Verification of Heap Manipulating with Ordered Data Extended Forest Automata

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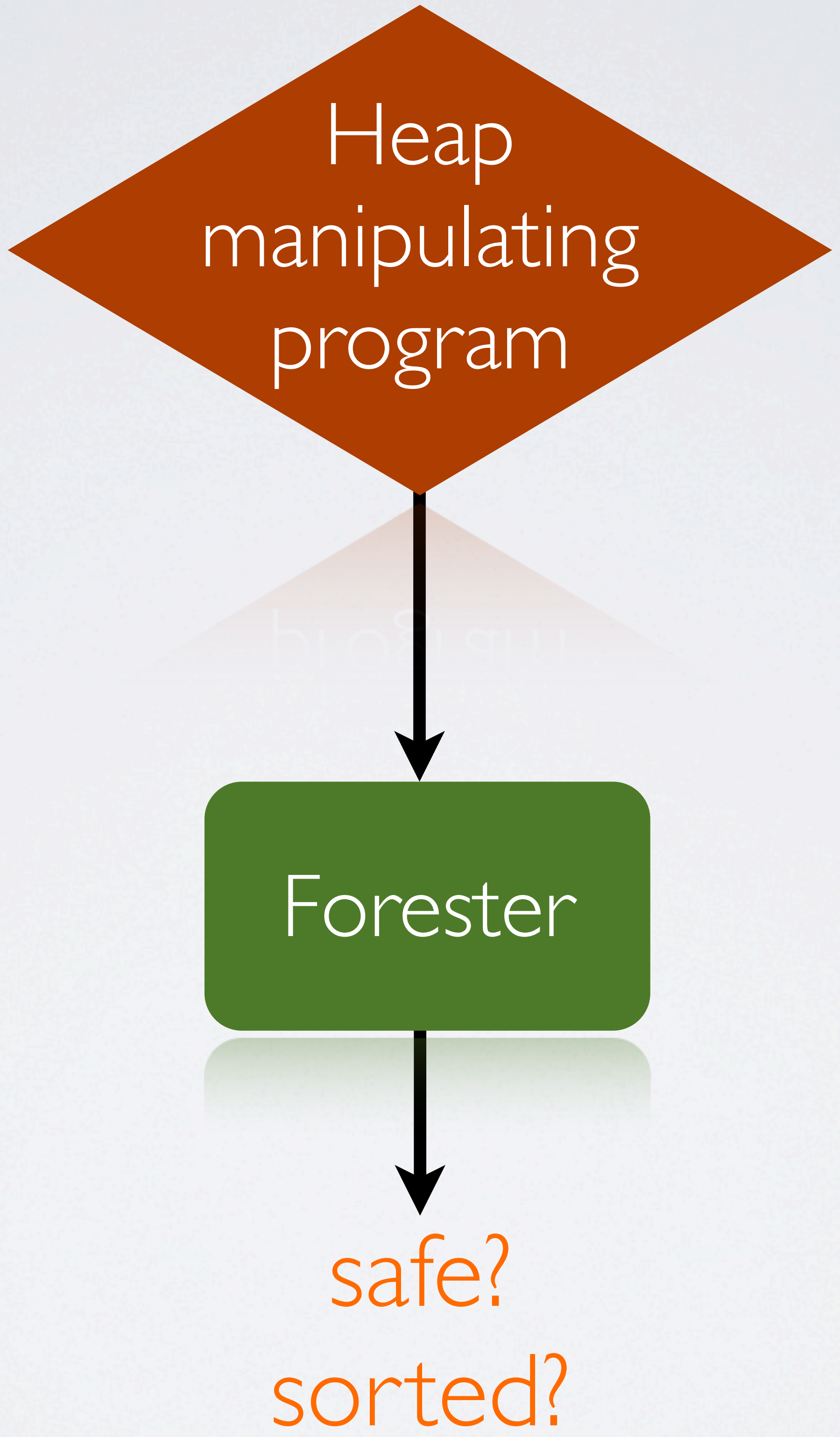
Heap manipulating program
Forester
safe?
sorted?

