CMPT 745
Software Engineering

# Static Analysis
## & Dataflow Analysis

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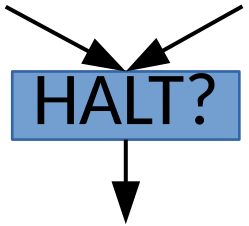


"Does my program terminate?"

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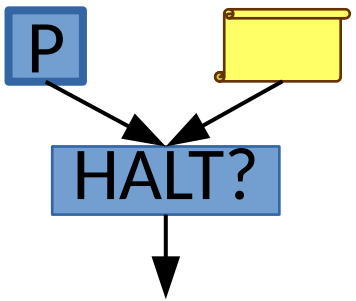

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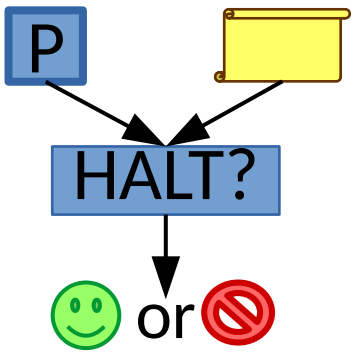

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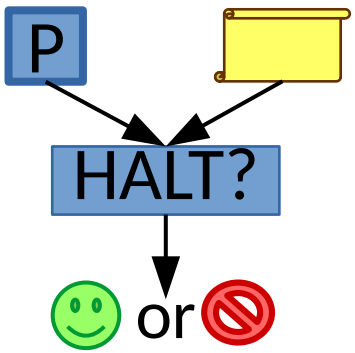


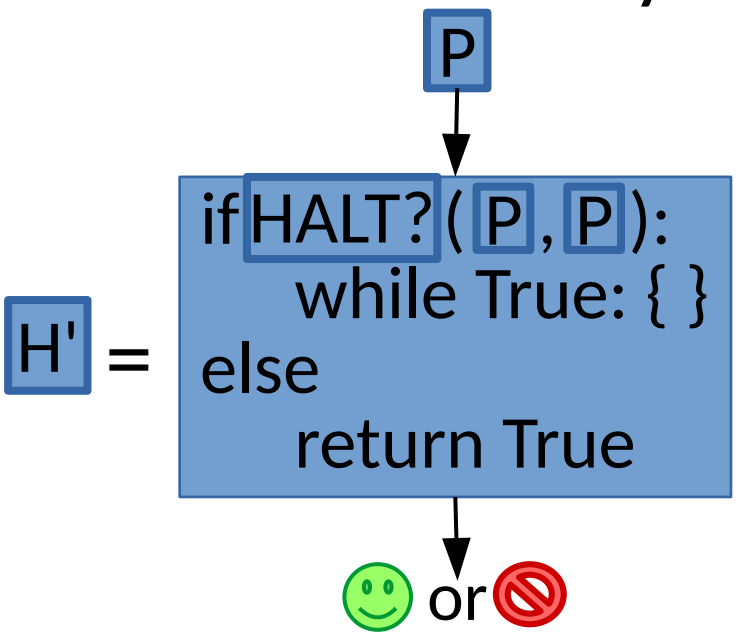

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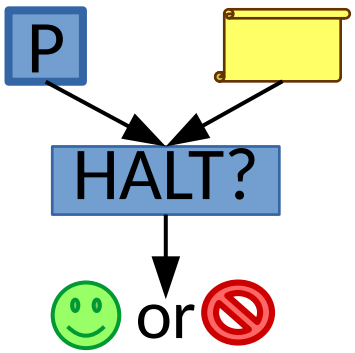


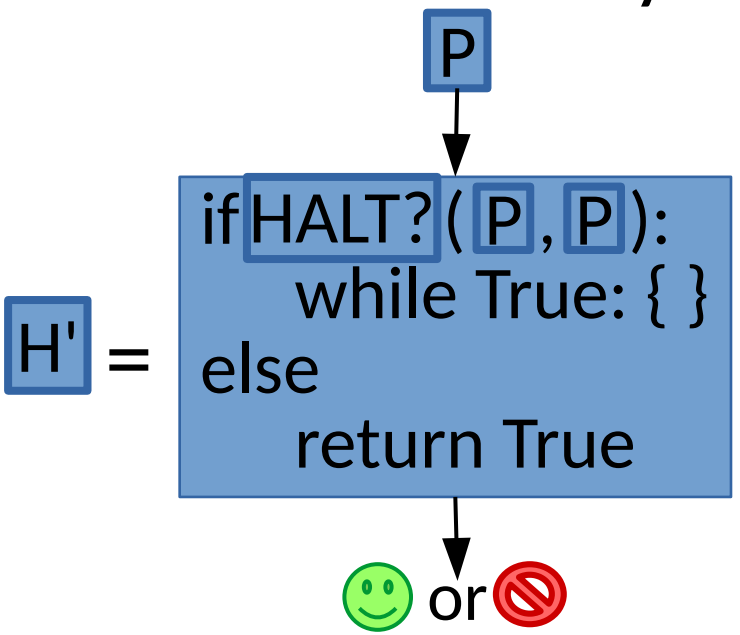


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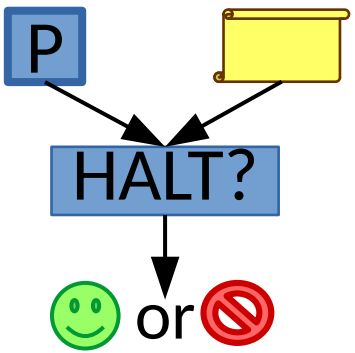


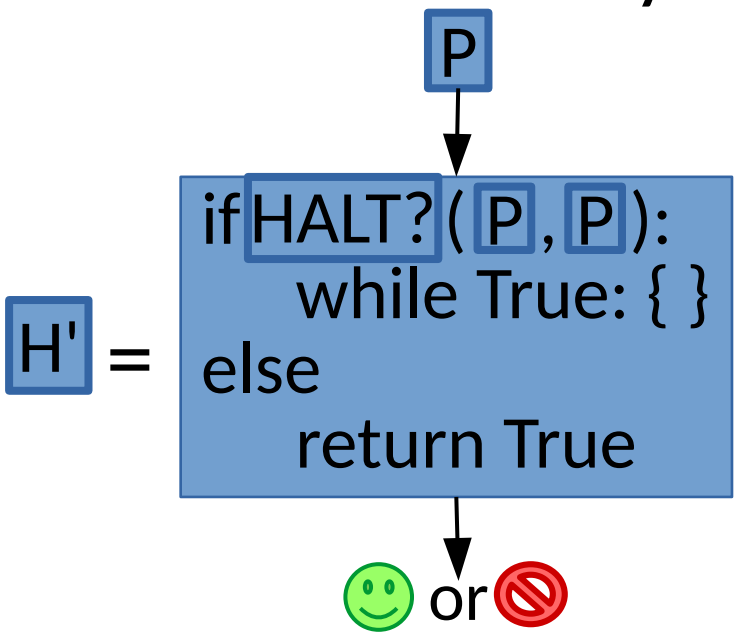


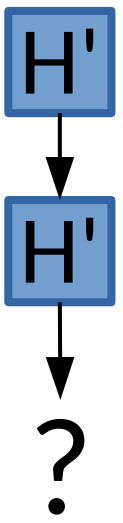


It's a classic paradox!

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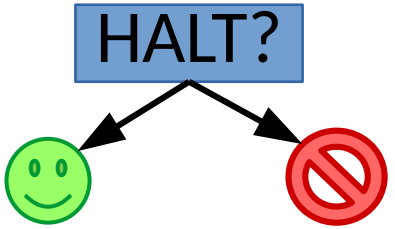

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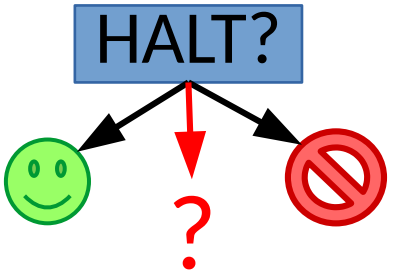

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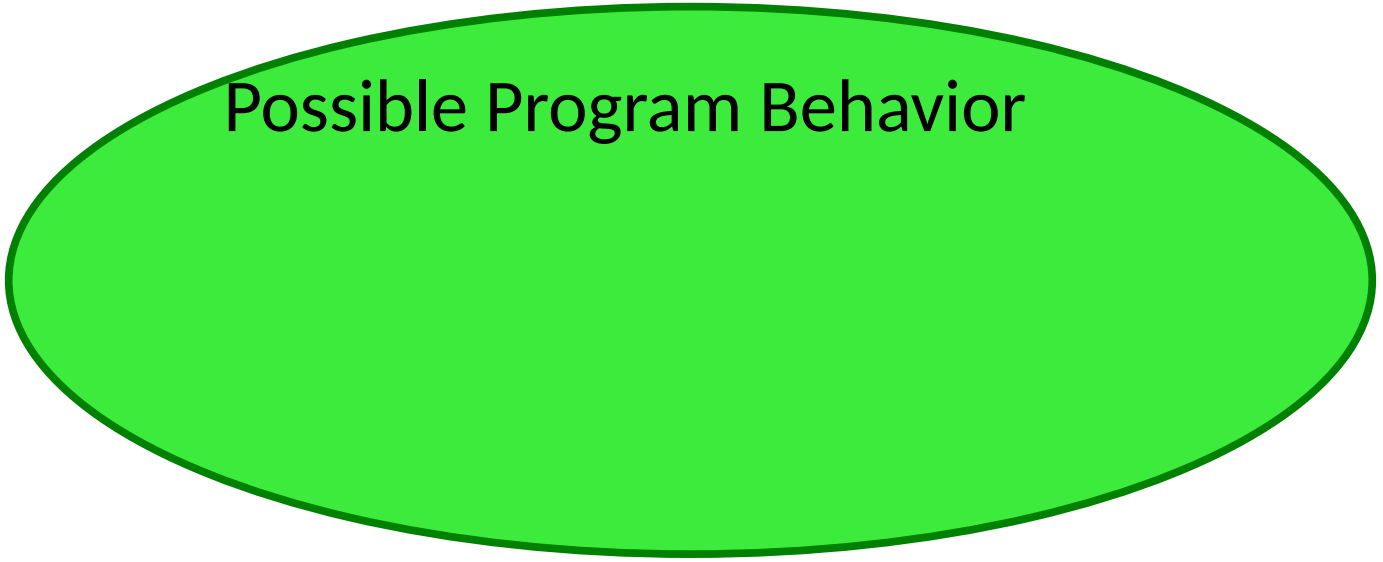
Striking the right balance is key to a useful analysis

# Approximation

Modeled program behaviors



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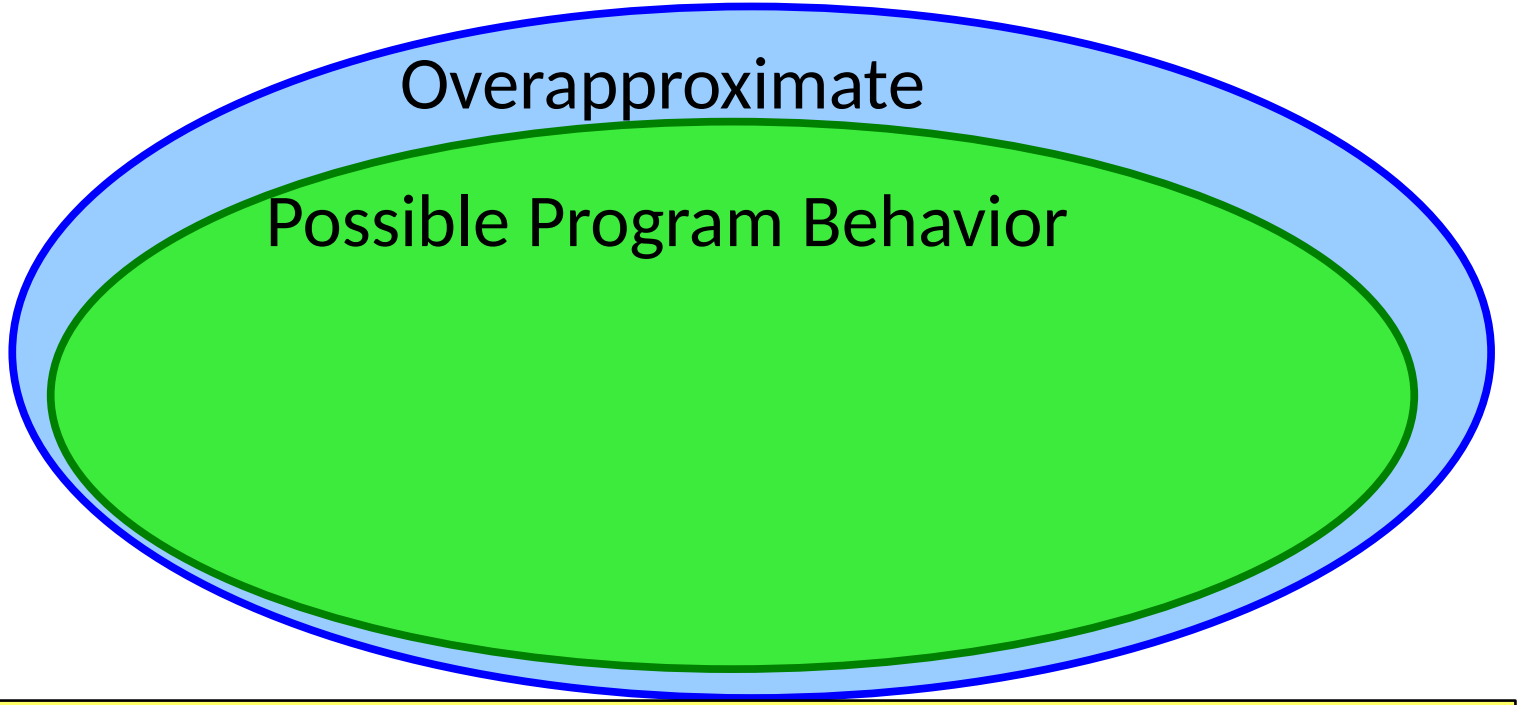


Consider some behaviors possible when they are not.

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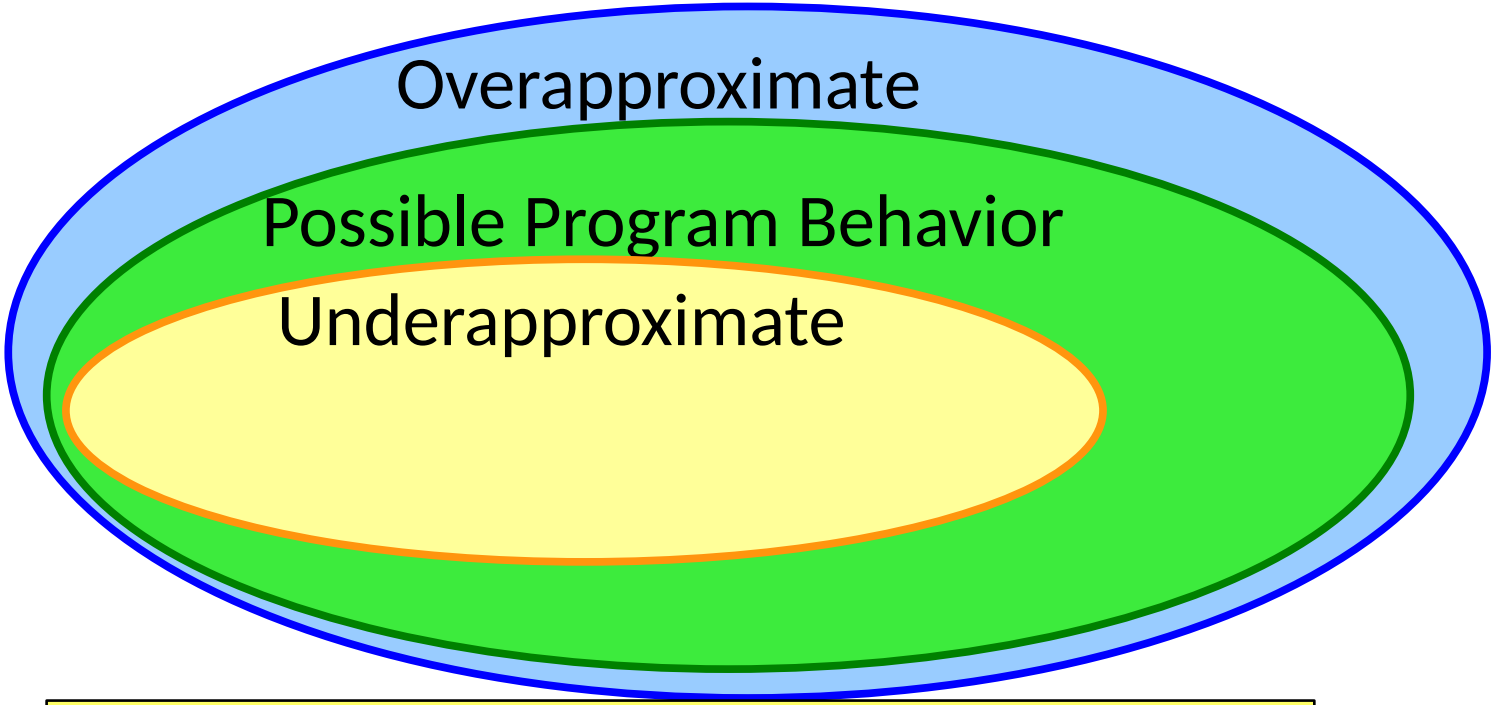


Ignore some behaviors that *are* possible.

