KLEE Workshop 2024

Complex Test Input Generation in KLEE

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Testing dynamically allocated structures

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```
 1 struct node {
 2   struct node *left;
 3   struct node *right;
 4   struct node *parent;
 5   int value;
 6 };
 7
 8 int main() {
 9   struct node *data = create_tree();
10
11   inspect(data);
12
13   return 0;
14 }
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- Dynamically allocated recursive structures are everywhere (lists, trees, graphs, etc.)

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  inspect(data);

  return 0;
}
```

- Dynamically allocated recursive structures are everywhere (lists, trees, graphs, etc.)
- Instances are operated with via a pointer to head
- The usual approach for testing is to write a test harness that generates an instance and then pass it to the function under test

Generating Procedure

Generating Procedure

```
 1 node *create_tree() {
 2   node *nodelast = NULL;
 3   node *node = NULL;
 4 
 5   while (make_symbolic_int()) {
 6     node = malloc(sizeof *node);
 7     *node = {NULL, nodelast, NULL, make_symbolic_int()};
 8 
 9     if (nodelast) {
10       nodelast->parent = node;
11     }
12 
13     nodelast = node;
14   }
15 
16   while (node != NULL) {
17     node->left = malloc(sizeof *node);
18     *node->left = {NULL, NULL, node, 42};
19 
20     node = node->right;
21   }
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23   return nodelast;
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- Detached from code under test

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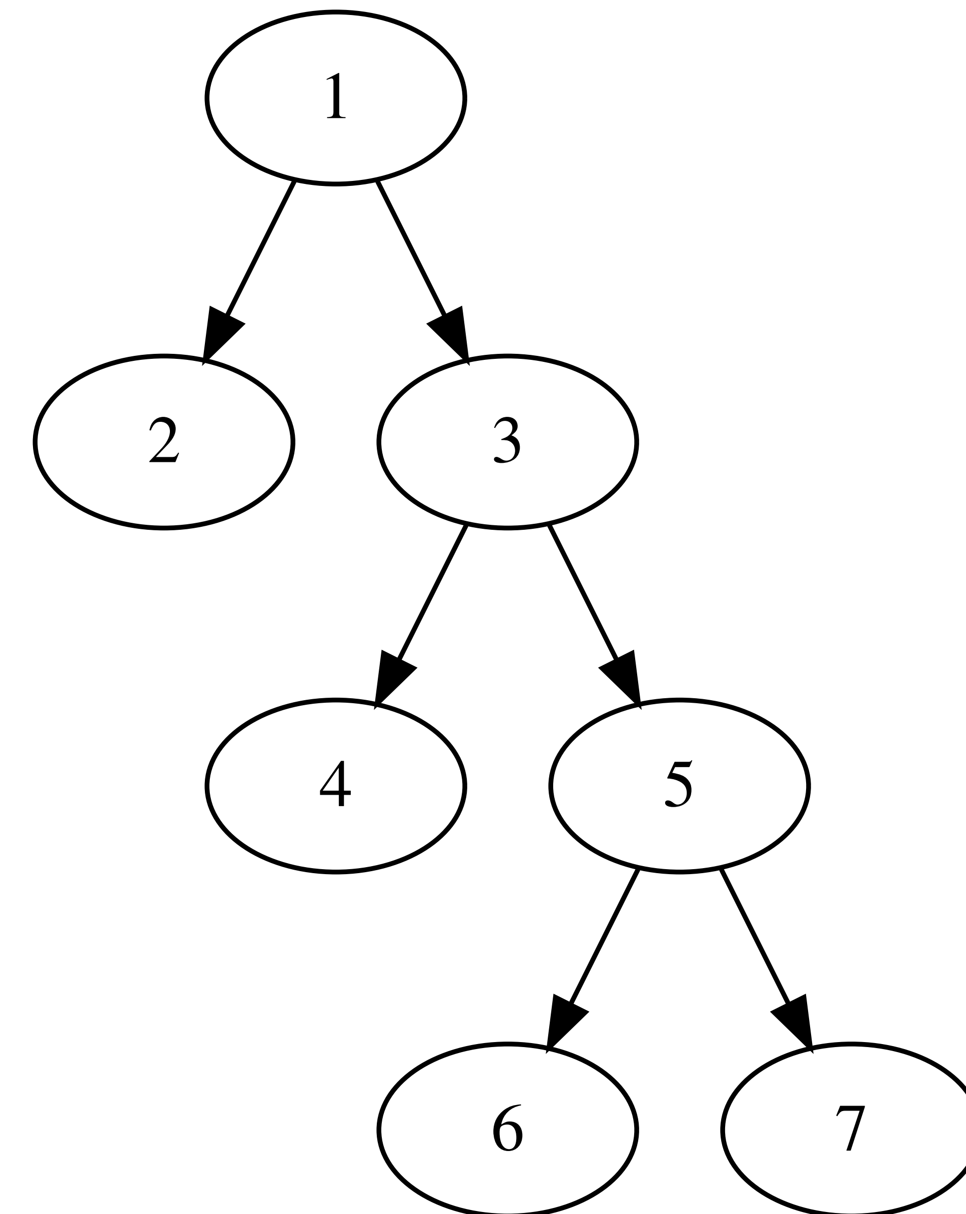
- Tedious to write
- Detached from code under test
- Usually incomplete in terms of generated instances



Lazy Initialization

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- Allows for automatic generation of recursive structures (lists, trees, etc.) by the code that operates on them
- Reference paper: Khurshid, S., Păsăreanu, C.S. and Visser, W. Generalized symbolic execution for model checking and testing. TACAS 2003 (pp. 553-568)

Lazy Initialization OFF (Vanilla KLEE)

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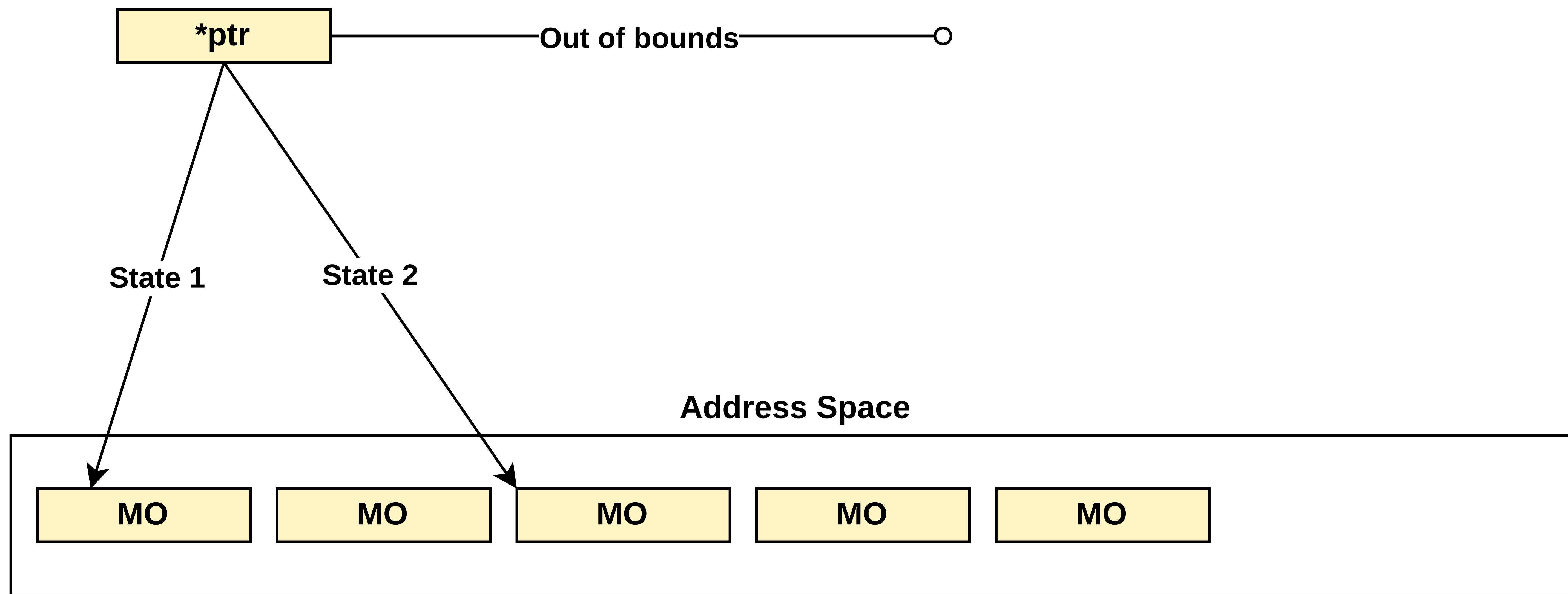

