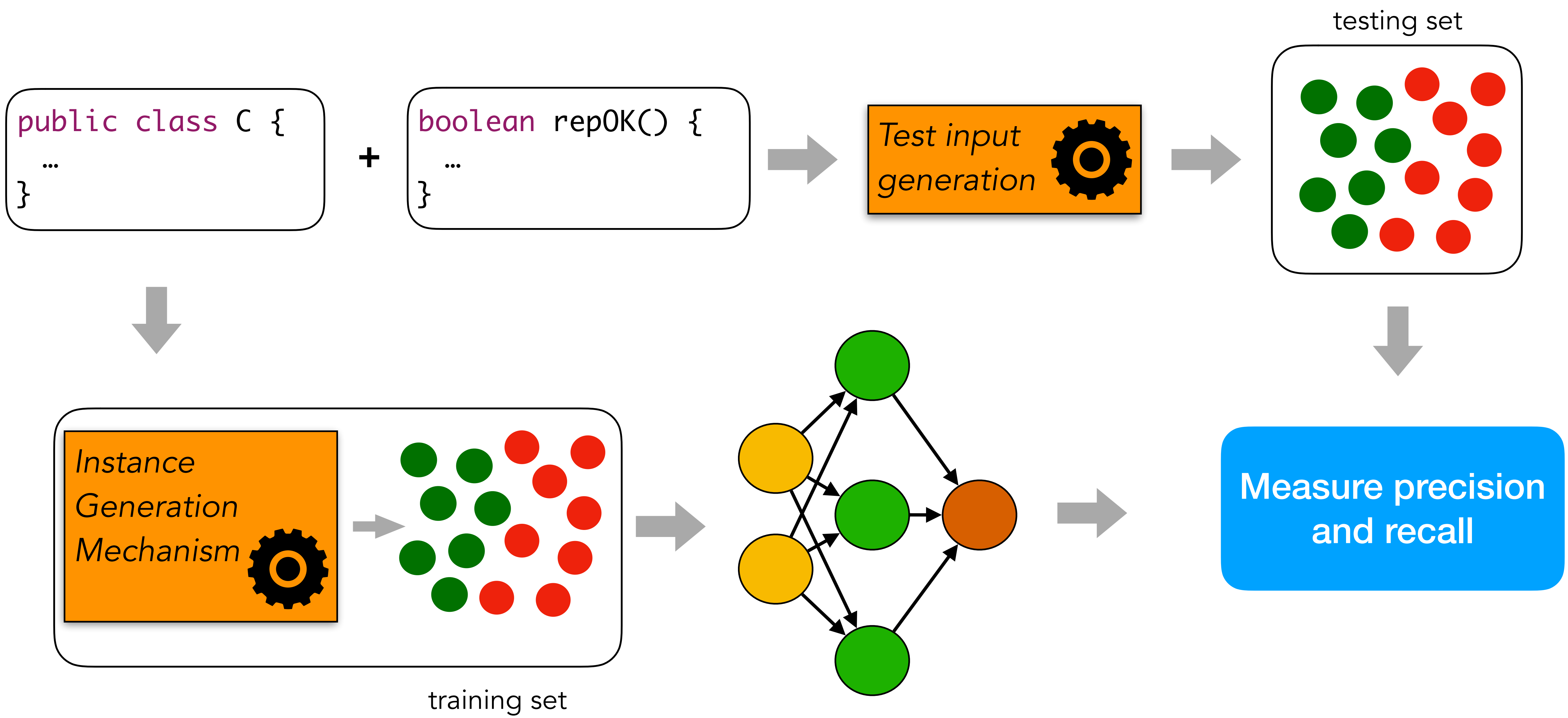
bound	negative instances	false negatives rate
3	144	5,56 %
4	604	3,31 %
5	2377	2,23 %
6	8535	1,53 %
7	26894	1,16 %
8	72099	0,96 %

RQ2: Neural Networks Precision and Recall
Classifying Data Structure Objects

```
public class C {
  …
}
```