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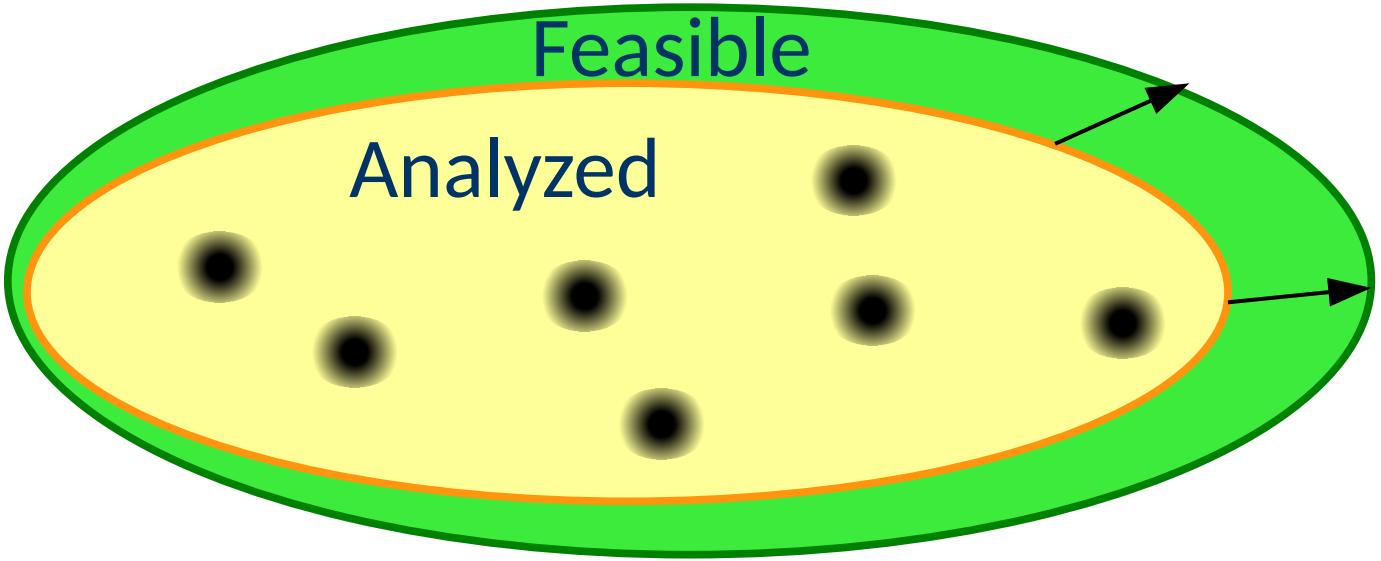
  - Analyzed ⊆ Feasible
  - As # tests ↑, Analyzed → Feasible



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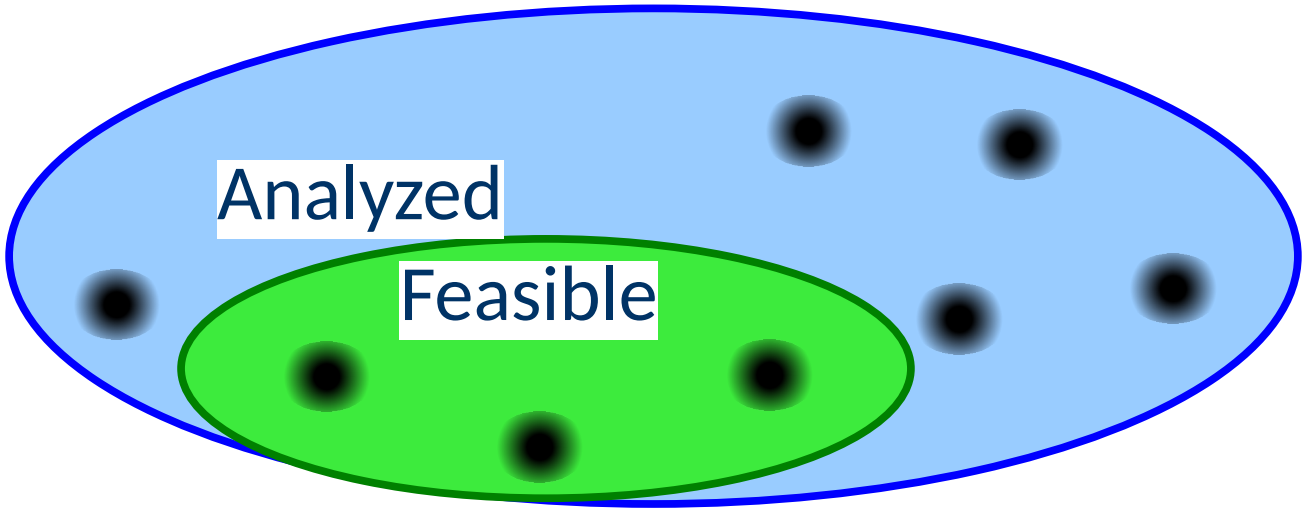

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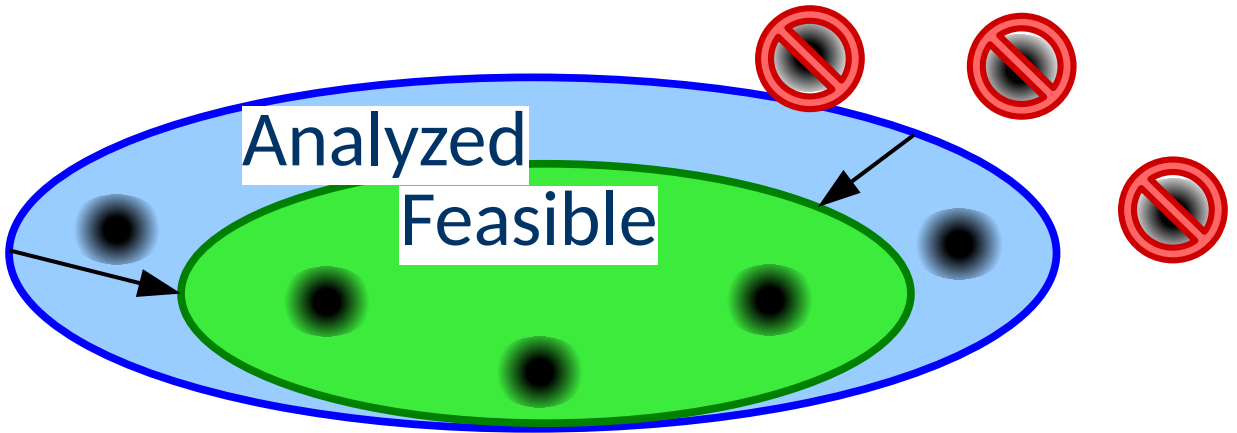

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- The two areas complement each other
  - Static analysis can help generate useful tests
  - Dynamic analysis can help identify infeasibility

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- Concrete domain: integers
- Abstract domain: {-,0,+} ⋃ {⊤,⊥}

concrete(x) = 5 ↦ abstract(x) = +
concrete(y) = -3 ↦ abstract(y) = -
concrete(z) = 0 ↦ abstract(z) = 0

Combines sets of the concrete domain

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This type of approximation is called *abstract interpretation*.

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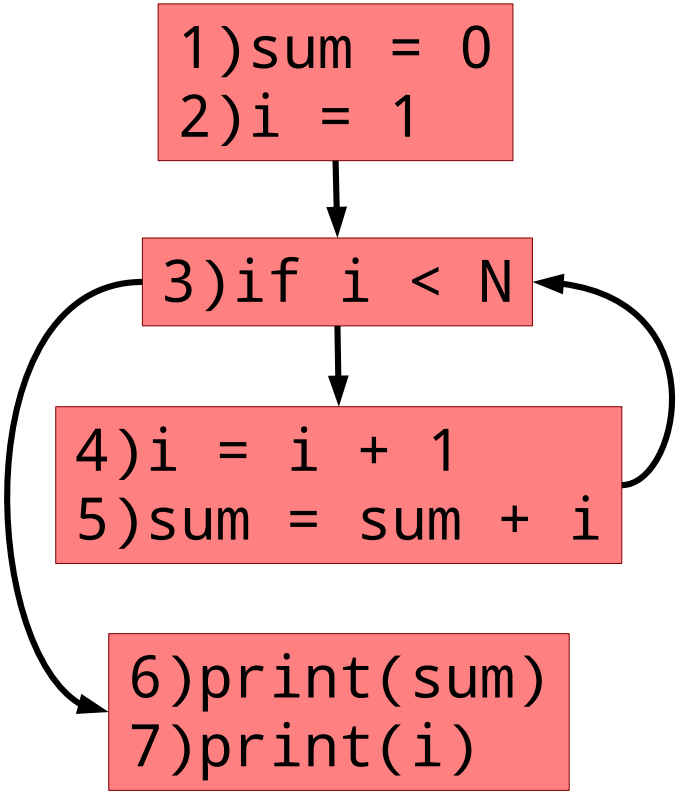

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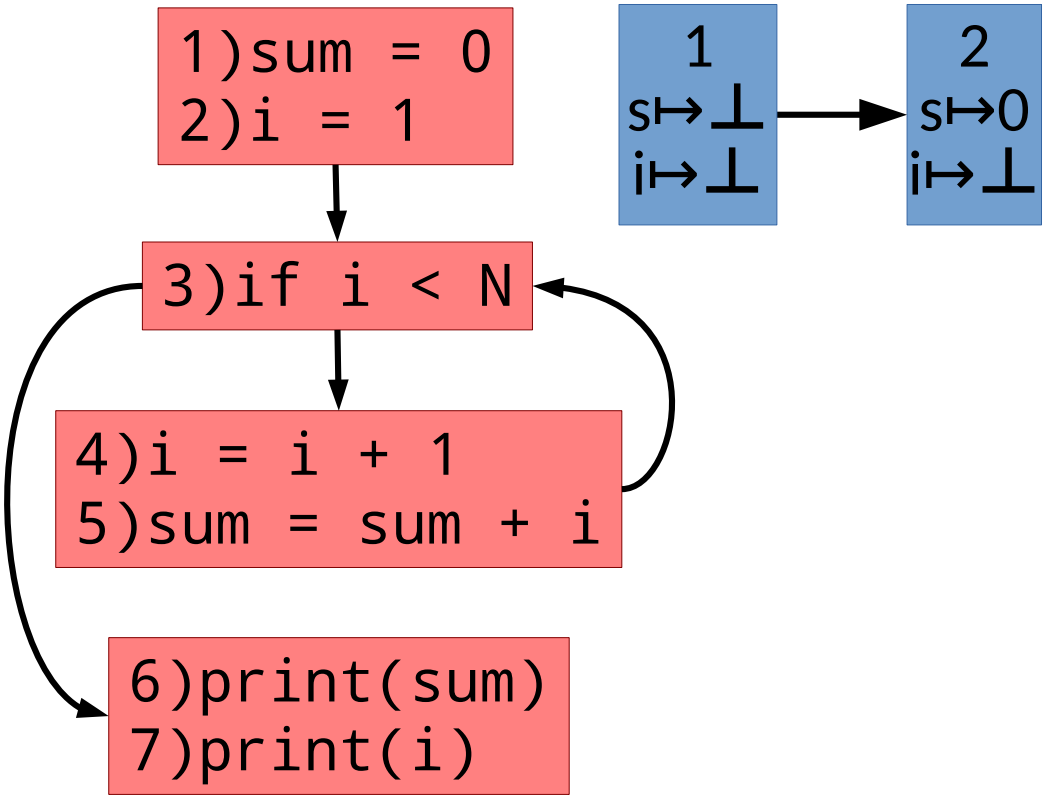

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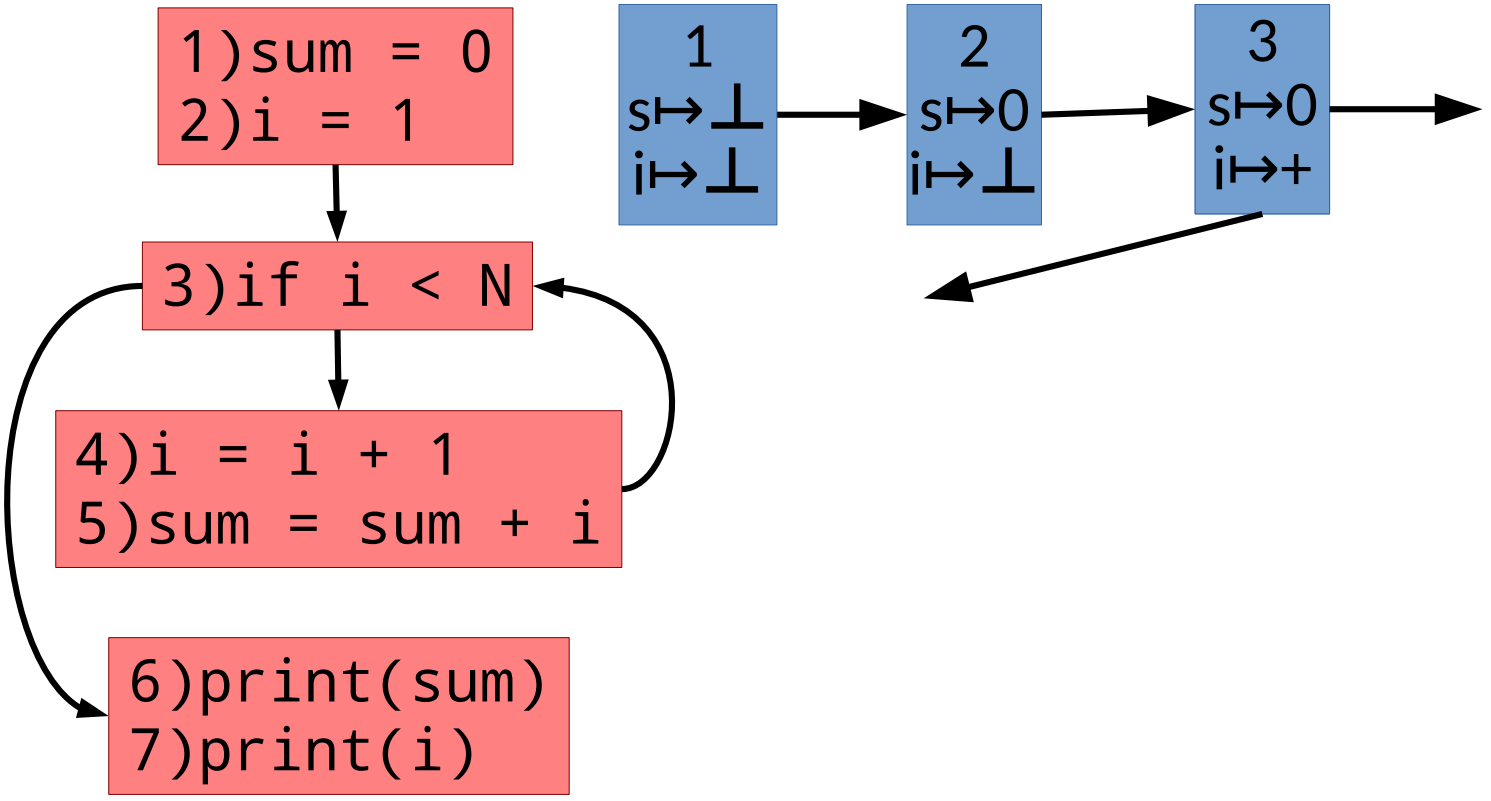

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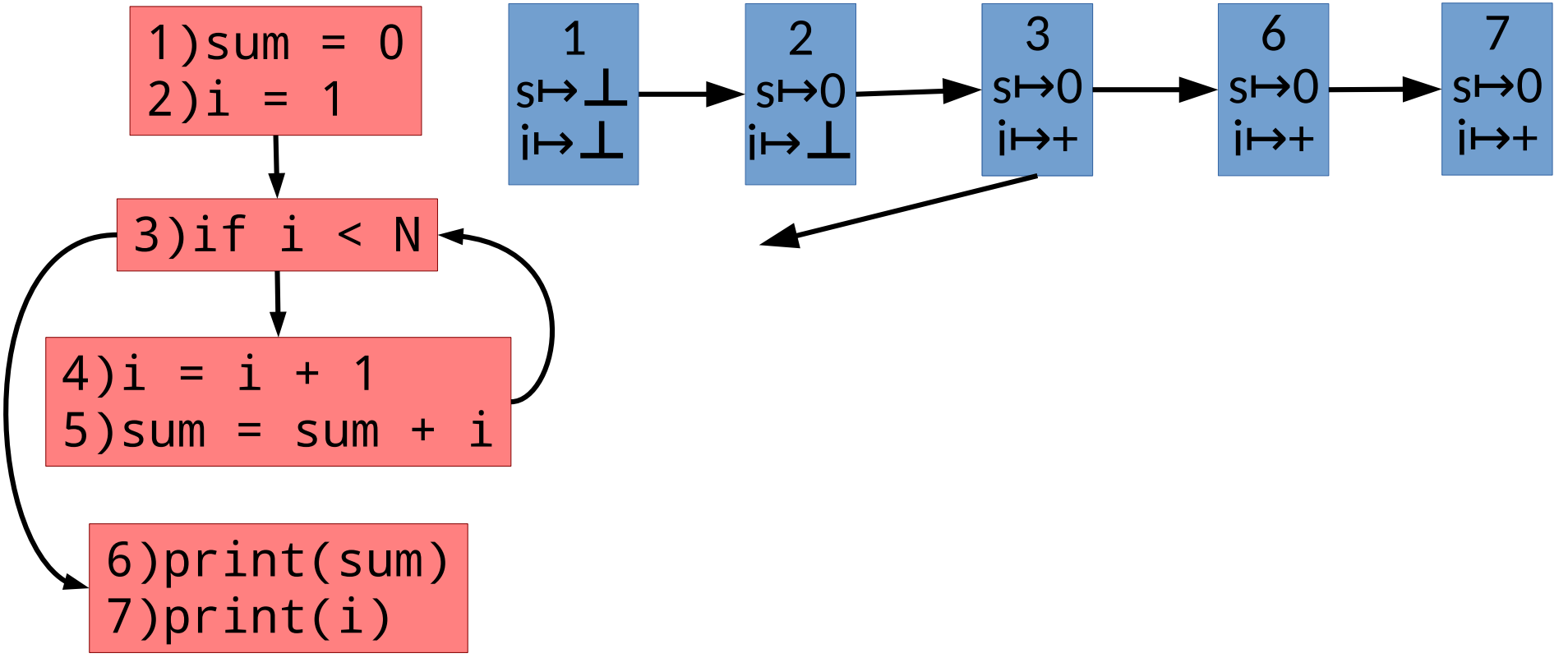