Heap manipulating program

```
Node *insert(Node *root, Data d){
    Node* newNode = calloc(sizeof(Node));
    if (!newNode) return NULL;
    newNode→data = d;
    if (!root) return newNode;
    Node *x = root;
    while (x→data != newNode→data)
        if (x→data < newNode→data)
            if (x→right) x = x→right;
            else x→right = newNode;
        else
            if (x→left) x = x→left;
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    if (x != newNode)
        free(newNode);
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Unbounded heaps   Data dependence   Multiply selectors

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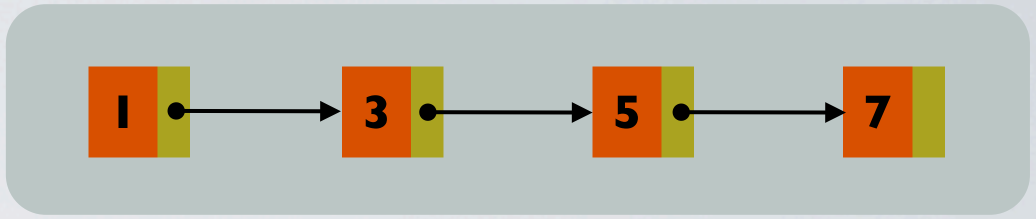
Unbounded heaps

Data dependence

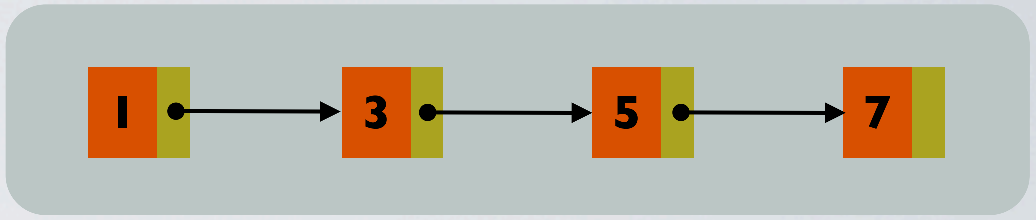
Multiply selectors

Heap manipulating program

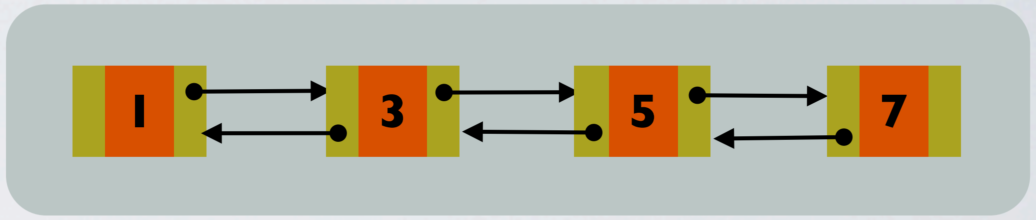


Singly linked lists

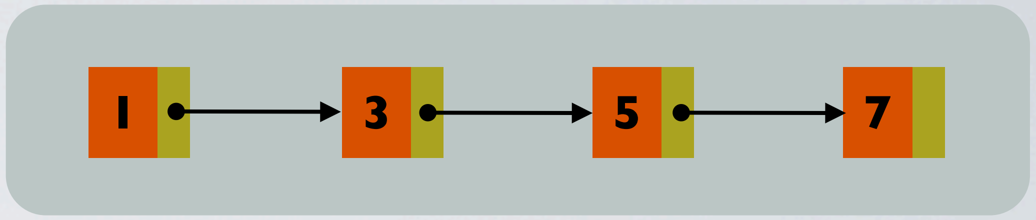
Heap manipulating program



Singly linked lists



Doubly linked lists



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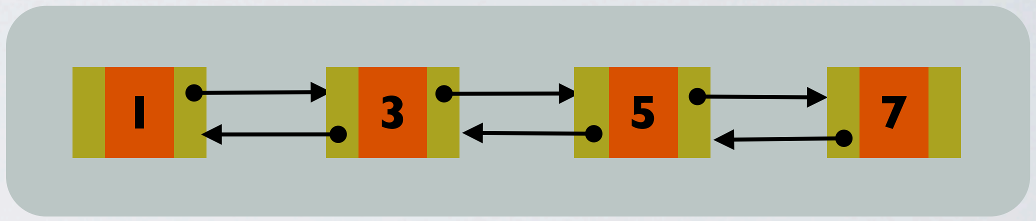

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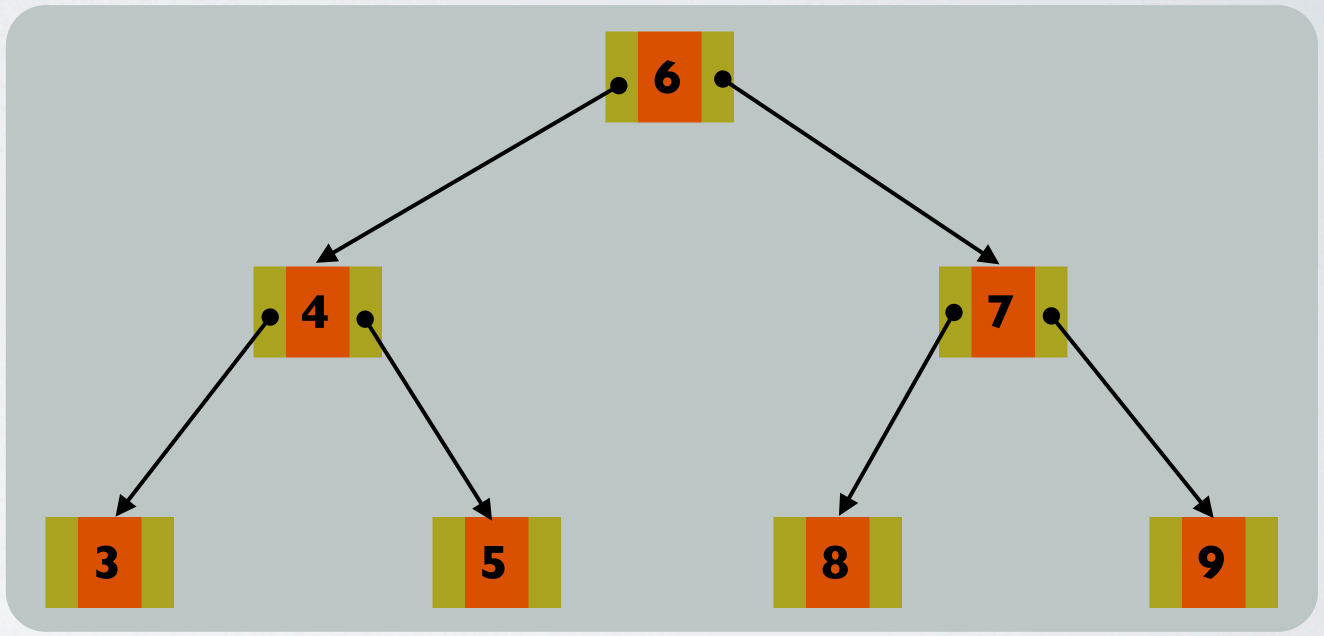
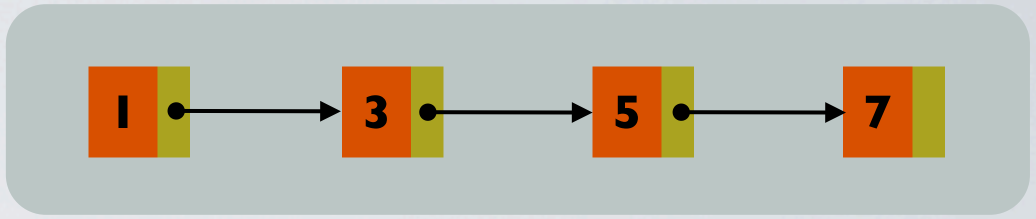


Binary Search Trees

Heap manipulating program



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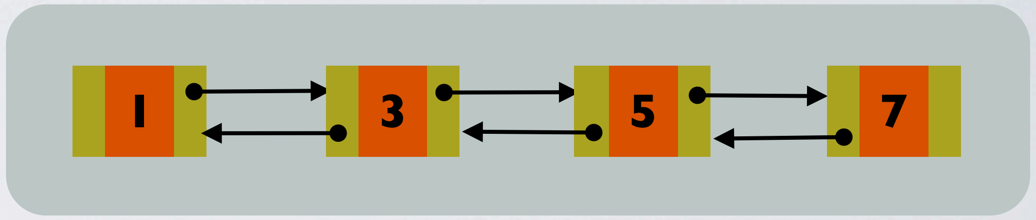

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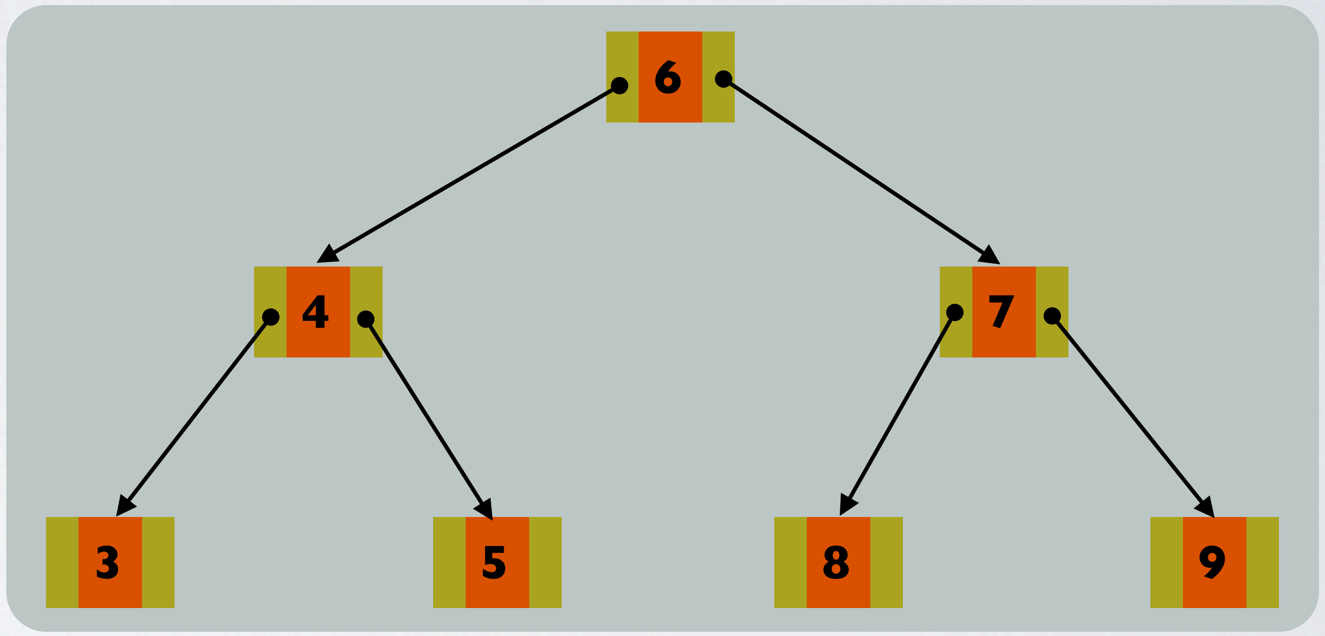
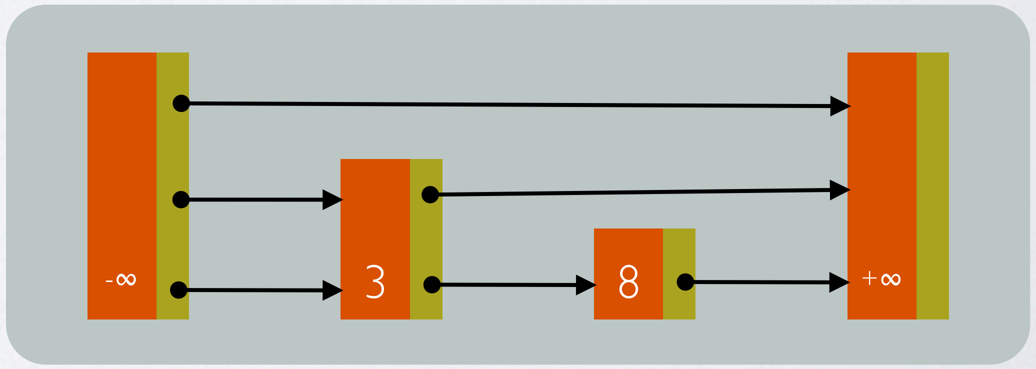


Binary Search Trees



Skip-lists

Forester

How does it work?

Program analysis

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program point

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All possible heaps represented by set of forest automata

program point

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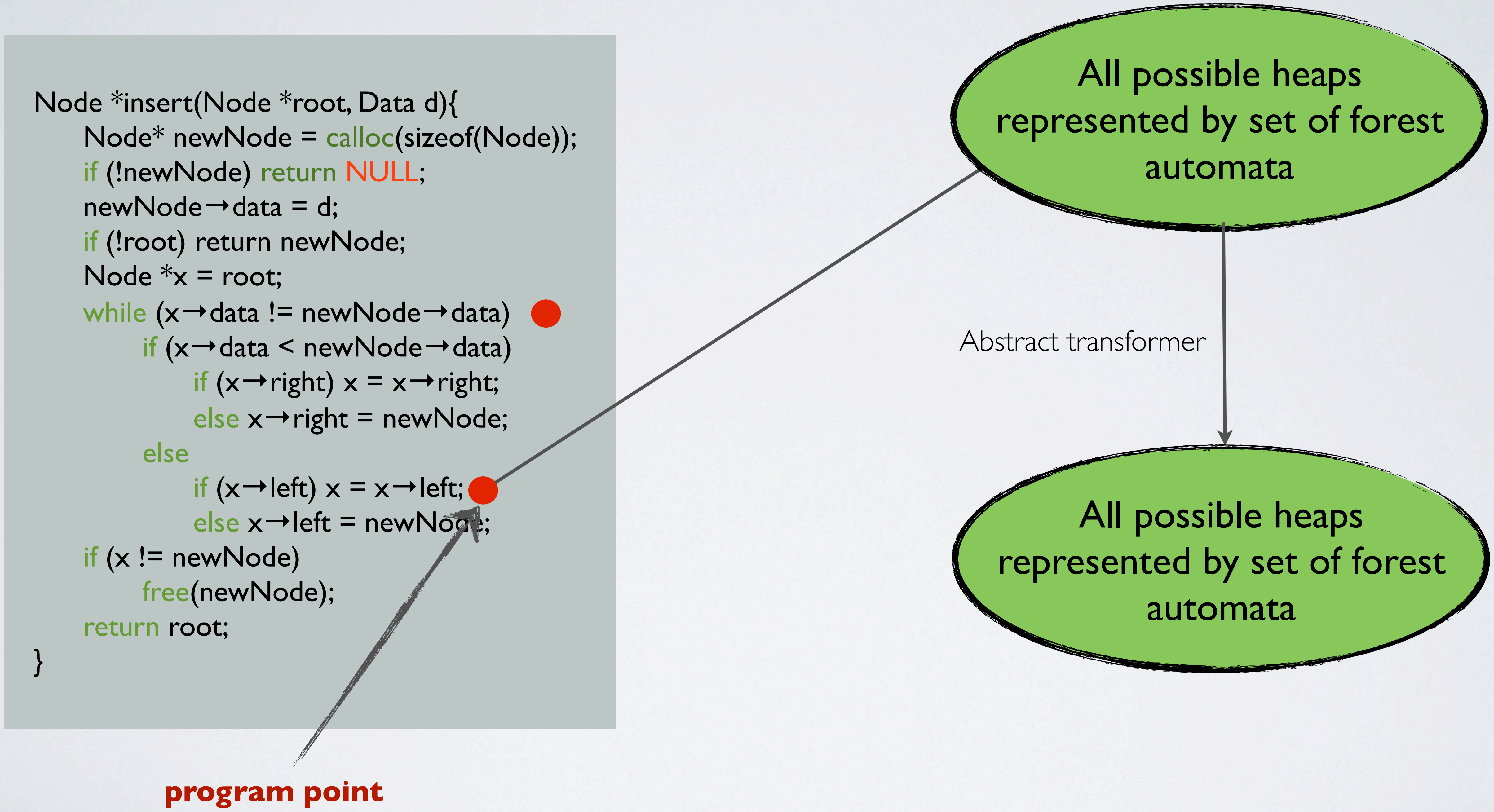

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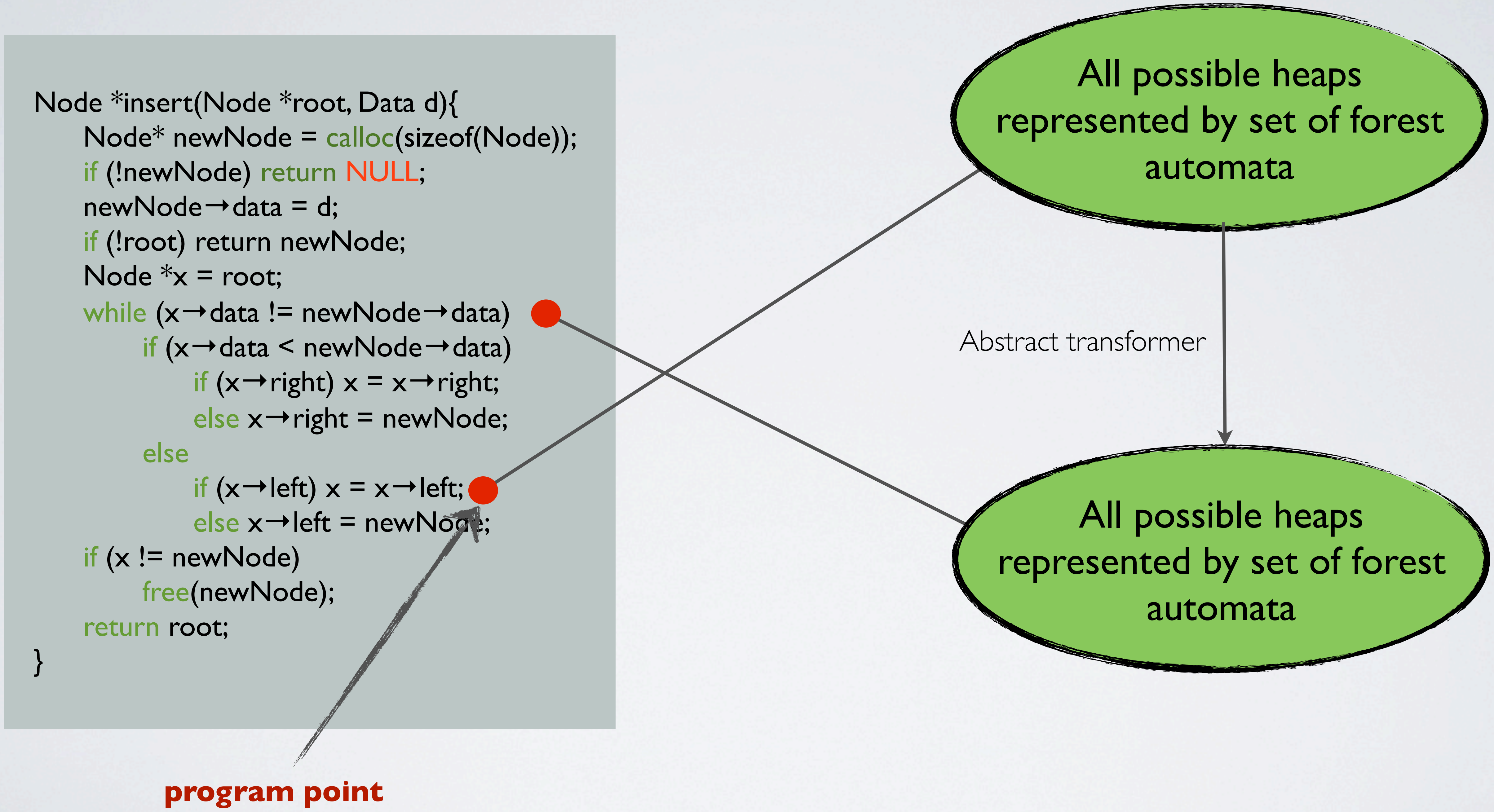
All possible heaps represented by set of forest automata
Abstract transformer
All possible heaps represented by set of forest automata
program point

Program analysis



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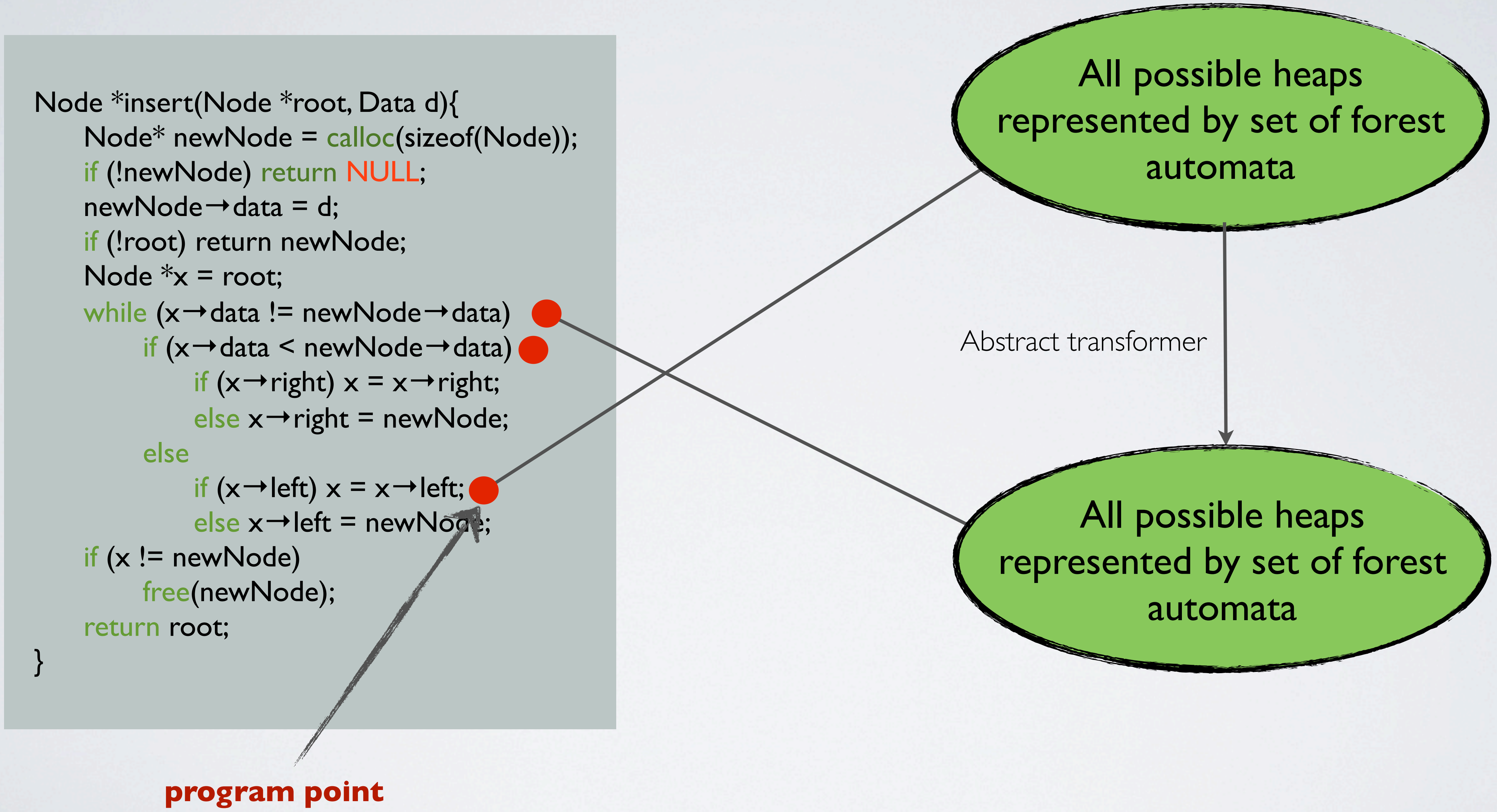

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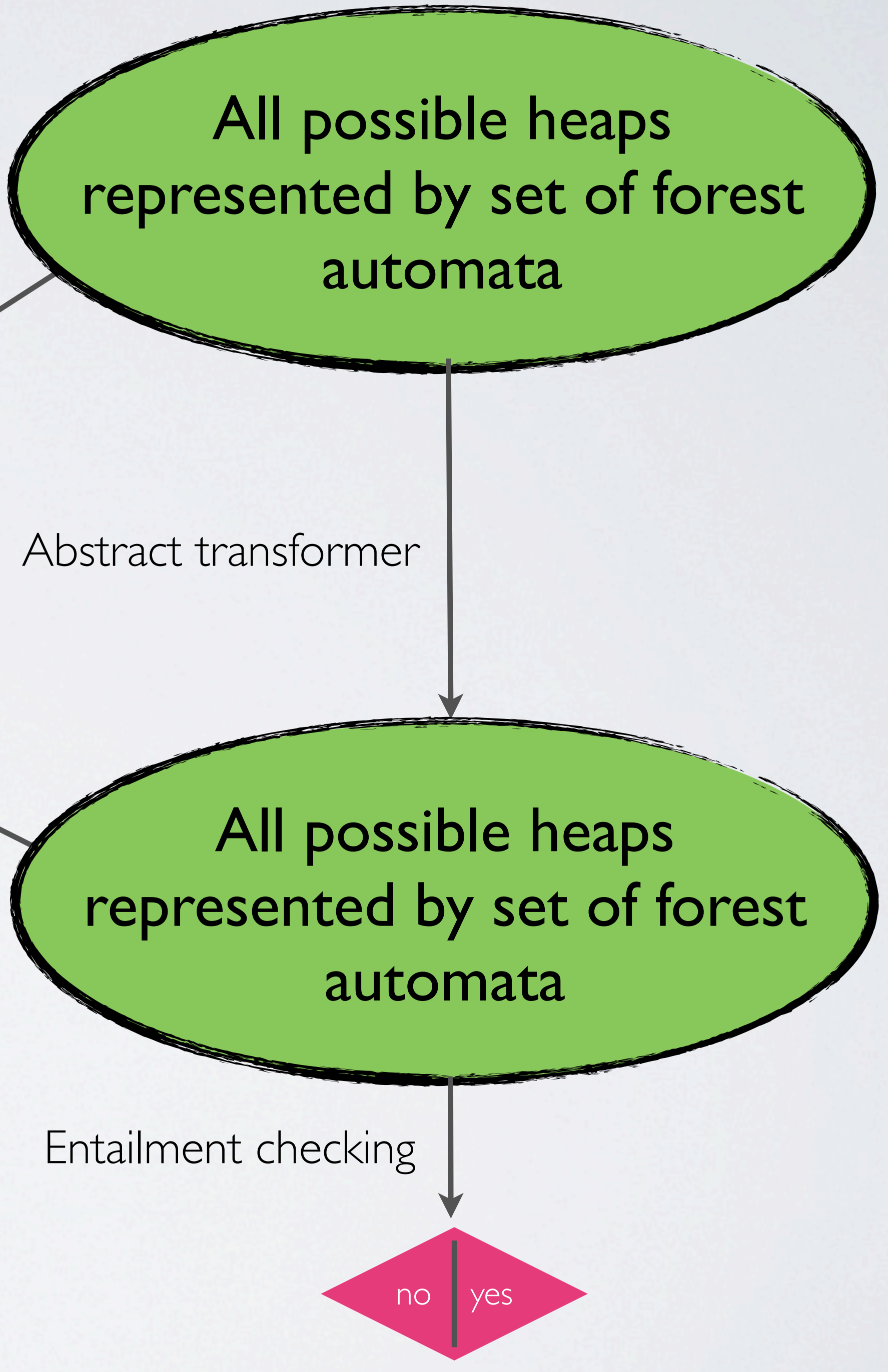
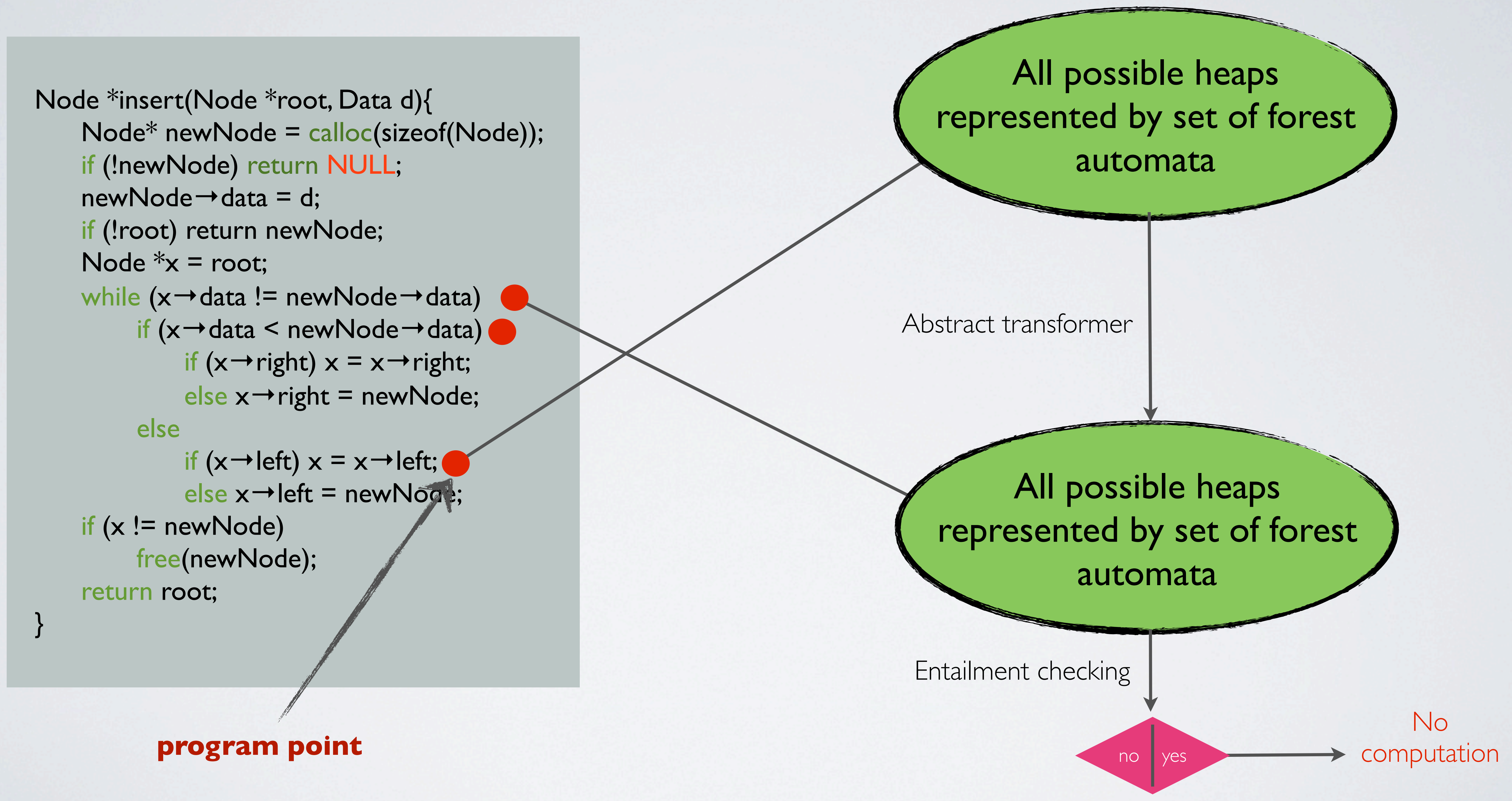

All possible heaps represented by set of forest automata
Abstract transformer
All possible heaps represented by set of forest automata
Entailment checking
no
yes

Program analysis



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program point