RQ2: Neural Networks Precision and Recall Classifying Data Structure Objects



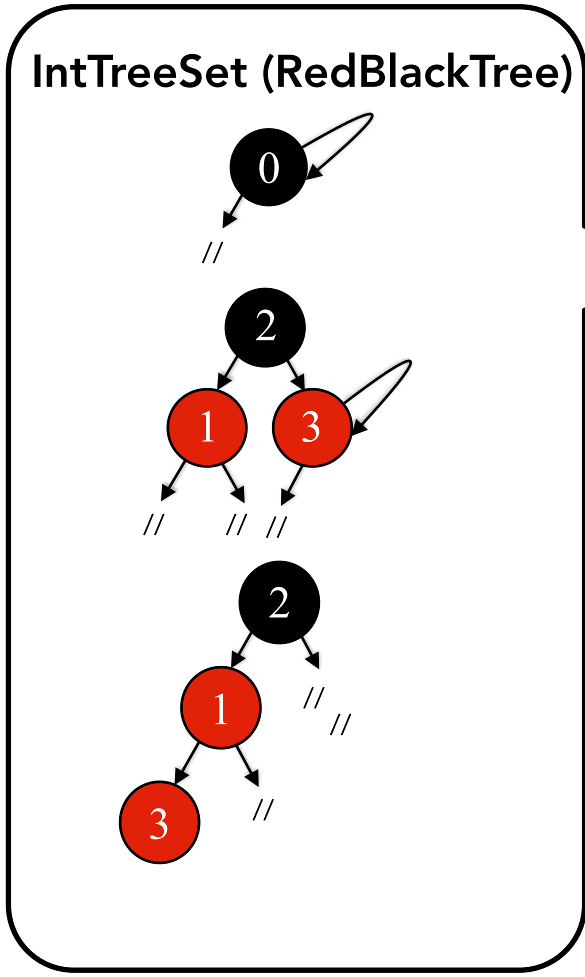
RQ2: Neural Networks Precision and Recall Classifying Data Structure Objects

	Training Set		Validation Set ✗	Validation Set ✓	Precision	Recall
SinglyLinkedList - 7	33456	✗	725966	7	99%	99%
	7867	✓	0	55897	99%	99%
SinglySortedList - 7	33949	✗	1617109	2	99%	99%
	830	✓	51	873	99%	94%
DoublyLinkedList - 7	76574	✗	8914742	8	99%	99%
	9381	✓	1	960800	99%	99%
BinaryTree - 7	21080	✗	17845	3	99%	99%
	567	✓	102	524	99%	83%
RedBlackTree - 7	26894	✗	110834	267	99%	99%
	464	✓	232	679	71%	74%

RQ3: Improved Bug Finding?

Case study	#bugs	#found without oracle	#found using NN
IntTreeSet	5	0	5
Antlr	1	0	1
FibHeap	1	0	1
BinTree	1	0	1
BinHeap	1	0	1
Schedule	8	3	4

RQ3: Improved Bug Finding?



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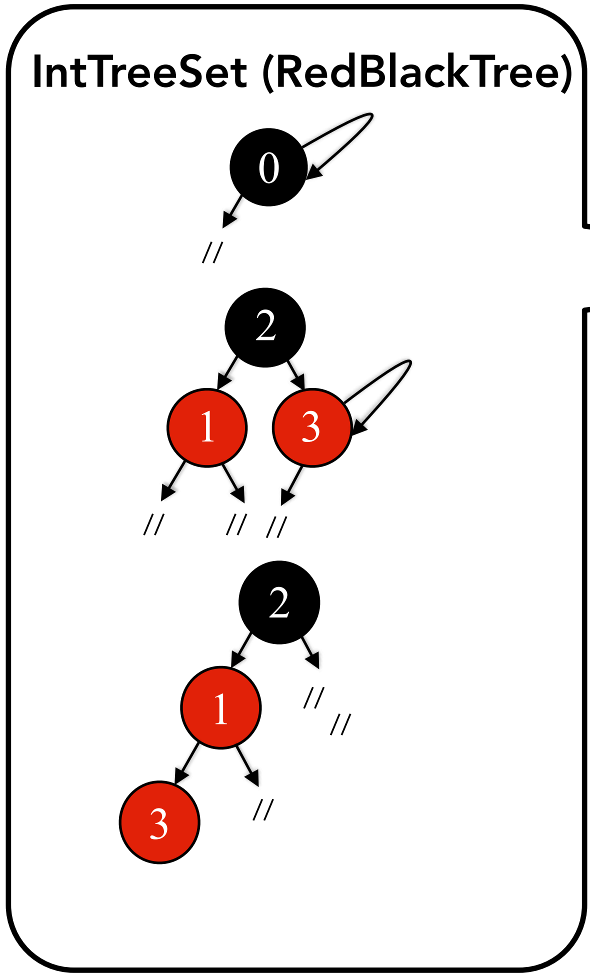