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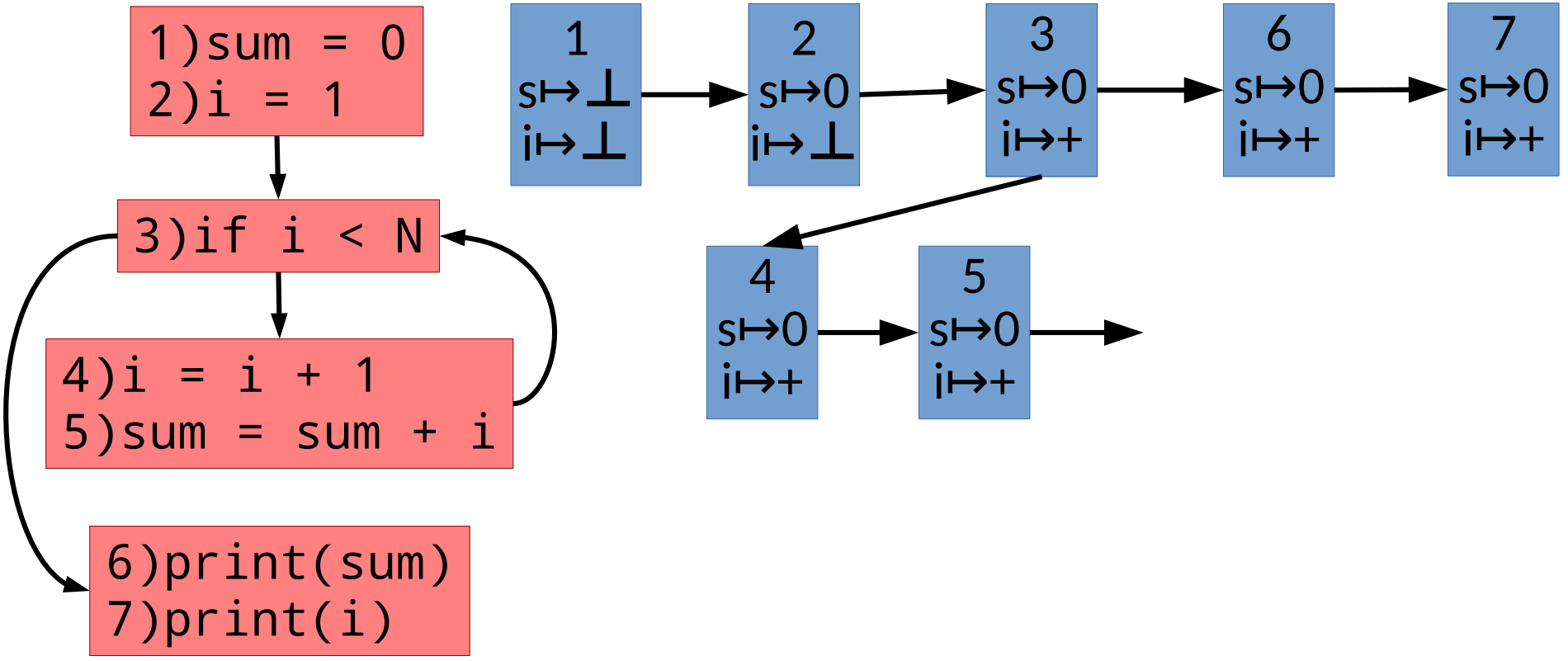

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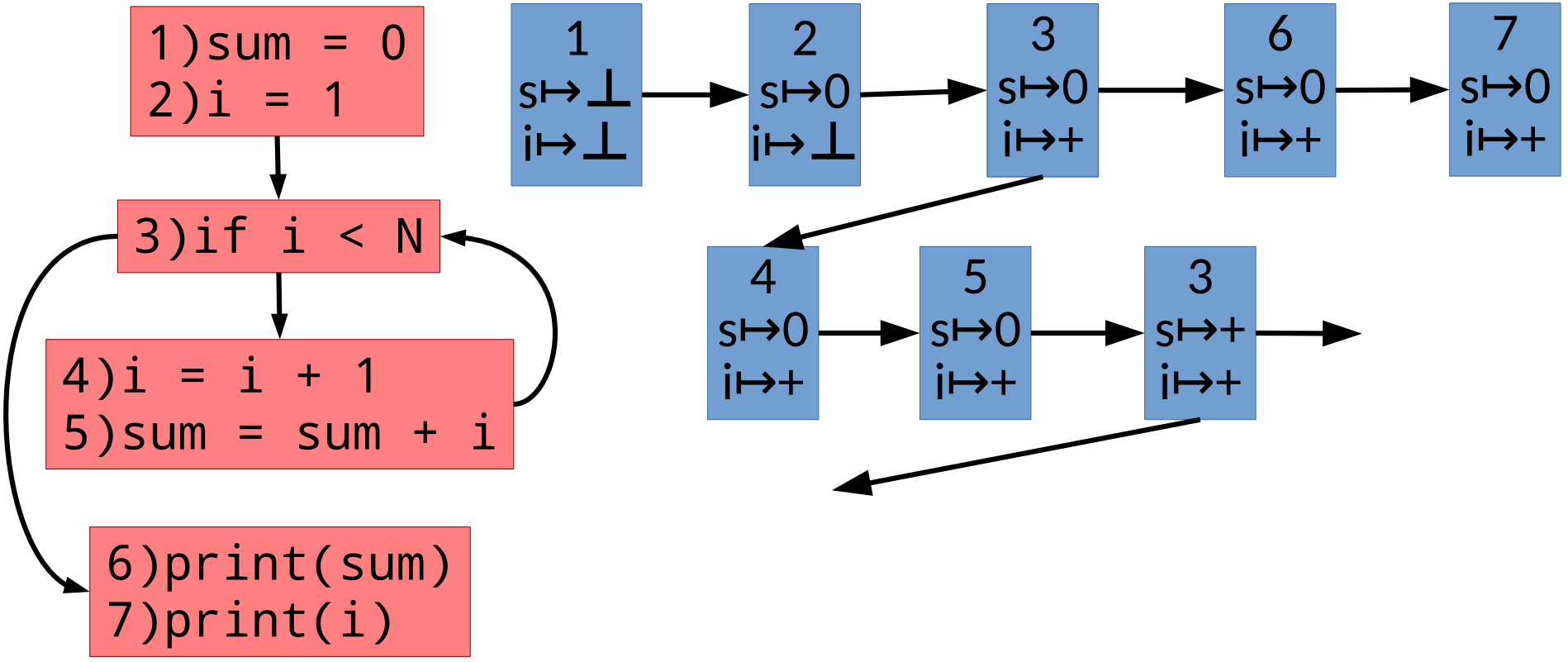

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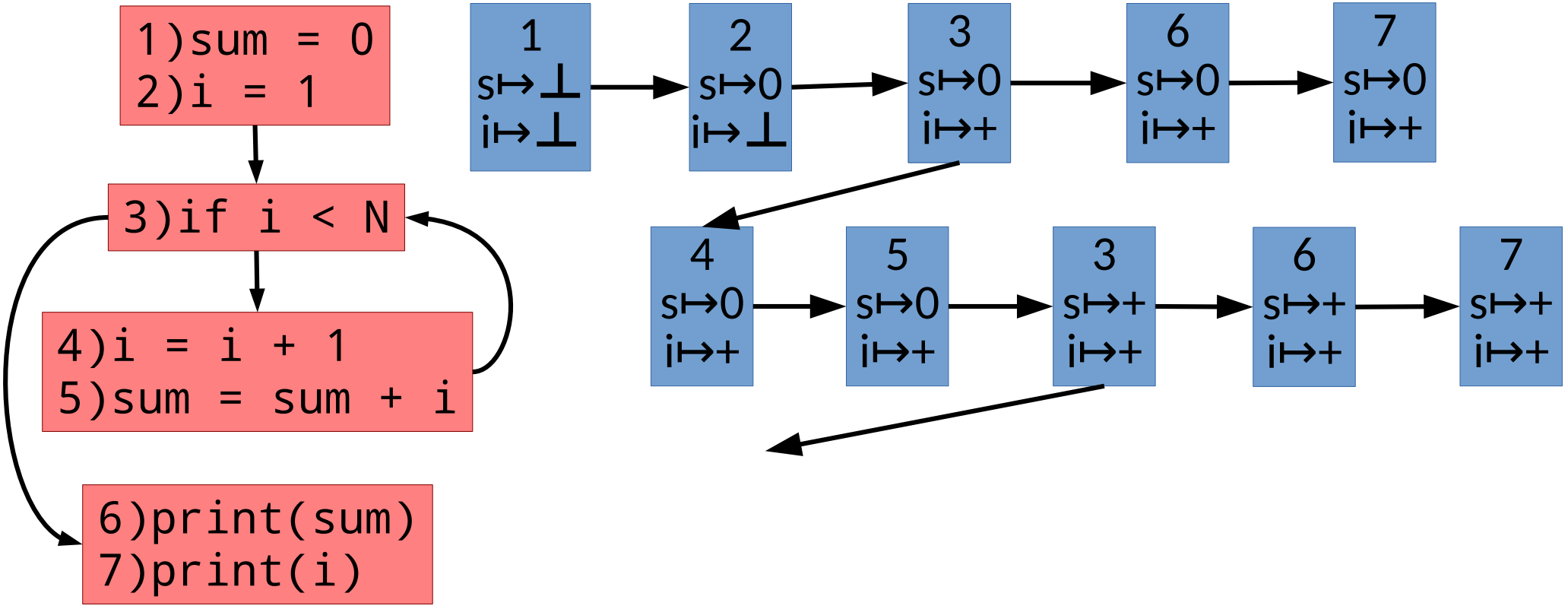

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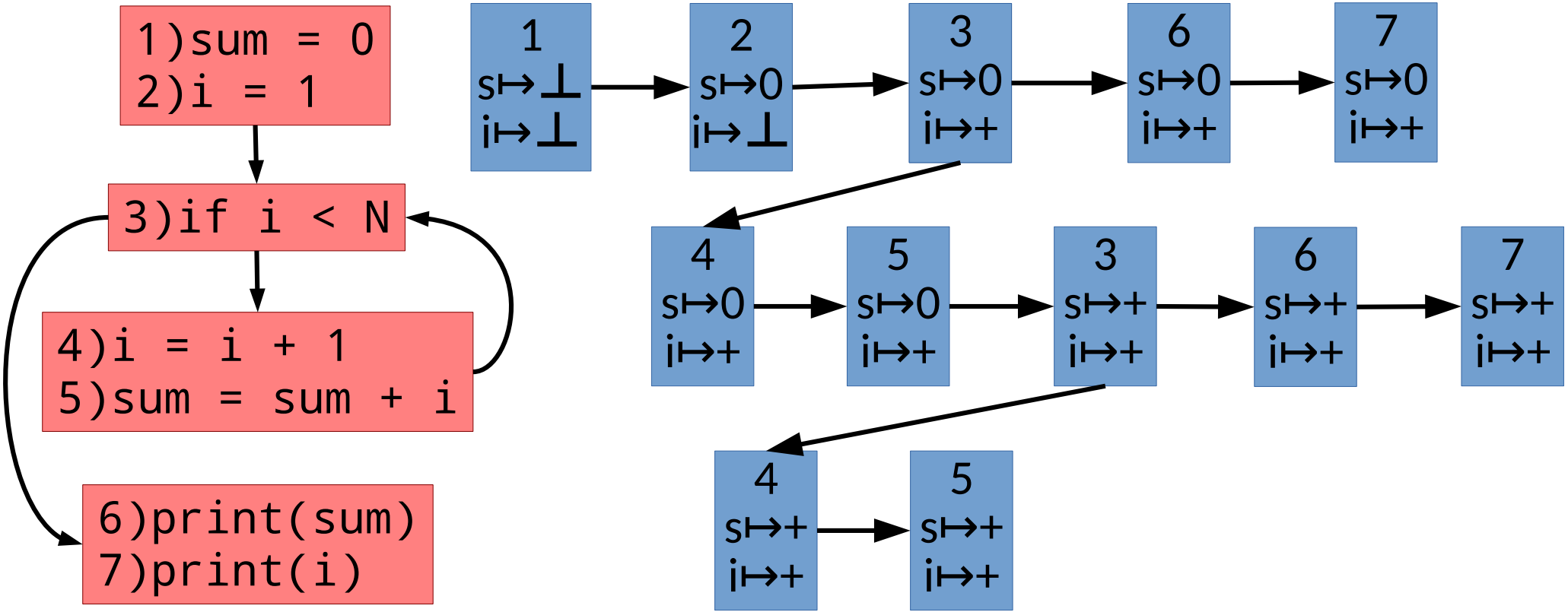

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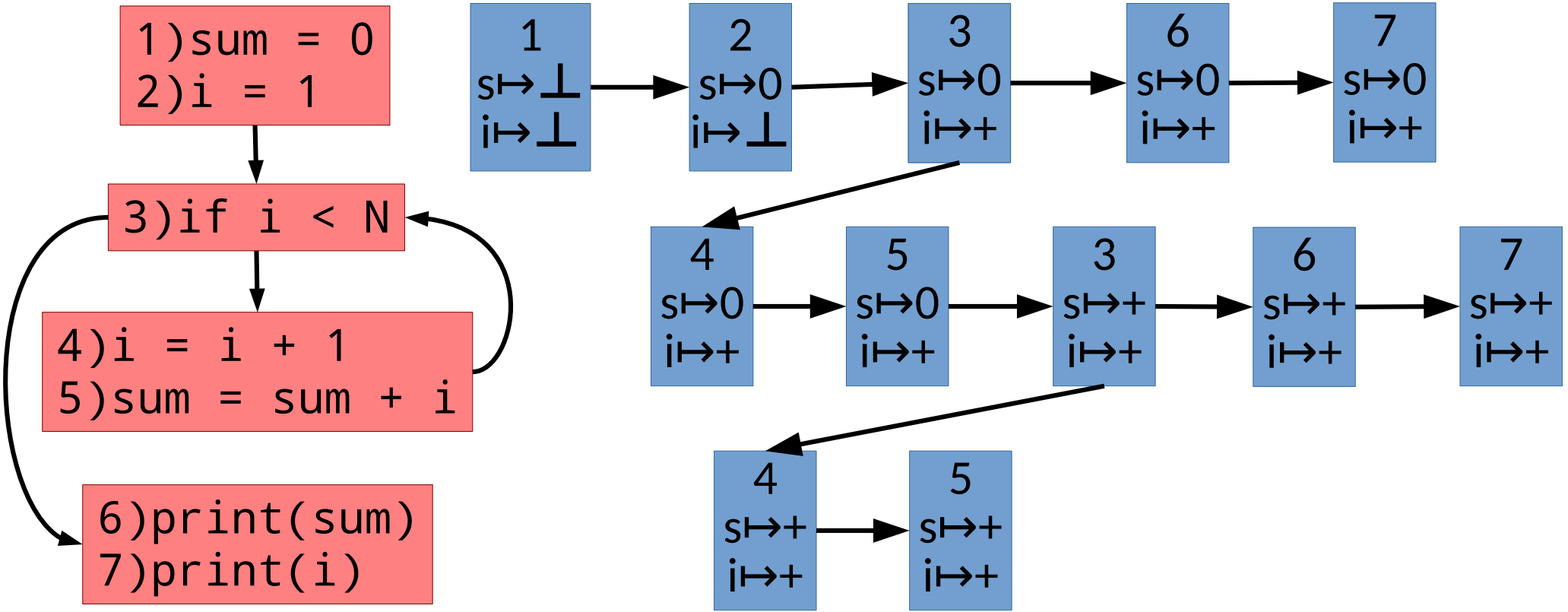


Does the process ever end?