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Abstract transformer
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Entailment checking
no
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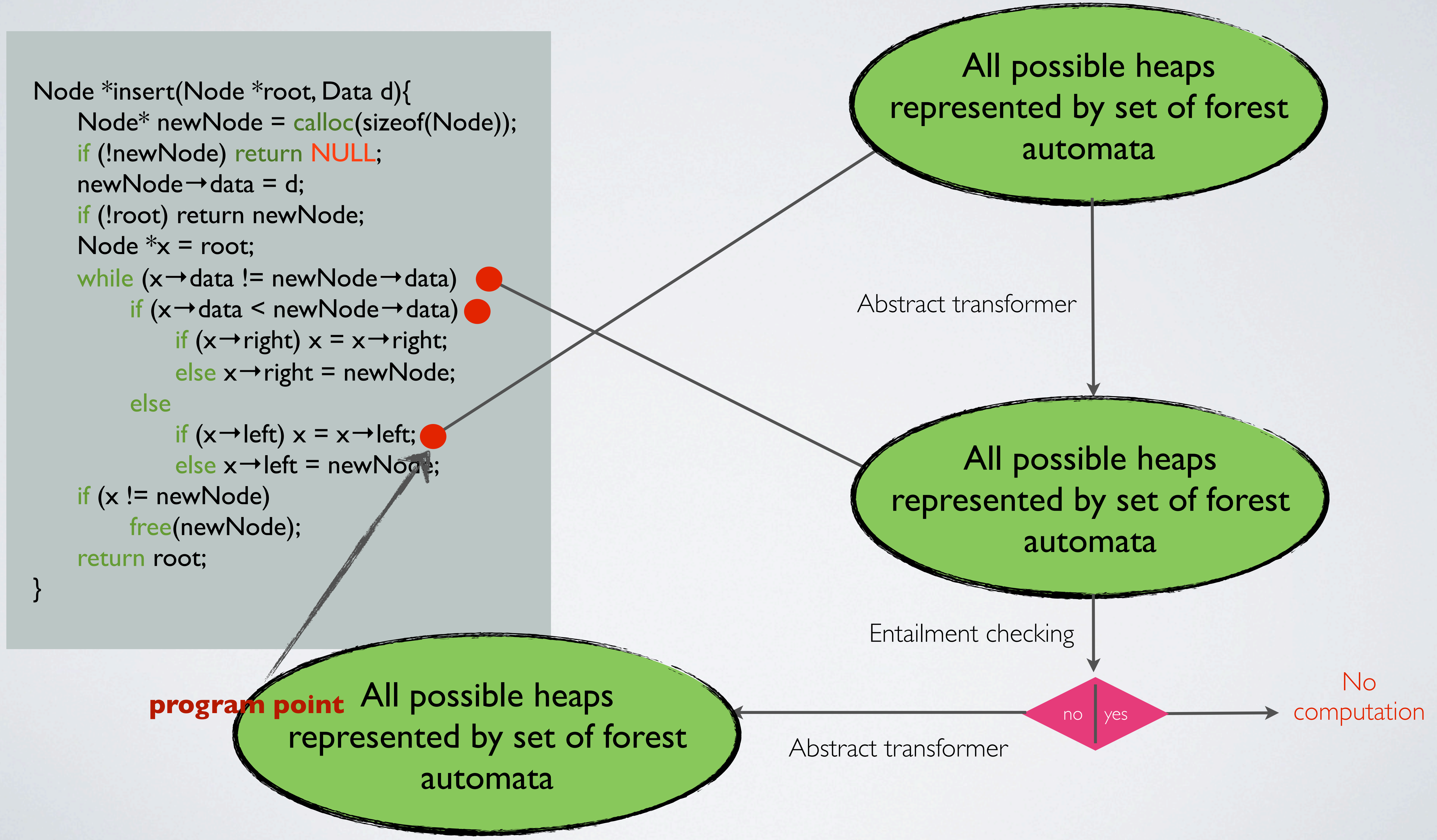
No computation

Program analysis



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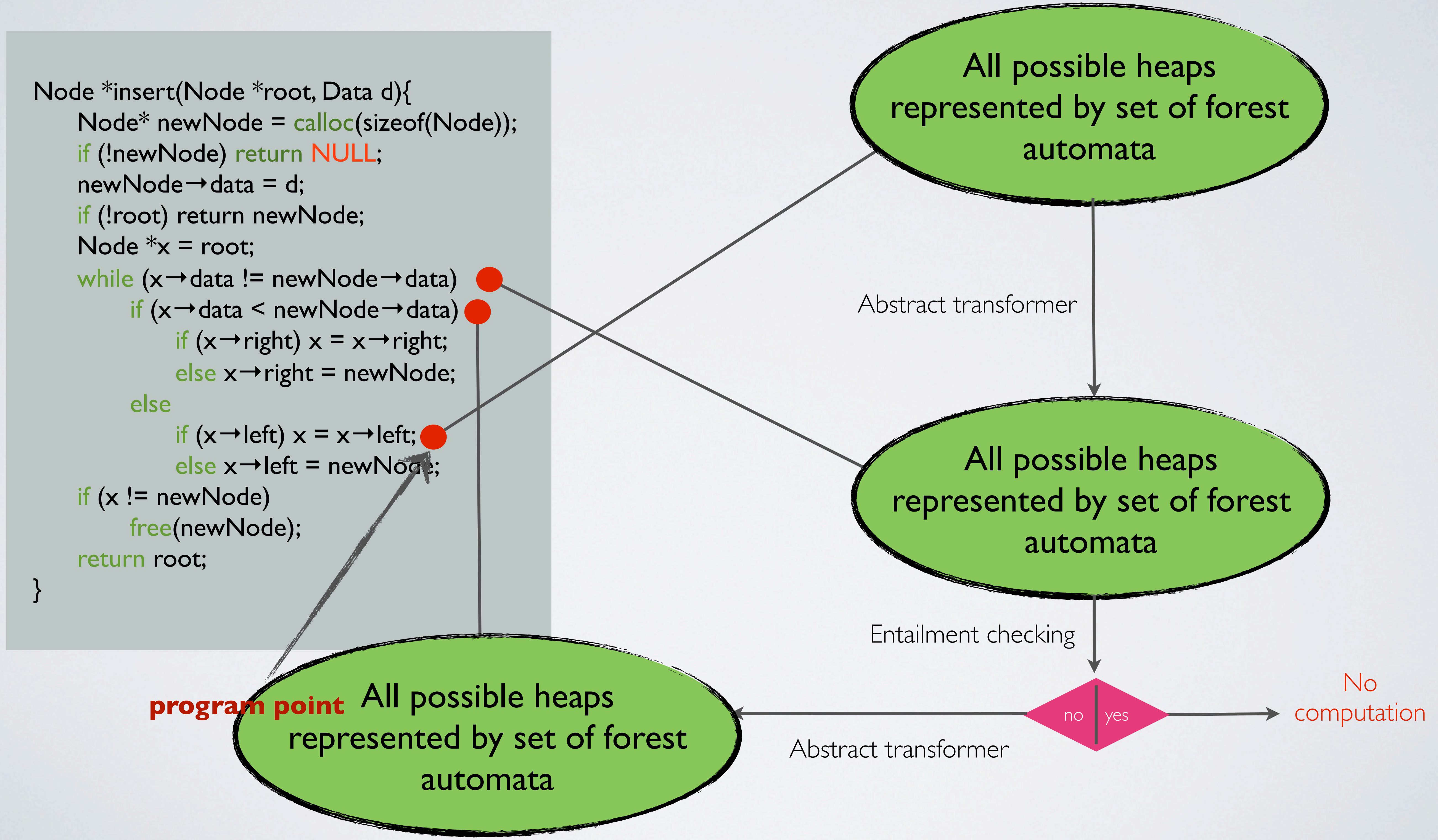

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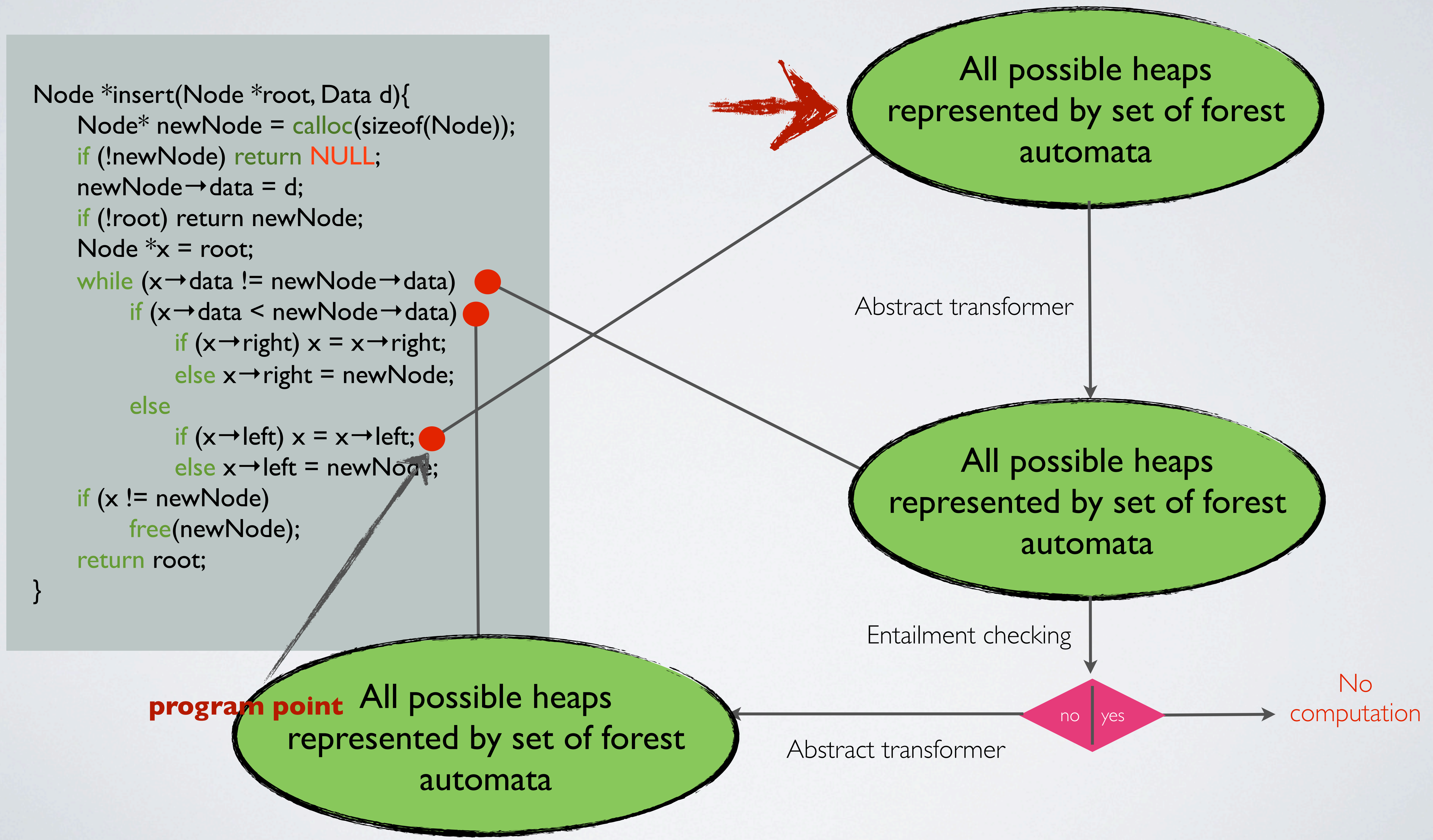

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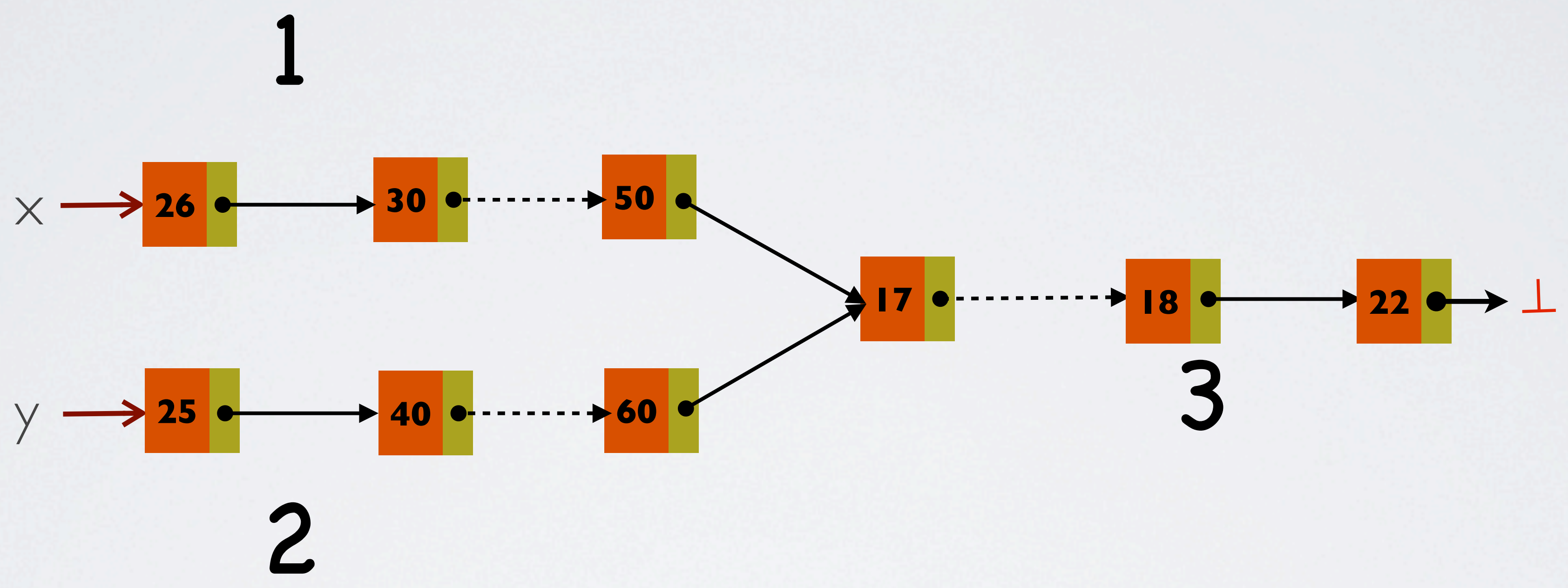
All possible heaps represented by set of forest automata

Forest automata representation

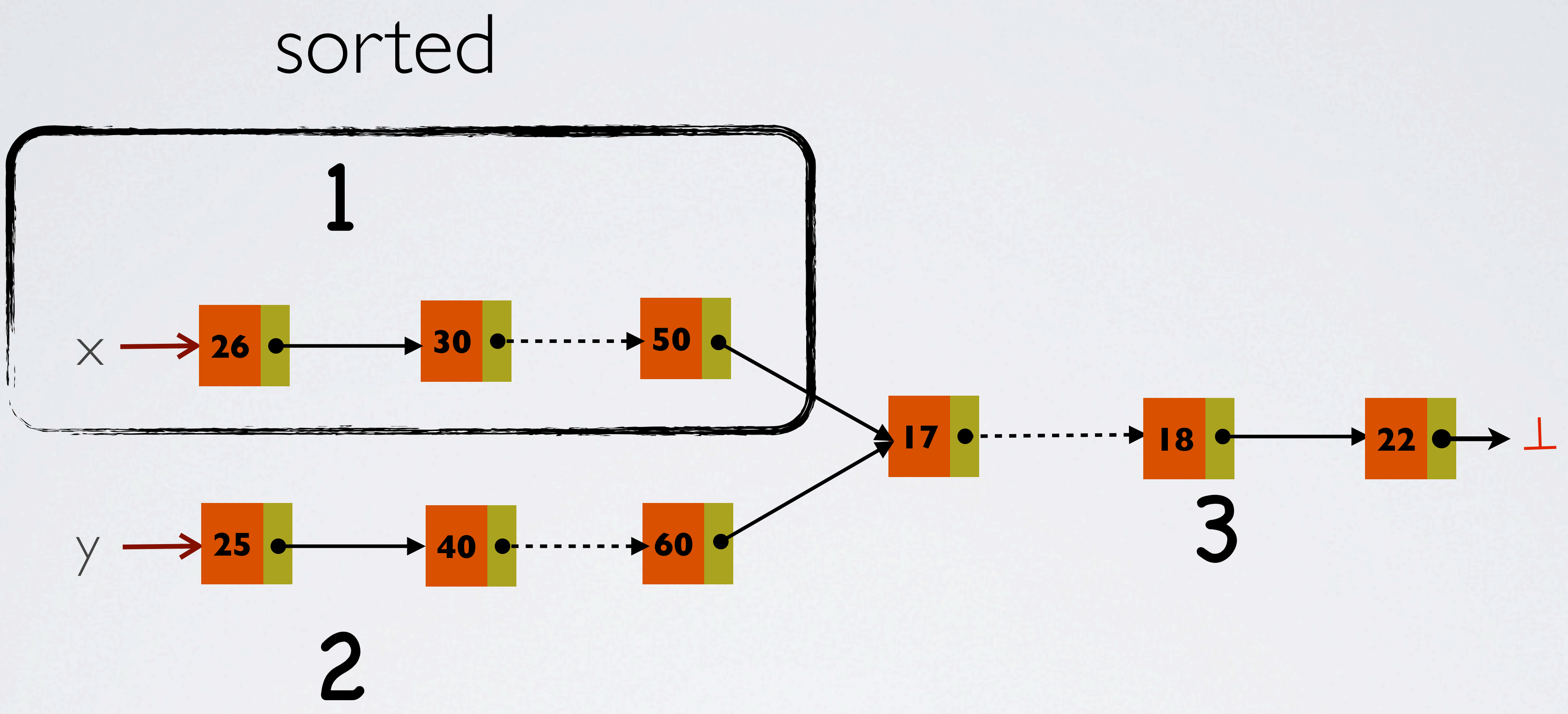
1. Heap representation
2. Decompose heaps into forests
3. Represent forests by forest automata

1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata



- Set of heaps
- List 1,2,3 are sorted and data of all cells in 3 are bigger than data of all cells in 1 and 2

1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata



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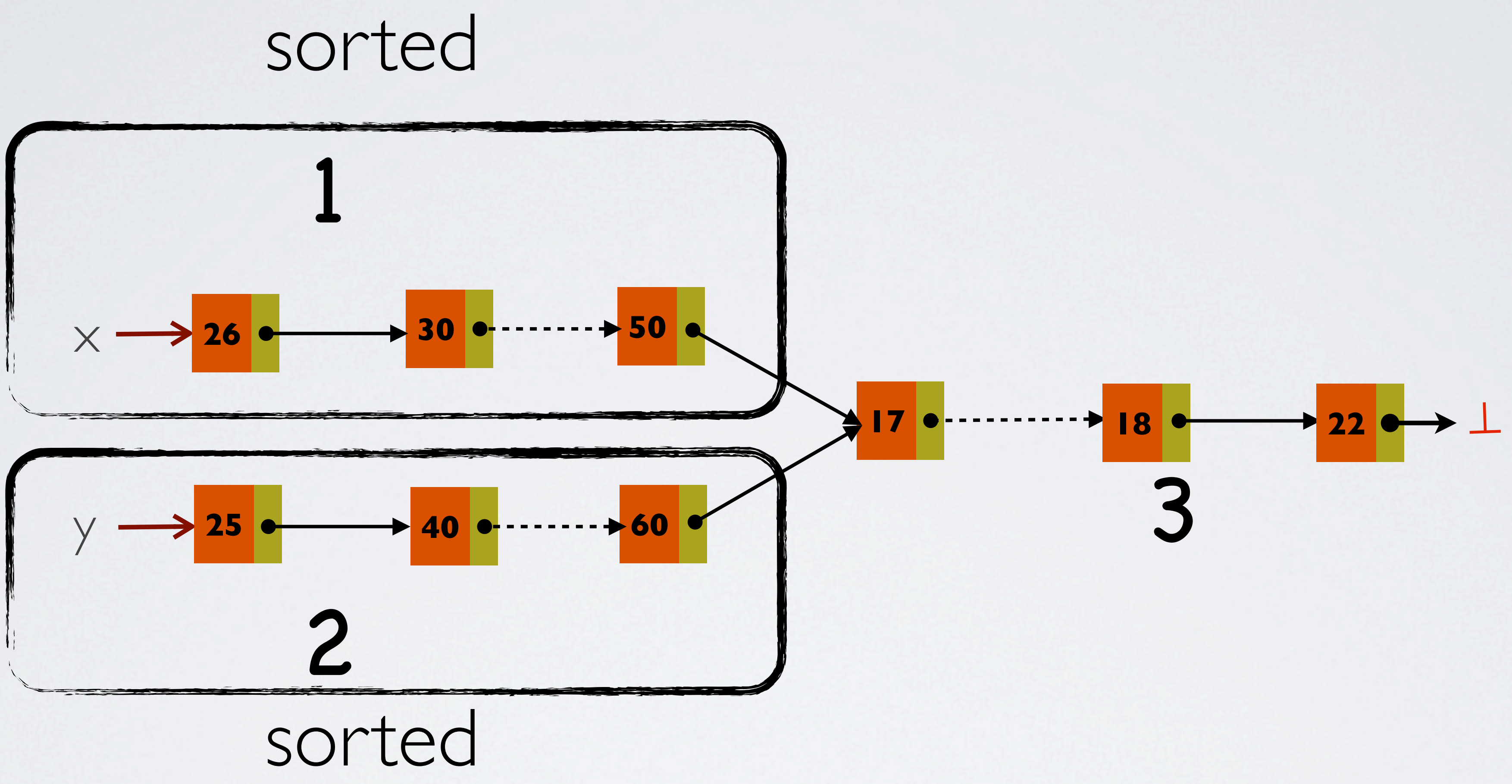

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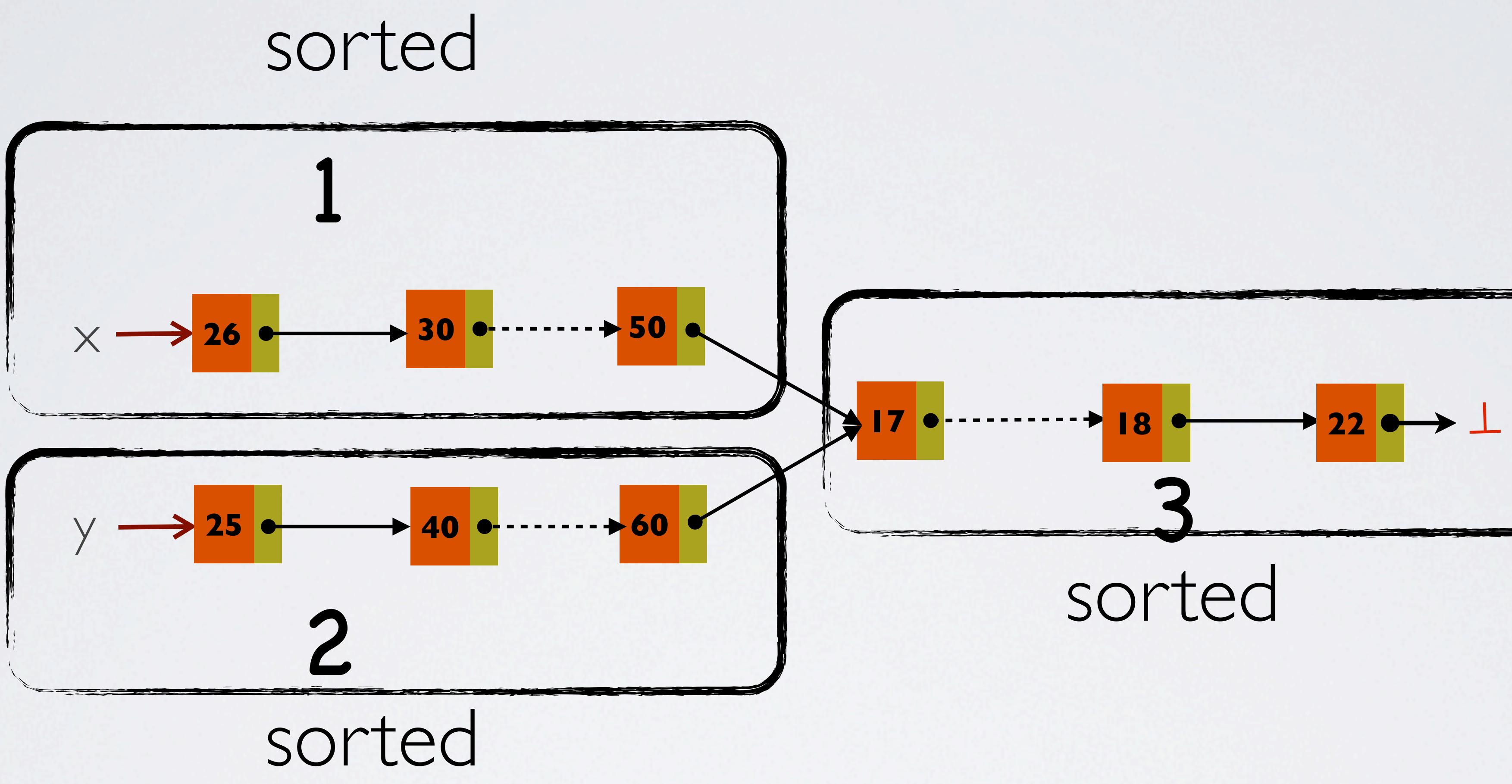

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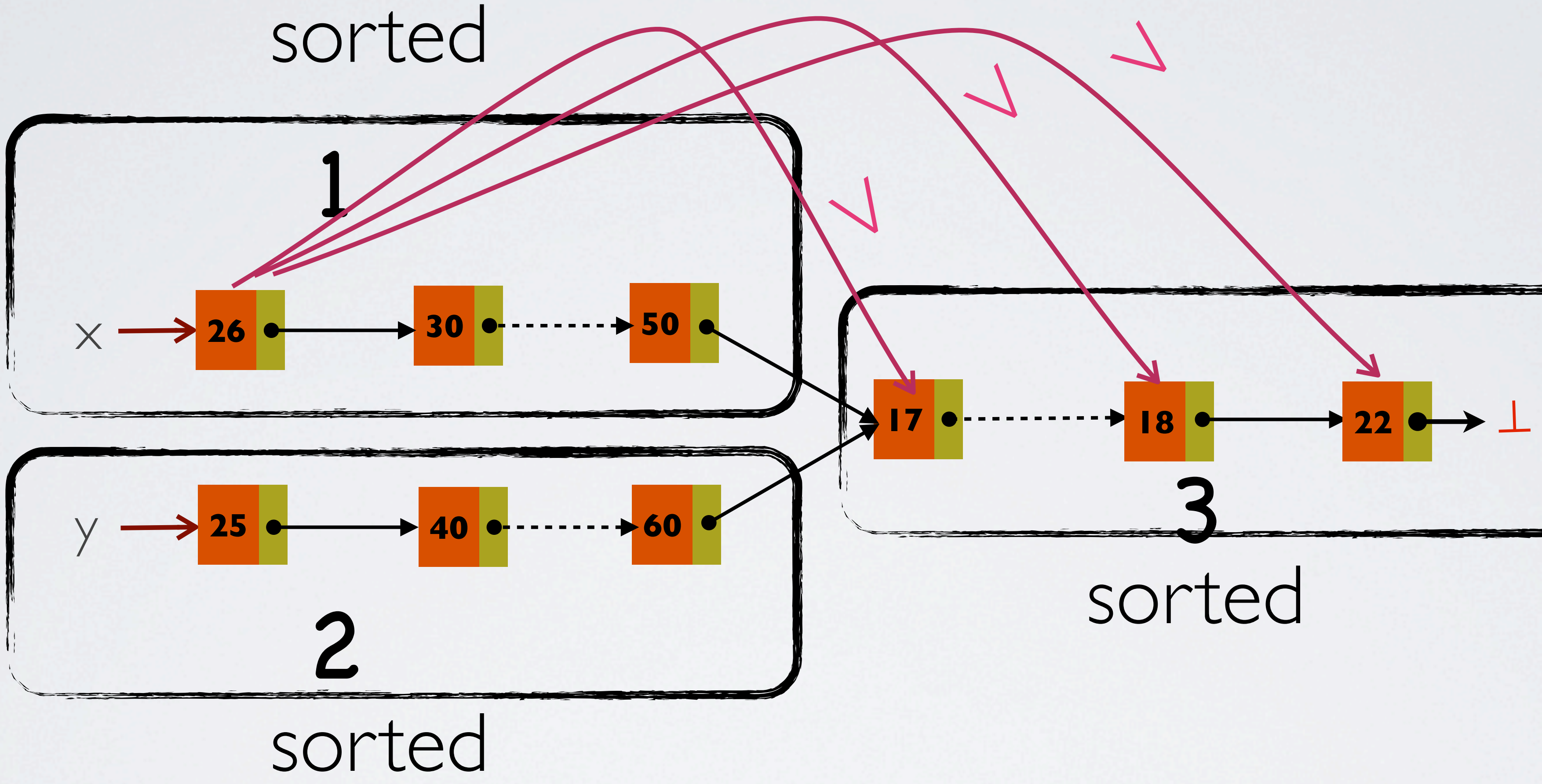

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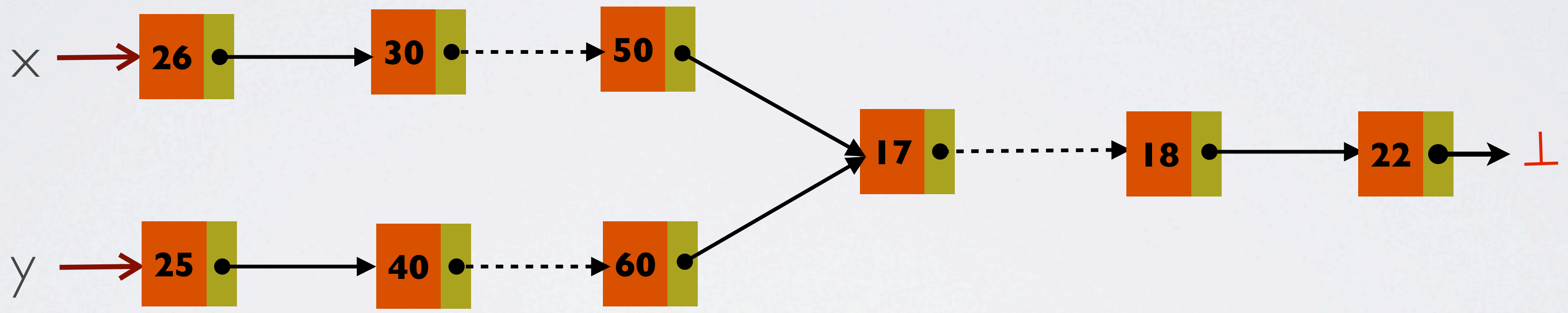
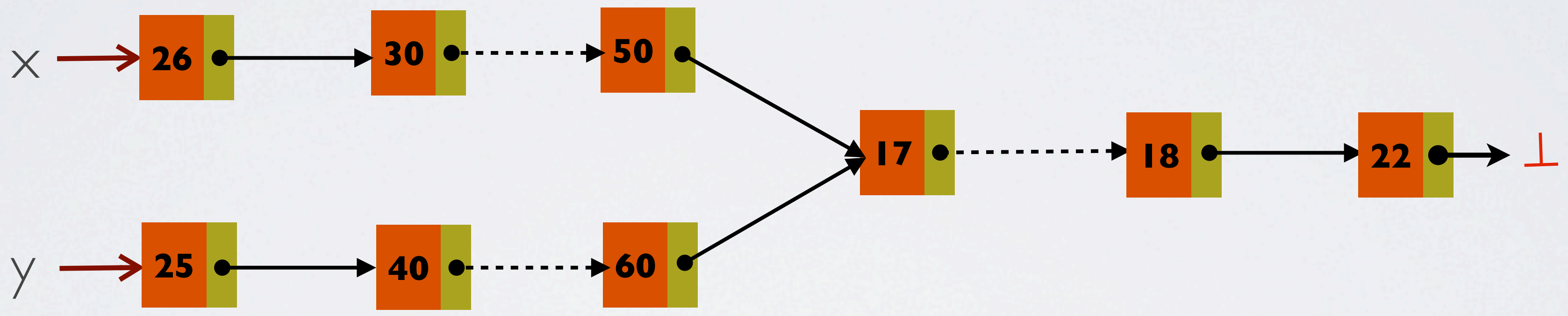


1. Heap representation | **2. Decompose heaps into forests** | 3. Represent forests by forest automata

Determine **cut-points:**
- Nodes pointed by variables
- Nodes with more incoming pointers



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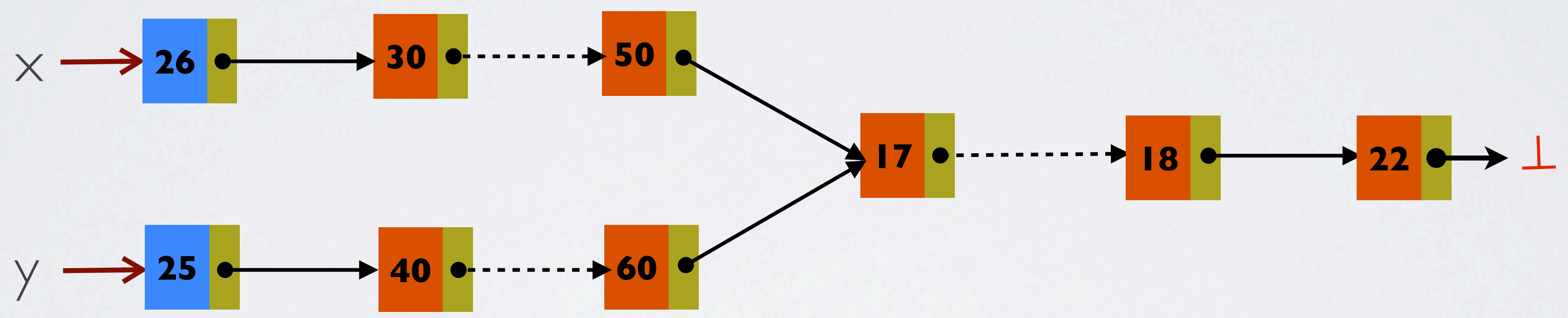

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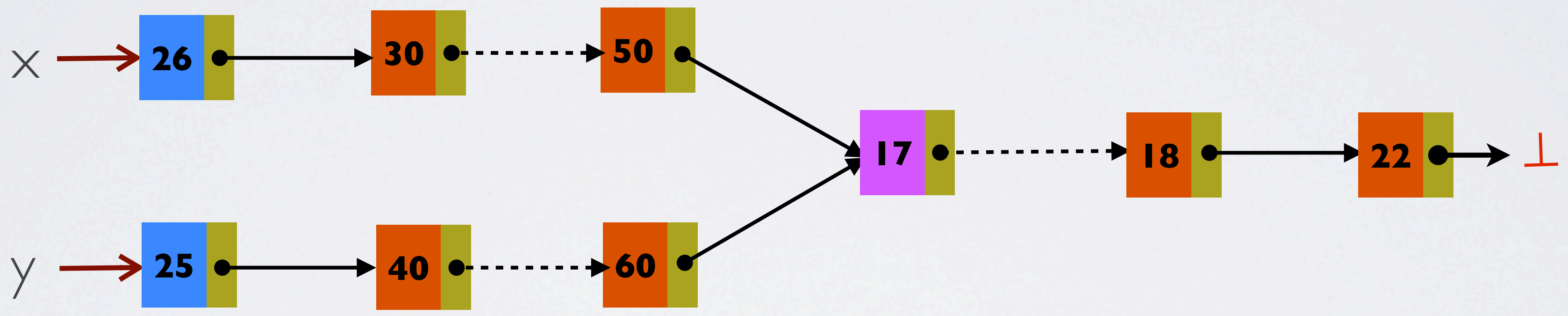

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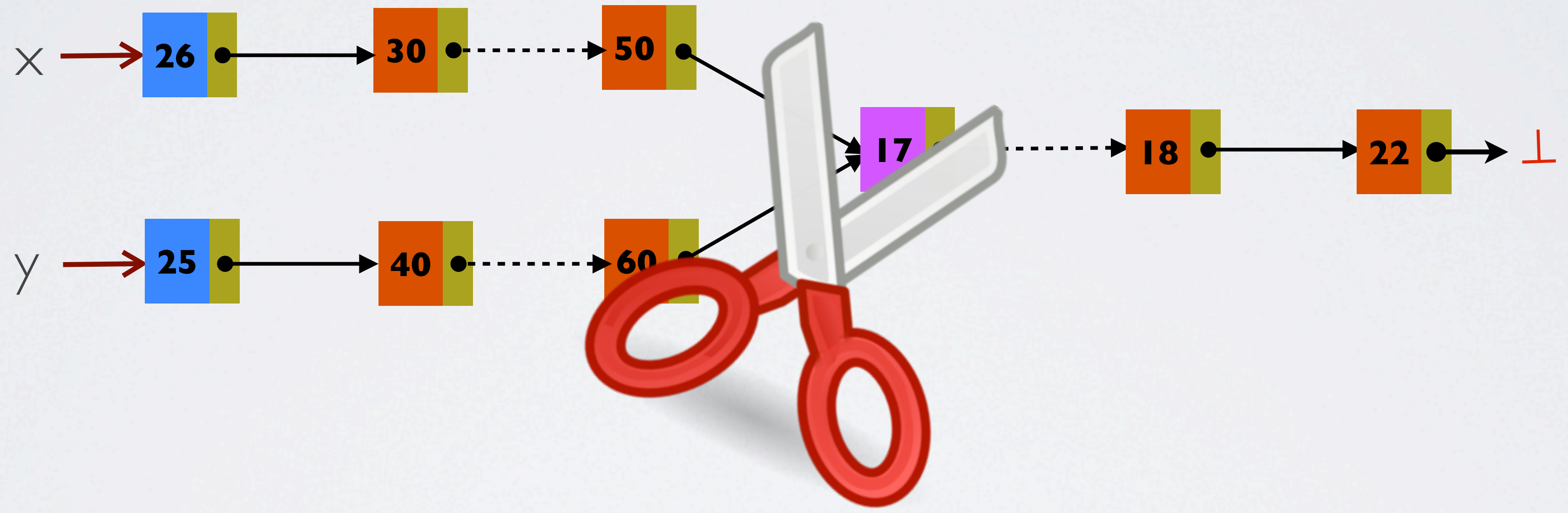

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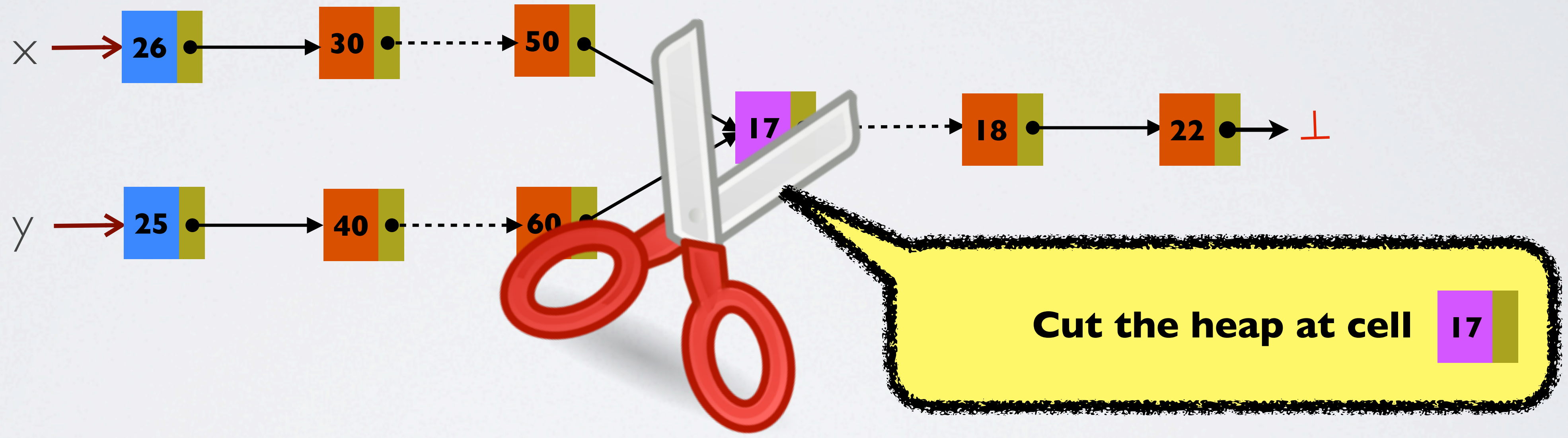

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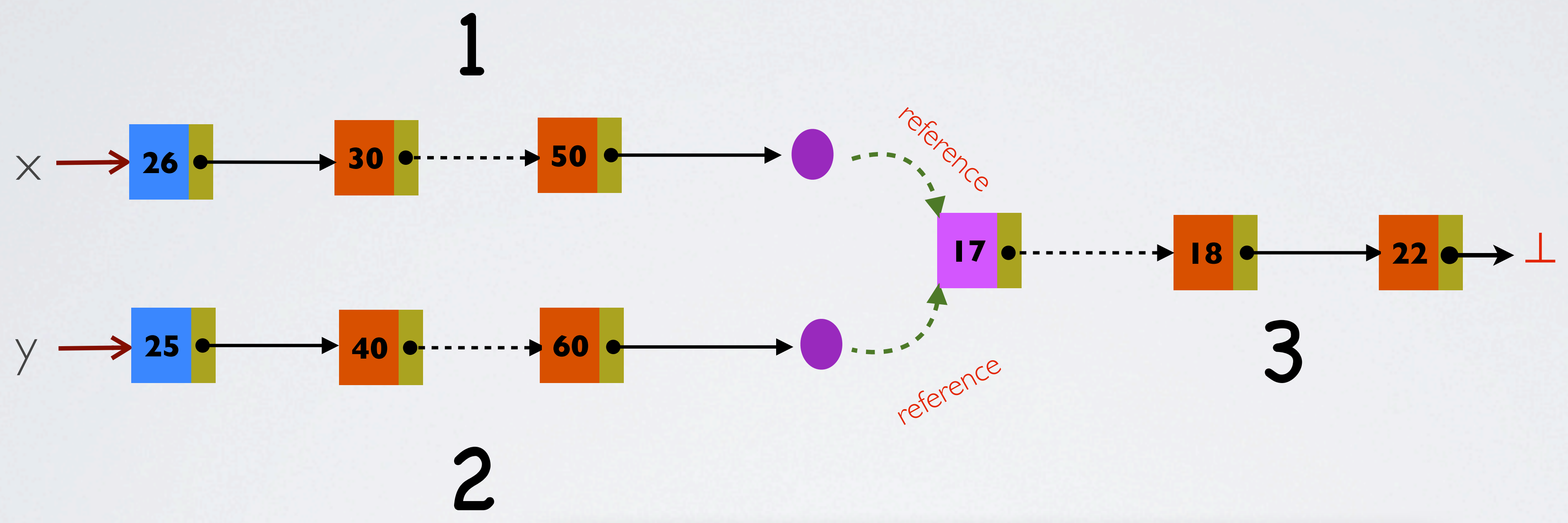
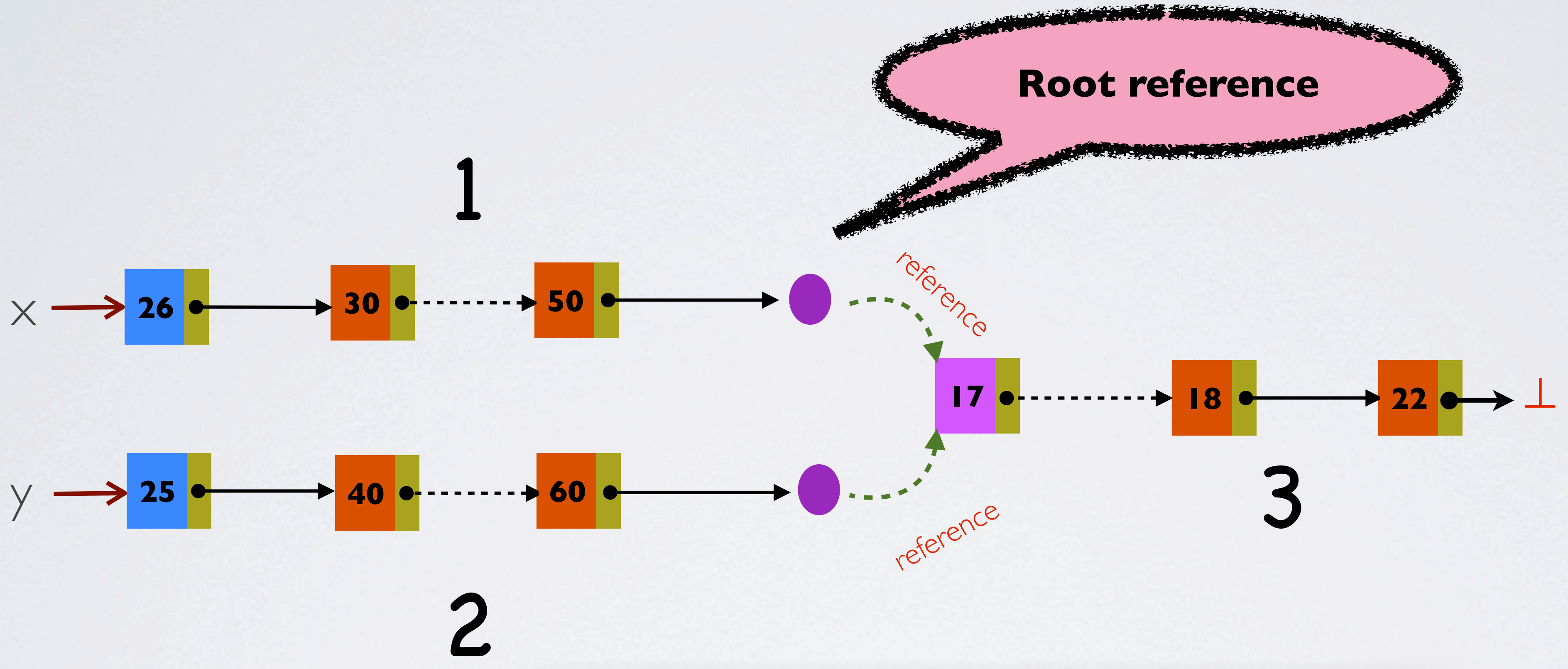


Forest presentation of the set of heaps

1. Heap representation

2. Decompose heaps into forests

3. Represent forests by forest automata



Forest presentation of the set of heaps

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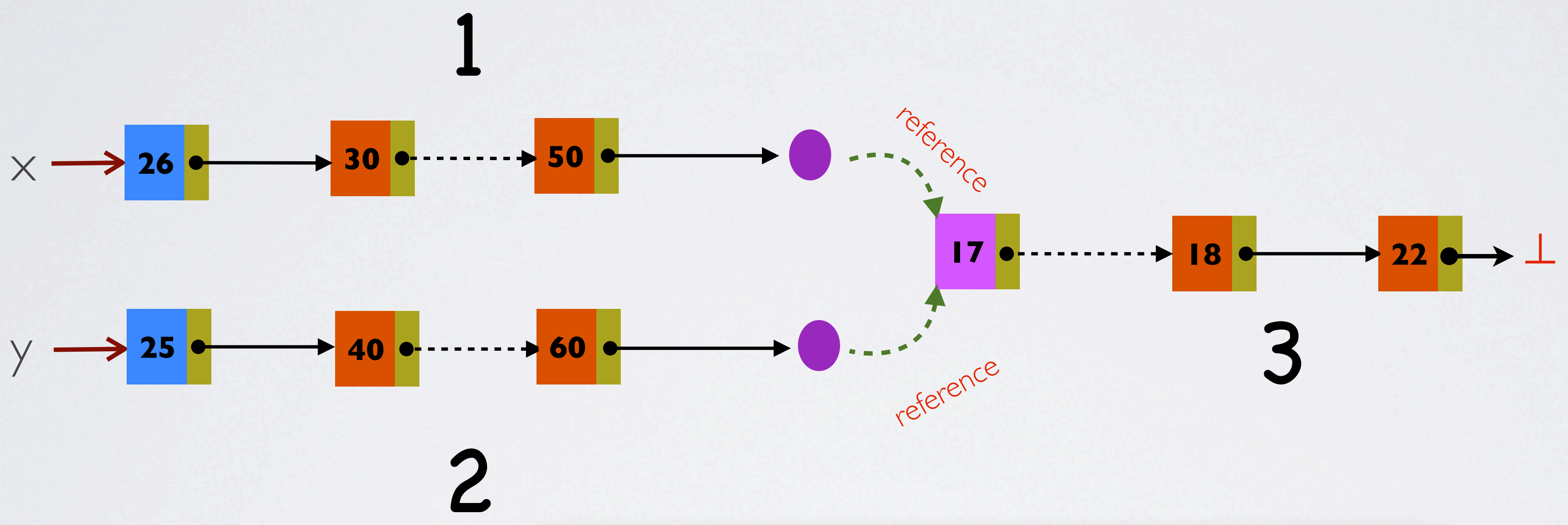
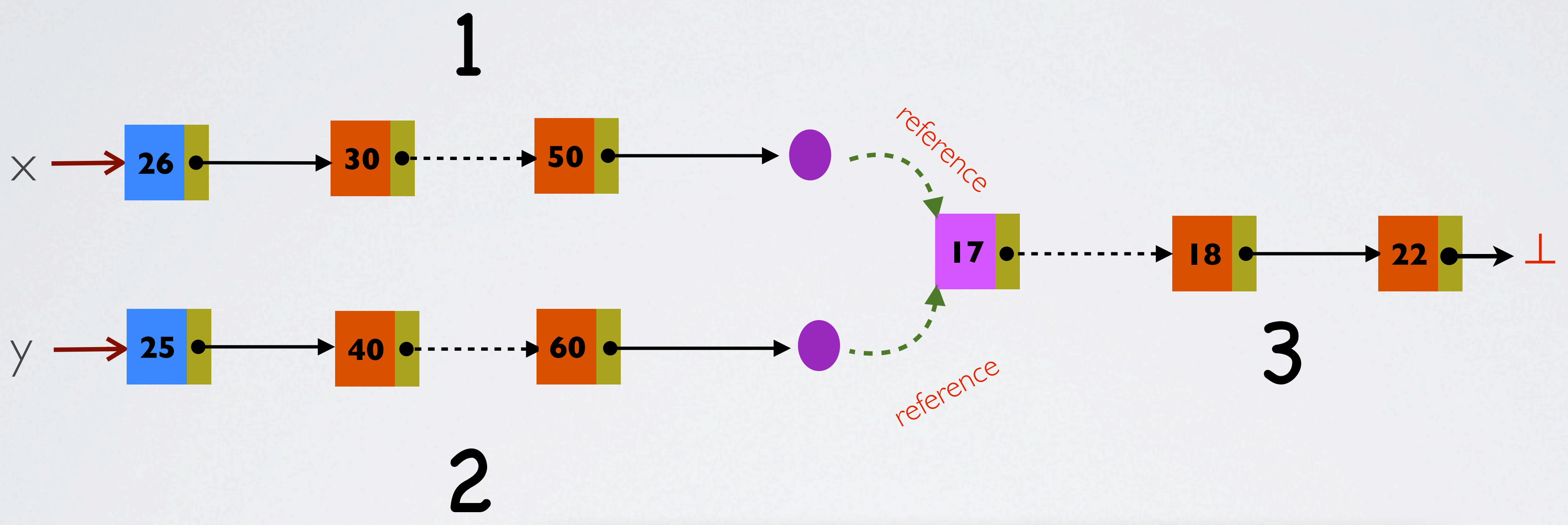


Forest presentation of the set of heaps

Without data



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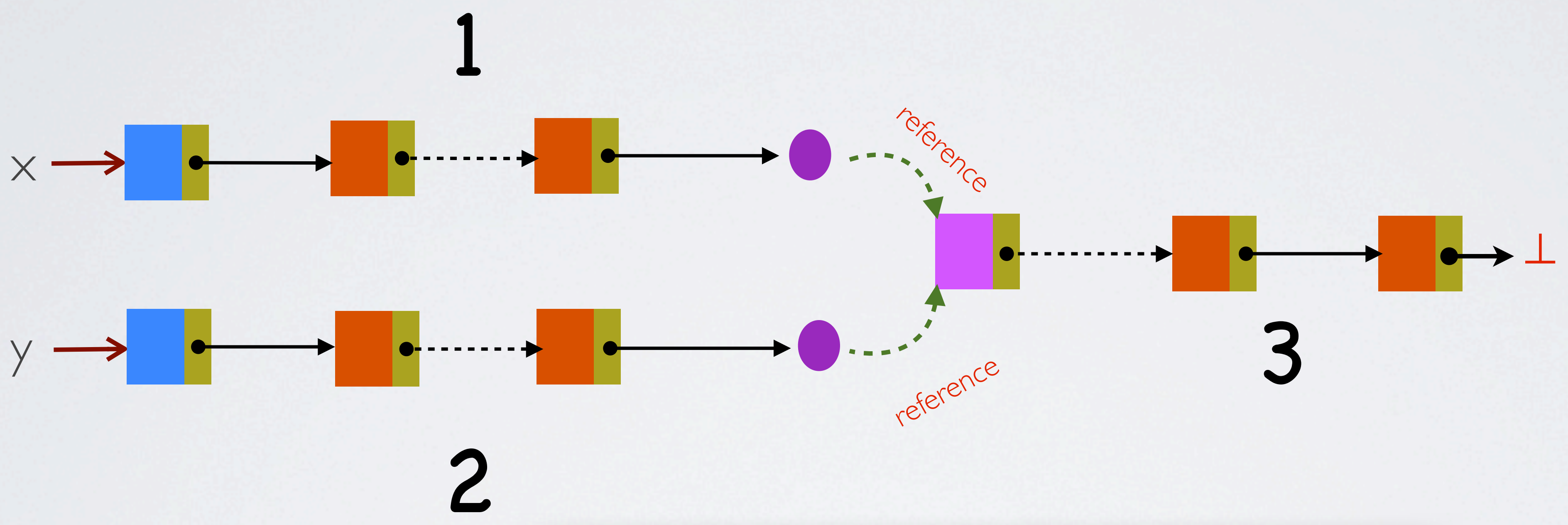
Without data



