Automated Detection of Non-Termination and `NullPointerExceptions` for Java Bytecode

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WST 2012, Obergurgl

Automated Non-Termination Analysis

- Logic programs:
  De Schreye '90 ..., Payet & Mesnard '06, ...
- TRSs and SRSs:
  Giesl et. al '05, Payet '06, ...
- C:
  Gupta et. al '08, ...
- JBC:
  Velroyen '08, Payet & Spoto '09

Static program analysis

- Programming languages *hard* $\curvearrowright$ Simpler representation needed

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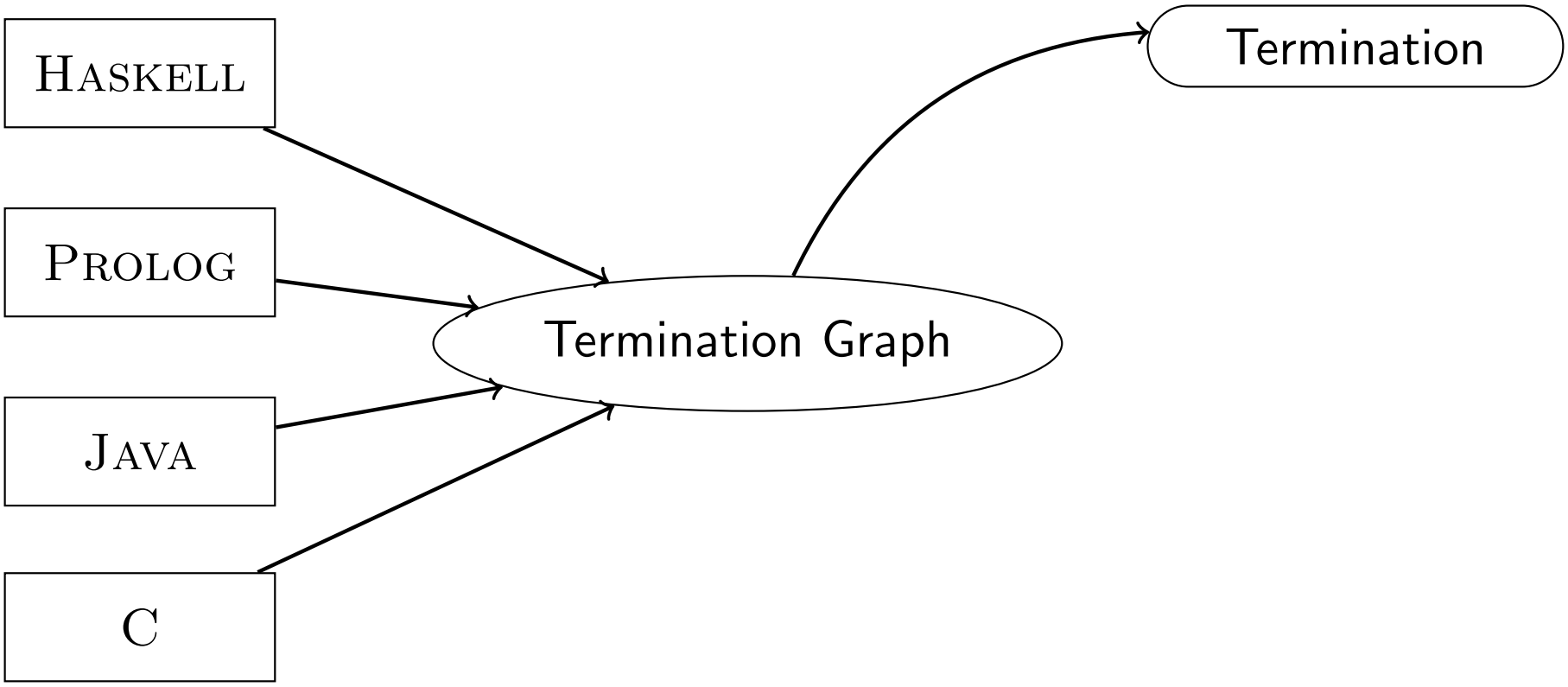
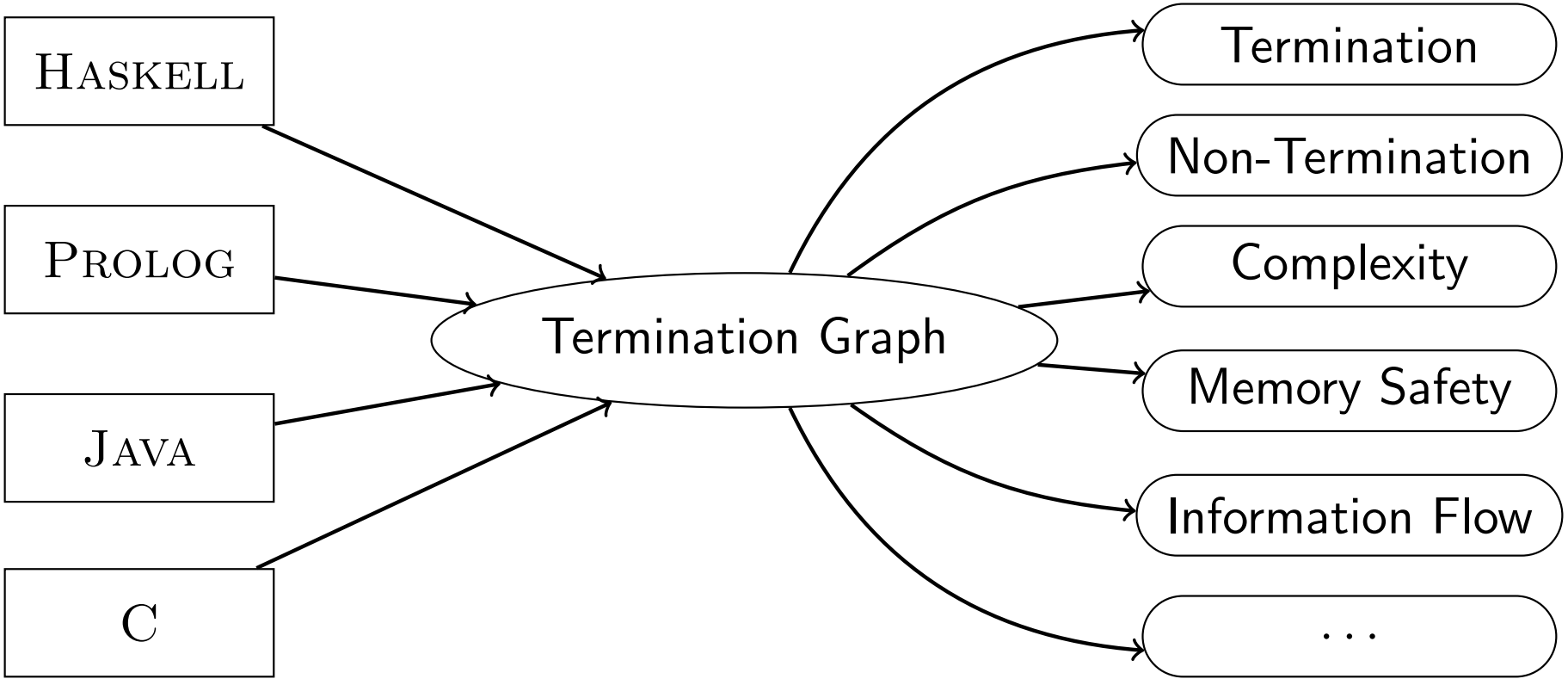
- Programming languages *hard* ↷ Simpler representation needed
- Termination Graphs: Simple, all information



Static program analysis

- Programming languages *hard* ↷ Simpler representation needed
- Termination Graphs: Simple, all information
- **Useful for properties other than termination.**



The example

```
Loop.main({``a'',``ab'',``b''})
```

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class Loop {
 void main(String[] a){
  int i = 0;
  int j = a.length;
  while (i < j) {
   i += a[i].length();}}}
```

1. Adds up lengths.

The example

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Loop.main({``a'',``ab'',``b''})
  i = 0      j = 2
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2. May not terminate.

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Abstract JAVA virtual machine states

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main(String[] a):
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- Next program instruction

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- at a_1 is String array content unknown, length is i_1

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- Unknown `String` object: `String(?)`

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Only explicit sharing

```
while (i < j)
 i+=a[i].length()
```

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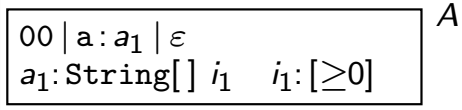

State A:

- What can happen when evaluating `main`?
- a_1: Unknown array of `String` objects
- i_1: a_1's unknown length

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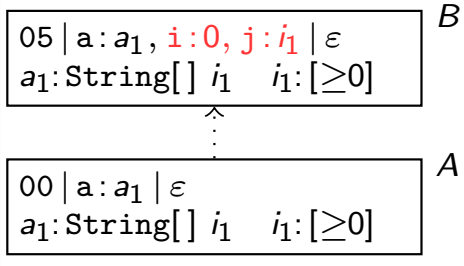

State *B*:

- Stored 0 to i
- Stored arraylength i_1 to j
- *Evaluations* from *A* to *B*

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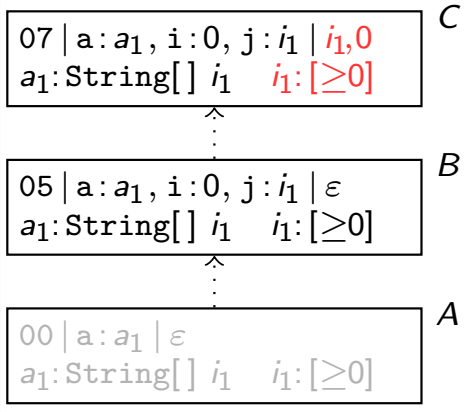

State C:

- Load i (0) and j (i_1) to operand stack
- if_icmpge cannot be evaluated

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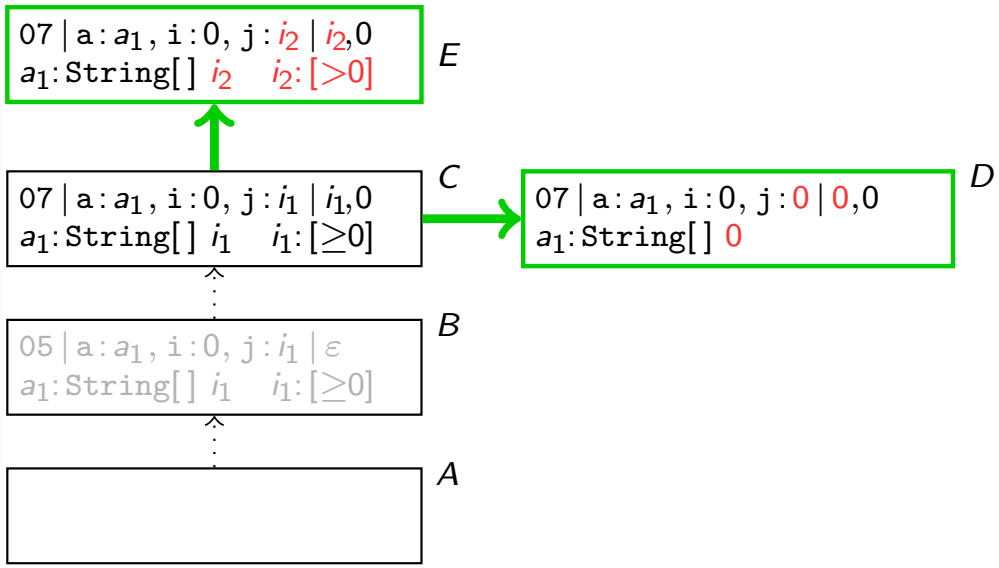

State C, D, E:

- Load i (0) and j (i_1) to operand stack
- if_icmpge cannot be evaluated yet:

$\Rightarrow$ *Refine* information:

- In D, consider case $i_1 = 0$
- In E, consider case $i_1 > 0$

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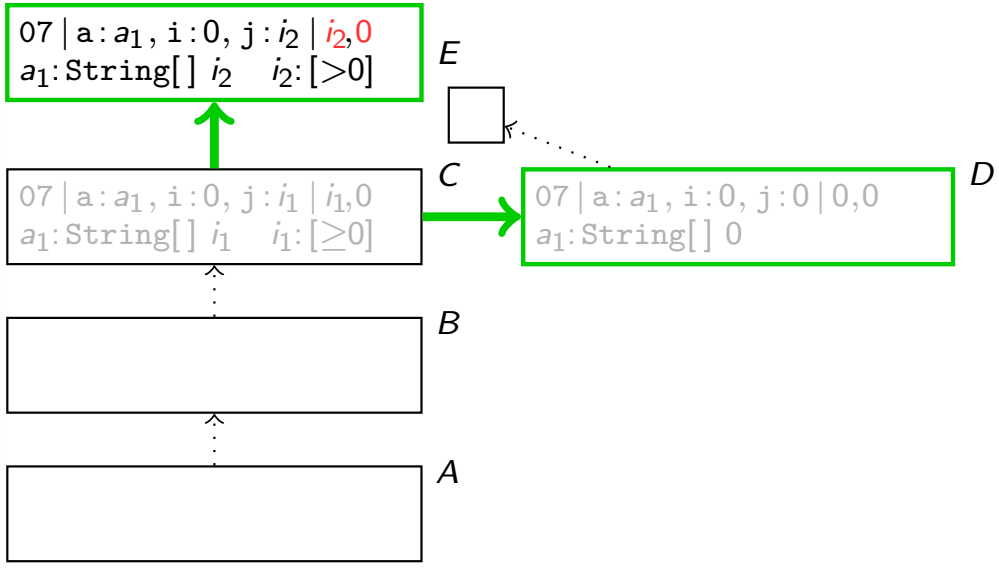

States D, E, F:

- D jumps to end of method

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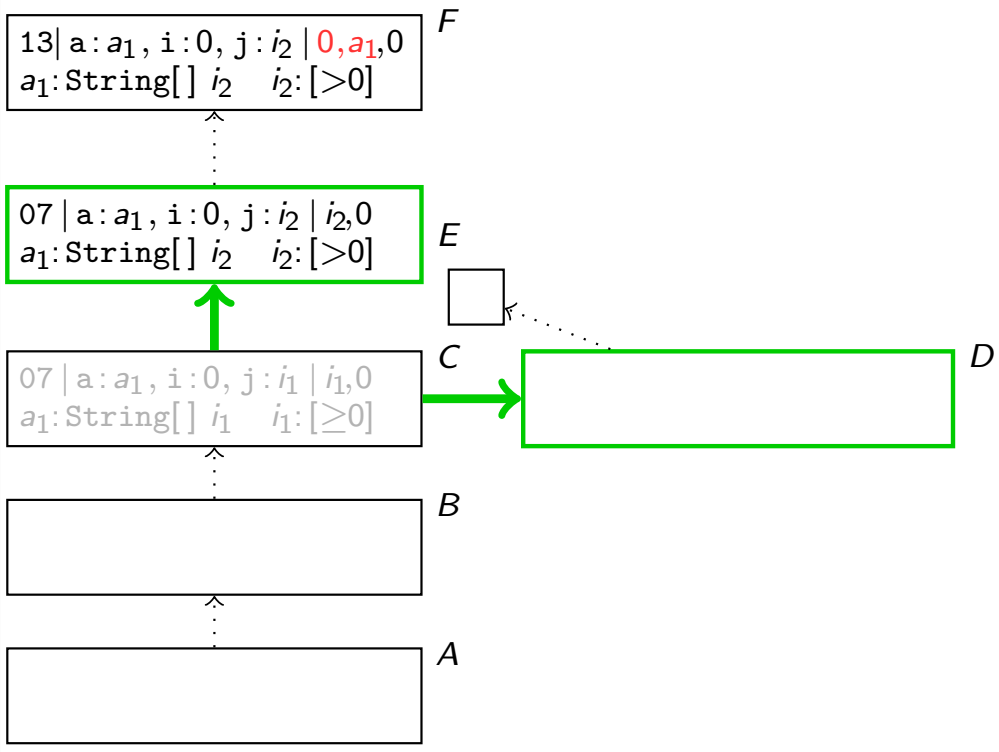

States D, E, F:

- D jumps to end of method
- E evaluates to F
- Loads array a (a_1) and index i (0) to stack
- Cannot evaluate aaload: $a_1[0]$ not known

```
while (i < j)
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```
 main(String[] a):
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05: iload_1
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17: iadd
18: istore_1
19: goto 05
22: return
 length():
00: aload_0
01: getfield count
04: ireturn
```

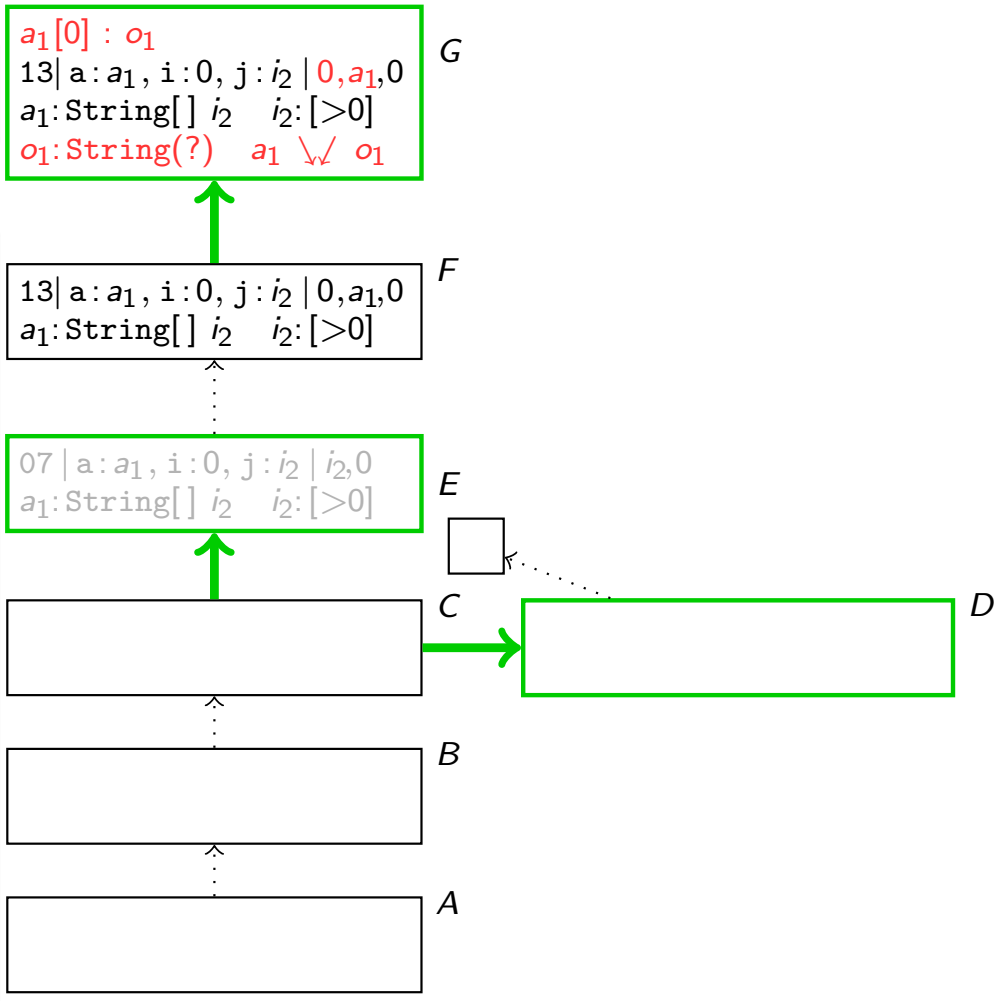

State G:

- *Refinement* of F
- o_1 created: `null` or unknown `String`
- a_1 ⩒ o_1: They *share*
- o_1 is value at $a_1[i_2]$

```
while (i < j)
 i+=a[i].length()
```

```
 main(String[] a):
00: iconst_0
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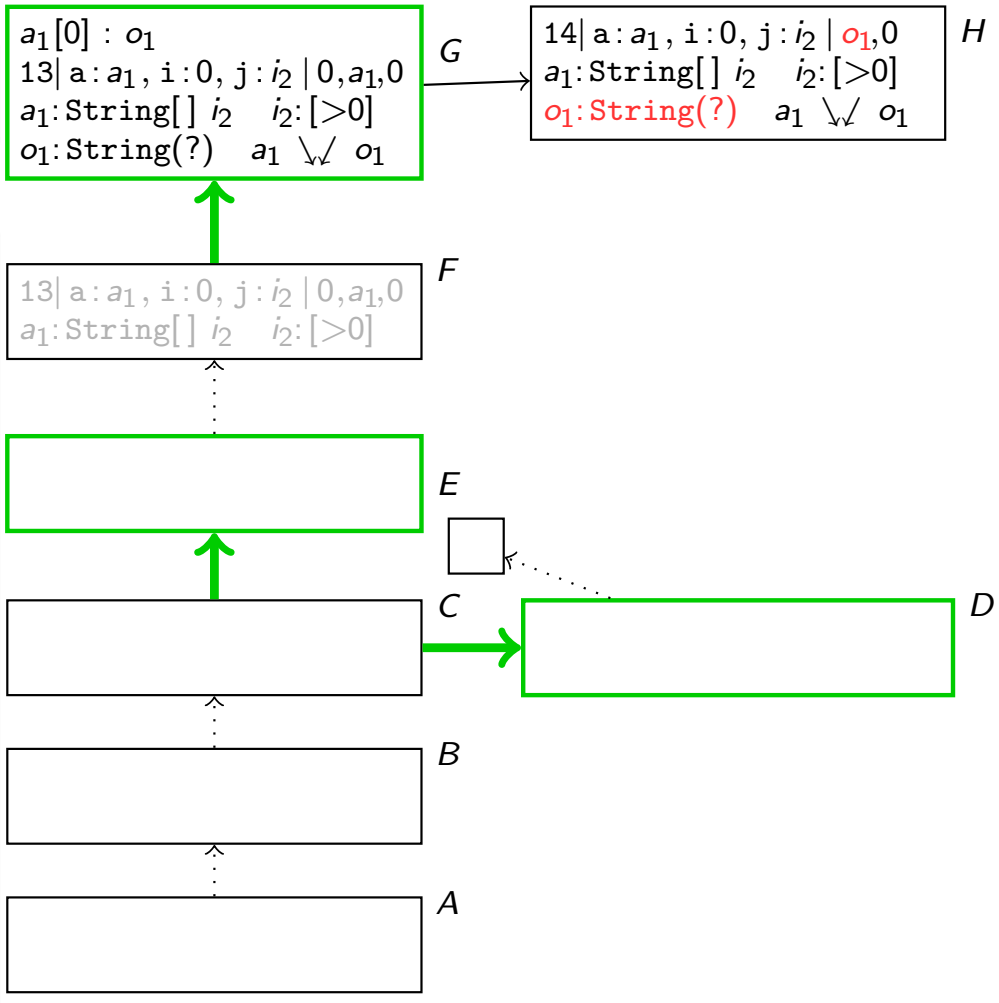

States H to K:

- H evaluated from G, loaded o_1 to stack
- `invoke` may throw `NullPointerException`