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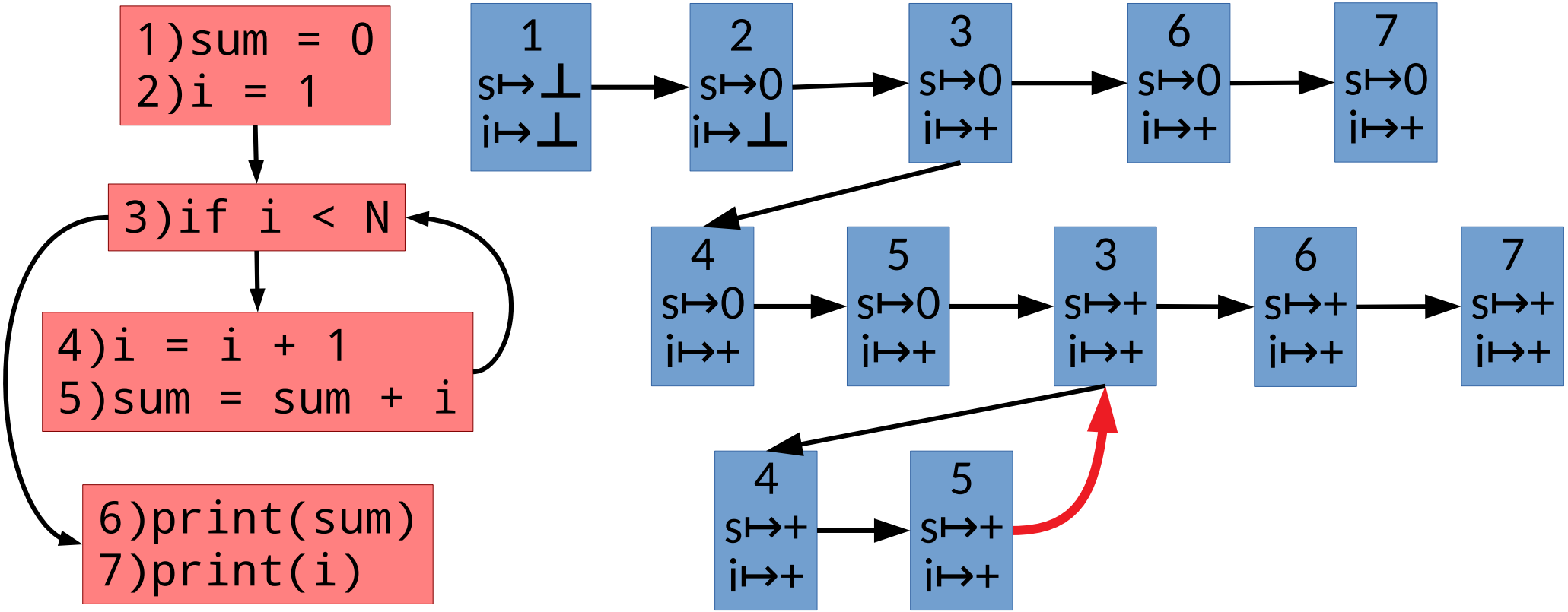

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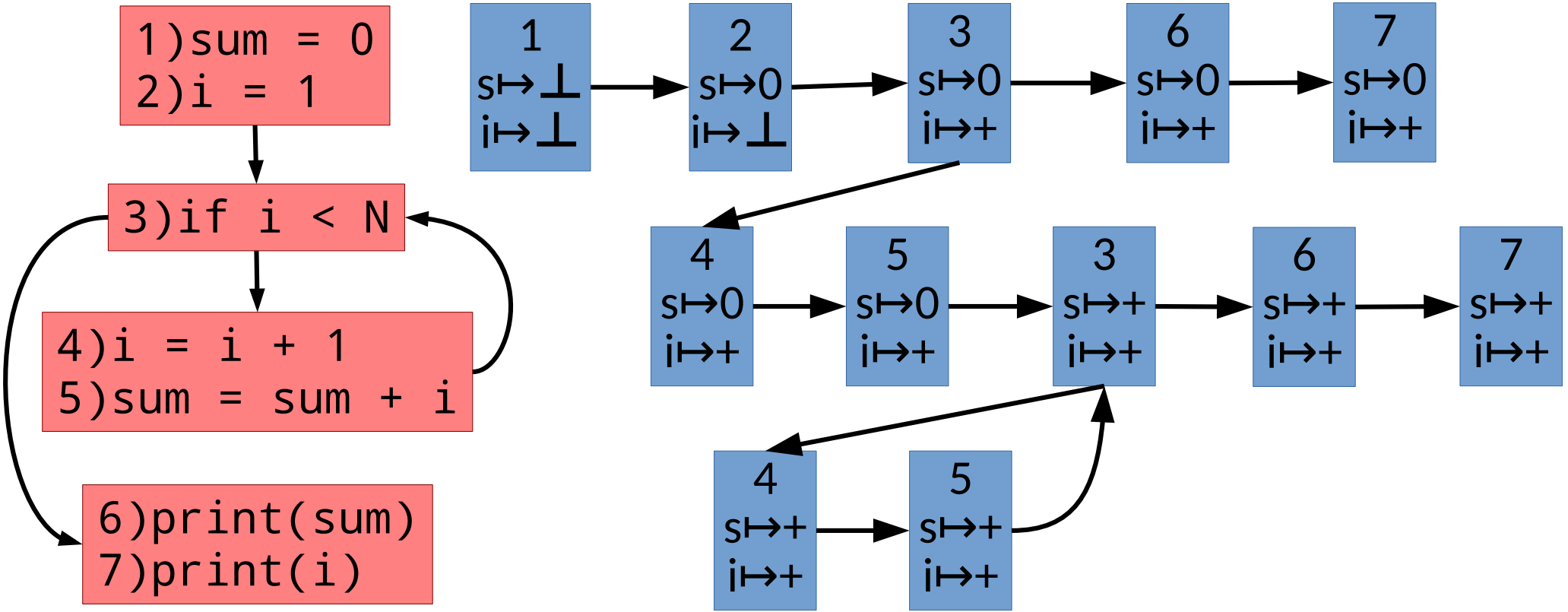


Can the final sum ever be negative?

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  Loosely: <CFG, Transfer Function, Lattice Abstraction>

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  - {-,0,+} ⋃ {⊤,⊥}
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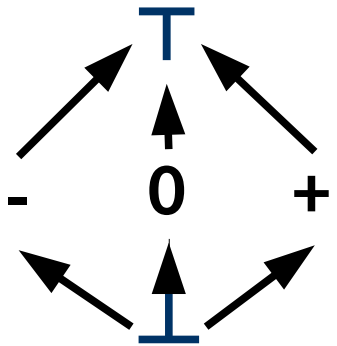

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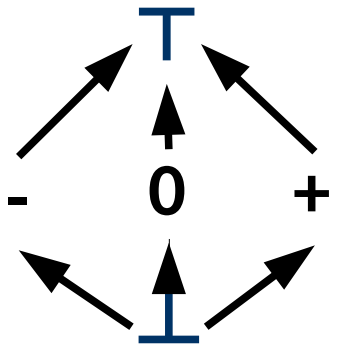


Why does this specific example terminate?

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- But in theory a lattice need not be finite!
  (ranges/intervals, linear constraints, …)

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- For basic analyses, use a monotone framework
- But in theory a lattice need not be finite!
  - *Widening* operators can still make it feasible (e.g., heuristically raise to $\top$)

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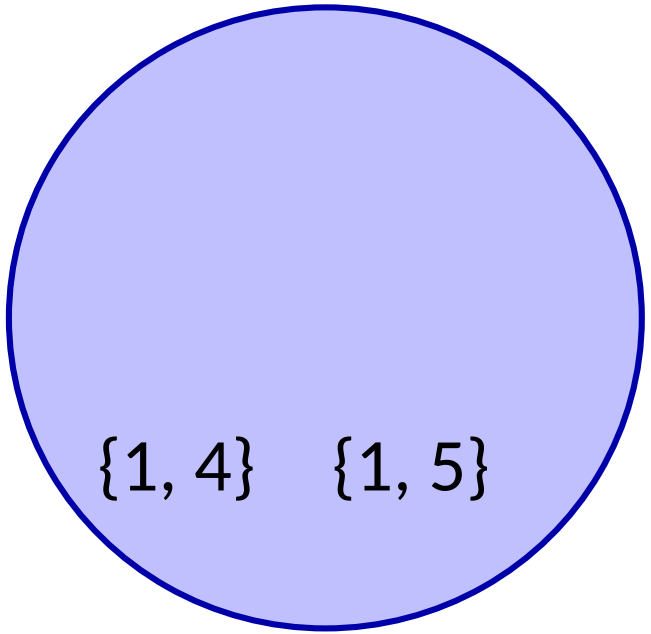

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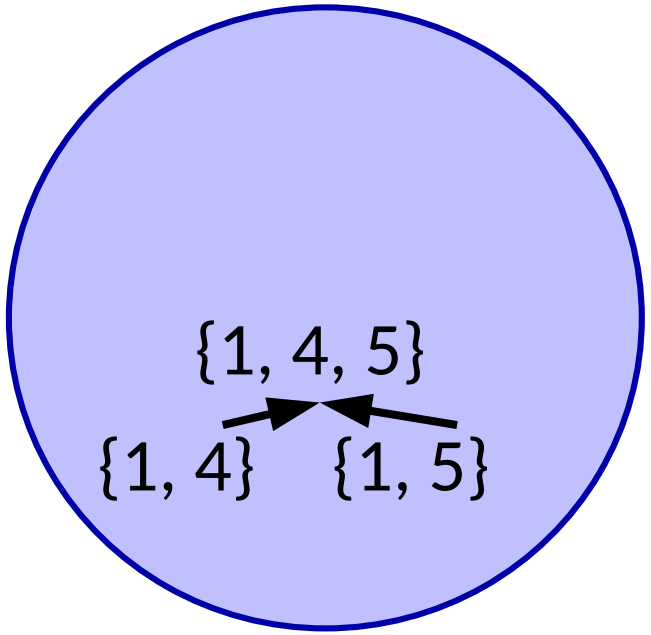

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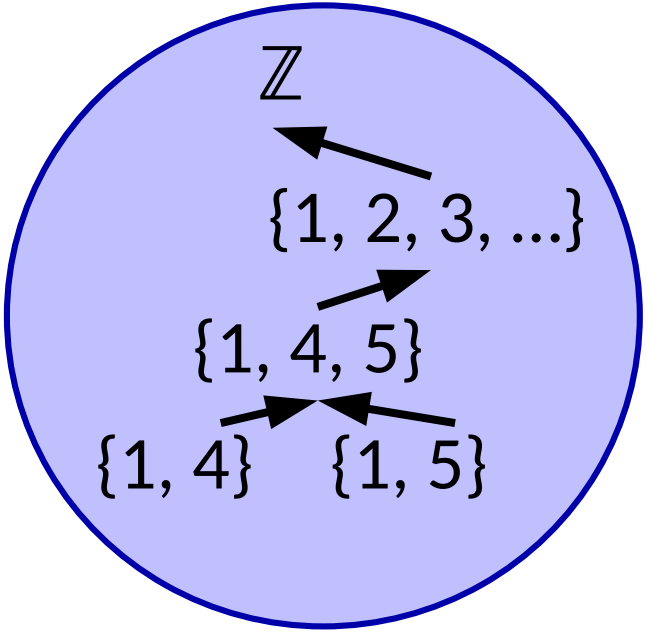


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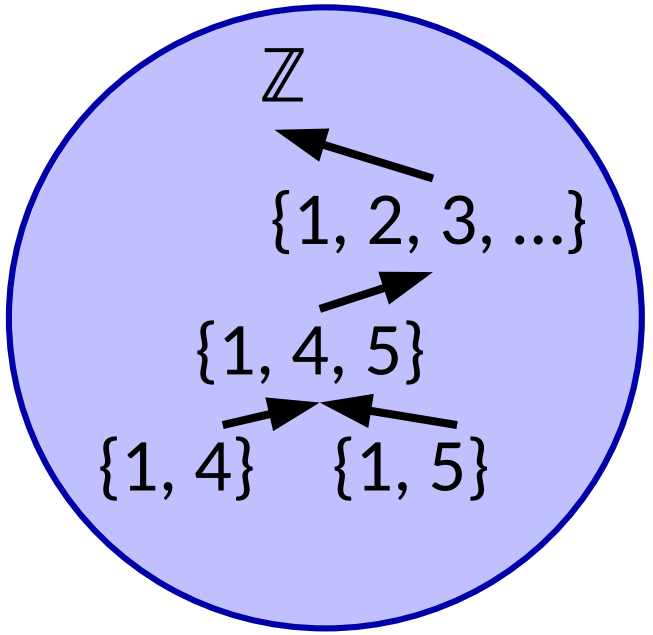


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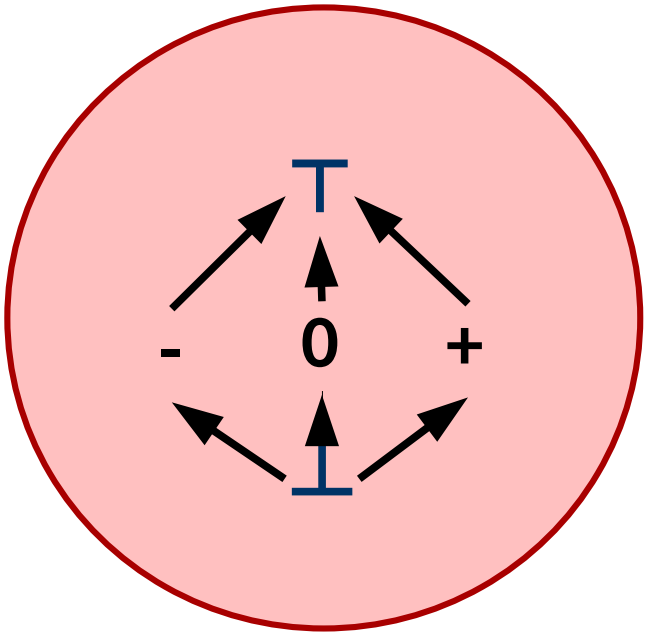


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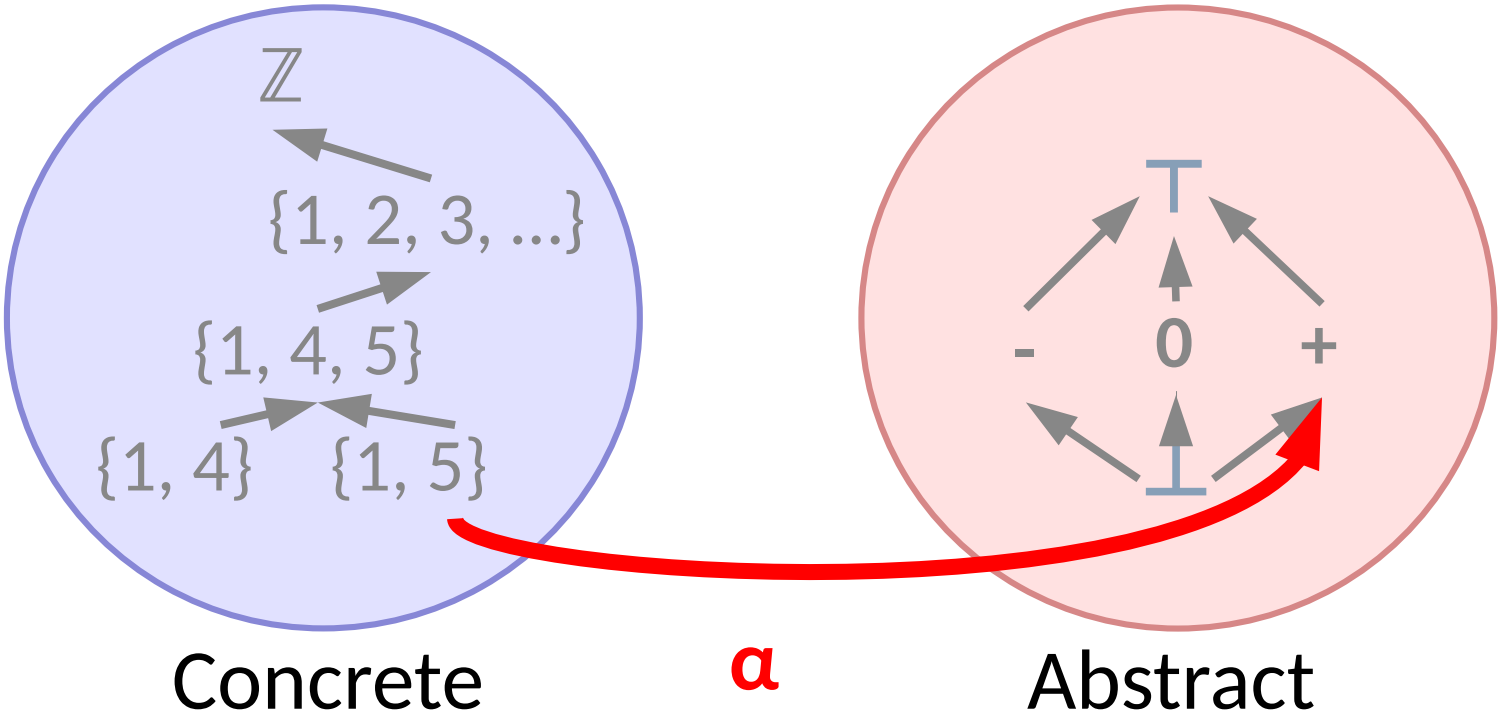

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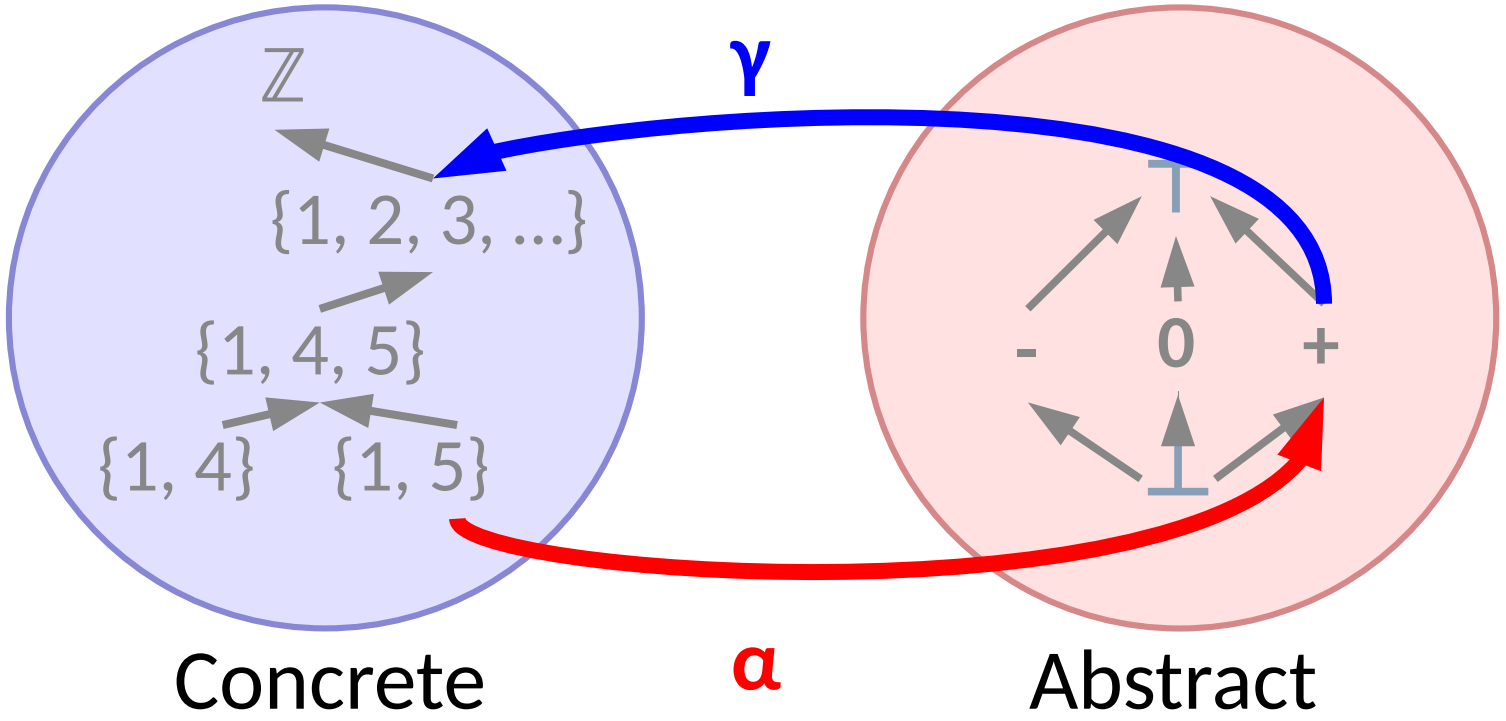