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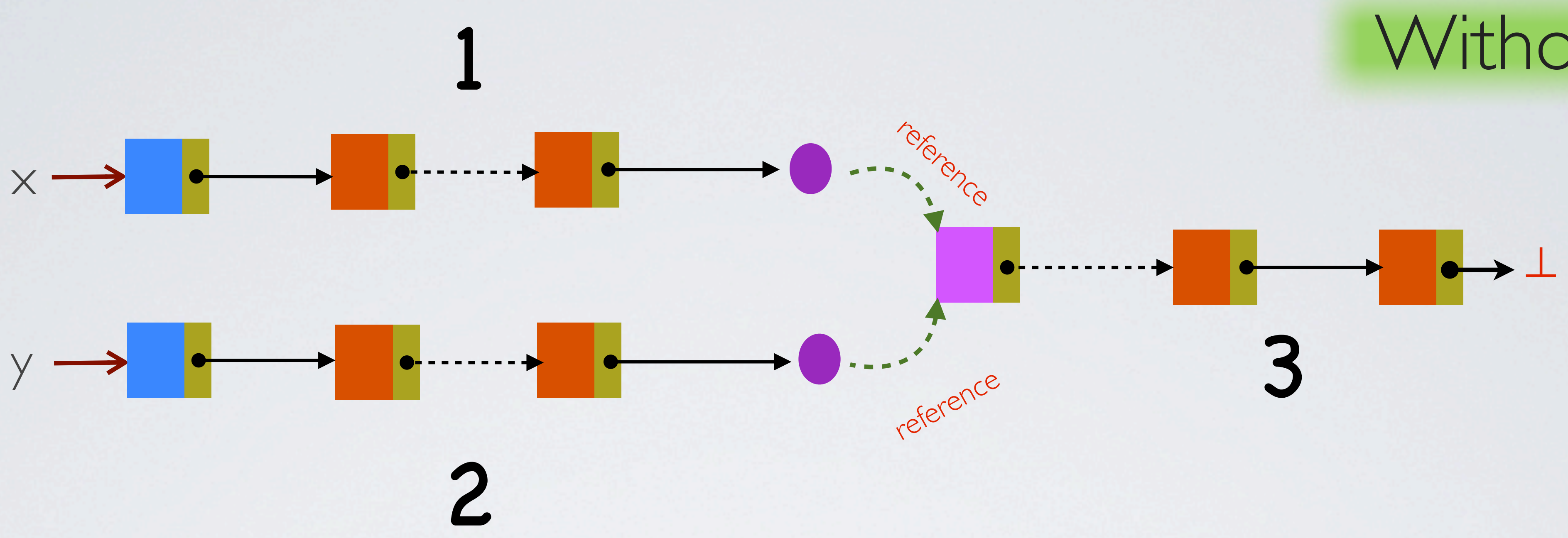
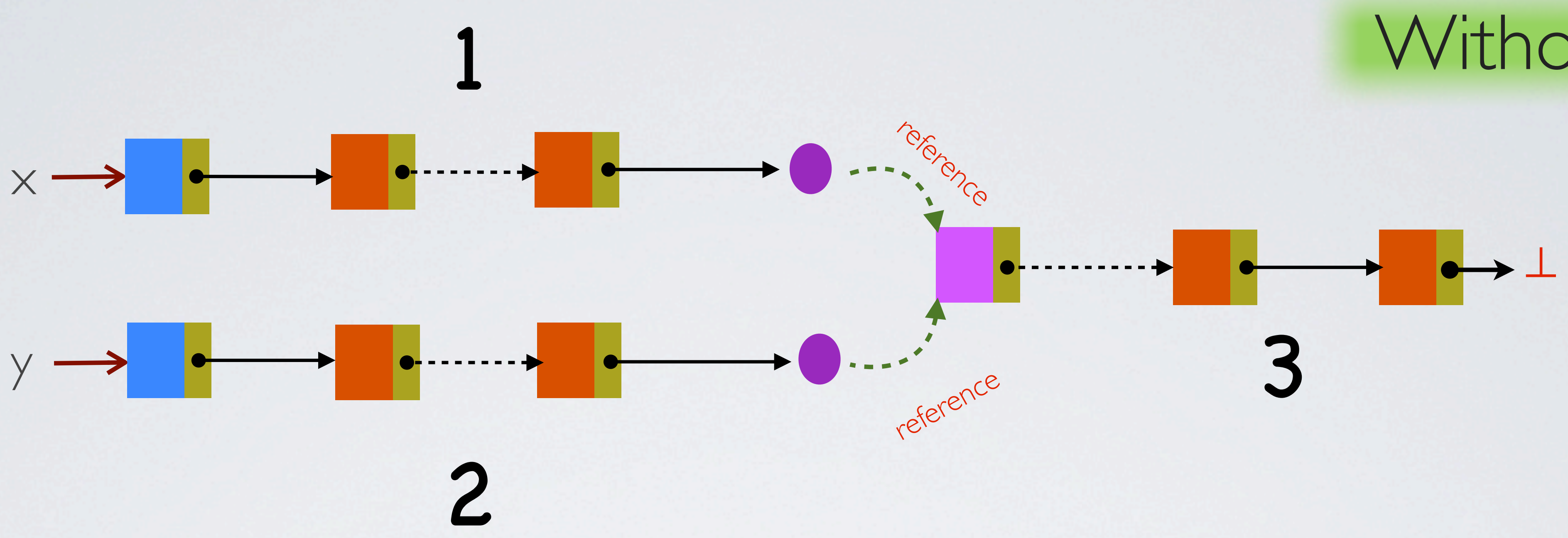
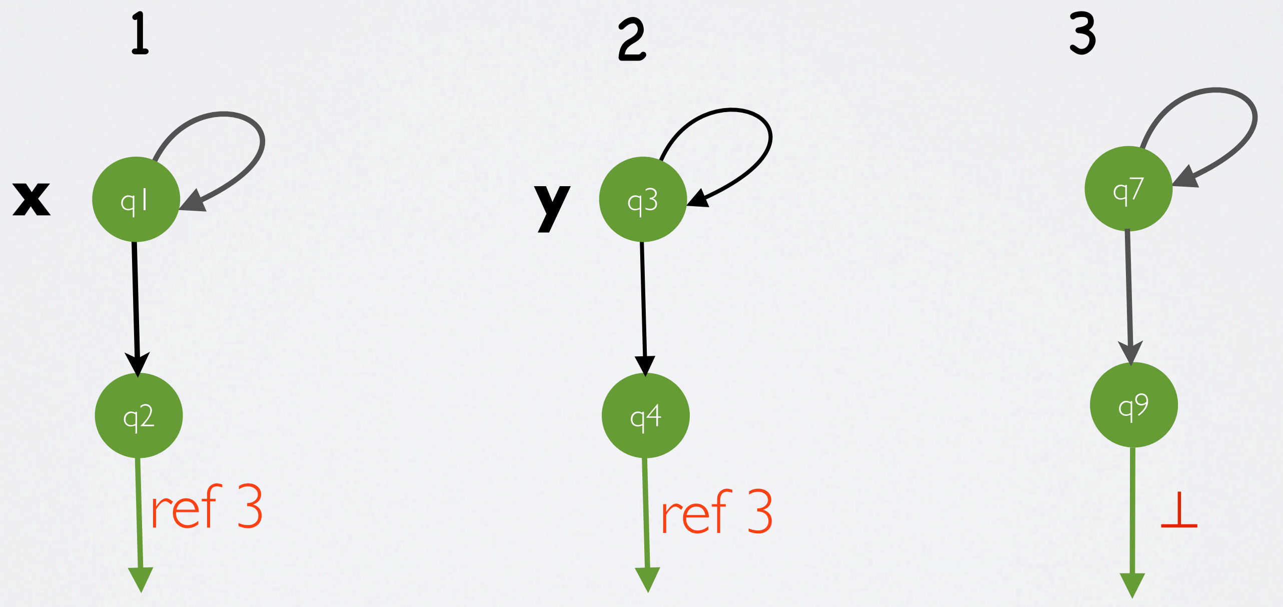


1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

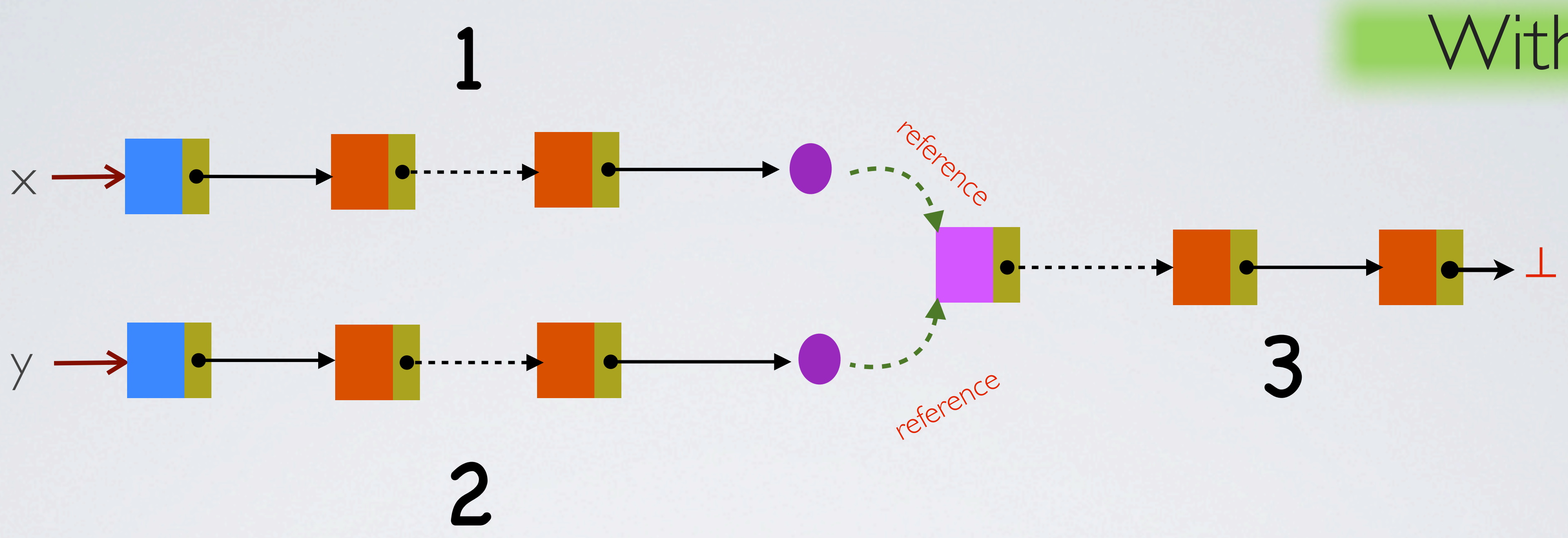
Without data

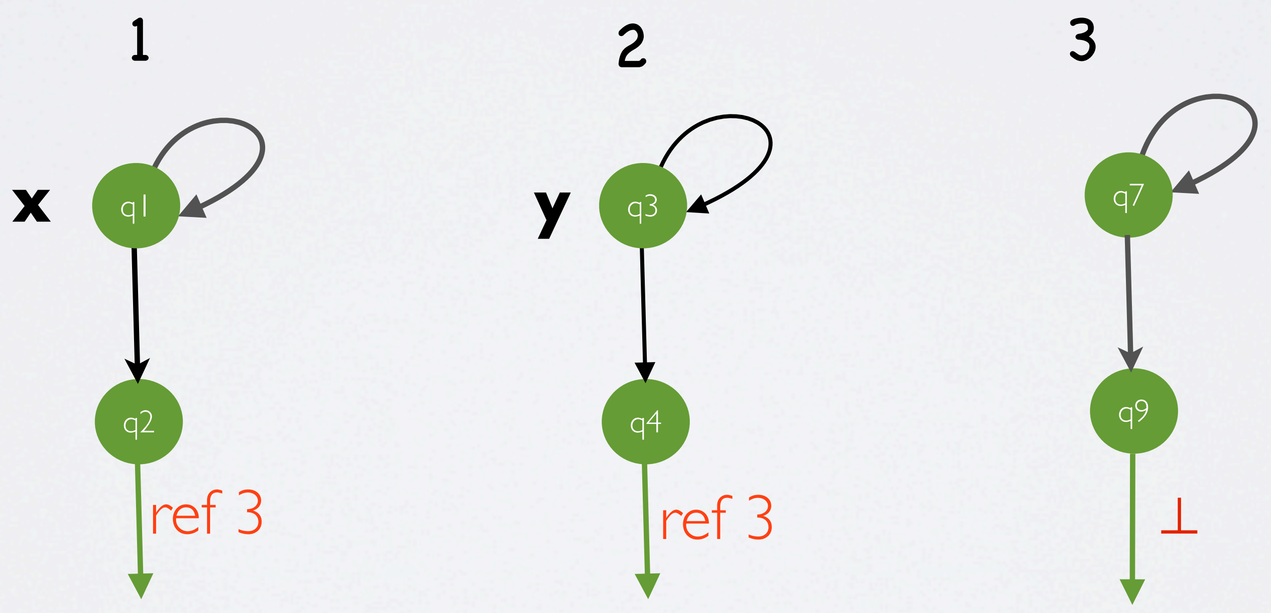




1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

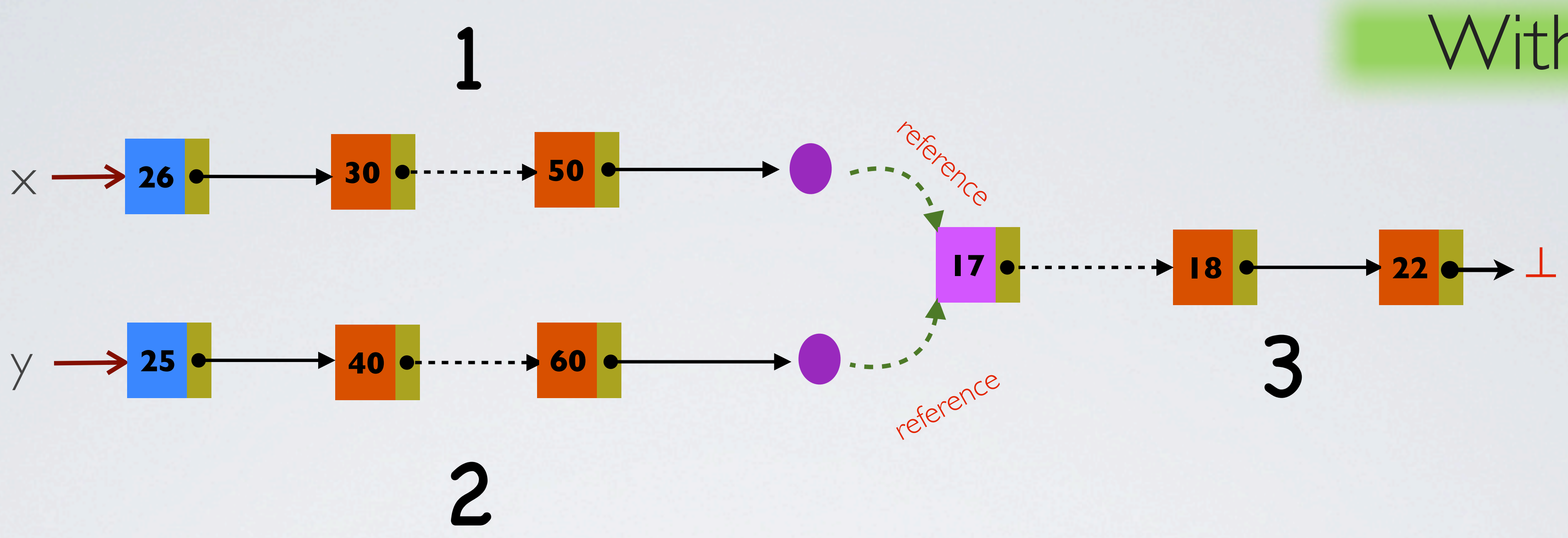
With data

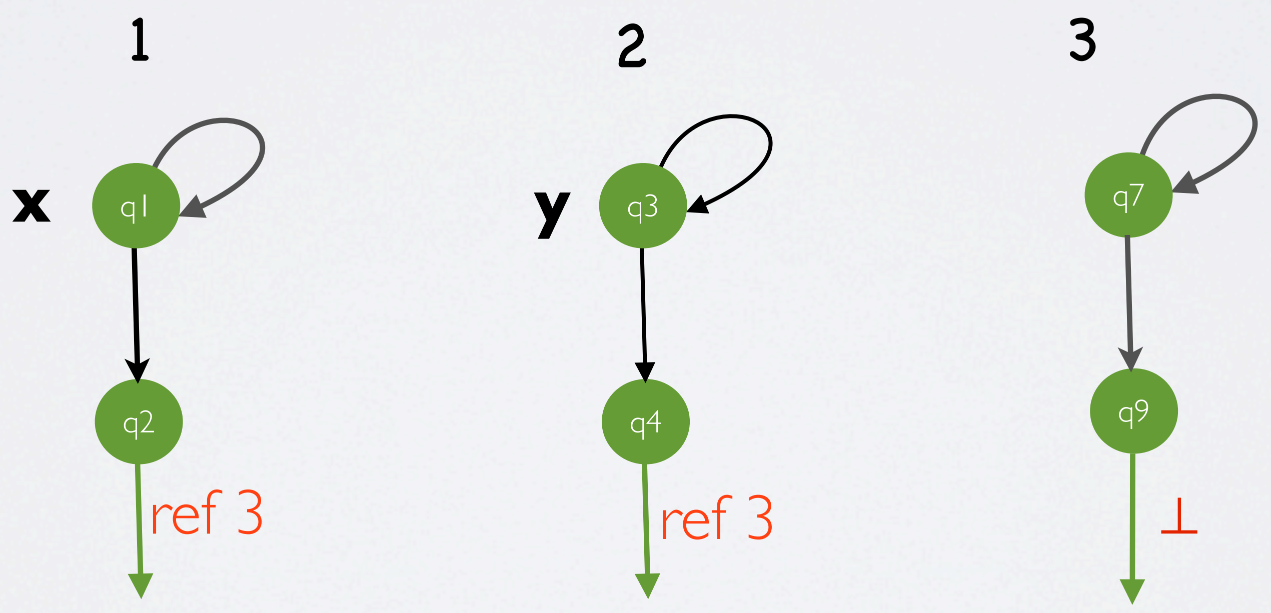




1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

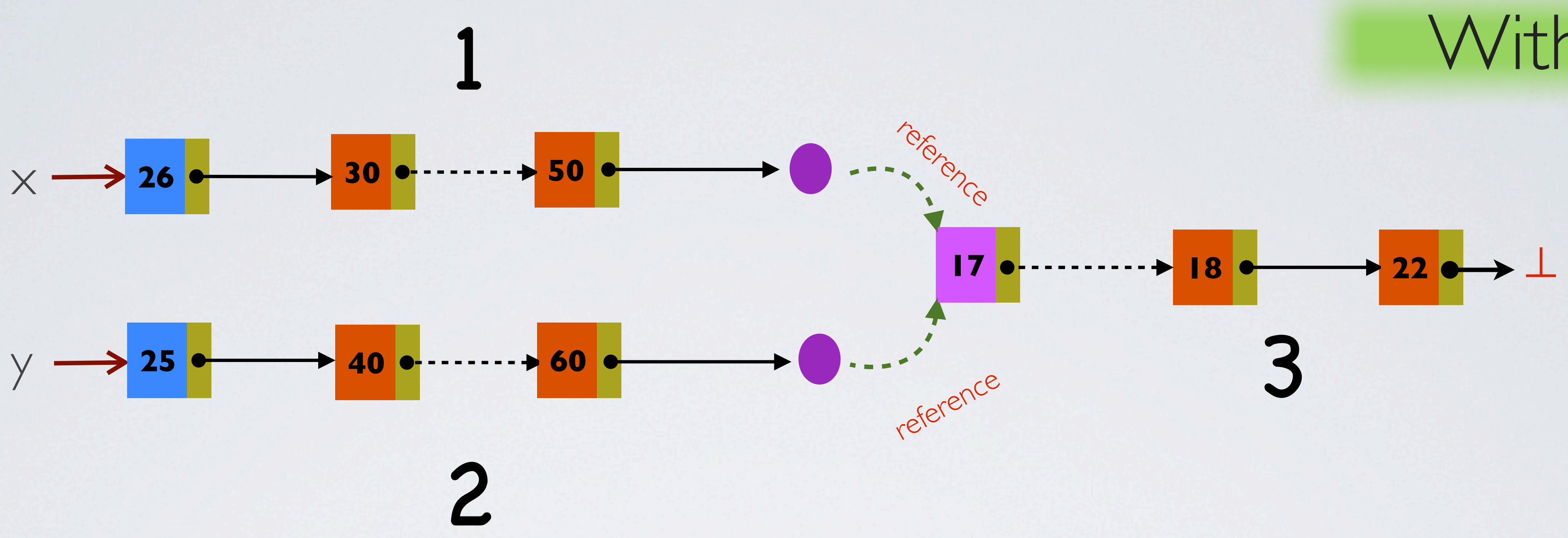
With data

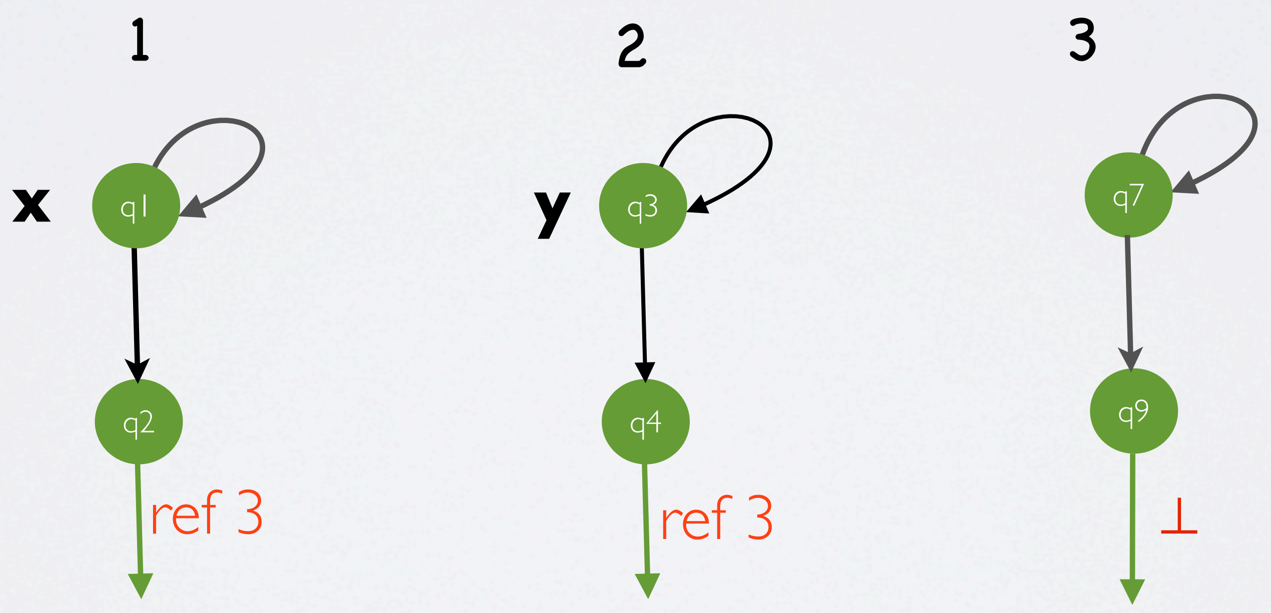




1. Heap representation 2. Decompose heaps into forests **3. Represent forests by forest automata**

With data

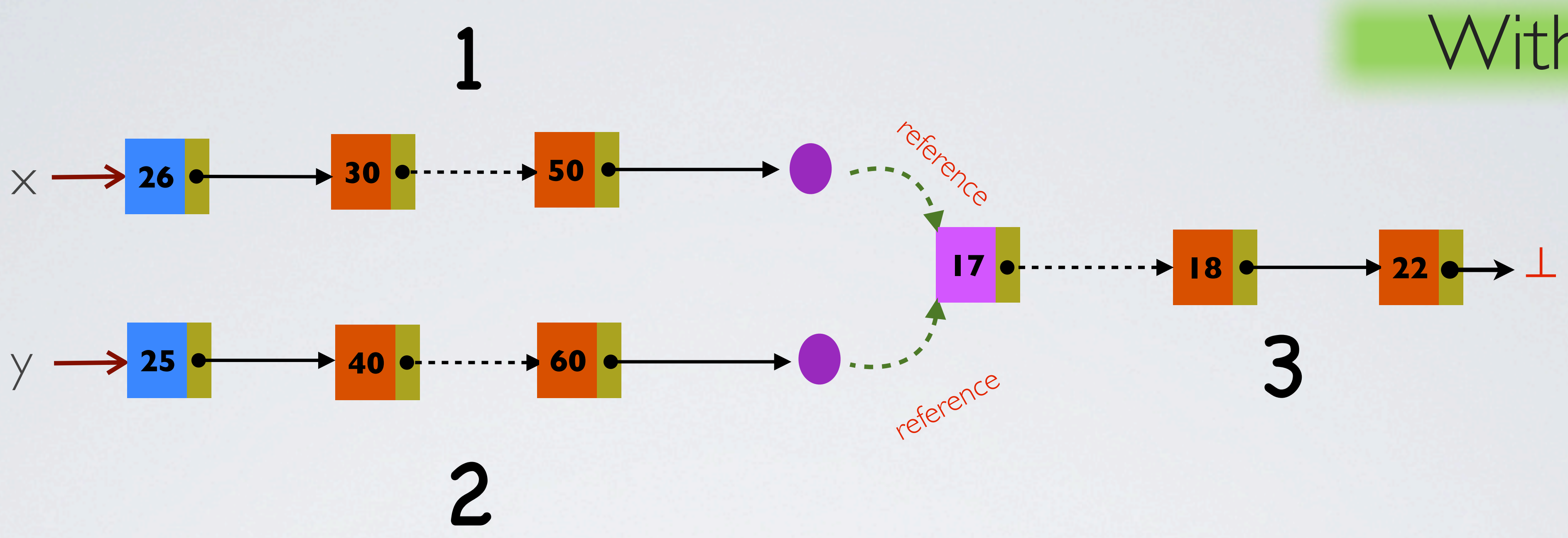


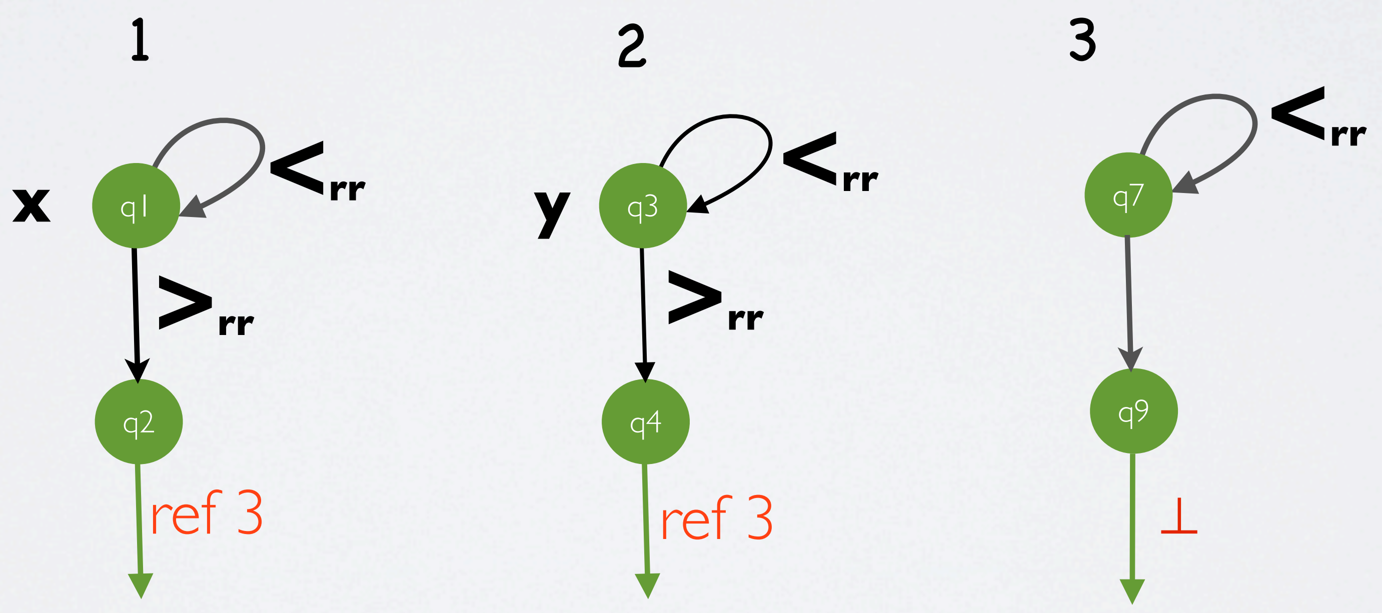


Add data constraints

1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

With data

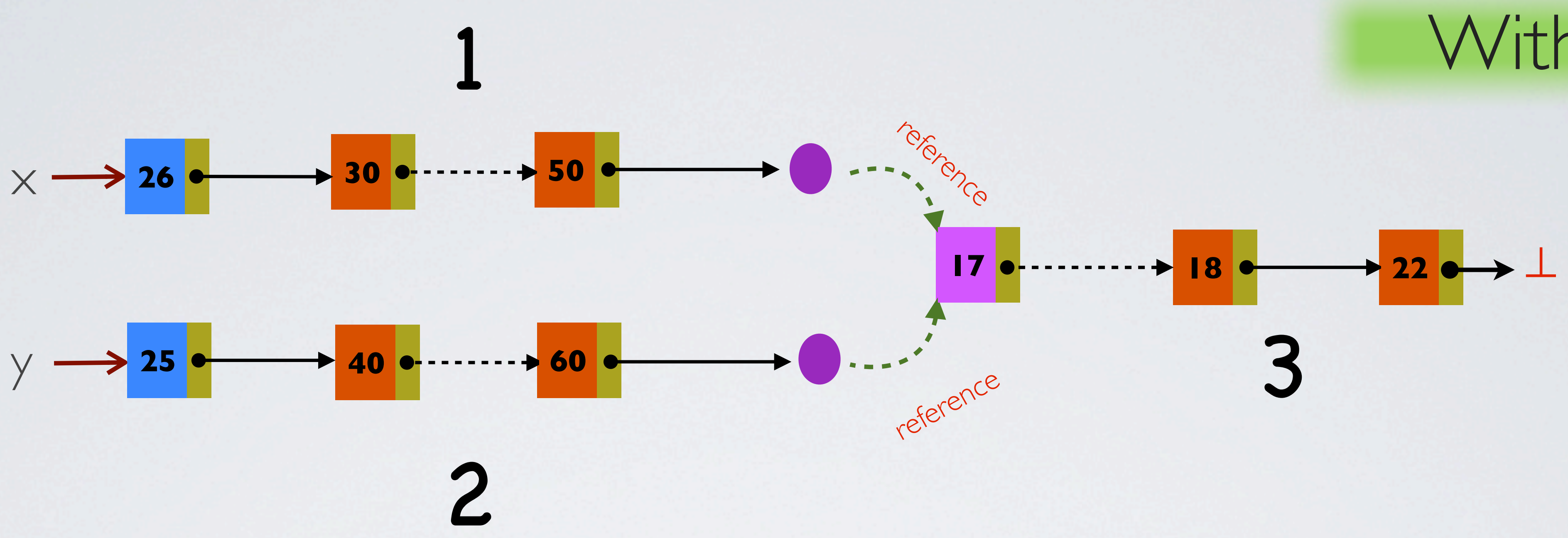


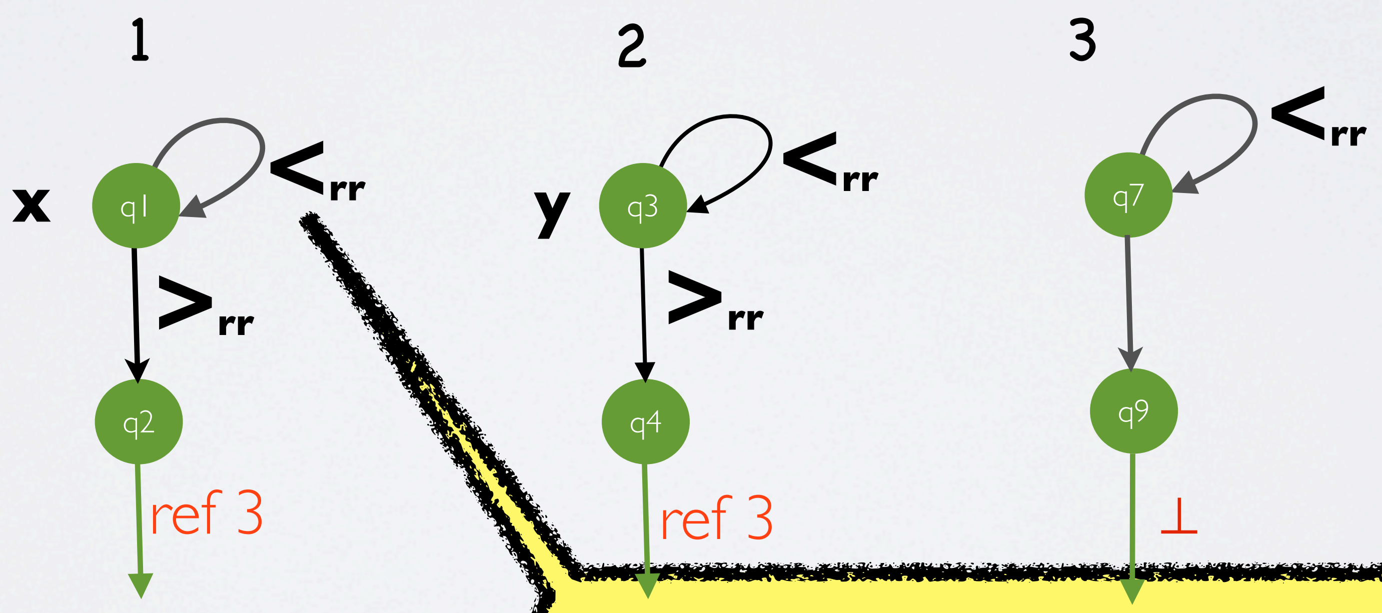


Add data constraints

1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

With data

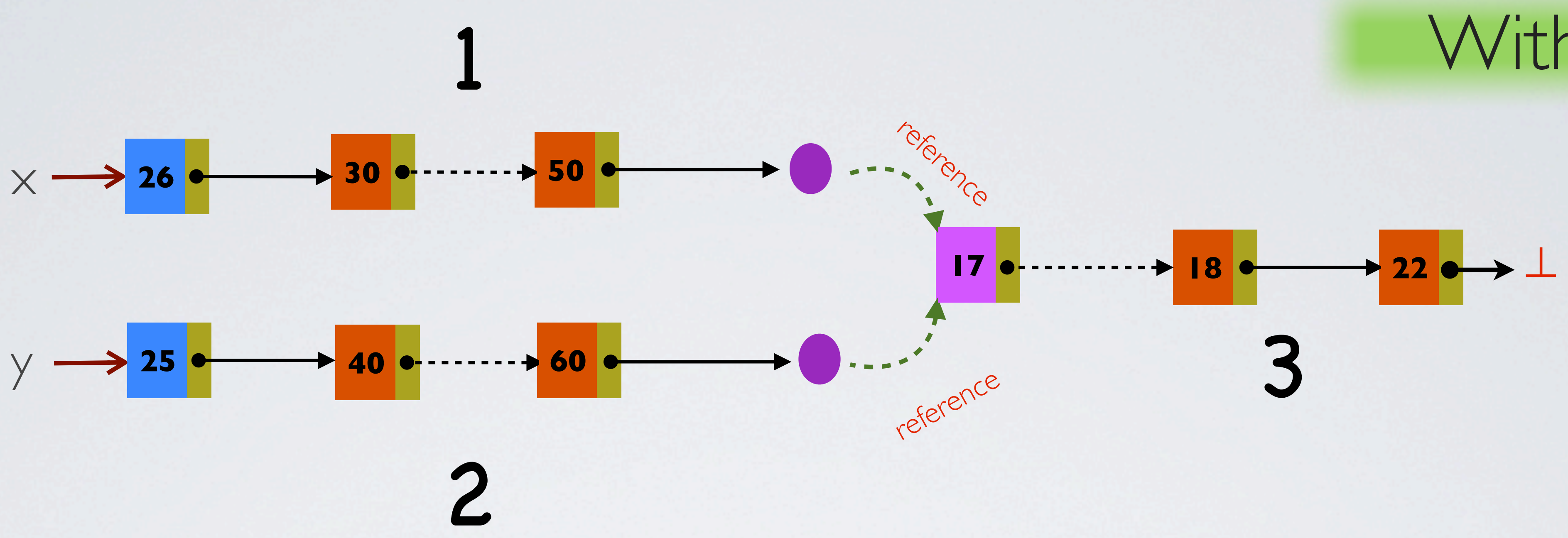


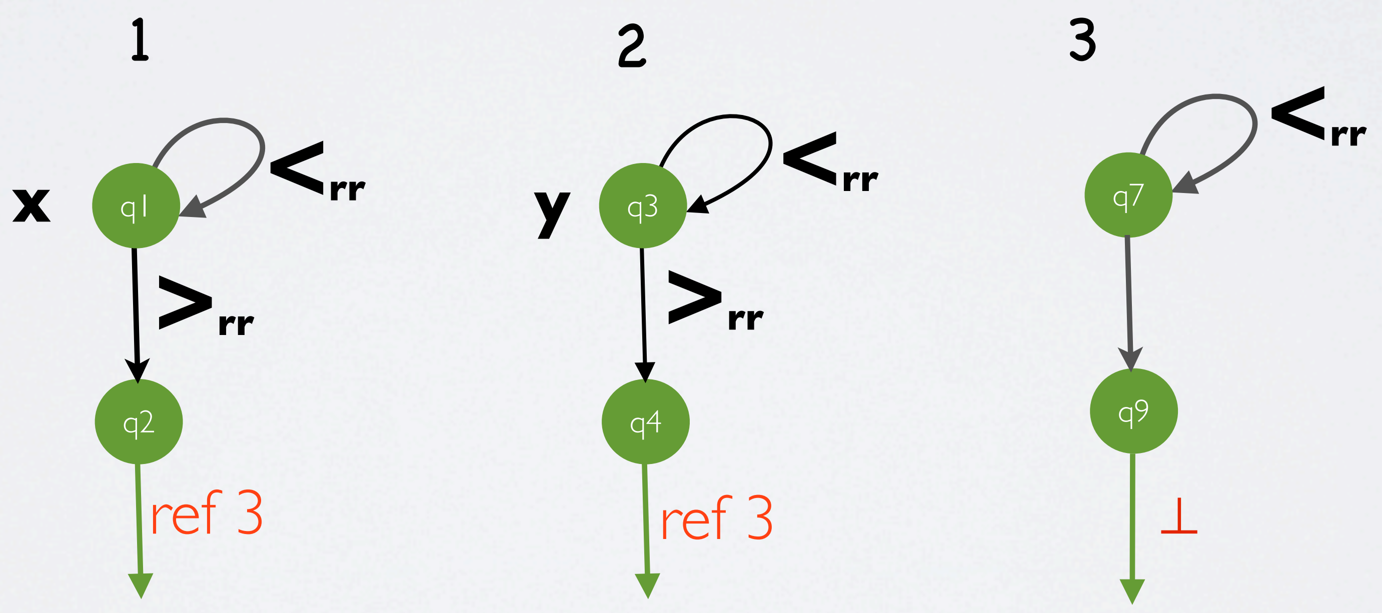


Data value of root node of any tree accepted at q1 is smaller than data value of root node of tree accepted at the next q1 of the cycle

1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

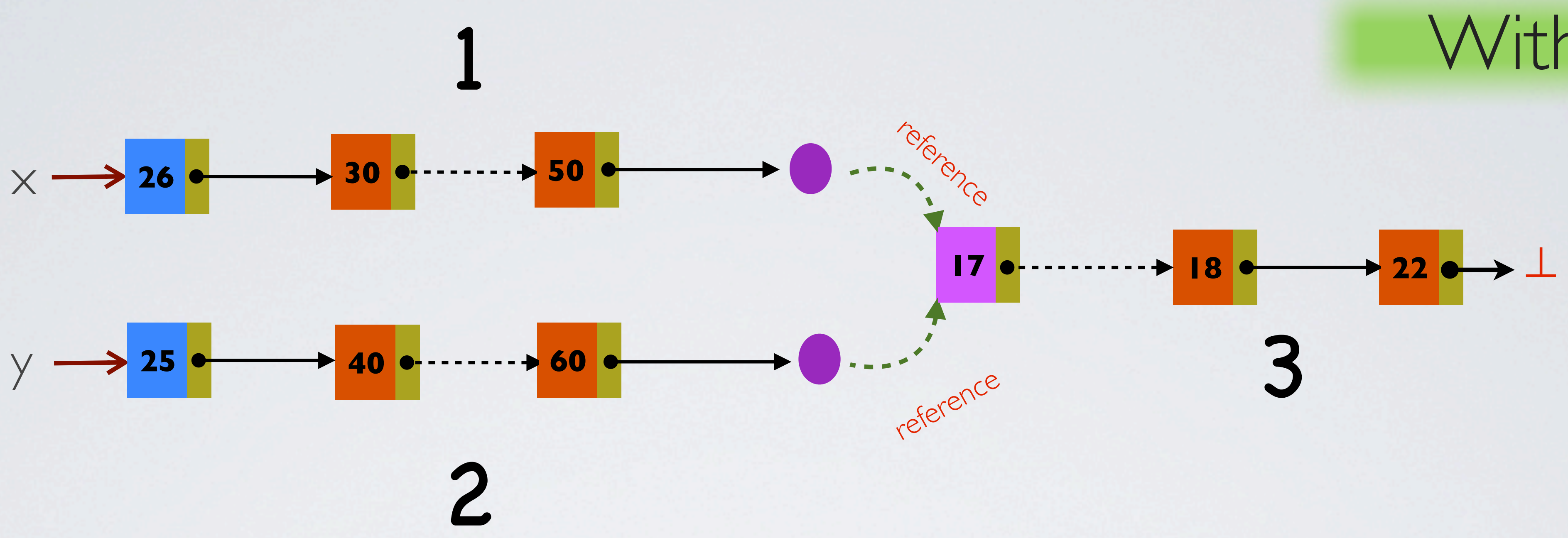
With data

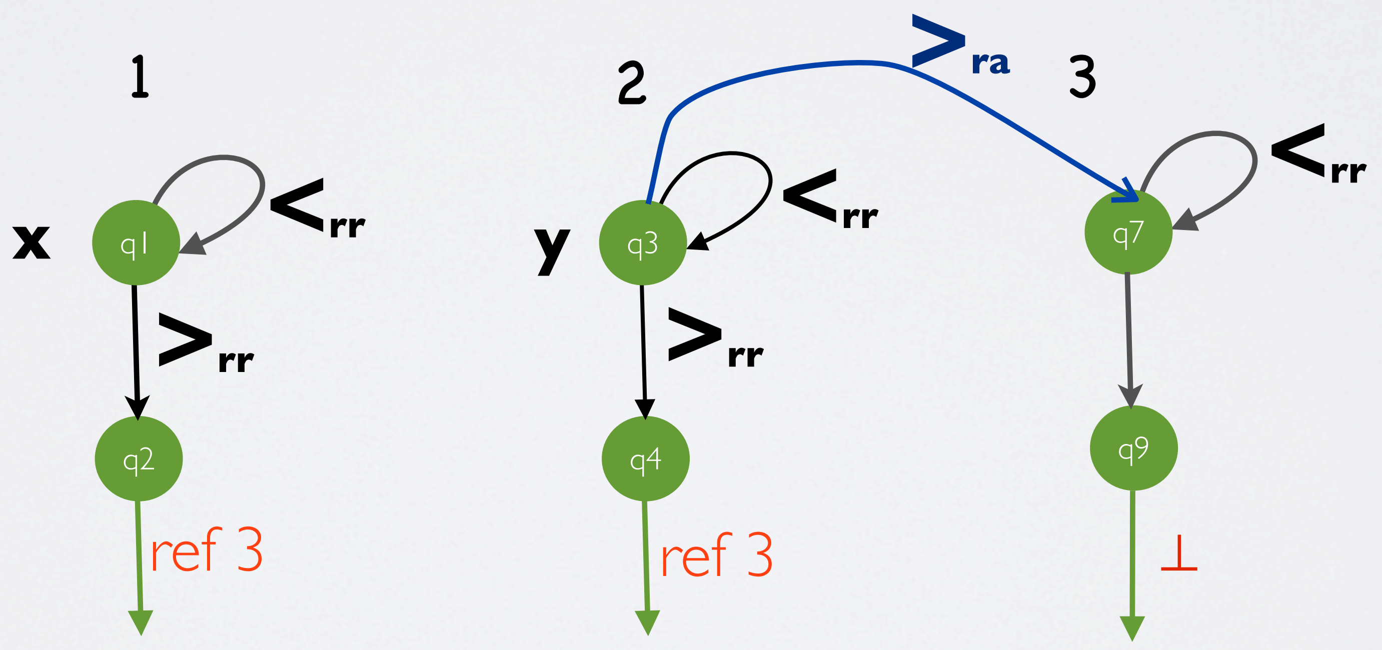




1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

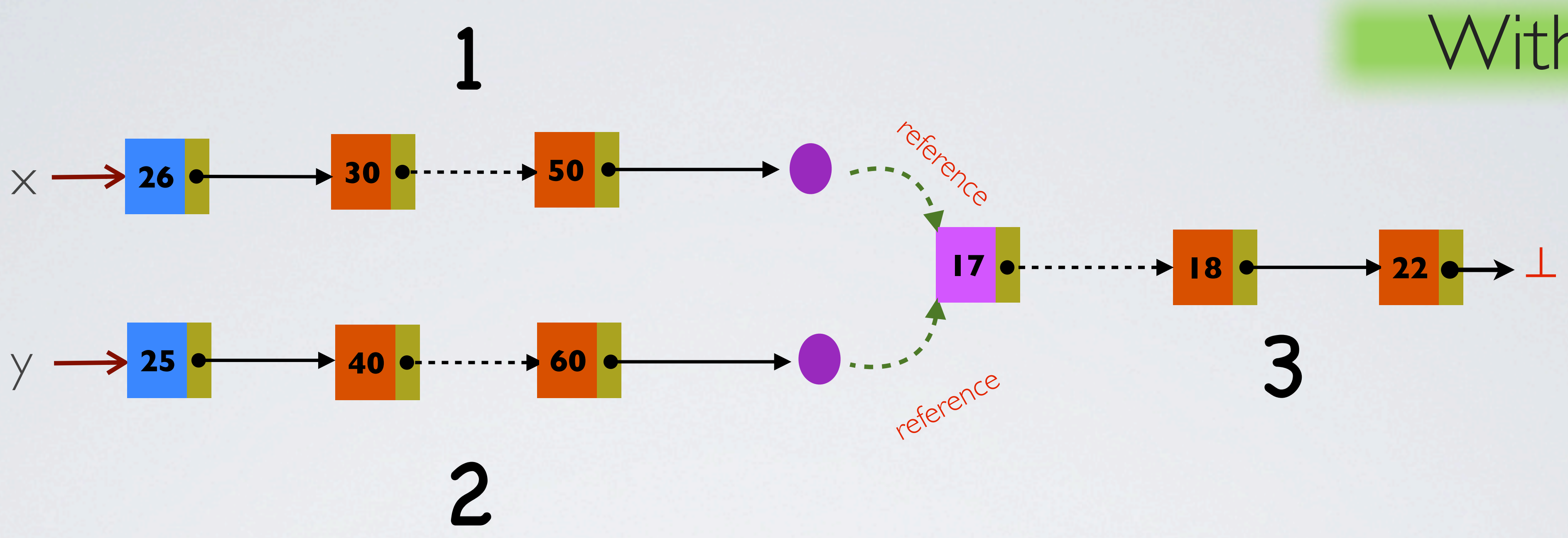
With data

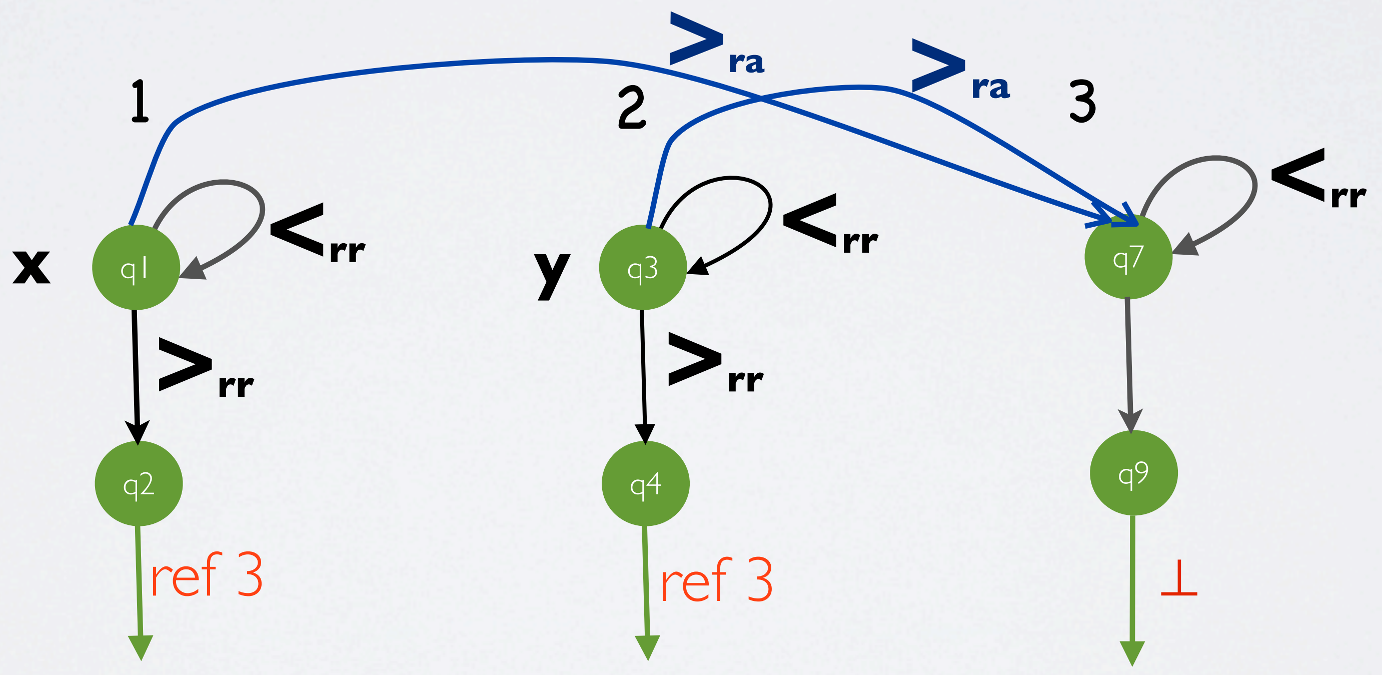




1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

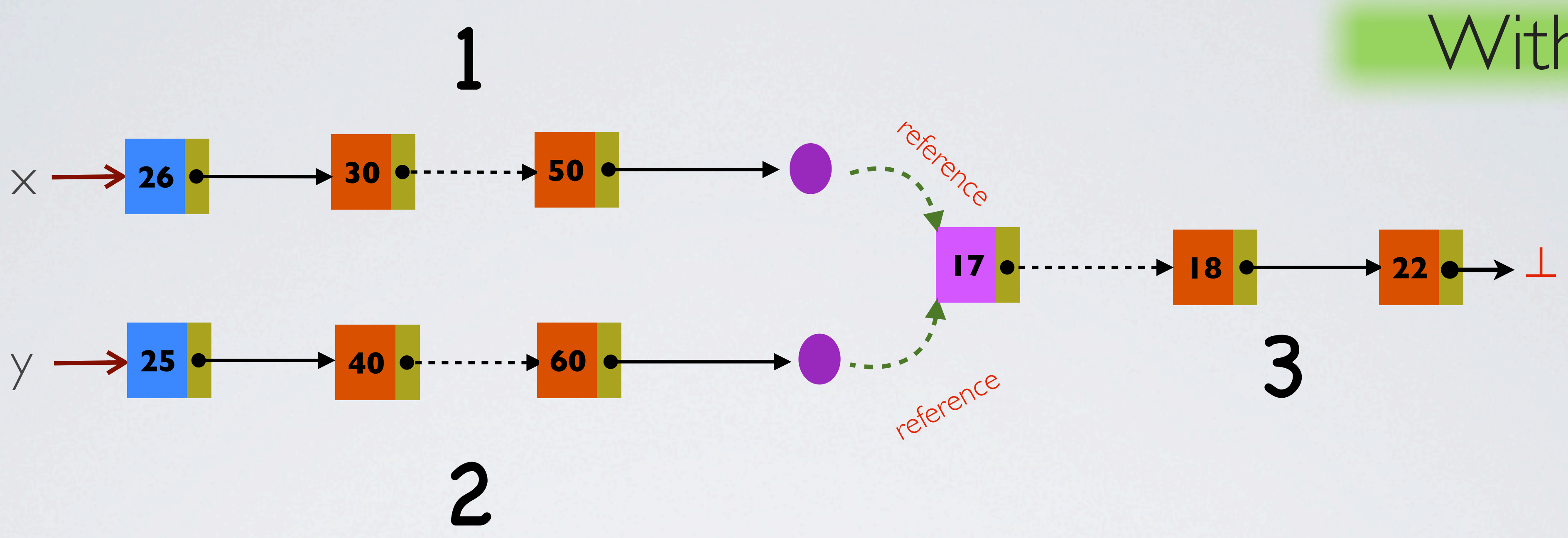
With data

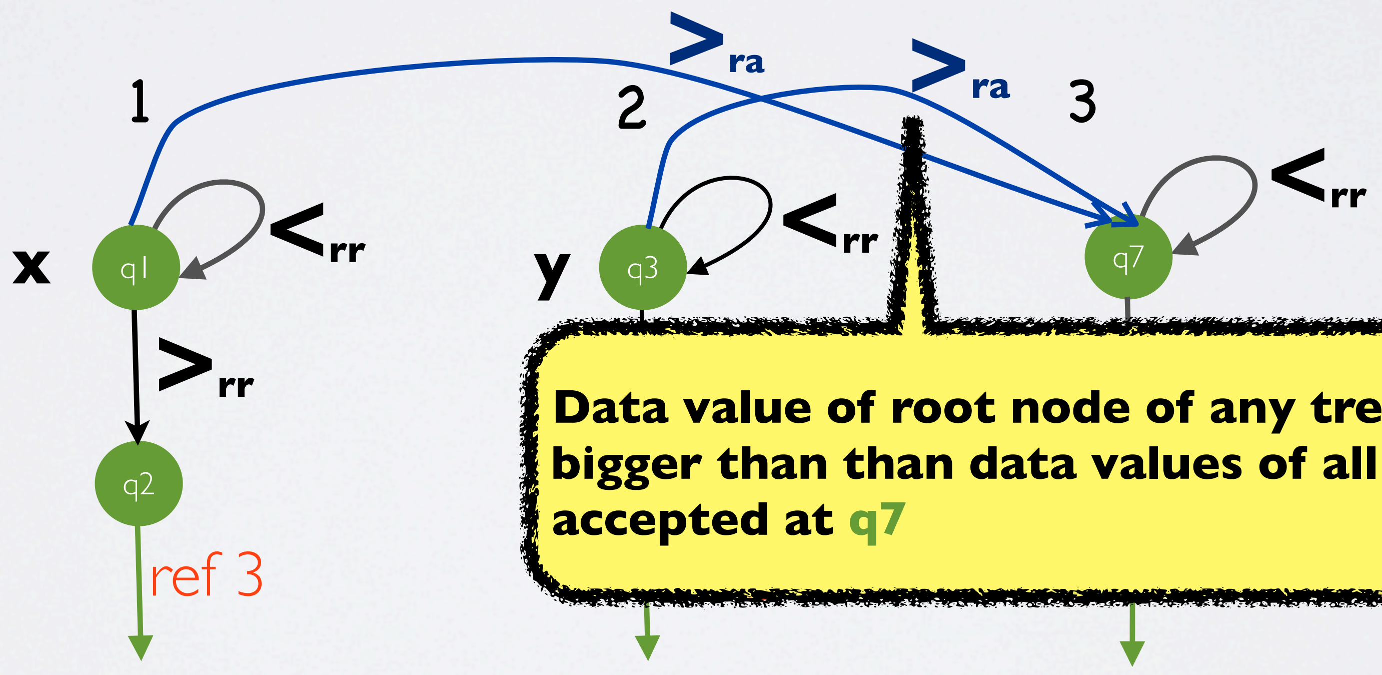




1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

With data

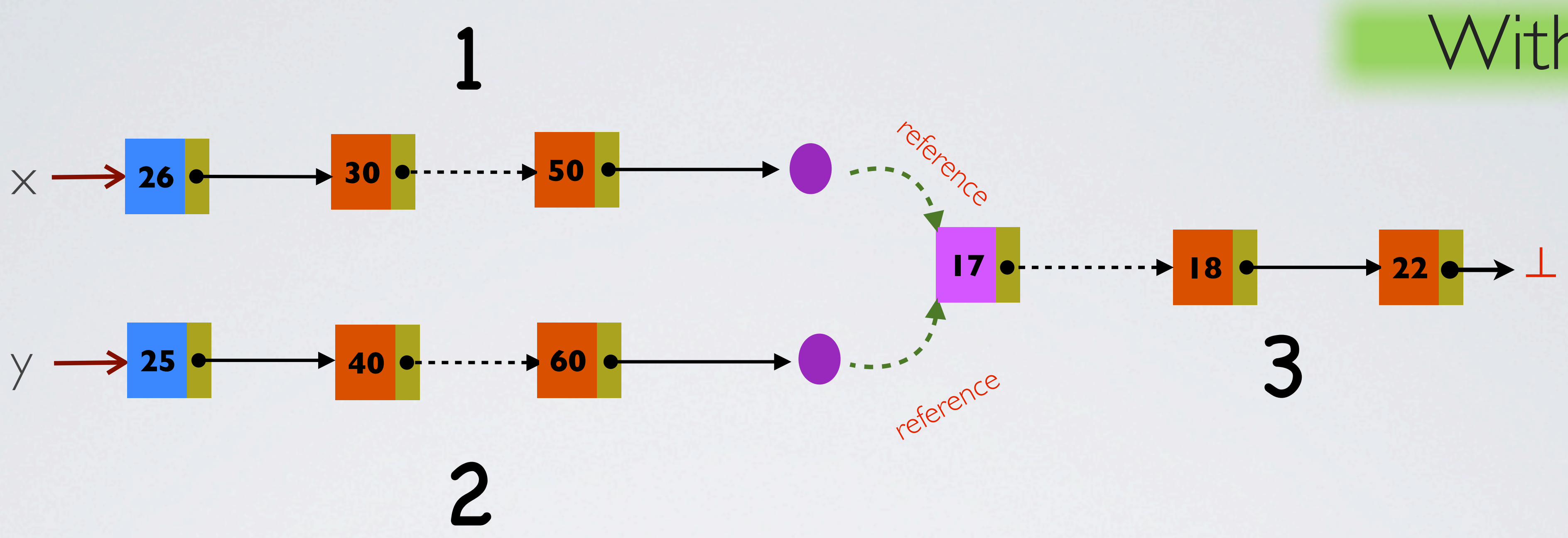


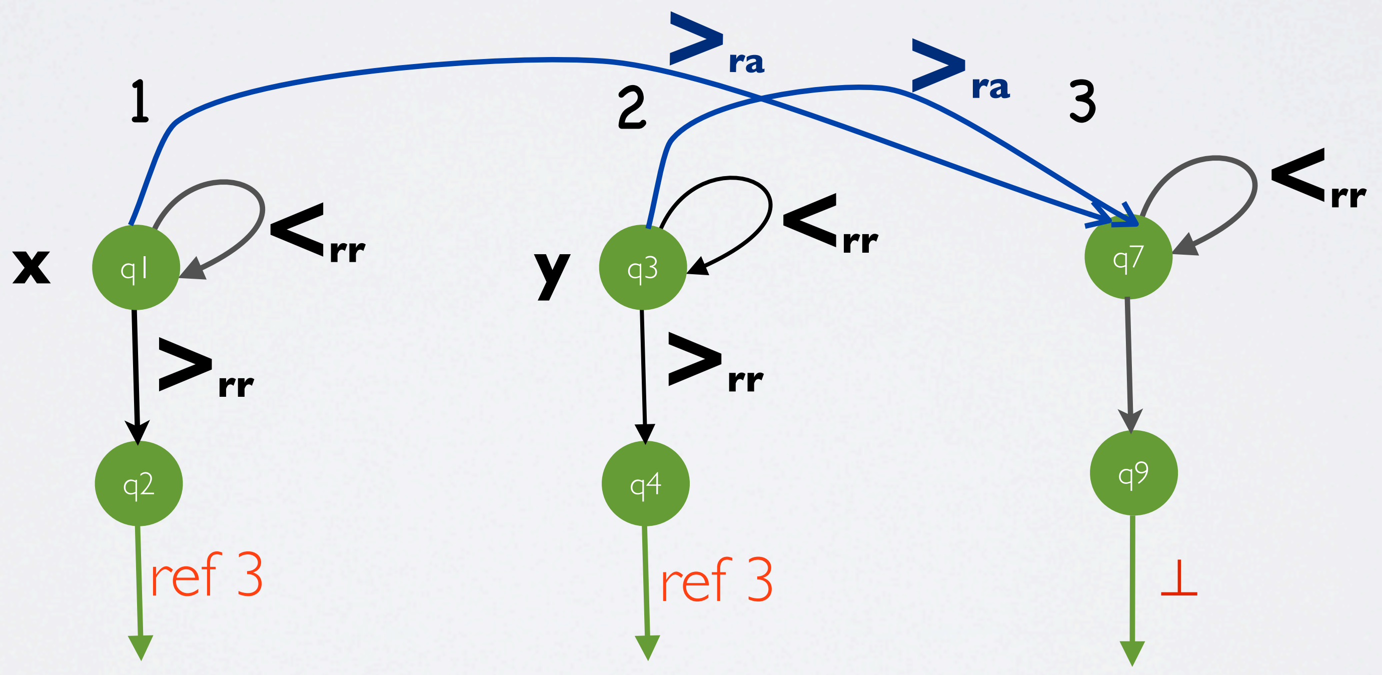


Data value of root node of any tree accepted at q1 is bigger than than data values of all nodes of any tree accepted at q7

1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

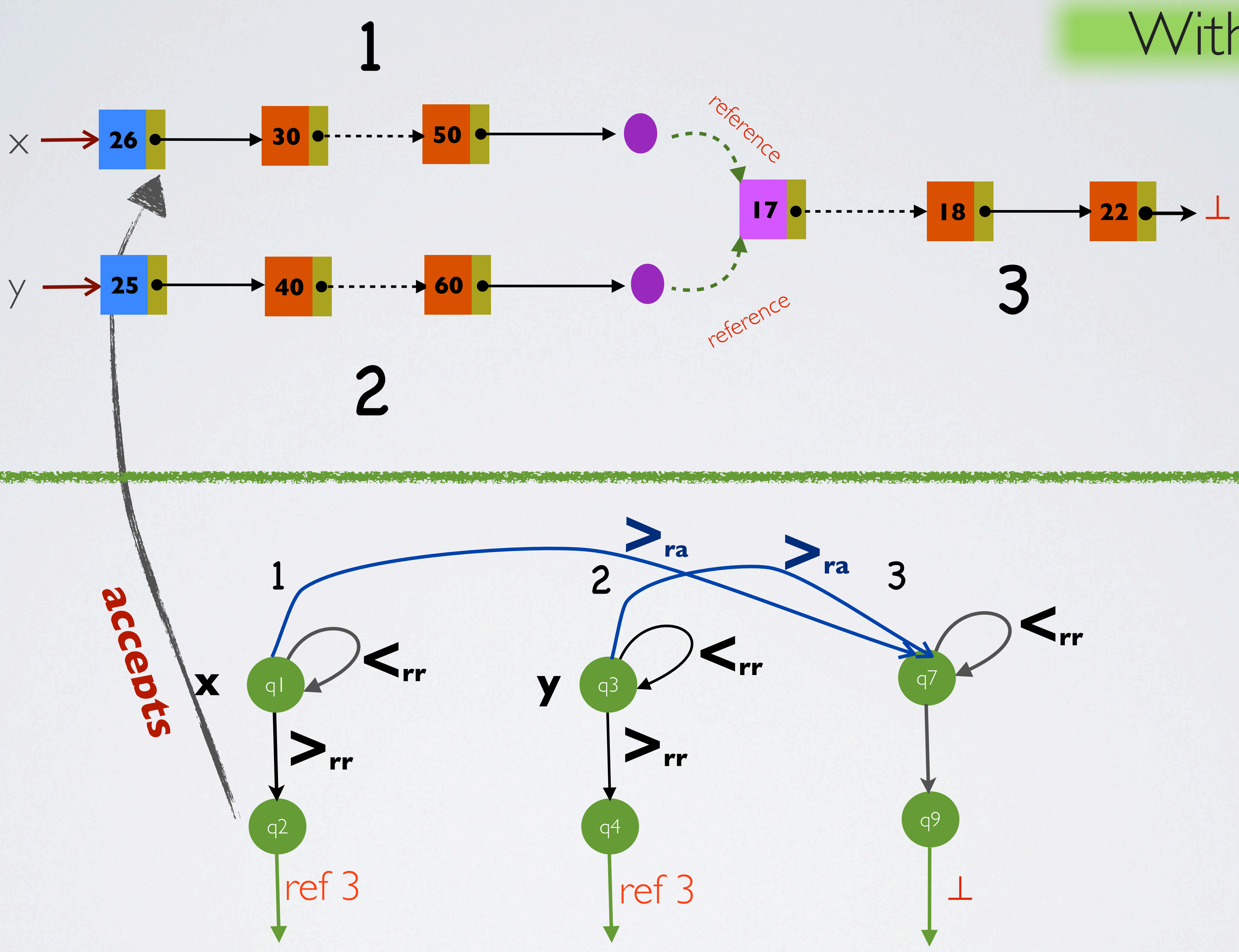
With data





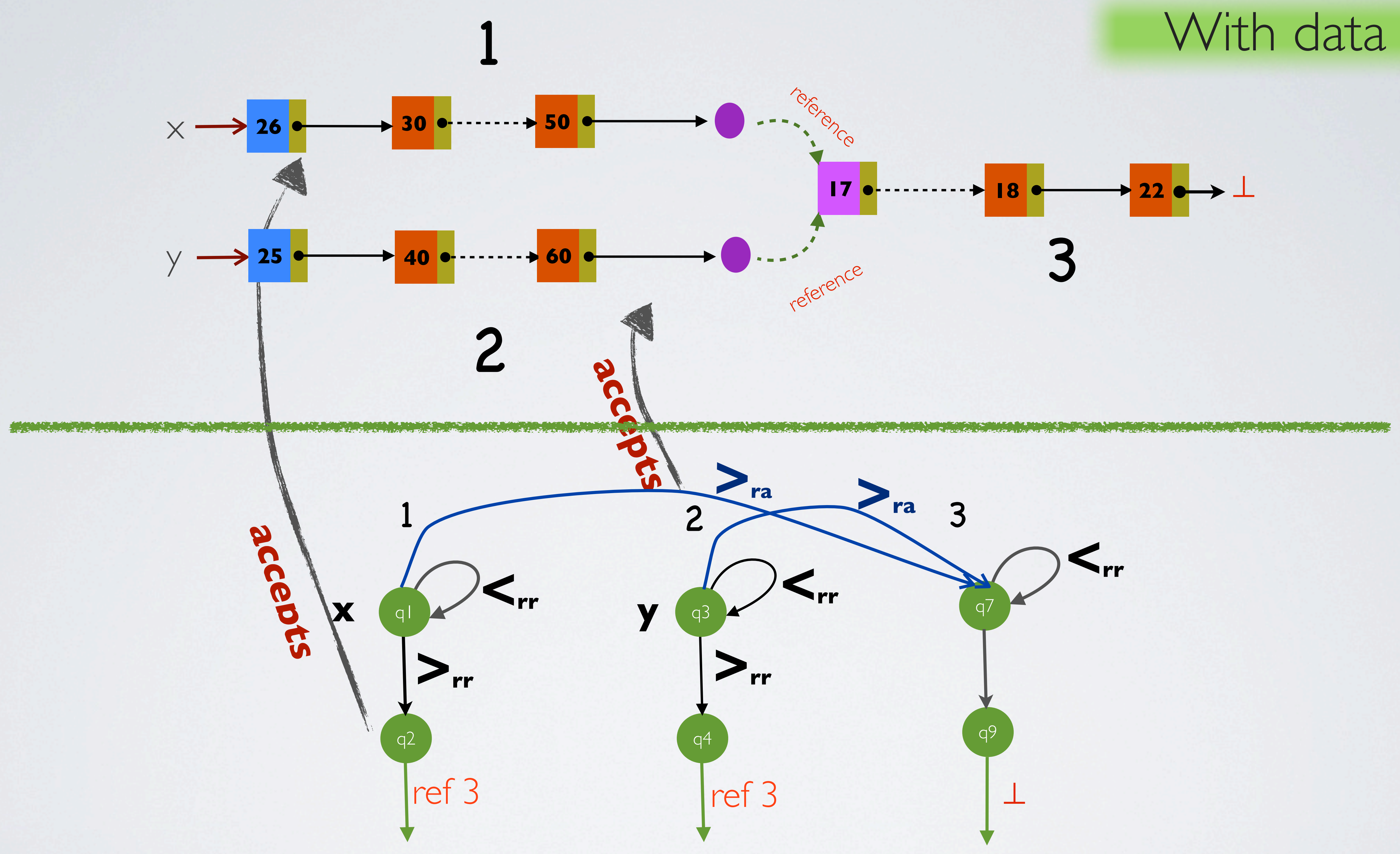
1. Heap representation 2. Decompose heaps into forests 3. Represent forests by forest automata

With data



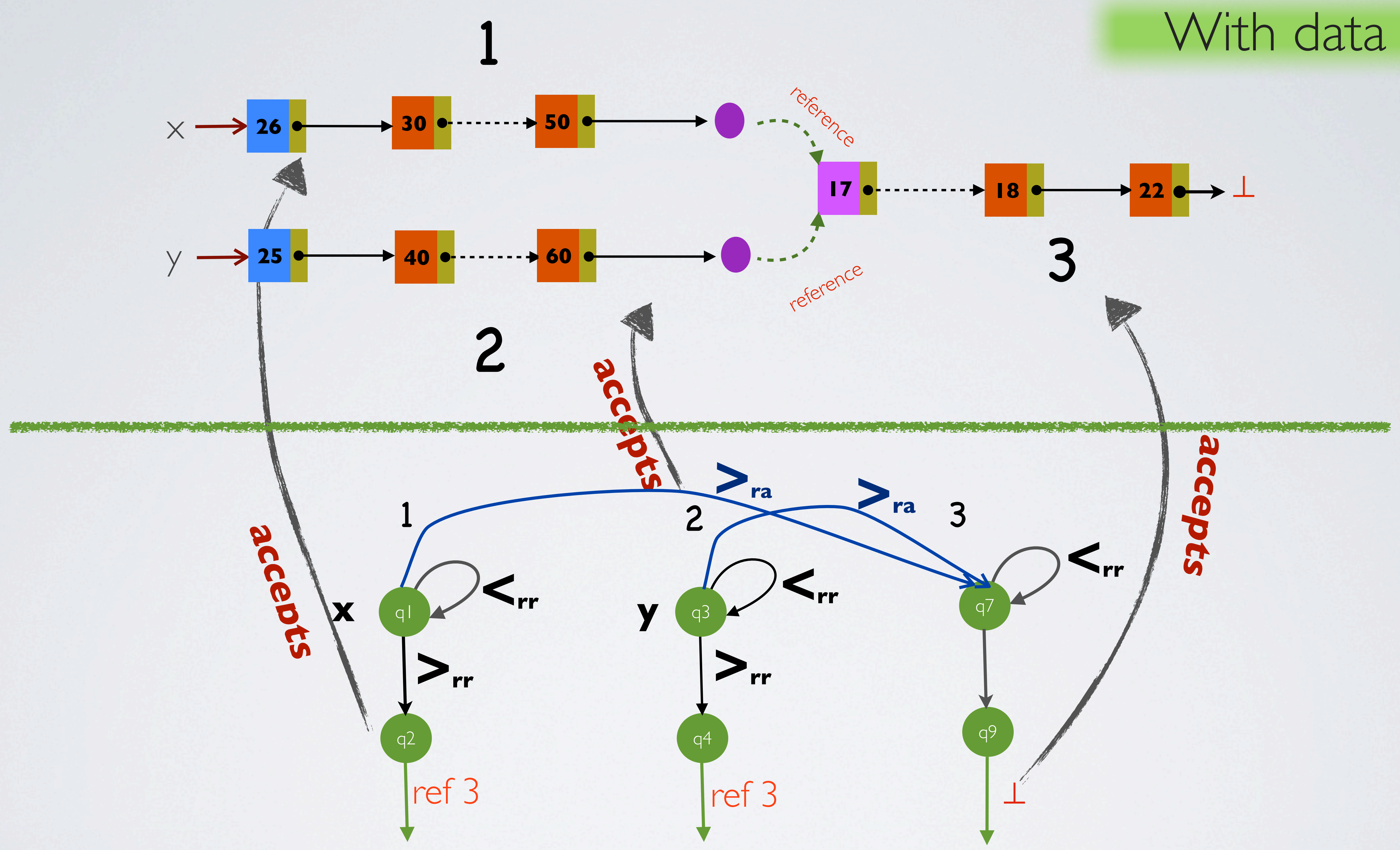
1. Heap representation   2. Decompose heaps into forests   3. Represent forests by forest automata

With data

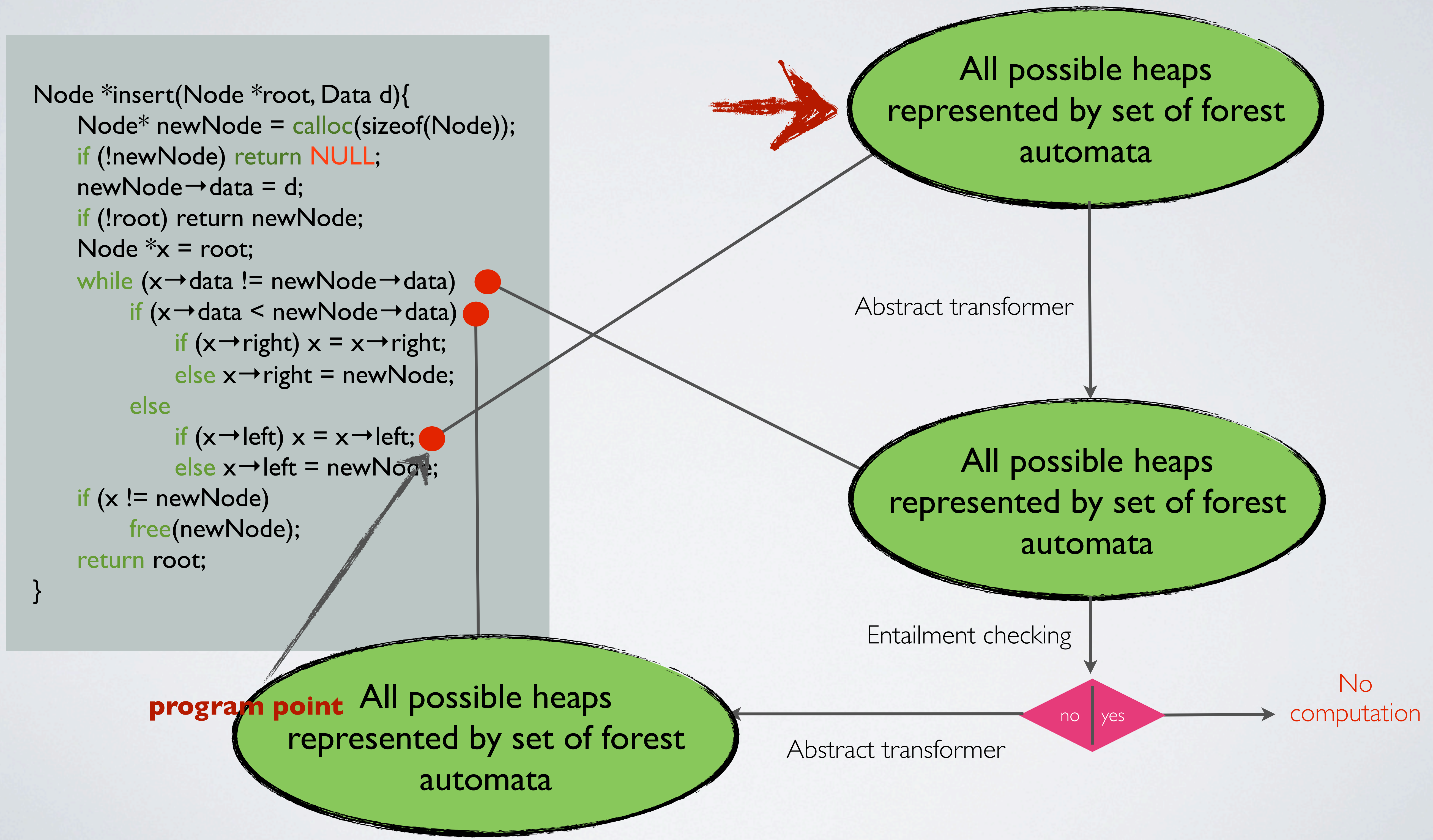


1. Heap representation   2. Decompose heaps into forests   3. Represent forests by forest automata

With data



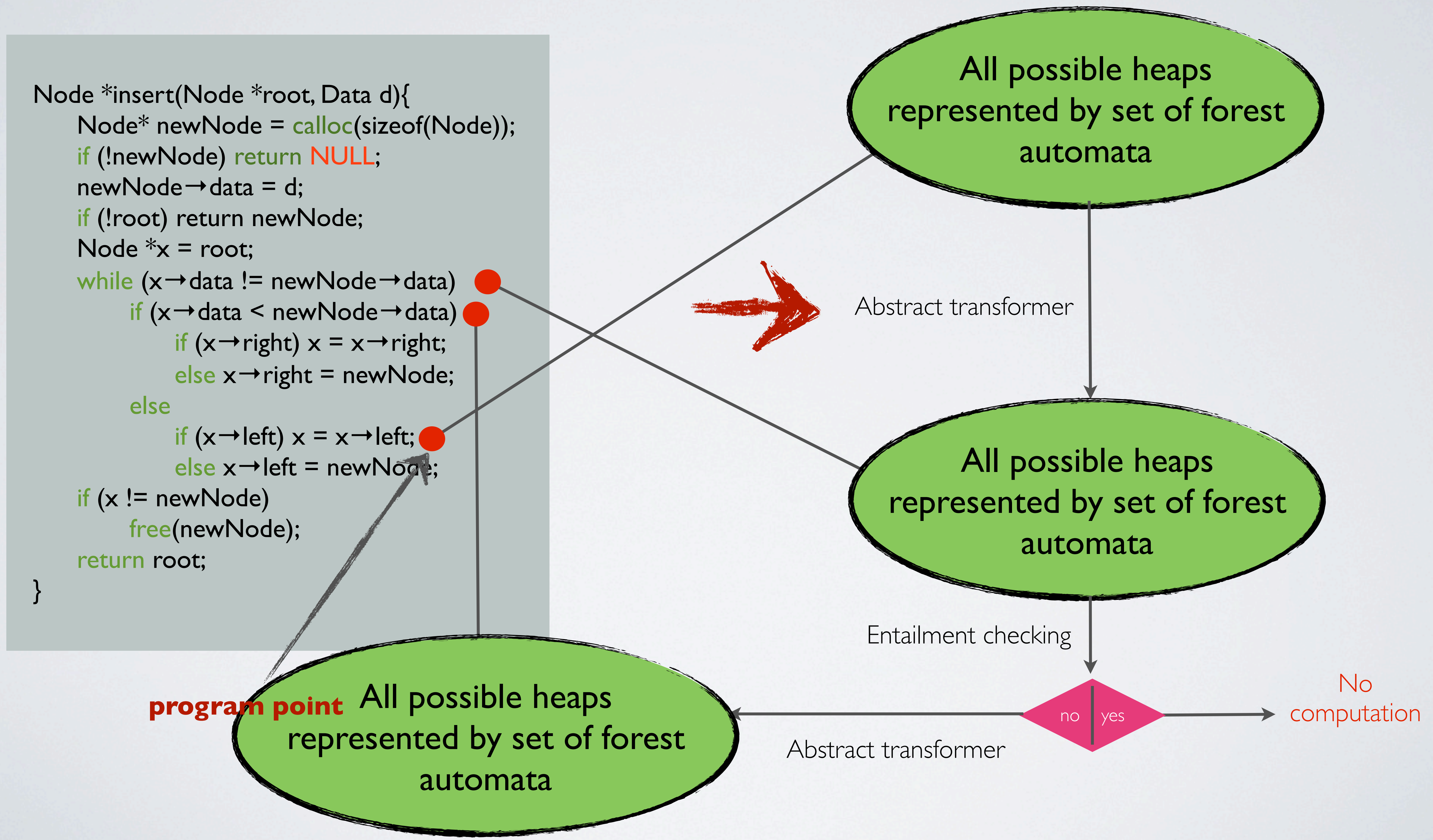
Program analysis