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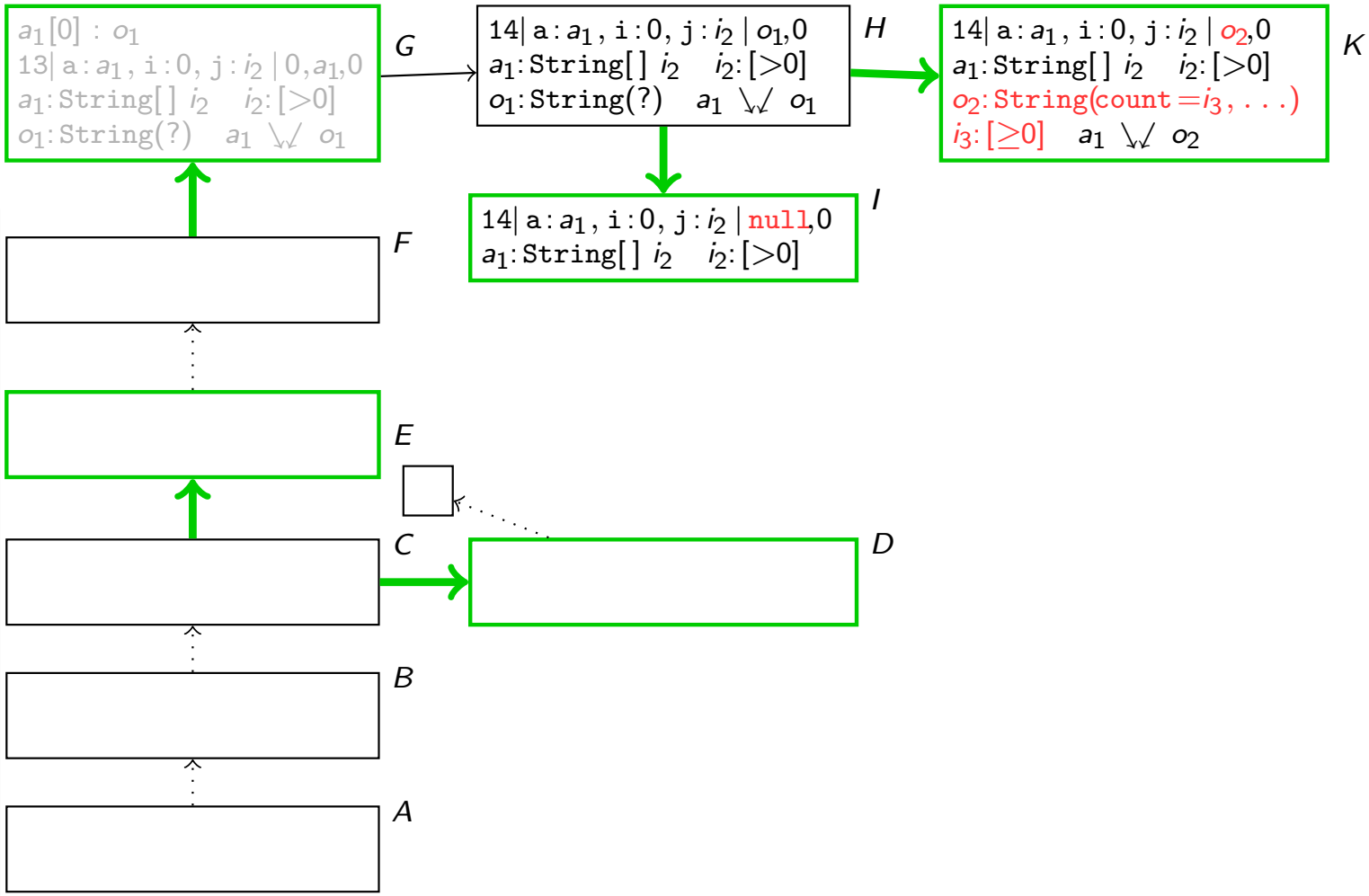

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⇒ *Refinement*:

- I: Case o_1 is `null`
- K: Case o_1 is some object with fields

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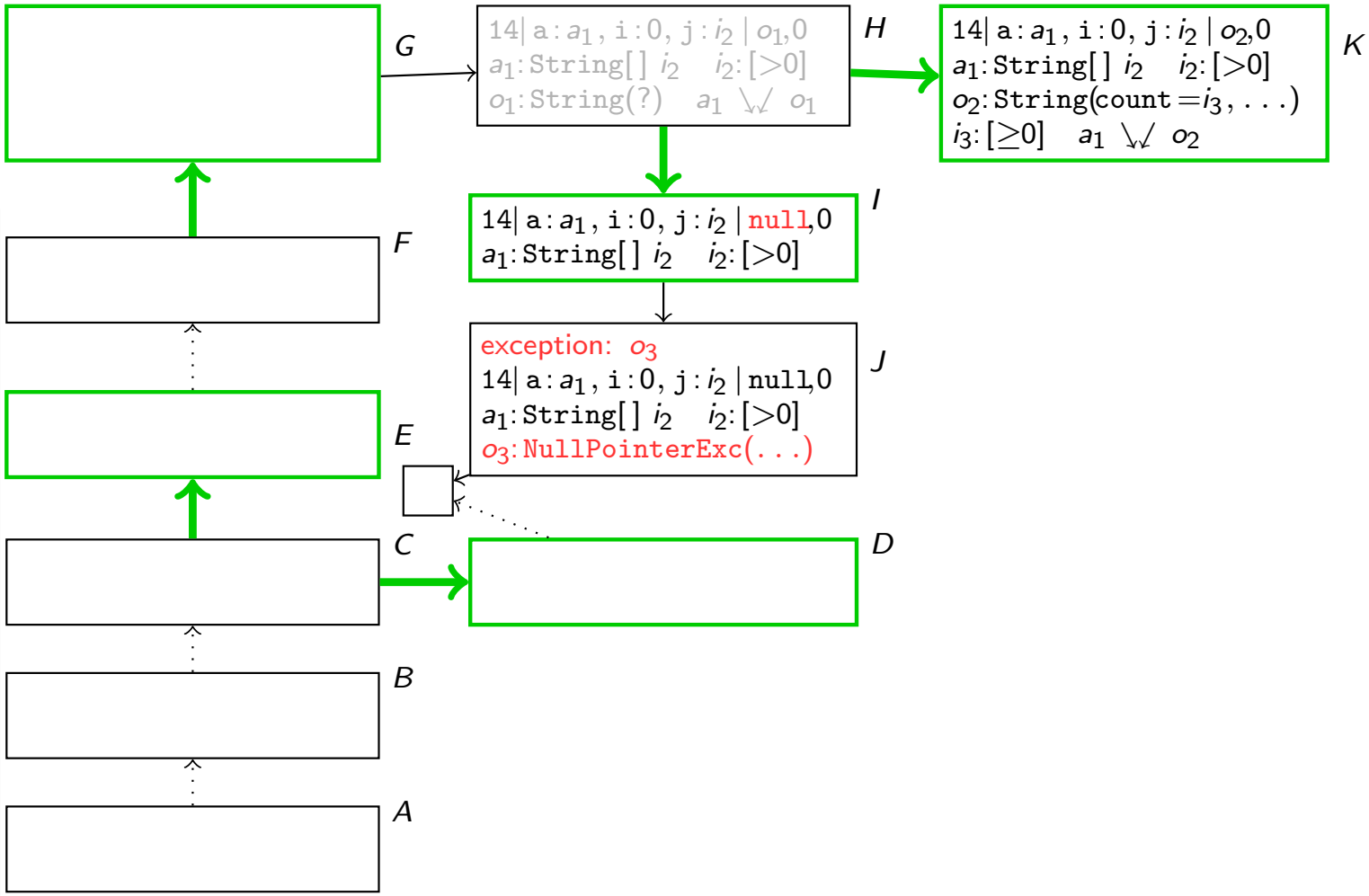

States H to K:

- H evaluated from G, loaded o_1 to stack
- `invoke` may throw `NullPointerException`

$\Rightarrow$ *Refinement*:

- I: Case o_1 is `null` (leads to NPE)
- K: Case o_1 is some object with fields

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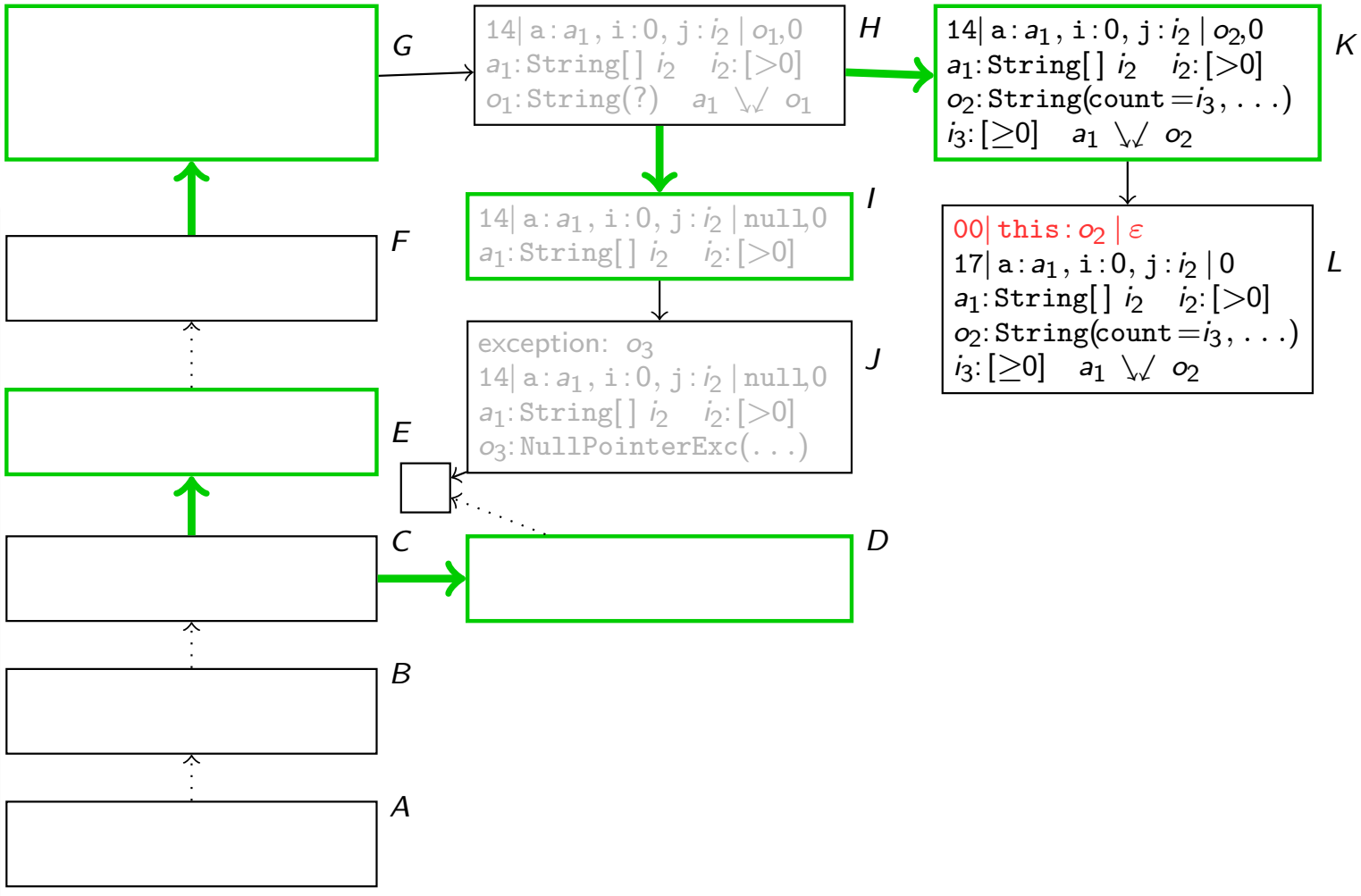

State L, M, N:

- Evaluation to L: New stack frame on top

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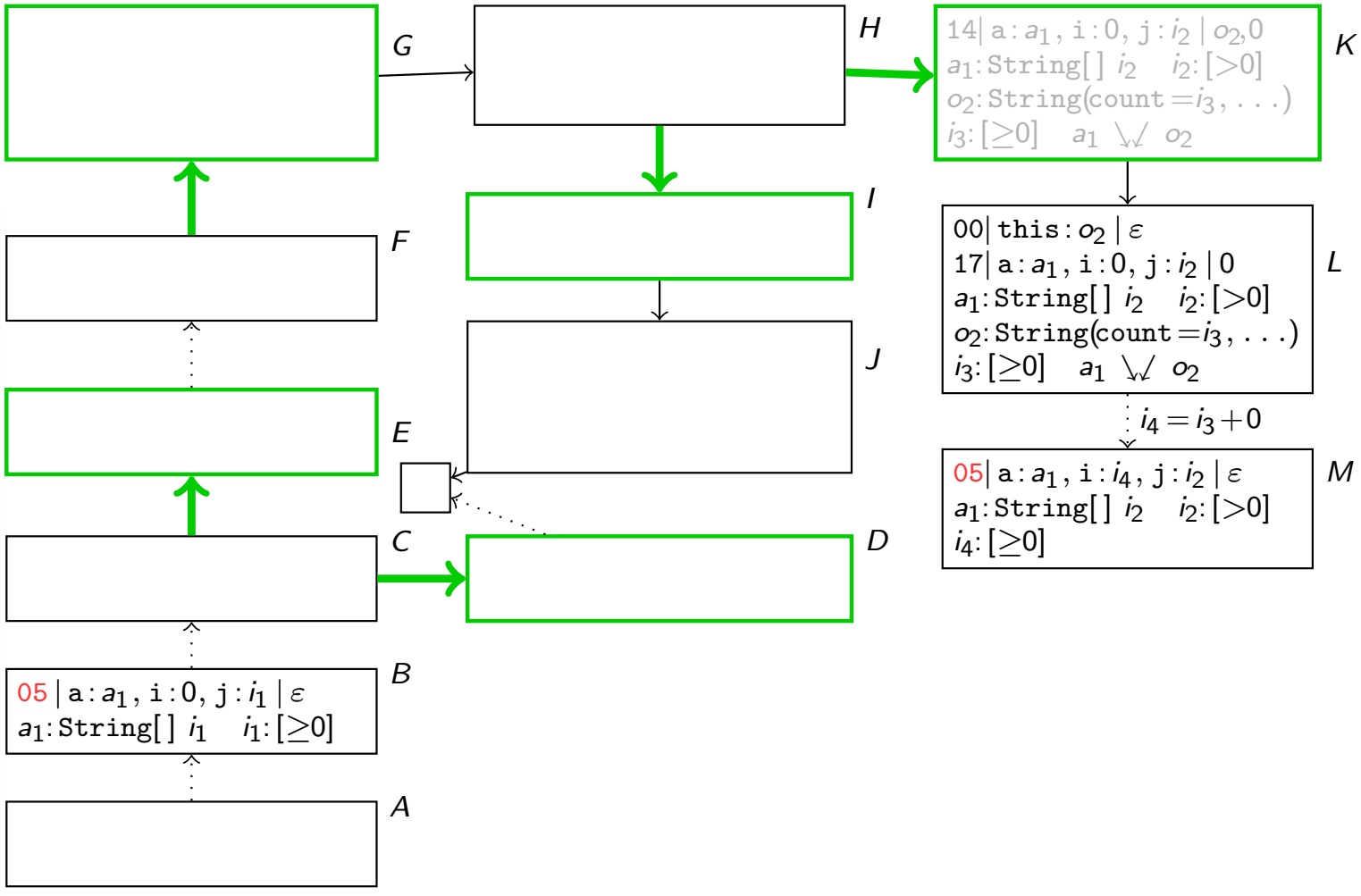

State L, M, N:

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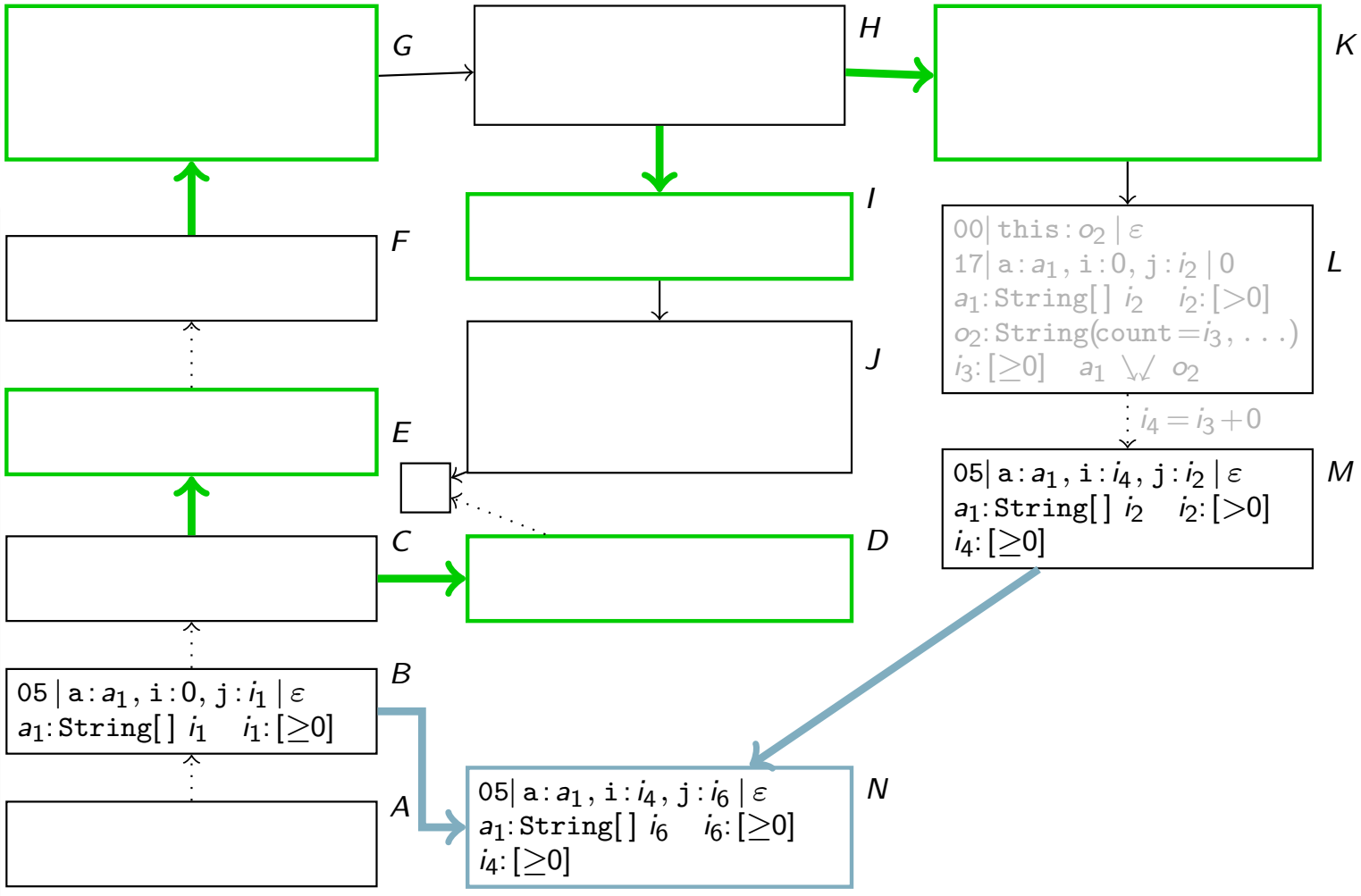

State L, M, N:

- Evaluation to L: New stack frame on top
- Evaluation to M: Retrieve length, add to i
- B and M similar: *Merge* states, get N
- N represents both B and M (*instances* of N)

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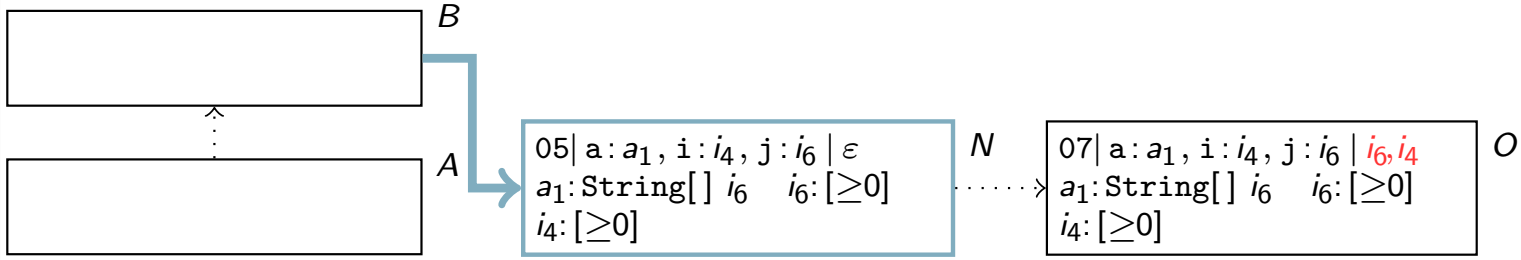

States O to S:

- Evaluate to O: Load `i`, `j` to stack

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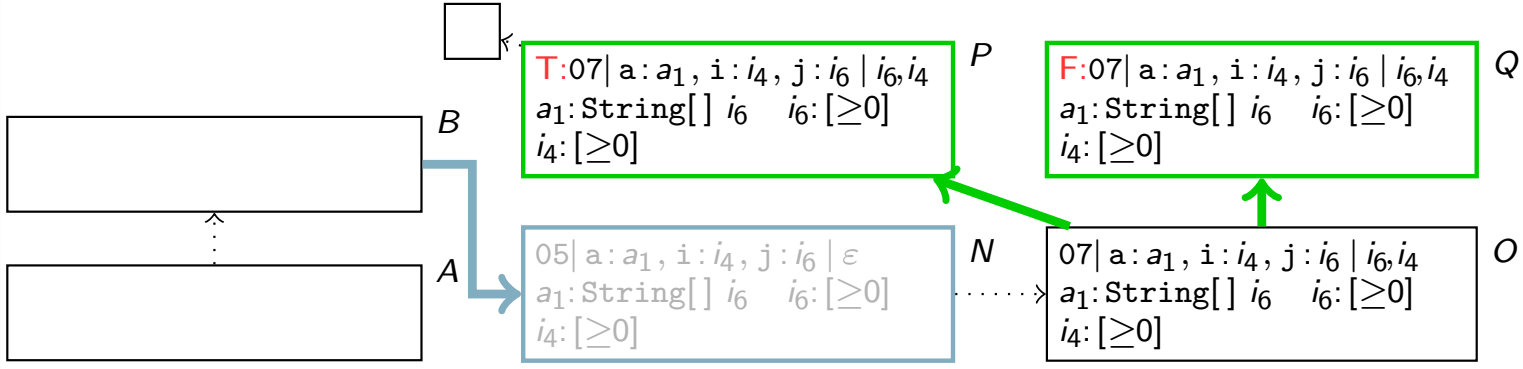

States O to S:

- Evaluate to O: Load i, j to stack
- Refine O to P, Q: Decide result of if_icmpge

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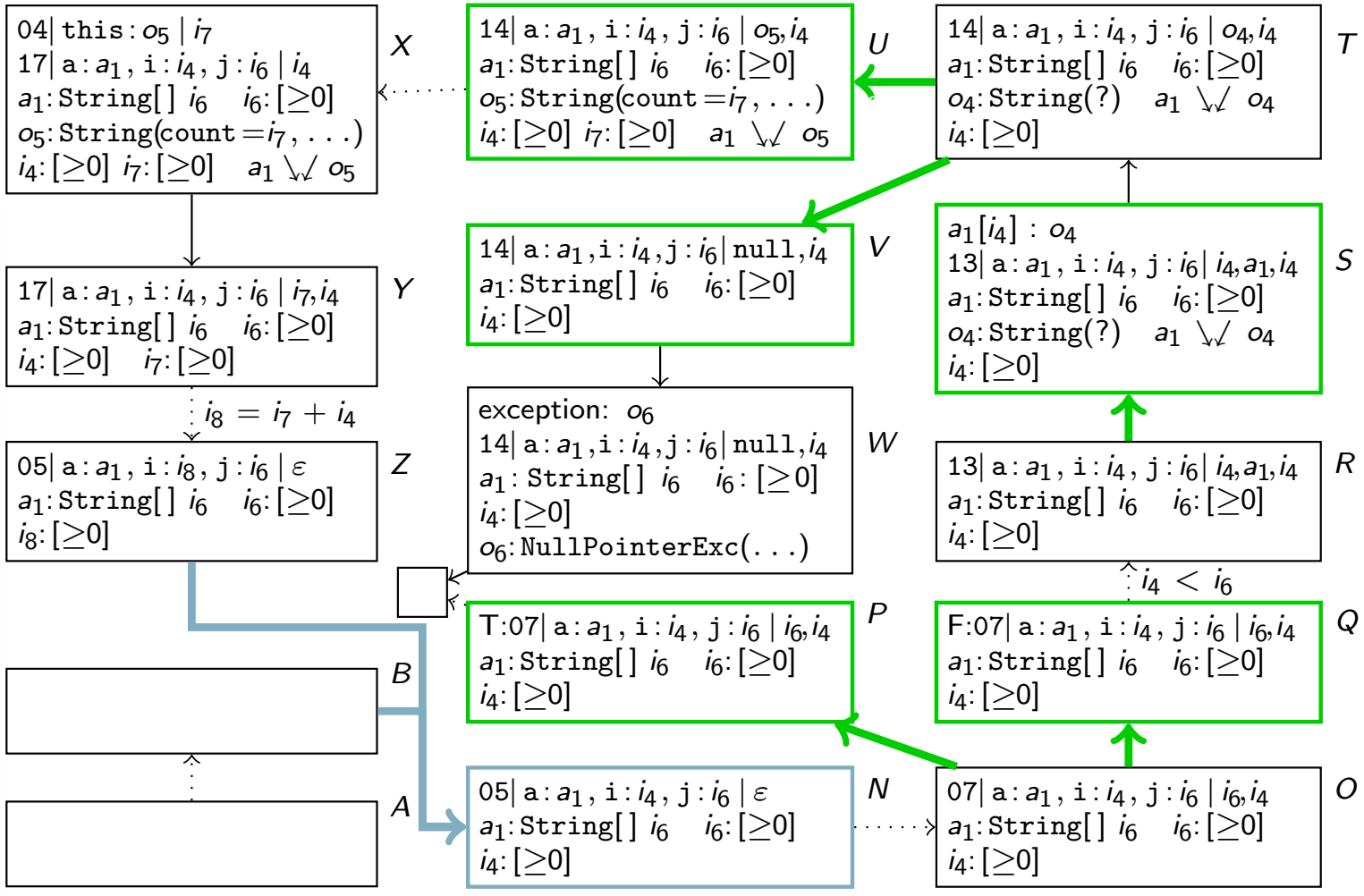