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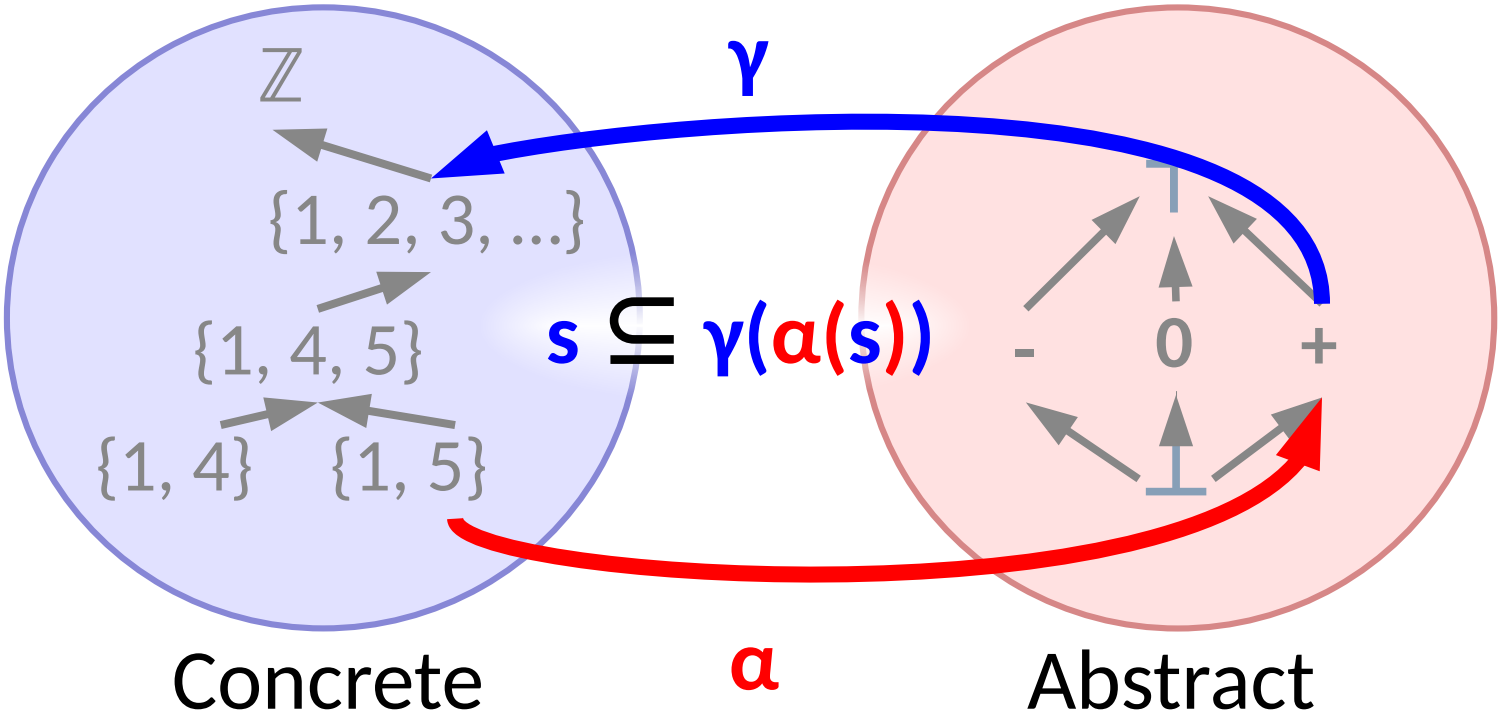

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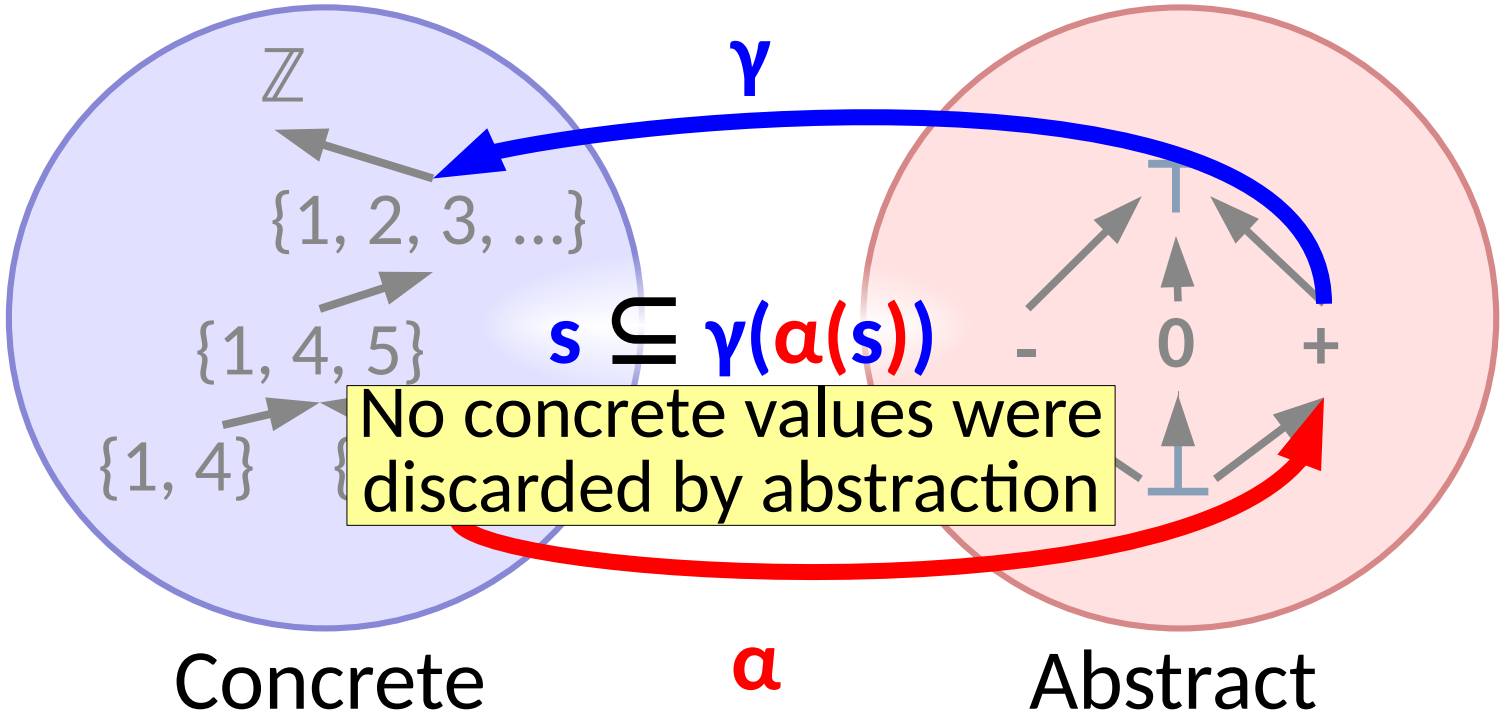

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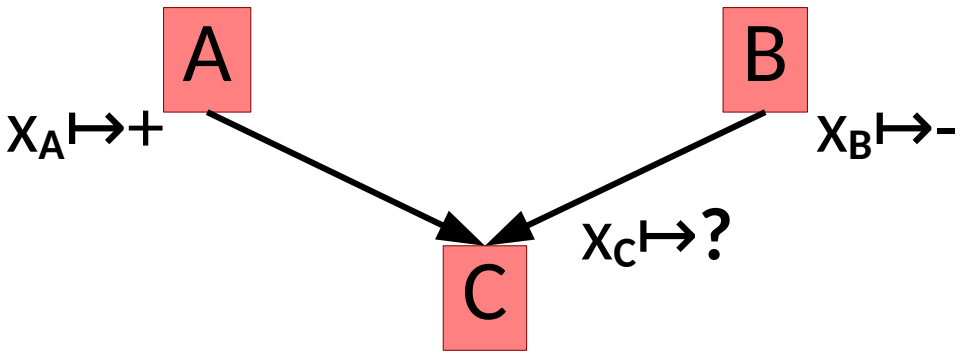


$$x_A \sqcap x_B = ?$$

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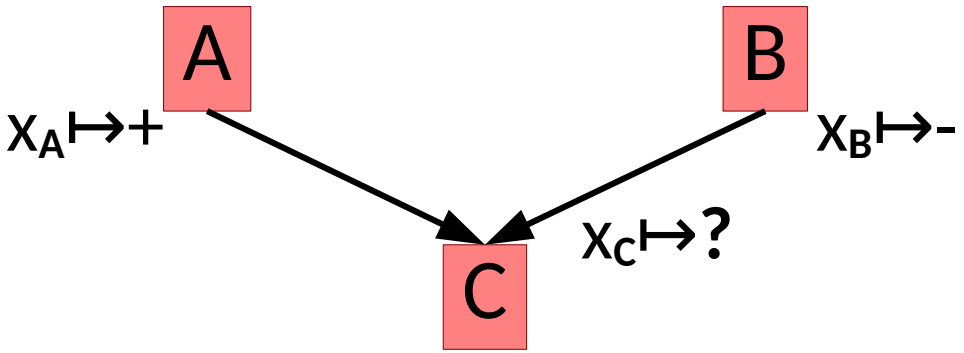


$$x_A \sqcap x_B = \alpha(x_A) \sqcap \alpha(x_B) = ?$$

# Dataflow Analysis

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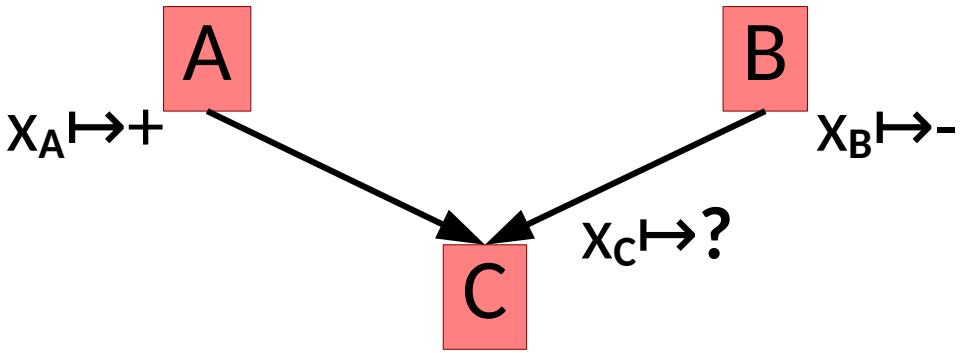
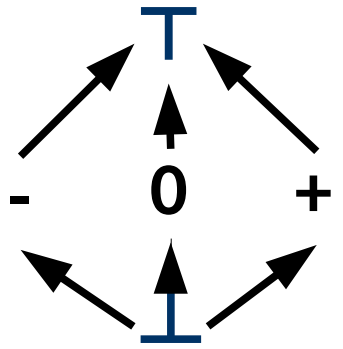



$$x_A \sqcap x_B = \alpha(x_A) \sqcup \alpha(x_B) = ?$$



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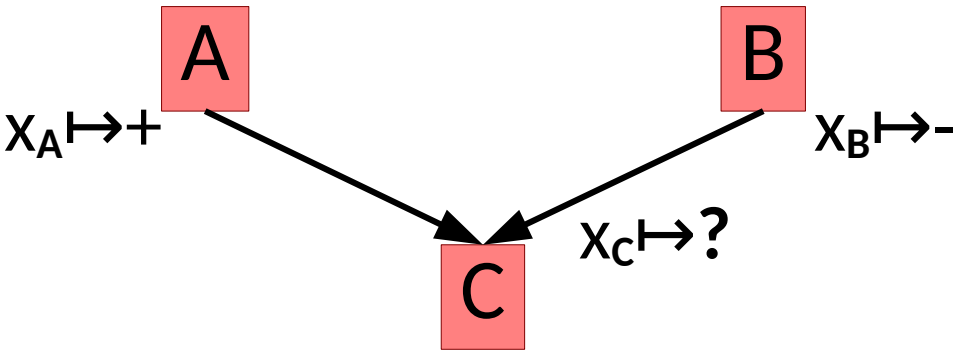


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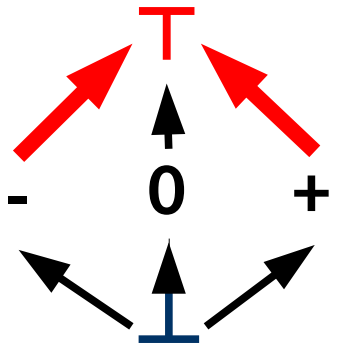

# Dataflow Analysis

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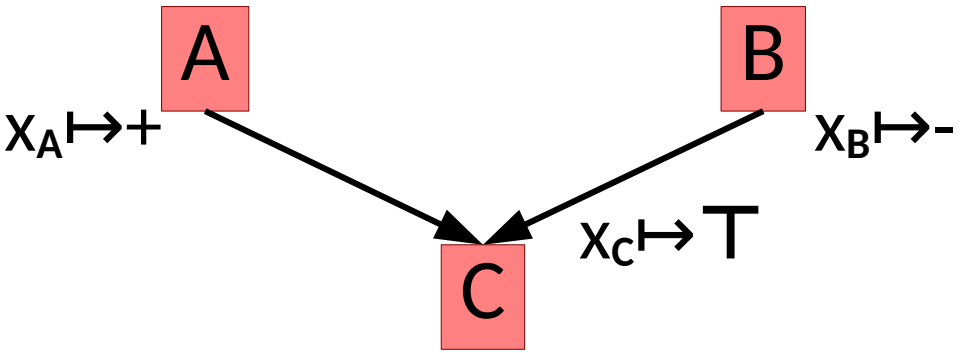
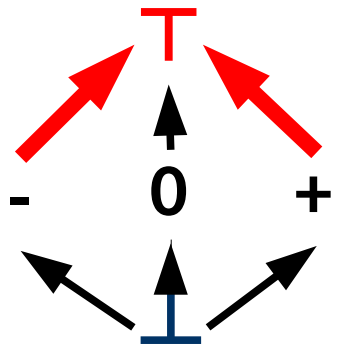
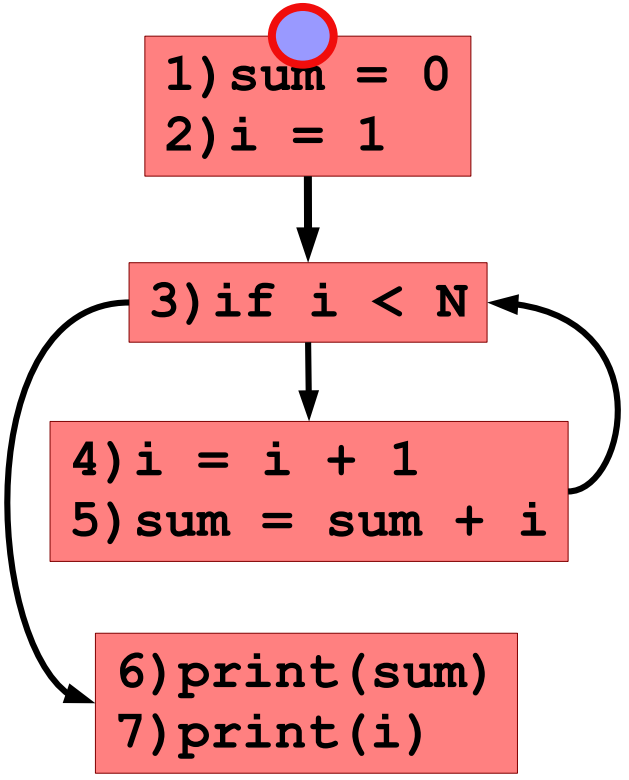



$$x_A \sqcap x_B = \alpha(x_A) \sqcup \alpha(x_B) = \top$$



# Dataflow Analysis

- Now model the abstract program state and propagate through the CFG.