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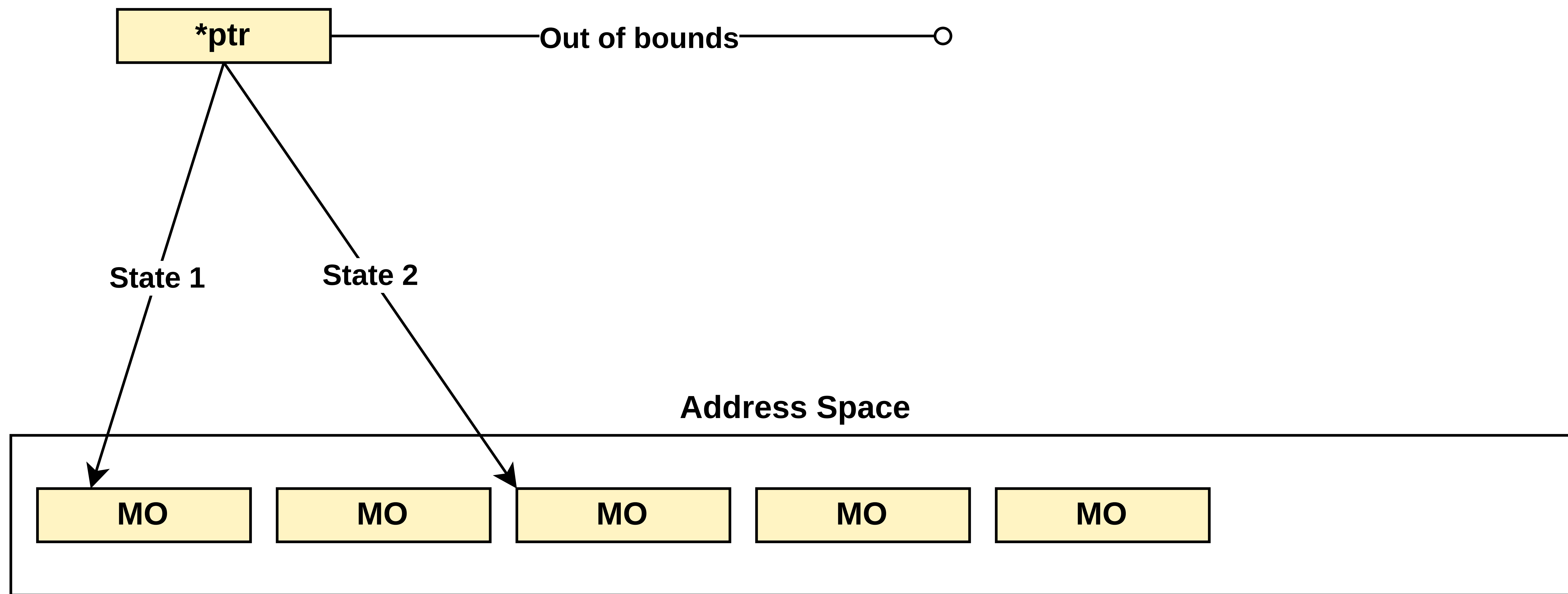
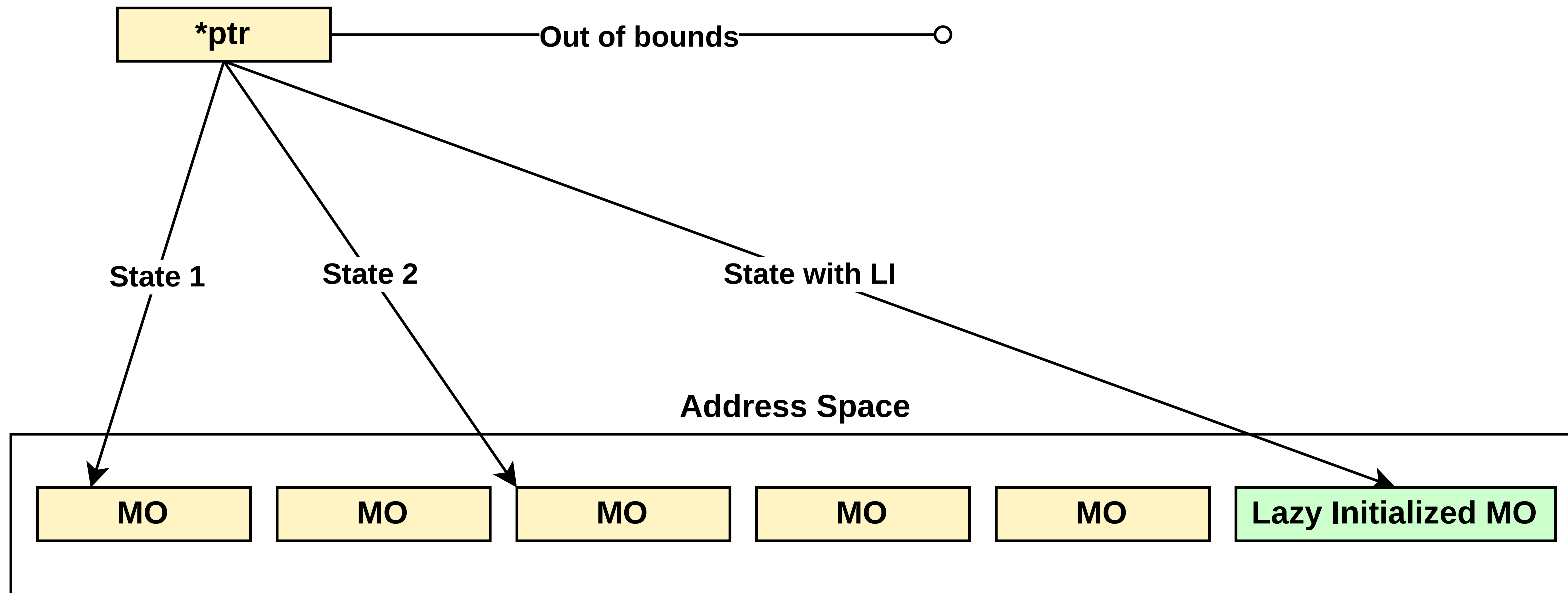
Lazy Initialization OFF (Vanilla KLEE)