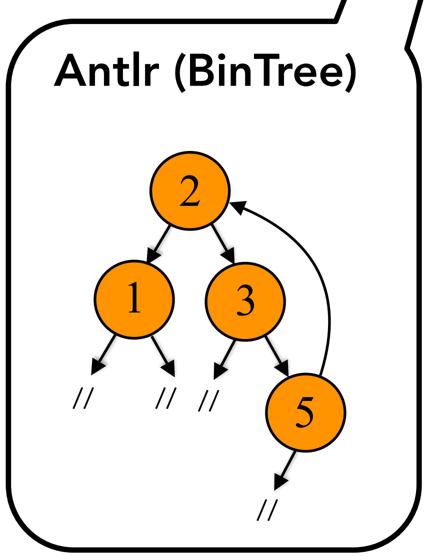

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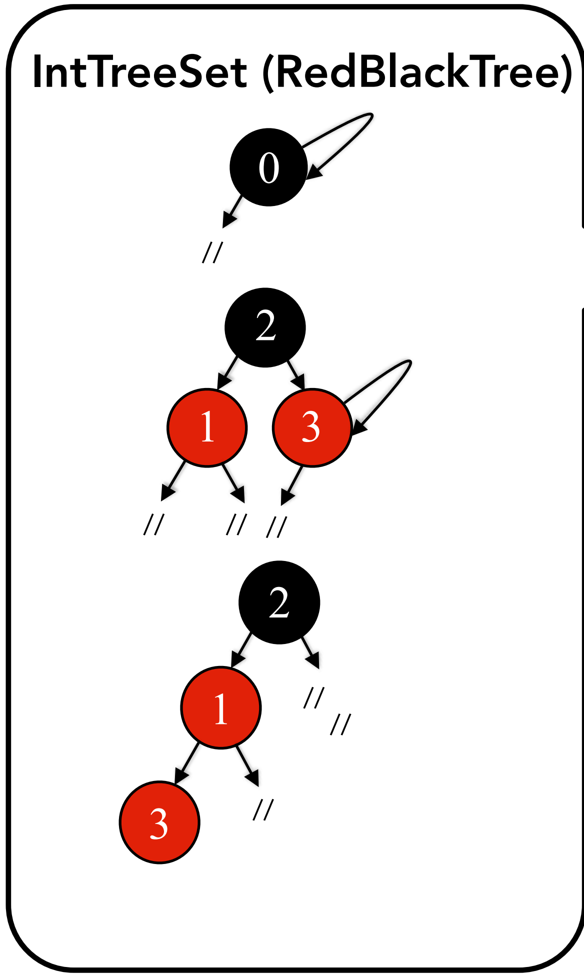
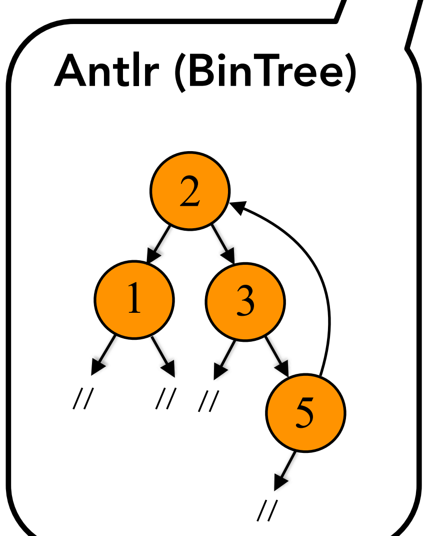
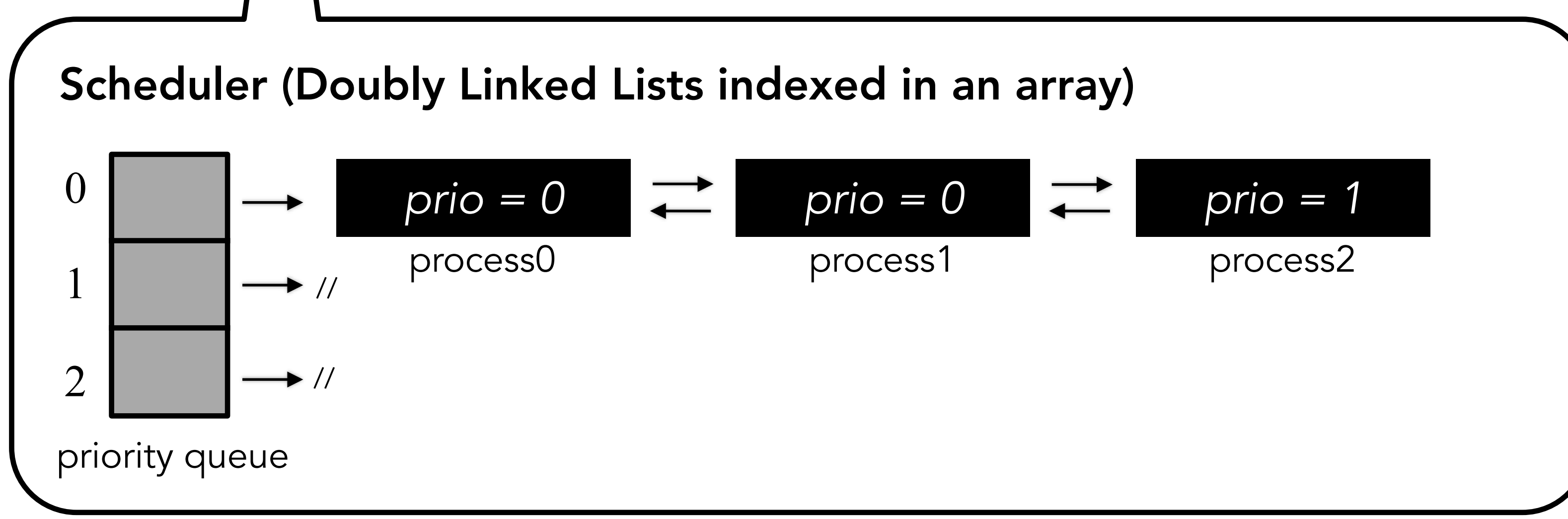