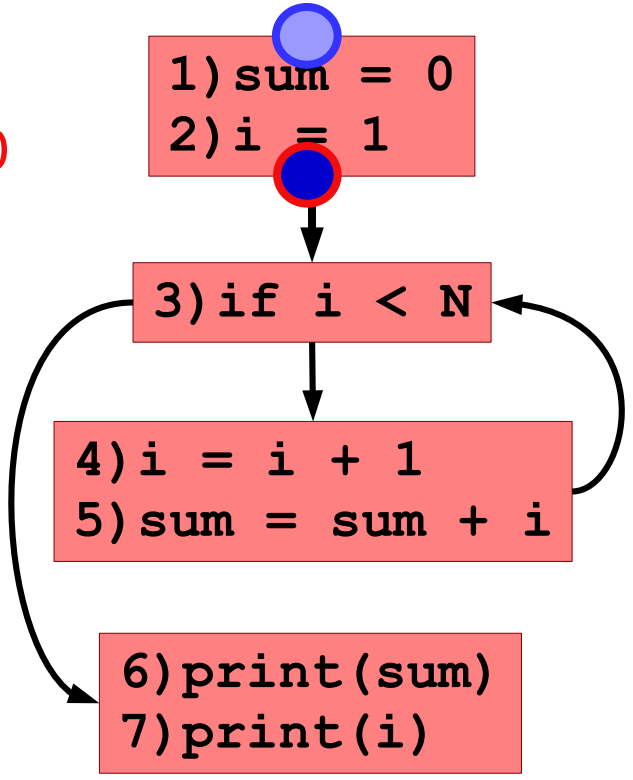

sum → ⊥
i → ⊥

# Dataflow Analysis

- Now model the abstract program state and propagate through the CFG.

sum → 0
i → +

sum → ⊥
i → ⊥



# Dataflow Analysis

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sum → 0
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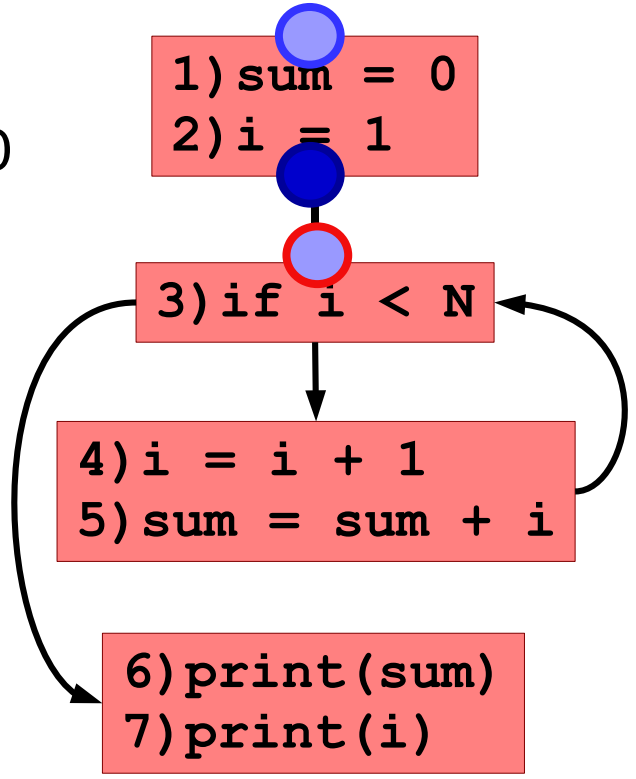


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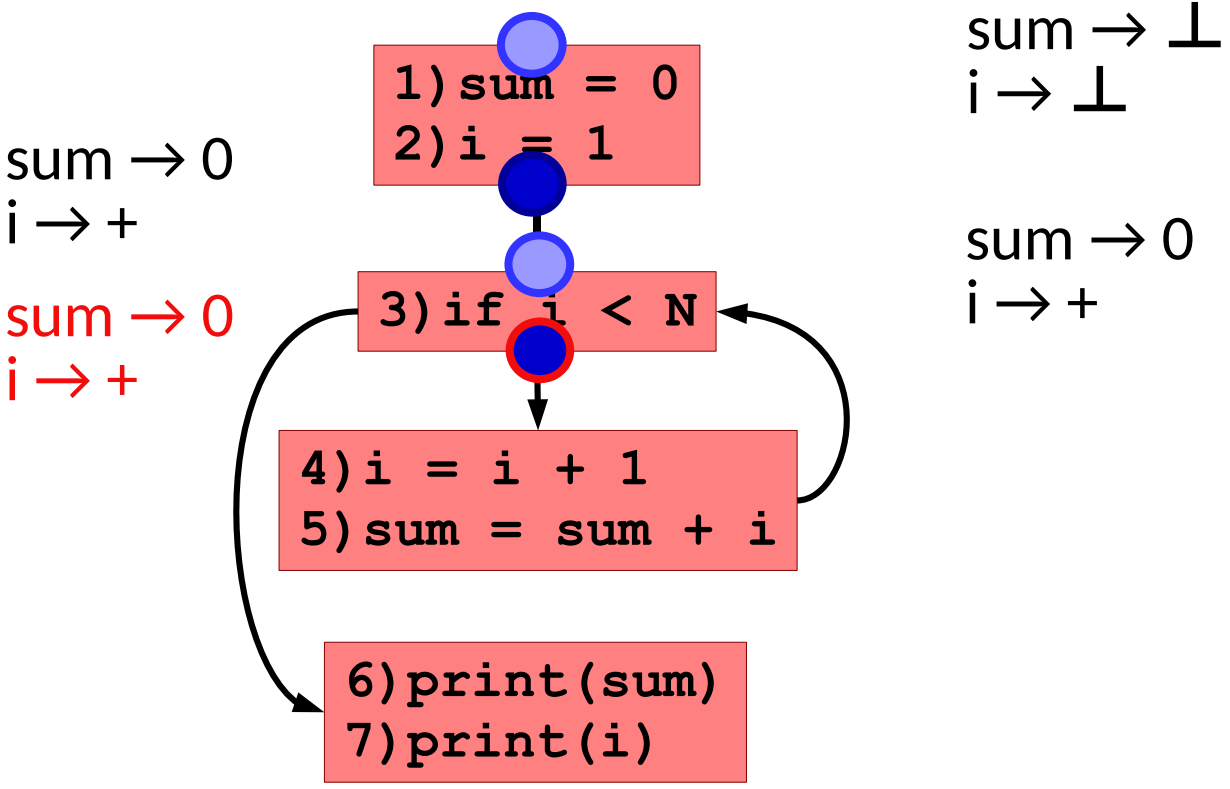

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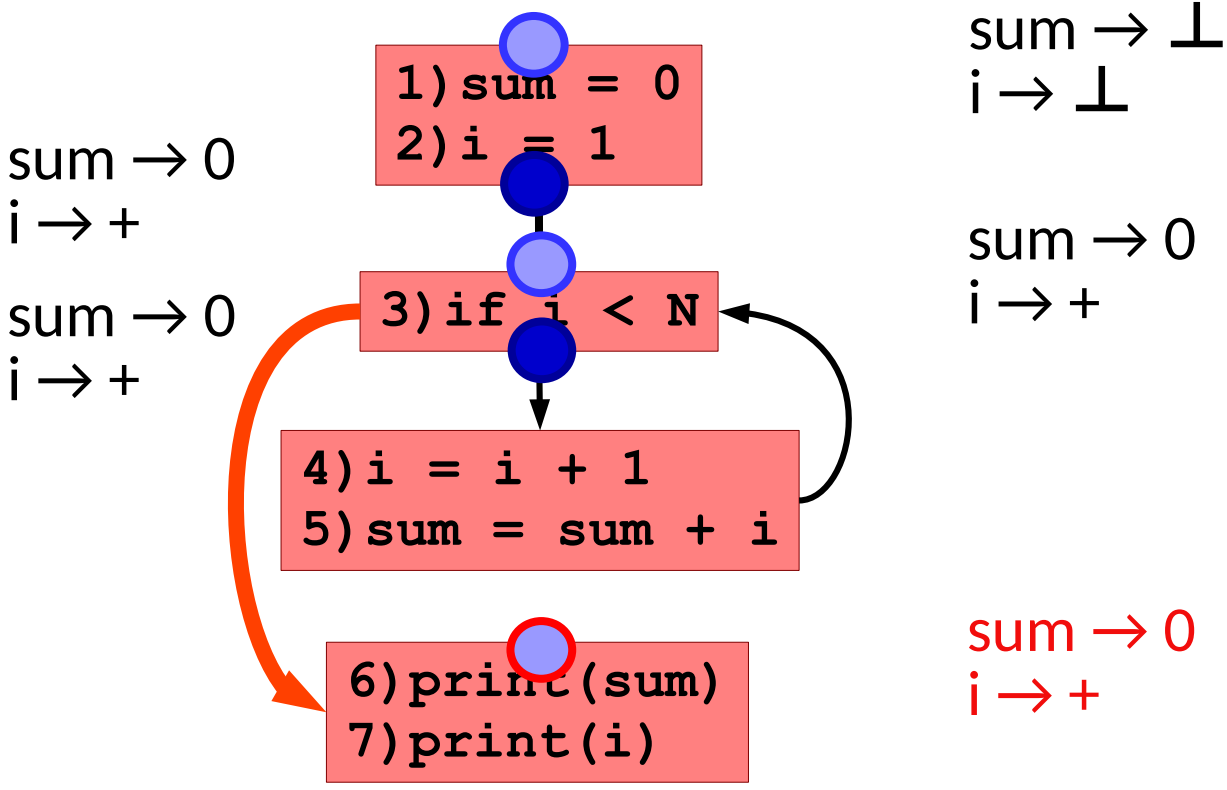

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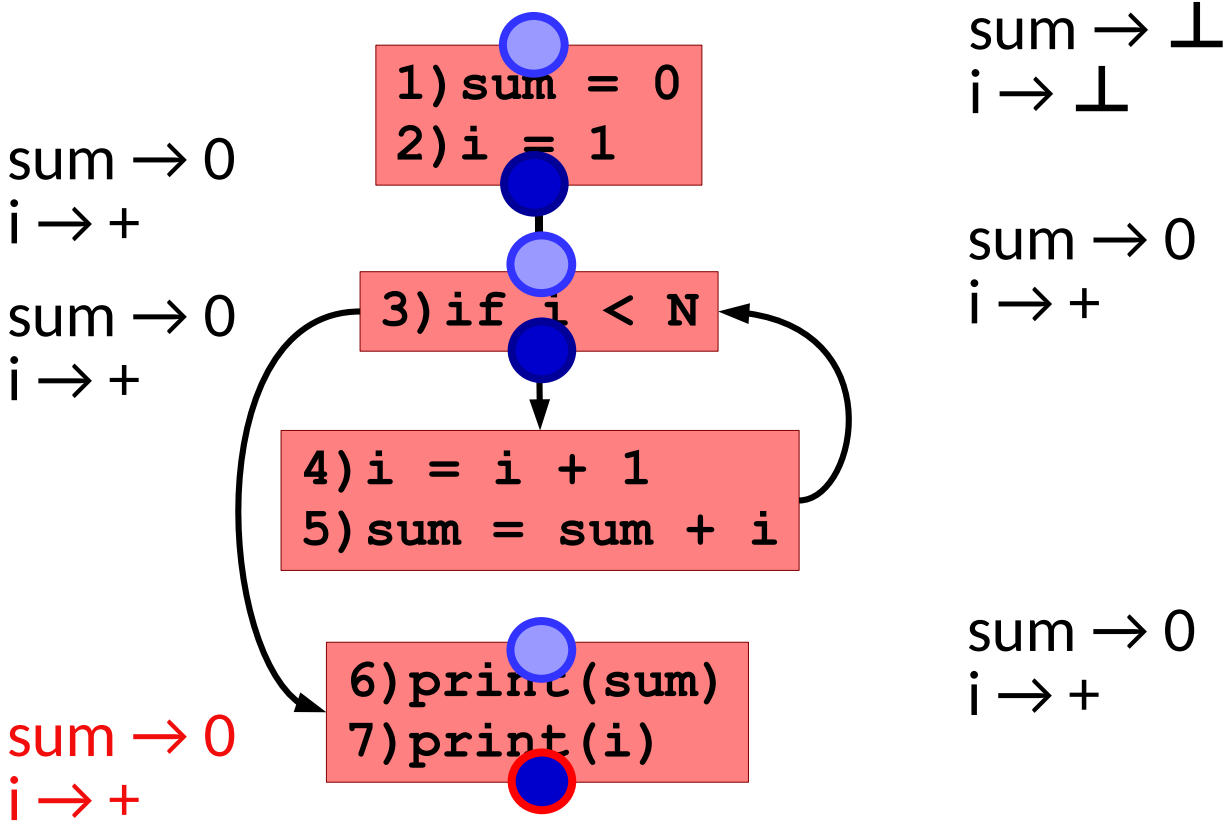

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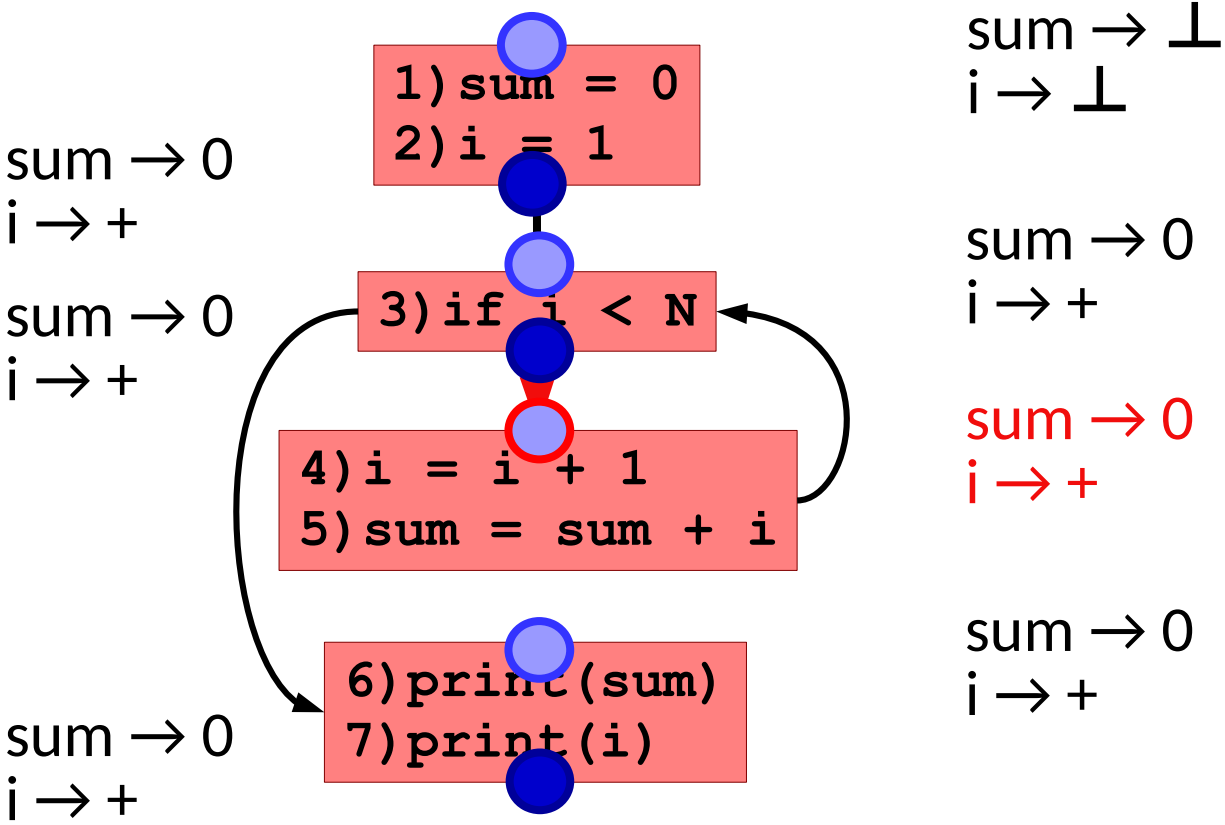

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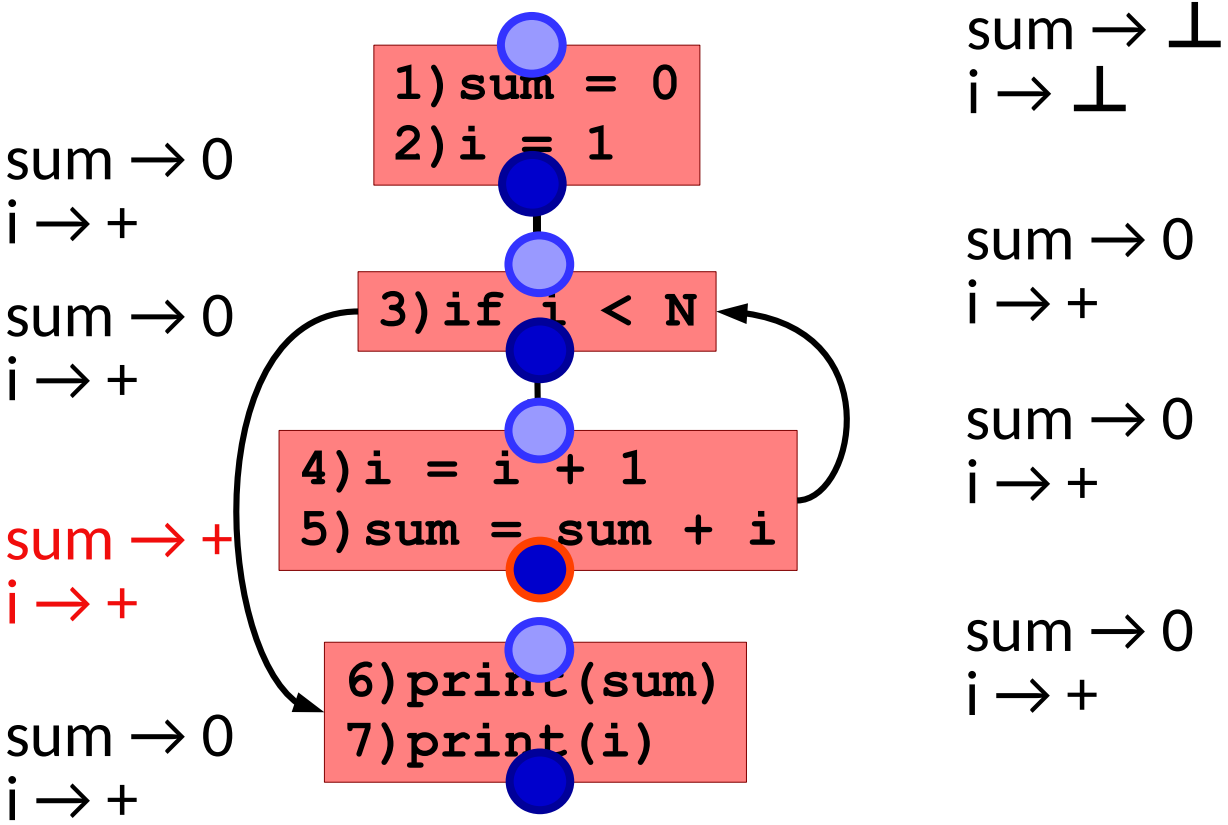