- A state for every suitable object + possible out-of-bounds state
- Each object separate in the address space, path constraints ensure that

Lazy Initialization ON



- A state for every suitable object + possible out-of-bounds state + **state with a new lazy initialized (LI) symbolic memory object**

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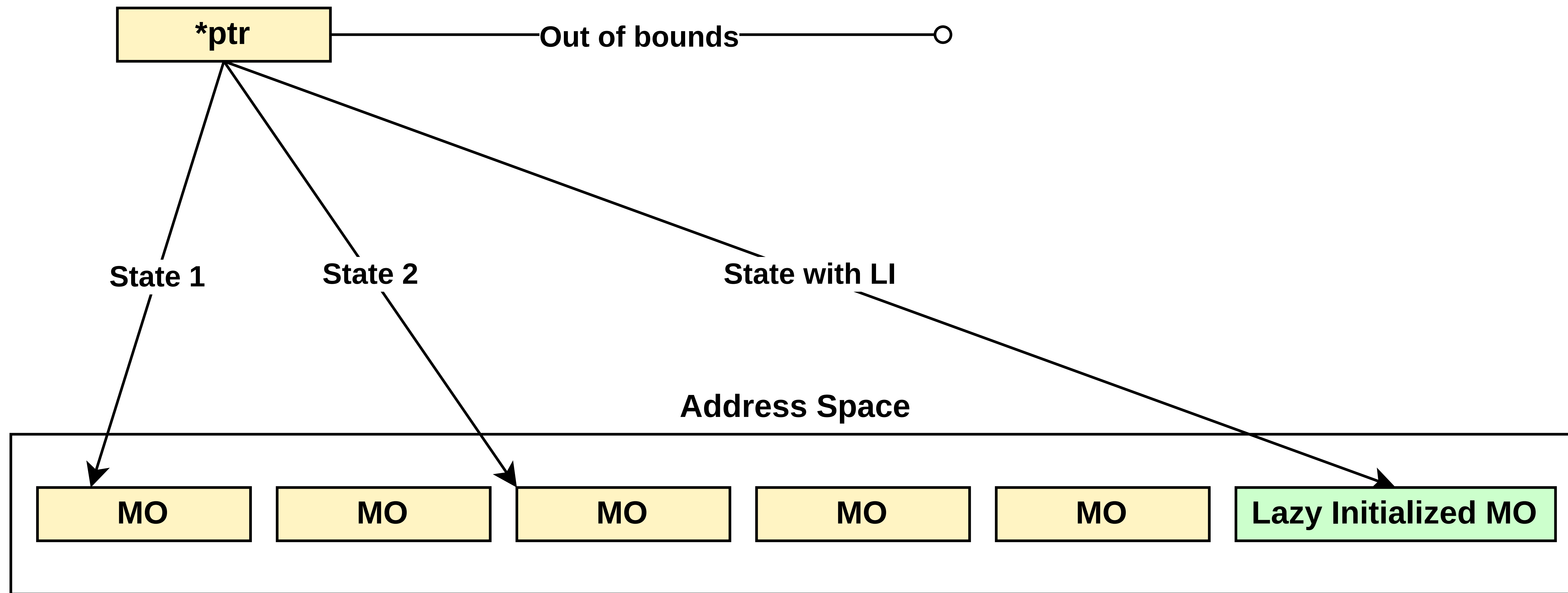

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- The LI object is associated with the pointer that is being dereferenced

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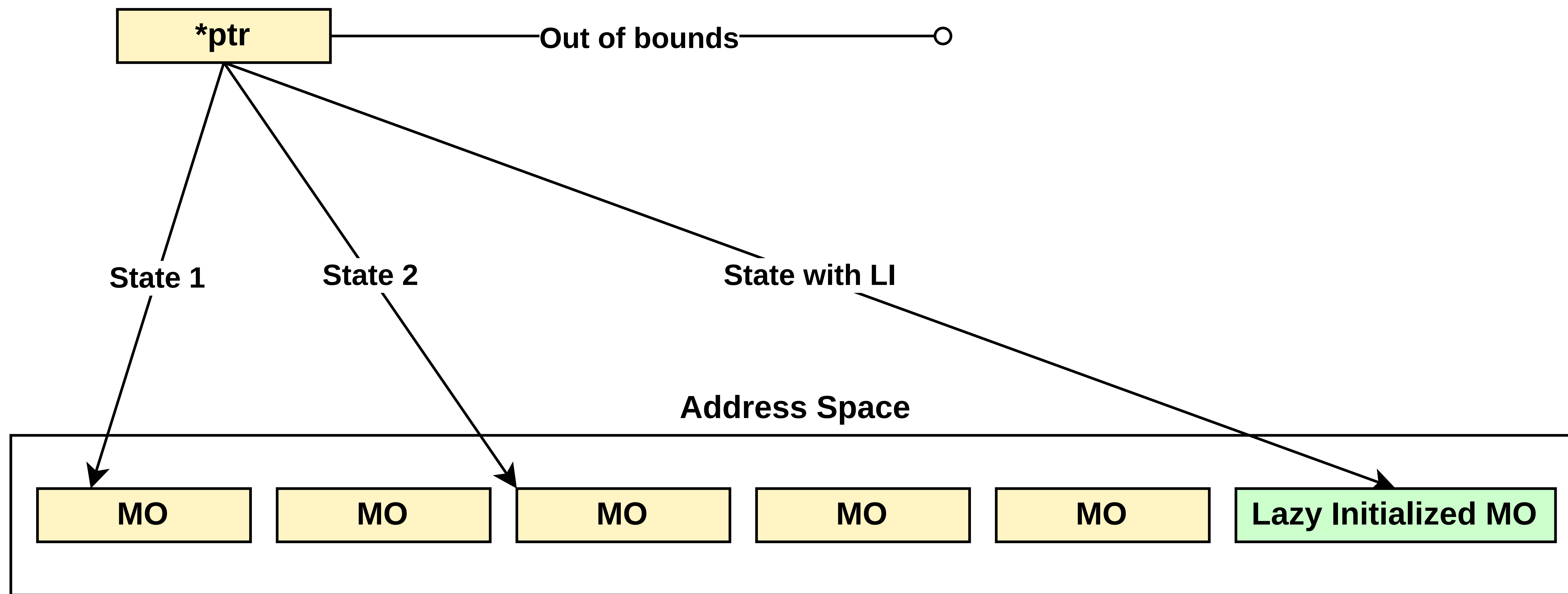

- A state for every suitable object + possible out-of-bounds state + **state with a new lazy initialized (LI) symbolic memory object**
- The LI object is associated with the pointer that is being dereferenced
- The pointer points inside the object:

$$\mathtt{LIAddress(ptr)} \leqslant \mathtt{ptr} < \mathtt{LIAddress(ptr)} + \mathtt{LISize(ptr)}$$