```
Node *insert(Node *root, Data d){
    Node* newNode = calloc(sizeof(Node));
    if (!newNode) return NULL;
    newNode→data = d;
    if (!root) return newNode;
    Node *x = root;
    while (x→data != newNode→data)
        if (x→data < newNode→data)
            if (x→right) x = x→right;
            else x→right = newNode;
        else
            if (x→left) x = x→left;
            else x→left = newNode;
    if (x != newNode)
        free(newNode);
    return root;
}
```

All possible heaps represented by set of forest automata
Abstract transformer
All possible heaps represented by set of forest automata
Entailment checking
no
yes
No computation
Abstract transformer
program point
All possible heaps represented by set of forest automata

Program analysis



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Node *insert(Node *root, Data d){
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    if (!newNode) return NULL;
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    while (x→data != newNode→data)
        if (x→data < newNode→data)
            if (x→right) x = x→right;
            else x→right = newNode;
        else
            if (x→left) x = x→left;
            else x→left = newNode;
    if (x != newNode)
        free(newNode);
    return root;
}
```

All possible heaps represented by set of forest automata
Abstract transformer
All possible heaps represented by set of forest automata
Entailment checking
no
yes
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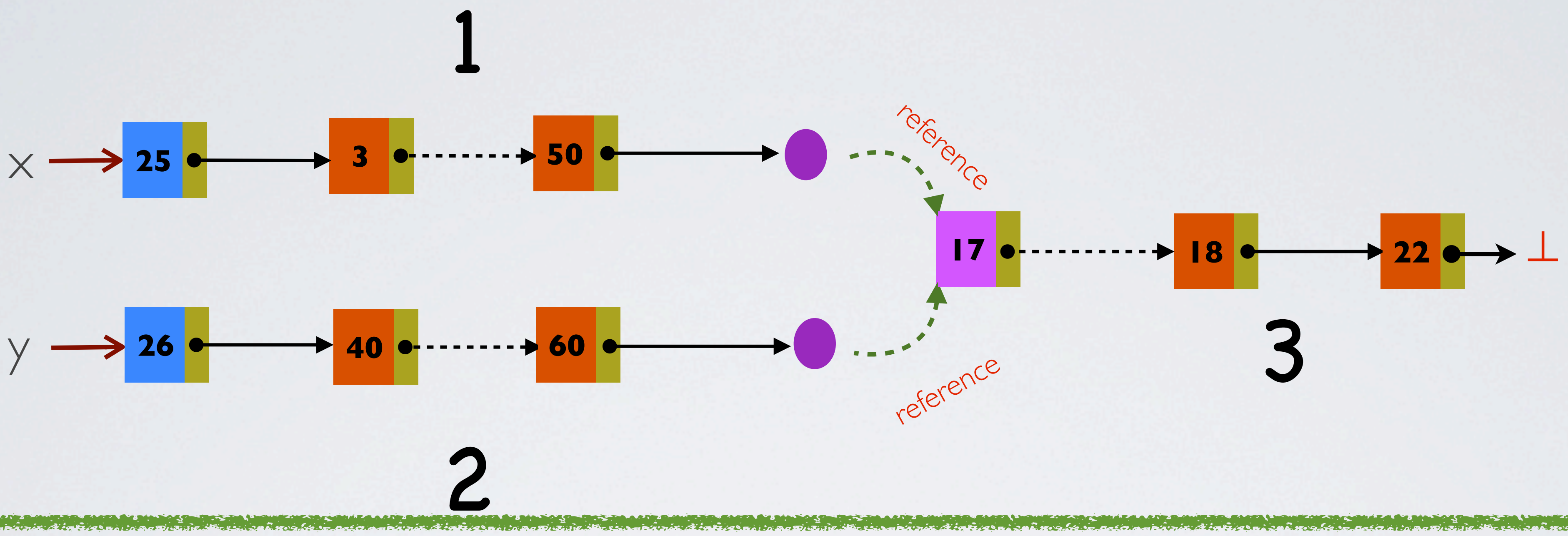
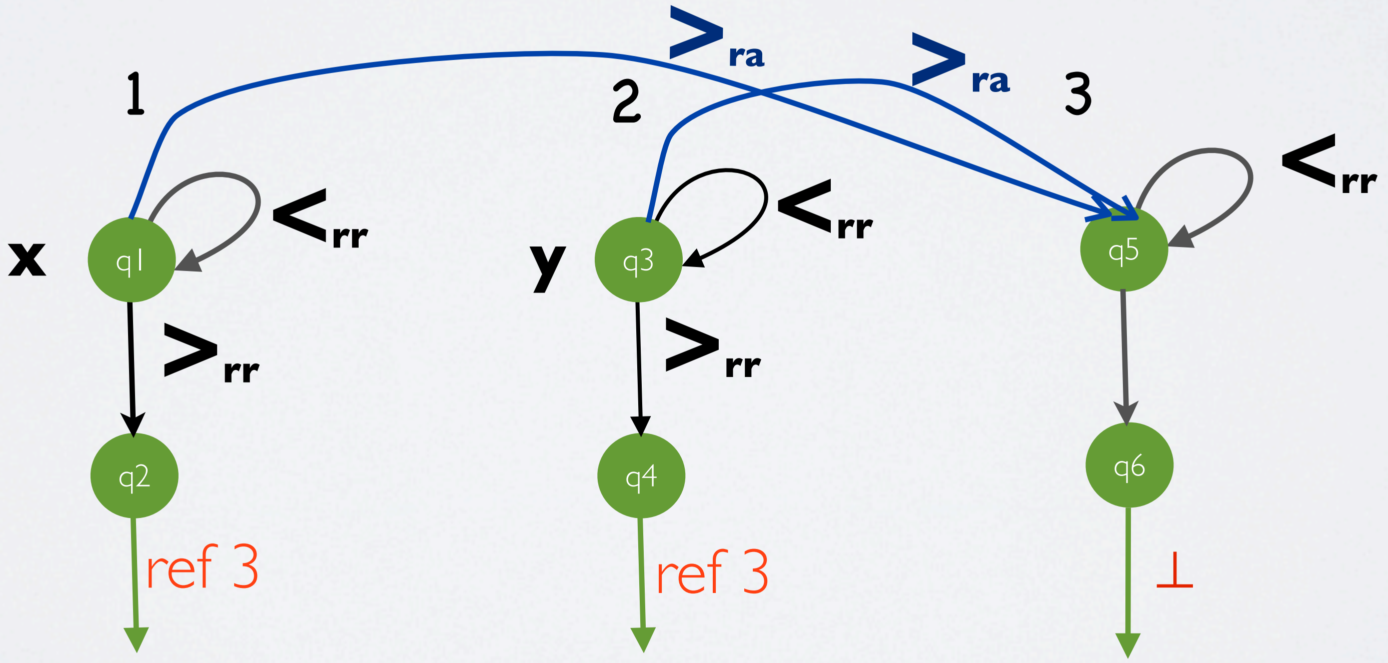
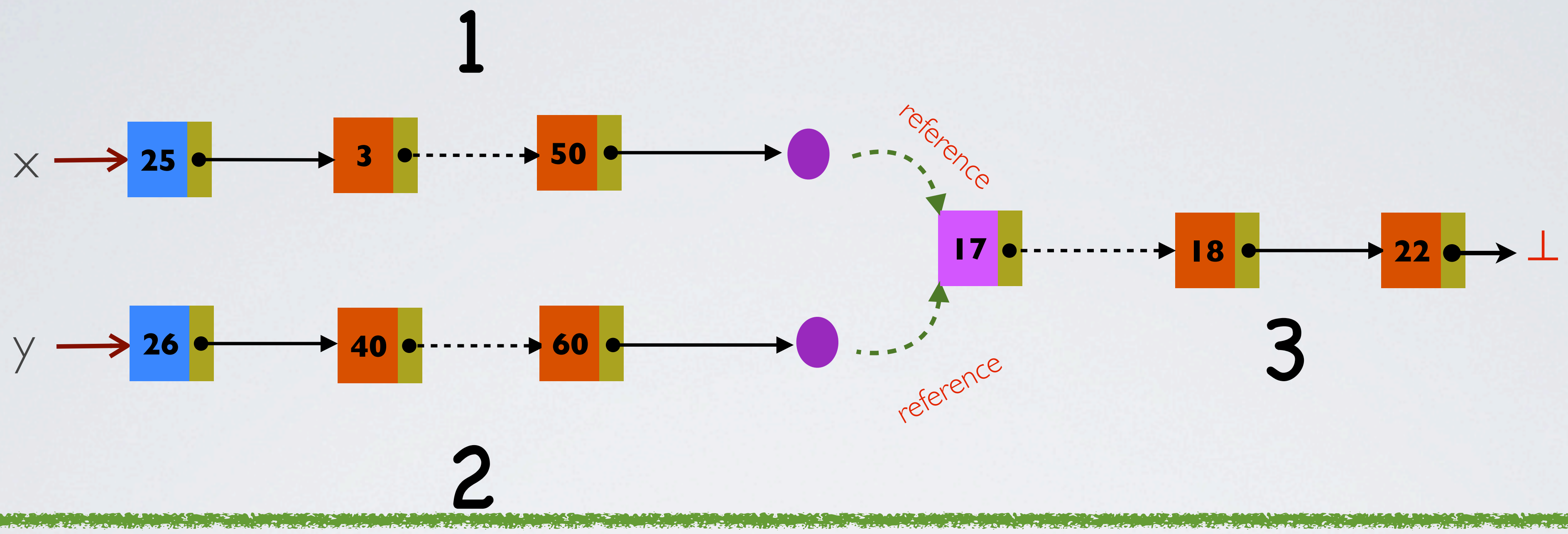
All possible heaps represented by set of forest automata