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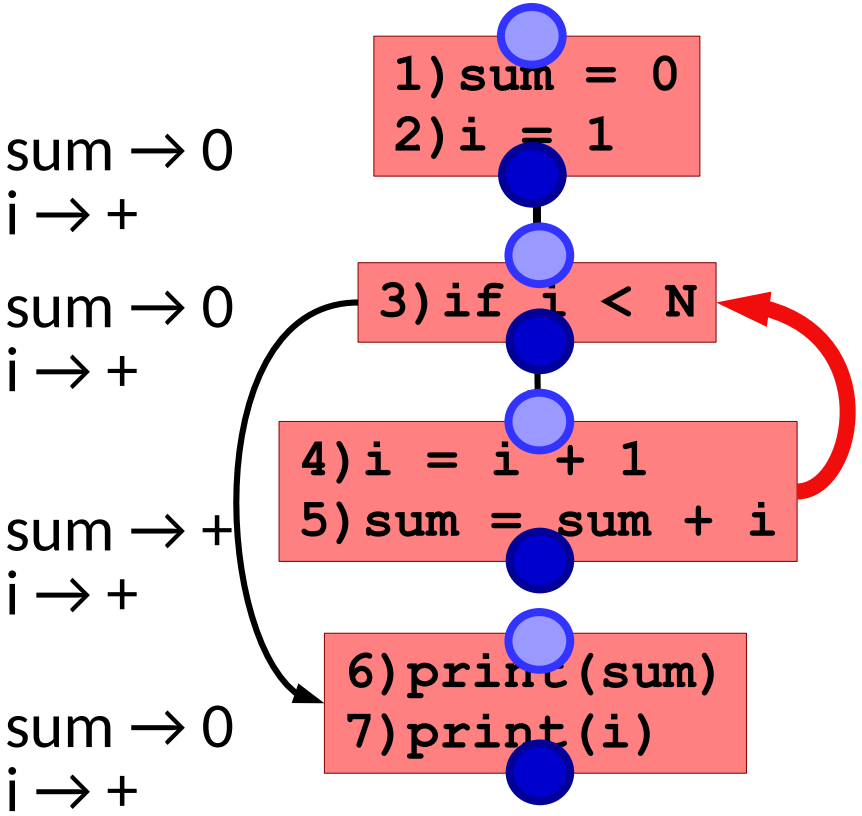
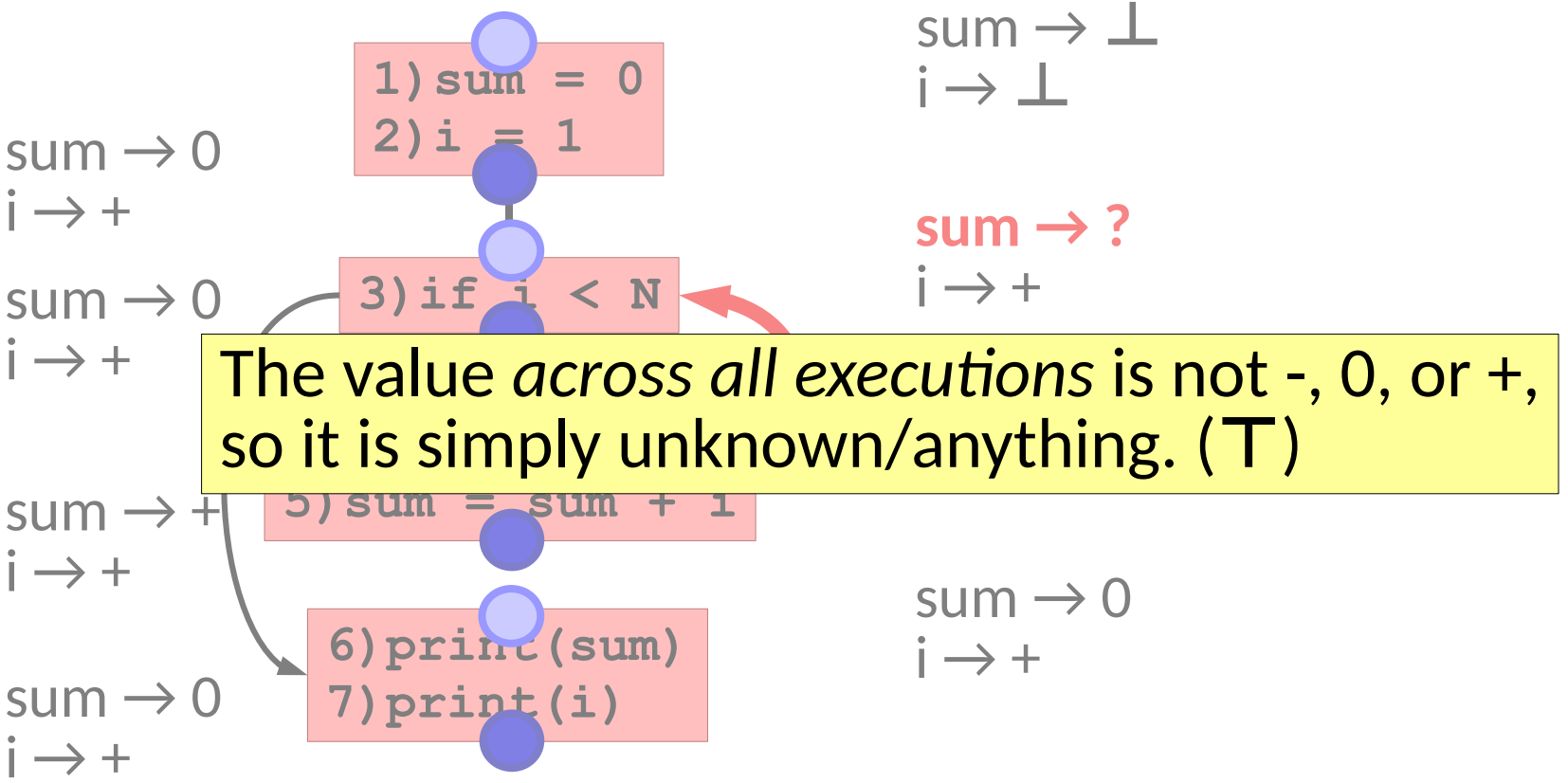



**Meet Operator**
sum was 0, but
what should it be now?

# Dataflow Analysis

- Now model the abstract program state and propagate through the CFG.



# Dataflow Analysis

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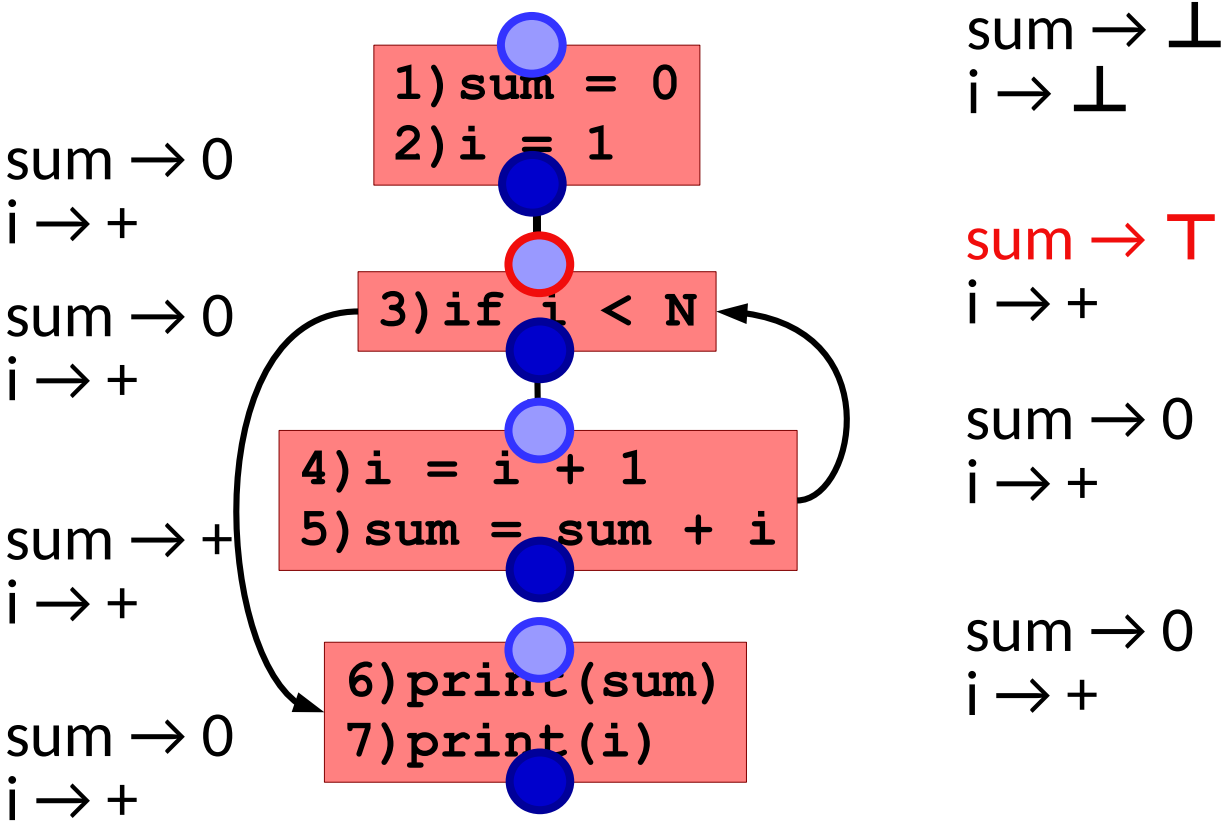

# Dataflow Analysis

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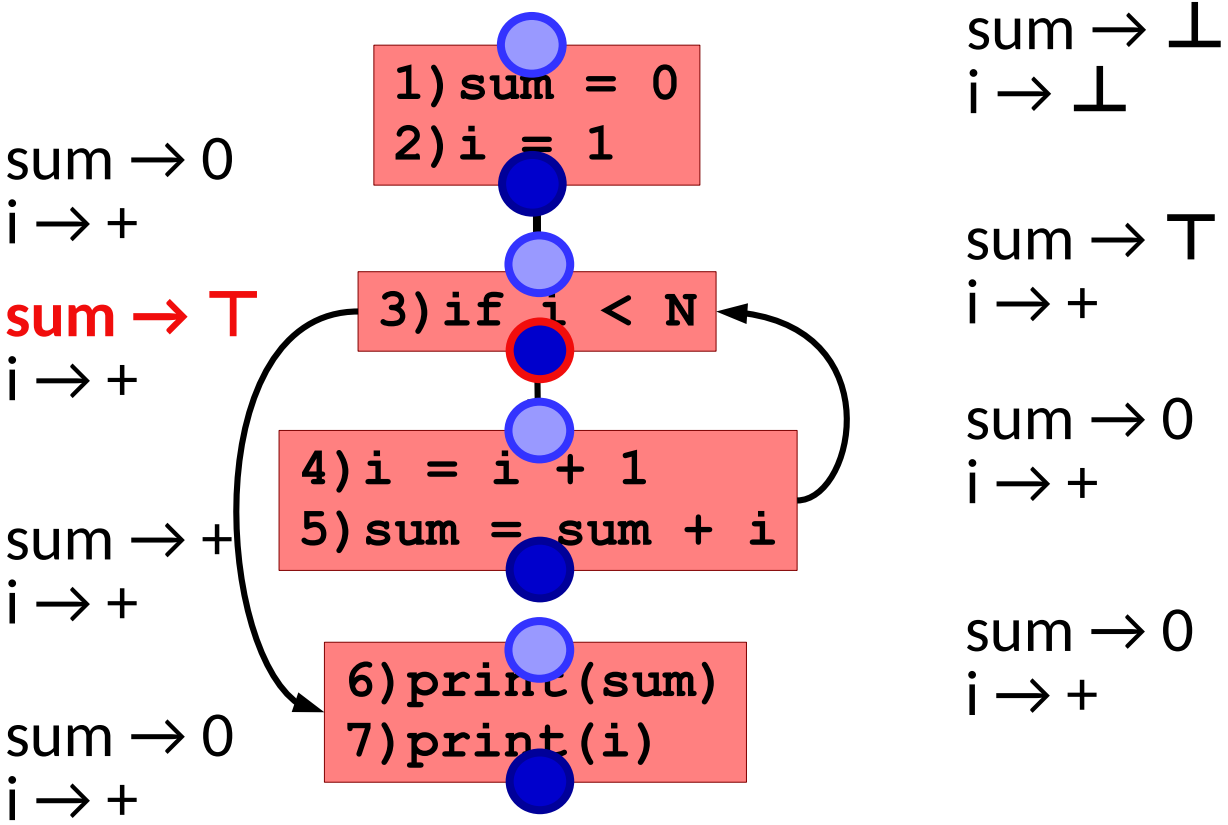

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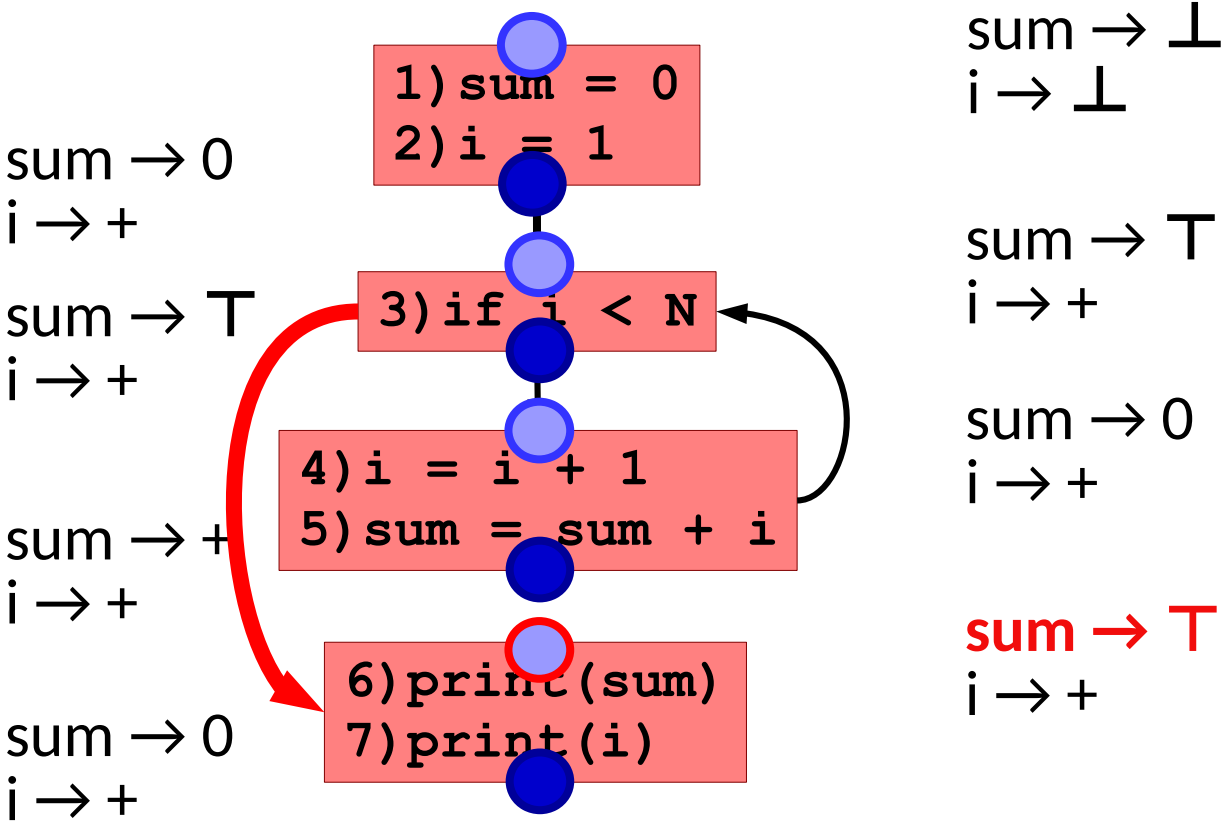