GetElementPtr and Pointer Resolution

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```
1 struct Foo {
2   int a;
3   int b;
4   int c;
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7 Foo *foo = make_symbolic_pointer();
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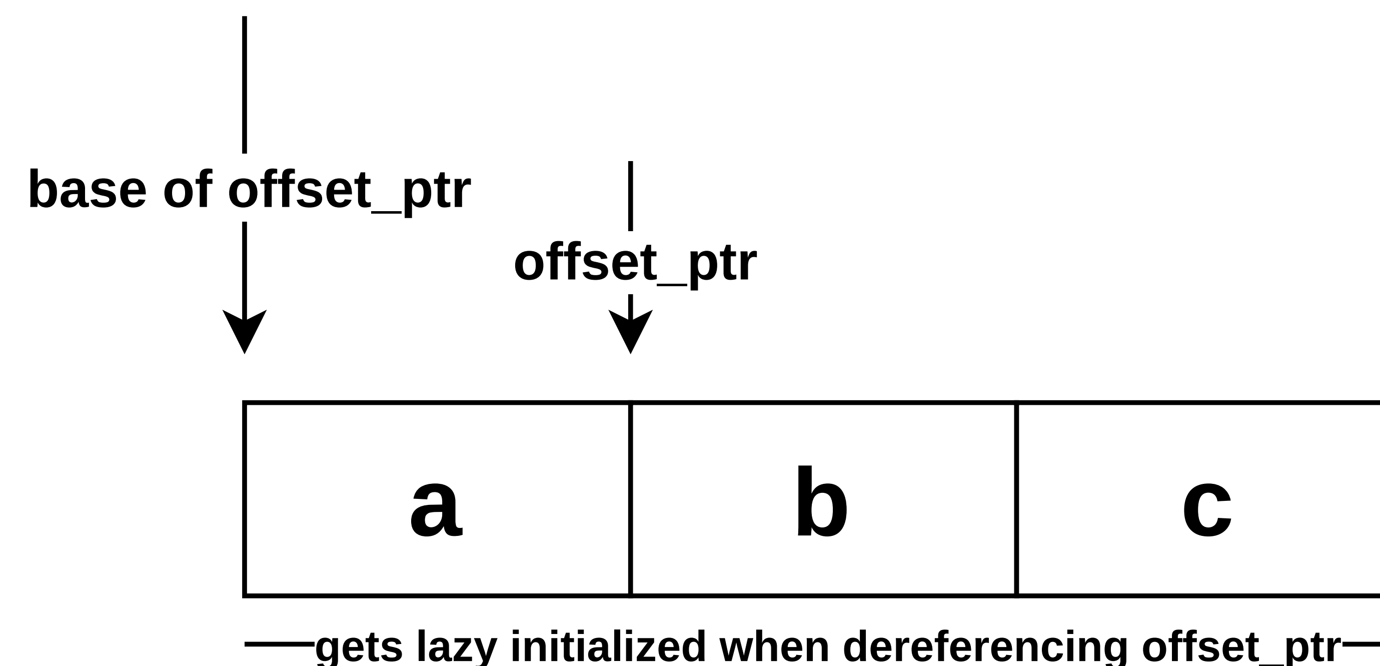
- Need to keep track of **GetElementPtr** instructions and lazy initialize accordingly



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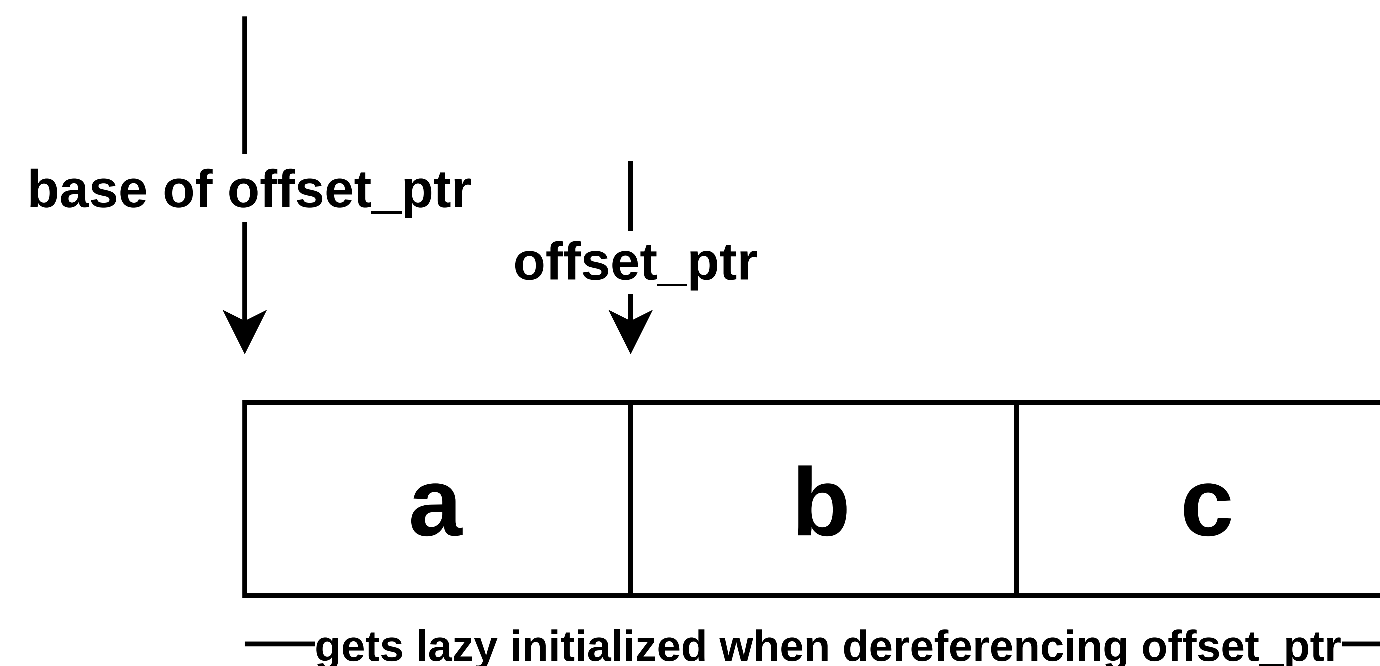
- Naive implementation would make two lazy initialized objects of type **i32**
- We would like one lazy initialized **Foo**
- Need to keep track of **GetElementPtr** instructions and lazy initialize accordingly
- GEPExprBases support already in KLEE 3.1 thanks to @tkuchta



Lazy Initialization for Arrays

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```
1 int *array = make_symbolic_pointer();
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3 int sum = 0;
4 for (size_t i = 0; i < 10; ++i) {
5   sum += array[i];
6 }
7
8 assert(sum > 30);
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- When accessing **T***, the underlying object might be an array

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- Heuristic: allocate an array of some fixed number of elements and hope it's going to be big enough (variable by CLI option from run to run)
- Possible solution: symbolic sizes

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- LI with restricted aliasing produces replayable tests

Available options:

- Resolve only to symbolic objects (make_symbolic and lazy initialized) or try to lazy initialize
- Resolve only to lazy initialized objects or try to lazy initialize
- Always try to lazy initialize without resolving to already existing objects