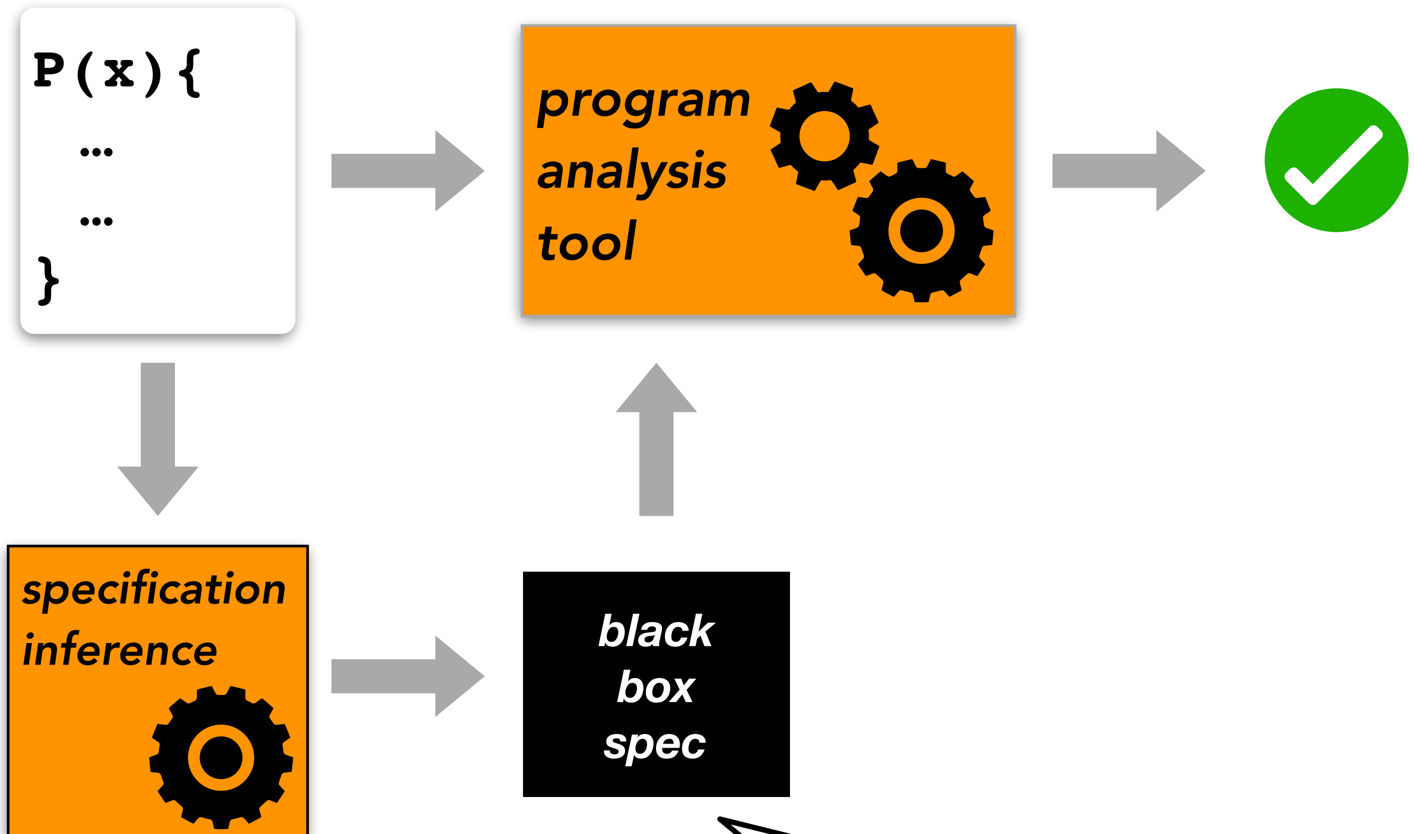
Remarks

- We defined a technique to generate valid and invalid objects from a set of assumed-correct object builders
- We proposed to use the generated objects to train a neural network to distinguish valid from invalid
- We used the trained neural network in place of an invariant for bug finding

Thank you :)

Questions?

Providing Specifications for Program Analysis

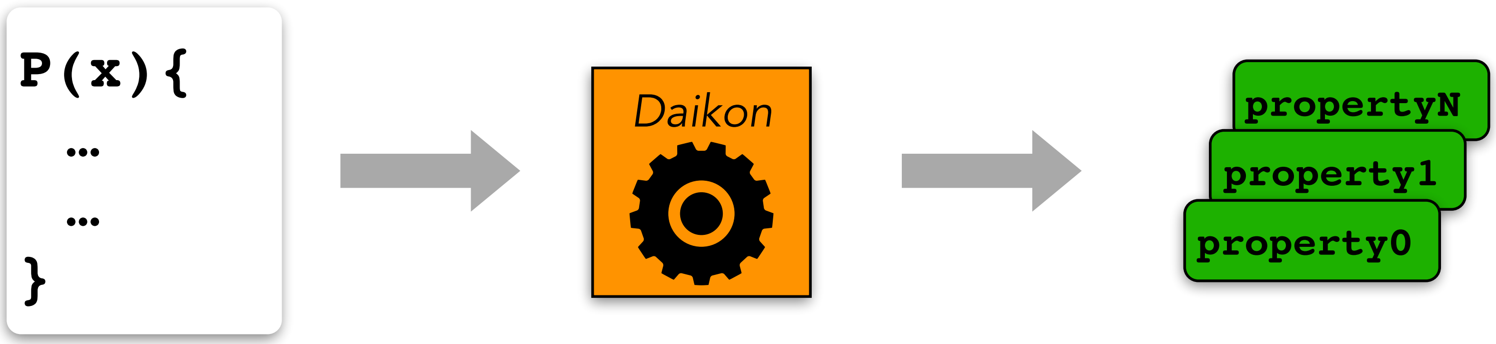


Daikon: derivation of ***likely*** invariants based on different executions of ***P***