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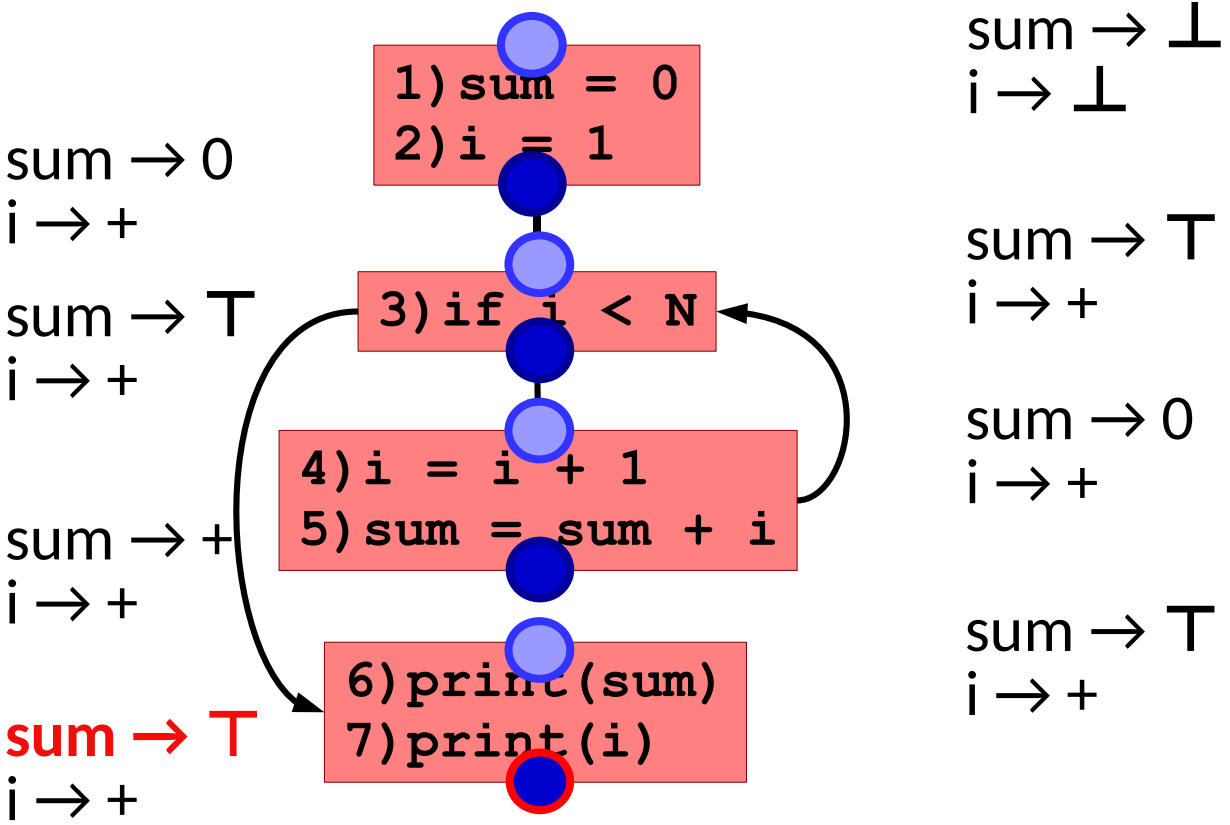

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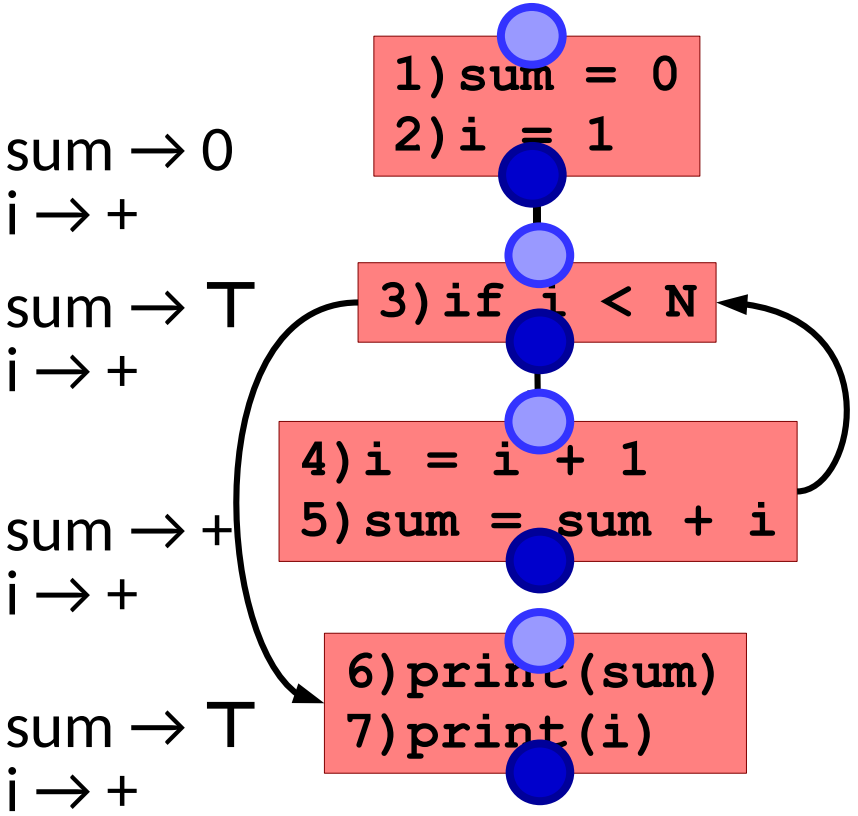
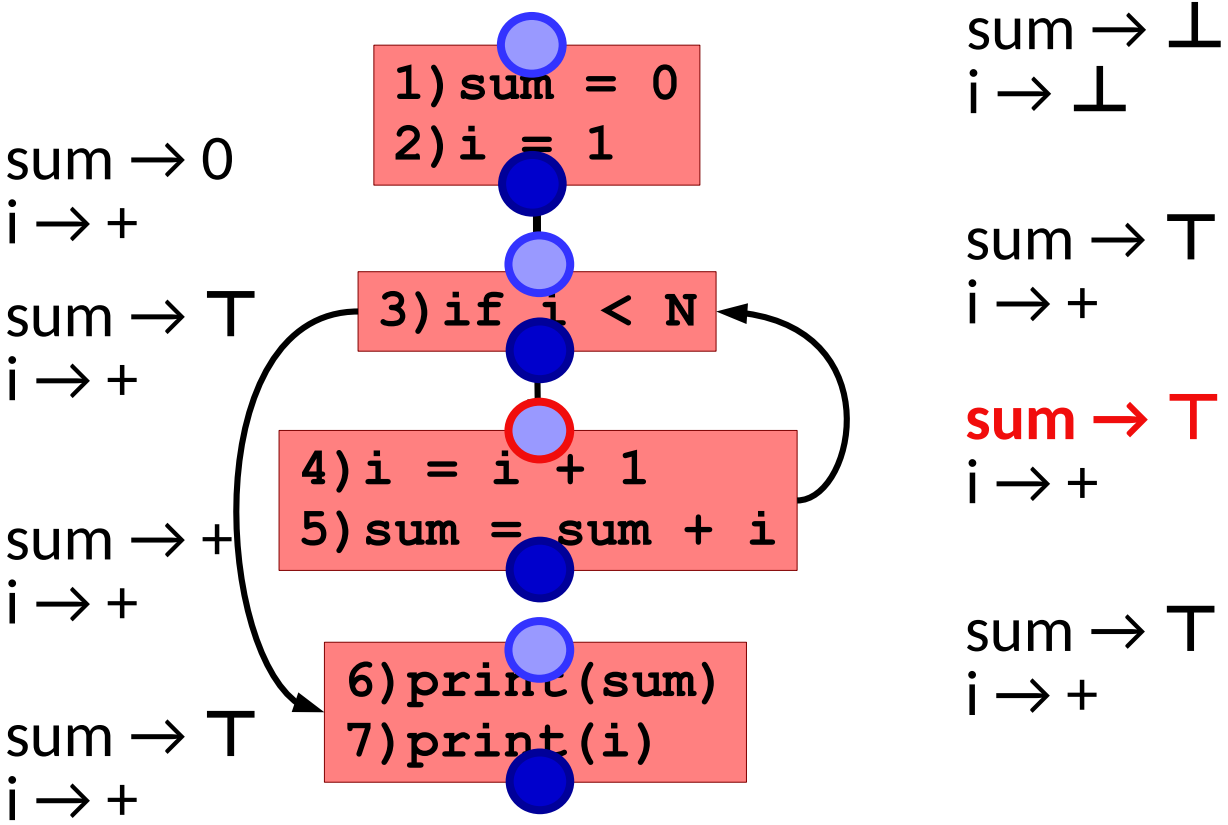



But we're not done yet!

# Dataflow Analysis

- Now model the abstract program state and propagate through the CFG.



# Dataflow Analysis

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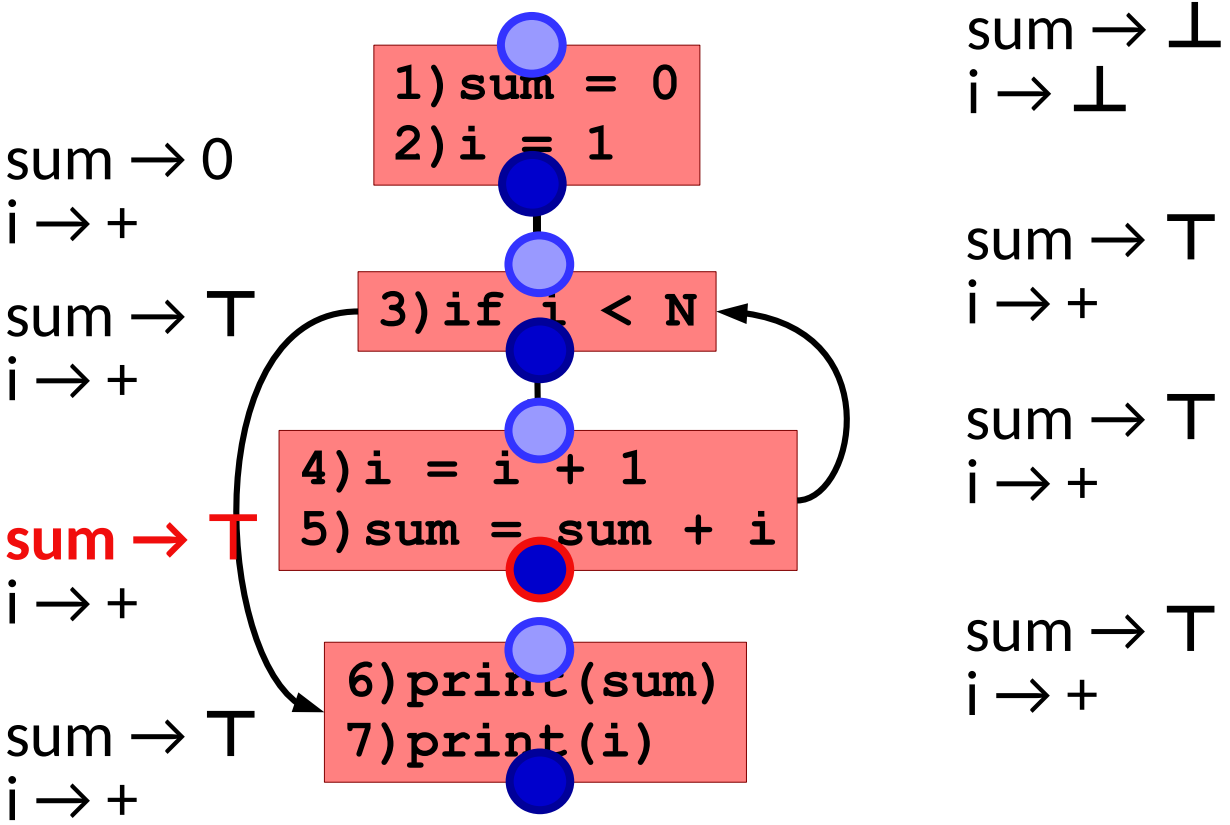

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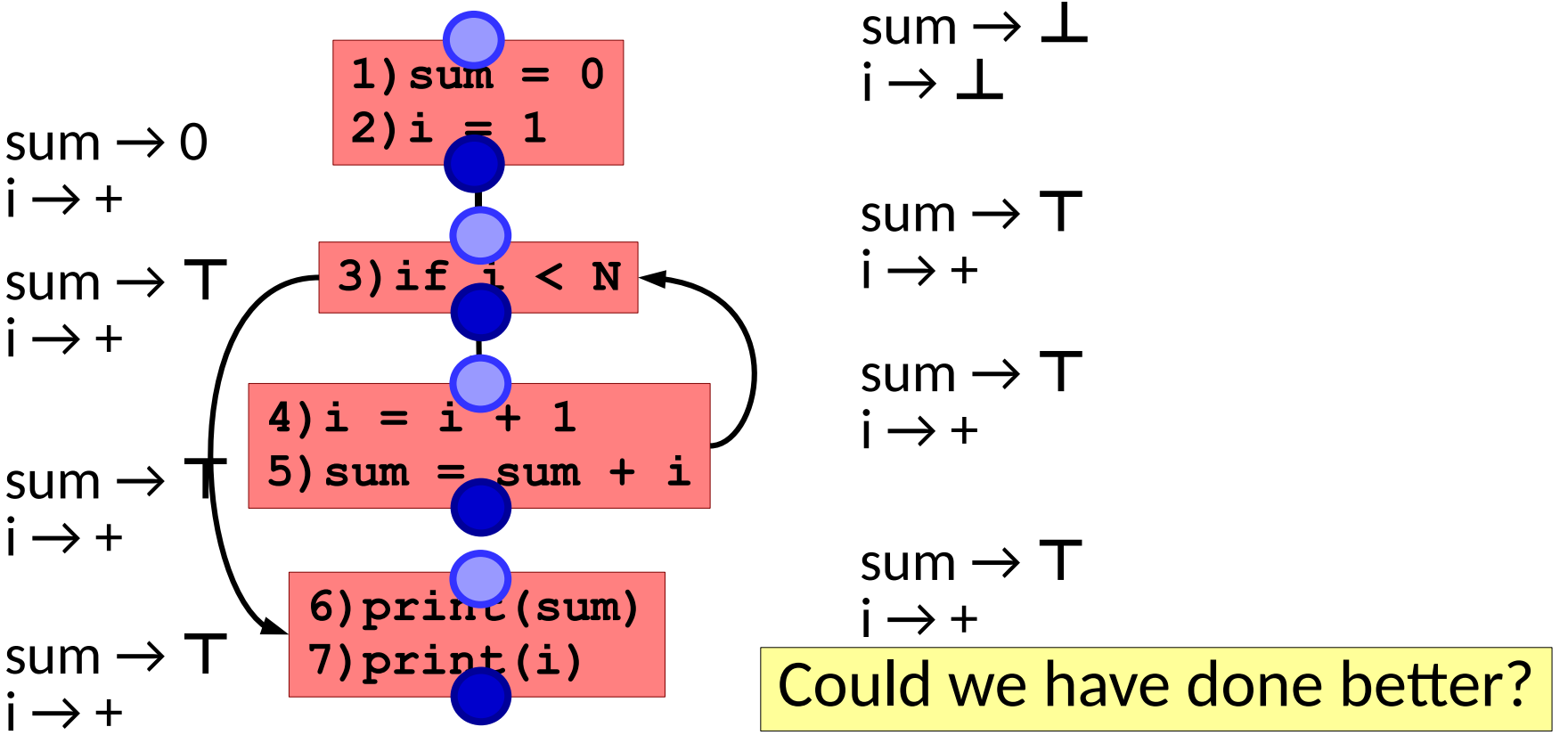


Could we have done better?

# Dataflow Analysis

- Now model the abstract program state and propagate through the CFG.
  - Continue until we reach a fixed point
    (No more changes)

# Dataflow Analysis

- Now model the abstract program state and propagate through the CFG.
  - Continue until we reach a fixed point
    (No more changes)
  - Proper ordering can improve the efficiency.
    (Topological Order, Strongly Connected Components)

# Dataflow Analysis

- Now model the abstract program state and propagate through the CFG.
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    (No more changes)
  - Proper ordering can improve the efficiency.
    - (Topological Order, Strongly Connected Components)

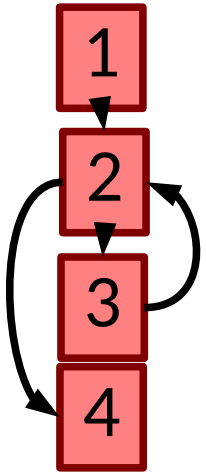
Will it always terminate?

# Dataflow Analysis

- Note: need to model program state before and after each statement
- Proper ordering & a work list algorithm improves the efficiency

# Worklist Algorithms

```
work = nodes()
state(n) = ⊥ ∀ n ∈ nodes()
while work ≠ ∅:
    unit = take(work)
    old = state(unit)
    before = ∏state(p)
                ∀ p ∈ preds(unit)
    new = transfer(before, unit)
    if old ≠ after:
        work = work ∪ succs(unit)
        state(unit) = new
```



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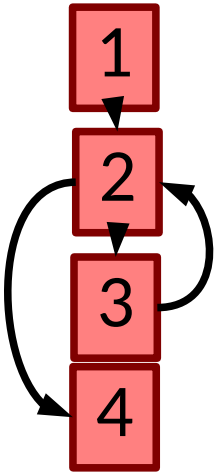


work: 1 2 3 4

state: { (1 ↦ ⊥) (2 ↦ ⊥) (3 ↦ ⊥) (4 ↦ ⊥) }

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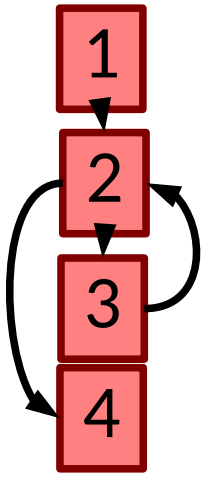
```

unit = 1




work: 2 3 4

state: { (1 ↦ ⊥) (2 ↦ ⊥) (3 ↦ ⊥) (4 ↦ ⊥) }

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    new = transfer(before, unit)
    if old ≠ after:
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        state(unit) = new
```
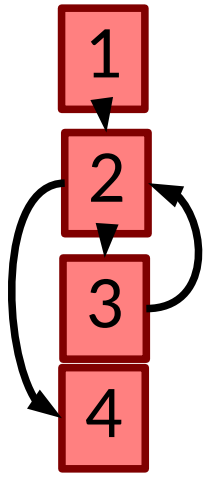

unit = 1

old = ⊥




work: 2 3 4

state: { (1 ↦ ⊥) (2 ↦ ⊥) (3 ↦ ