

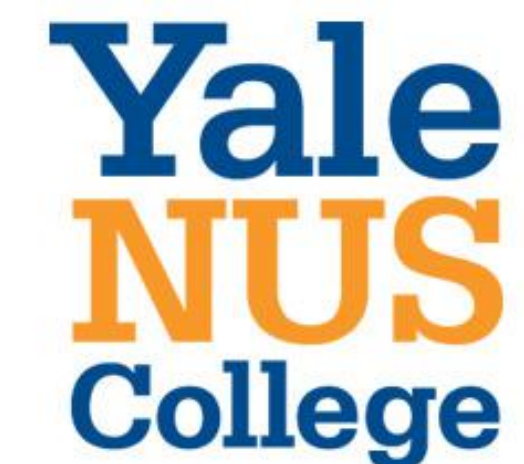
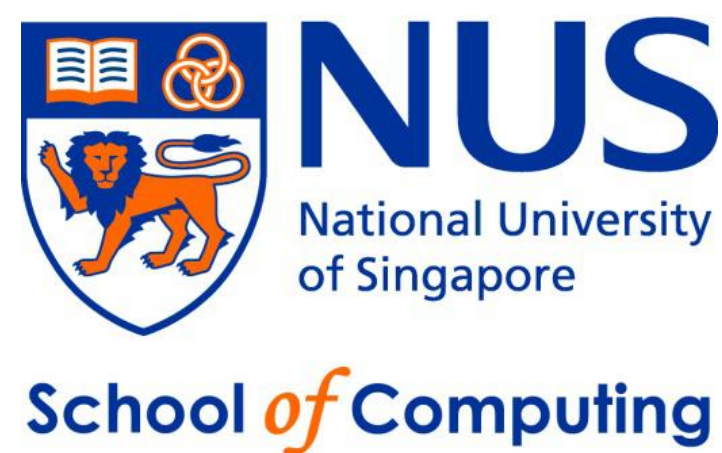
# Synthesis of Programs with Pointers via Read-Only Specifications

Andreea Costea

Amy Zhu

Nadia Polikarpova

Ilya Sergey



# Synthesis of Programs with Pointers

## via Read-Only Specifications

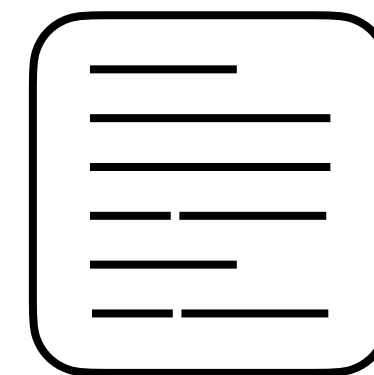
Specification



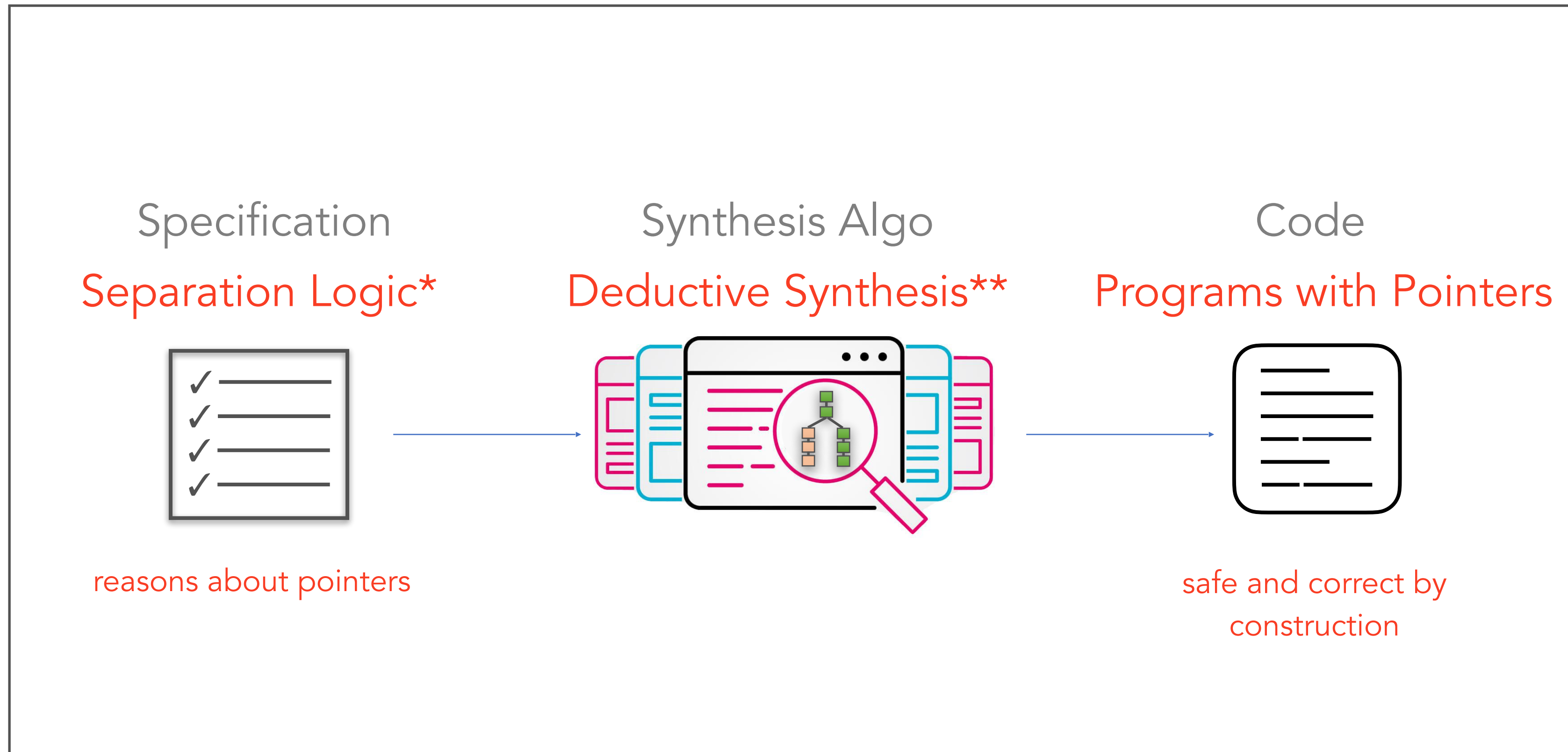
Synthesis Algo



Code



## SSL: Synthetic Separation Logic



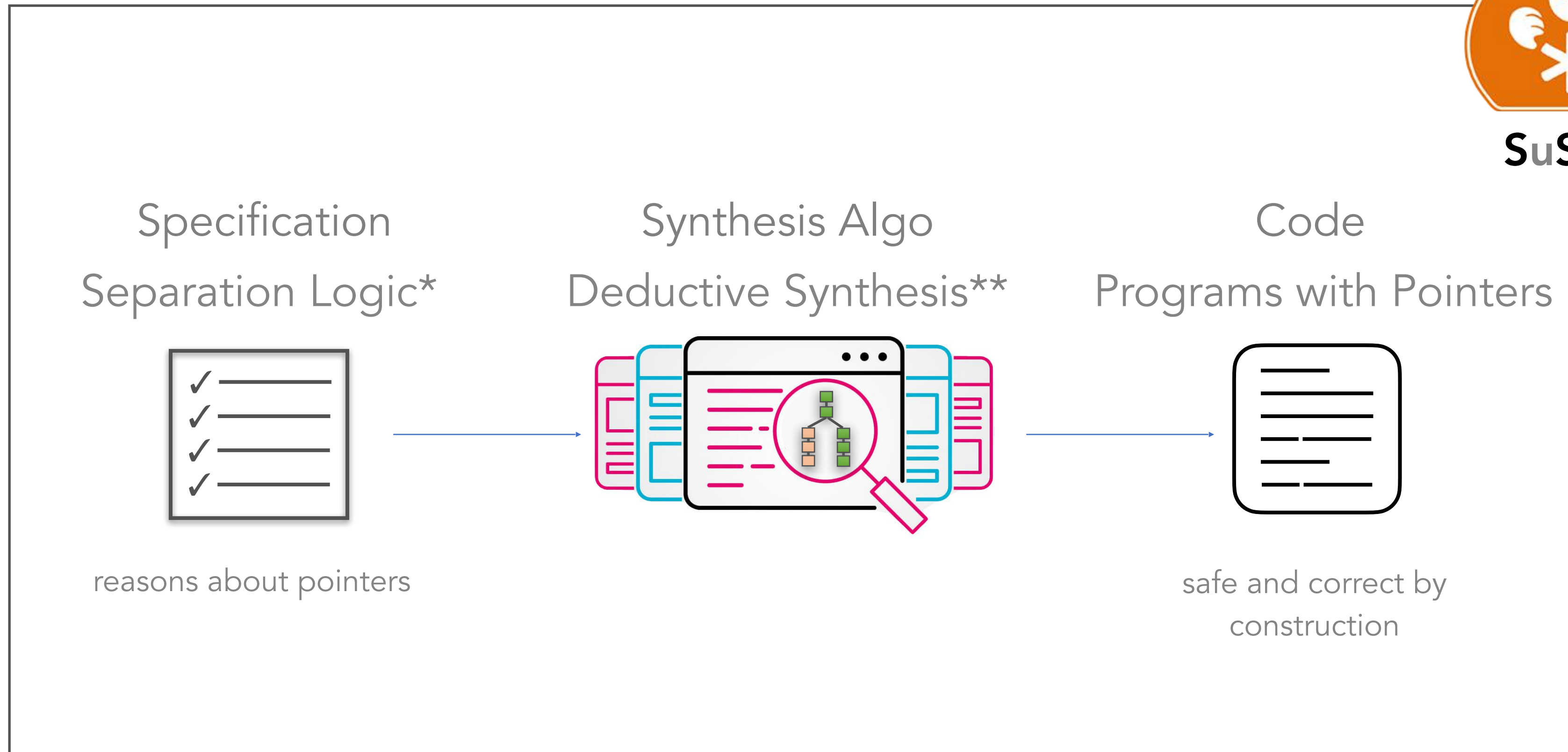
\* *Local Reasoning about Programs that Alter Data Structures*, O'Hearn, Reynolds, Yang: CSL 2001

\*\* *Structuring the Synthesis of Heap-Manipulating Programs*, Polikarpova & Sergey @POPL'19

# SSL: Synthetic Separation Logic



**SuSLik**

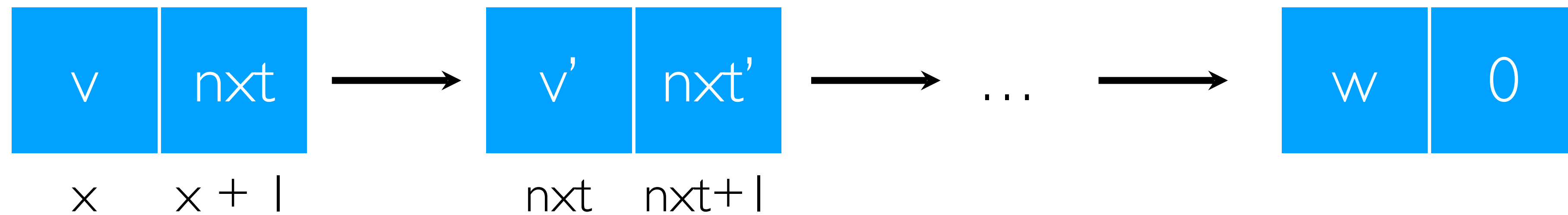


\* *Local Reasoning about Programs that Alter Data Structures*, O'Hearn, Reynolds, Yang: CSL 2001

\*\* *Structuring the Synthesis of Heap-Manipulating Programs*, Polikarpova & Sergey @POPL'19

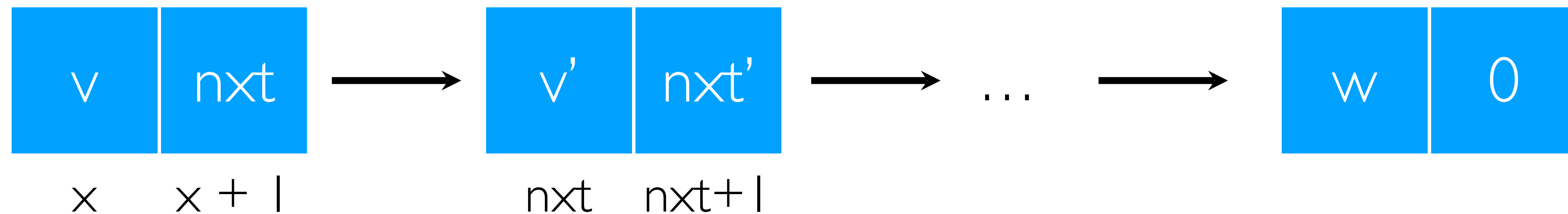
Example: copy a linked list

# Example: copy a **linked list**



▼  
**predicate**  $ls$  (**loc**  $x$ , **set**  $S$ ) {  
  |  $x = 0 \wedge \{ S = \emptyset \} \quad ; emp$  }  
  |  $x \neq 0 \wedge \{ S = \{v\} \cup S' \} ; [x, 2] * x \mapsto v * (x + 1) \mapsto nxt * ls(nxt, S')$  }  
}

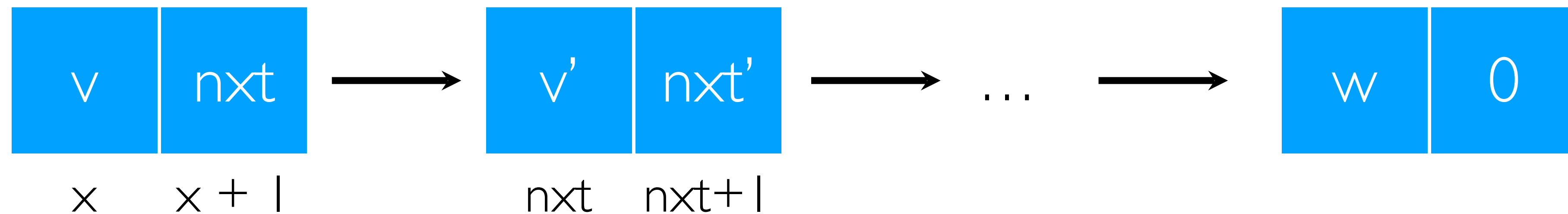
# Example: copy a **linked list**



```
predicate ls (loc x, set S) {  
  ▶ |  $x = 0 \wedge \{ S = \emptyset \}$  ; emp }  
  |  $x \neq 0 \wedge \{ S = \{v\} \cup S' \}$  ;  $[x, 2] * x \mapsto v * (x + 1) \mapsto nxt * ls(nxt, S') \}$   
}
```



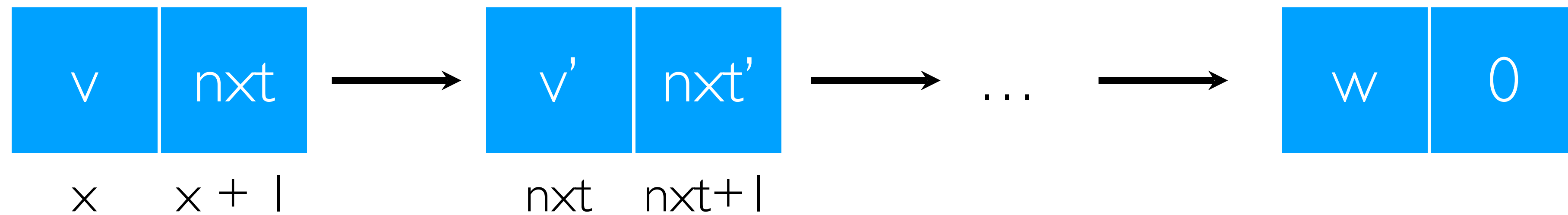
# Example: copy a **linked list**



pure constraints

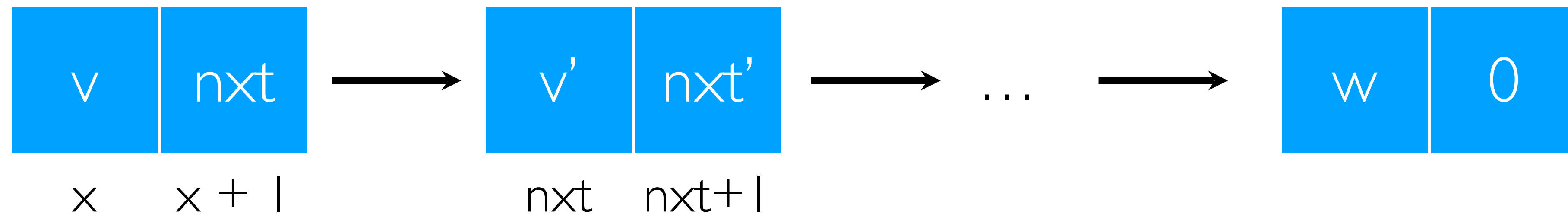
```
predicate ls (loc x, set S) {  
  |  $x = 0 \wedge \{ S = \emptyset \}$  ; emp }  
  |  $x \neq 0 \wedge \{ S = \{v\} \cup S' \}$  ;  $[x, 2] * x \mapsto v * (x + 1) \mapsto nxt * ls(nxt, S') \}$   
}
```

# Example: copy a **linked list**



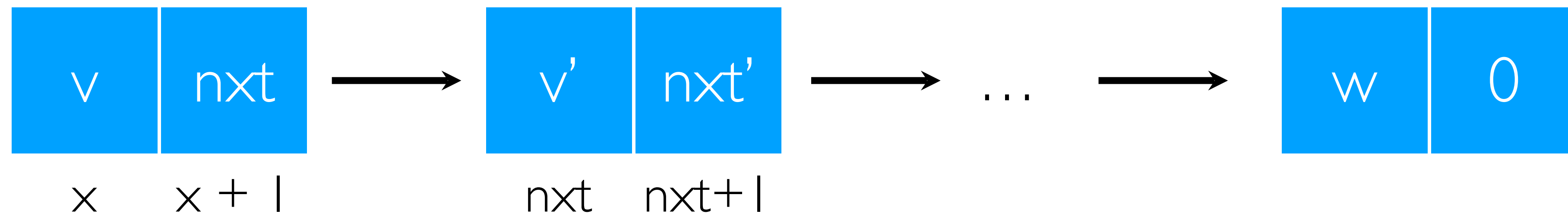
```
predicate ls (loc x, set S) {  
  |  $x = 0 \wedge \{ S = \emptyset \}$  ; emp }  
  |  $x \neq 0 \wedge \{ S = \{v\} \cup S' \}$  ;  $[x, 2] * x \mapsto v * (x + 1) \mapsto nxt * ls(nxt, S') \}$   
}
```

# Example: copy a **linked list**



```
predicate ls (loc x, set S) {  
  |  $x = 0 \wedge \{ S = \emptyset \}$  ; emp }  
  |  $x \neq 0 \wedge \{ S = \{v\} \cup S' \}$  ;  $[x, 2] * x \mapsto v * (x + 1) \mapsto nxt * ls(nxt, S') \}$   
}
```