States O to S:

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- Rest as before

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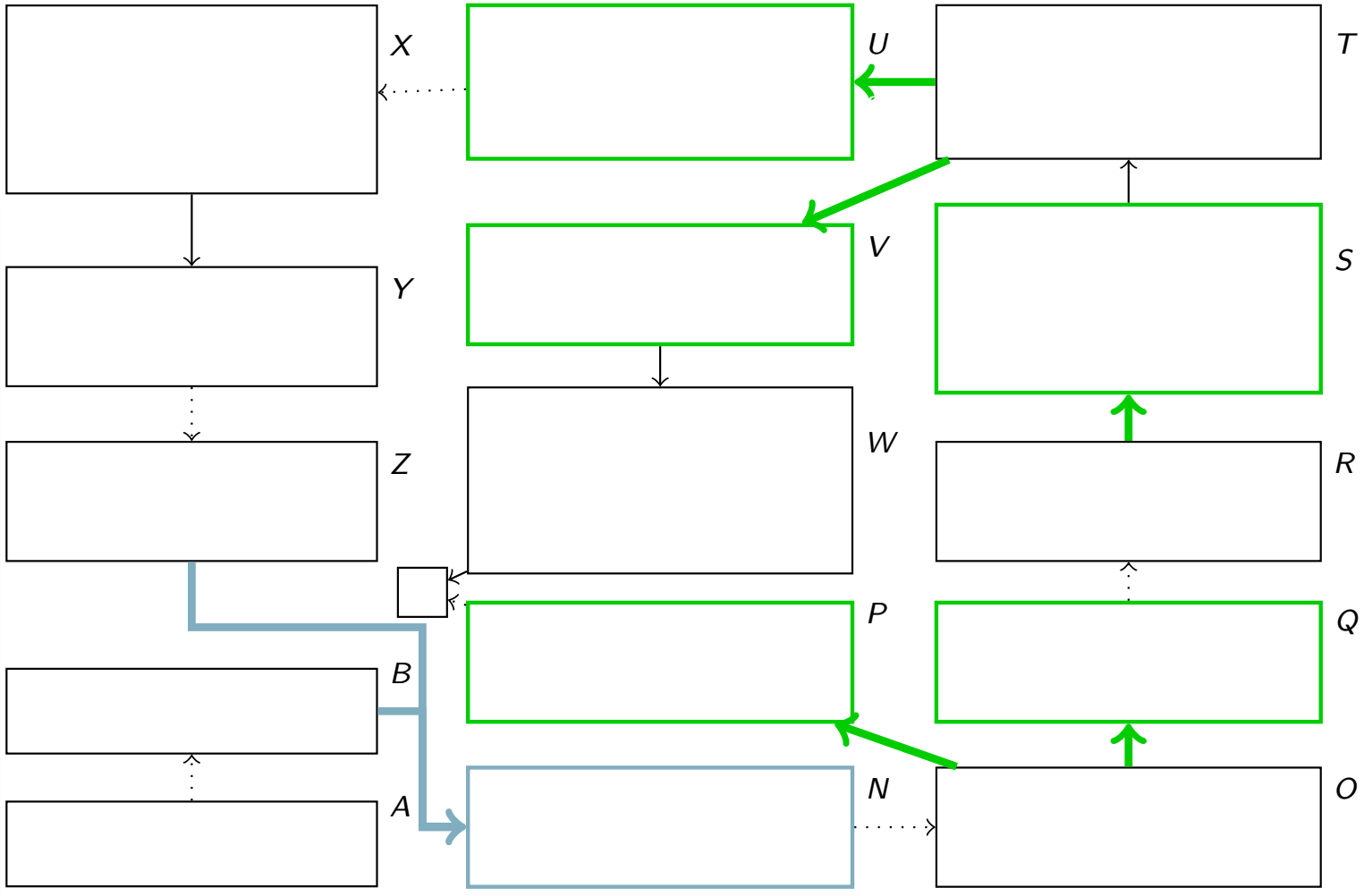

States O to S:

- Evaluate to O: Load `i`, `j` to stack
- Refine O to P, Q: Decide result of `if_icmpge`
- Rest as before
- All leaves program ends $\Rightarrow$ construction finished

Witness generation

- Termination graphs are *over*approximations of all runs

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- Let state e occur in graph starting in s
- e really occurring in runs from s?

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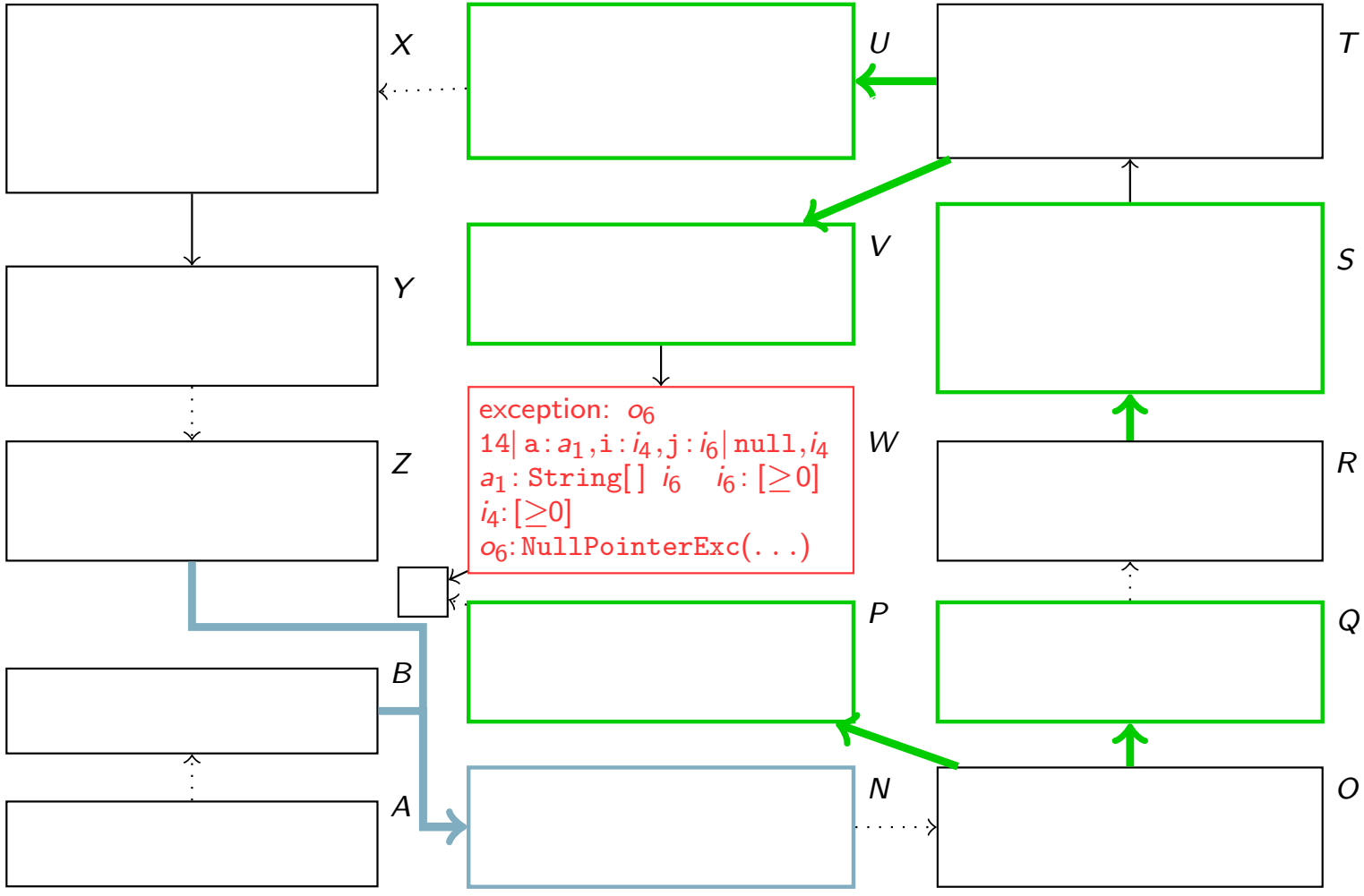
Definition

w *witness* for $e \Leftrightarrow$ all runs from w lead to e

Re-use graph: Traverse edges backwards

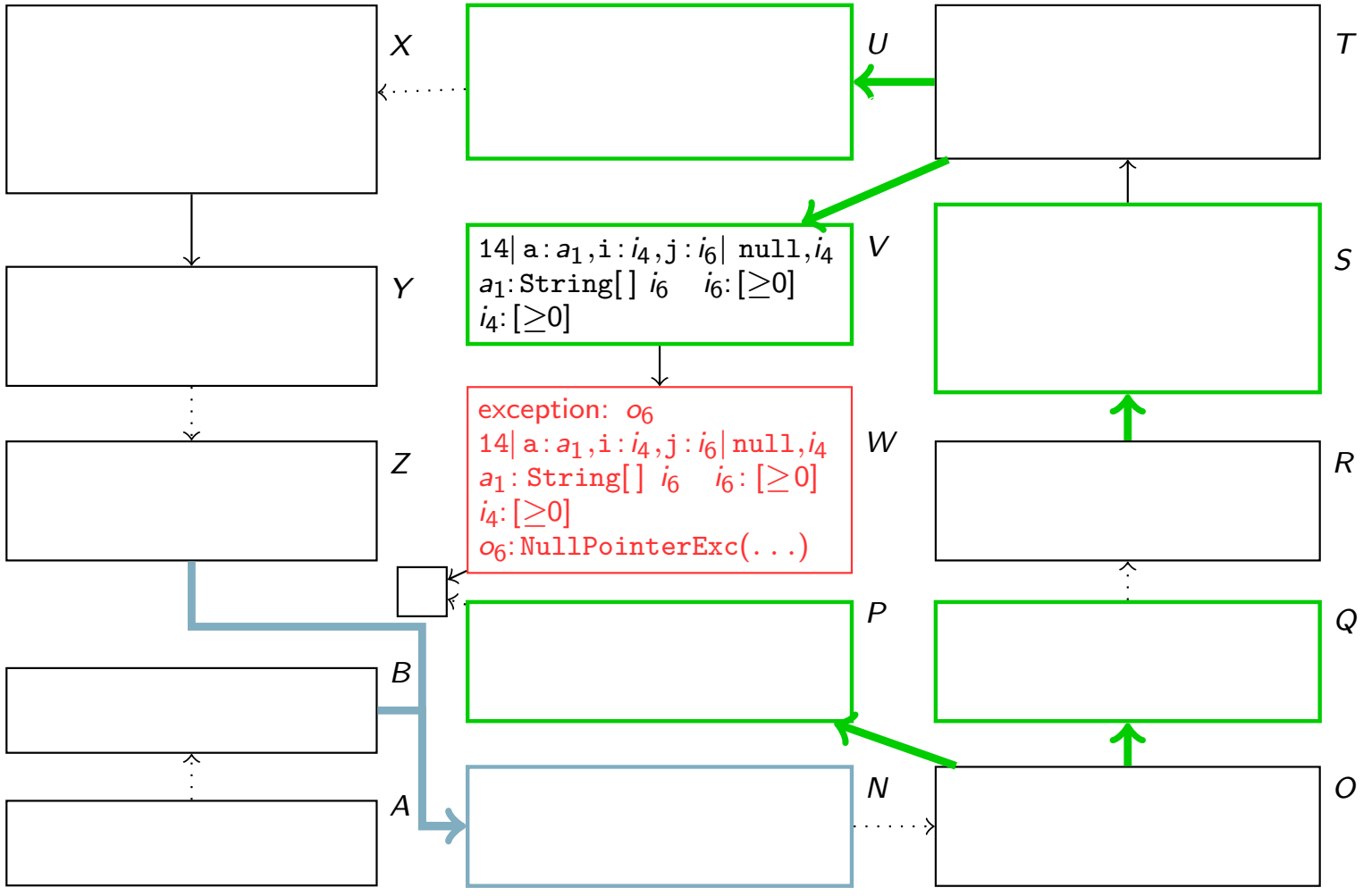


- W: program ends with a `NullPointerException`

$\Rightarrow$ Find witness

Witness for W

exception: o_6
$14|\,\mathtt{a}:a_1,\mathtt{i}:i_4,\mathtt{j}:i_6|\,\mathtt{null},i_4$
a_1 : String[ ] i_6 i_6 : $[\geq 0]$
i_4: $[\geq 0]$
o_6: NullPointerExc(. . .)



- V evaluated to W

Witness for W

exception: o_6
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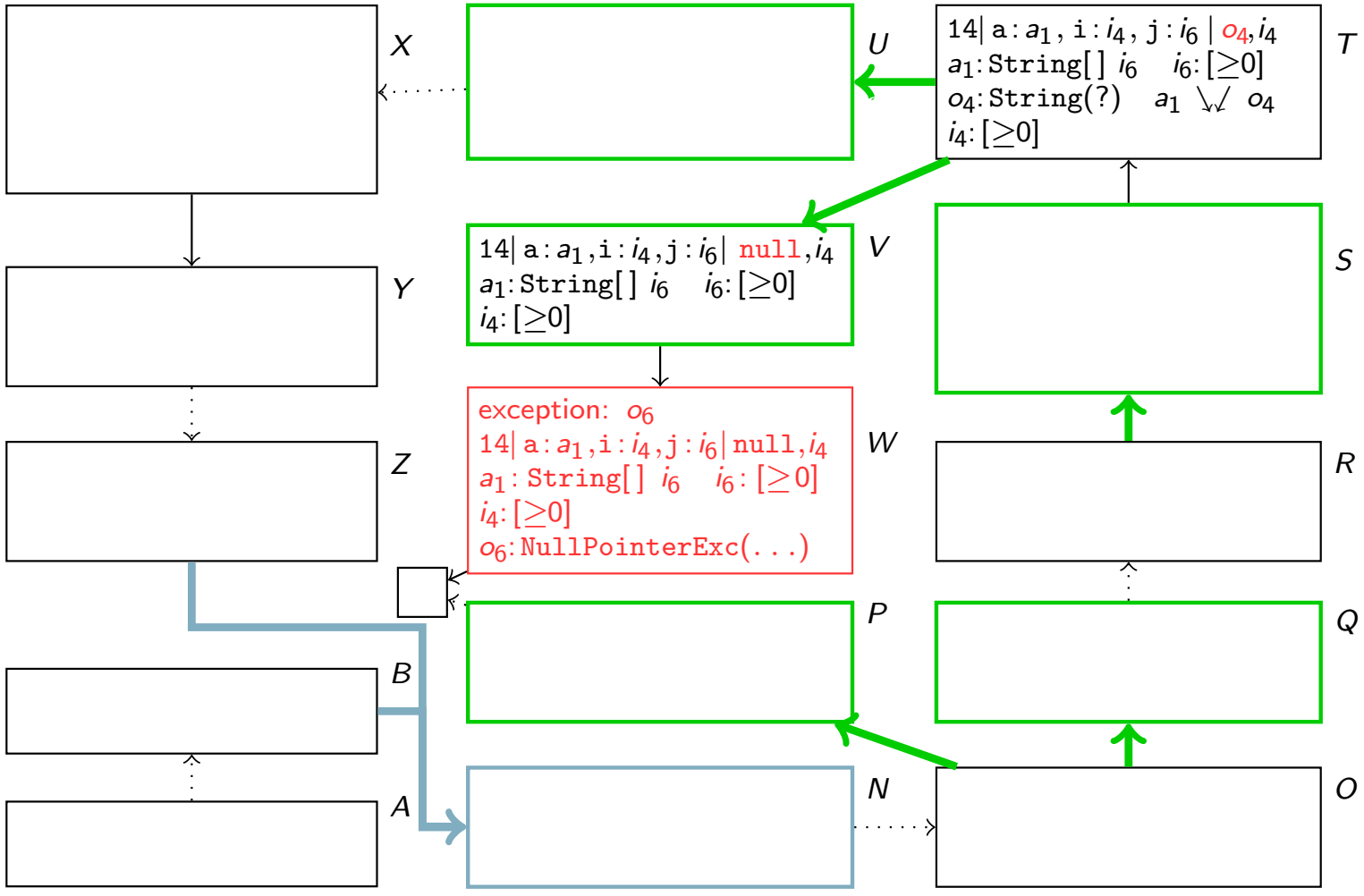
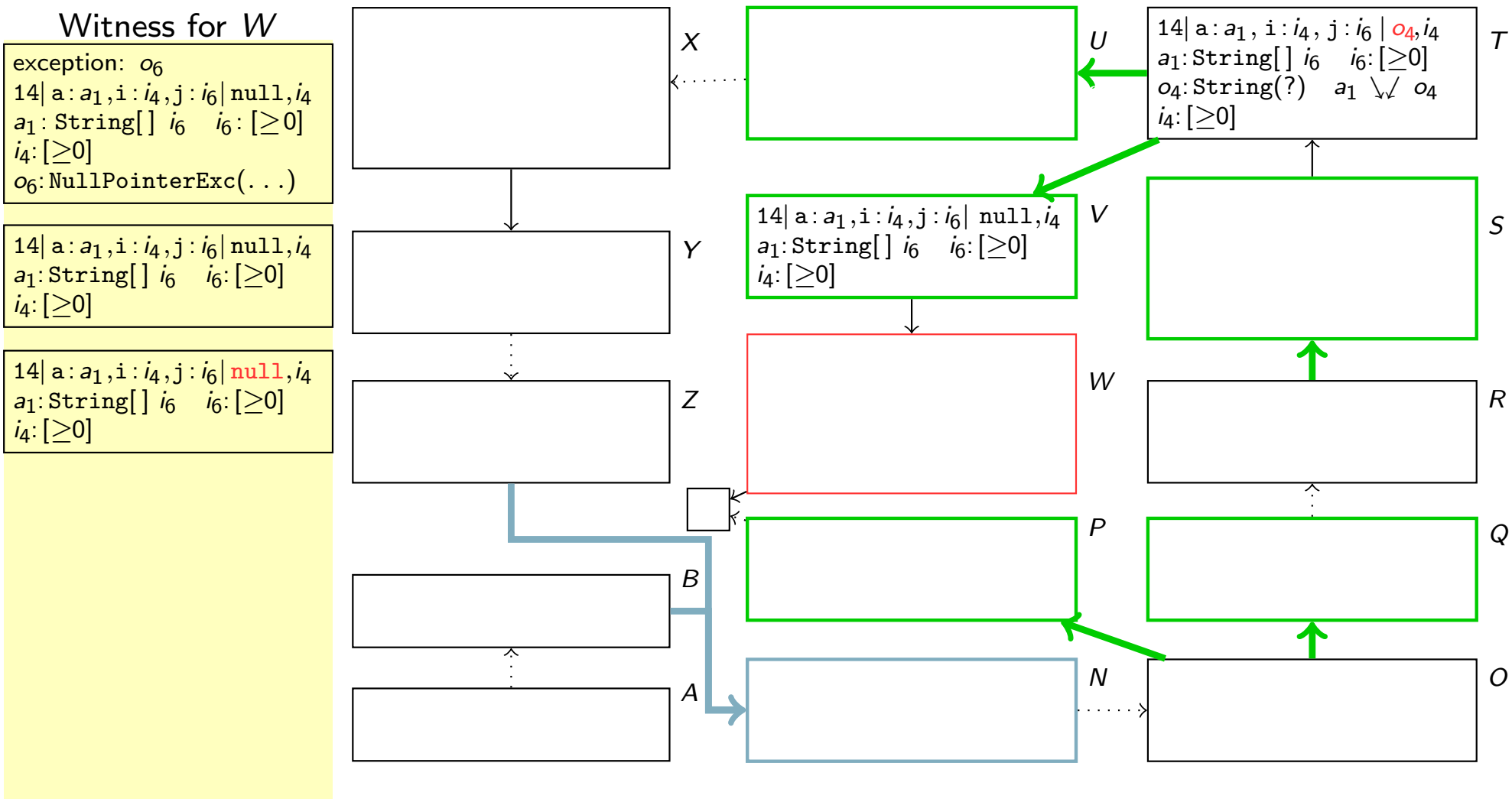


- V evaluated to W

$\Rightarrow$ Reverse evaluation step

- T refined to V



- V evaluated to W

$\Rightarrow$ Reverse evaluation step

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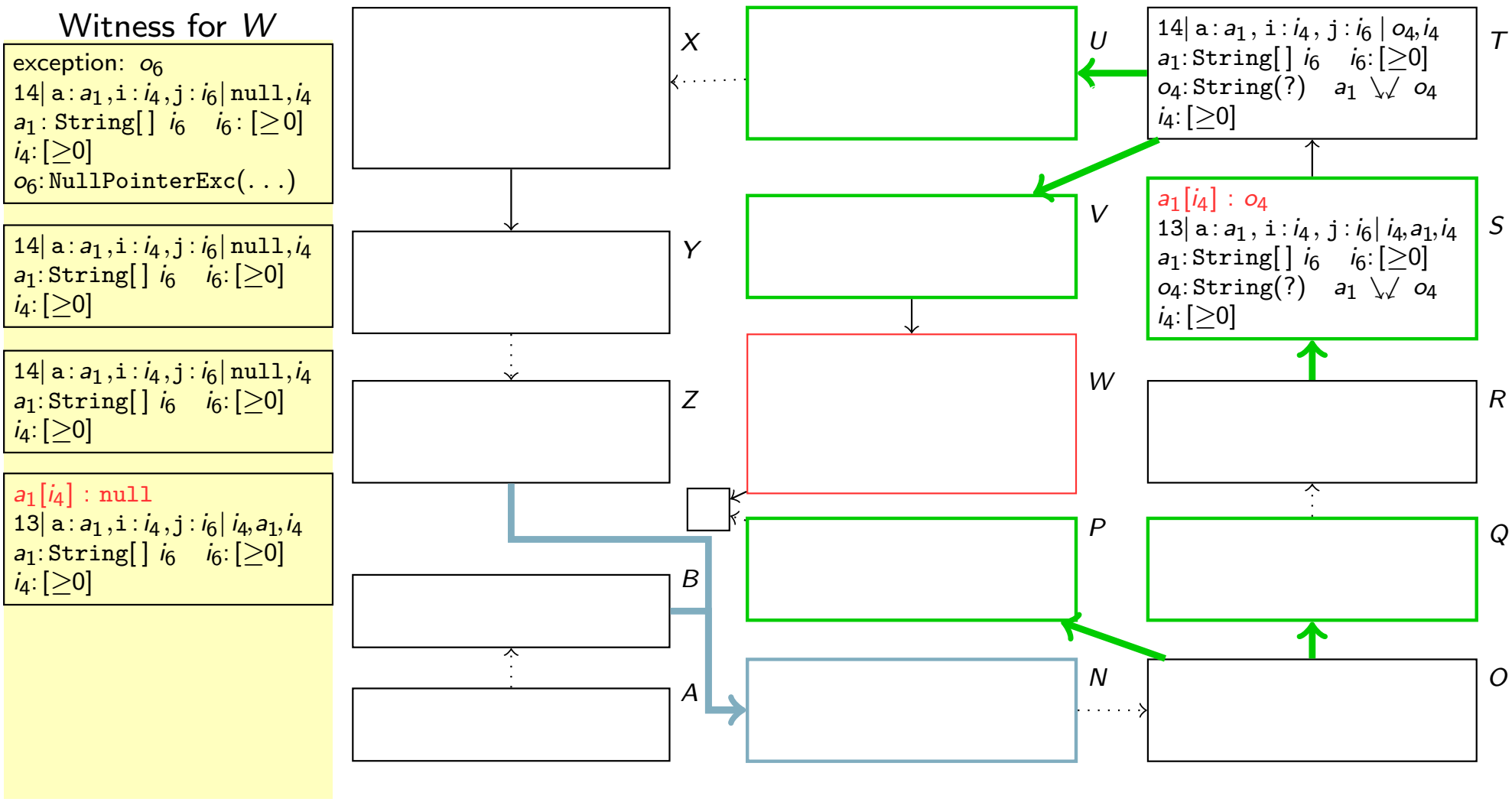
$\Rightarrow$ Re-use current witness