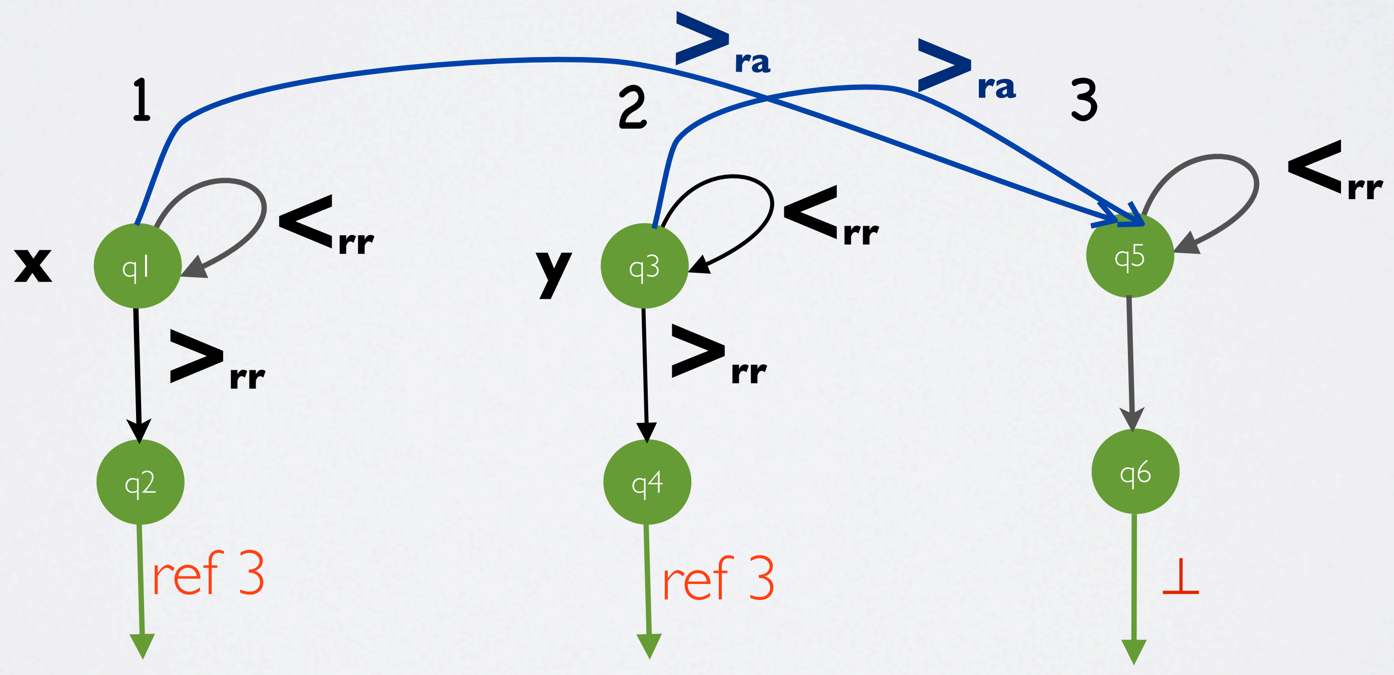
Abstract transformers


1
x
25
3
50
reference
17
18
22
⊥
3
y
26
40
60
reference
2

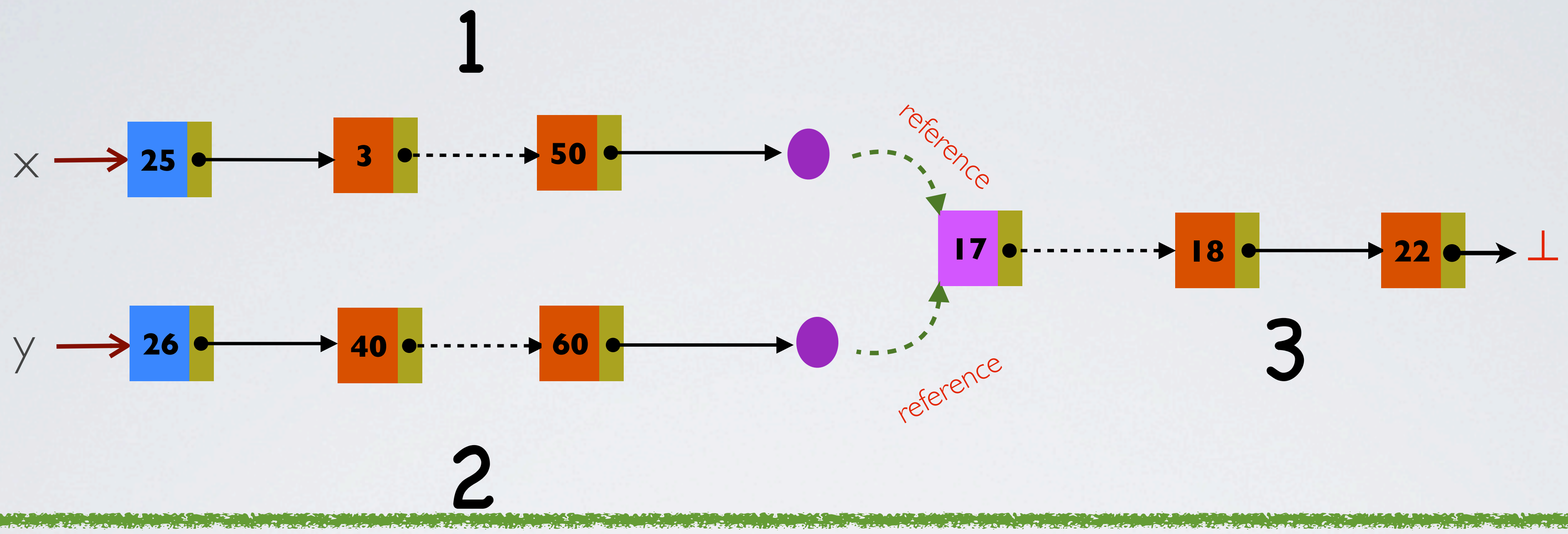

>ra
>ra
1
2
3
<rr
<rr
<rr
x
q1
y
q3
q5
>rr
>rr
q2
q4
q6
ref 3
ref 3
⊥

Effect of **z = x.next** on a concrete forest

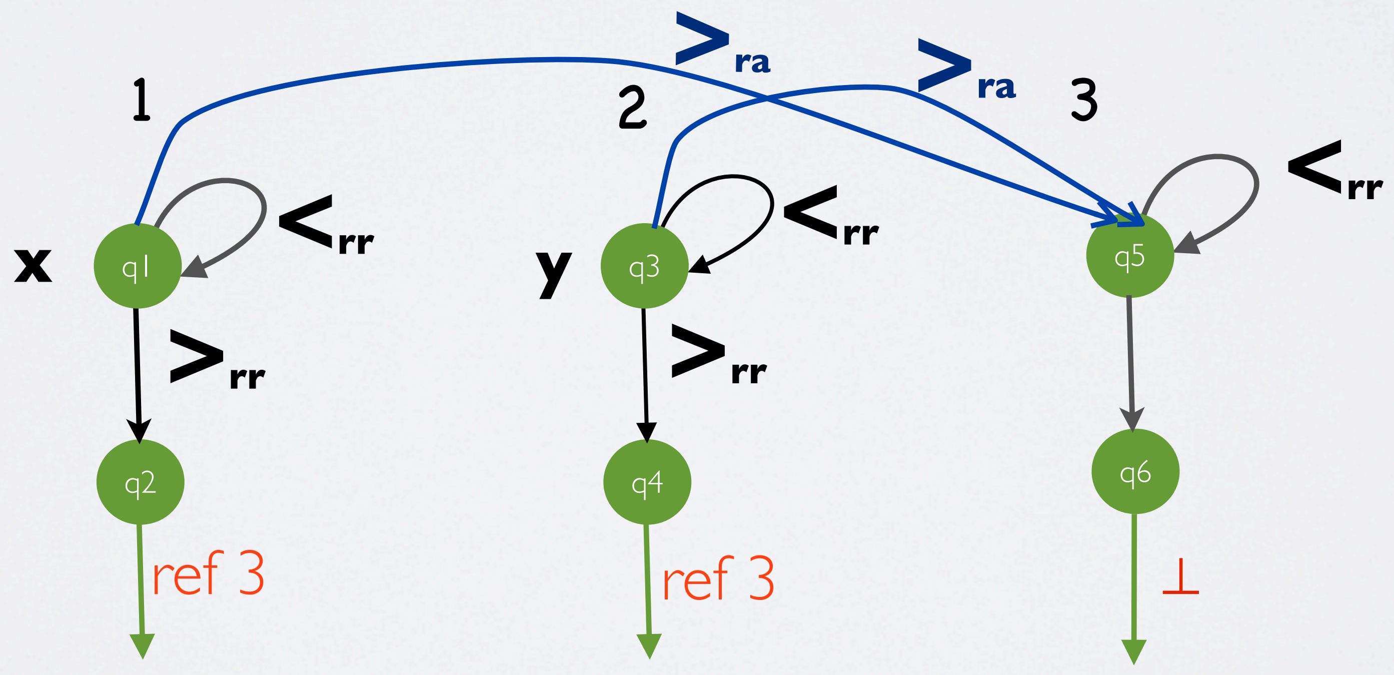




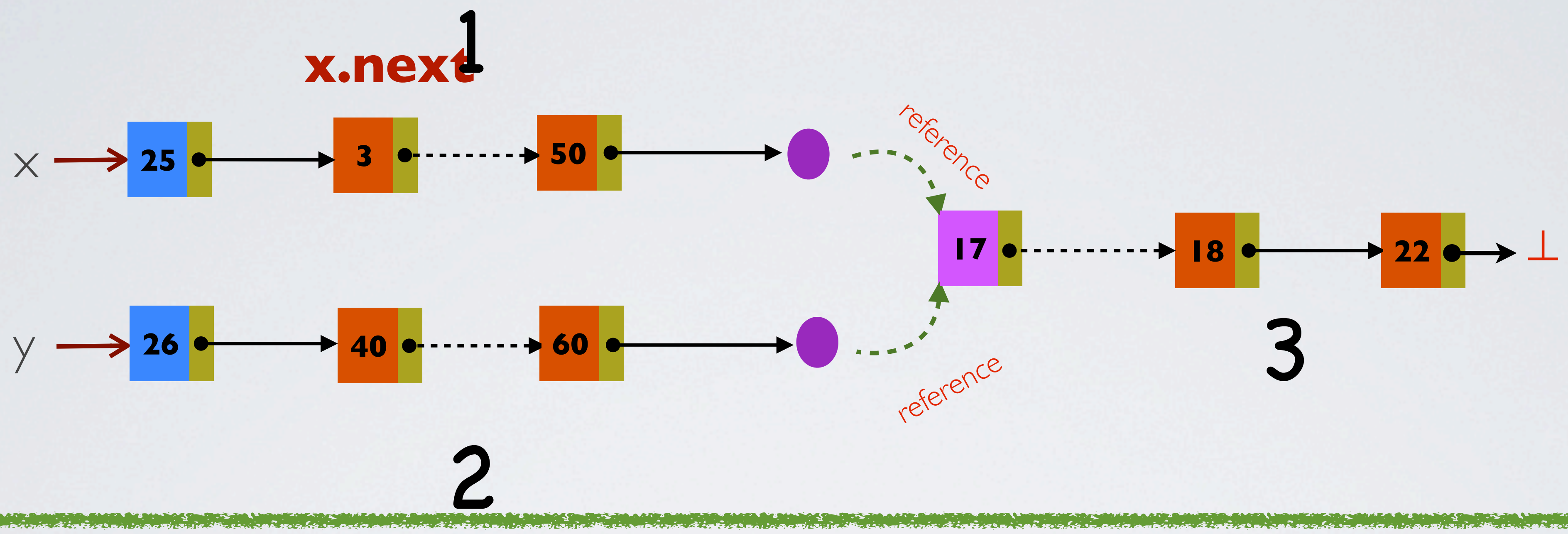
Effect of **z = x.next** on a concrete forest



✓ Access to **x.next**
✓ Split the tree 1 at this node



Effect of **z = x.next** on a concrete forest



- ✓ Access to **x.next**
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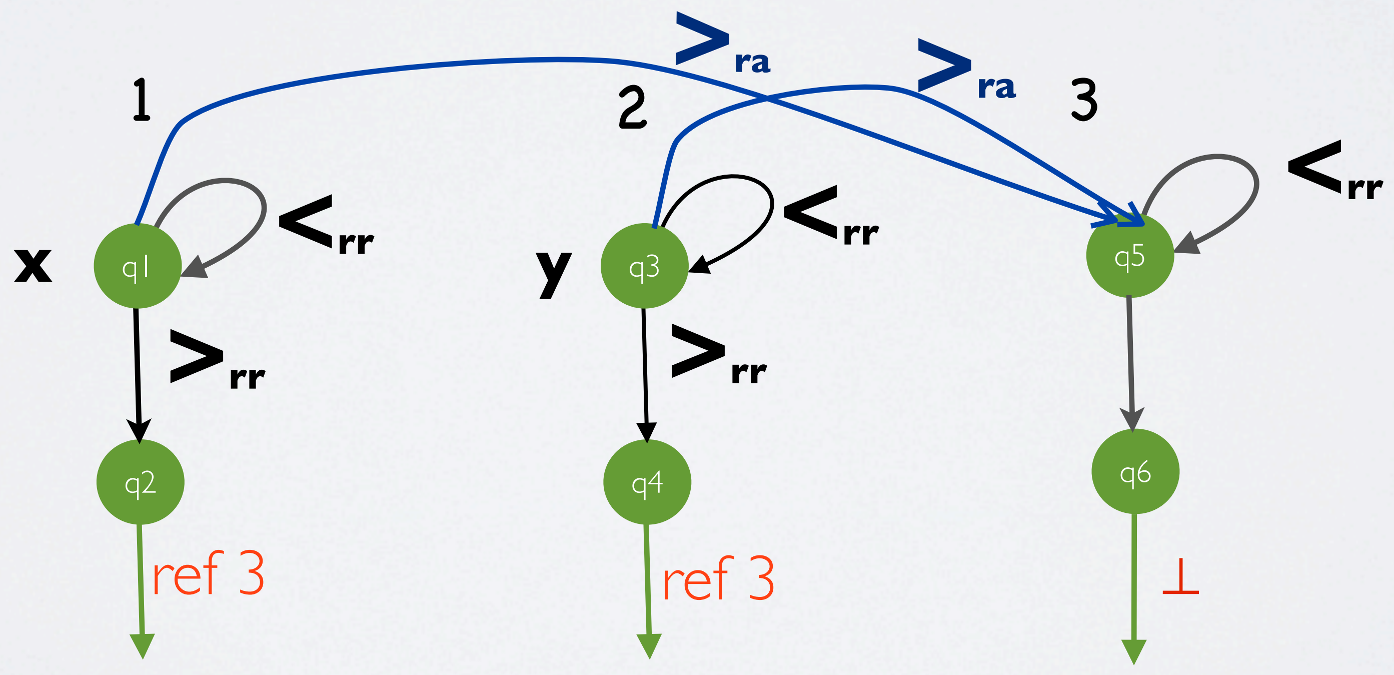

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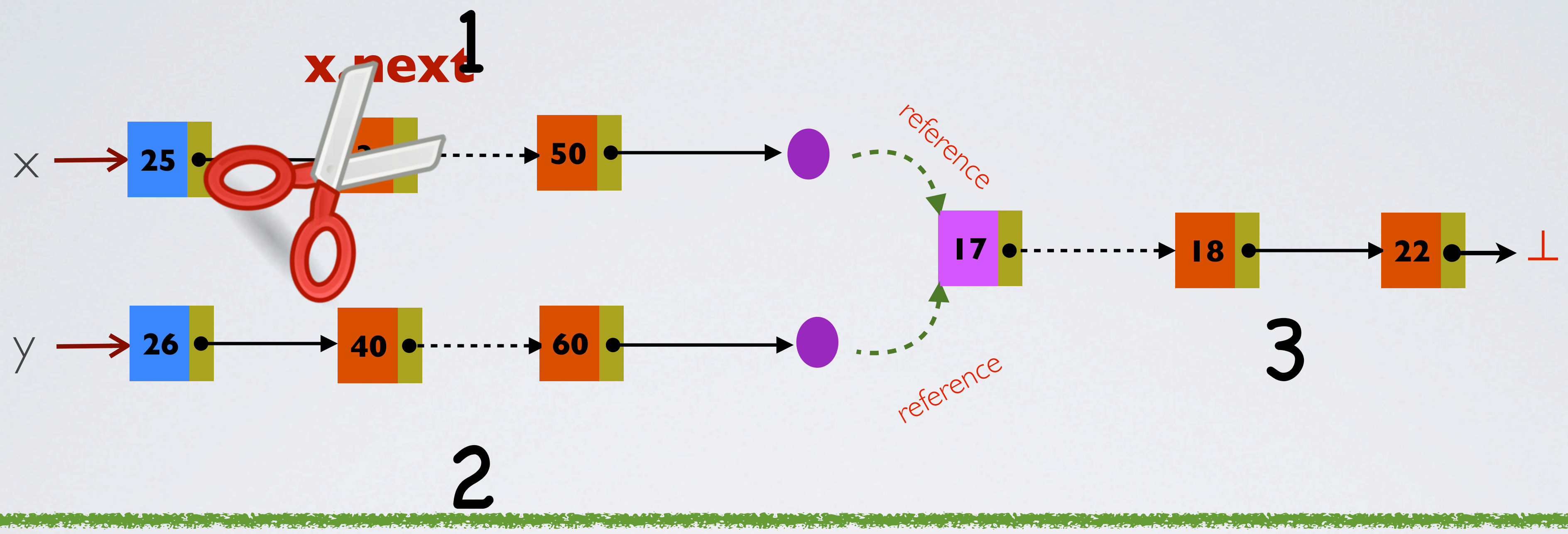

- ✓ Access to **x.next**
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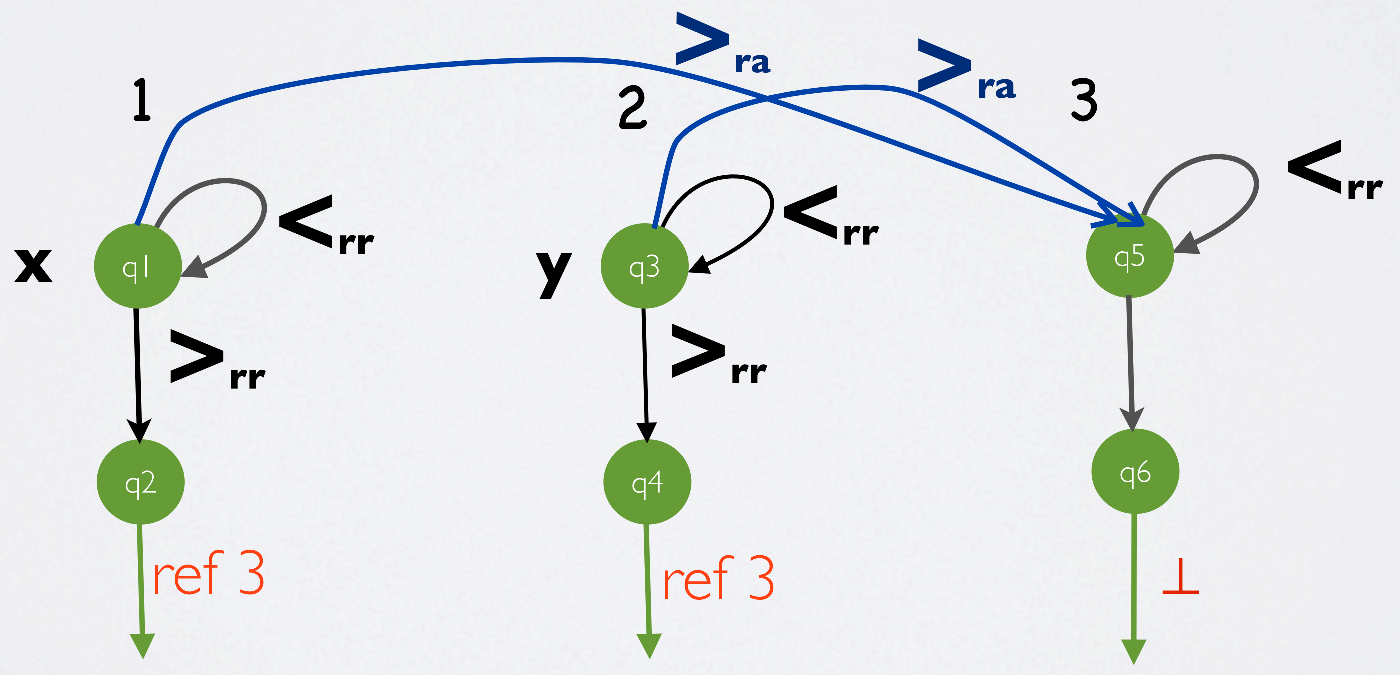
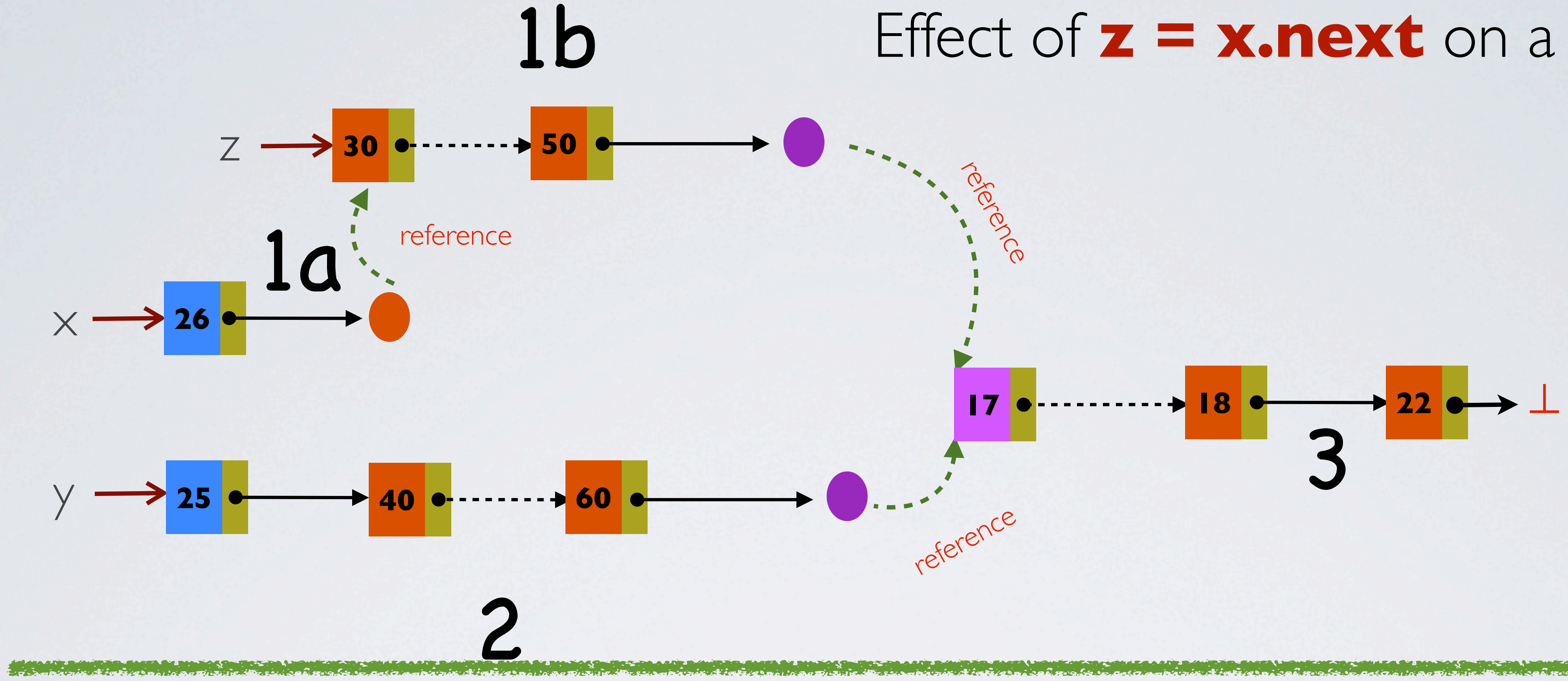
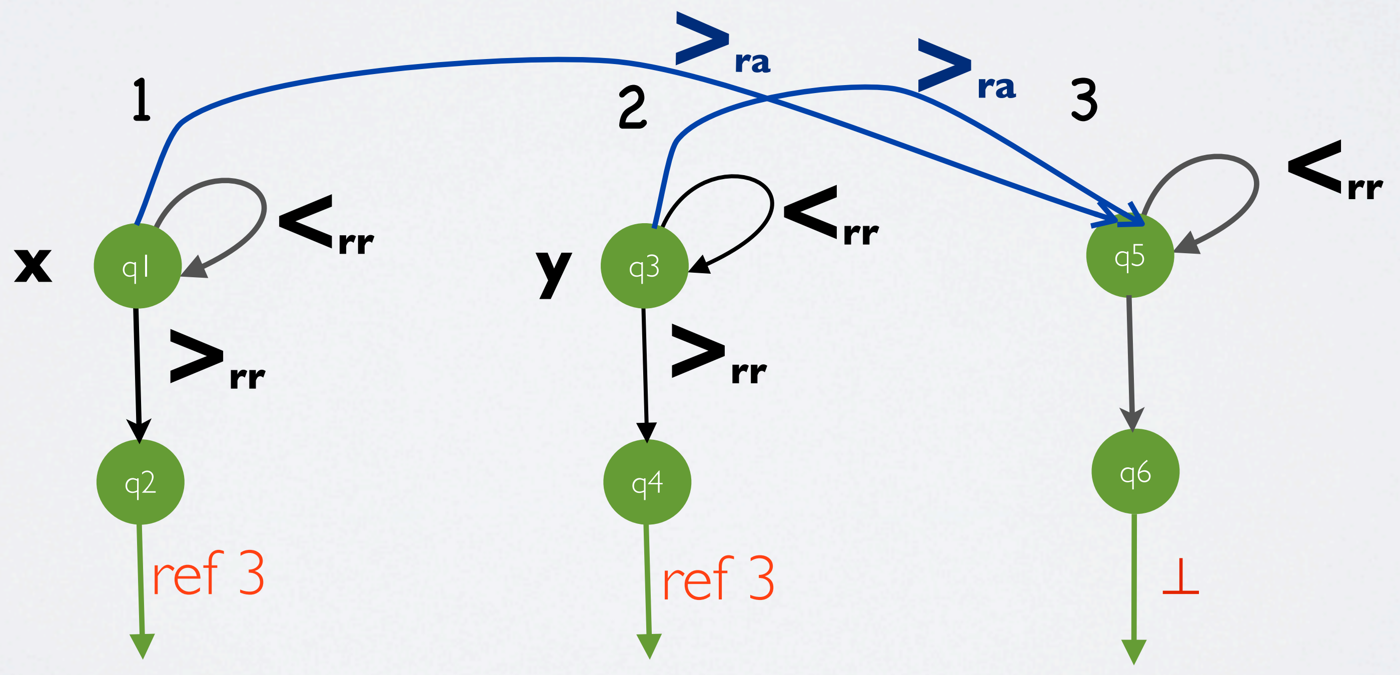


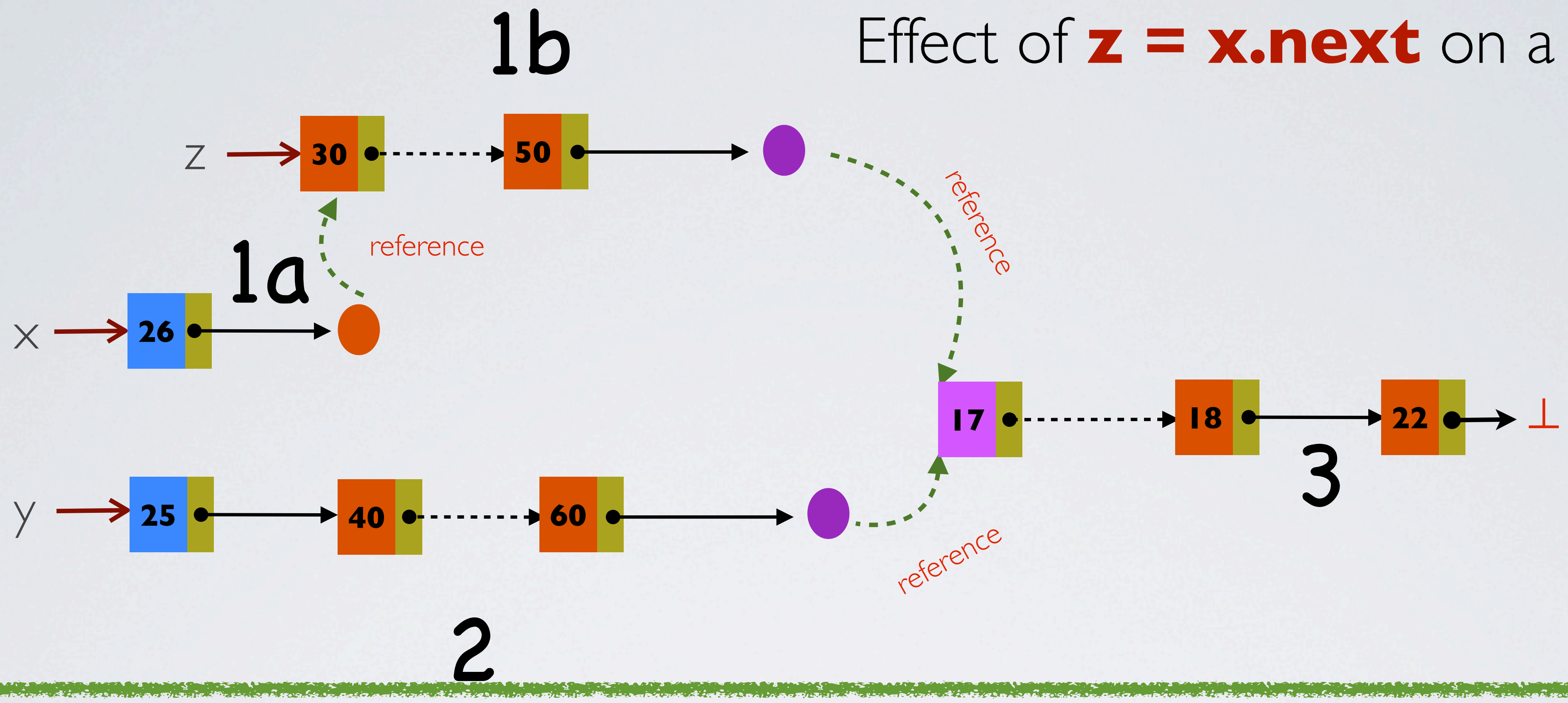
Effect of **z = x.next** on a concrete forest



- ✓ Access to **x.next**
- ✓ Split the tree 1 at this node

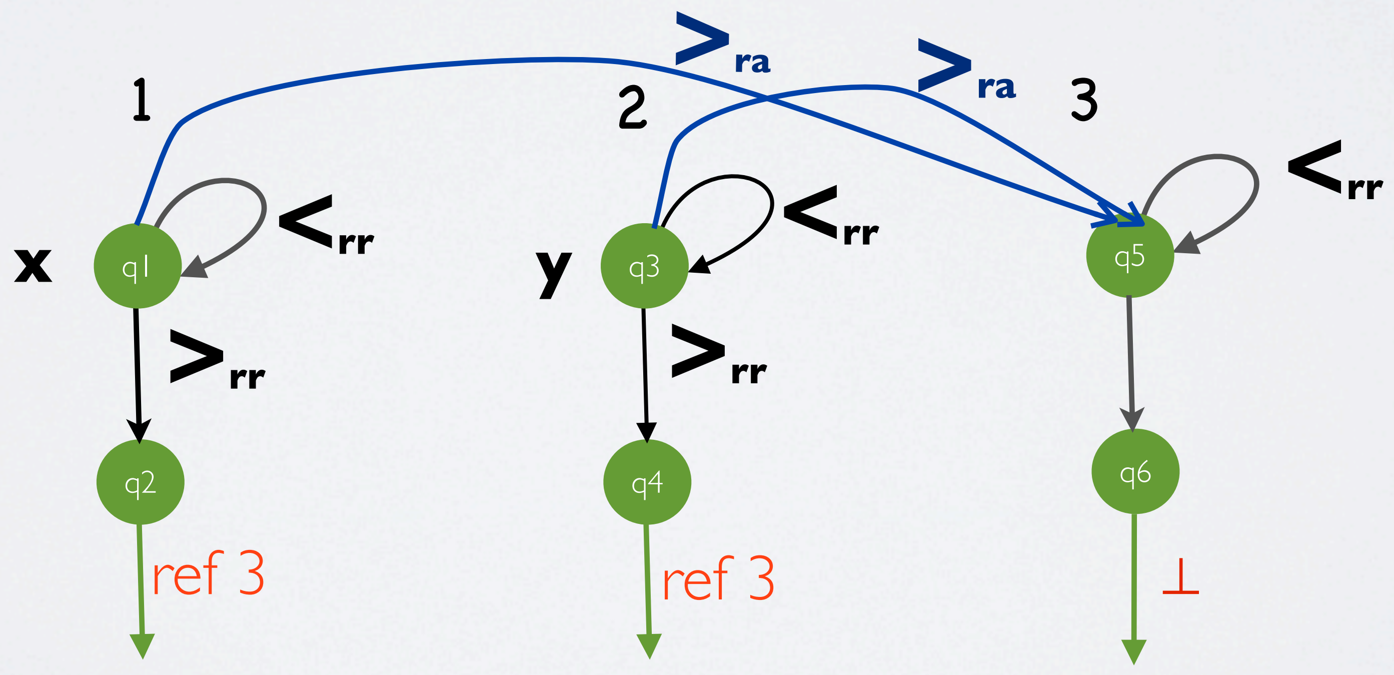


Effect of **z = x.next** on a concrete forest

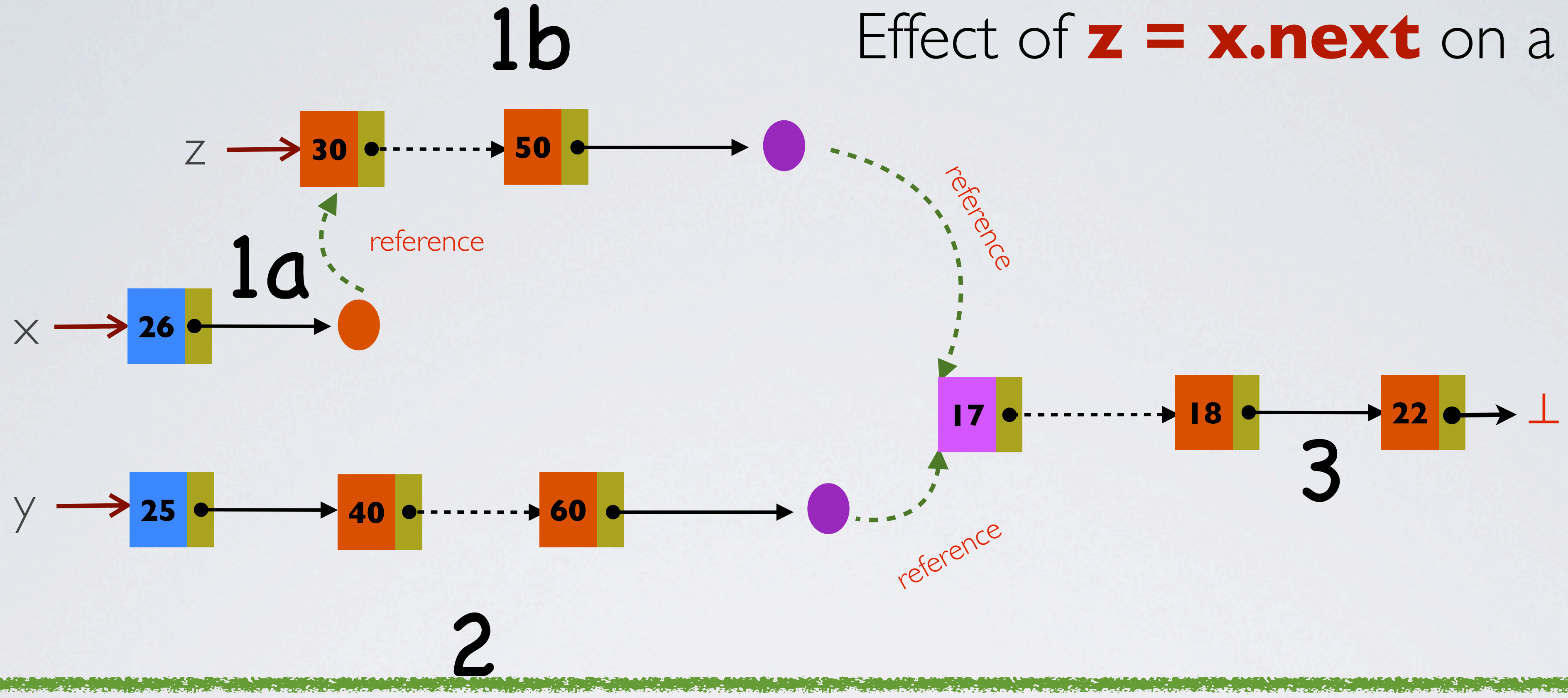


✓ Access to **x.next**
✓ Split the tree 1 at this node

Effect of **z = x.next** on forest automata

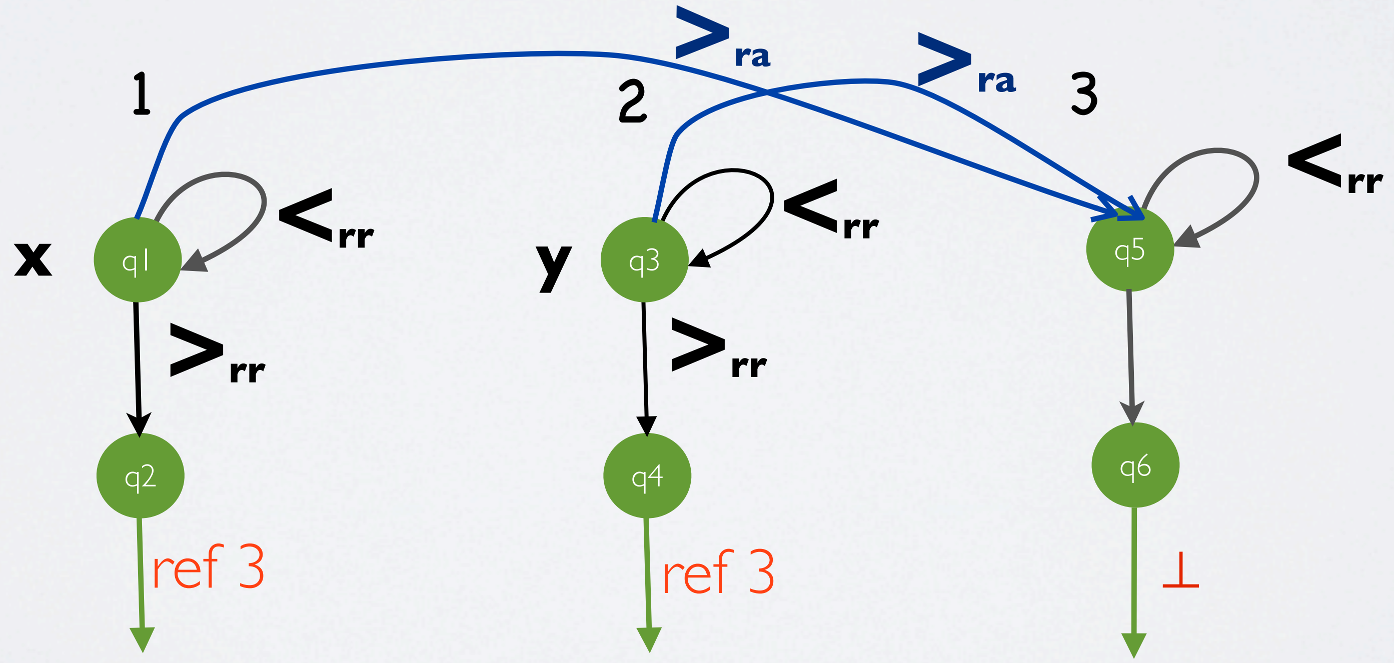


Effect of **z = x.next** on a concrete forest



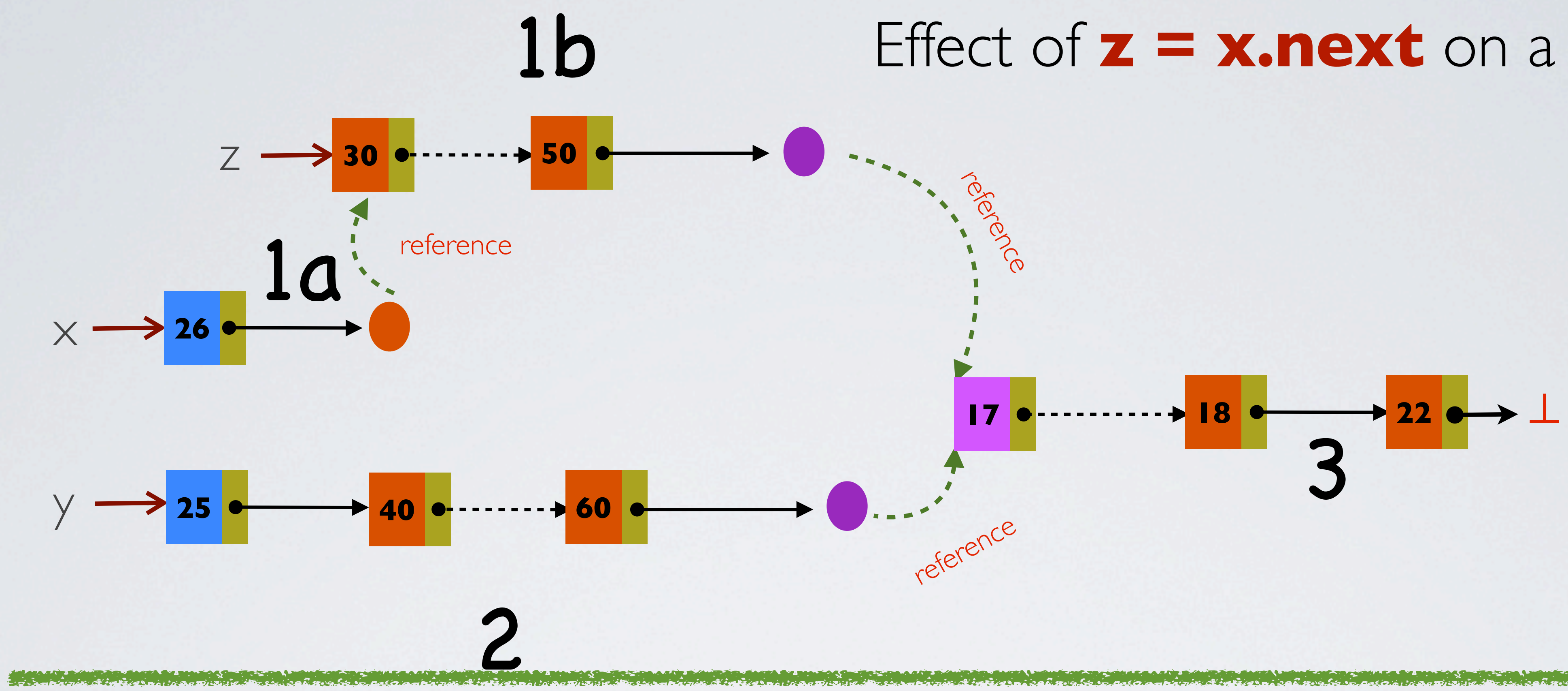
✓ Access to **x.next**
✓ Split the tree 1 at this node