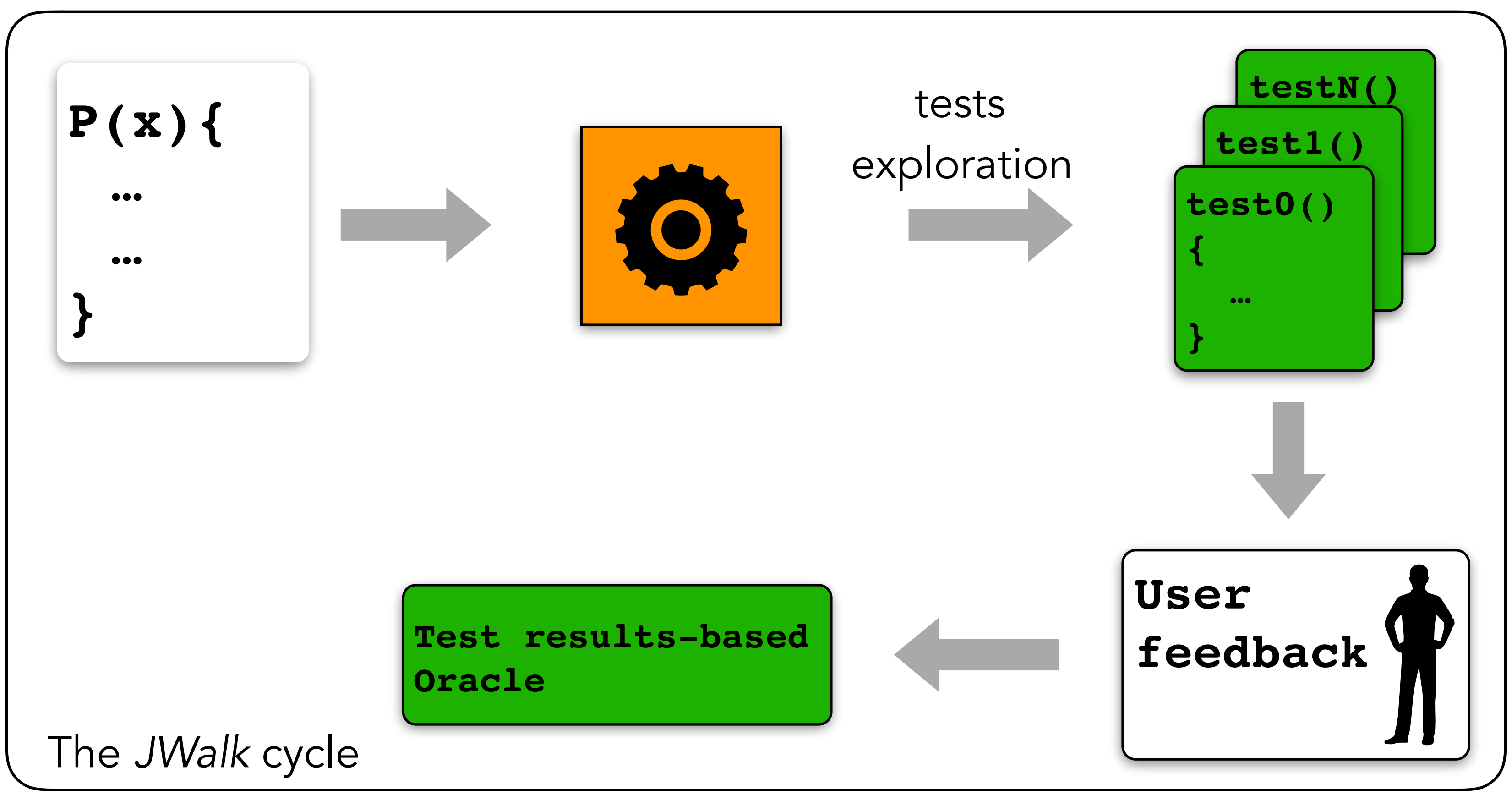
Can be thought as a classifier of correct and incorrect software behaviors