Example

Example

```
1  struct node {
2    node *left;
3    node *right;
4    int64 value;
5  };
6
7  int main() {
8    node *root = make_symbolic_pointer();
9
10   klee_assert(root->value == 1);
11   klee_assert(root->left->value == 2);
12   klee_assert(root->left->left->value == 3);
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15   return 0;
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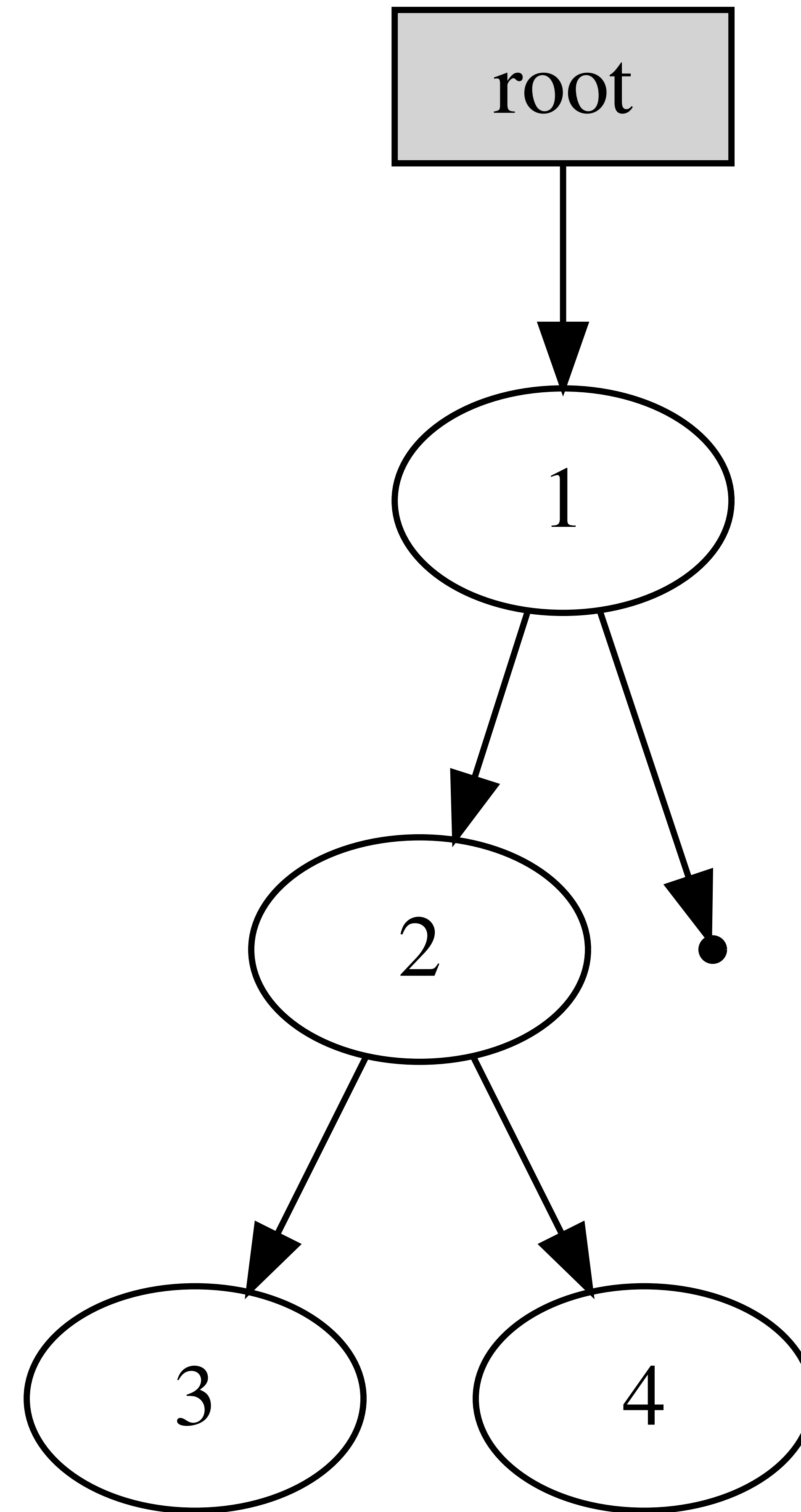

KTest Extension

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```
ktest file : 'test000009.ktest'
args       : ['tree.bc']
num objects: 5  // Root pointer and 4 vertices

object 0: name: 'root'
object 0: size: 8
object 0: hex : 0x0000000000000000
object 0: pointers: [(0, 1, 0)] // Pointer at offset 0 points to object 1 at offset 0

object 1: name: 'lazy_initialized'