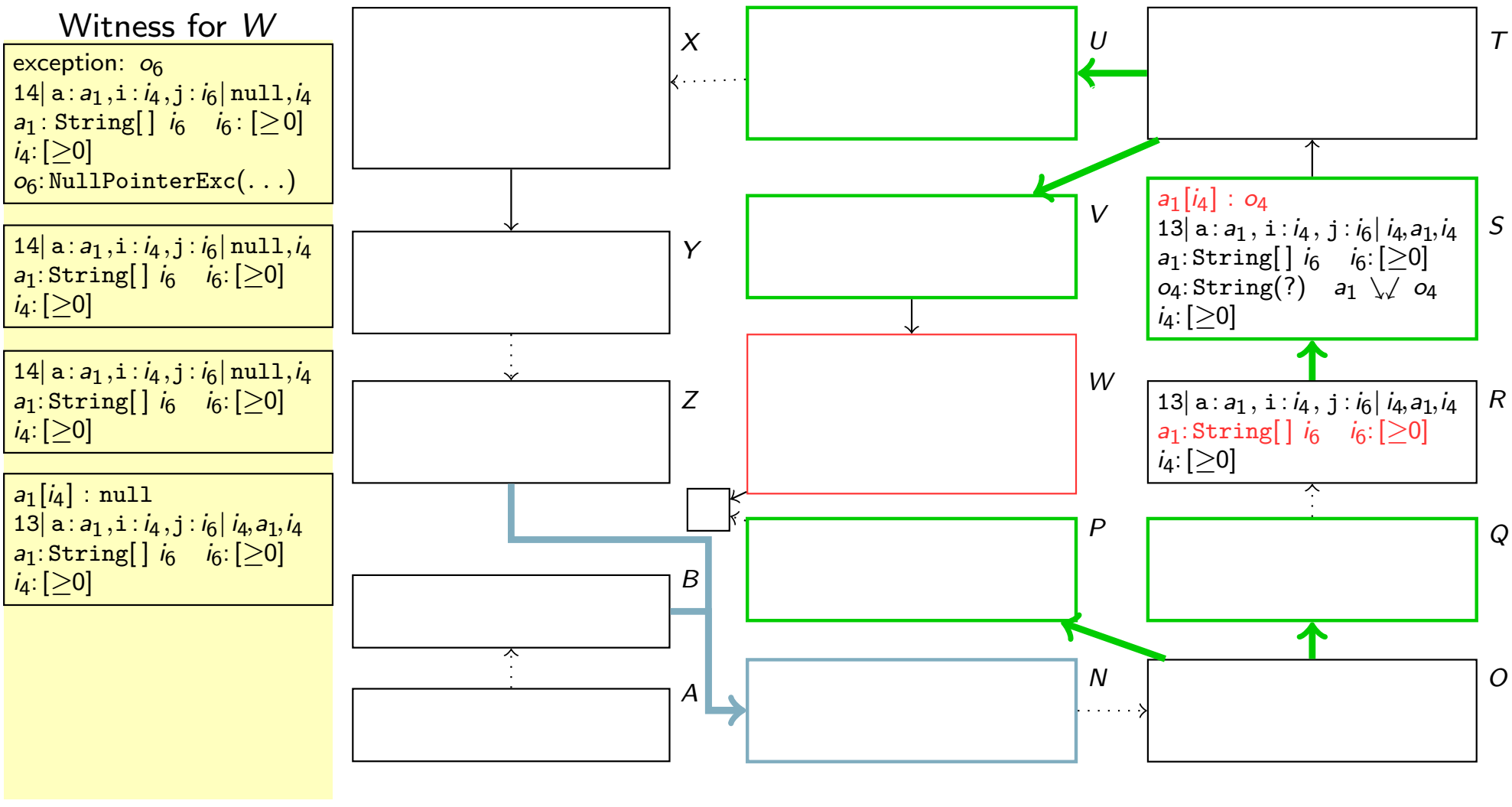
- V evaluated to W

$\Rightarrow$ Reverse evaluation step

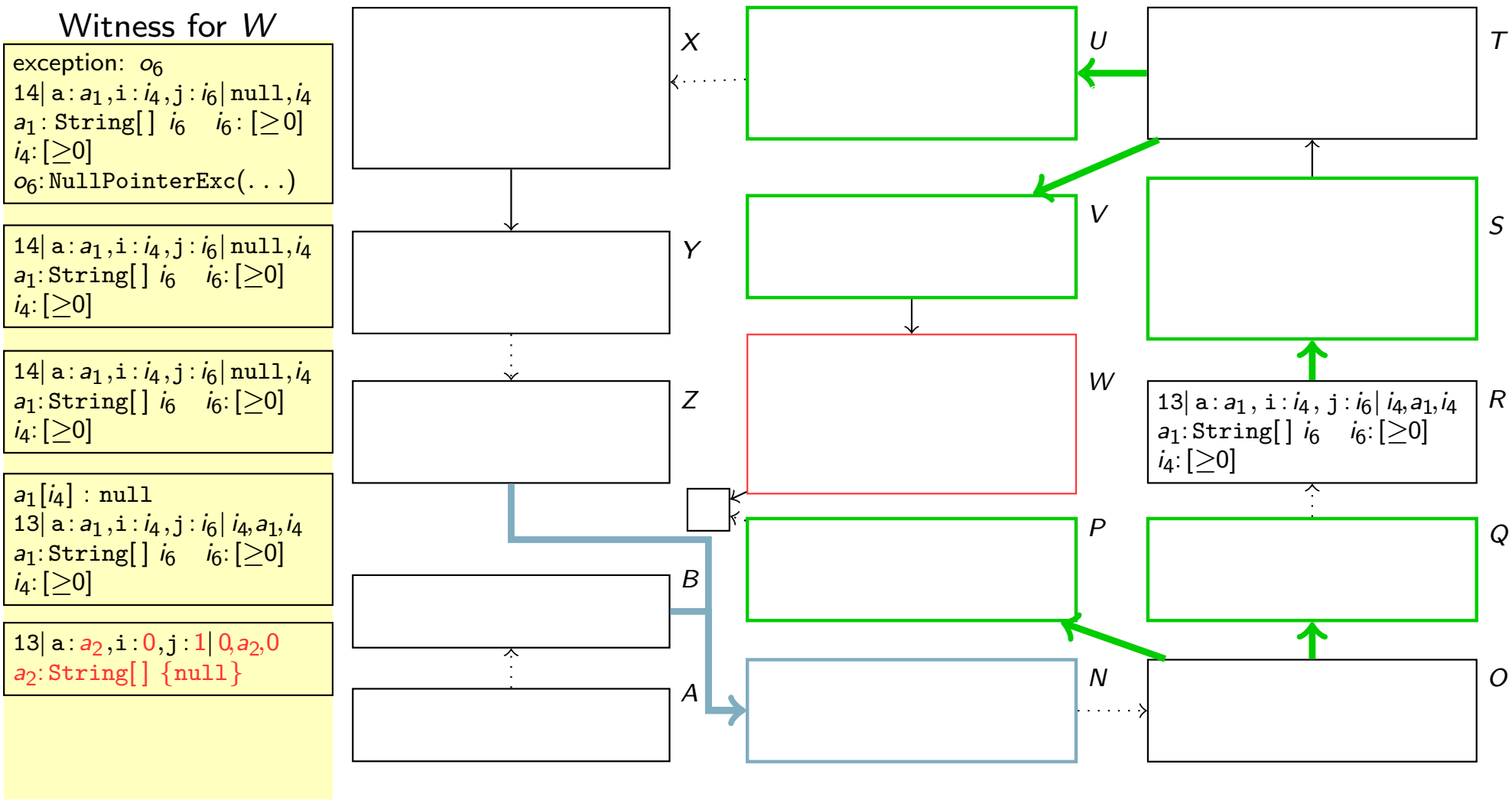
- T refined to V

$\Rightarrow$ Re-use current witness

- S evaluated to T: Reverse evaluation

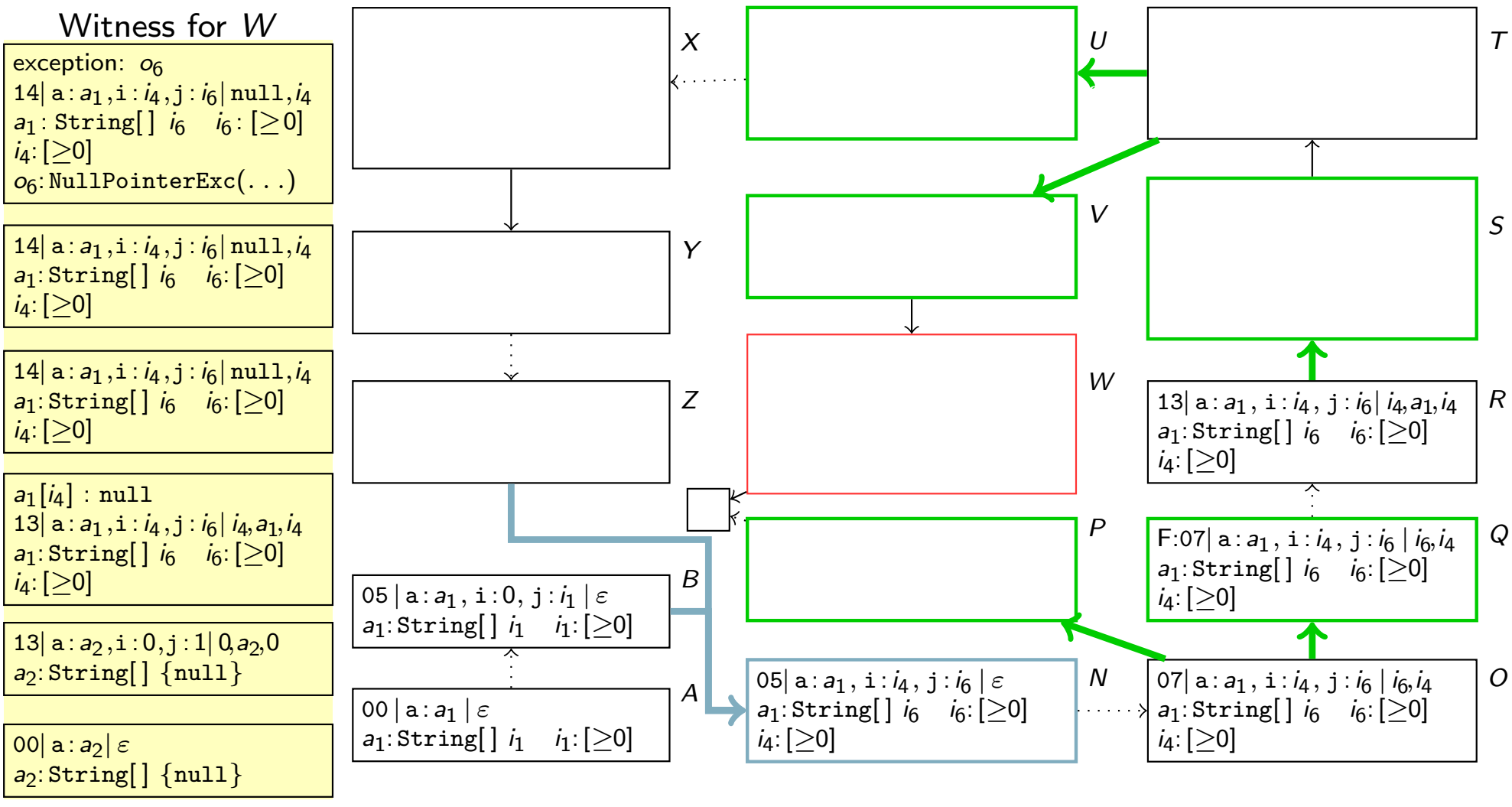


- R refined to S: Re-use current witness



- R refined to S: Re-use current witness - No!
- a_1 too abstract to keep information

$\Rightarrow$ Instantiate array and index by concrete values



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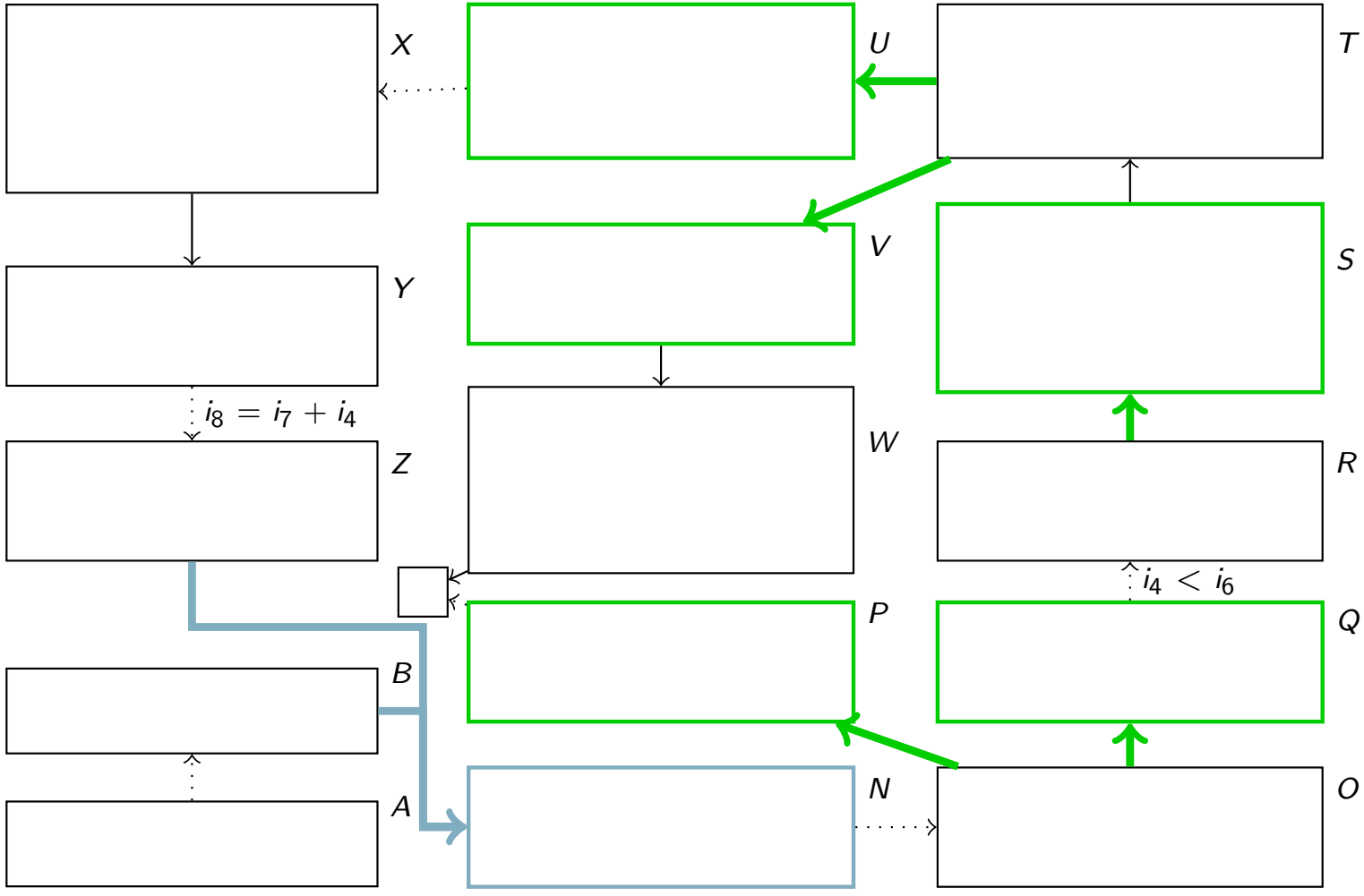
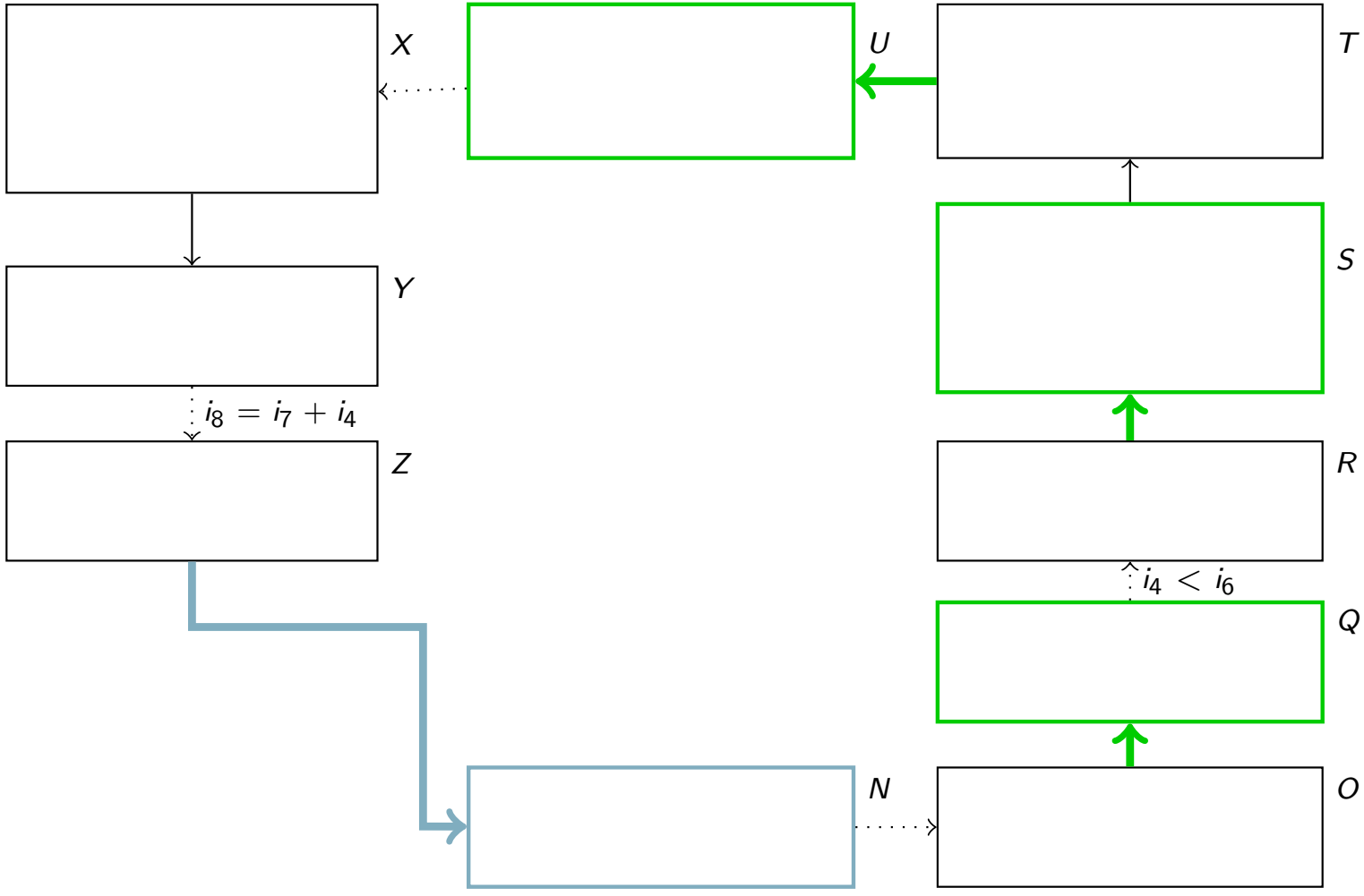
- Rest analogously, yields witness



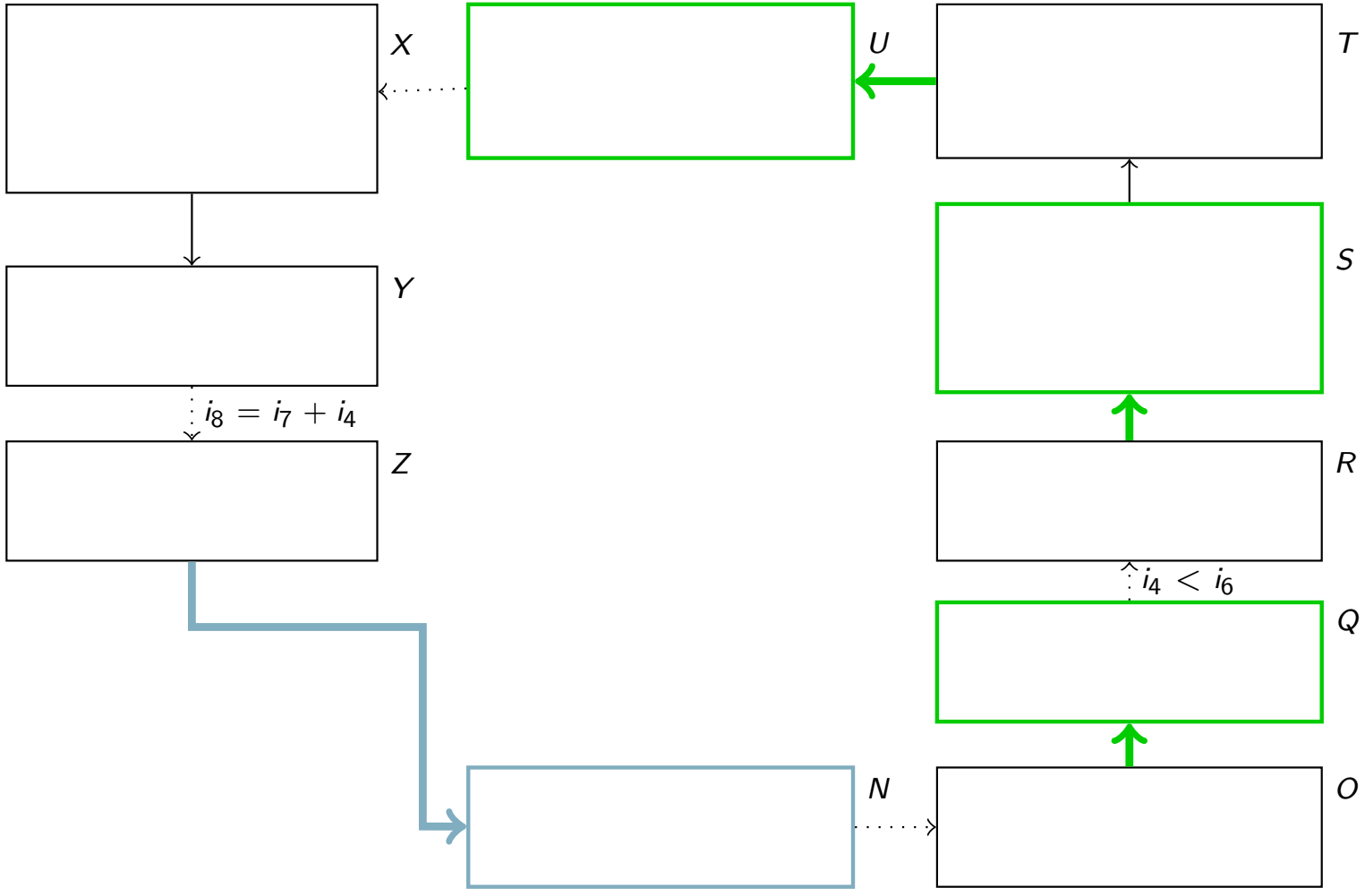
- Goal: Find state that is visited again and again