Current approaches to the Lack of Specifications

- Derivation of ***likely*** invariants based on different ***P*** executions



- ***JWalk***: allows dynamic inference of specifications with a feedback-based approach



Current approaches to the Lack of Specifications

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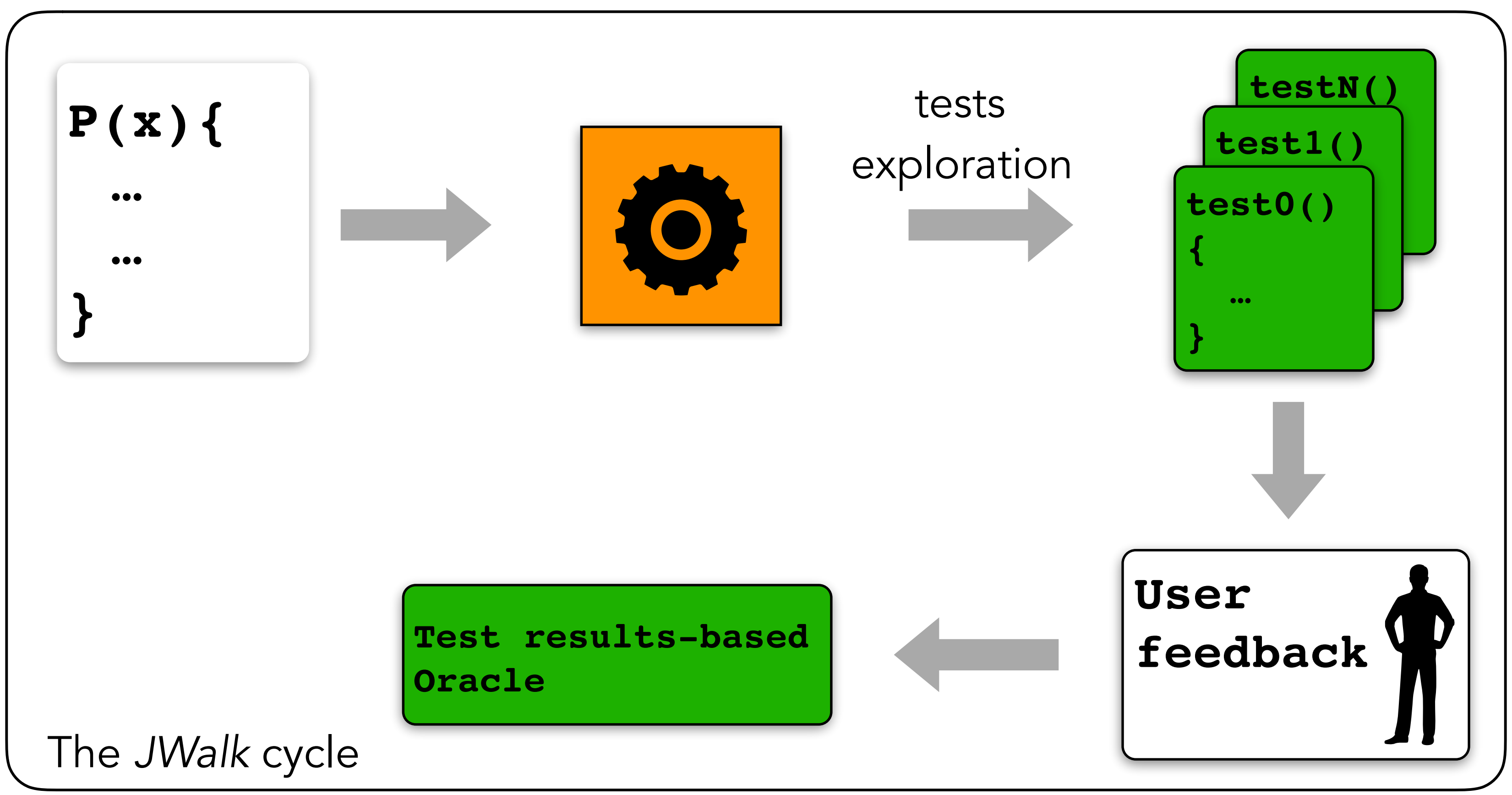