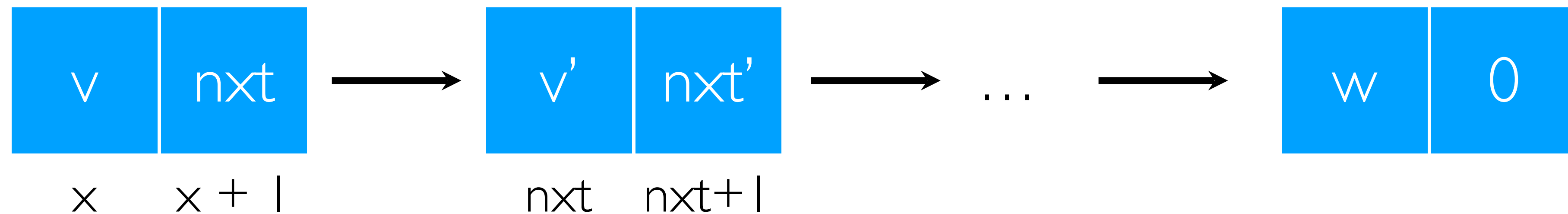
# Example: copy a **linked list**



```
predicate ls (loc x, set S) {  
  | x = 0  $\wedge$  { S =  $\emptyset$  ; emp }  
  | x  $\neq$  0  $\wedge$  { S = {v}  $\cup$  S' ; [x, 2] * x  $\mapsto$  v * (x + 1)  $\mapsto$  nxt * ls(nxt, S') }  
}
```

▲  
memory block

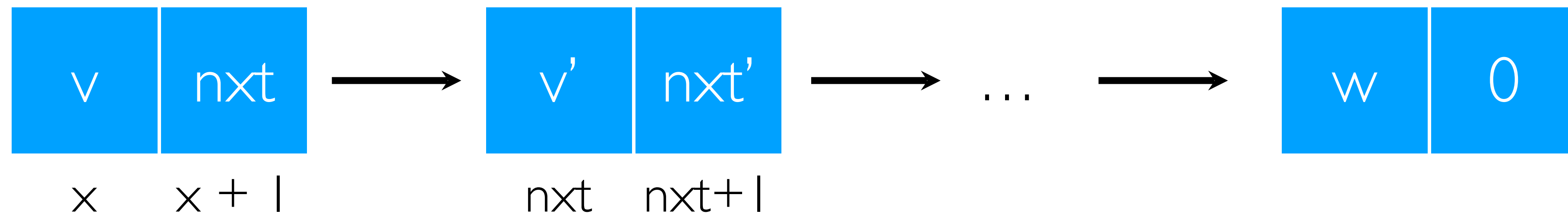
# Example: copy a **linked list**



```
predicate ls (loc x, set S) {  
  |  $x = 0 \wedge \{ S = \emptyset \}$  ; emp }  
  |  $x \neq 0 \wedge \{ S = \{v\} \cup S' \}$  ;  $[x, 2] * x \mapsto v * (x + 1) \mapsto nxt * ls(nxt, S') \}$   
}
```

points-to

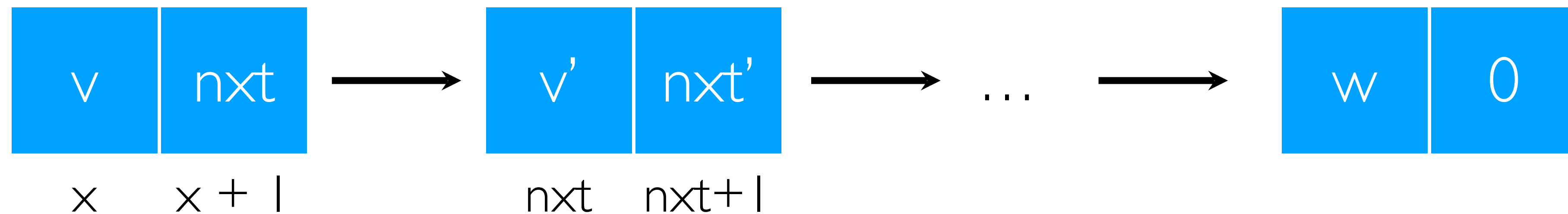
# Example: copy a **linked list**



```
predicate ls (loc x, set S) {  
  |  $x = 0 \wedge \{ S = \emptyset \}$  ; emp }  
  |  $x \neq 0 \wedge \{ S = \{v\} \cup S' \}$  ;  $[x, 2] * x \mapsto v * (x + 1) \mapsto nxt * ls(nxt, S') \}$   
}
```

points-to

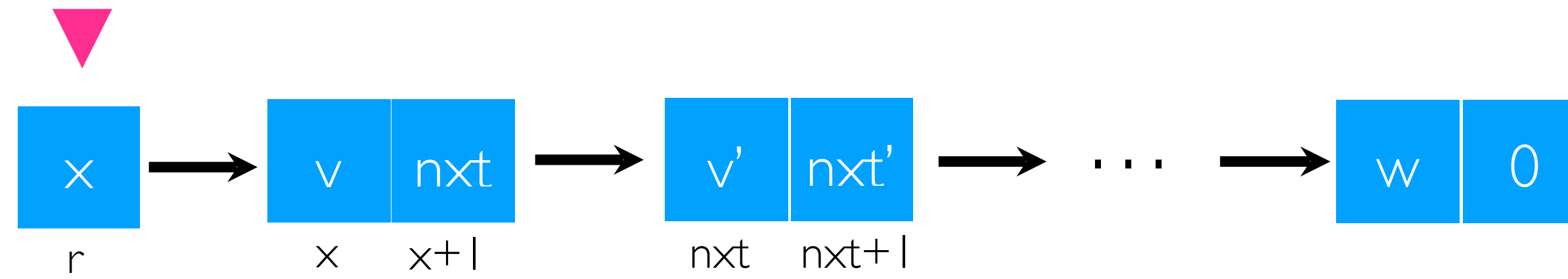
# Example: copy a **linked list**



```
predicate ls (loc x, set S) {  
  | x = 0  $\wedge$  { S =  $\emptyset$  ; emp }  
  | x  $\neq$  0  $\wedge$  { S = {v}  $\cup$  S' ; [x, 2] * x  $\mapsto$  v * (x + 1)  $\mapsto$  nxt * ls(nxt, S') }  
}
```

separating conjunction

# Example: copy a linked list



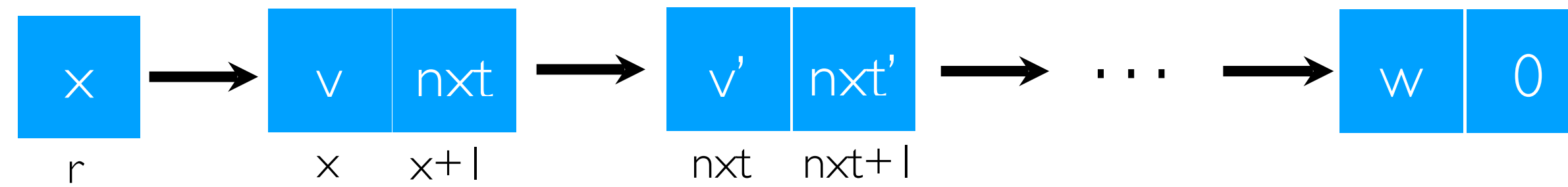
Precondition:

$\{r \mapsto x * \text{lseg}(x, S)\}$

`void listcopy (loc r)`



# Example: copy a linked list



Precondition:

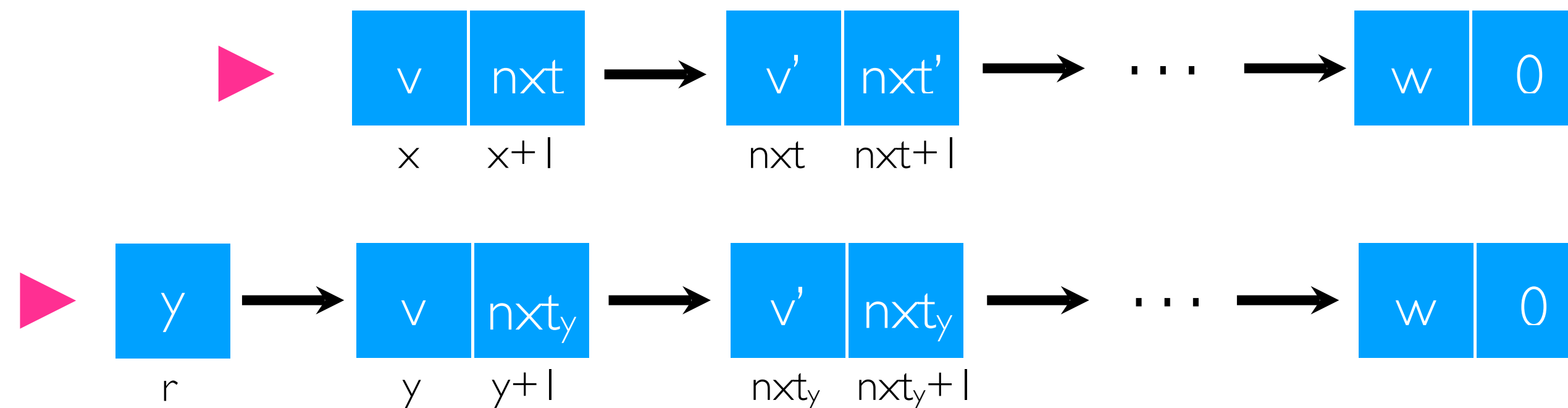
$\{r \mapsto x * \text{lseg}(x, S)\}$

```
void listcopy (loc r)
```

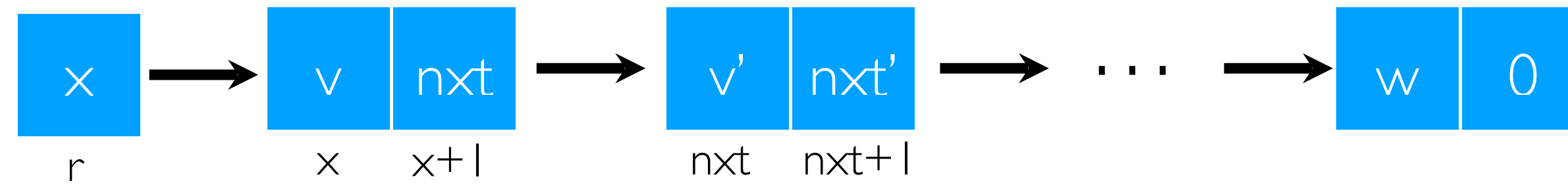


Postcondition:

$\{r \mapsto y * \text{lseg}(x, S) * \text{lseg}(y, S)\}$



# Example: copy a linked list

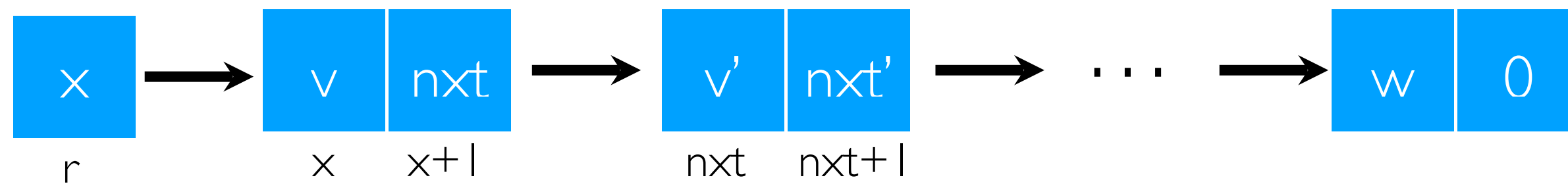


`{r ↦ x * lseg(x, S)}`

```
void listcopy (loc r)
```

`{r ↦ y * lseg(x, S) * lseg(y, S)}`

# Example: copy a linked list

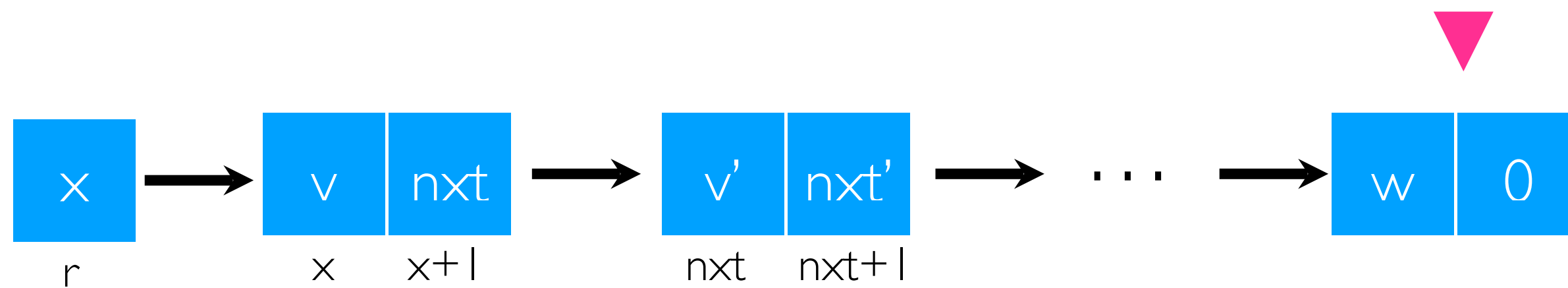


$\{r \mapsto x * \text{lseg}(x, S)\}$

```
1 void listcopy (loc r) {
2   let x = *r;
3   if (x == 0) {
4   } else {
5     let v = *x;
6     let nxt = *(x + 1);
7     *r = nxt;
8     ▶ listcopy(r);
9     let y1 = *r;
10    let y = malloc(2);
11    *(x + 1) = y1;
12    *r = y;
13    *(y + 1) = nxt;
14    *y = v;
15  } }
```

$\{r \mapsto y * \text{lseg}(x, S) * \text{lseg}(y, S)\}$

# Example: copy a linked list

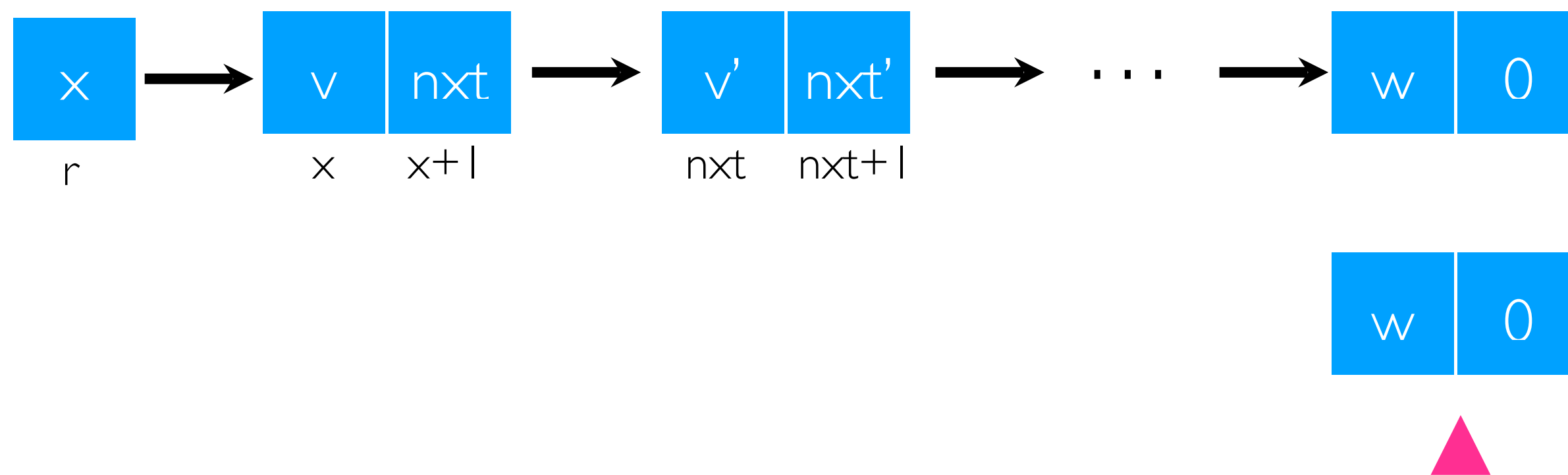


$\{r \mapsto x * \text{lseg}(x, S)\}$

```
1 void listcopy (loc r) {
2   let x = *r;
3   ▶ if (x == 0) {
4     } else {
5       let v = *x;
6       let nxt = *(x + 1);
7       *r = nxt;
8       listcopy(r);
9       let y1 = *r;
10      let y = malloc(2);
11      *(x + 1) = y1;
12      *r = y;
13      *(y + 1) = nxt;
14      *y = v;
15    } }
```

$\{r \mapsto y * \text{lseg}(x, S) * \text{lseg}(y, S)\}$

# Example: copy a linked list

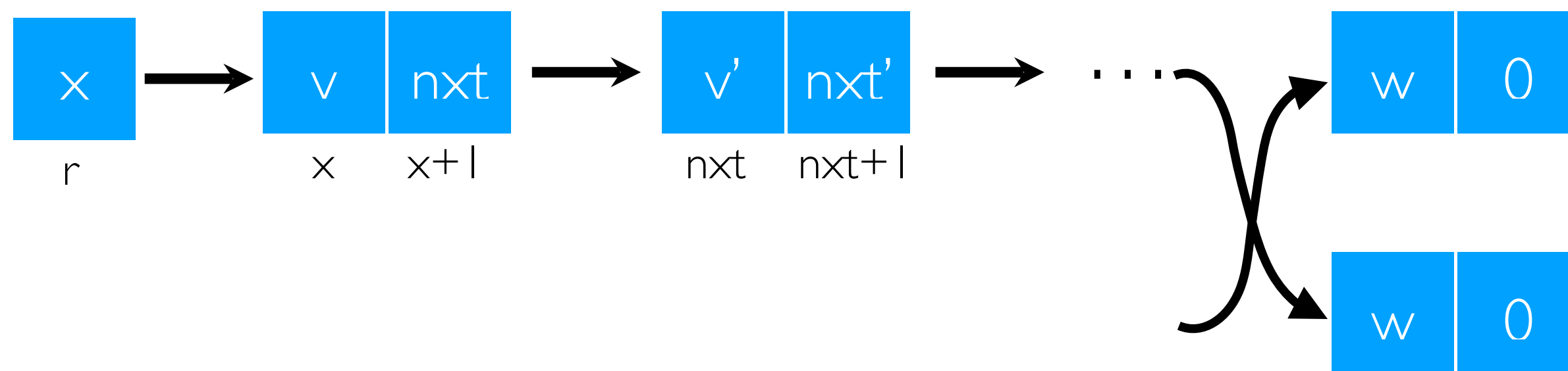


$\{r \mapsto x * \text{lseg}(x, S)\}$

```
1 void listcopy (loc r) {
2   let x = *r;
3   if (x == 0) {
4   } else {
5     let v = *x;
6     let nxt = *(x + 1);
7     *r = nxt;
8     listcopy(r);
9     let y1 = *r;
10    ▶ let y = malloc(2);
11     *(x + 1) = y1;
12     *r = y;
13     *(y + 1) = nxt;
14     *y = v;
15   }
```