- Goal: Find state that is visited again and again

$\Rightarrow$ Only consider cycles

- Heuristic: Integers: Find values by SMT
  Objects: Find values by witness generation



- Goal: Find state that is visited again and again

$\Rightarrow$ Only consider cycles

- Heuristic: Integers: Find values by SMT
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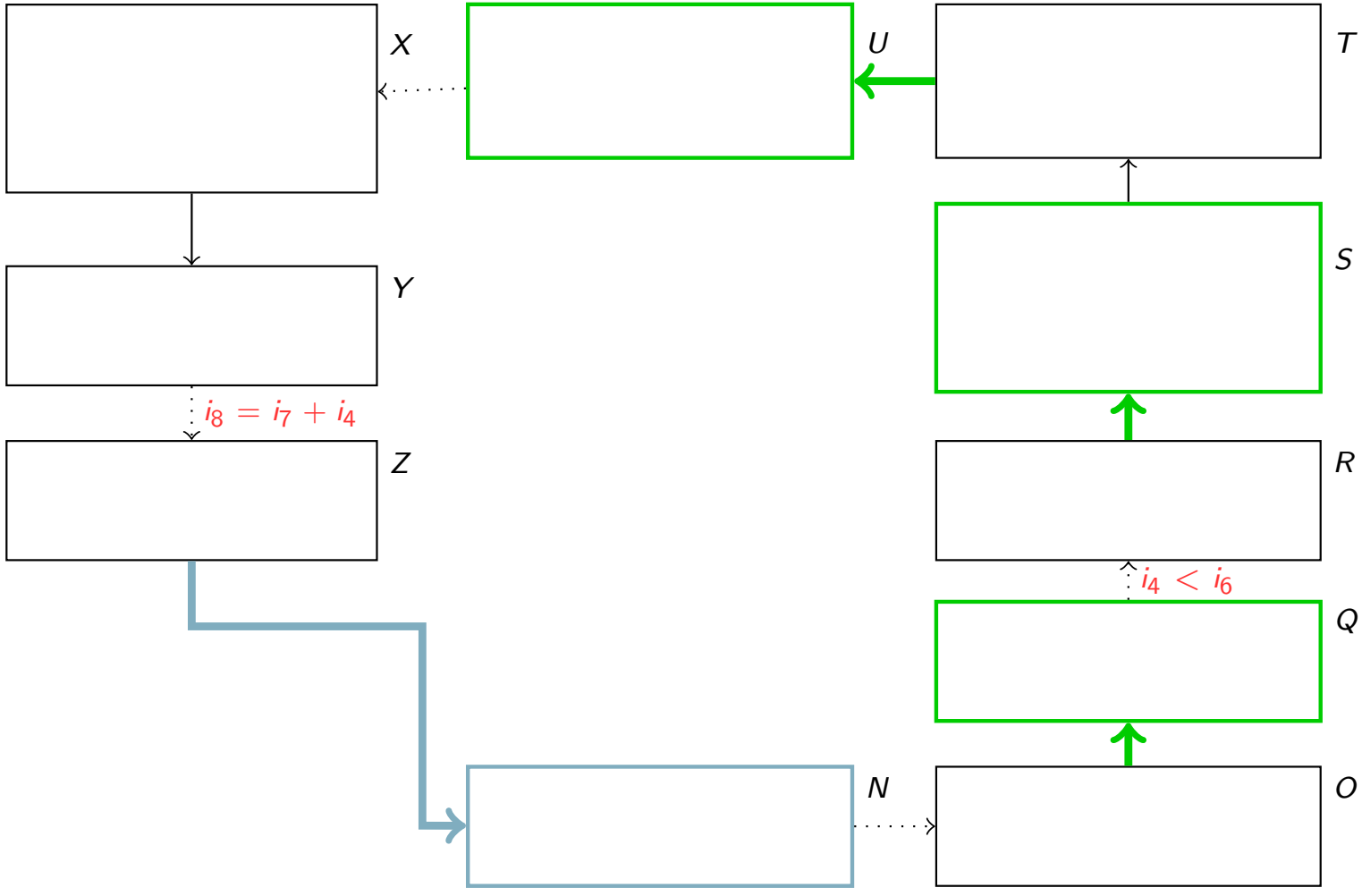
- Verification: By symbolic evaluation

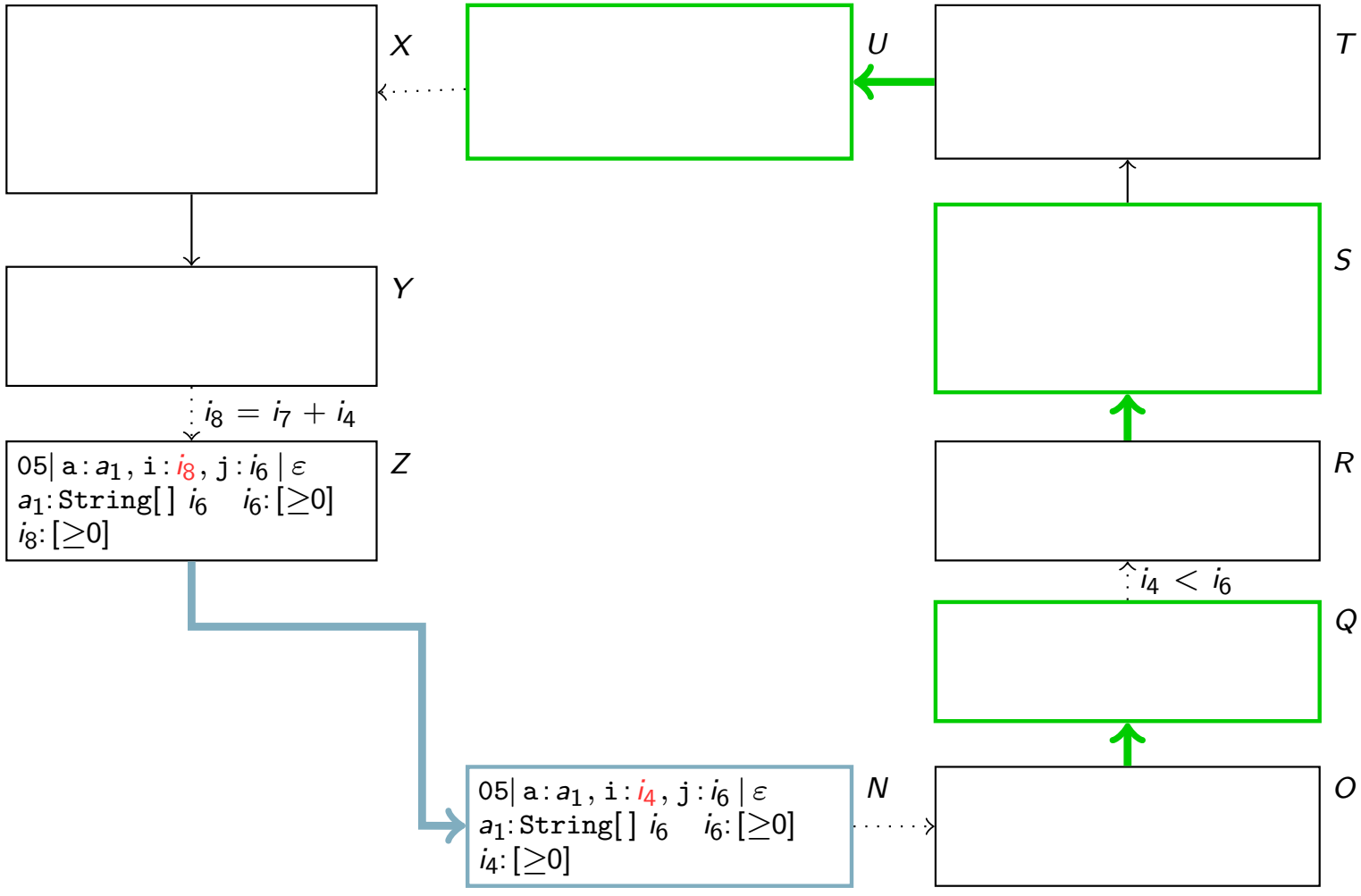
$i_4 < i_6$
$\wedge\ i_8 = i_7 + i_4$



Finding integer values by SMT

- Use conditions on edges

$$
\begin{aligned}
& i_4 < i_6 \\
\wedge\ & i_8 = i_7 + i_4 \\
\wedge\ & i_4 = i_8
\end{aligned}
$$

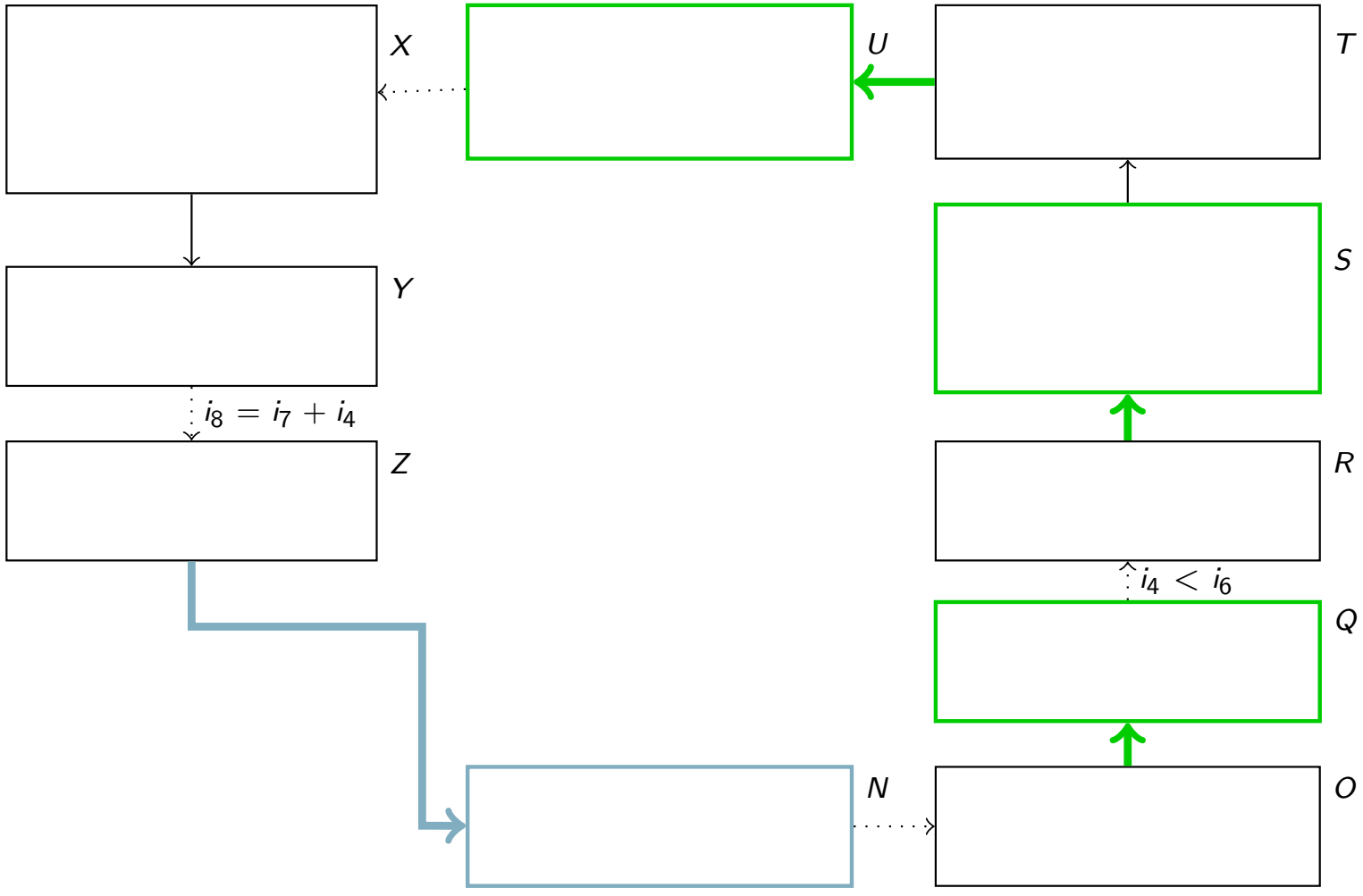


Finding integer values by SMT

- Use conditions on edges
- Refinement, Instance renamings ⇒ Equalities

⇒ Last instance edge ∼ values stay the same

$$i_4 < i_6 \wedge i_8 = i_7 + i_4 \wedge i_4 = i_8$$



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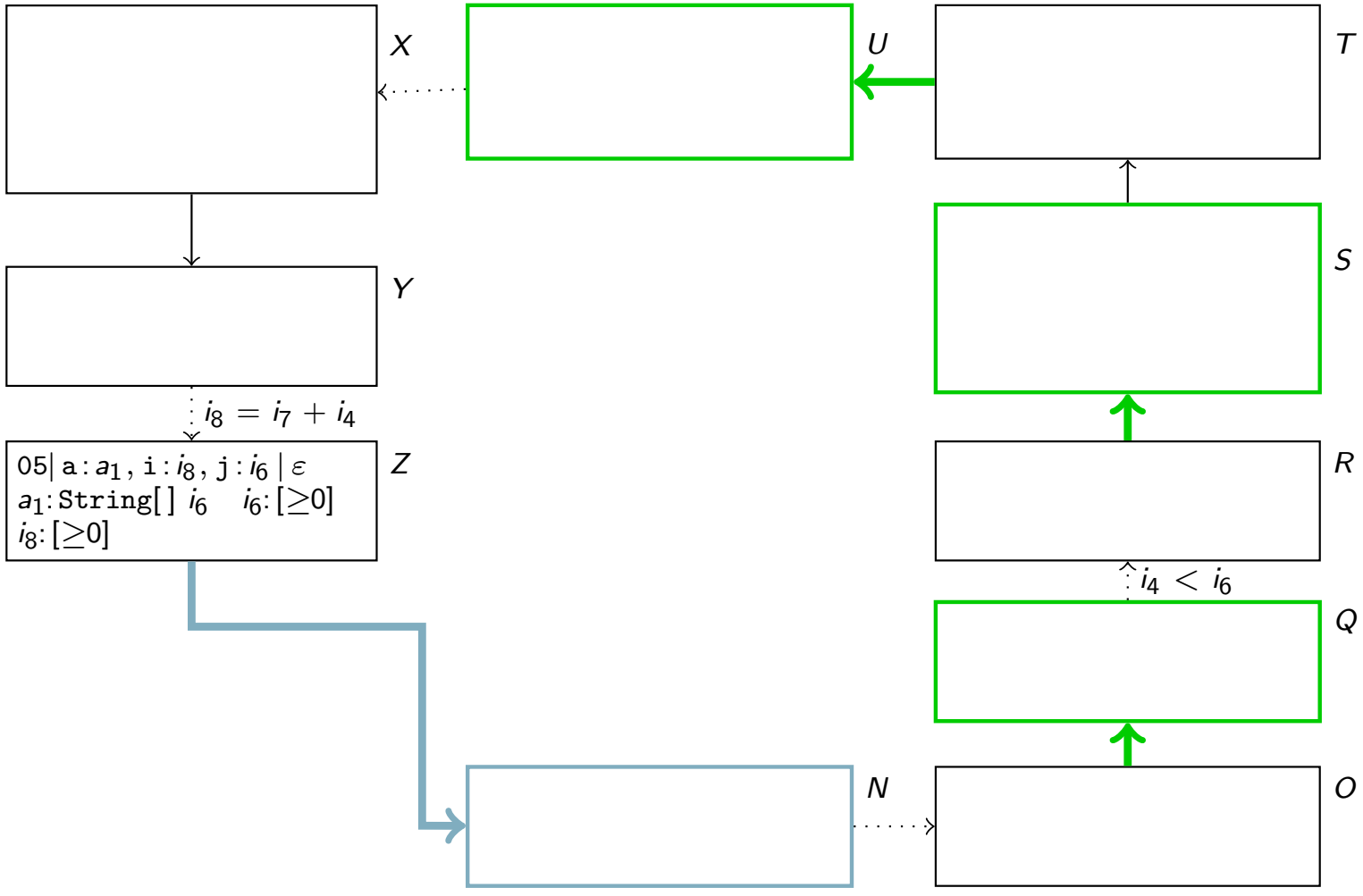
SMT Solution:
$i_4 = i_7 = i_8 = 0$
$i_6 = 1$

Witness

05| a : a_1 , i : 0, j : 1 | ε
a_1 : String[ ] 1



Finding object values by witness generation

- Instantiate last loop state with integer solution

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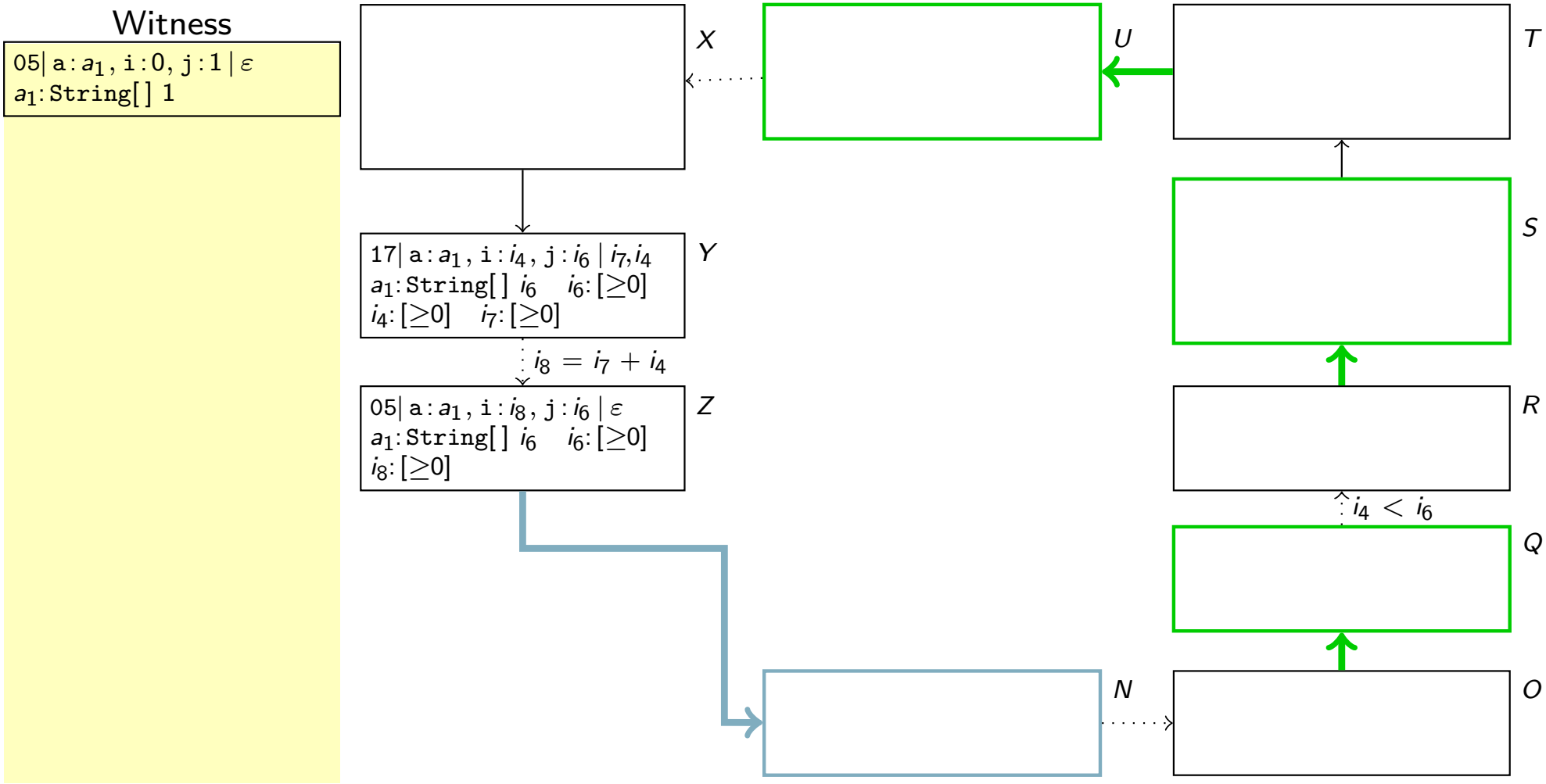

Finding object values by witness generation

- Instantiate last loop state with integer solution
- Perform witness generation

SMT Solution:

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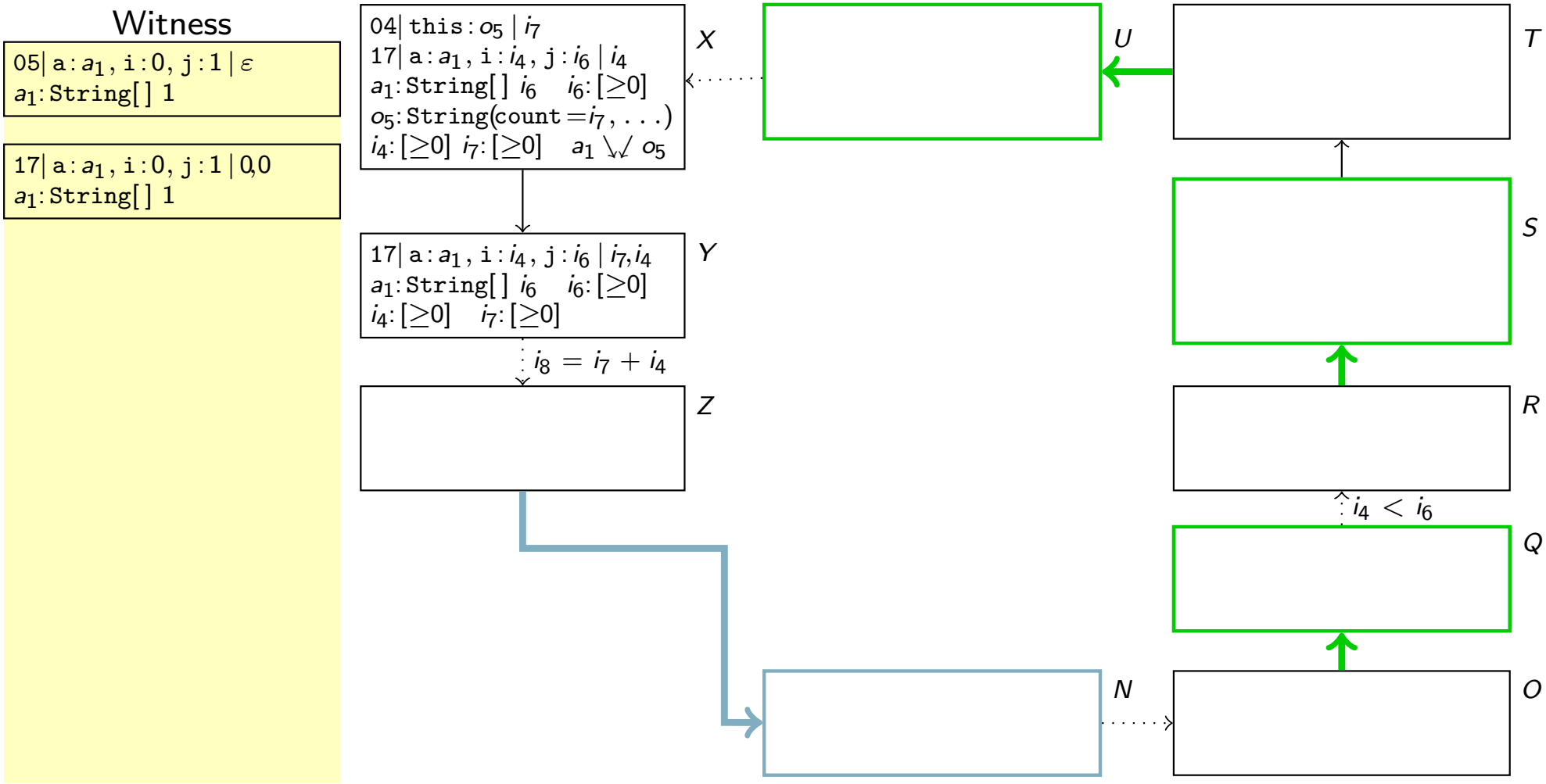

Finding object values by witness generation

- Instantiate last loop state with integer solution
- Perform witness generation
- Use integer solution if possible

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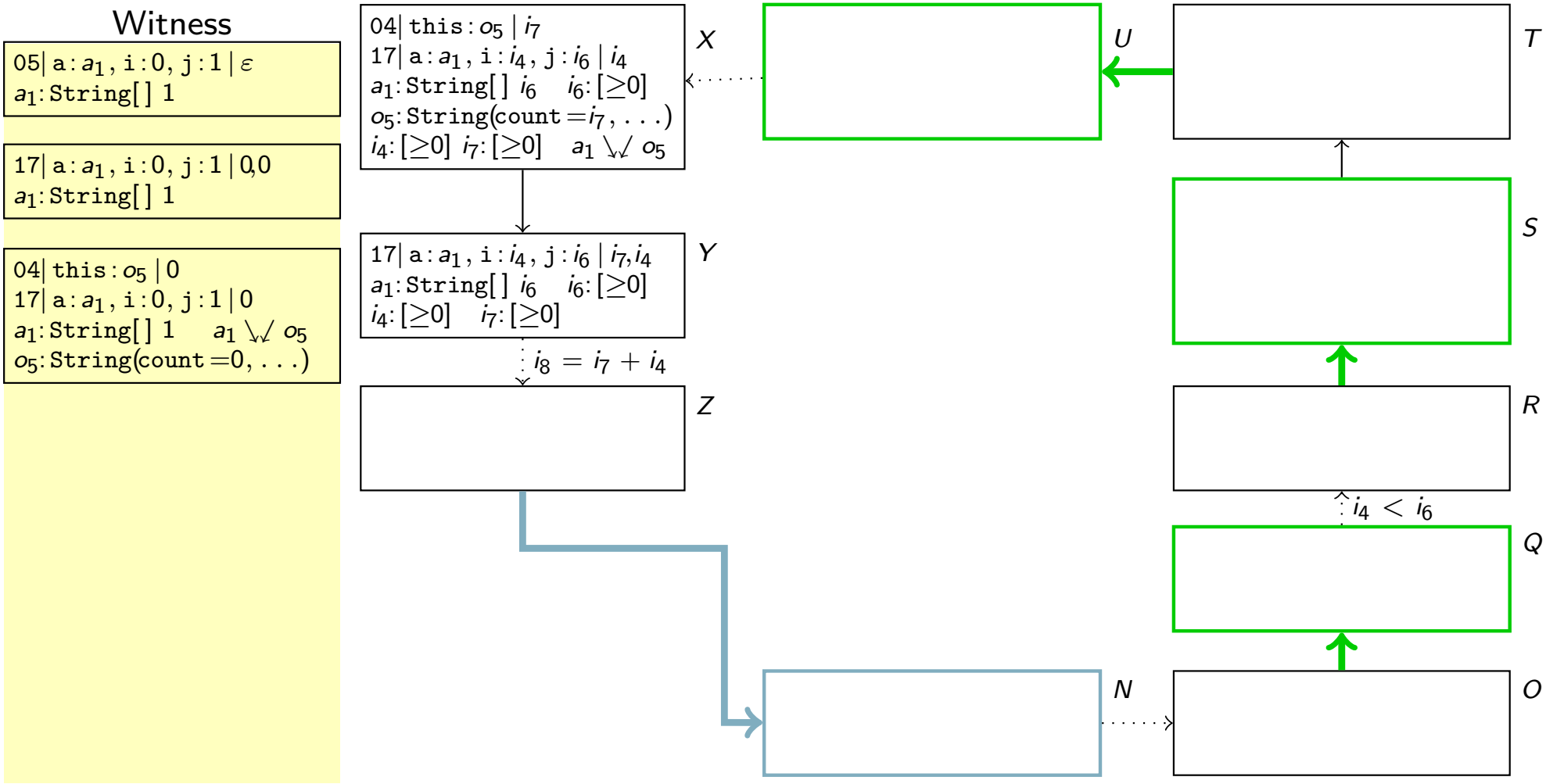

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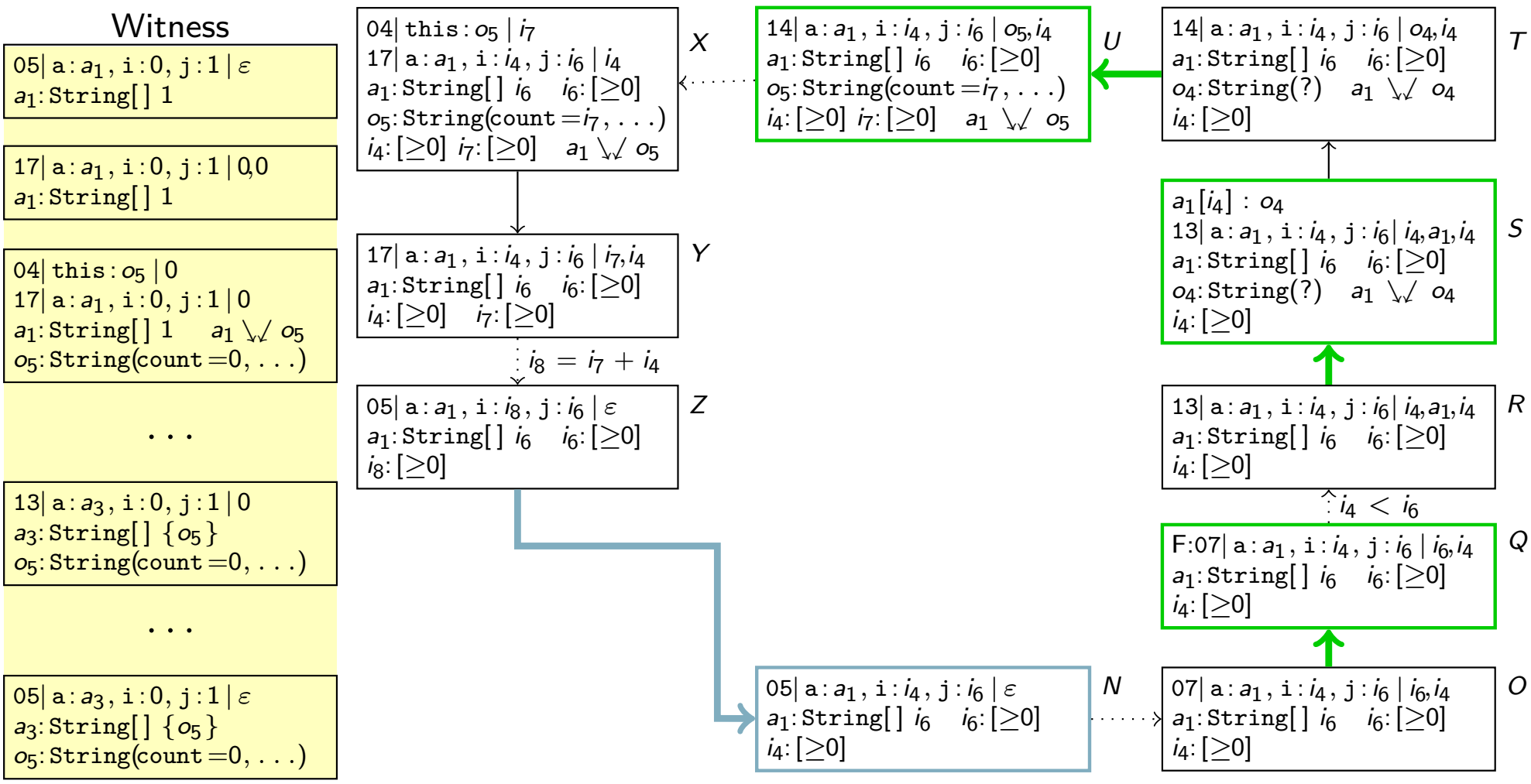

Finding object values by witness generation

- Instantiate last loop state with integer solution
- Perform witness generation
- Use integer solution if possible
- Continue until state at loop start

SMT Solution:

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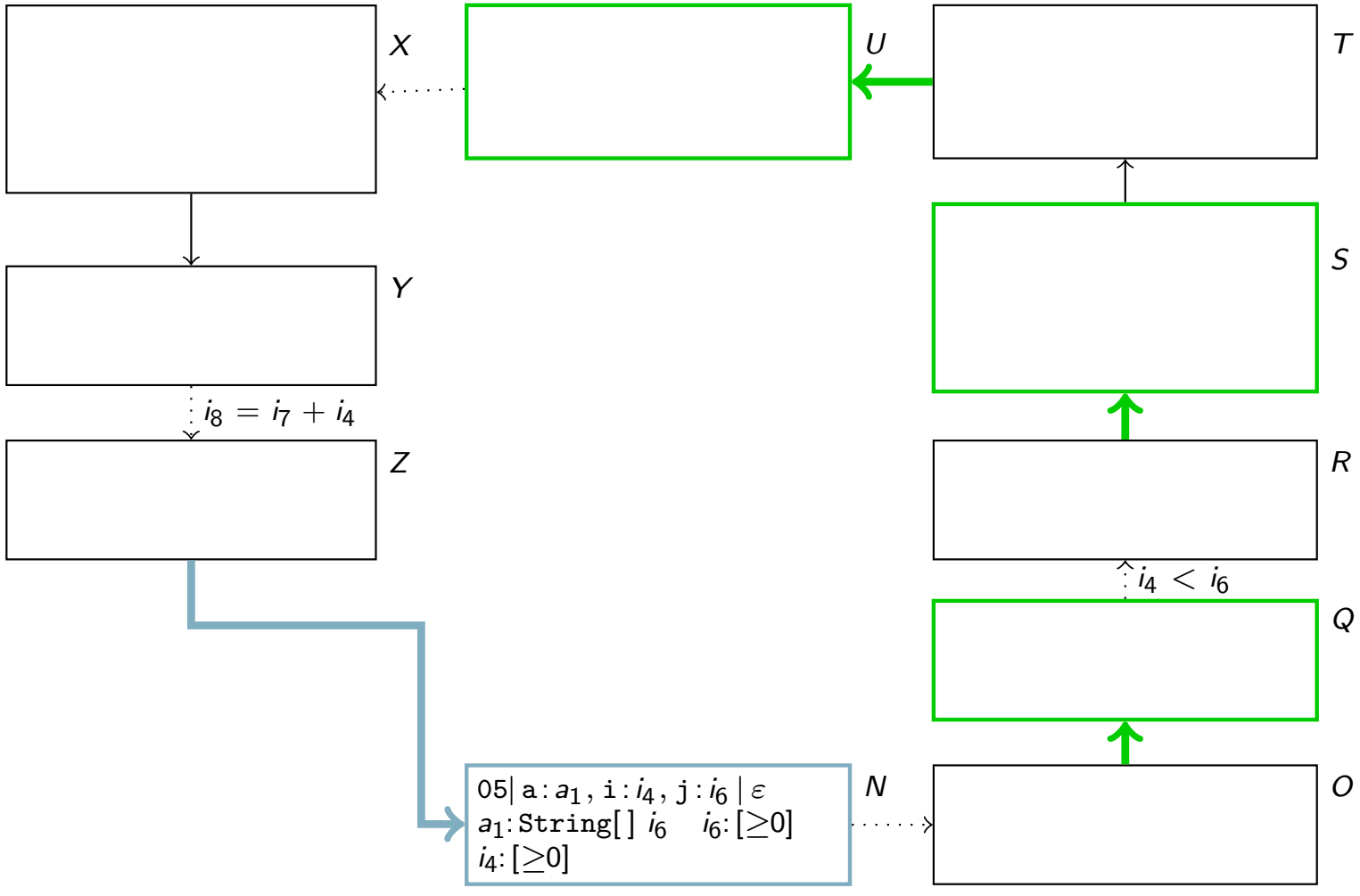
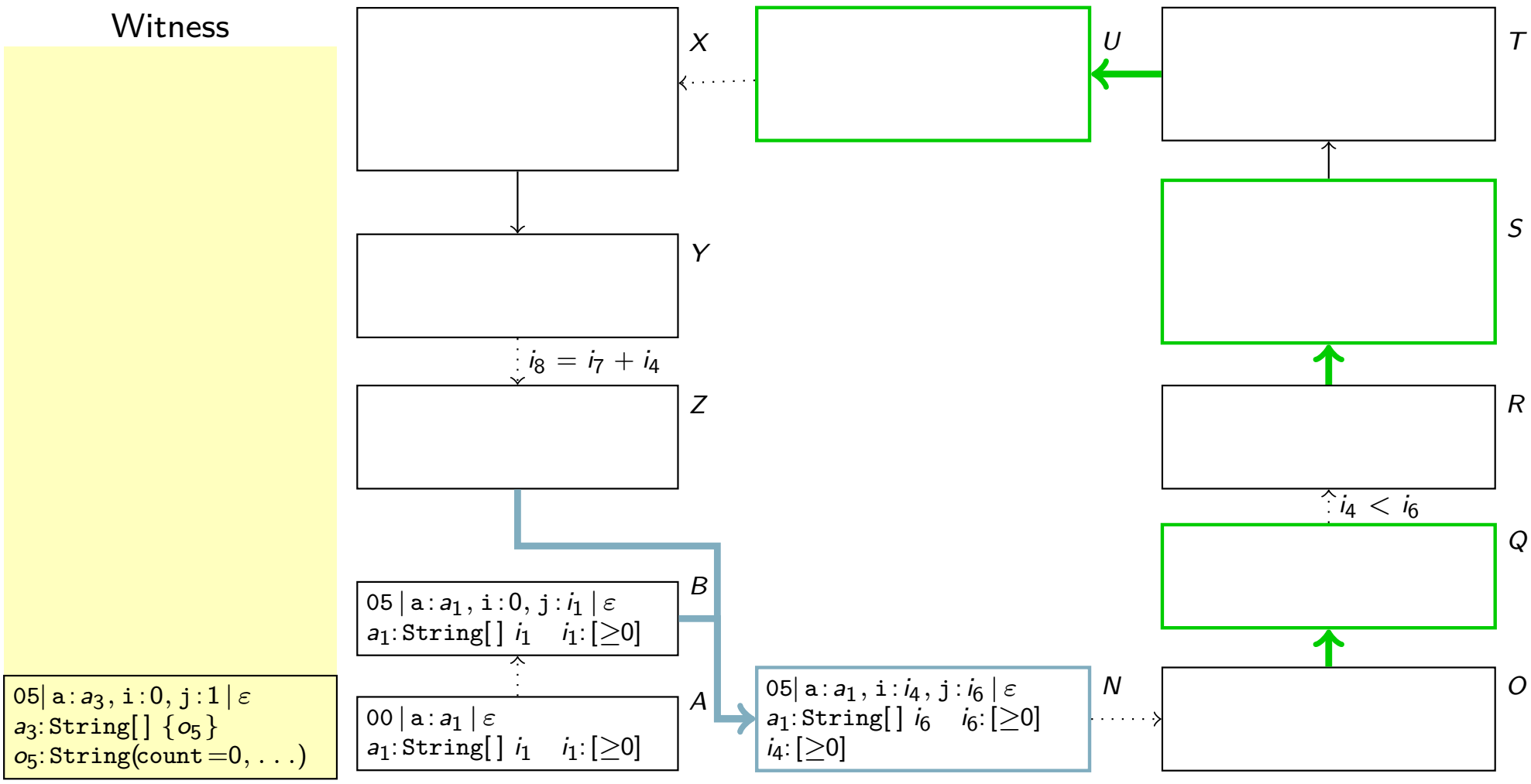
Witness



Verification

- Check that object values stay the same:

$\Rightarrow$ Perform symbolic evaluation.



Verification

- Check that object values stay the same:

$\Rightarrow$ Perform symbolic evaluation.

00| a : a_3 | ε
a_3 : String[ ] {o_5}
o_5 : String(count = 0, . . .)

Witness

- Find start state witness

```
static void nonLoop(
 int x, int y) {
  if (y >= 0) {
   1 while(x >= y) {
       int z = x - y;
    2 if (z > 0) {
     3 x--;
       } else {
     4 x = 2*x + 1;
        y++; }}}}
```

- nonLoop does not terminate for $x = 1, y = 1$:

$$(1,1) \rightarrow (3,2) \rightarrow (2,2) \rightarrow (5,3) \rightarrow (4,3) \rightarrow (3,3) \rightarrow \ \ldots$$

```
static void nonLoop(
 int x, int y) {
  if (y >= 0) {
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- nonLoop does not terminate for $x = 1, y = 1$:
- Program run is *non-periodic*:

$$(1,1) \xrightarrow{4} (3,2) \xrightarrow{3} (2,2) \xrightarrow{4} (5,3) \xrightarrow{3} (4,3) \xrightarrow{3} (3,3) \xrightarrow{4} \ldots$$

```
static void nonLoop(
 int x, int y) {
  if (y >= 0) {
   1 while(x >= y) {
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    2  if (z > 0) {
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       } else {
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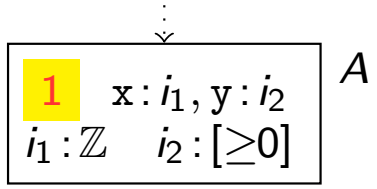

- nonLoop does not terminate for $x = 1, y = 1$:
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- Always: Generate Termination Graph

```
static void nonLoop(
 int x, int y) {
  if (y >= 0) {
   1 while(x >= y) {
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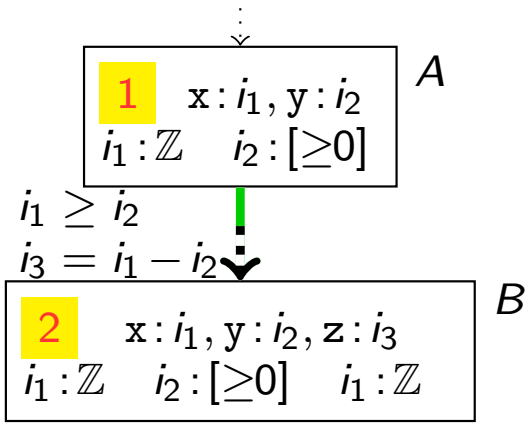

- A to B: Refine + Evaluation

```
static void nonLoop(
 int x, int y) {
  if (y >= 0) {
   1 while(x >= y) {
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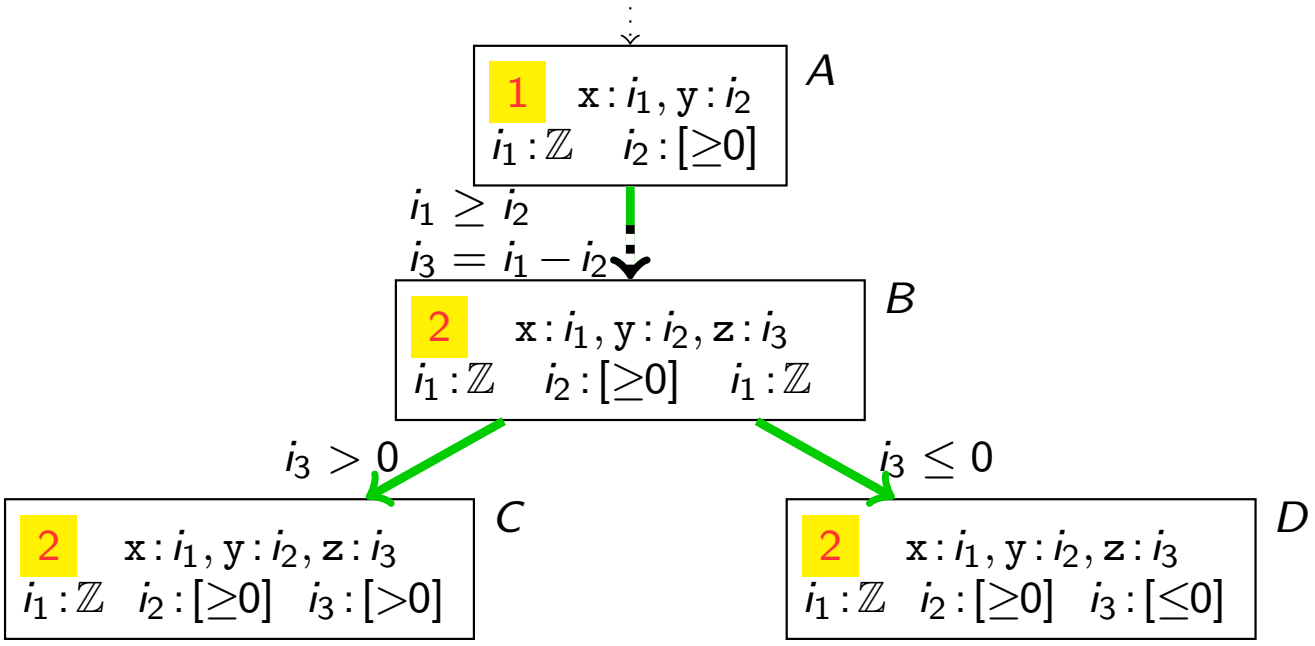

- A to B: Refine + Evaluation
- B to C, D: Refine z/i_3

```
static void nonLoop(
 int x, int y) {
  if (y >= 0) {
   1 while(x >= y) {
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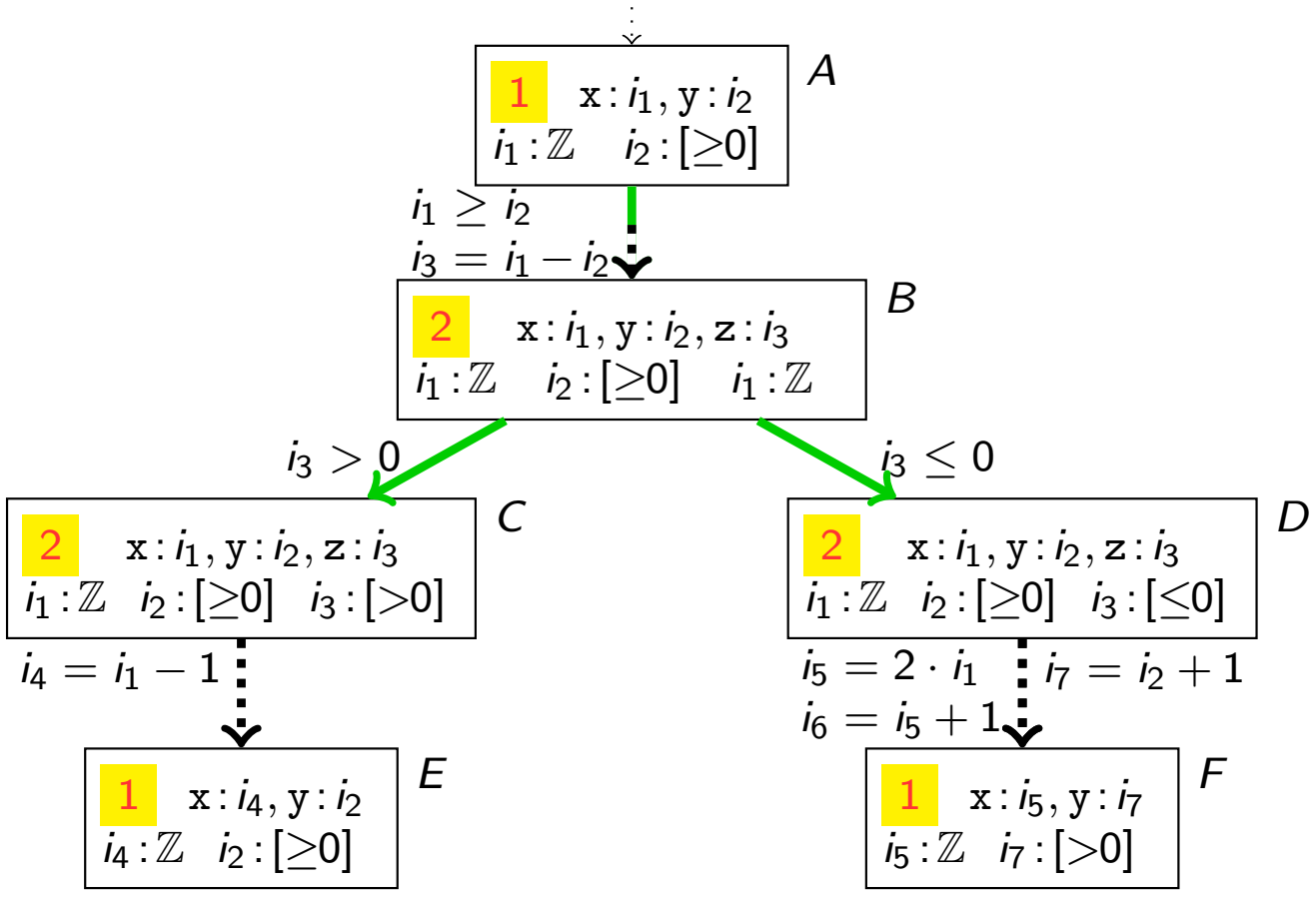

- A to B: Refine + Evaluation
- B to C, D: Refine z/i_3
- C to E, D to F: Evaluation

```
static void nonLoop(
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  if (y >= 0) {
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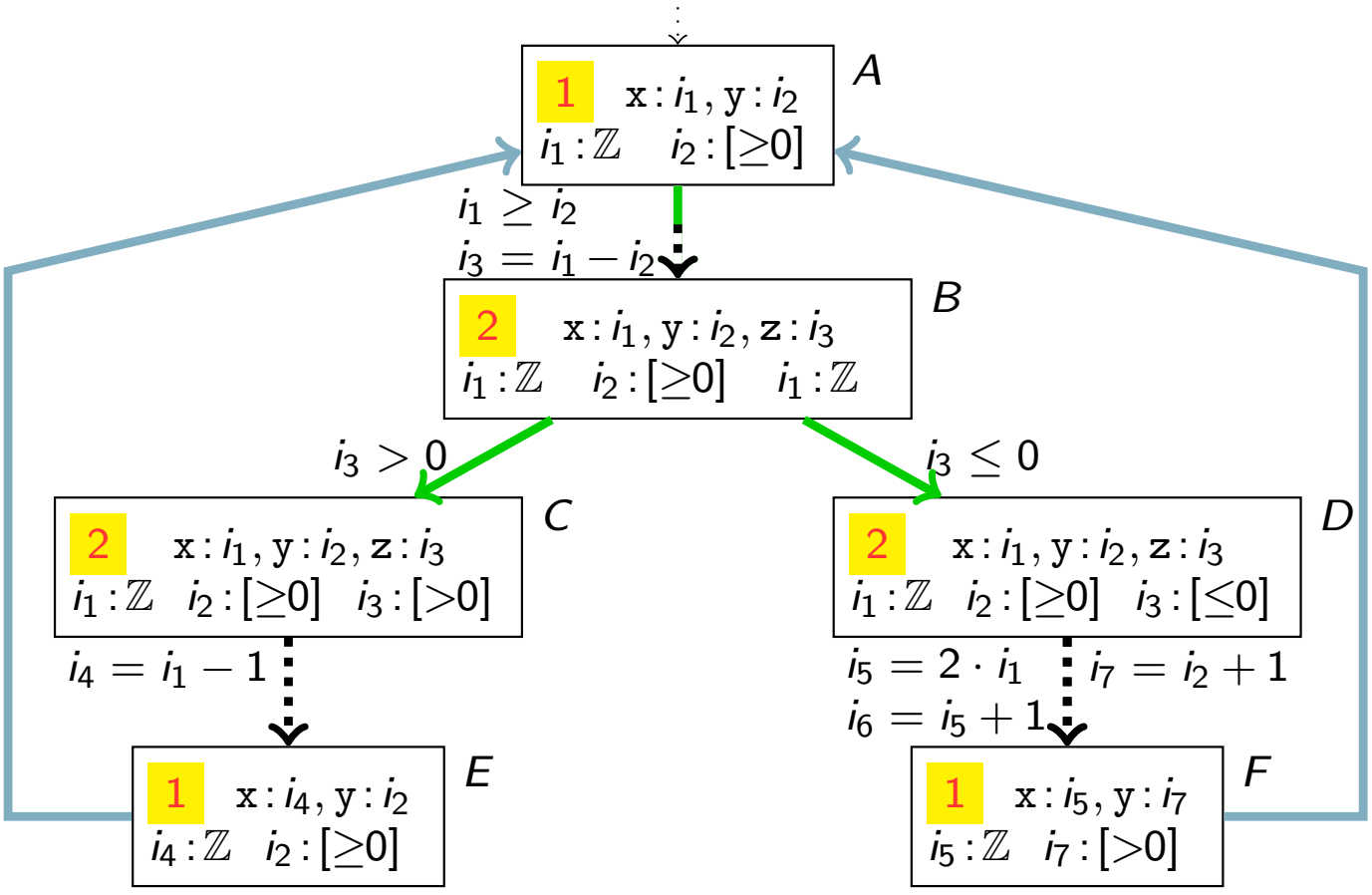

- A to B: Refine + Evaluation
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- C to E, D to F: Evaluation
- E, F represented by A: Instantiation

```
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  if (y >= 0) {
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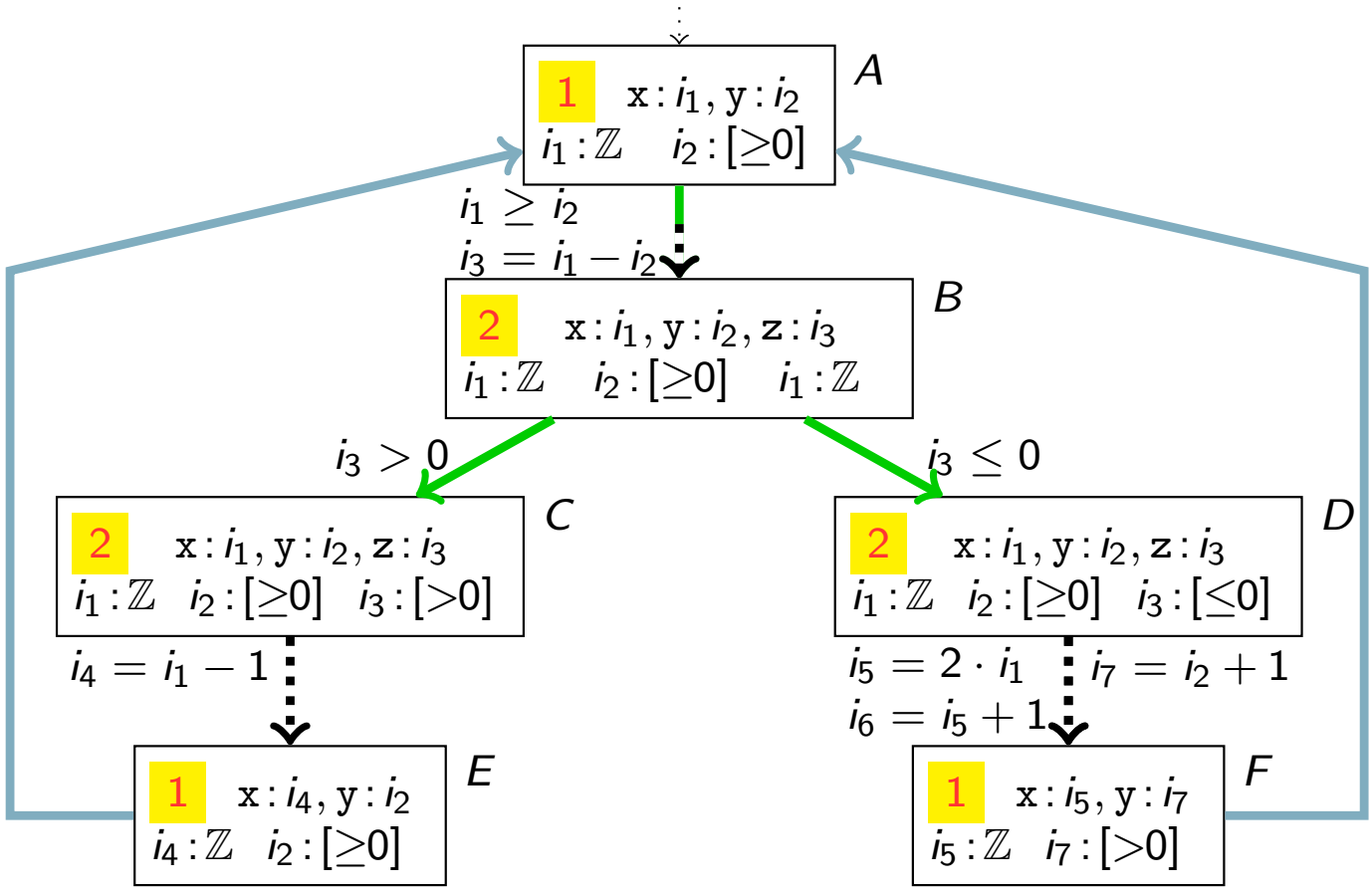

- A to B: Refine + Evaluation
- B to C, D: Refine z/i_3
- C to E, D to F: Evaluation
- E, F represented by A: Instantiation
- Prove (condition & computation) $\rightarrow$ condition

```
static void nonLoop(
 int x, int y) {
  if (y >= 0) {
   1 while(x >= y) {
       int z = x - y;
    2  if (z > 0) {
     3   x--;
       } else {
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         y++; }}}}
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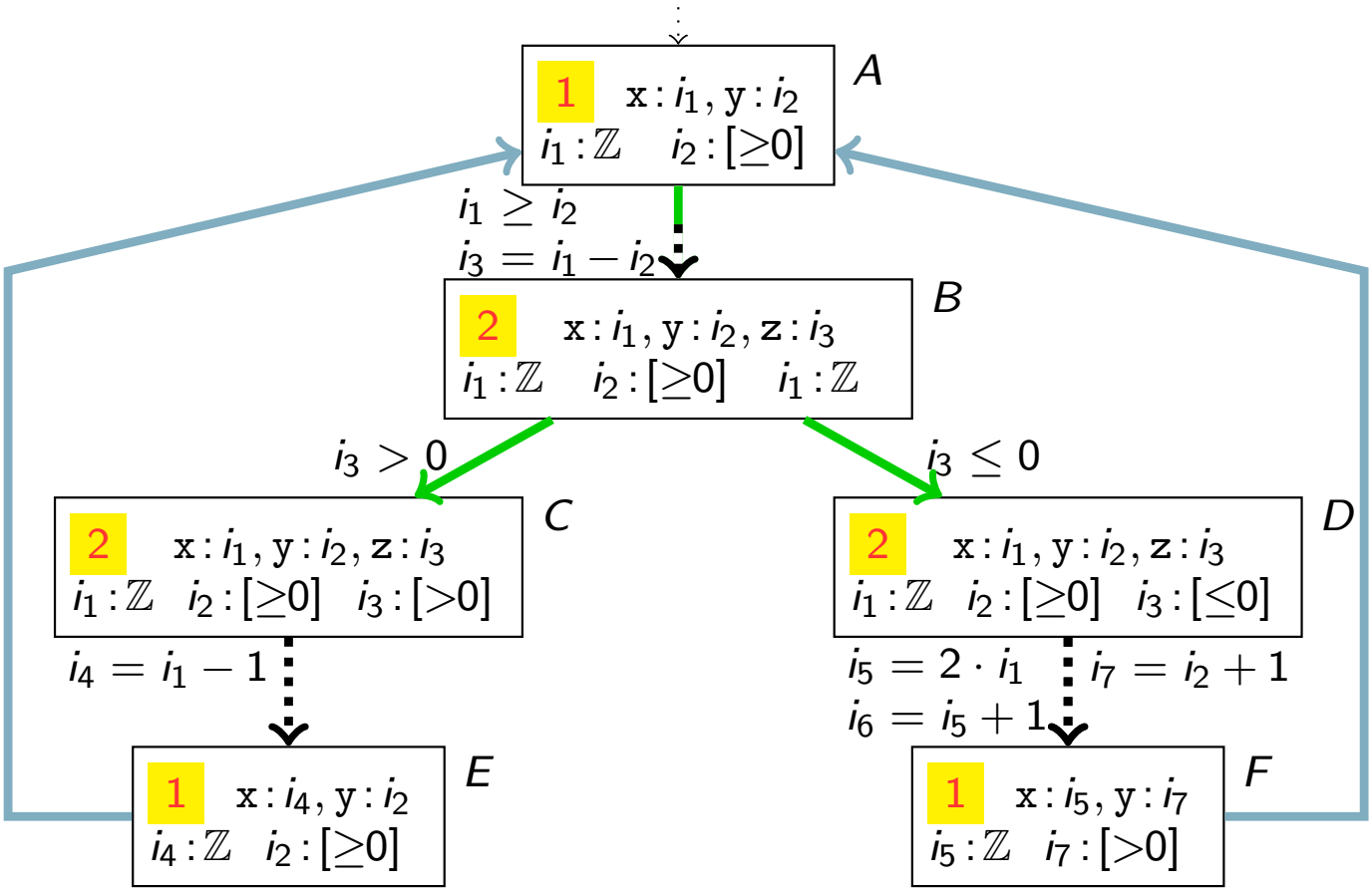

- Consider each path separately

```
static void nonLoop(
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  if (y >= 0) {
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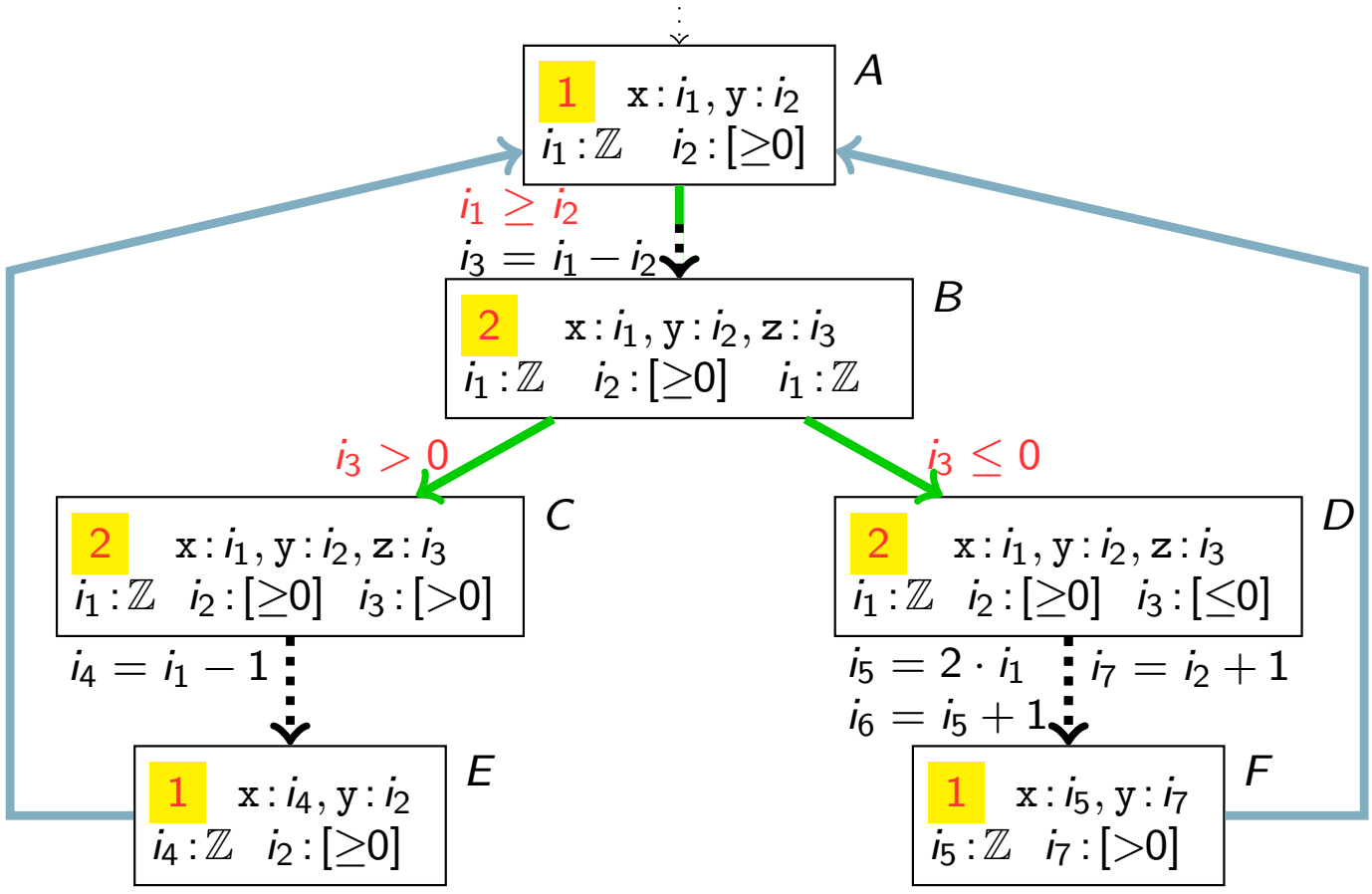
```

$\varphi_1 : i_1 \geq i_2 \wedge i_3 > 0$

$\varphi_2 : i_1 \geq i_2 \wedge i_3 \leq 0$



- Consider each path separately
- Condition formulas φ_i from refinements

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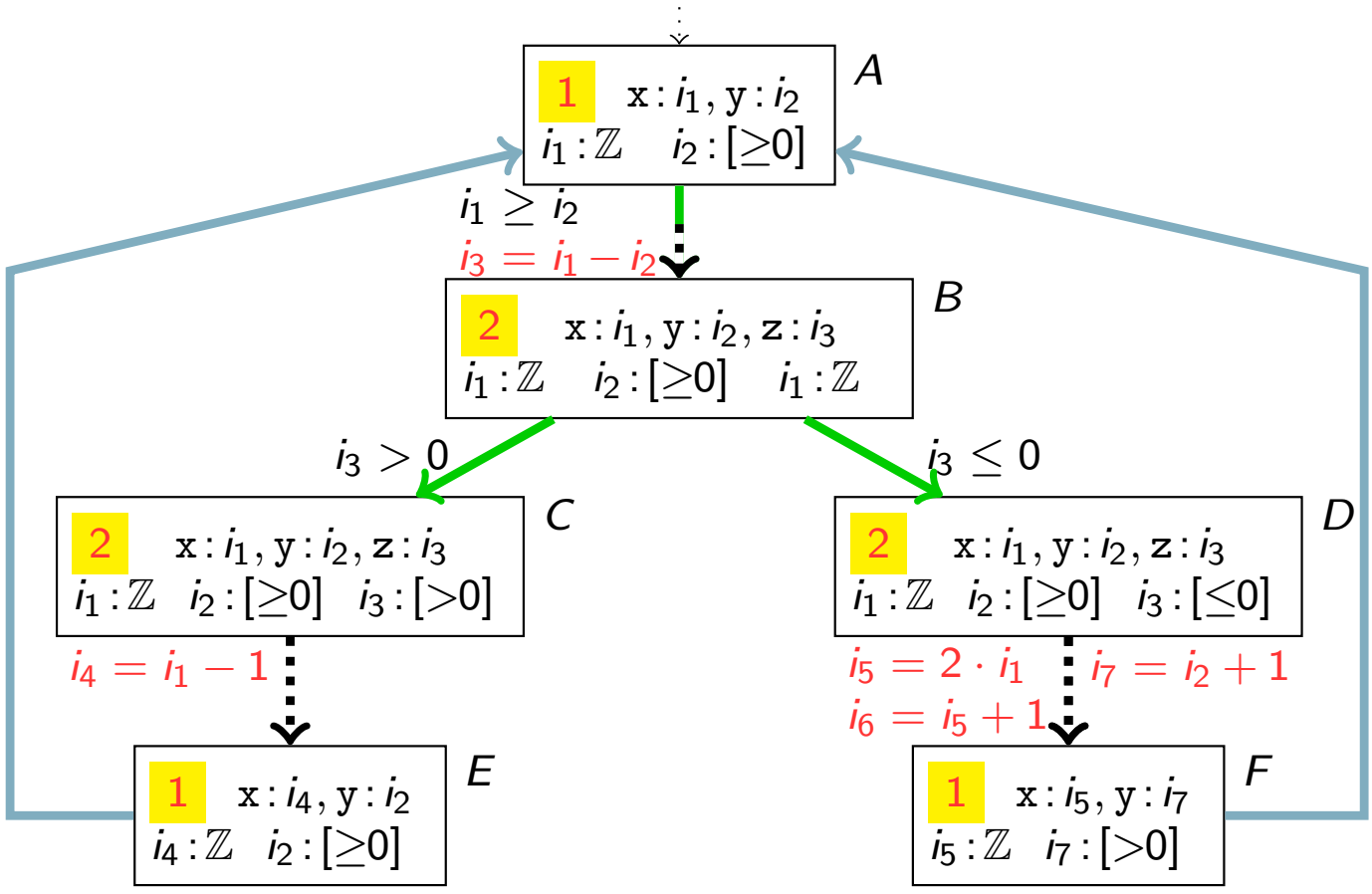

φ_1: $i_1 \geq i_2 \wedge i_3 > 0$

φ_2: $i_1 \geq i_2 \wedge i_3 \leq 0$

ψ_1: $i_3 = i_1 - i_2 \wedge i_4 = i_1 - 1$

ψ_2: $i_3 = i_1 - i_2 \wedge i_5 = 2 \cdot i_1$
$\wedge i_6 = i_5 + 1 \wedge i_7 = i_2 + 1$

- Consider each path separately
- Condition formulas φ_i from refinements
- Computation formulas ψ_i from evaluations