object 1: size: 24
object 1: hex : 0x000000000000000000000000000000000100000000000000
object 1: pointers: [(0, 2, 0)]

object 2: name: 'lazy_initialized'
object 2: size: 24
object 2: hex : 0x000000000000000000000000000000000200000000000000
object 2: pointers: [(0, 3, 0), (8, 4, 0)]

object 3: name: 'lazy_initialized'
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- Keep track of allocated objects and their addresses during replay
- Recursively allocate objects the current object points to (if not already allocated) and write their addresses to respective pointers in the current object
- When encountering a call to **klee_make_symbolic**, take next not lazy initialized object in the KTest
- Replay procedure otherwise unchanged

Replay Example

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 2   node *left;
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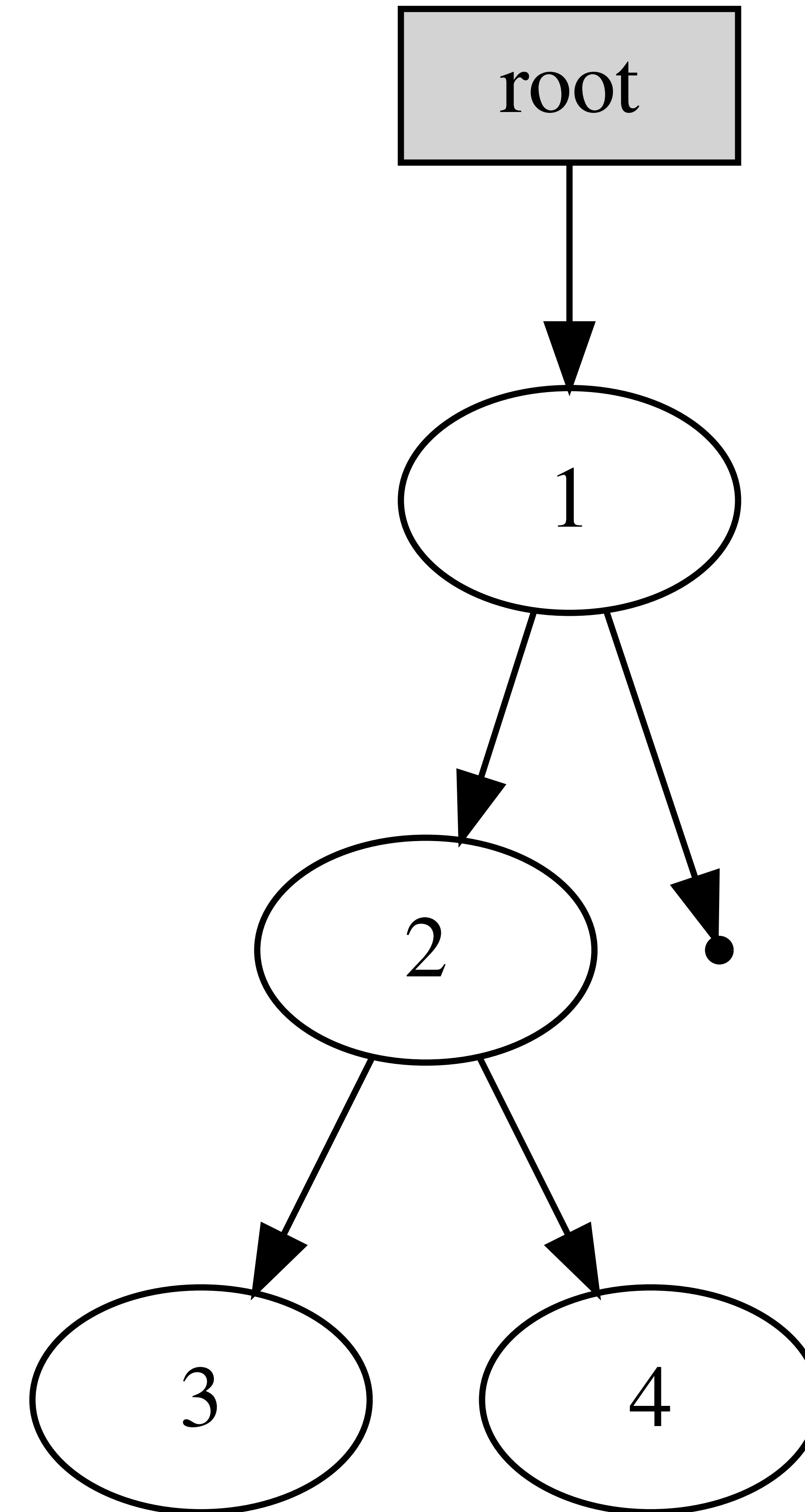

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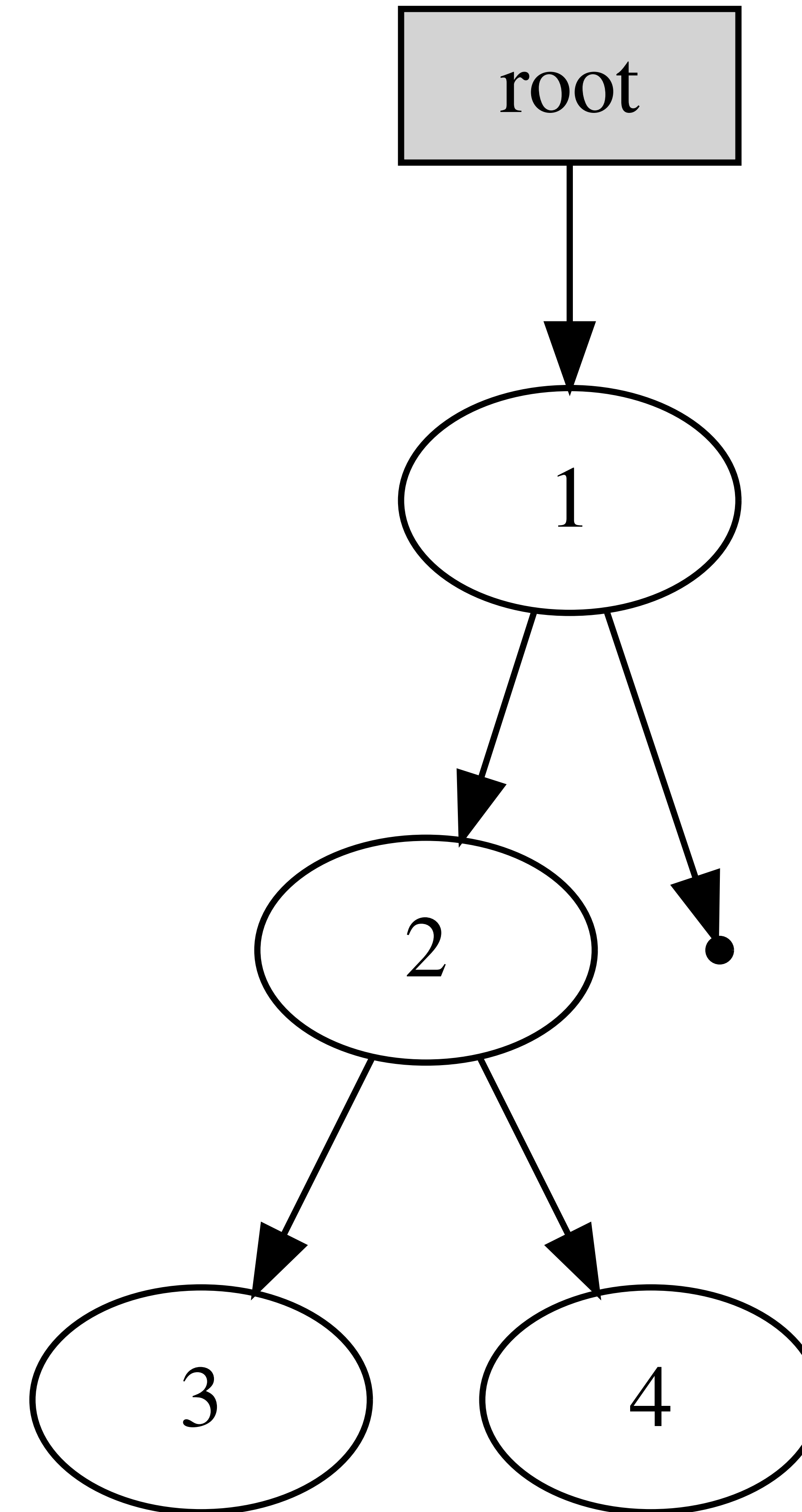

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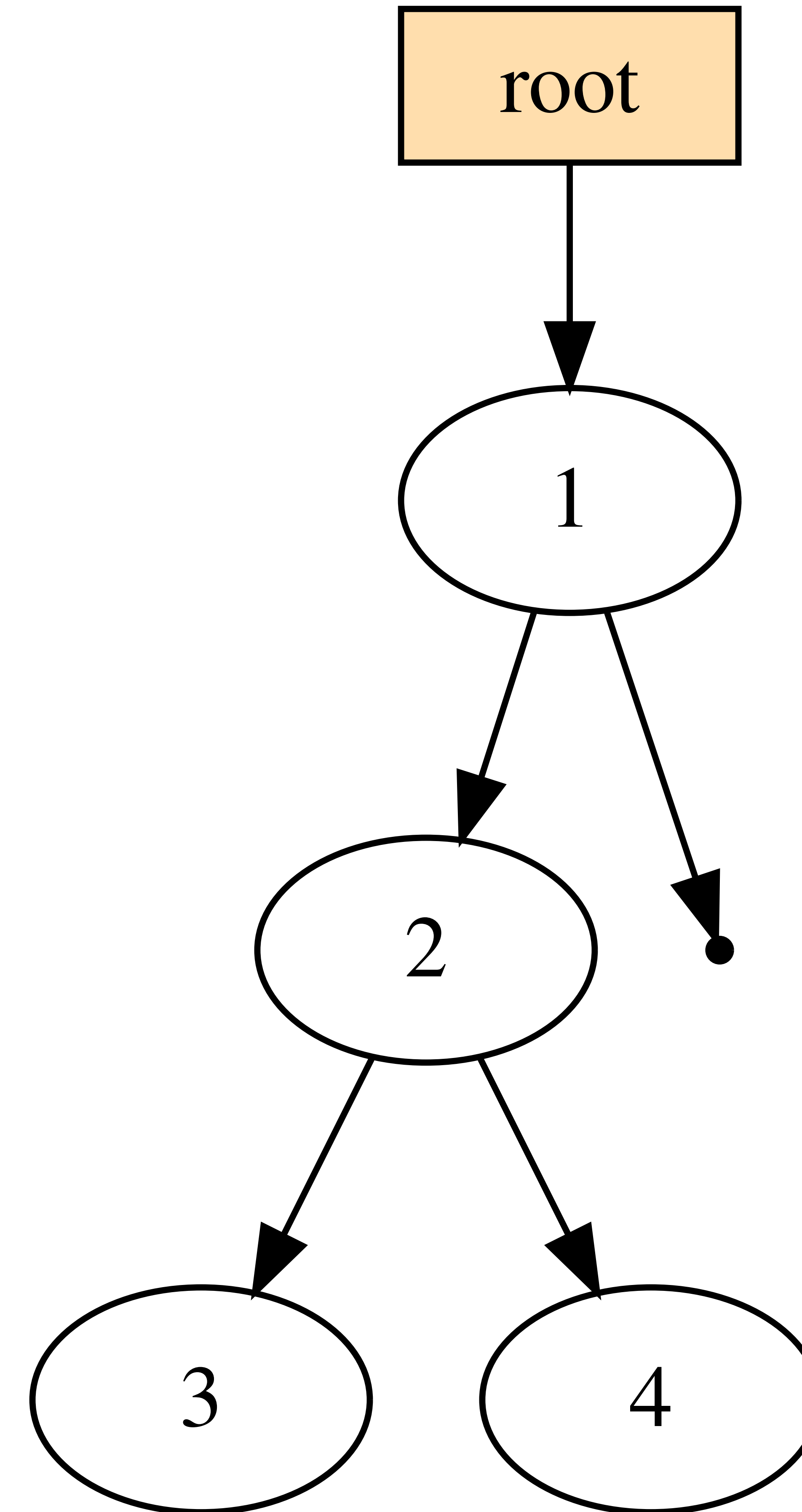

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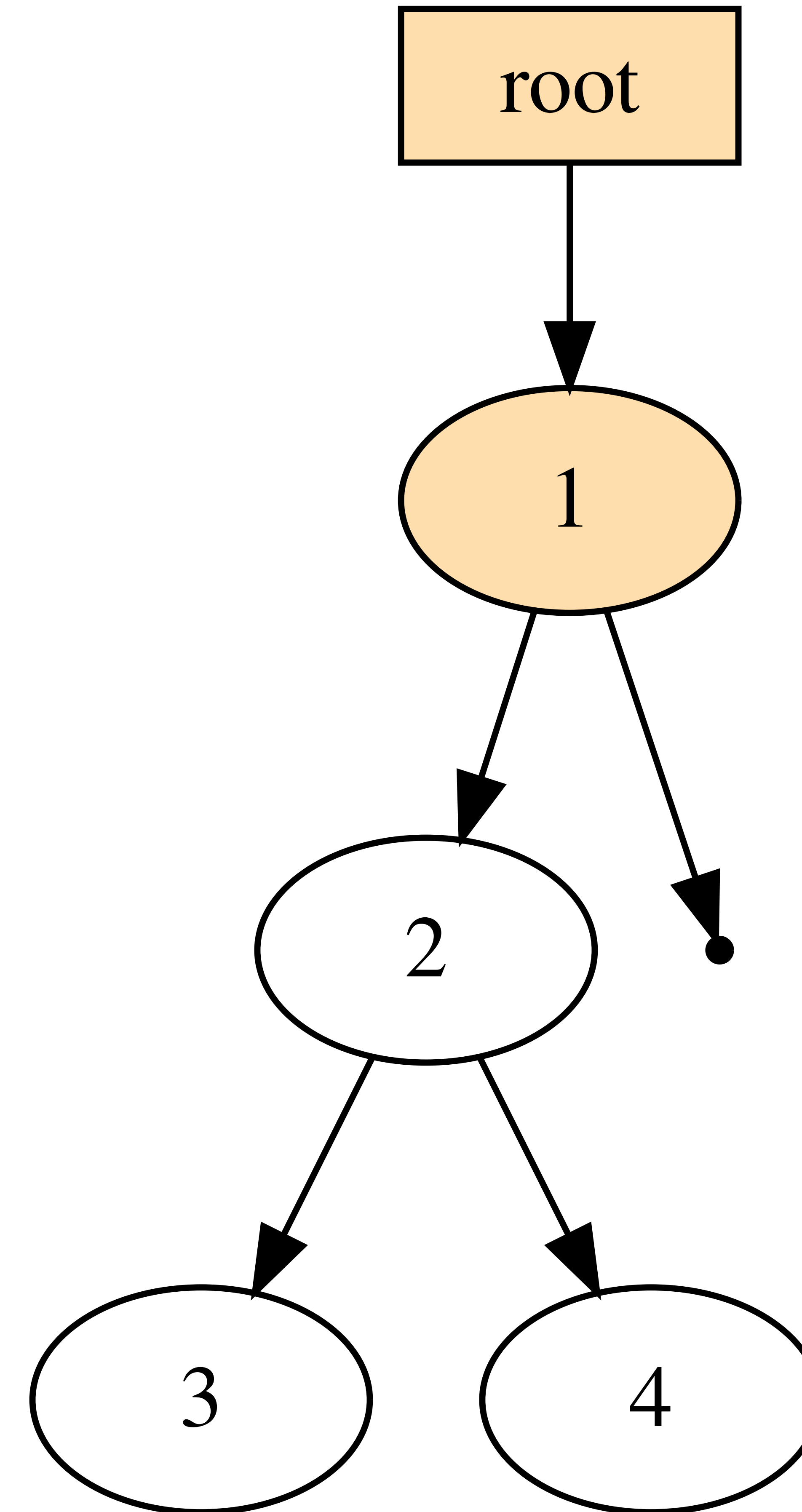

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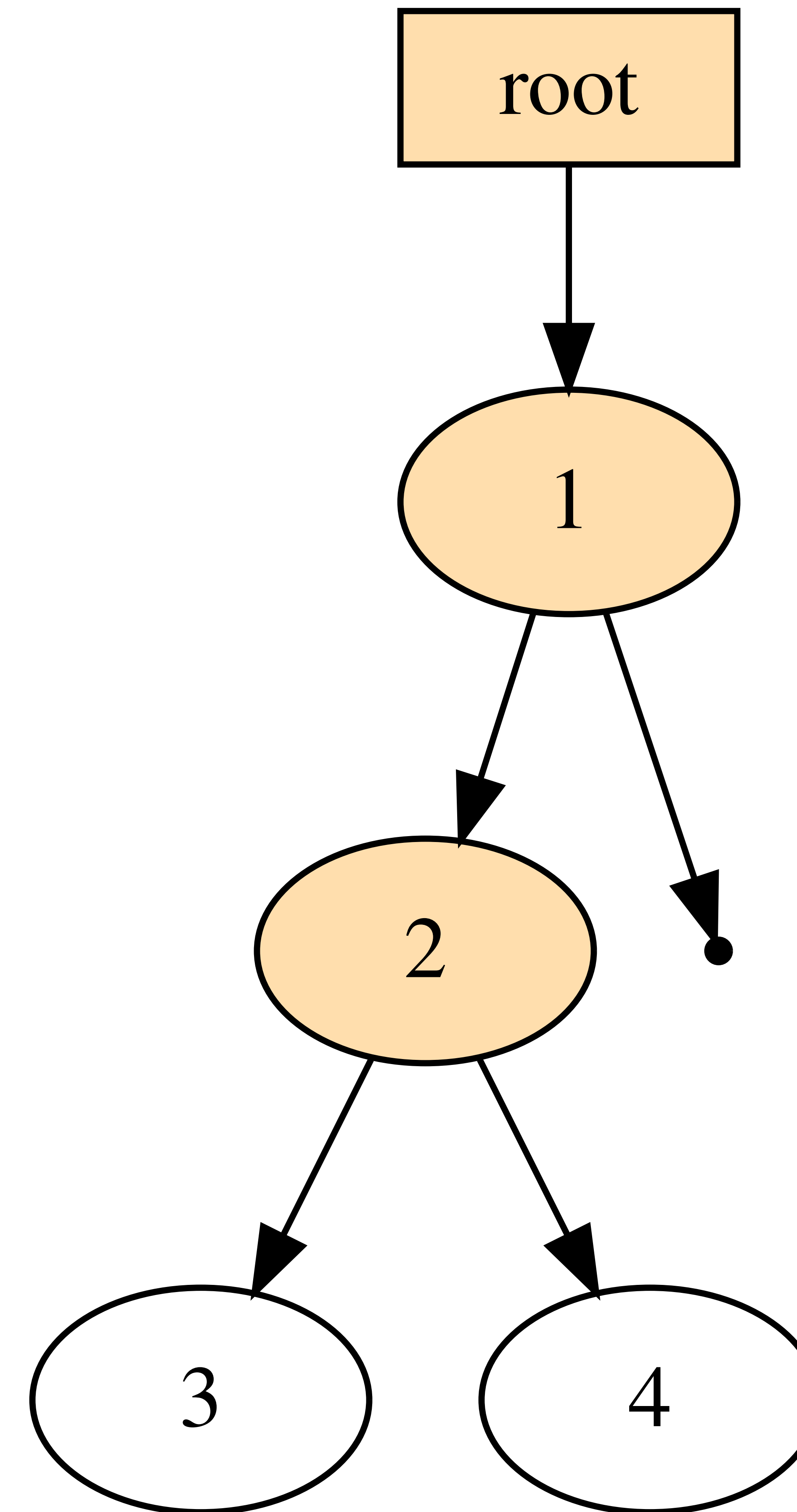

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6
7  int main() {
8    node *root = make_symbolic_pointer();
9
10   klee_assert(root->value == 1);
11   klee_assert(root->left->value == 2);
12   klee_assert(root->left->left->value == 3);
13   klee_assert(root->left->right->value == 4);
14
15   return 0;
16 }
```