Effect of **z = x.next** on forest automata



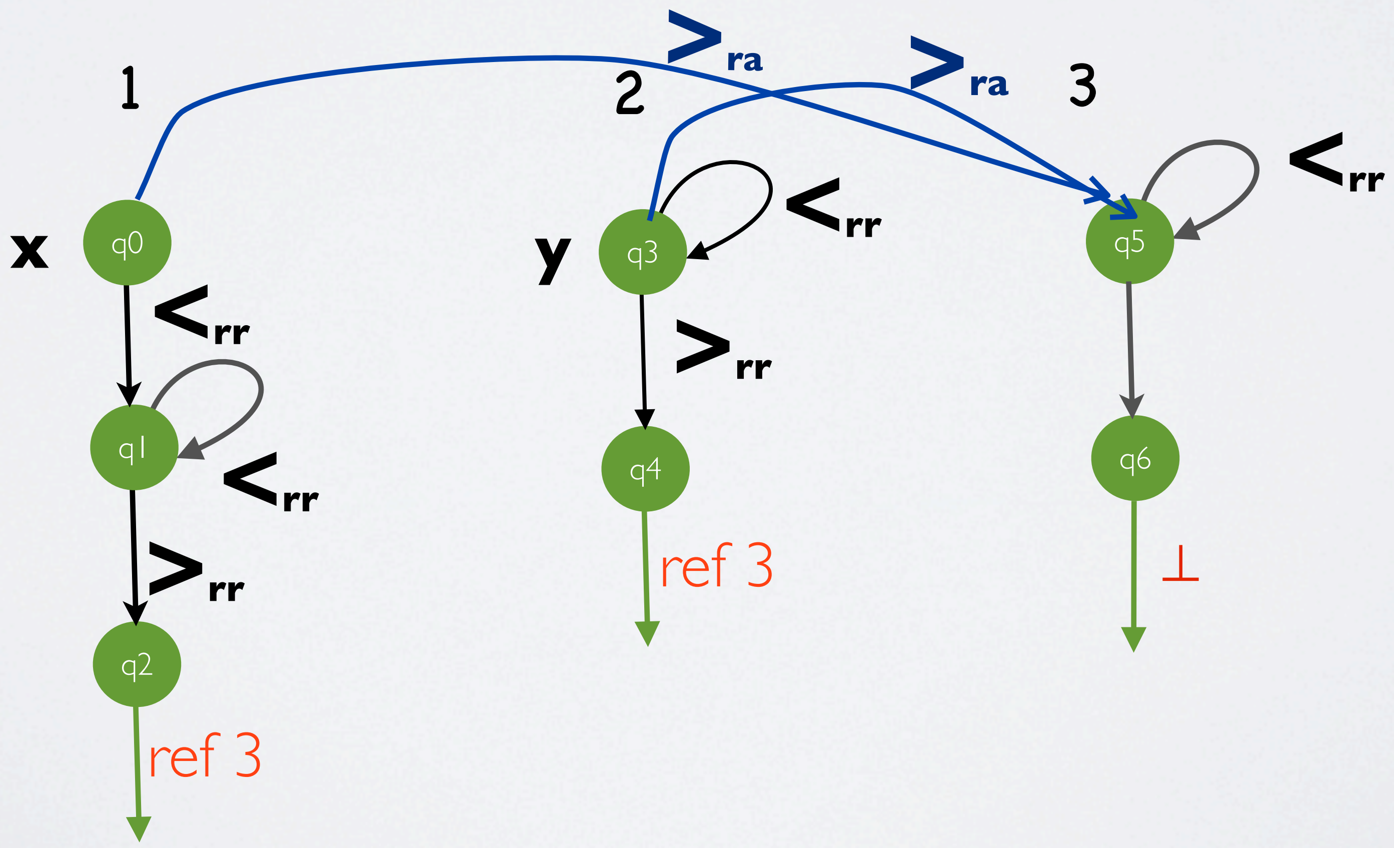
✓ Access to **x.next** by expanding cycle at **q1**
✓ Split the TA1 at the accessed state

Effect of **z = x.next** on a concrete forest



- ✓ Access to **x.next**
- ✓ Split the tree 1 at this node

Effect of **z = x.next** on forest automata



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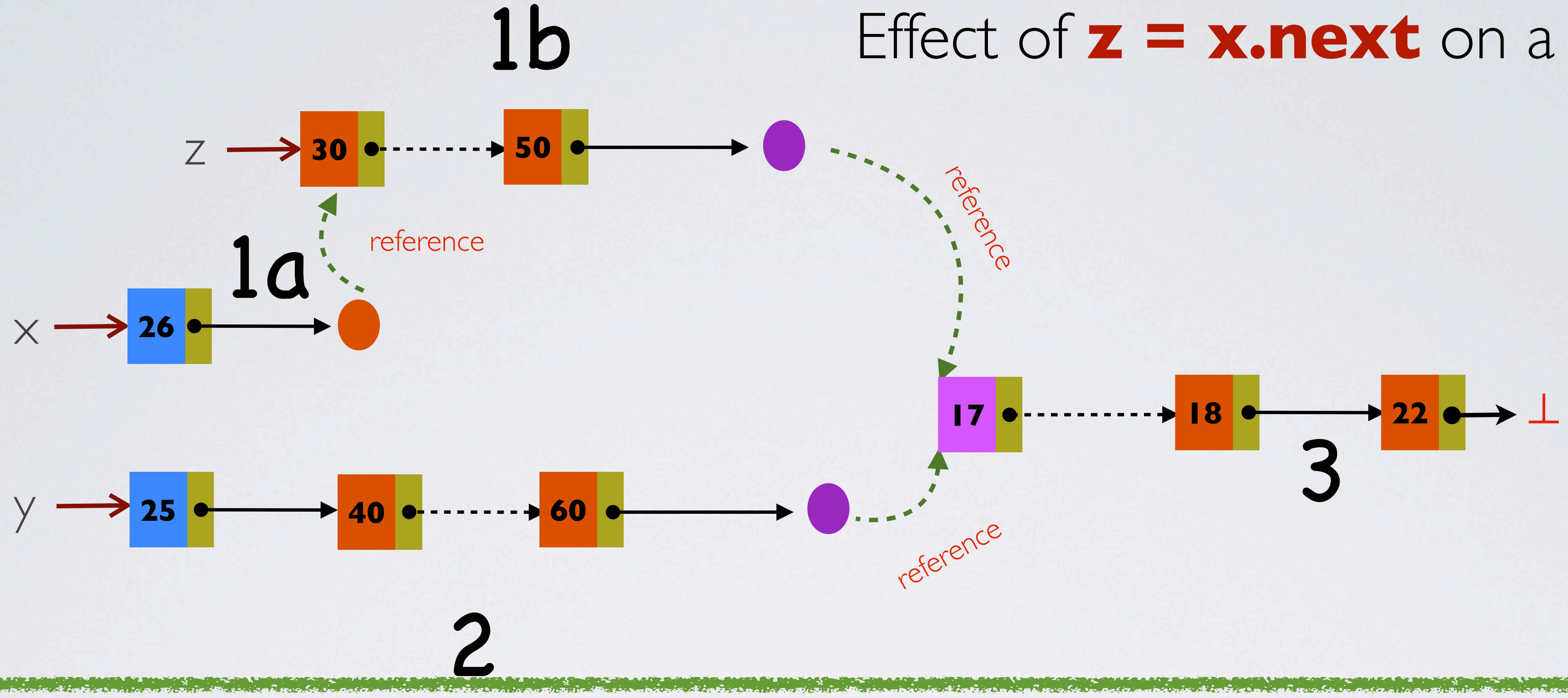
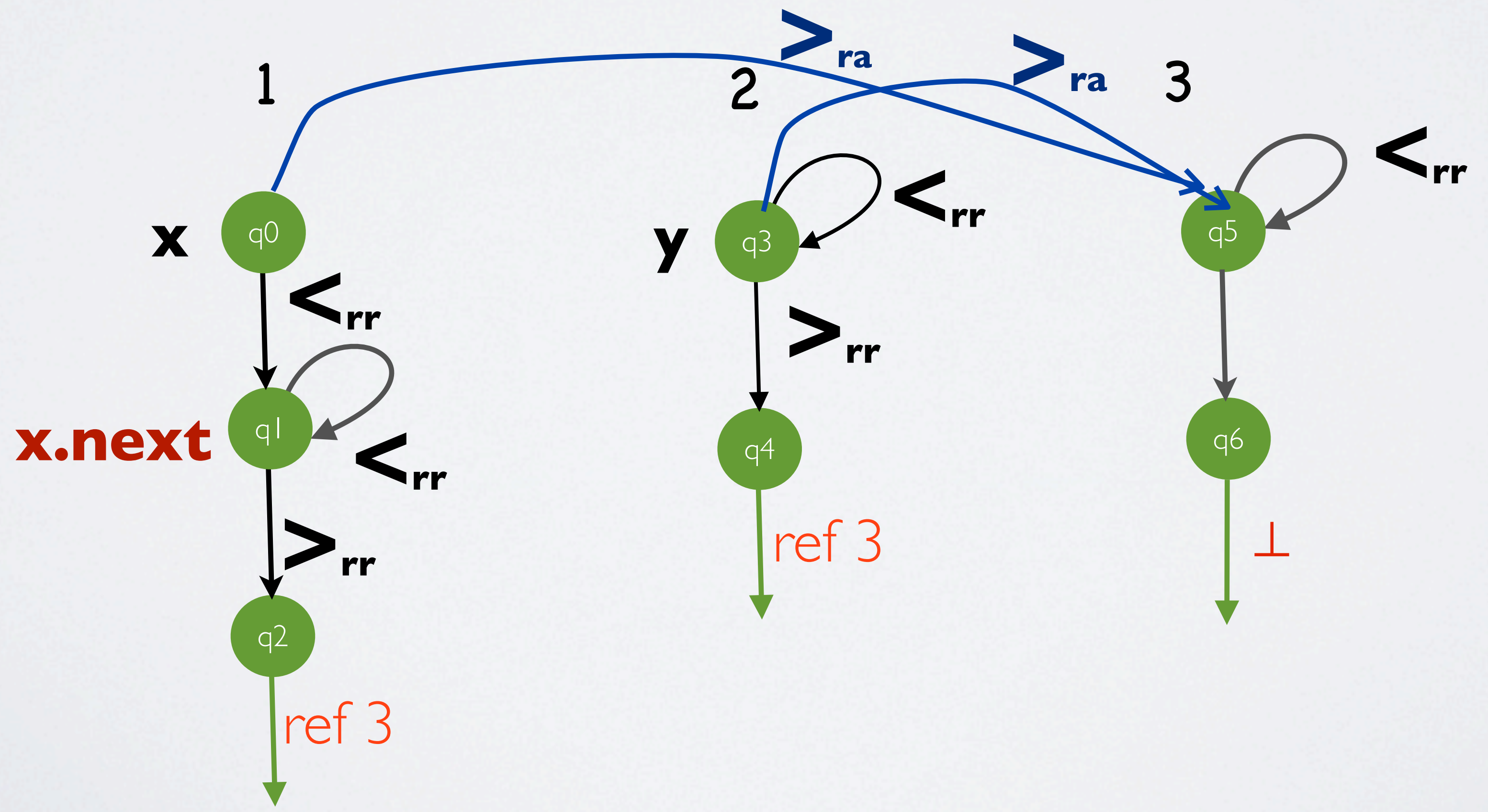
Effect of **z = x.next** on a concrete forest



- ✓ Access to **x.next**
- ✓ Split the tree 1 at this node

Effect of **z = x.next** on forest automata



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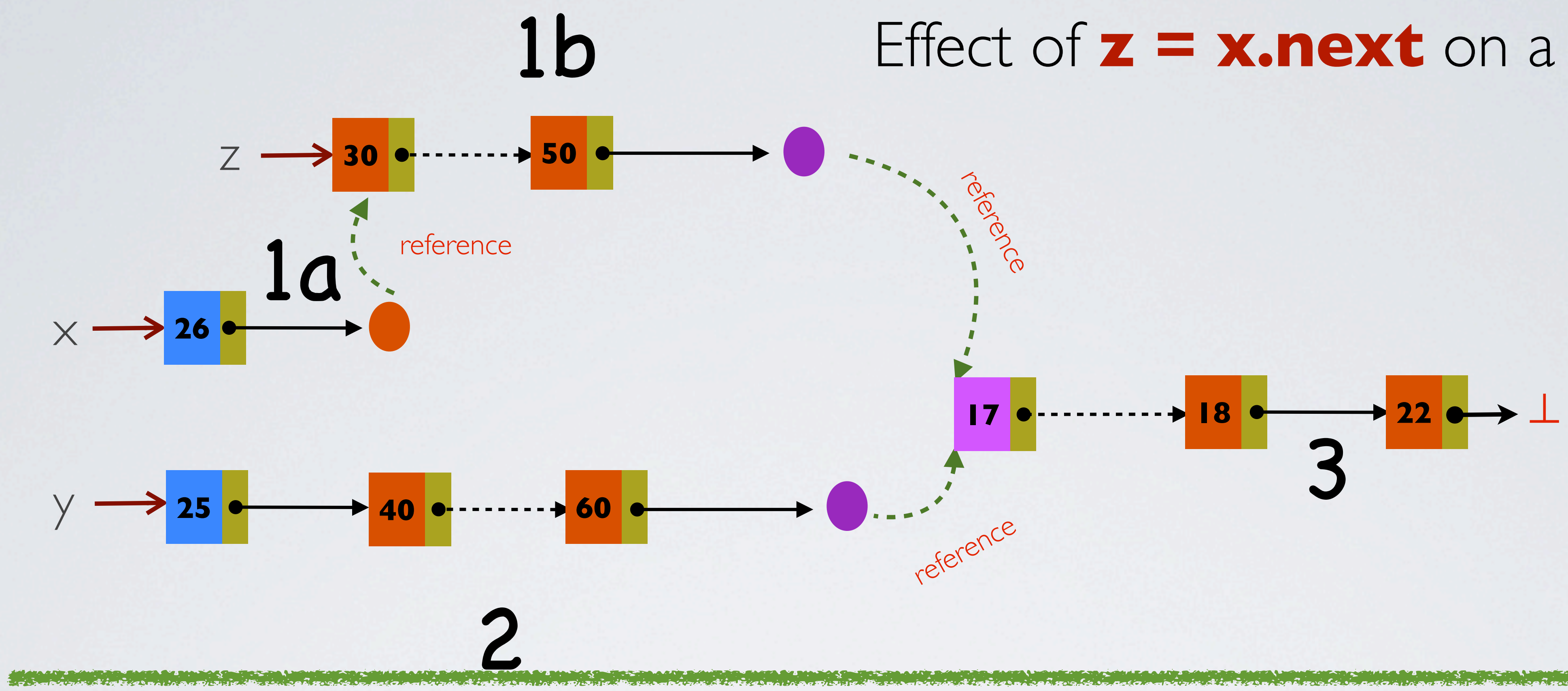
Effect of **z = x.next** on a concrete forest



- ✓ Access to **x.next**
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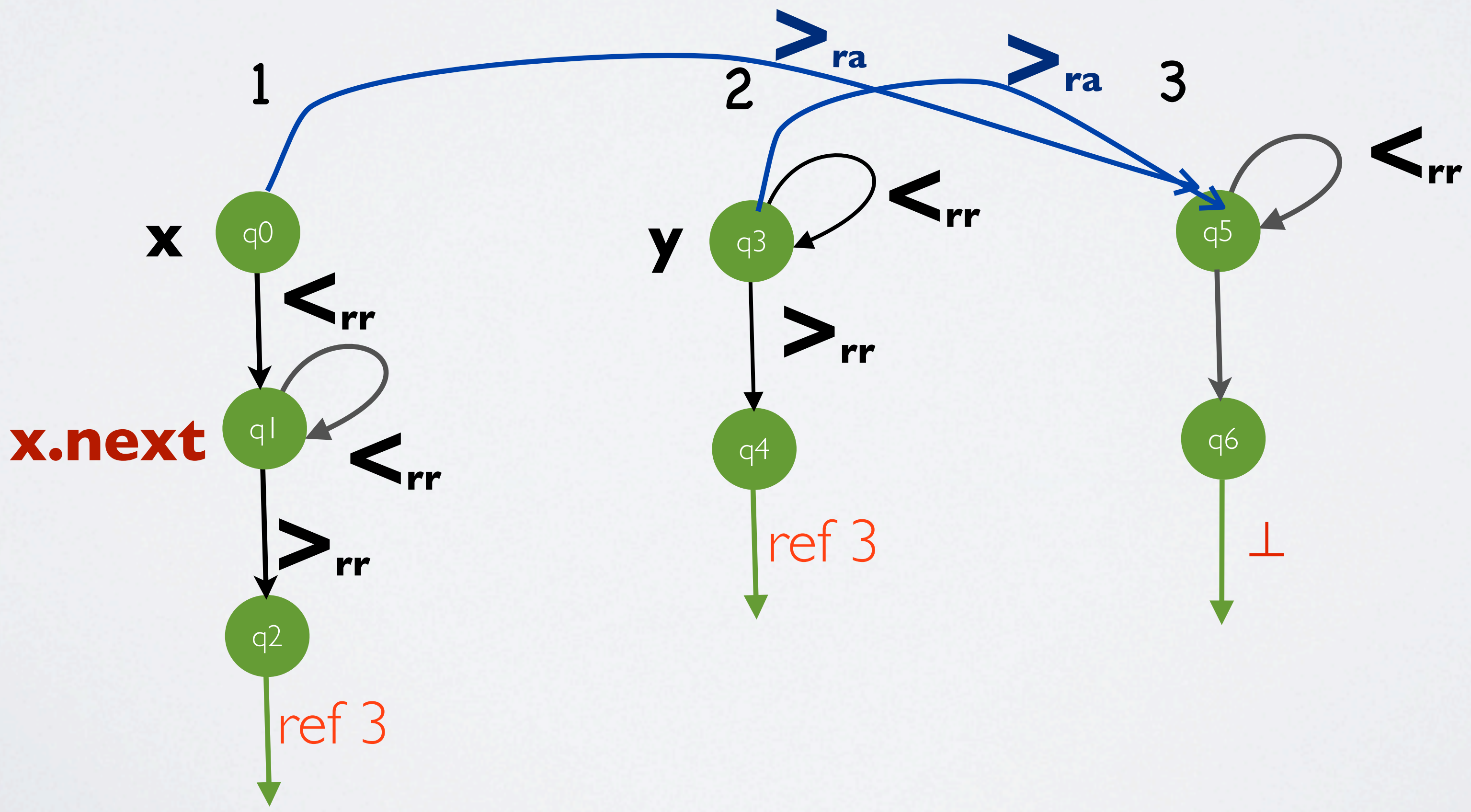
Effect of **z = x.next** on forest automata



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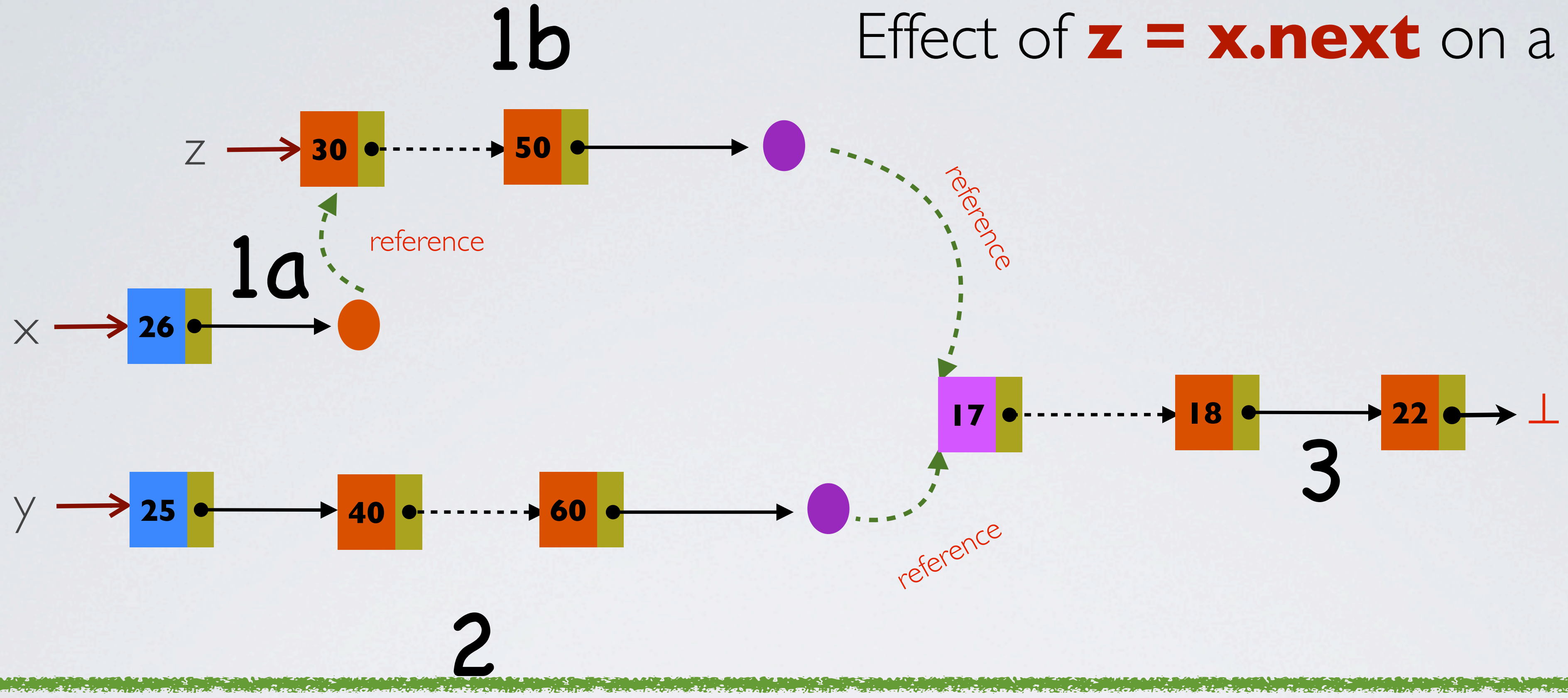
Effect of **z = x.next** on a concrete forest



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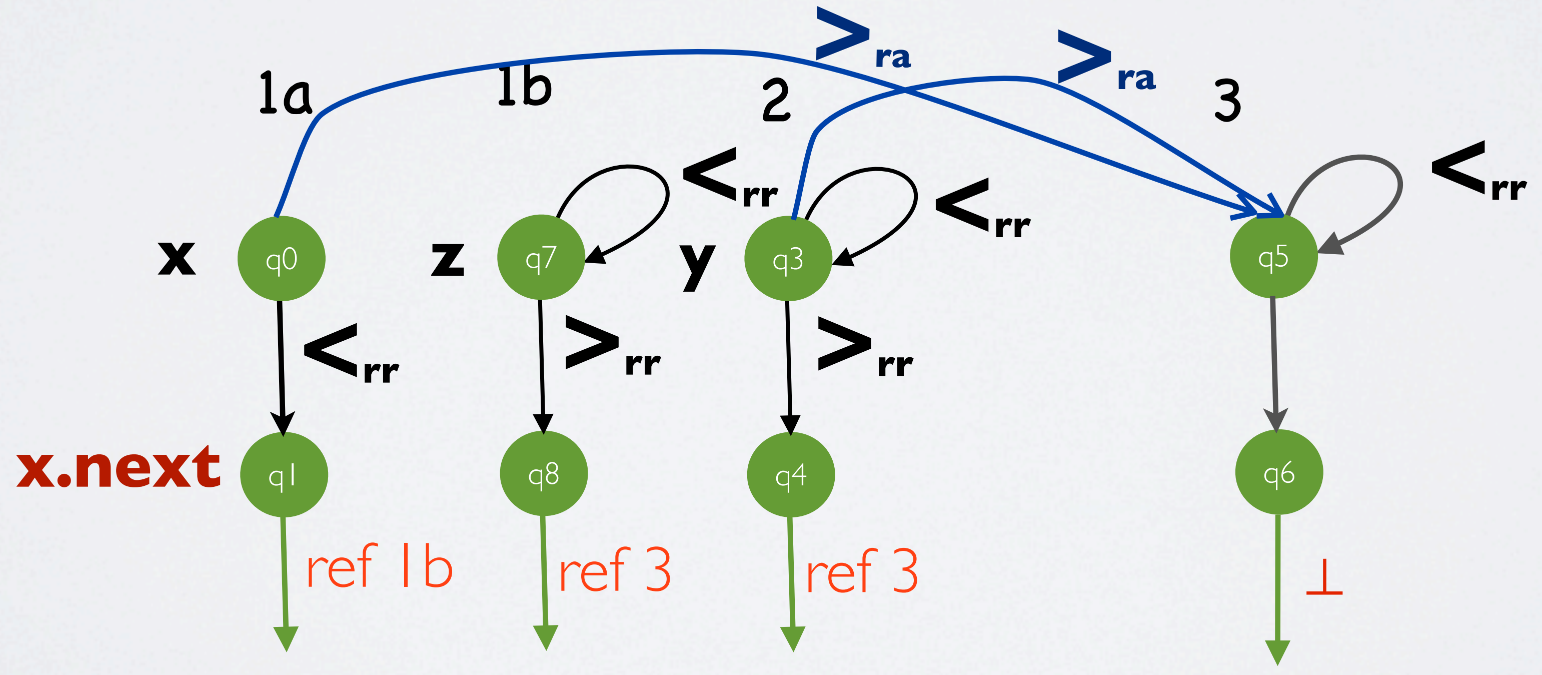
Effect of **z = x.next** on forest automata



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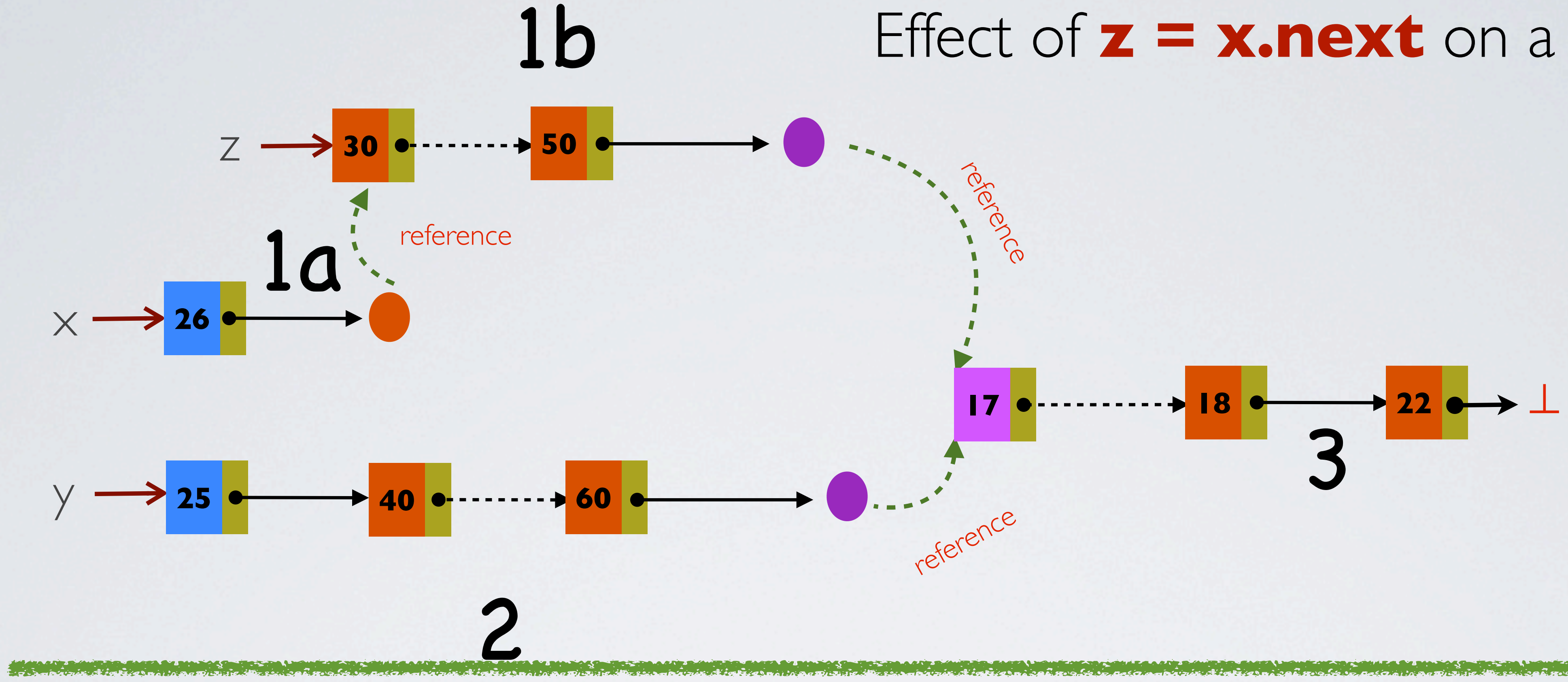
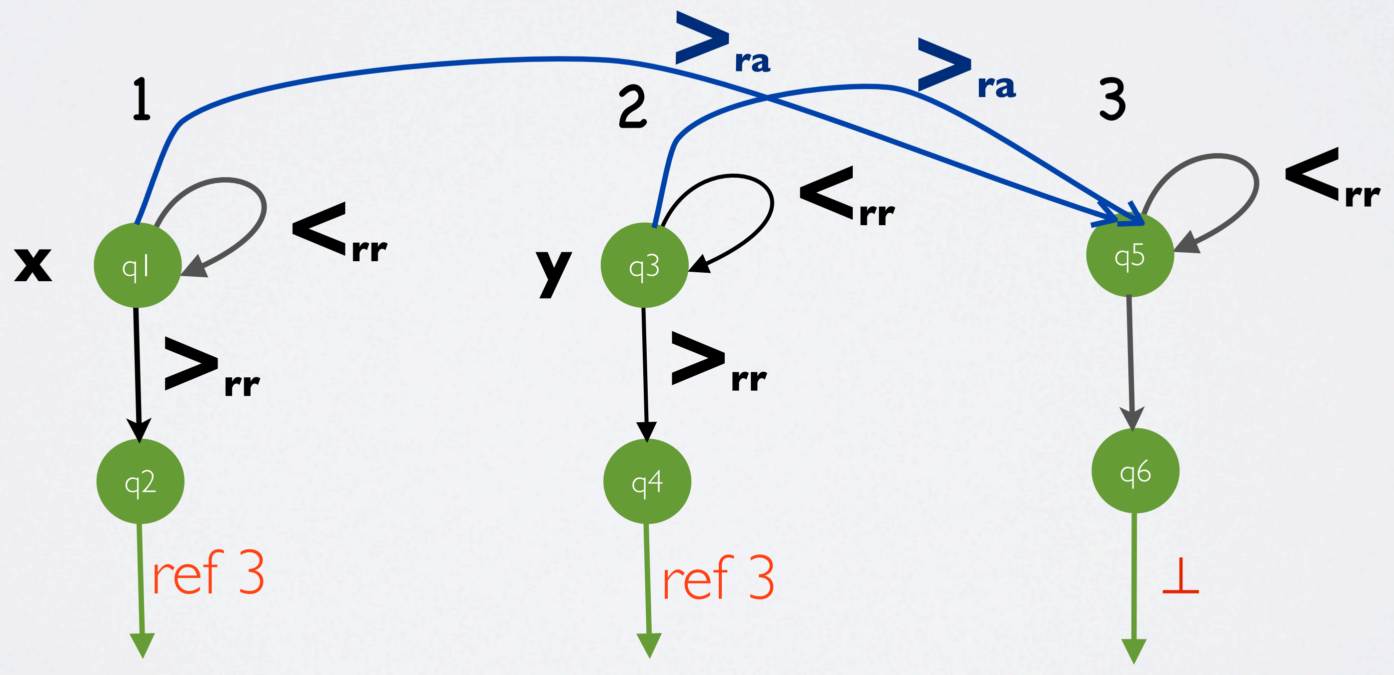
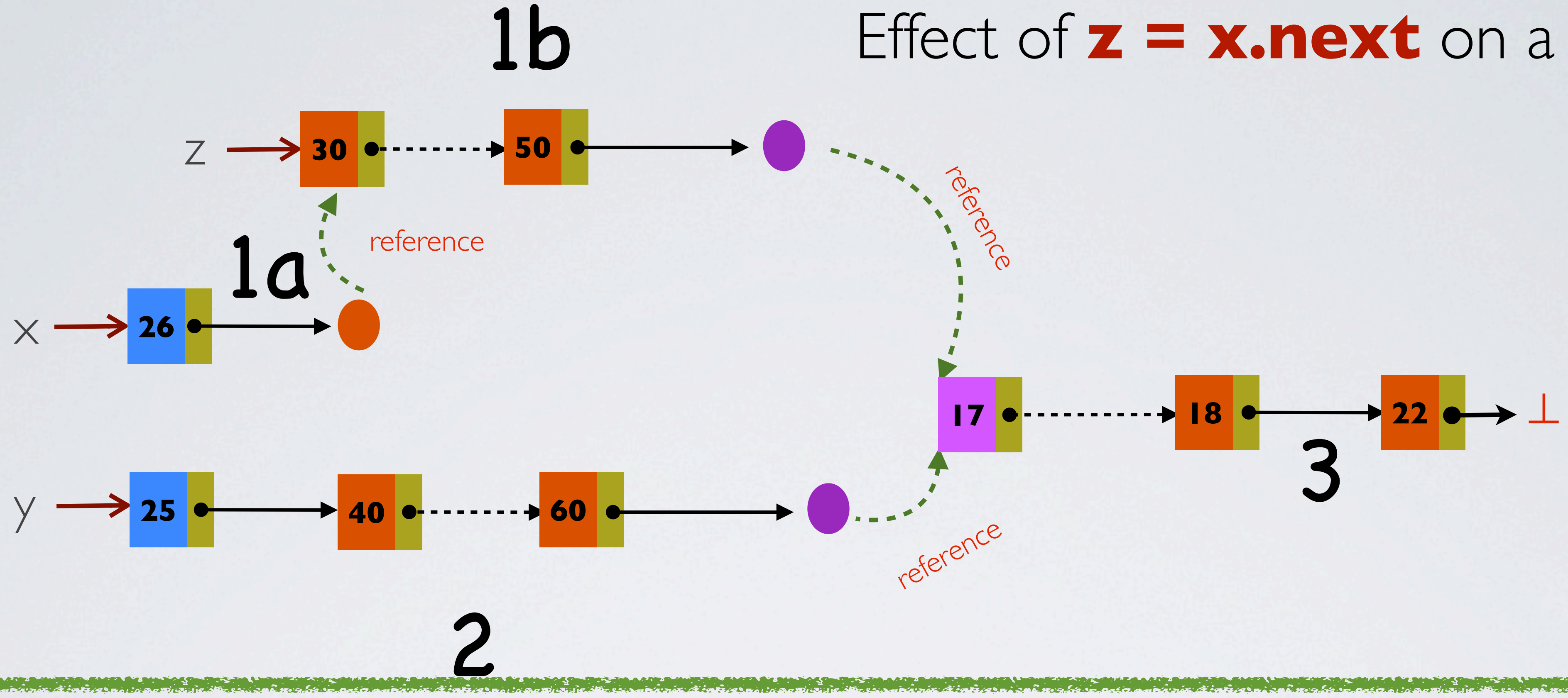
Effect of **z = x.next** on a concrete forest