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static void nonLoop(
 int x, int y) {
  if (y >= 0) {
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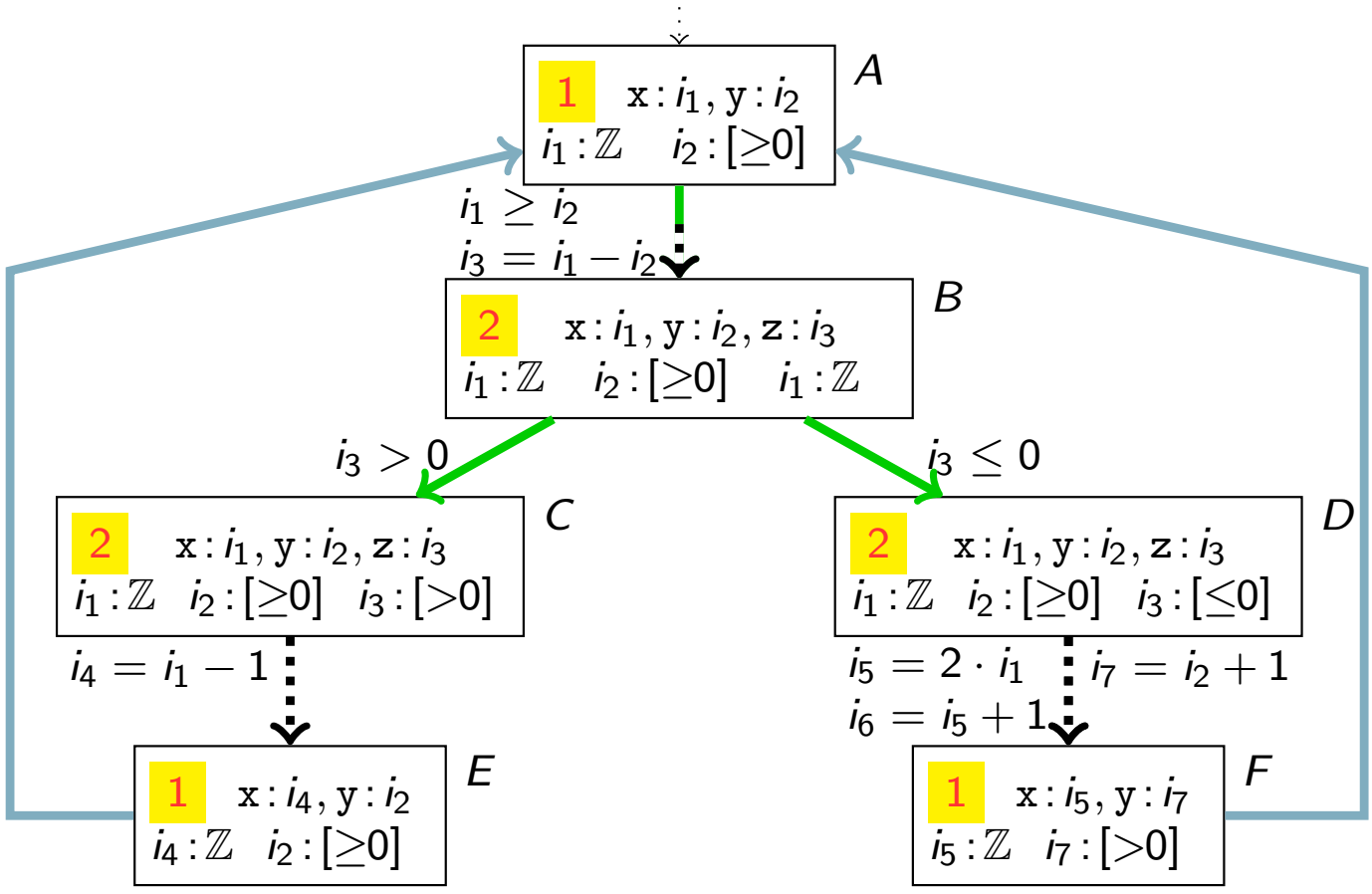

φ_1^1: $i_1^1 \geq i_2^1 \wedge i_3^1 > 0$

φ_2^1: $i_1^1 \geq i_2^1 \wedge i_3^1 \leq 0$

ψ_1^1: $i_3^1 = i_1 - i_2^1 \wedge i_4^1 = i_1^1 - 1$

ψ_2^1: $i_3^1 = i_1 - i_2^1 \wedge i_5^1 = 2 \cdot i_1^1$
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- Consider each path separately
- Condition formulas φ_i from refinements
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- Label formulas for loop run k with ^{k}

```
static void nonLoop(
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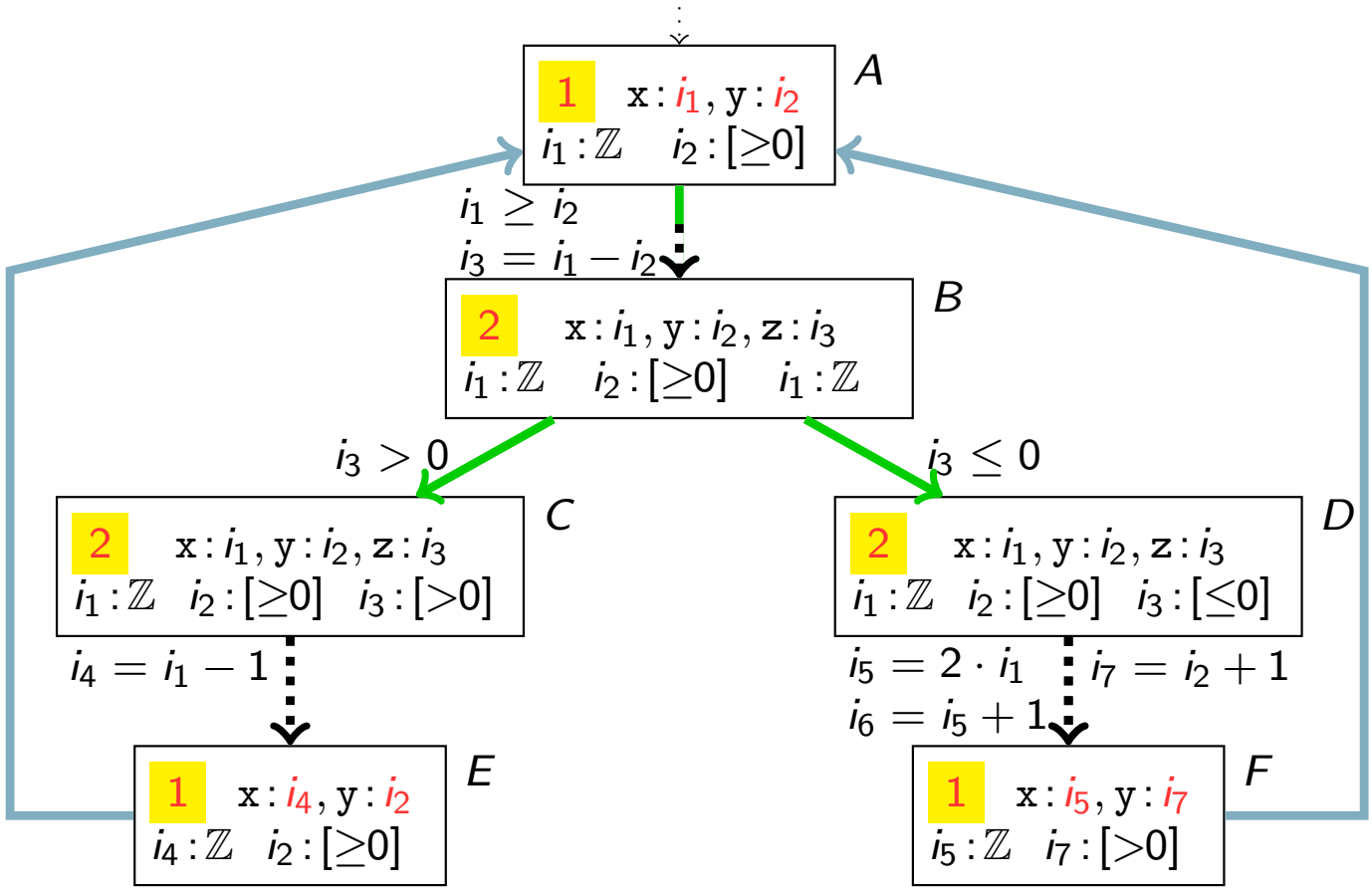

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- Consider each path separately
- Condition formulas φ_i from refinements
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- Connect runs using ι_j from instantiations

```
static void nonLoop(
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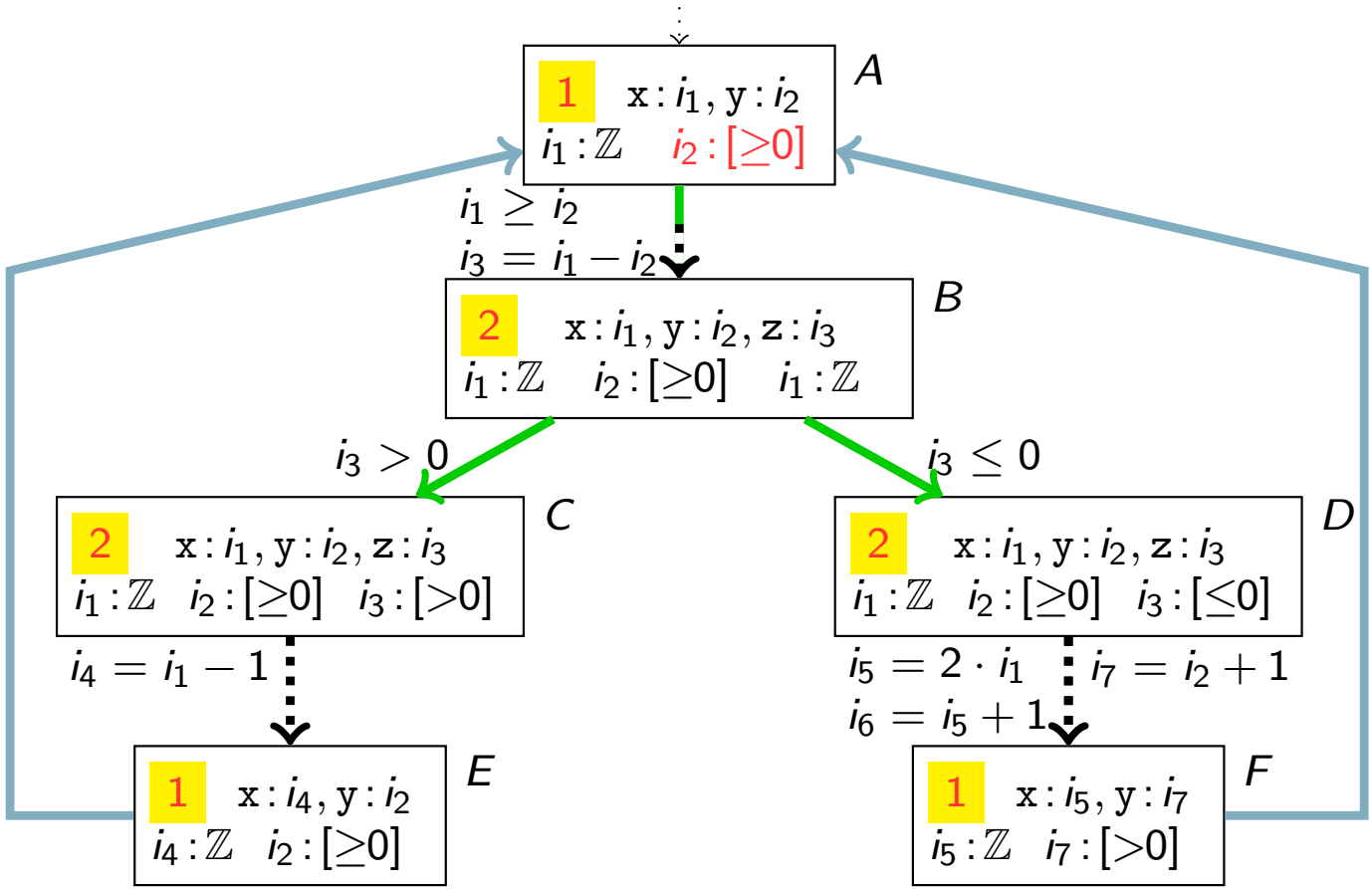

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ι_1: $i_4^1 = i_1^2 \wedge i_2^1 = i_2^2$

ι_2: $i_4^1 = i_1^2 \wedge i_2^1 = i_2^2$

μ: $i_2^1 \geq 0$

- Consider each path separately
- Condition formulas φ_i from refinements
- Computation formulas ψ_i from evaluations
- Label formulas for loop run k with ^{k}
- Connect runs using ι_j from instantiations
- Add invariant μ from loop start

```
static void nonLoop(
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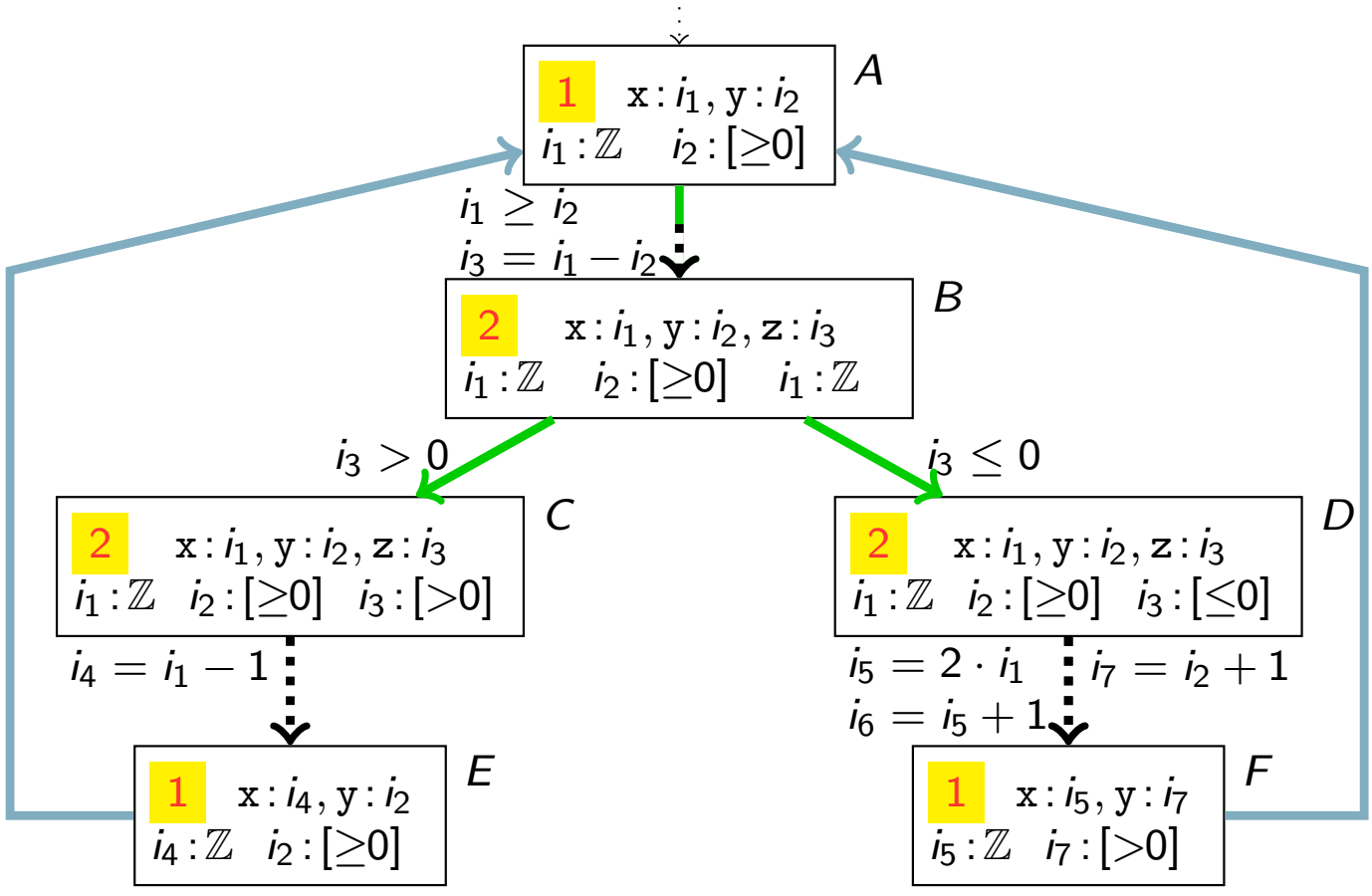

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- All conditions (φ_i^2) false $\curvearrowright$ loop is left

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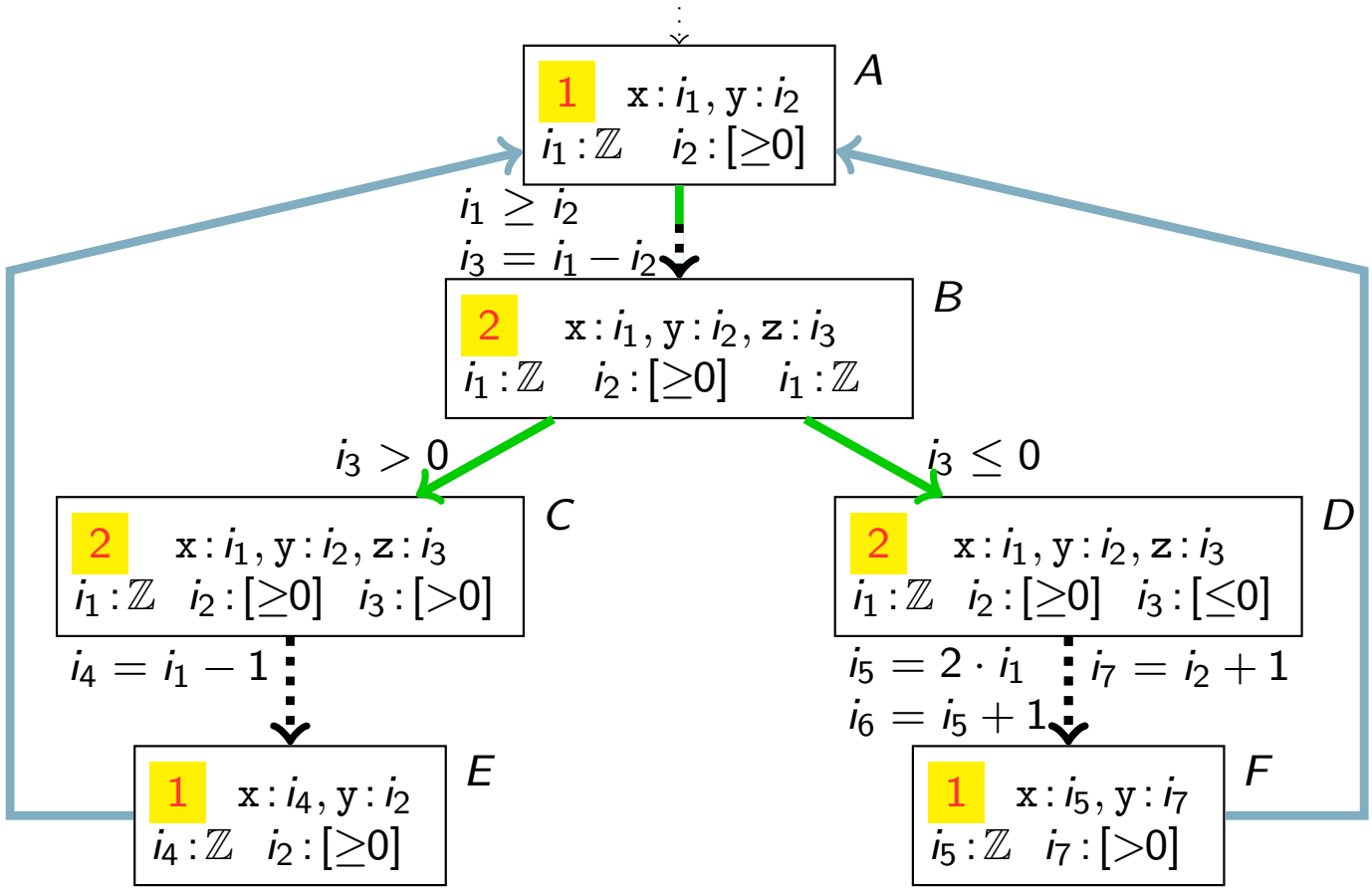

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- All conditions (φ_i^2) false $\curvearrowright$ loop is left
- Put together:

$$\underbrace{\mu}_{\text{invariants}} \wedge \underbrace{(\bigvee_{j=1}^{n} (\varphi_j^1 \wedge \psi_j^1 \wedge \iota_j))}_{\text{first run through the loop}} \wedge \underbrace{(\bigwedge_{j=1}^{n} (\neg\varphi_j^2 \wedge \psi_j^2)}_{\text{second run, leaving the loop}}$$

- SMT Solver says UNSAT $\curvearrowright$ loop never left

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static void nonLoop(
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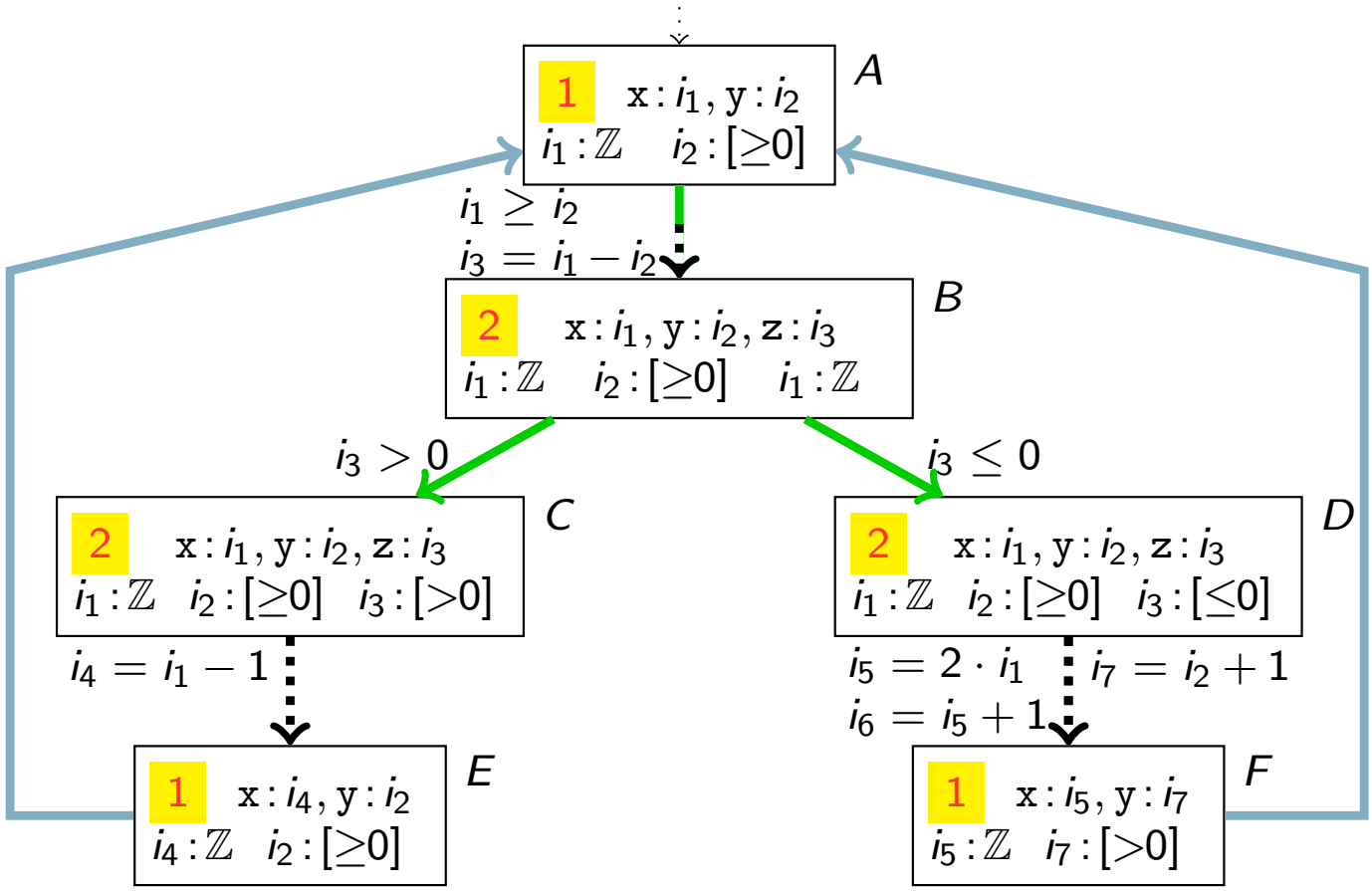

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$\Rightarrow$ Prove that one loop run occurs (SMT, witness)

Non-termination analysis of JBC

- Implemented in AProVE for full single-threaded Java

Non-termination analysis of JBC

- Implemented in AProVE for full single-threaded Java
- Evaluated on 325 examples:
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  - 55 from the evaluation of Invel
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	Invel Ex.					Other Ex.				
	Y	**N**	**F**	**T**	**R**	**Y**	**N**	**F**	**T**	**R**
AProVE-No	1	51	0	3	5	204	30	12	24	11
AProVE	1	0	5	49	54	204	0	27	39	15
Julia	1	0	54	0	2	166	22	82	0	4
Invel	0	42	13	0	?					

Yes, **N**o, **F**ailed proof, **T**imeout, **R**untime (average)

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http://aprove.informatik.rwth-aachen.de/eval/JBC-Nonterm