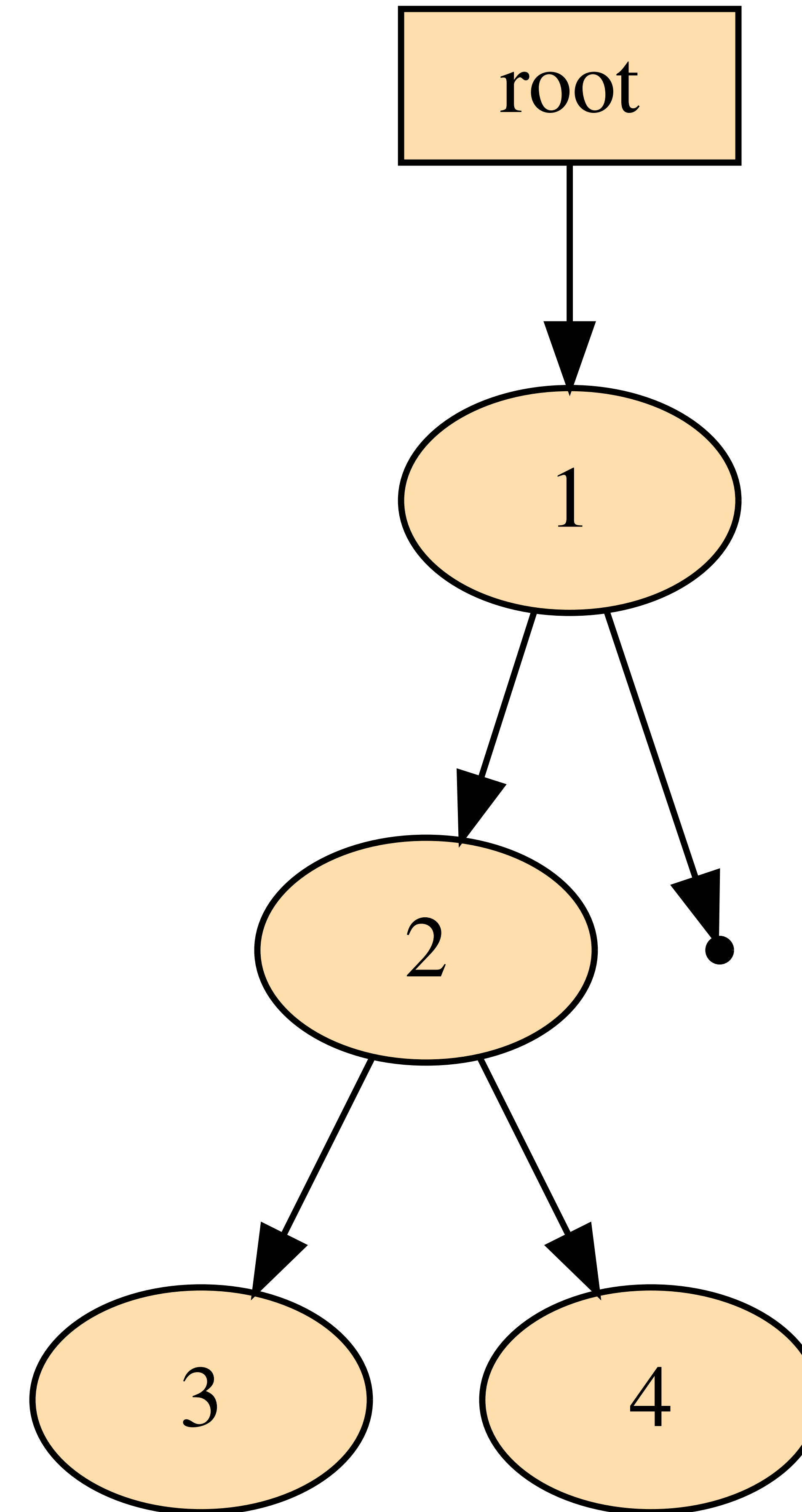

Evaluation on Dynamic Data Structures

Comparison against KLEE 3.0 (LI Off), 30 seconds test timeout, 5 seconds solver timeout, coverage computed by GCOV, "0" means all produced tests cause a segmentation fault

Test	LI Off Branch Coverage (%)	LI On Branch Coverage (%)	Branch Count
avl_balance	0	50	32
avl_insert	0	78.1	46
rb_insert_find	0	94.8	58
rb_remove	0	78.9	90
tree_delete_find	28.9	92.3	26

- Feasible way to test recursive data structures without generating procedures
- Full results: https://gitlab.com/ocelaiwo/klee_li_recursive_datastructs/
- Our fork of KLEE: https://github.com/UnitTestBot/klee
- Test-Comp 2024 (3rd in the Overall category): Misonizhnik, A., Morozov, S., Kostyukov, Y., Kalugin, V., Babushkin, A., Mordvinov, D. and Ivanov, D., 2024, April. KLEEF: Symbolic Execution Engine (Competition Contribution). In International Conference on Fundamental Approaches to Software Engineering (pp. 314-319)