✓ human readable properties

✗ complex structural constrains are missed

✗ scenario specific oracles

Daikon in the SinglyLinkedList case

```java
public class SinglyLinkedList {
  private Node header;
  private int size;

  public void SinglyLinkedList() {
    header = new Node(0);
    size = 0;
  }

  public void add(int n) {
    …
  }

}

public class Node {
  private int value;
  private Node next;
  …
}
```

```java
public void test00100() {
public void test002() {
public void test001() {
  SinglyLinkedList l = new SinglyLinkedList();
  l.add(0);
}
```

Daikon

```java
this.header.value == 0;
this.size >= 0;
```

✗ the acyclicity property is missed

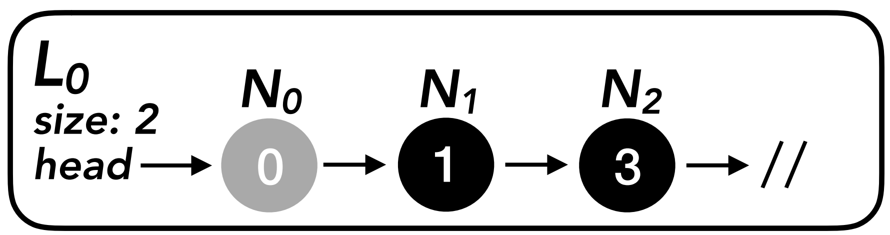
✗ the size property is missed

Precision and Recall vs the True Invariant for scope 7

	Validation Set ✗	Validation Set ✓	Precision	Recall
✗	9	725964	100%	1%
✓	0	55987	7%	100%

Instances as Vectors

- Given an bound ***k***: use it to define the maximum number of different values for each field
- The vector representation will have as many positions as necessary to represent ***k*** objects/values of each type



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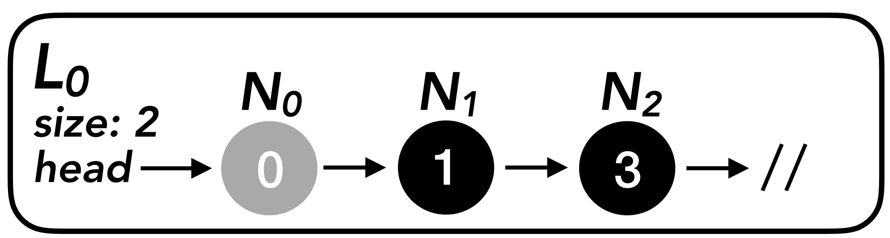
Example:



k = *3*

int: 0..3
Node: 0..3

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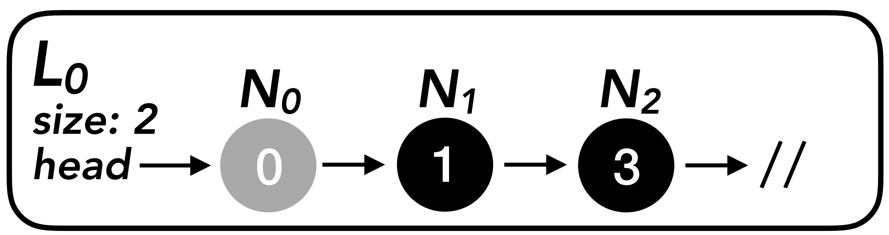

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int: 0..3
Node: 0..3

size	head	val_0	$next_0$	val_1	$next_1$	val_2	$next_2$
2	1	0	2	1	3	3	0
L_0		N_0		N_1		N_2	

RQ1: Measure of False Negatives Rate