$\{r \mapsto y * \text{lseg}(x, S) * \text{lseg}(y, S)\}$

# Example: copy a linked list

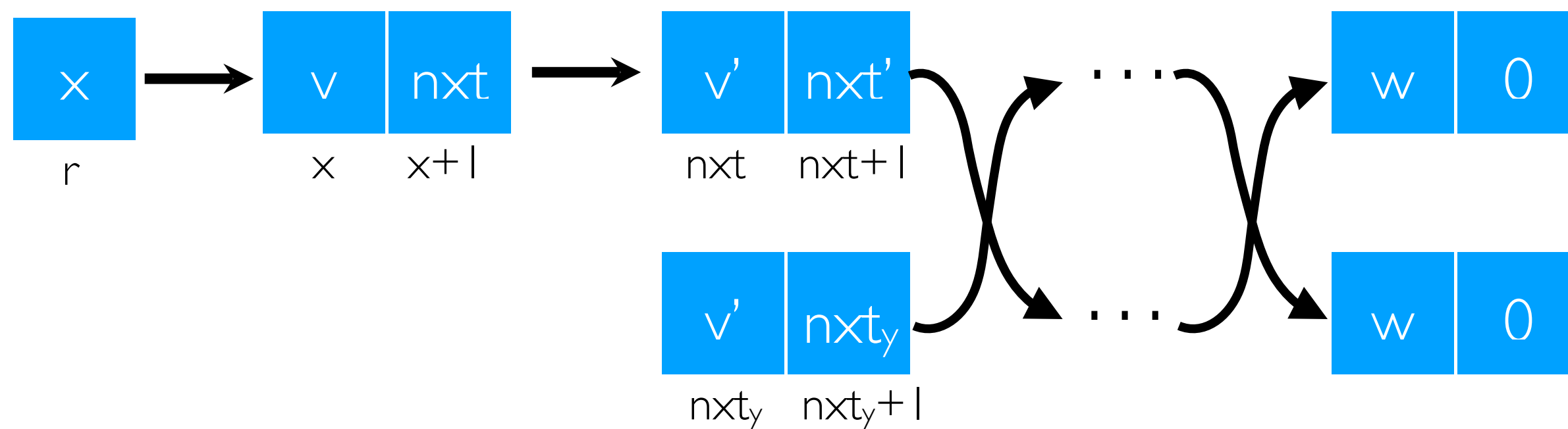


$\{r \mapsto x * \text{lseg}(x, S)\}$

```
1 void listcopy (loc r) {
2   let x = *r;
3   if (x == 0) {
4   } else {
5     let v = *x;
6     let nxt = *(x + 1);
7     *r = nxt;
8     listcopy(r);
9     let y1 = *r;
10    let y = malloc(2);
11    ▶ *(x + 1) = y1;
12    *r = y;
13    *(y + 1) = nxt;
14    *y = v;
15  } }
```

$\{r \mapsto y * \text{lseg}(x, S) * \text{lseg}(y, S)\}$

# Example: copy a linked list

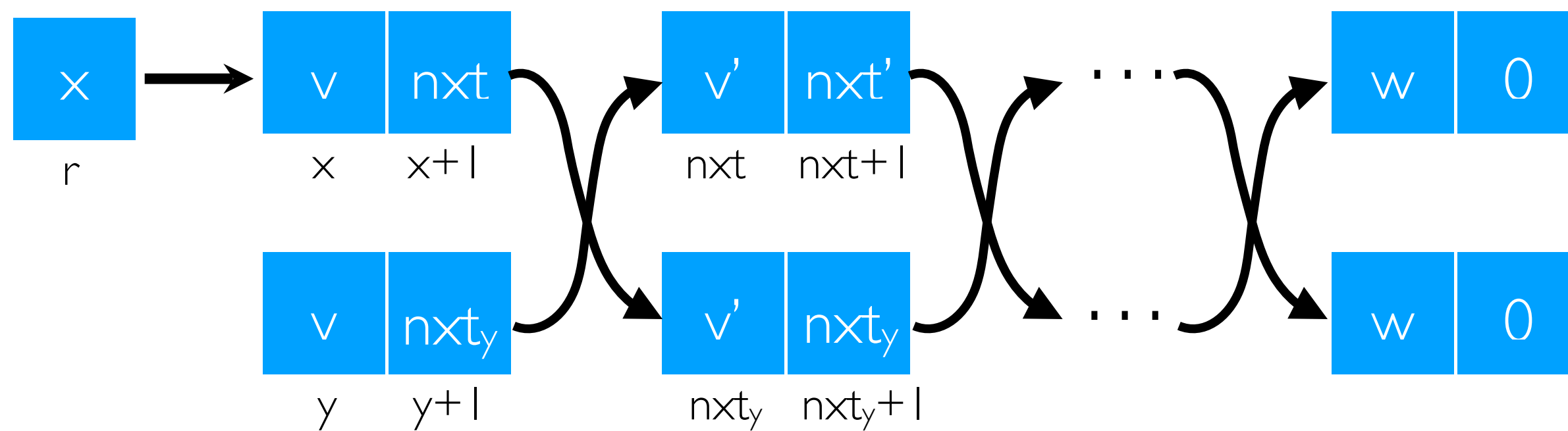


```
{r ↦ x * lseg(x, S)}
```

```
1 void listcopy (loc r) {  
2   let x = *r;  
3   if (x == 0) {  
4     } else {  
5     let v = *x;  
6     let nxt = *(x + 1);  
7     *r = nxt;  
8     listcopy(r);  
9     let y1 = *r;  
10    let y = malloc(2);  
11    *(x + 1) = y1;  
12    *r = y;  
13    *(y + 1) = nxt;  
14    *y = v;  
15  } }
```

```
{r ↦ y * lseg(x, S) * lseg(y, S)}
```

# Example: copy a linked list



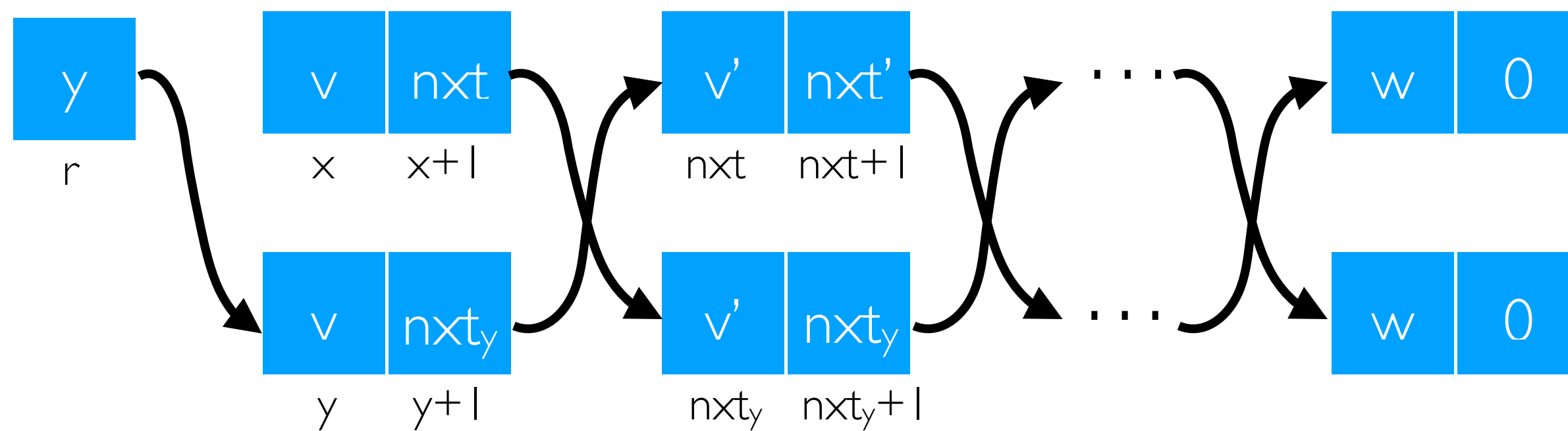
```
{r ↦ x * lseg(x, S)}
```

```
1 void listcopy (loc r) {  
2   let x = *r;  
3   if (x == 0) {  
4   } else {  
5     let v = *x;  
6     let nxt = *(x + 1);  
7     *r = nxt;  
8     listcopy(r);  
9     let y1 = *r;  
10    let y = malloc(2);  
11    *(x + 1) = y1;  
12    *r = y;  
13    *(y + 1) = nxt;  
14    *y = v;  
15  } }
```

```
{r ↦ y * lseg(x, S) * lseg(y, S)}
```



# Example: copy a linked list

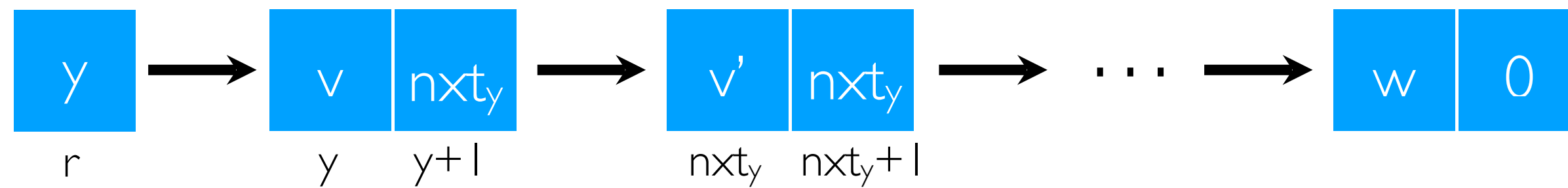
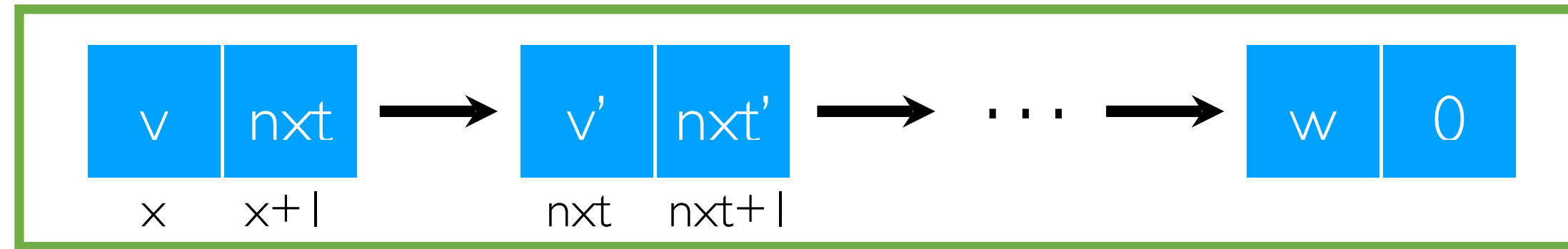


$\{r \mapsto x * \text{lseg}(x, S)\}$

```
1 void listcopy (loc r) {
2   let x = *r;
3   if (x == 0) {
4   } else {
5     let v = *x;
6     let nxt = *(x + 1);
7     *r = nxt;
8     listcopy(r);
9     let y1 = *r;
10    let y = malloc(2);
11    *(x + 1) = y1;
12    *r = y;
13    *(y + 1) = nxt;
14    *y = v;
15  } }
```

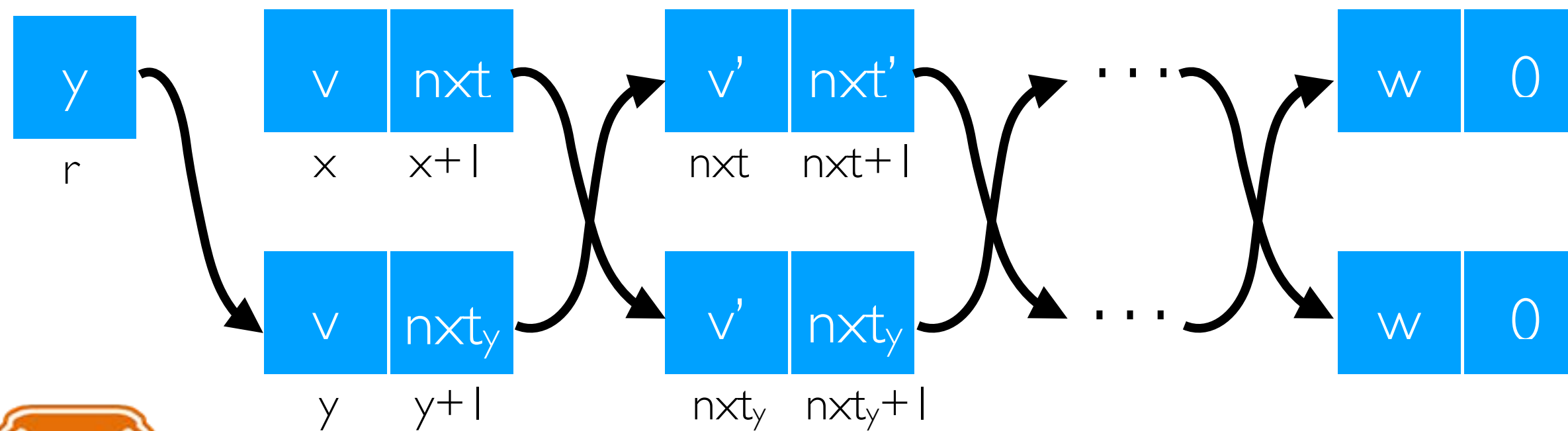
$\{r \mapsto y * \text{lseg}(x, S) * \text{lseg}(y, S)\}$

# Example: copy a linked list



expected

result



Spurious writes.



$\{r \mapsto x * lseg(x, S)\}$

```

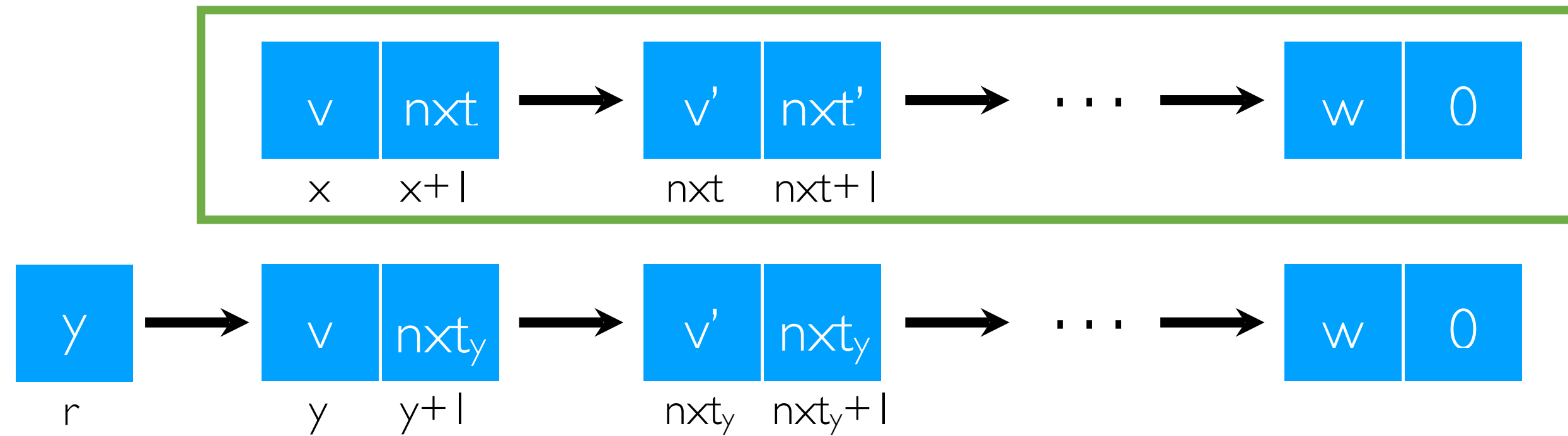
1 void listcopy (loc r) {
2   let x = *r;
3   if (x == 0) {
4   } else {
5     let v = *x;
6     let nxt = *(x + 1);
7     *r = nxt;
8     listcopy(r);
9     let y1 = *r;
10    let y = malloc(2);
11    *(x + 1) = y1;
12    *r = y;
13    *(y + 1) = nxt;
14    *y = v;
15  } }

```

$\{r \mapsto y * lseg(x, S) * lseg(y, S)\}$

# Example: copy a linked list

$\{r \mapsto x * \text{lseg}(x, S)\}$



```

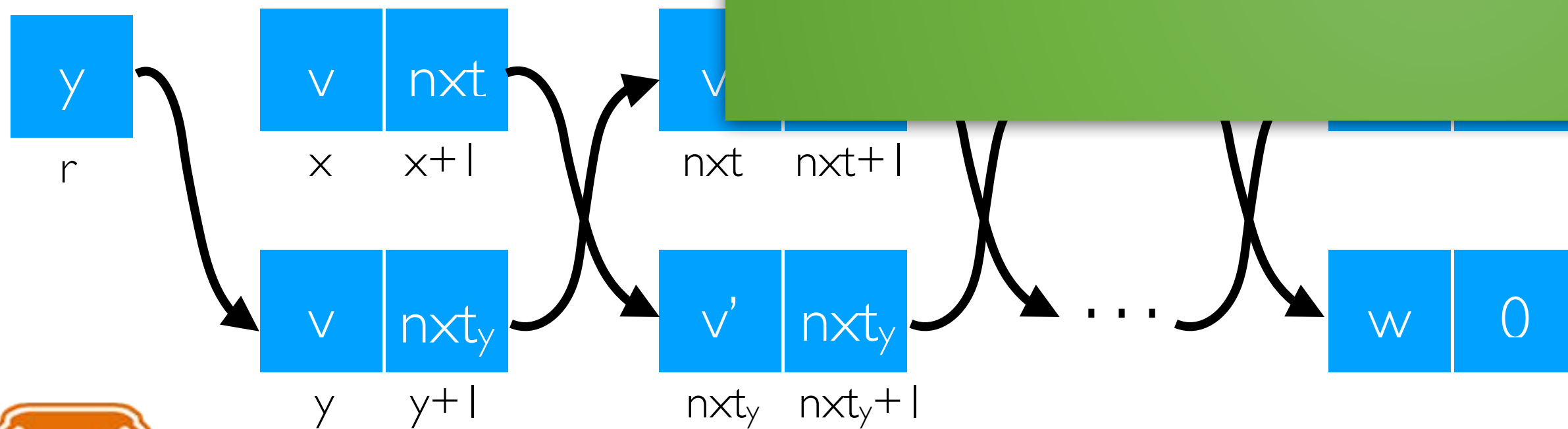
1 void listcopy (loc r) {
2   let x = *r;
3   if (x == 0) {
4   } else {
5     let v = *x;
6     let nxt = *(x + 1);

```

expected

result

Make the initial list *Read-Only*:  
it must not be altered



```

12   *r = y;
13   *(y + 1) = nxt;
14   *y = v;
15 } }

```



Spurious writes.