- ✓ Access to **x.next**
- ✓ Split the tree 1 at this node



Effect of **z = x.next** on a concrete forest



- ✓ Access to **x.next**
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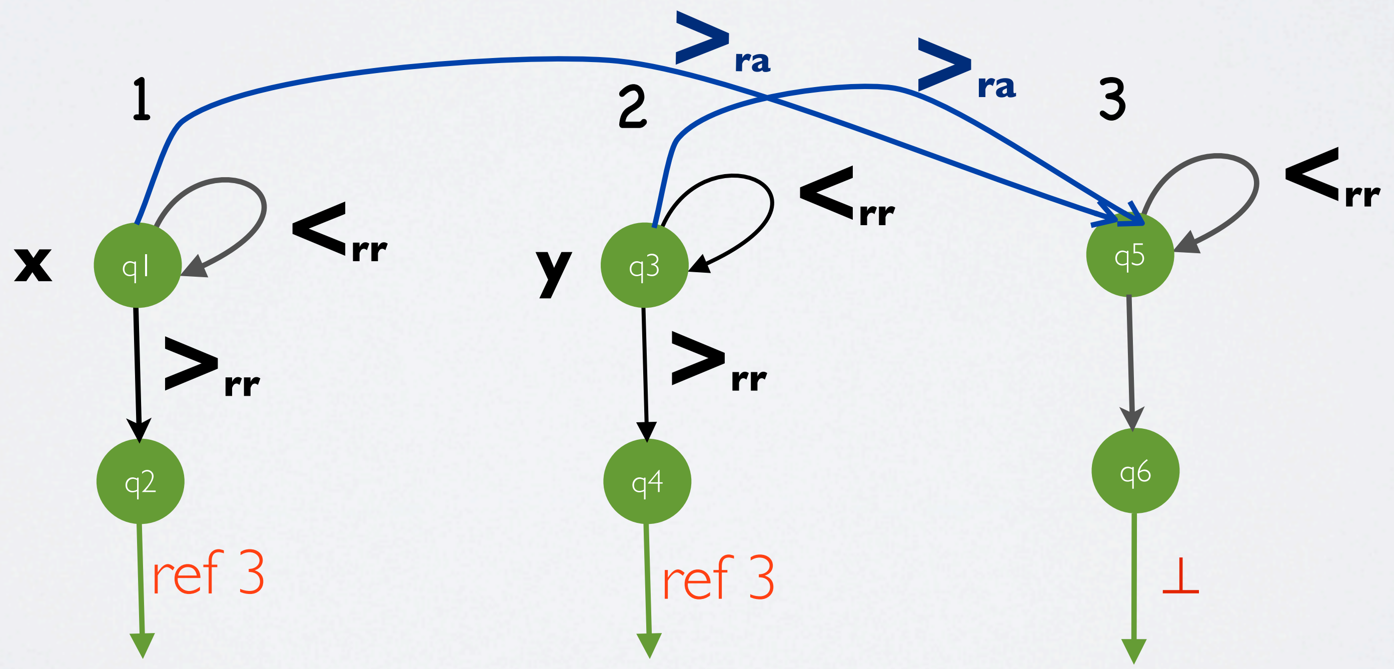
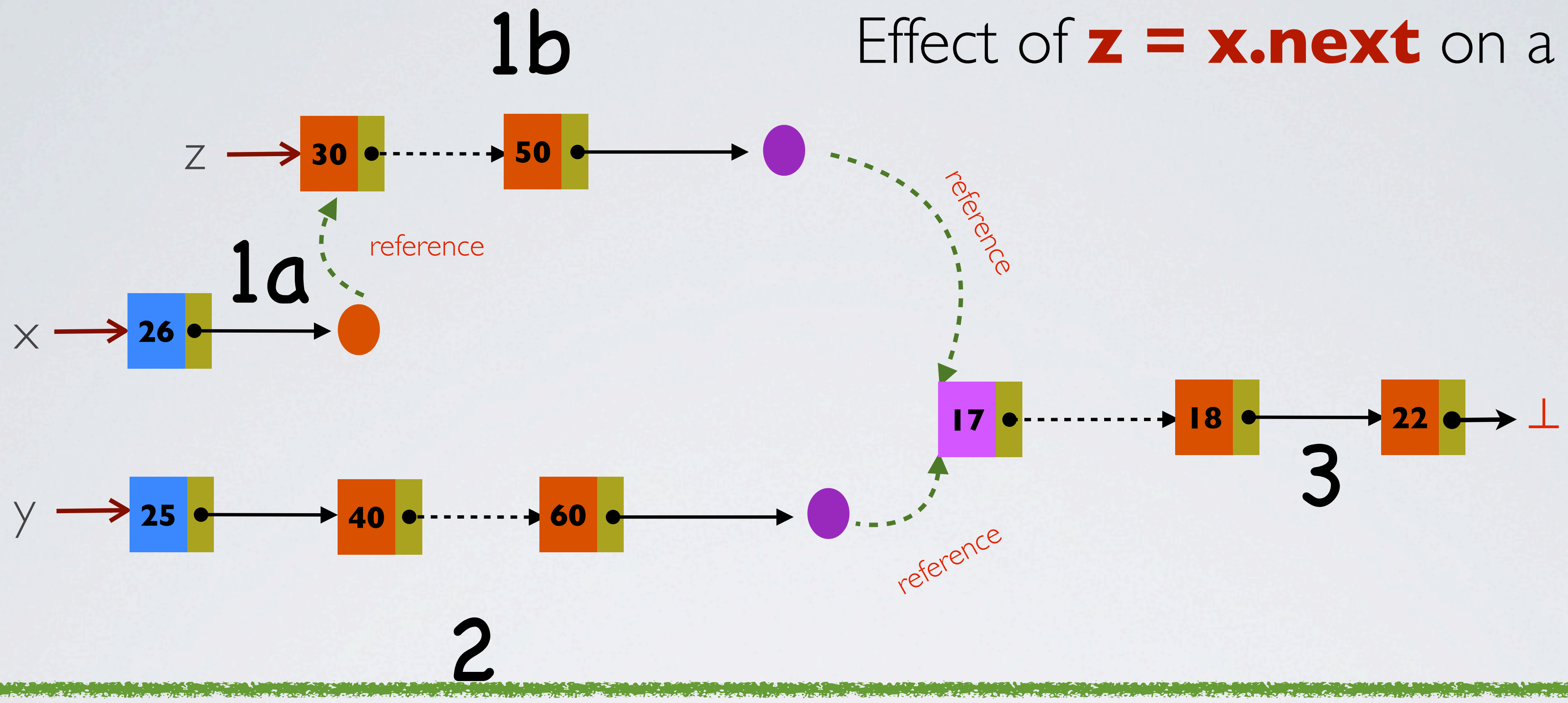
Effect of **z = x.next** on forest automata

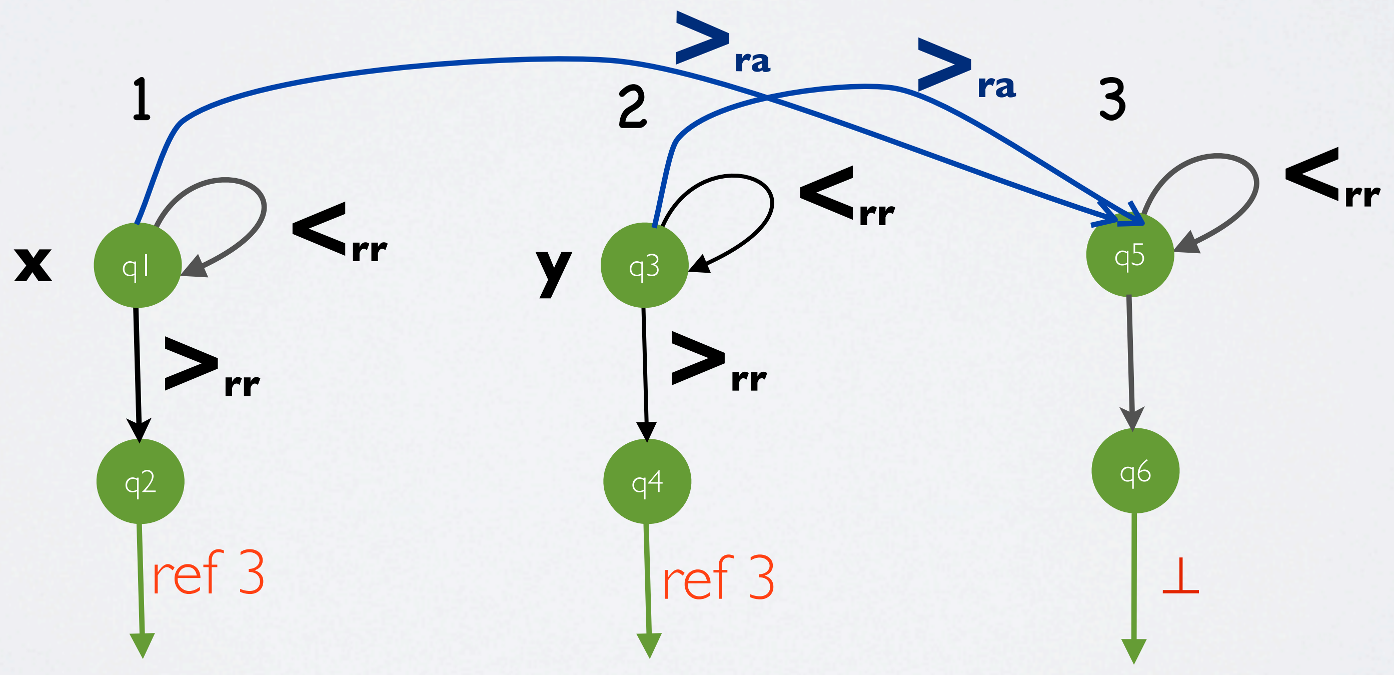


Effect of **z = x.next** on a concrete forest



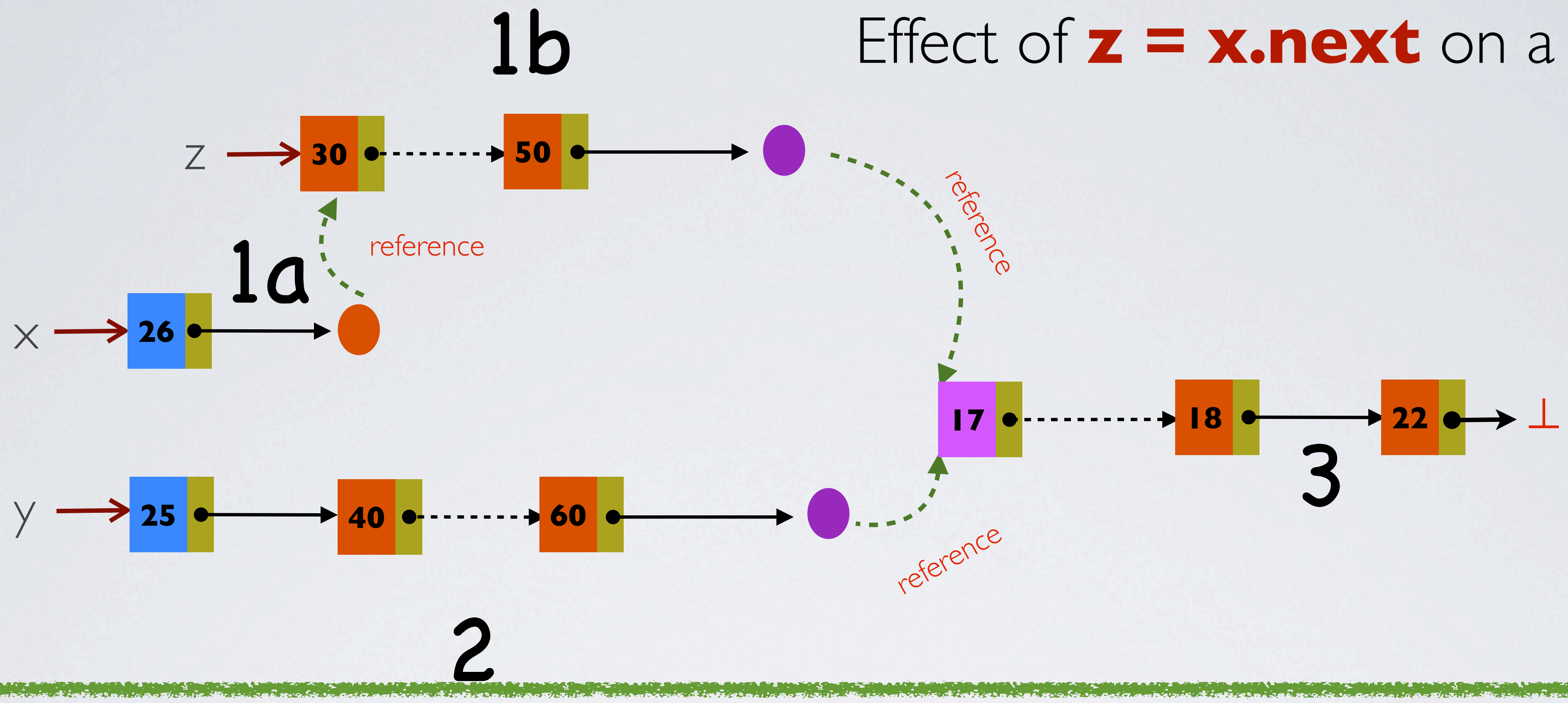
- ✓ Access to **x.next**
- ✓ Split the tree 1 at this node

Effect of **z = x.next** on forest automata



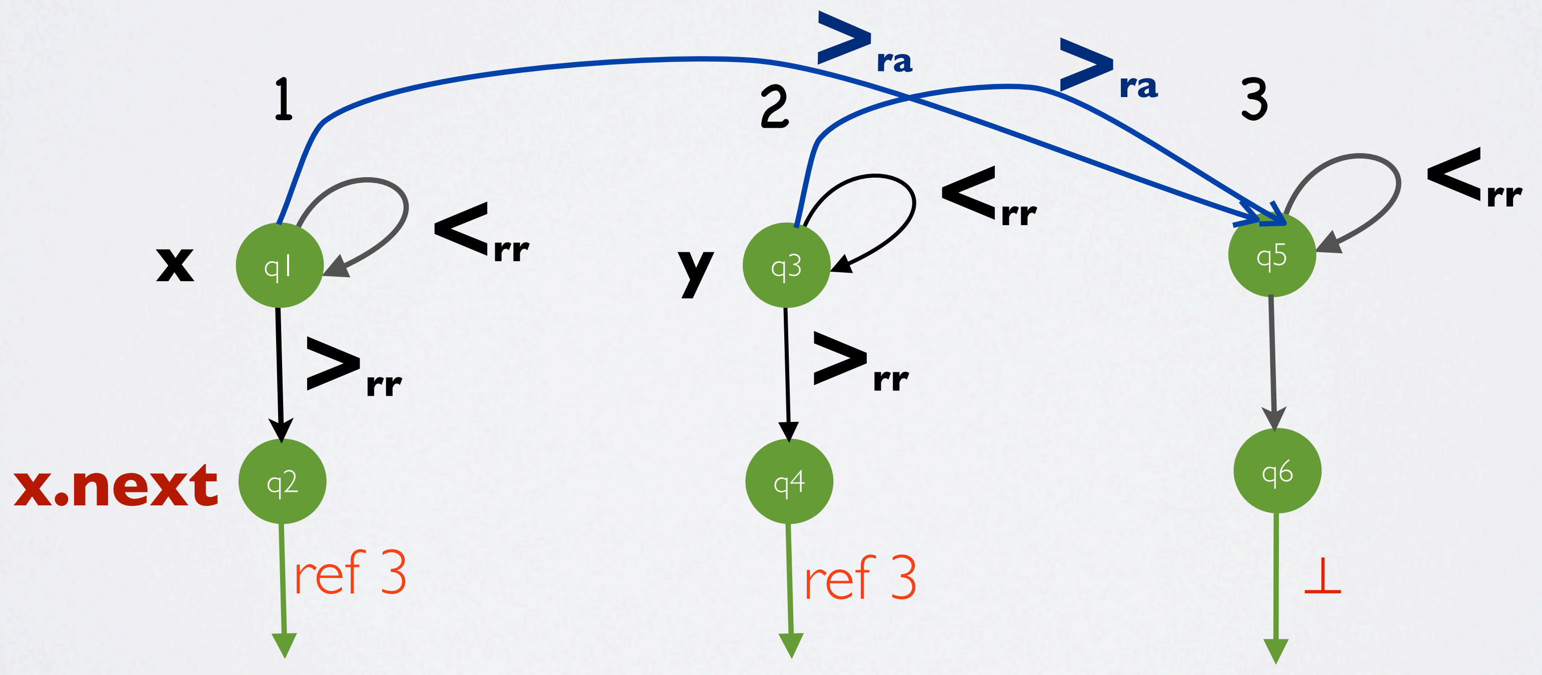
- ✓ Access to **x.next** directly at **q2**
- ✓ Assign variable **z** to the root of the TA 3

Effect of **z = x.next** on a concrete forest



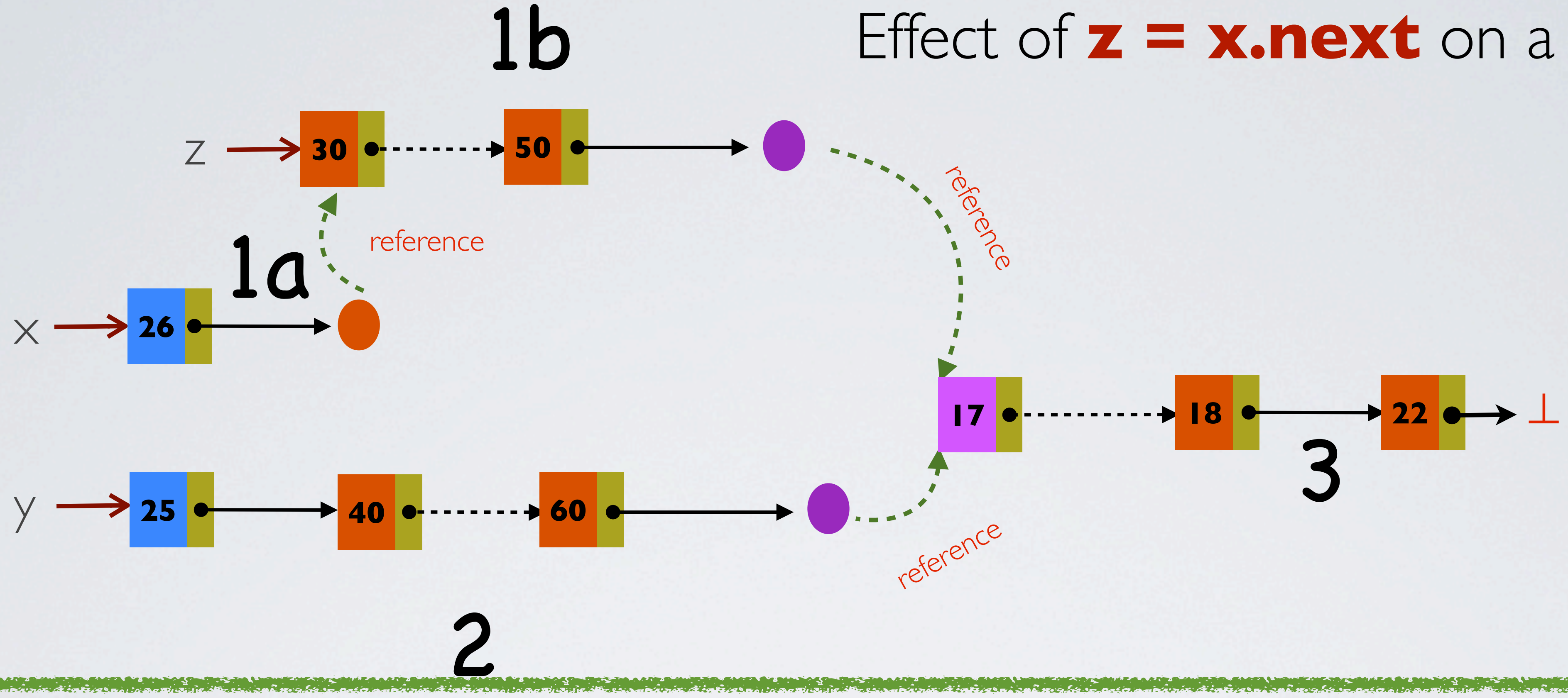
✓ Access to **x.next**
✓ Split the tree 1 at this node

Effect of **z = x.next** on forest automata



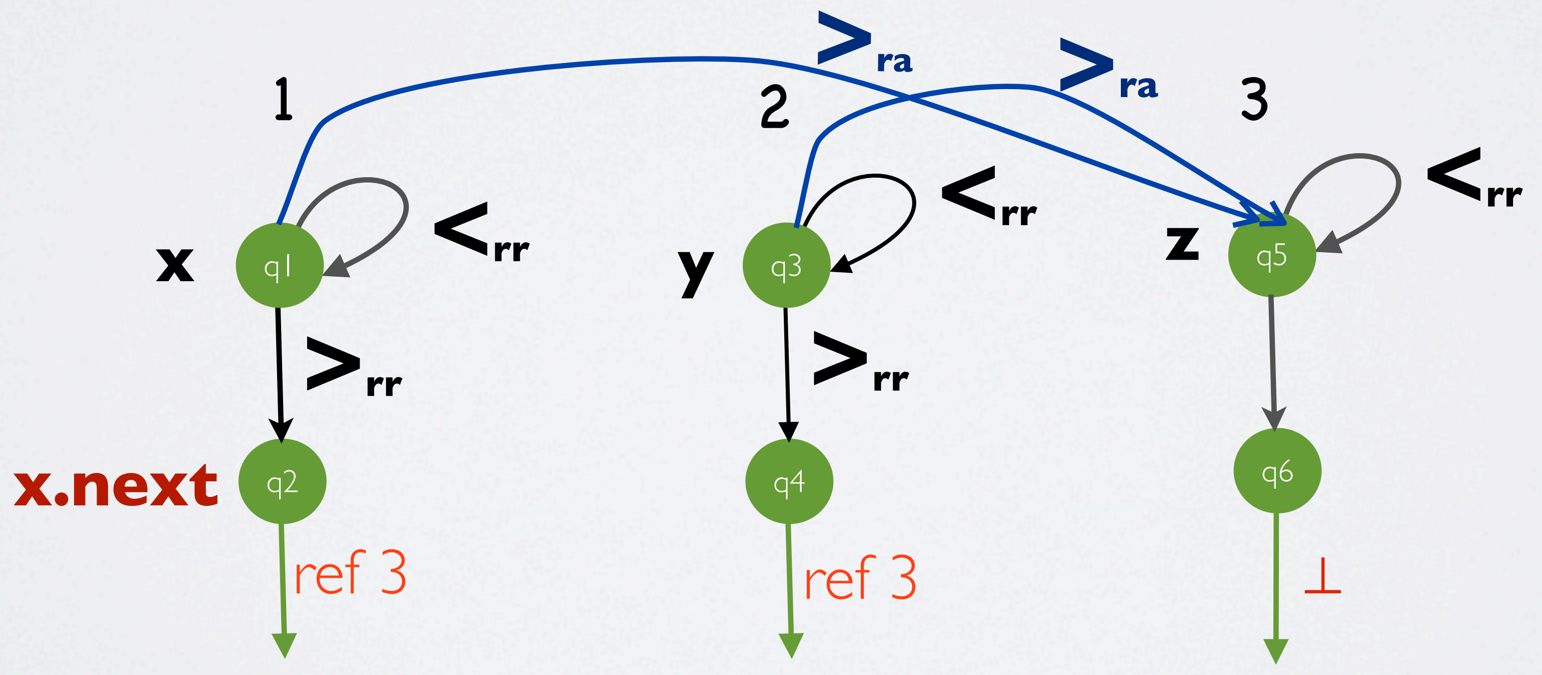
✓ Access to **x.next** directly at **q2**
✓ Assign variable **z** to the root of the TA 3

Effect of **z = x.next** on a concrete forest



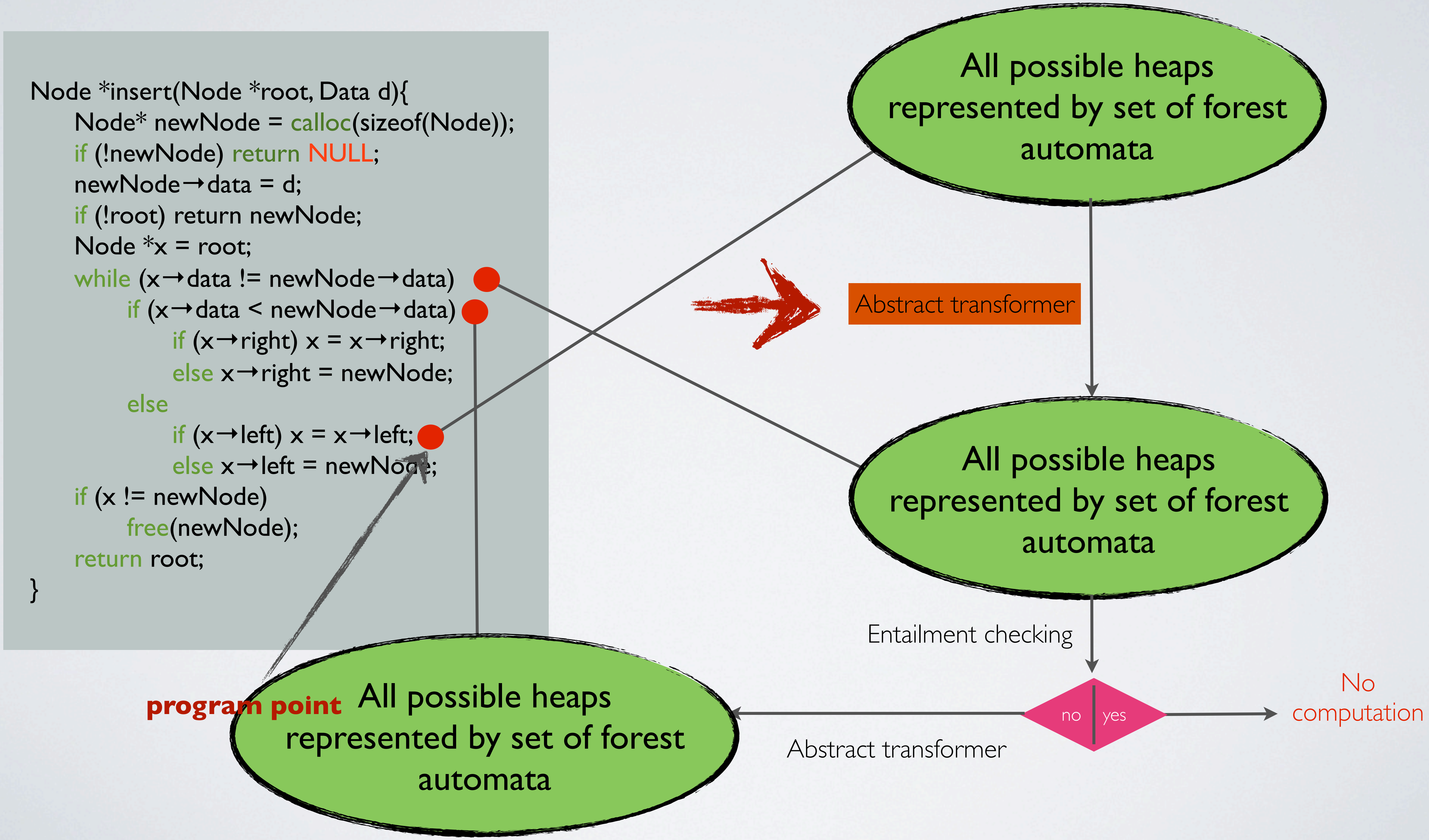
✓ Access to **x.next**
✓ Split the tree 1 at this node

Effect of **z = x.next** on forest automata



✓ Access to **x.next** directly at **q2**
✓ Assign variable **z** to the root of the TA 3

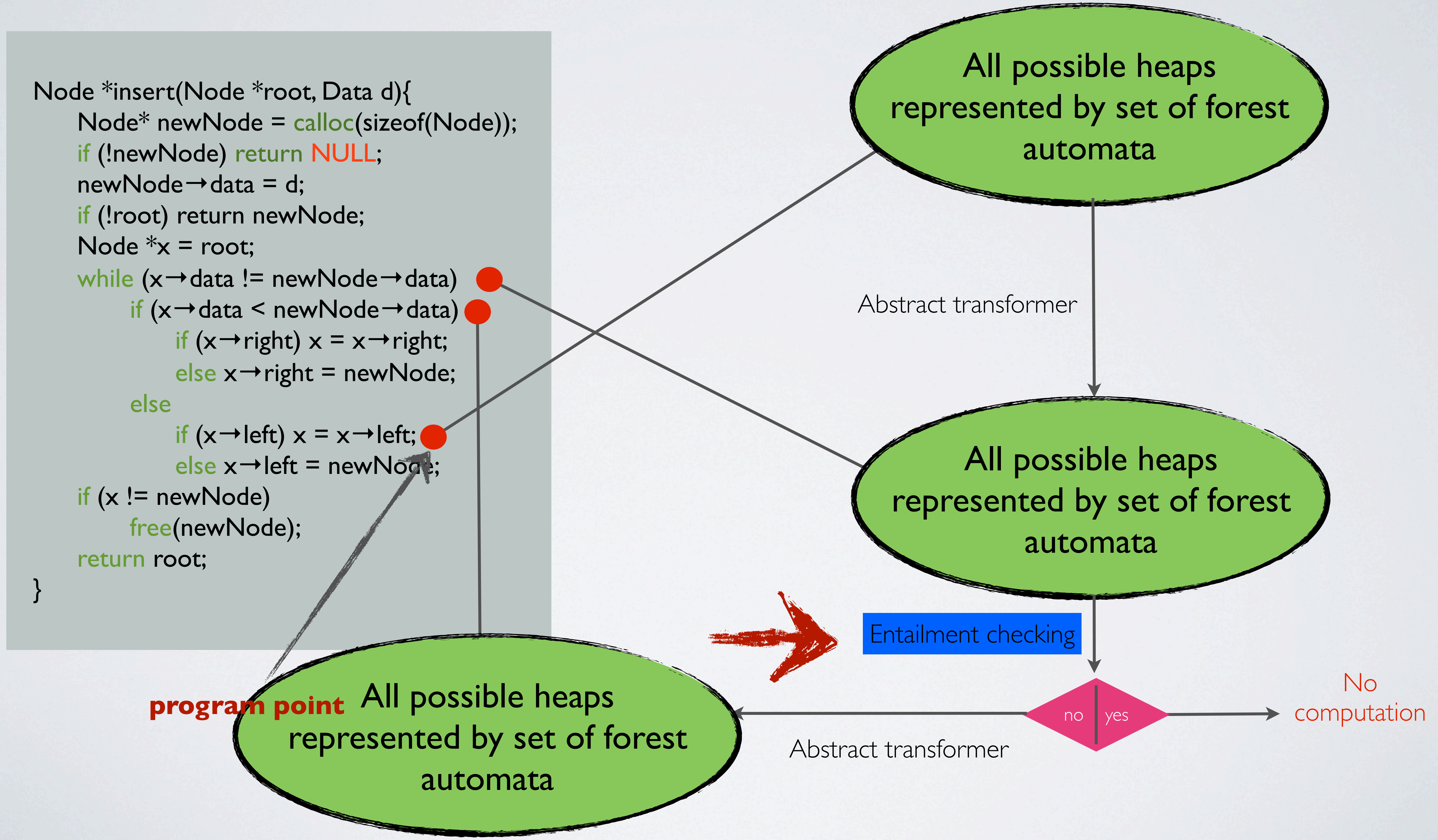
Program analysis



```
Node *insert(Node *root, Data d){
    Node* newNode = calloc(sizeof(Node));
    if (!newNode) return NULL;
    newNode→data = d;
    if (!root) return newNode;
    Node *x = root;
    while (x→data != newNode→data)
        if (x→data < newNode→data)
            if (x→right) x = x→right;
            else x→right = newNode;
        else
            if (x→left) x = x→left;
            else x→left = newNode;
    if (x != newNode)
        free(newNode);
    return root;
}
```

All possible heaps represented by set of forest automata
Abstract transformer
All possible heaps represented by set of forest automata
Entailment checking
no
yes
No computation
Abstract transformer
program point
All possible heaps represented by set of forest automata

Program analysis



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Entailment checking

Widening technique

Language Inclusion

EXPERIMENTS

Examples	Time (in s)
SLL insert	0.06
SLL delete	0.08
SLL reverse	0.07
SLL bubblesort	0.13
SLL insert-sort	0.10

Singly linked list(SLL)

Examples	Time (in s)
BST insert	6.87
BST delete	15.8
BST left rotate	7.35
BST right rotate	6.25

Binary search tree(BST)

Examples	Time (in s)
DLL insert	0.14
DLL delete	0.38
DLL reverse	0.16
DLL bubblesort	0.39
DLL insert-sort	0.43

Double linked list(DLL)

Examples	Time (in s)
SL2 insert	9.65
SL2 delete	10.14
SL3 insert	56.99
SL3 delete	57.35

Skiplist with 2 & 3 levels(SL2 & SL3)

EXPERIMENTS

Examples	Time (in s)
SLL insert	0.06
SLL delete	0.08
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Singly linked list(SLL)

Safety

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Binary search tree(BST)

Examples	Time (in s)
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DLL delete	0.38
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DLL bubblesort	0.39
DLL insert-sort	0.43

Double linked list(DLL)

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SL2 insert	9.65
SL2 delete	10.14
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Skiplist with 2 & 3 levels(SL2 & SL3)

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Binary search tree(BST)

Safety

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Double linked list(DLL)

Sortedness

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Skiplist with 2 & 3 levels(SL2 & SL3)

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Singly linked list(SLL)

Safety

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Skiplist with 2 & 3 levels(SL2 & SL3)

SUMMARY

- Verify heap manipulating programs with
- Data dependence
- Unbounded heaps
- Multiple selectors
- We can verify both memory safety and data-dependent properties

FUTURE WORKS

- Fine-grained locking programs
- Concurrent heap manipulating programs
- Recursive heap manipulating programs

Thank you for attention!