$\{r \mapsto y * \text{lseg}(x, S) * \text{lseg}(y, S)\}$

# Synthesis of Programs with Pointers via Read-Only Specifications

(our contribution)


Effective: more natural and shorter programs

Efficient: smaller search space—faster synthesis

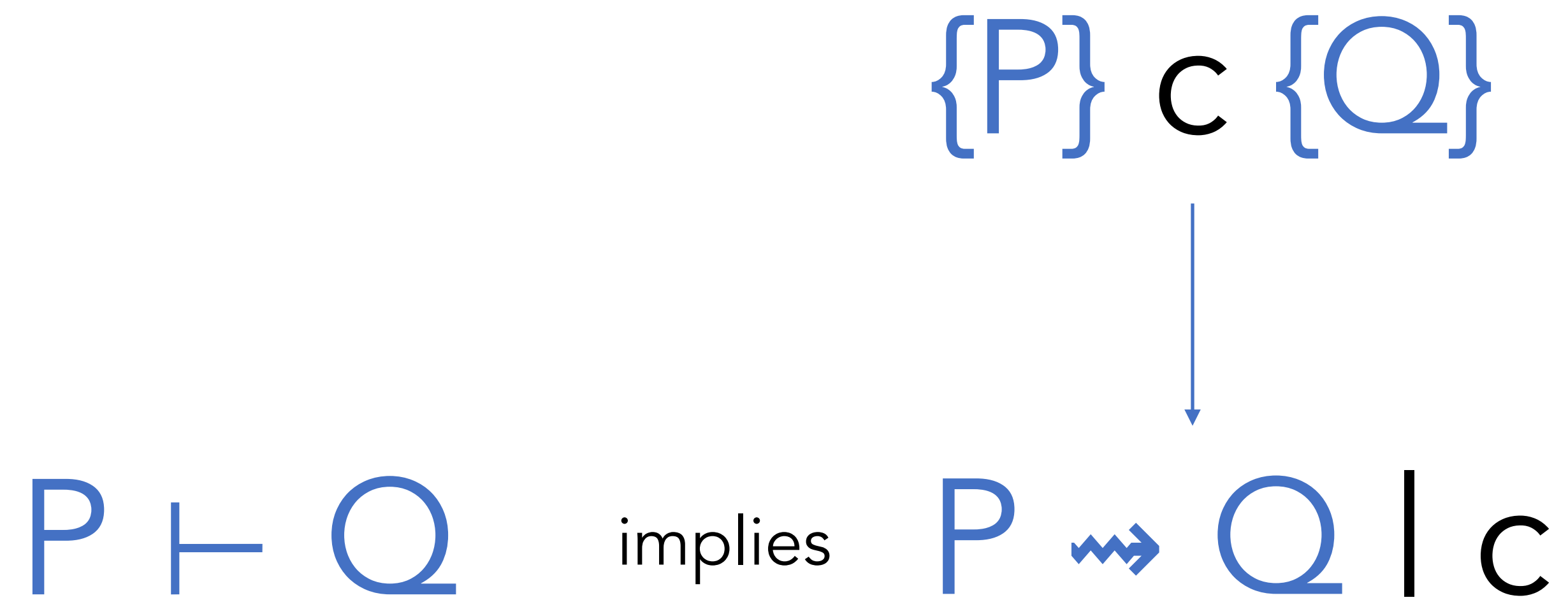
Robust: better performance in “worst case scenarios”

# A Primer on Synthetic Separation Logic

# Syntactic Separation Logic

$$\{P\} \text{ c } \{Q\}$$

$$P \rightsquigarrow Q \mid c$$

# Syntactic Separation Logic



# Example: **pick** - equalises the values of two distinct memory locations

Precondition:



x



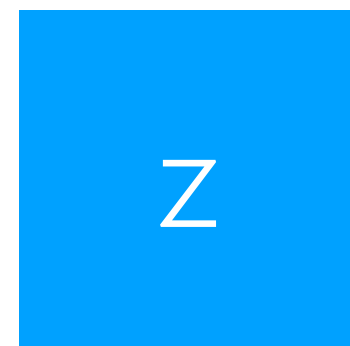
y

$$\{ x \mapsto a * y \mapsto b \}$$

Postcondition:



x



y

$$\{ x \mapsto z * y \mapsto z \}$$



# Example: **pick** - equalises the values of two distinct memory locations

Precondition:



$\{ x \mapsto a * y \mapsto b \}$

```
void pick(loc x, loc y) {  
    let a2 = *x;  
    let b2 = *y;  
    *y = a2;  
}
```

Postcondition:



$\{ x \mapsto z * y \mapsto z \}$

# Example: **pick** - equalises the values of two distinct memory locations

Precondition:



$\{ x \mapsto a * y \mapsto b \}$

```
void pick(loc x, loc y) {  
    let a2 = *x;  
    let b2 = *y;  
    *y = a2;  
}
```

Postcondition:



$\{ x \mapsto z * y \mapsto z \}$

# Example: **pick** - equalises the values of two distinct memory locations

Precondition:



$\{ x \mapsto a * y \mapsto b \}$

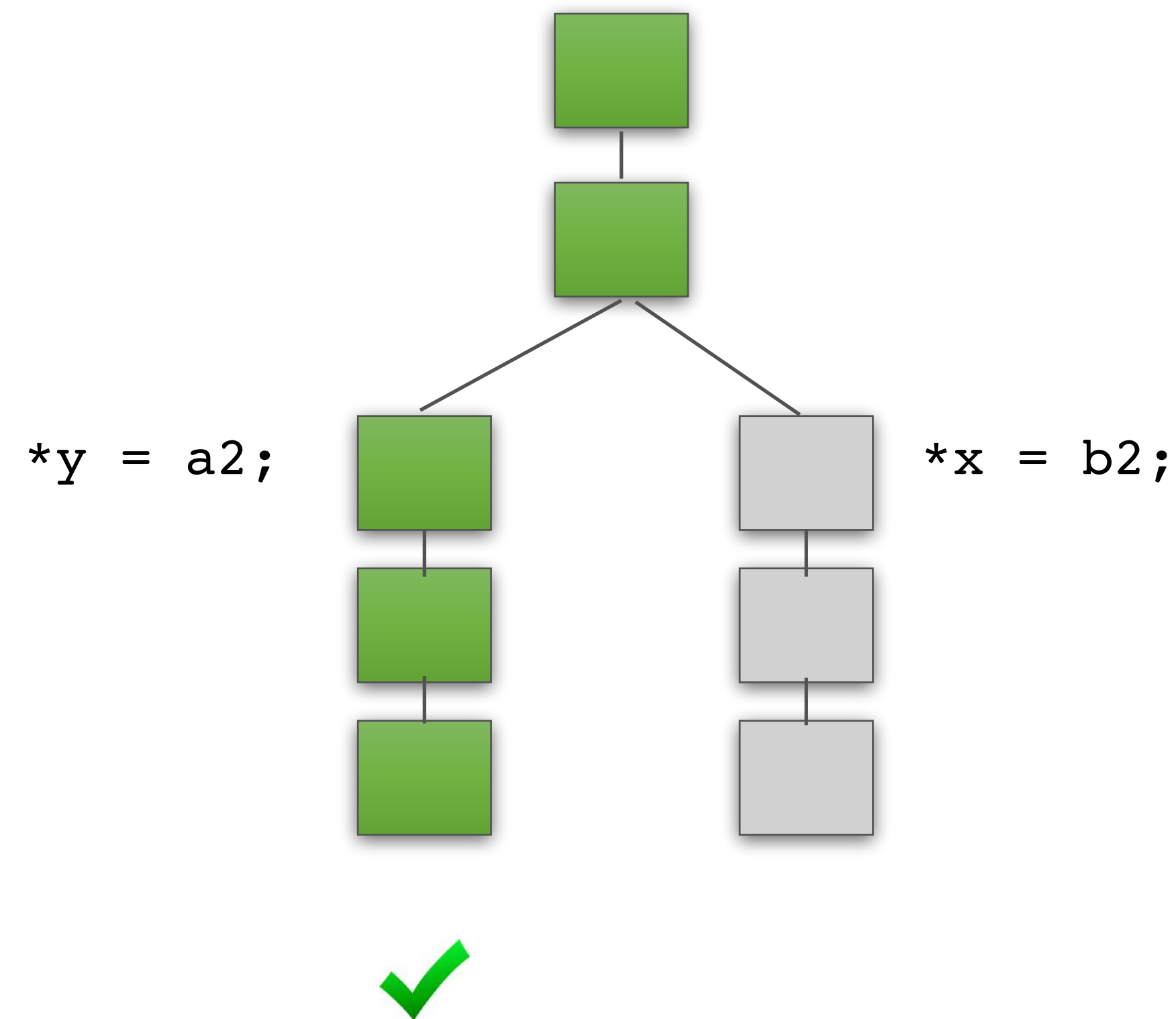
```
void pick(loc x, loc y) {  
    let a2 = *x;  
    let b2 = *y;  
    *x = b2;  
}
```

Postcondition:



$\{ x \mapsto z * y \mapsto z \}$

Example: **pick** - equalises the values of two distinct memory locations



```
{ x ↦ a * y ↦ b }
```

```
void pick(loc x, loc y) {
```

```
    let a2 = *x;
```

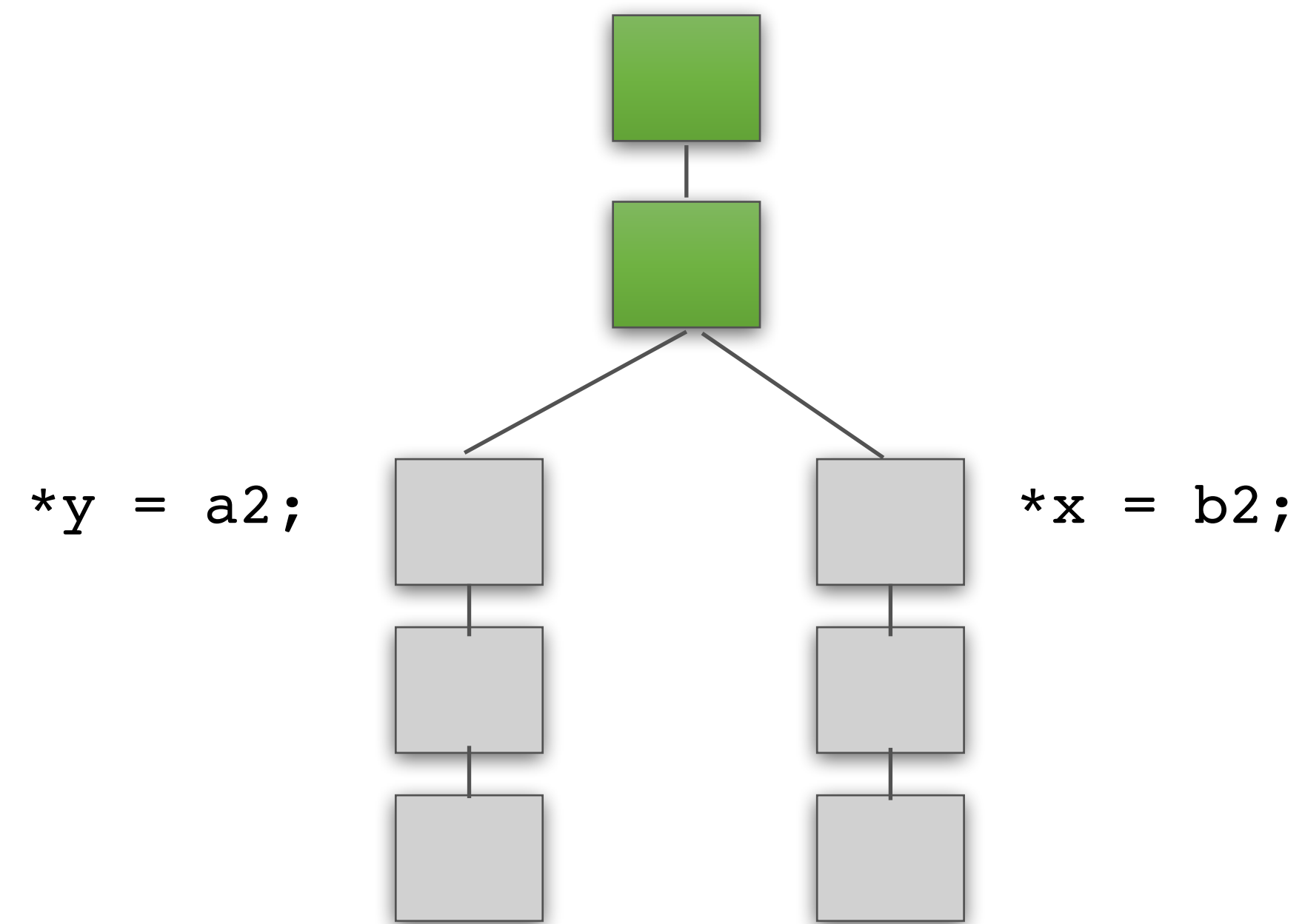
```
    let b2 = *y;
```

```
    *y = a2;
```

```
}
```

```
{ x ↦ z * y ↦ z }
```

Example: **pick** - equalises the values of two distinct memory locations

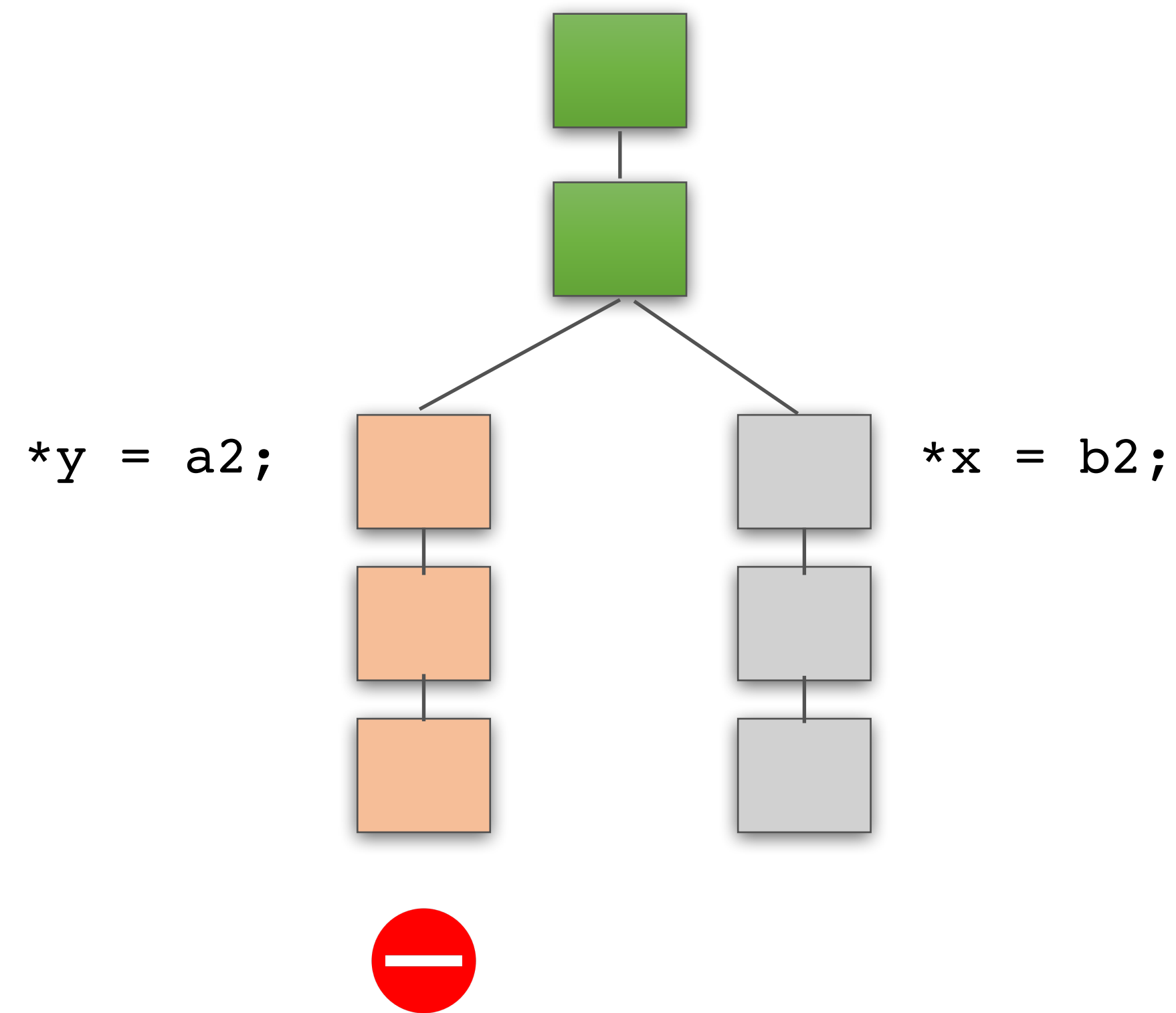


$\{ x \mapsto a * y \mapsto b \}$

```
void pick(loc x, loc y) {  
    let a2 = *x;  
    let b2 = *y;  
  
}
```

$\{ x \mapsto z * y \mapsto z \}$

Example: **pick** - equalises the values of two distinct memory locations

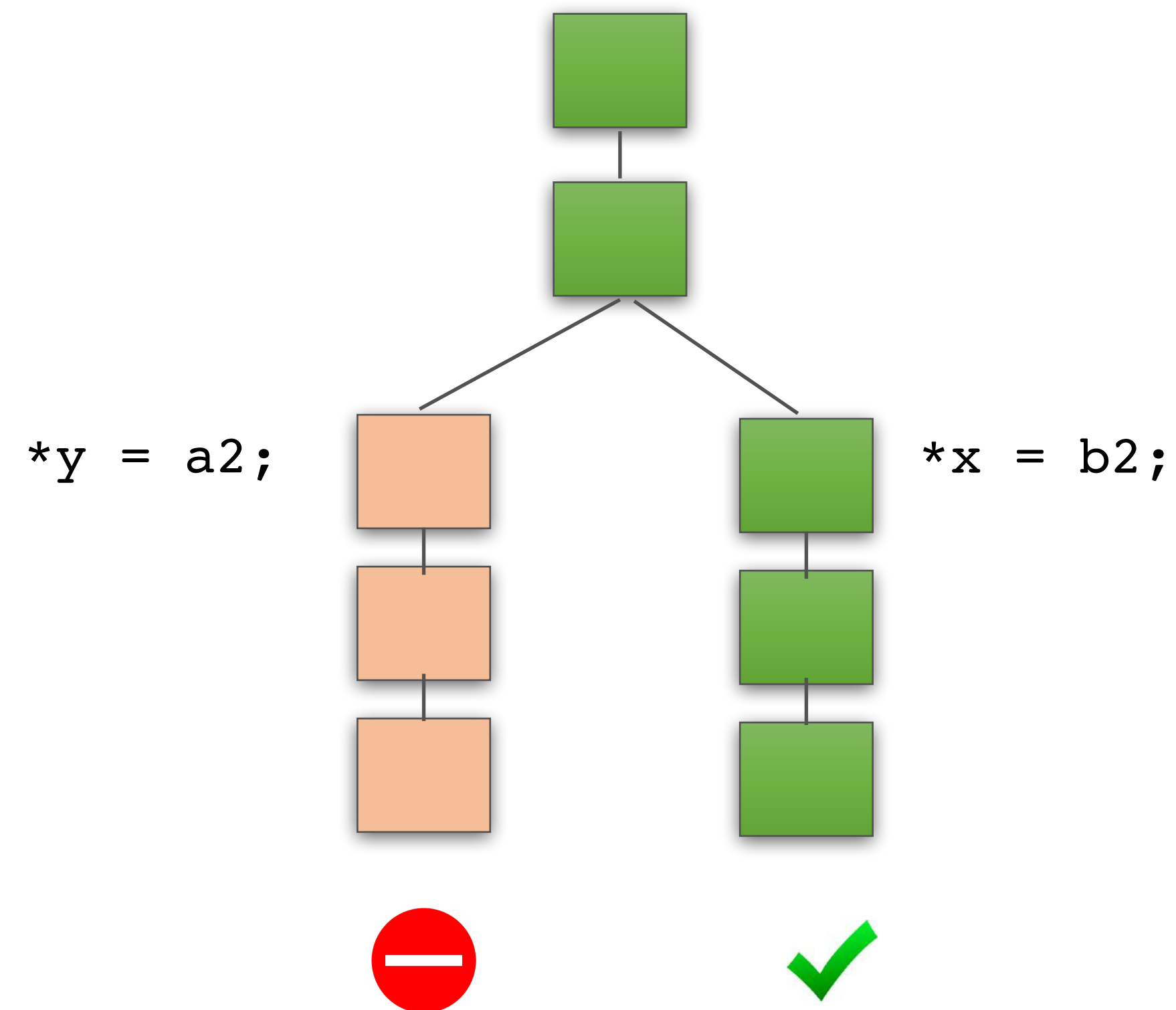


$\{ x \mapsto a * y \mapsto b \}$

```
void pick(loc x, loc y) {  
    let a2 = *x;  
    let b2 = *y;  
  
}
```

$\{ x \mapsto z * y \mapsto z \}$

Example: **pick** - equalises the values of two distinct memory locations



$\{ x \mapsto a * y \mapsto b \}$

```
void pick(loc x, loc y) {  
    let a2 = *x;  
    let b2 = *y;  
    *x = b2;  
}
```

$\{ x \mapsto z * y \mapsto z \}$

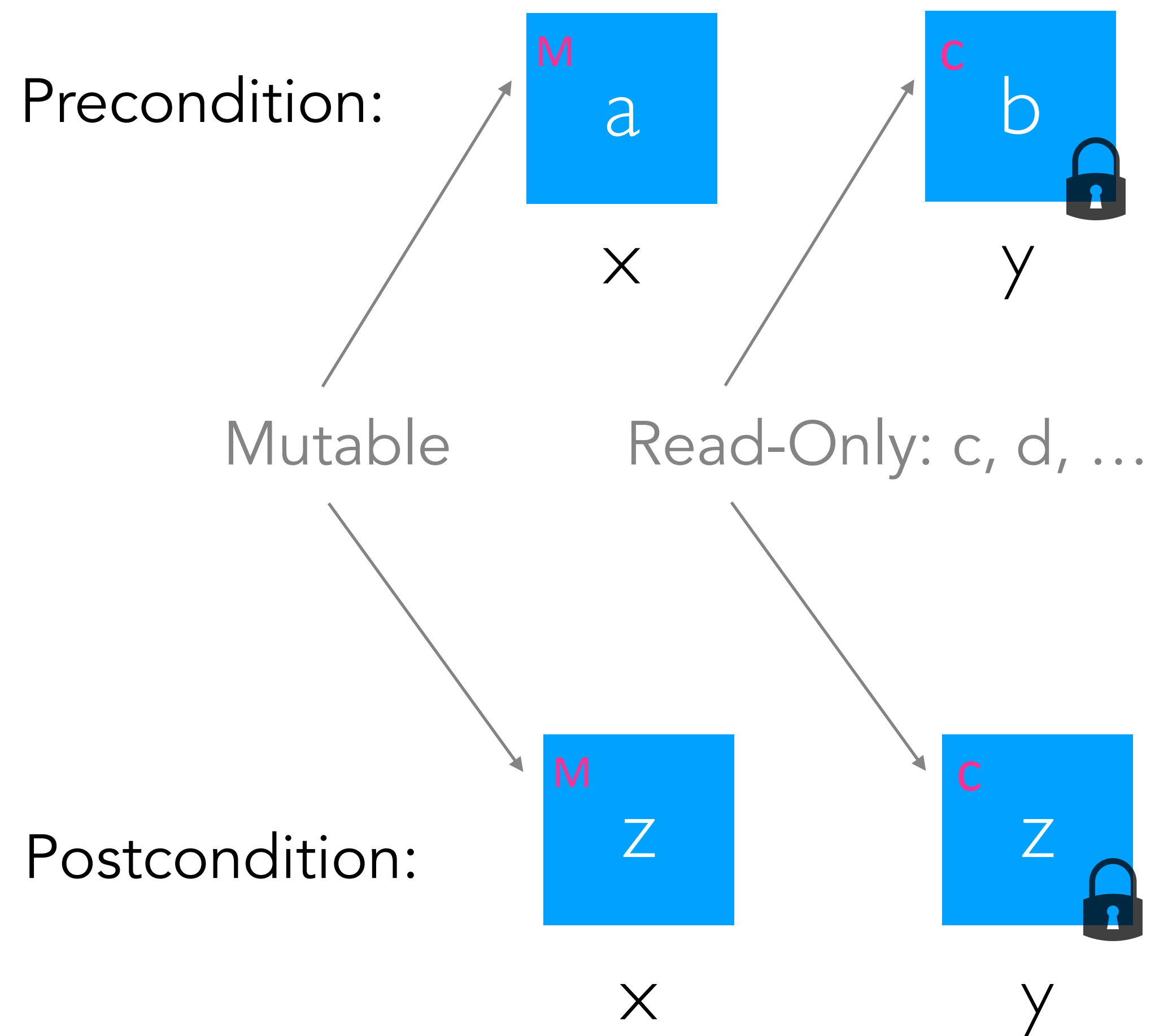
Example: **pick** - equalises the values of two distinct memory locations





# Read-Only Specifications

# Example: pick with **Read-Only Specifications**



```
{ x M ↦ a * y C ↦ b }
```

```
void pick(loc x, loc y) {  
    let a2 = *x;  
    let b2 = *y;  
    *y = a2;  
}
```

```
{ x M ↦ z * y C ↦ z }
```

# Example: pick with **Read-Only Specifications**

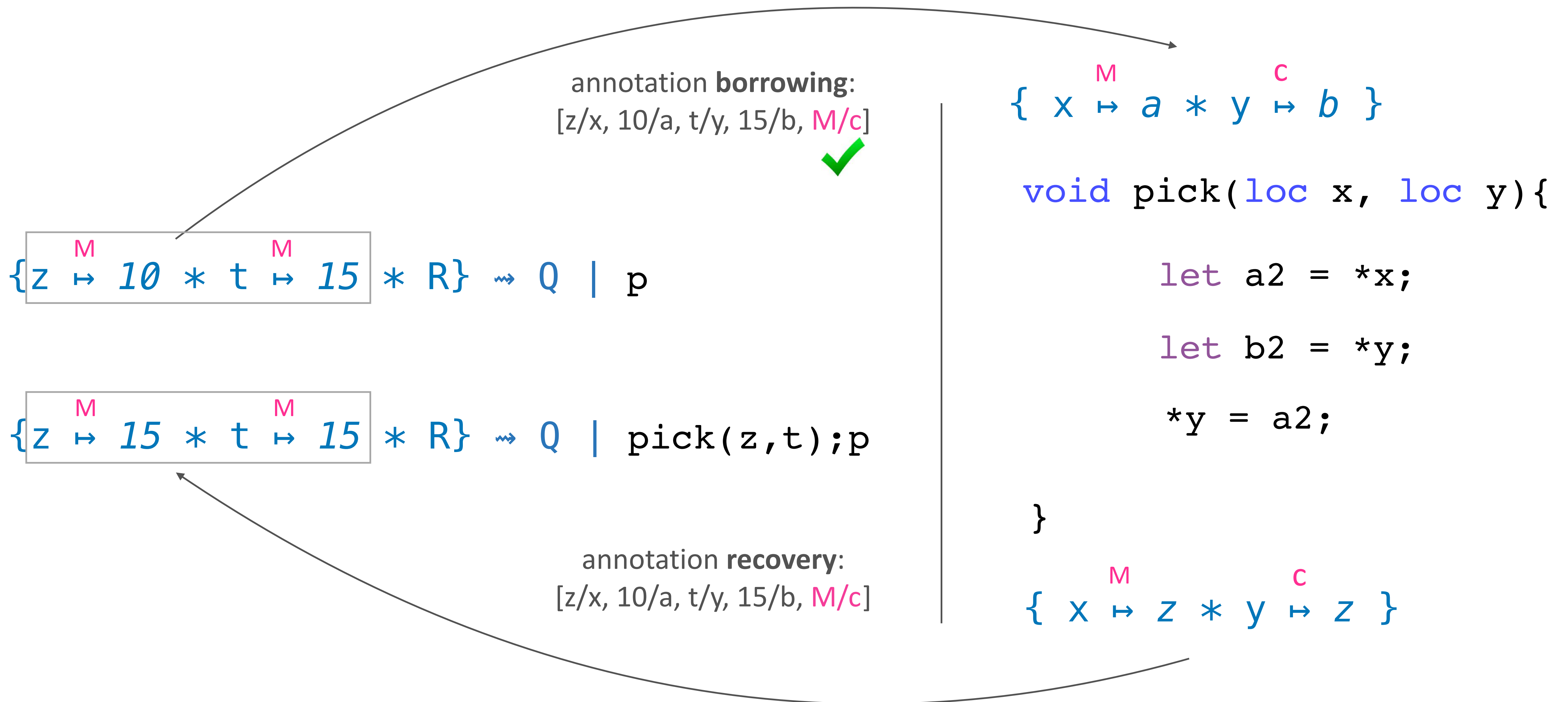
$\{z \overset{M}{\mapsto} 10 * t \overset{M}{\mapsto} 15 * R\} \rightsquigarrow Q \mid p$

$\{x \overset{M}{\mapsto} a * y \overset{C}{\mapsto} b\}$

```
void pick(loc x, loc y) {  
    let a2 = *x;  
    let b2 = *y;  
    *y = a2;  
}
```

$\{x \overset{M}{\mapsto} z * y \overset{C}{\mapsto} z\}$

# Example: pick with **Read-Only Specifications**



# Example: pick with **Read-Only Specifications**

$\{z \overset{d}{\mapsto} 10 * t \overset{M}{\mapsto} 15 * R\} \rightsquigarrow Q \mid p$

annotation borrowing:  
[z/x, 10/a, **d/M**, t/y, 15/b, **M/c**]

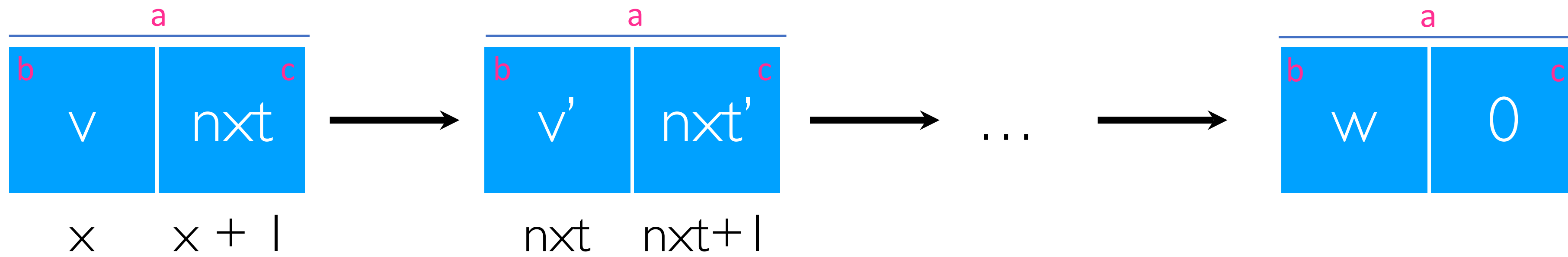


$\{x \overset{M}{\mapsto} a * y \overset{C}{\mapsto} b\}$

```
void pick(loc x, loc y) {  
    let a2 = *x;  
    let b2 = *y;  
    *y = a2;  
}
```

$\{x \overset{M}{\mapsto} z * y \overset{C}{\mapsto} z\}$

# Example: copy of a linked list Read-Only Specifications



# Example: copy of a linked list

`{r ↦ x * lseg(x,S,a,b,c) }`

`void listcopy (loc r)`

`{r ↦ y * lseg(x,S,a,b,c) * lseg(y,S,M,M,M)}`

read-only

mutable

# Example: copy of a linked list

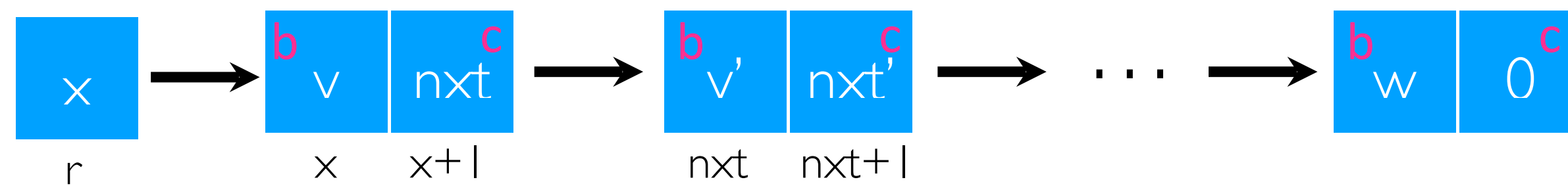
```
{r ↦ x * lseg(x,S,a,b,c) }
```

```
void listcopy (loc r)
```

```
{r ↦ y * lseg(x,S,a,b,c) * lseg(y,S,M,M,M)}
```



# Example: copy of a linked list

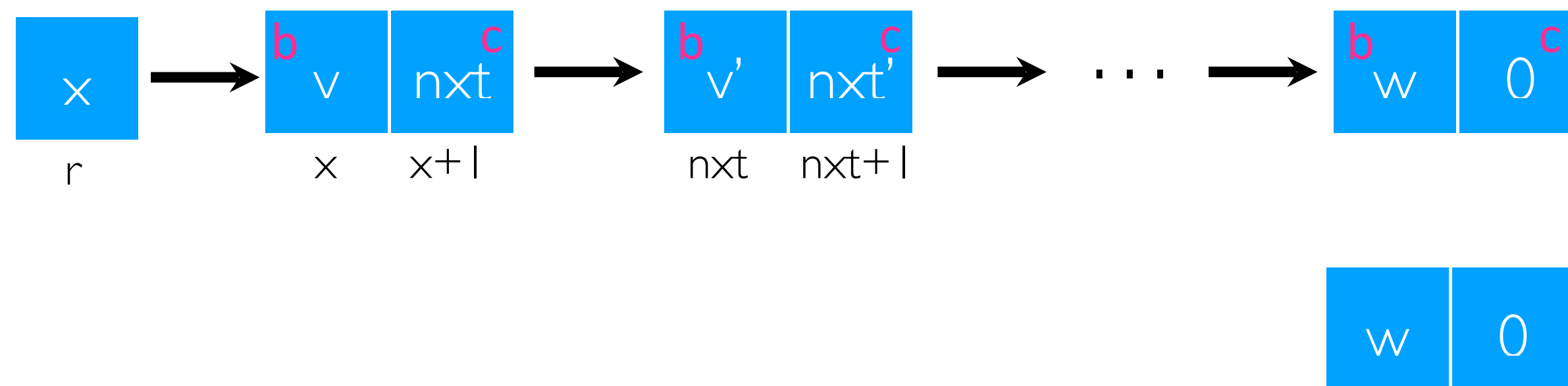


```
{r ↦ x * lseg(x,S,a,b,c) }
```

```
1 void listcopy (loc r) {  
2   let x = *r;  
3   if (x == 0) {  
4   } else {  
5     let v = *x;  
6     let nxt = *(x + 1);  
7     *r = nxt;  
8     listcopy(r);  
9     let y1 = *r;  
10    let y = malloc(2);  
11    *(x + 1) = y1;  
12    *r = y;  
13    *(y + 1) = nxt;  
14    *y = v;  
15  } }
```

```
{r ↦ y * lseg(x,S,a,b,c) * lseg(y,S,M,M,M)}
```

# Example: copy of a linked list

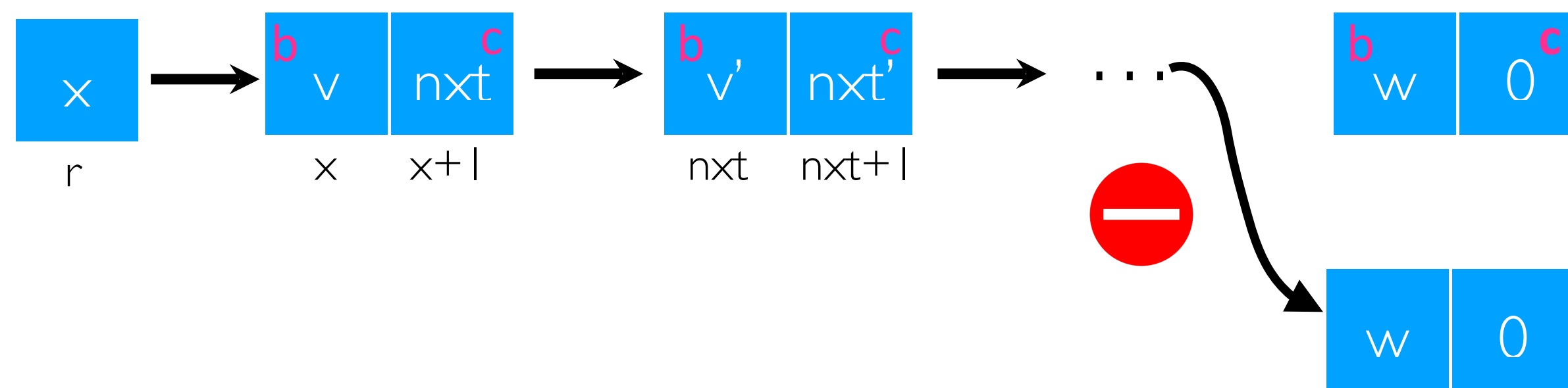


```
{r ↦ x * lseg(x,S,a,b,c) }
```

```
1 void listcopy (loc r) {  
2   let x = *r;  
3   if (x == 0) {  
4   } else {  
5     let v = *x;  
6     let nxt = *(x + 1);  
7     *r = nxt;  
8     listcopy(r);  
9     let y1 = *r;  
10    let y = malloc(2);  
11    *(x + 1) = y1;  
12    *r = y;  
13    *(y + 1) = nxt;  
14    *y = v;  
15  } }
```

```
{r ↦ y * lseg(x,S,a,b,c) * lseg(y,S,M,M,M)}
```

# Example: copy of a linked list



$\nabla$   
 $\{r \mapsto x * \text{lseg}(x, S, a, b, c) \}$

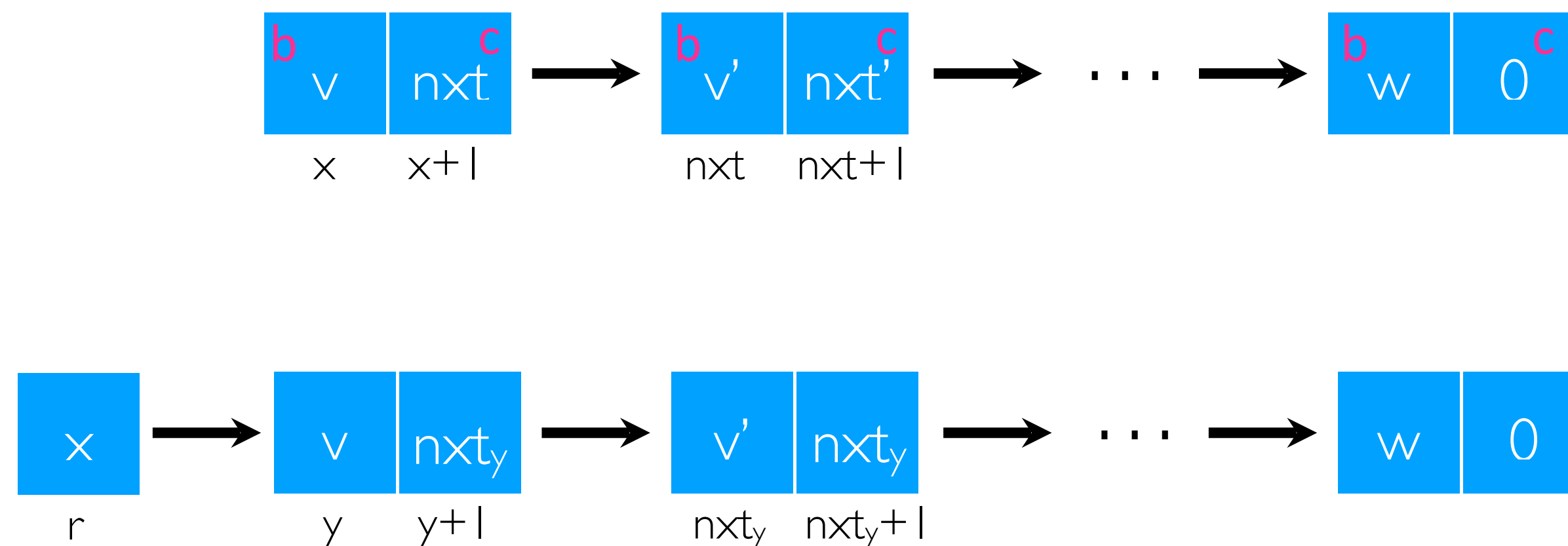
```

1 void listcopy (loc r) {
2   let x = *r;
3   if (x == 0) {
4   } else {
5     let v = *x;
6     let nxt = *(x + 1);
7     *r = nxt;
8     listcopy(r);
9     let y1 = *r;
10    let y = malloc(2);
11    *(x + 1) = y1;
12    *r = y;
13    *(y + 1) = nxt;
14    *y = v;
15  } }

```

$\{r \mapsto y * \text{lseg}(x, S, a, b, c) * \text{lseg}(y, S, M, M, M) \}$

# Example: copy of a linked list



```
{r ↦ x * lseg(x, S, a, b, c) }
```

```

1 void listcopy (loc r) {
2   let x = *r;
3   if (x == 0) {
4   } else {
5     let v = *x;
6     let nxt = *(x + 1);
7     *r = nxt;
8     listcopy(r);
9     let y1 = *r;
10    let y = malloc(2);
11
12    *r = y;
13    *(y + 1) = y1 ;
14    *y = v;
15  } }

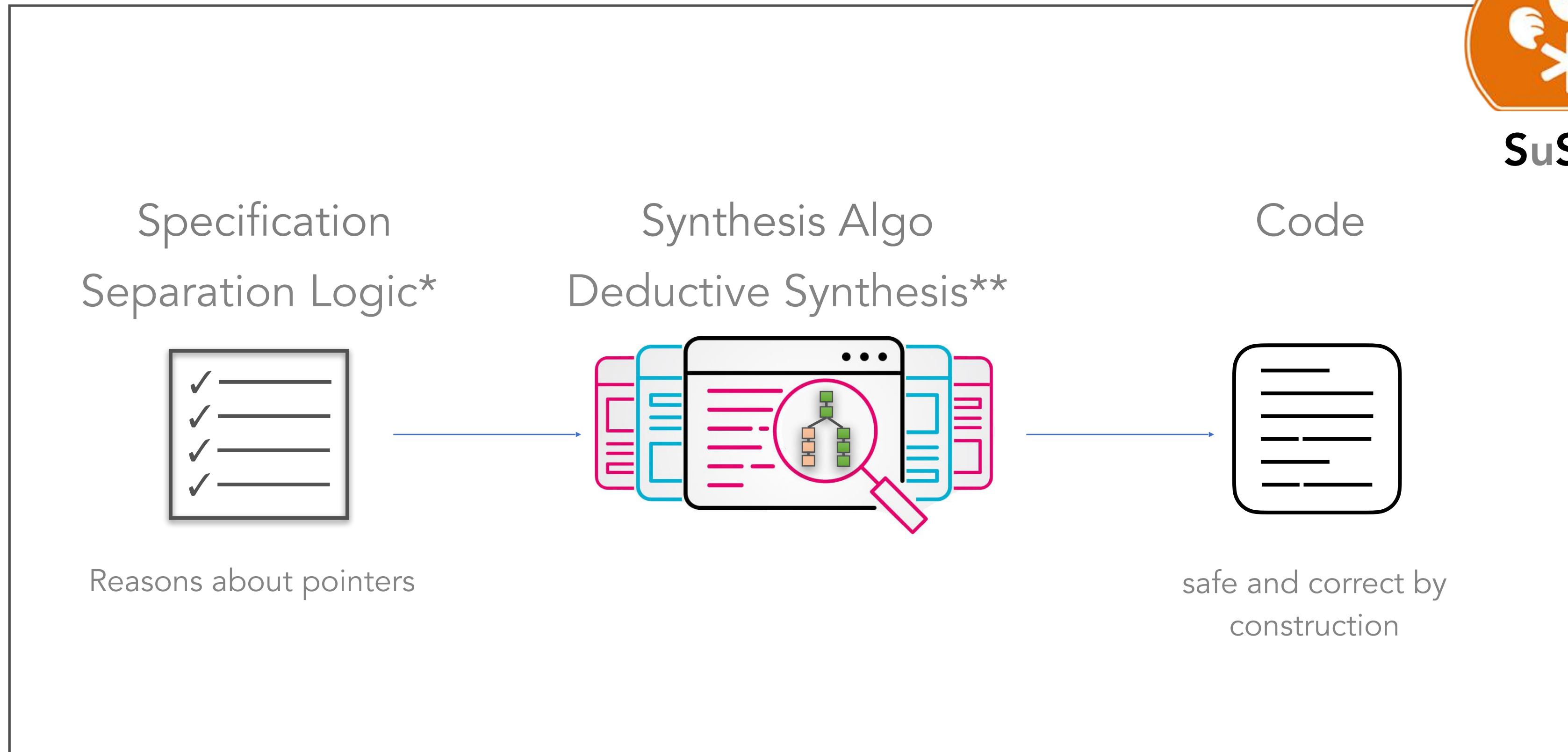
```

```
{r ↦ y * lseg(x, S, a, b, c) * lseg(y, S, M, M, M)}
```

# SSL: Synthetic Separation Logic



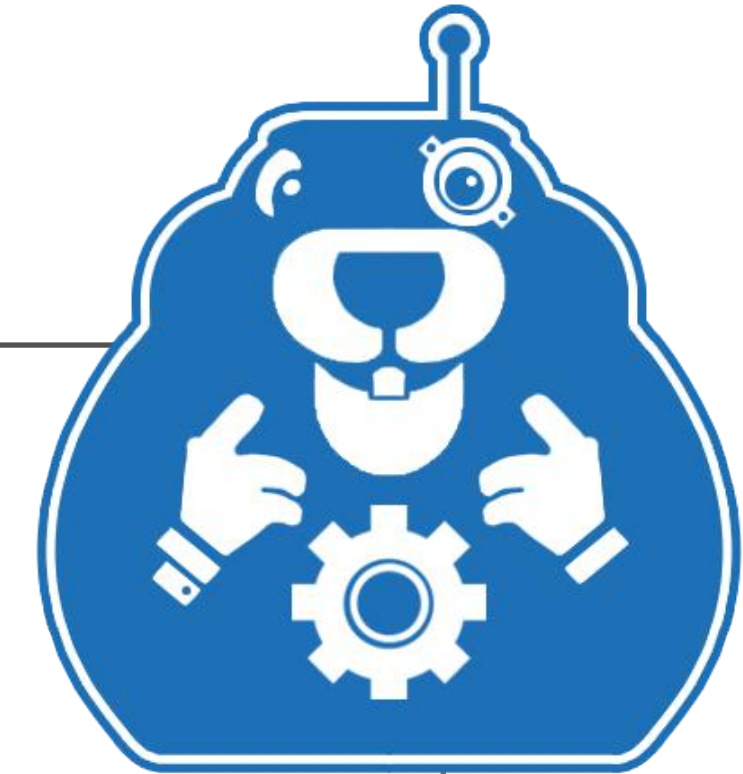
**SuSLik**



\* *Local Reasoning about Programs that Alter Data Structures*, O'Hearn, Reynolds, Yang: CSL 2001

\*\* *Structuring the Synthesis of Heap-Manipulating Programs*, Polikarpova & Sergey @POPL'19

# BoSSL: Borrowing Synthetic Separation Logic



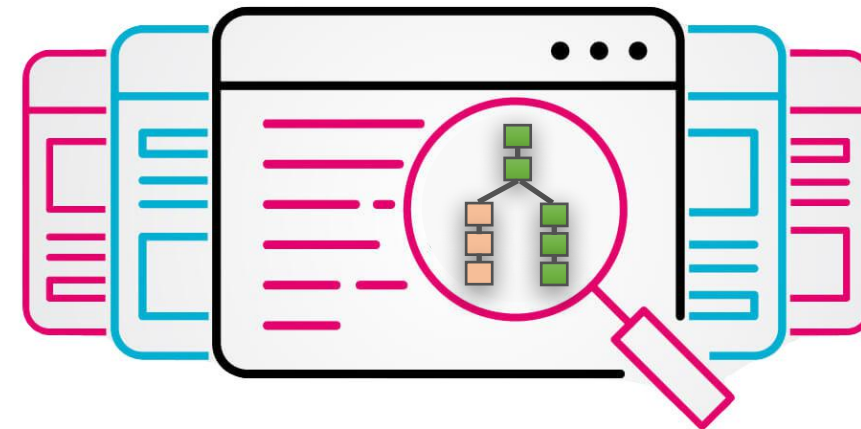
Specification  
Separation Logic\*



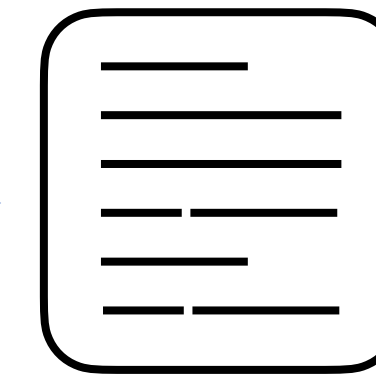
Reasons about pointers



Synthesis Algo  
Deductive Synthesis\*\*

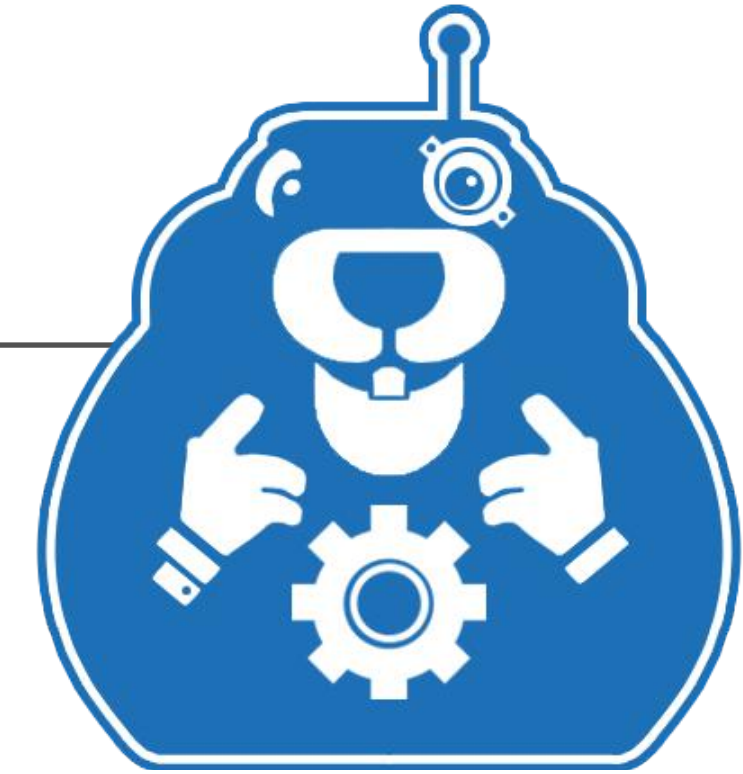


Code

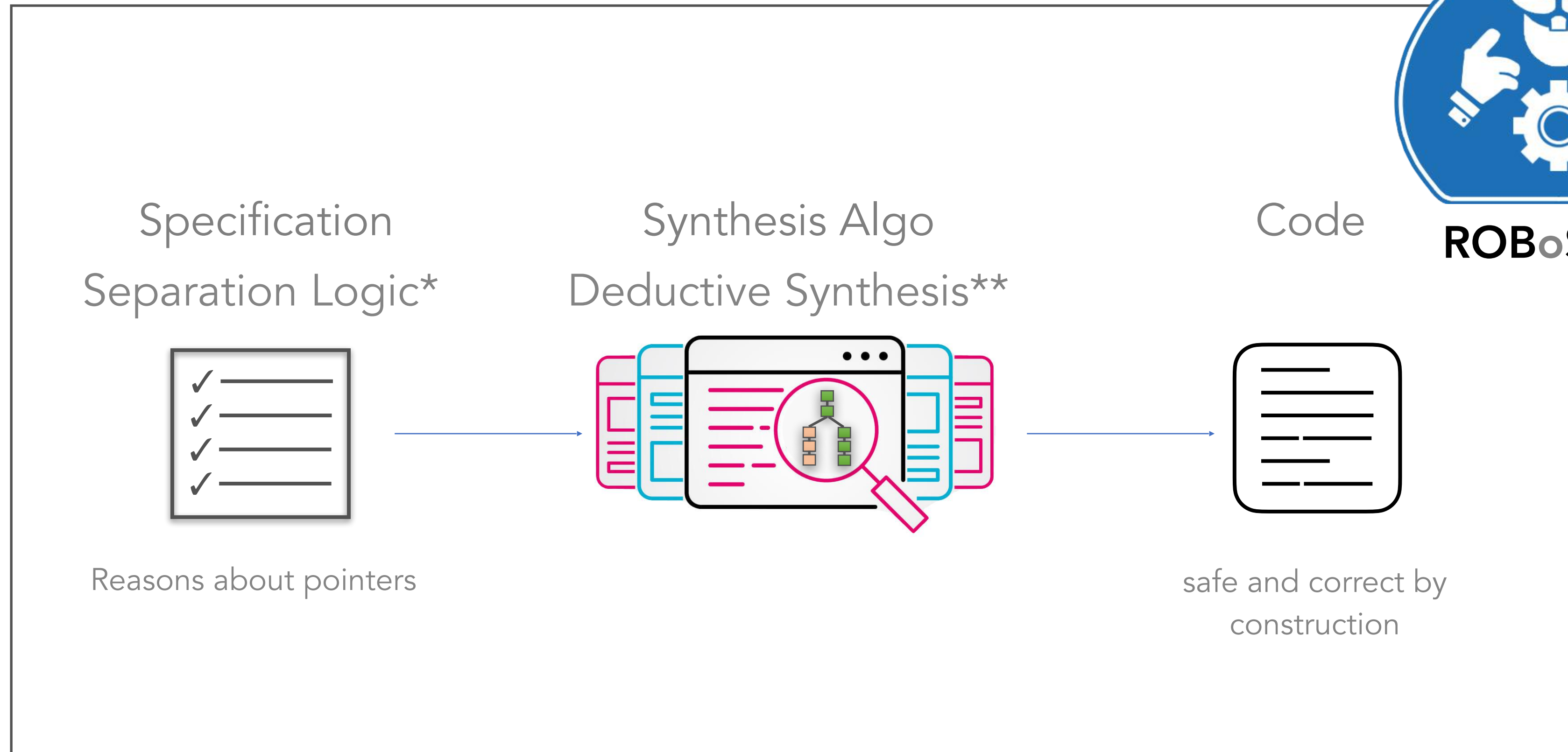


safe and correct by  
construction

# BoSSL: Borrowing Synthetic Separation Logic



**ROBoSuSLik**



<https://github.com/TyGuS/robosuslik>

# Synthesis of Programs with Pointers via Read-Only Specifications

(our contribution)

Effective: more natural and shorter programs

Efficient: smaller search space—faster synthesis

Robust: better performance in “worst case scenarios”



# Synthesis of Programs with Pointers via Read-Only Specifications

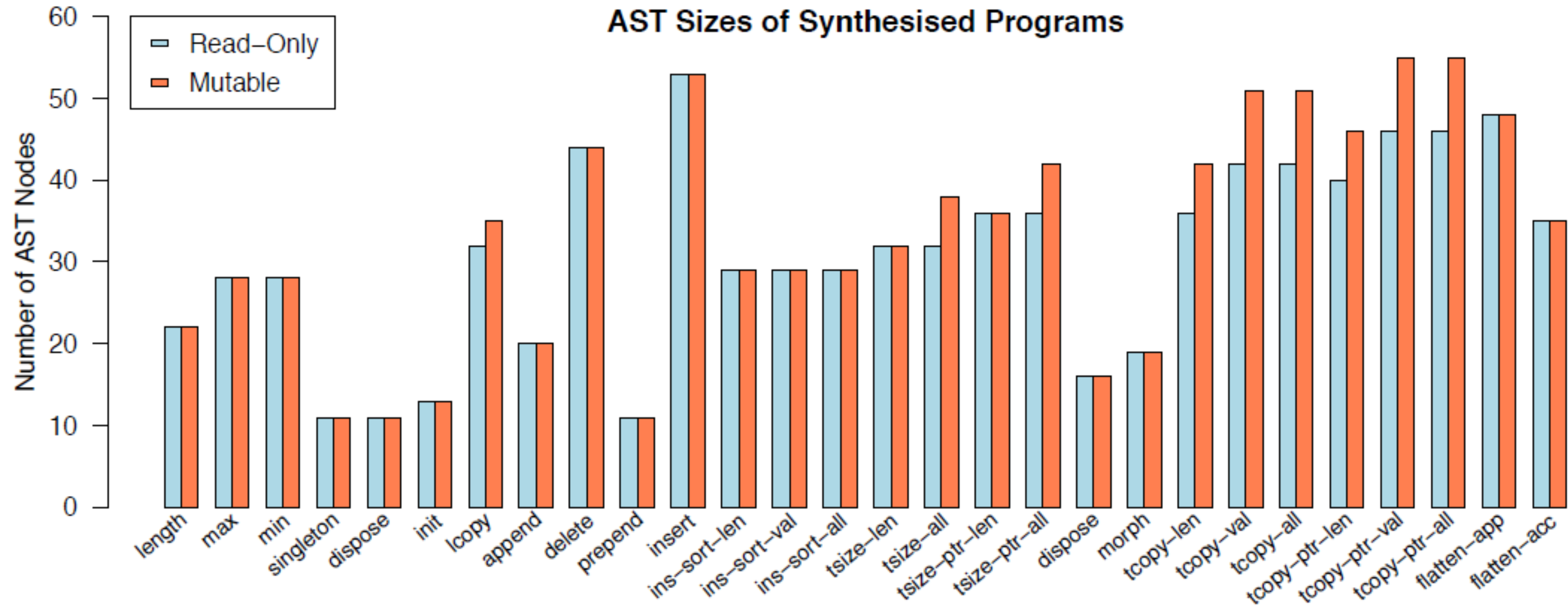
(our contribution)

Effective: more natural and shorter programs

Efficient: smaller search space—faster synthesis

Robust: better performance in “worst case scenarios”

# Results 1 – AST size



# Synthesis of Programs with Pointers via Read-Only Specifications

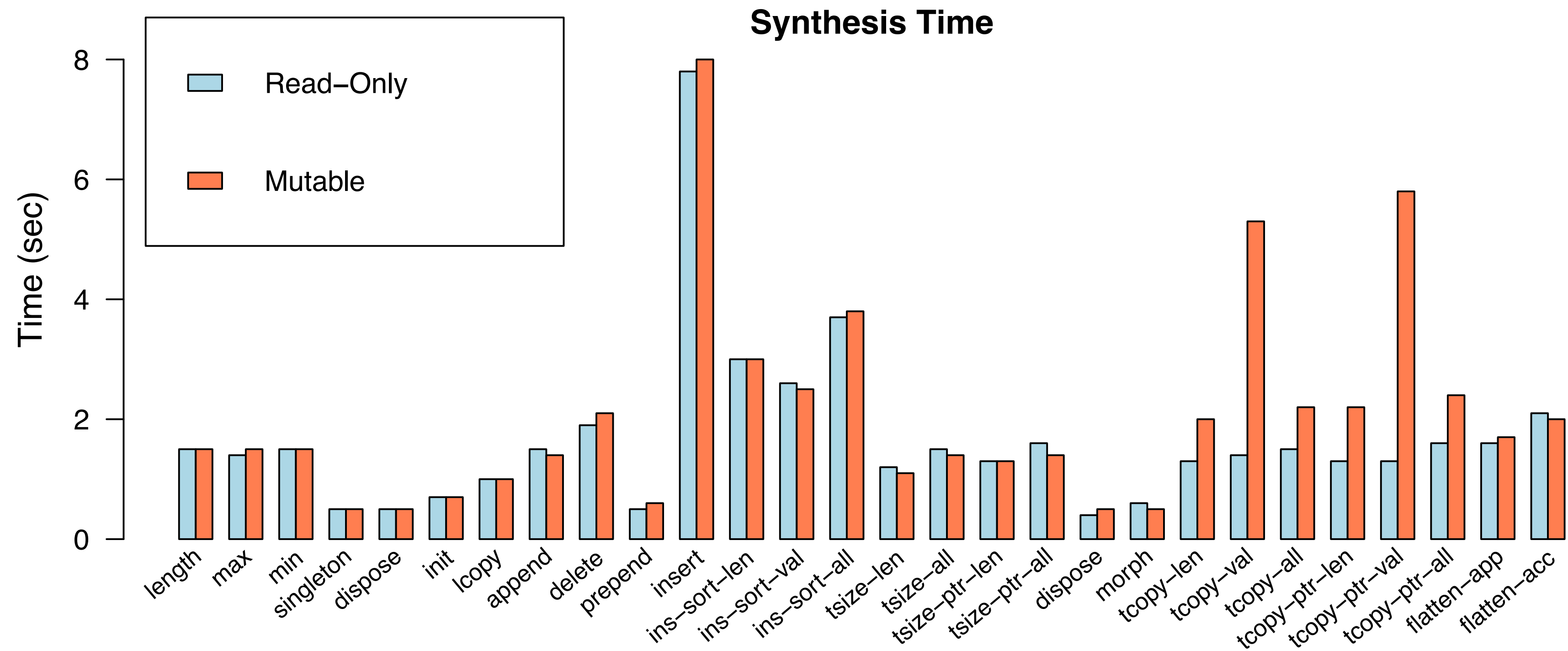
(our contribution)

Effective: more natural and shorter programs

Efficient: smaller search space—faster synthesis

Robust: better performance in “worst case scenarios”

# Results 2 – Synthesis time



# Synthesis of Programs with Pointers via Read-Only Specifications

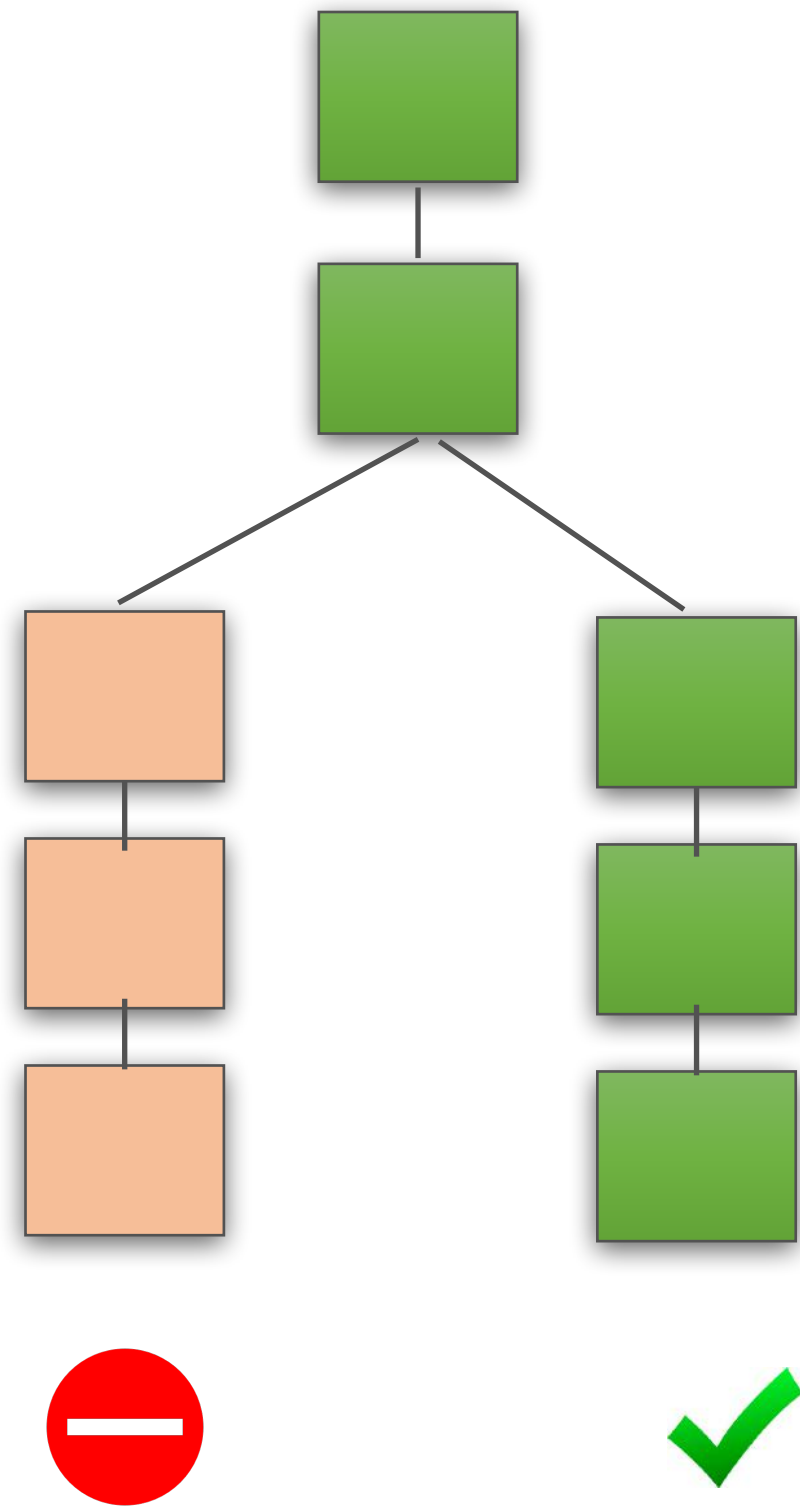
(our contribution)

Effective: more natural and shorter programs

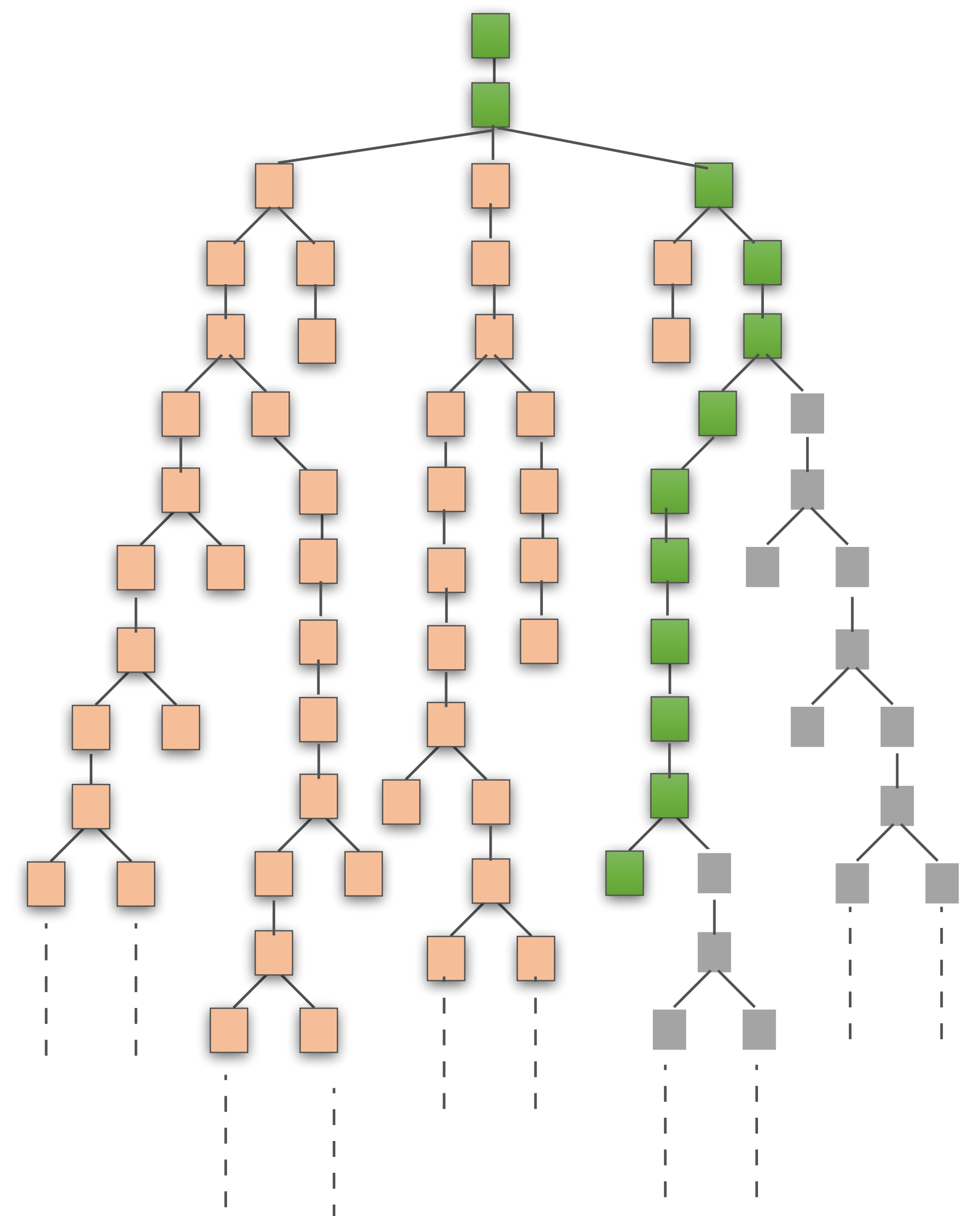
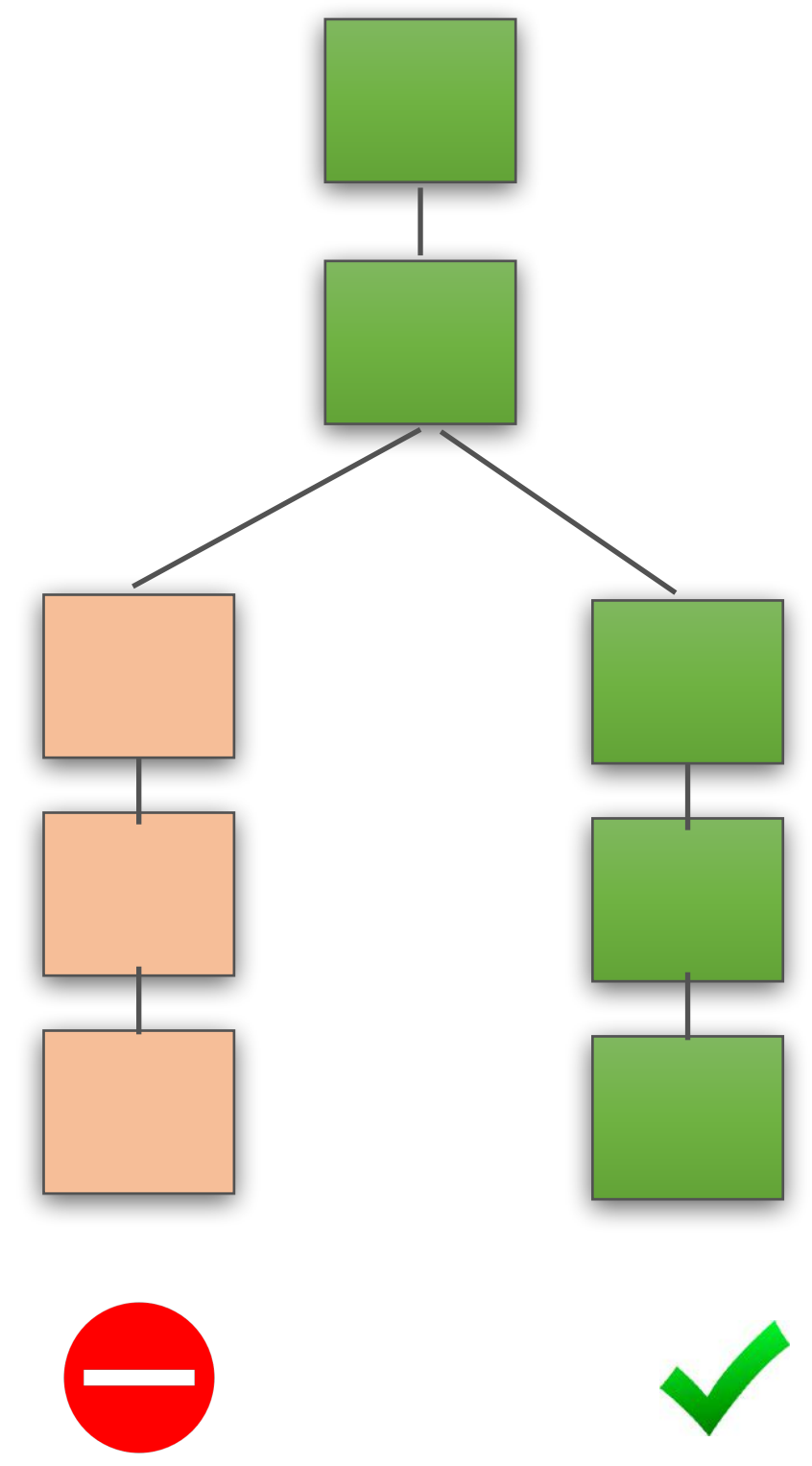
Efficient: smaller search space—faster synthesis

Robust: better performance in “worst case scenarios”

# Robustness

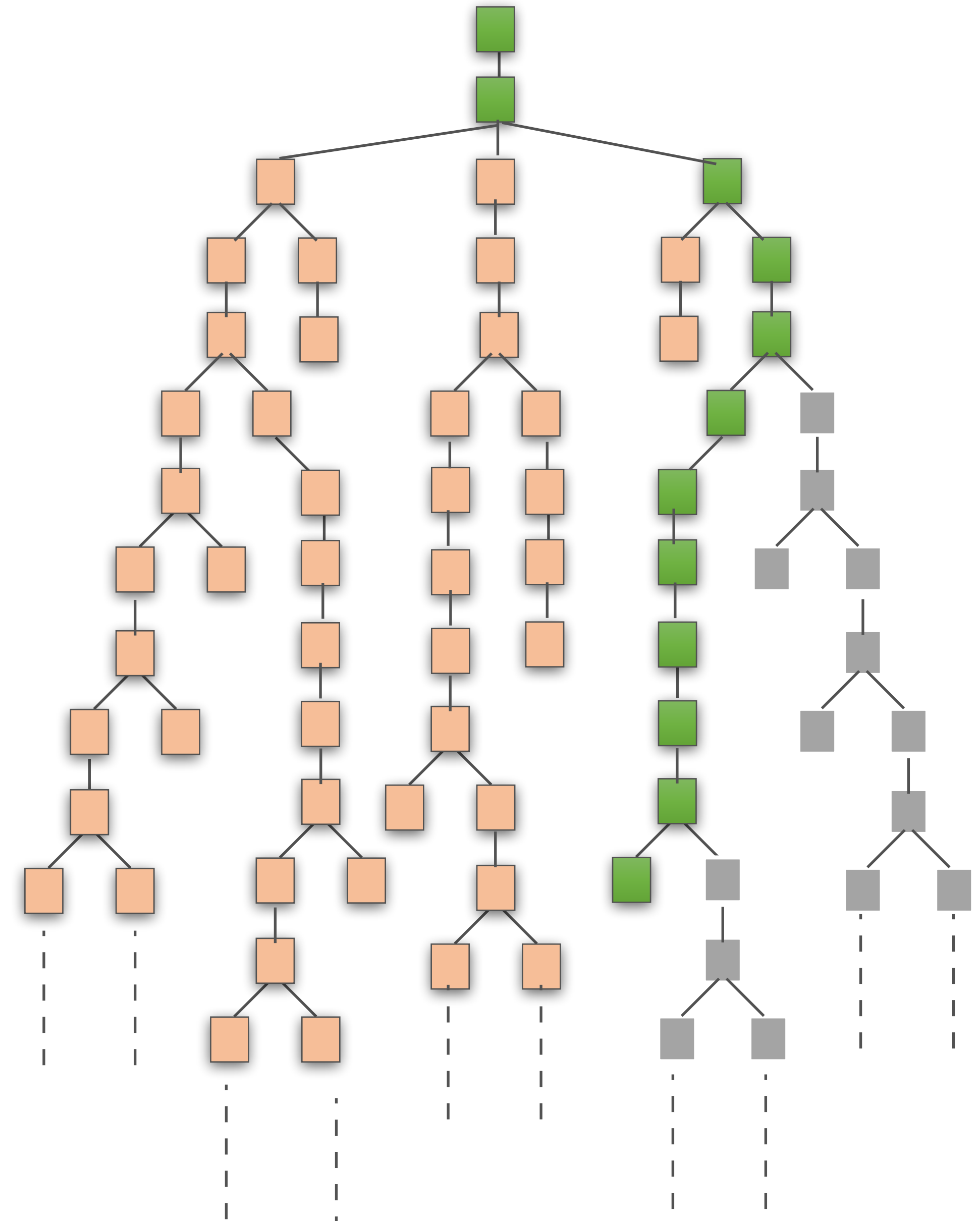


# Robustness



# Robustness

Is ROBoSuSLik always outperforming SuSLik irrespective of the employed search heuristic?



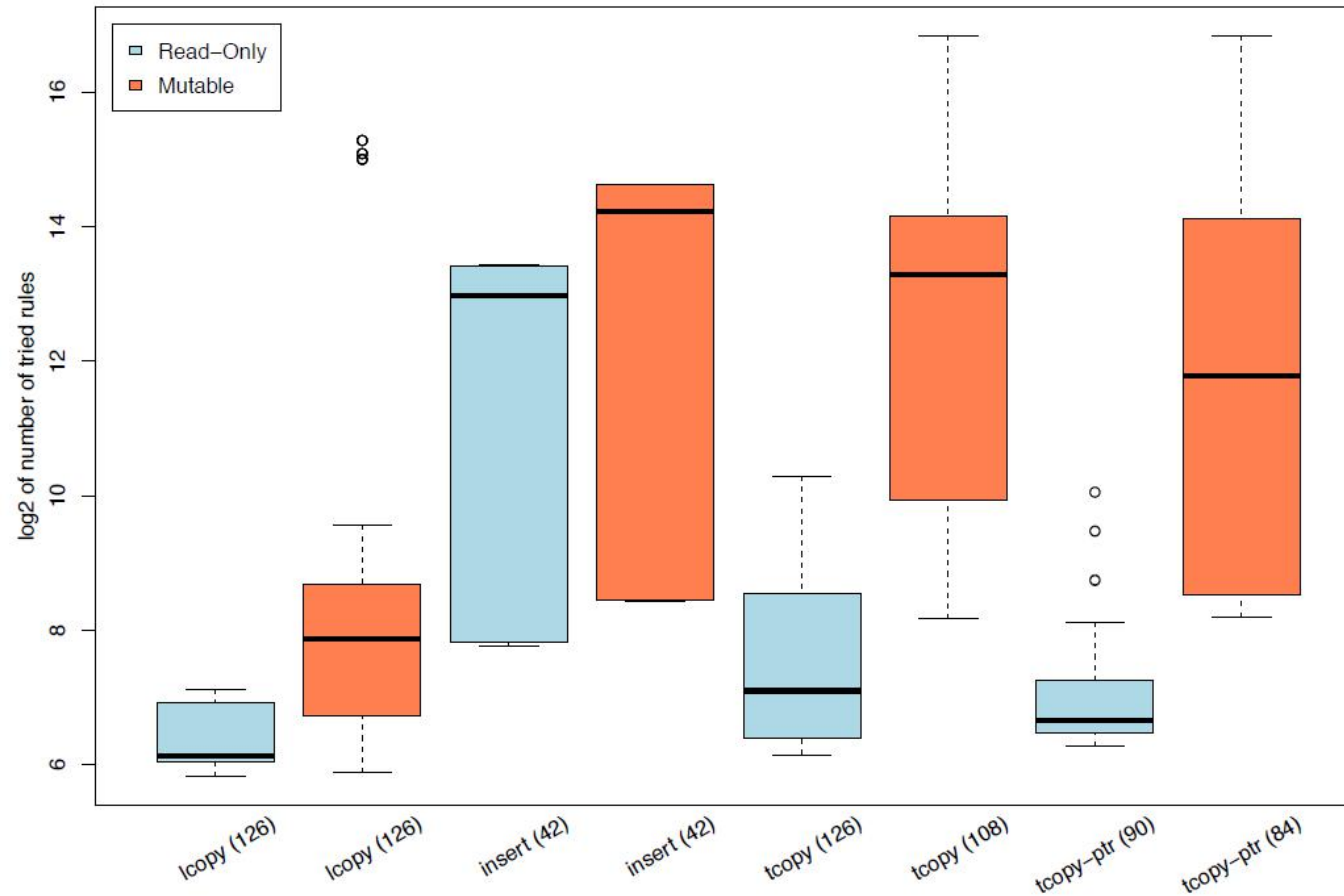


# Robustness - search heuristics variations

We explored:

- ▶ 3 variants of specification
- ▶ 6 different unification orders strategies
- ▶ 7 different search strategies

# Results 3 – No of fired rules



the shorter the  
boxplots the better 🍌

# Synthesis of Programs with Pointers via Read-Only Specifications

(our contribution)

Effective: more natural and shorter programs

Efficient: smaller search space—faster synthesis

Robust: better performance in “worst case scenarios”

# Read-Only Specifications: Related Work

Fractional Permissions [Boyland 2003]

Chalice [Leino et al. 2009],  
Verifast [Jacobs et al. 2011]

Abstract permissions [Heule et al., 2013]

Viper [Muller et al. 2016]

Immutable Specifications [David et al. 2011]

Read-Only Assertions [Chargueraud et al. 2017]

Disjoint Permissions [Bach et al. 2018]



Tailored for verification,  
not for synthesis!

# Synthesis of Programs with Pointers via Read-Only Specifications

(our contribution)

Effective: more natural and shorter programs

Efficient: smaller search space—faster synthesis

Robust: better performance in “worst case scenarios”

**Thank You!**

# To Take-Away

Adding borrows to SSL improves the synthesis efficiency:

synthesised programs of better **quality**

improved synthesis **performance**

**stronger correctness guarantees**

**robust** synthesis

**Thank You!**

# References

- Karl Naden, Robert Bocchino, Jonathan Aldrich, and Kevin Bierho. A type system for borrowing permissions. In POPL, pages 557 - 570. ACM, 2012.
- John Boyland. Checking Interference with Fractional Permissions. In SAS, volume 2694 of LNCS, pages 55 - 72. Springer, 2003.
- K. Rustan M. Leino and Peter Muller. A Basis for Verifying Multi-threaded Programs. In ESOP, volume 5502 of LNCS, pages 378-393. Springer, 2009.
- K. Rustan M. Leino, Peter Muller, and Jan Smans. Verification of Concurrent Programs with Chalice. In Foundations of Security Analysis and Design V, FOSAD 2007/2008/2009 Tutorial Lectures, volume 5705 of LNCS, pages 195-222. Springer, 2009.
- Bart Jacobs, Jan Smans, Pieter Philippaerts, Frederic Vogels, Willem Penninckx, and Frank Piessens. VeriFast: A Powerful, Sound, Predictable, Fast Verifier for C and Java. In NASA Formal Methods, volume 6617 of LNCS, pages 41-55. Springer, 2011.
- Peter Muller, Malte Schwerhoff, and Alexander J. Summers. Viper: A Verification Infrastructure for Permission-Based Reasoning. In VMCAI, volume 9583 of LNCS, pages 41-62. Springer, 2016.
- Cristina David and Wei-Ngan Chin. Immutable specifications for more concise and precise verification. In OOPSLA, pages 359 - 374. ACM, 2011.
- Arthur Chargueraud and Francois Pottier. Temporary Read-Only Permissions for Separation Logic. In ESOP, volume 10201 of LNCS, pages 260 - 286. Springer, 2017.
- Xuan Bach Le and Aquinas Hobor. Logical reasoning for disjoint permissions. In ESOP, volume 10801 of LNCS, pages 385-414. Springer, 2018.

# Proof Search Algorithm

- Goal-driven, with *backtracking* (in CPS), trying a fixed set of rules;
- *Branching*: some rules emit many alternatives;
- Along with the program, emits the *complete proof tree*.
- *Optimisations*: Invertible Rules (*cf. Focusing in Proof Theory*),
- phased search, “Early Failure” rules



# Separation Logic

starting in a state that satisfies **P**,  
program **c** will execute *without memory errors*, and  
upon its termination the state will satisfy **Q**.

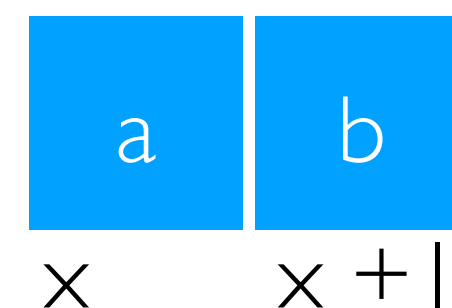
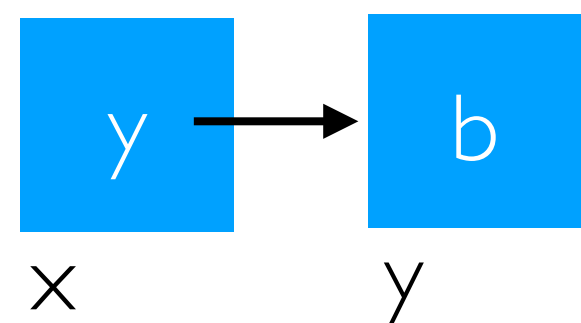
$$\{P\} c \{Q\}$$

empty heap  
singleton heap  
separating conjunction  
memory block  
pure constraints

$\{ \text{emp} \}$   
 $\{ x \mapsto a \}$   
 $\{ x \mapsto y * y \mapsto b \}$   
 $\{ [x, 2] * x \mapsto a * (x+1) \mapsto b \}$   
 $\{ a > 0 ; x \mapsto a \}$

do nothing  
read from heap  
write to heap  
allocate block  
free block  
procedure call  
sequential composition  
conditional

skip  
let  $y = *(x + n)$   
 $*(x + n) = e$   
let  $y = \text{malloc}(n)$   
free(x)  
 $p(e_1, \dots, e_n)$   
 $c_1; c_2$   
if (e) {c1} else {c2}



# Read-Only Specifications: Related Work

Fractional Permissions [Boyland 2003]

Chalice [Leino et al. 2009],  
Verifast [Jacobs et al. 2011]

Abstract permissions [Heule et al., 2013]

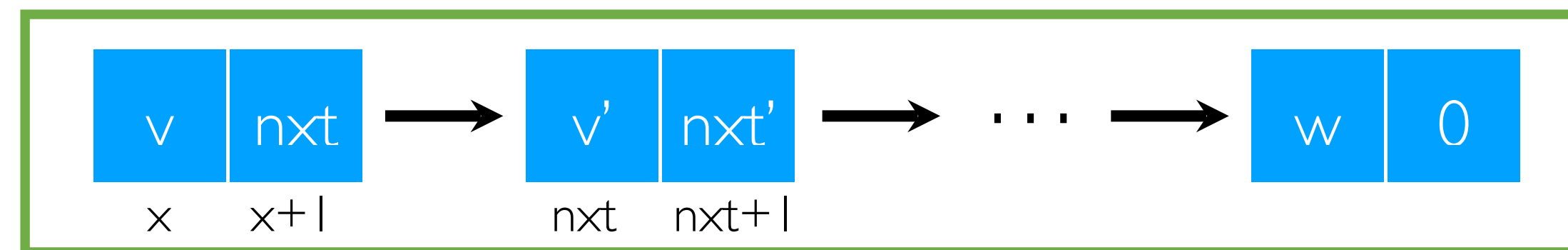
Viper [Muller et al. 2016]

Immutable Specifications [David et al. 2011]

Read-Only Assertions [Chargueraud et al. 2017]



Tailored for verification,  
not for synthesis!



# Example

$\{r \mapsto x * \text{ls}(x, S)\}$

void listcopy (loc r)

$\{r \mapsto y * \text{ls}(x, S) * \text{ls}(y, S)\}$



R: Add RO permissions.

# Example

$\{r \mapsto x * \text{ls}(x, S)[\text{RO}, \text{RO}]\}$

void listcopy (loc r)

$\{r \mapsto y * \text{ls}(x, S)[\text{RO}, \text{RO}] * \text{ls}(y, S)[\text{M}, \text{M}]\}$



R: Add RO permissions.

# Example

$\{r \mapsto x * \text{ls}(x, S)[RO,RO] \}$

void listcopy (loc r)

$\{r \mapsto y * \text{ls}(x, S)[RO,RO] * \text{ls}(y, S)[M,M] \}$

# Example

```
{r ↦ x * ls(x, S)[RO,RO] }
```

```
void listcopy (loc r)
```

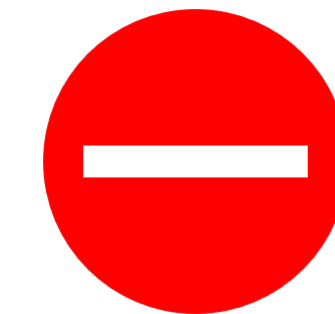
```
{r ↦ y * ls(x, S)[RO,RO] * ls(y, S)[M,M] }
```

```
// ... <caller>...:
```

```
// z ↦ x' * ls(x', S')[M,M]
```

```
listcopy(z)
```

```
// z ↦ y * ls(x', S')[RO,RO] * ls(y, S')[M,M]
```



# Example

```
{r ↦ x * ls(x, S)[a,b] }  
void listcopy (loc r)  
{r ↦ y * ls(x, {0})[a,b] * ls(y, S)[M,M] }  
  
// ... <caller>...:  
// r ↦ x * ls(x, S)[M,M]  
listcopy(z)  
// r ↦ x * ls(x, S)[M,M]
```

# Setup

*Varied* the properties captured in the inductive definitions.

Applied 42 kinds of *perturbations* to stress the proof search strategy.



# SuSLik -> ROBoSuSLik

<https://github.com/TyGuS/suslik>



(**Synthesis using Separation Logik**)<sup>1</sup>

1. [Polikarpova & Sergey @POPL'19]

<https://github.com/TyGuS/suslik/tree/borrows>



(**Read-Only Borrows for Synthesis using Separation Logik**)<sup>2</sup>

2. [Costea, Zhu, Polikarpova, Sergey @ESOP'20]

# SSL: basic rules

(Emp)

$\{\text{emp}\} \rightsquigarrow \{\text{emp}\} \mid ??$

# SSL: basic rules

(Emp)

$\{\text{emp}\} \rightsquigarrow \{\text{emp}\} \mid \text{skip}$

# SSL: basic rules

(Read)

---

$$\{ x \mapsto A * P \} \rightsquigarrow \{ Q \} |$$

# SSL: basic rules

(Read)

$$\frac{[y/A] \{x \mapsto A * P\} \rightsquigarrow [y/A] \{Q\} \mid c}{\{x \mapsto A * P\} \rightsquigarrow \{Q\} \mid \text{let } y = *x; c}$$

# SSL: basic rules

(Read)

$$\frac{[y/A] \{x \mapsto A * P\} \rightsquigarrow [y/A] \{Q\} \mid c}{\{x \mapsto A * P\} \rightsquigarrow \{Q\} \mid \text{let } y = *x; c}$$

(Write)

---

$$\{x \mapsto \_ * P\} \rightsquigarrow \{x \mapsto e * Q\} \mid$$

# SSL: basic rules

(Read)

$$\frac{[y/A] \{x \mapsto A * P\} \rightsquigarrow [y/A] \{Q\} \mid c}{\{x \mapsto A * P\} \rightsquigarrow \{Q\} \mid \text{let } y = *x; c}$$

(Write)

$$\frac{\{x \mapsto e * P\} \rightsquigarrow \{x \mapsto e * Q\} \mid c}{\{x \mapsto \_ * P\} \rightsquigarrow \{x \mapsto e * Q\} \mid *x = e; c}$$

# SSL: basic rules

(Frame)

$$\frac{\{P\} \rightsquigarrow \{Q\} \mid c}{\{P * R\} \rightsquigarrow \{Q * R\} \mid c}$$

(UnifyHeaps)

$$\frac{[\sigma]R' = R \quad \{P * R\} \rightsquigarrow [\sigma]\{Q * R'\} \mid c}{\{P * R\} \rightsquigarrow \{Q * R'\} \mid c}$$



```
void pick(loc x, loc y)
```

$\{x \mapsto a * y \mapsto b\} \rightsquigarrow \{x \mapsto z * y \mapsto z\} \quad | \quad ??$

$\{x \mapsto a2 * y \mapsto b2\} \rightsquigarrow \{x \mapsto z * y \mapsto z\} \quad | \quad ??$

(Read)

$\{x \mapsto a2 * y \mapsto b\} \rightsquigarrow \{x \mapsto z * y \mapsto z\} \quad | \quad \text{let } b2 = *y; ??$

(Read)

$\{x \mapsto a * y \mapsto b\} \rightsquigarrow \{x \mapsto z * y \mapsto z\} \quad | \quad \text{let } a2 = *x; ??$

$$\sigma = [a2/z] \quad \{ x \mapsto a2 * y \mapsto b2 \} \rightsquigarrow \{ x \mapsto a2 * y \mapsto a2 \} \quad | \quad ??$$

---

(UnifyHeaps)

$$\{ x \mapsto a2 * y \mapsto b2 \} \rightsquigarrow \{ x \mapsto z * y \mapsto z \} \quad | \quad ??$$

---

(Read)

$$\{ x \mapsto a2 * y \mapsto b \} \rightsquigarrow \{ x \mapsto z * y \mapsto z \} \quad | \quad \text{let } b2 = *y; ??$$

---

(Read)

$$\{ x \mapsto a * y \mapsto b \} \rightsquigarrow \{ x \mapsto z * y \mapsto z \} \quad | \quad \text{let } a2 = *x; ??$$

$$\{y \mapsto b2\} \rightsquigarrow \{y \mapsto a2\} \mid ??$$

---


$$\sigma = [a2/z] \quad \{x \mapsto a2 * y \mapsto b2\} \rightsquigarrow \{x \mapsto a2 * y \mapsto a2\} \mid ?? \quad \text{(Frame)}$$

---


$$\{x \mapsto a2 * y \mapsto b2\} \rightsquigarrow \{x \mapsto z * y \mapsto z\} \mid ?? \quad \text{(UnifyHeaps)}$$

---


$$\{x \mapsto a2 * y \mapsto b\} \rightsquigarrow \{x \mapsto z * y \mapsto z\} \mid \text{let } b2 = *y; ?? \quad \text{(Read)}$$

---


$$\{x \mapsto a * y \mapsto b\} \rightsquigarrow \{x \mapsto z * y \mapsto z\} \mid \text{let } a2 = *x; ?? \quad \text{(Read)}$$

$$\{y \mapsto a2\} \rightsquigarrow \{y \mapsto a2\} \mid ??$$

(Write)

$$\{y \mapsto b2\} \rightsquigarrow \{y \mapsto a2\} \mid *y = a2; ??$$

(Frame)

$$\sigma = [a2/z] \quad \{x \mapsto a2 * y \mapsto b2\} \rightsquigarrow \{x \mapsto a2 * y \mapsto a2\} \mid ??$$

(UnifyHeaps)

$$\{x \mapsto a2 * y \mapsto b2\} \rightsquigarrow \{x \mapsto z * y \mapsto z\} \mid ??$$

(Read)

$$\{x \mapsto a2 * y \mapsto b\} \rightsquigarrow \{x \mapsto z * y \mapsto z\} \mid \text{let } b2 = *y; ??$$

(Read)

$$\{x \mapsto a * y \mapsto b\} \rightsquigarrow \{x \mapsto z * y \mapsto z\} \mid \text{let } a2 = *x; ??$$

$$\begin{array}{c}
\frac{}{\{ \text{emp} \} \rightsquigarrow \{ \text{emp} \} \mid \text{skip}} \text{(Emp)} \\
\frac{}{\{ y \mapsto a2 \} \rightsquigarrow \{ y \mapsto a2 \} \mid ??} \text{(Frame)} \\
\frac{}{\{ y \mapsto b2 \} \rightsquigarrow \{ y \mapsto a2 \} \mid *y = a2; ??} \text{(Write)} \\
\frac{}{\sigma = [a2/z] \quad \{ x \mapsto a2 * y \mapsto b2 \} \rightsquigarrow \{ x \mapsto a2 * y \mapsto a2 \} \mid ??} \text{(Frame)} \\
\frac{}{\{ x \mapsto a2 * y \mapsto b2 \} \rightsquigarrow \{ x \mapsto z * y \mapsto z \} \mid ??} \text{(UnifyHeaps)} \\
\frac{}{\{ x \mapsto a2 * y \mapsto b \} \rightsquigarrow \{ x \mapsto z * y \mapsto z \} \mid \text{let } b2 = *y; ??} \text{(Read)} \\
\frac{}{\{ x \mapsto a * y \mapsto b \} \rightsquigarrow \{ x \mapsto z * y \mapsto z \} \mid \text{let } a2 = *x; ??} \text{(Read)}
\end{array}$$

$$\begin{array}{c}
\frac{}{\{ \text{emp} \} \rightsquigarrow \{ \text{emp} \} \mid \text{skip}} \text{(Emp)} \\
\frac{}{\{ y \mapsto a2 \} \rightsquigarrow \{ y \mapsto a2 \} \mid ??} \text{(Frame)} \\
\frac{}{\{ y \mapsto b2 \} \rightsquigarrow \{ y \mapsto a2 \} \mid \boxed{*y = a2;} ??} \text{(Write)} \\
\frac{}{\sigma = [a2/z] \quad \{ x \mapsto a2 * y \mapsto b2 \} \rightsquigarrow \{ x \mapsto a2 * y \mapsto a2 \} \mid ??} \text{(Frame)} \\
\frac{}{\{ x \mapsto a2 * y \mapsto b2 \} \rightsquigarrow \{ x \mapsto z * y \mapsto z \} \mid ??} \text{(UnifyHeaps)} \\
\frac{}{\{ x \mapsto a2 * y \mapsto b \} \rightsquigarrow \{ x \mapsto z * y \mapsto z \} \mid \boxed{\text{let } b2 = *y;} ??} \text{(Read)} \\
\frac{}{\{ x \mapsto a * y \mapsto b \} \rightsquigarrow \{ x \mapsto z * y \mapsto z \} \mid \boxed{\text{let } a2 = *x;} ??} \text{(Read)}
\end{array}$$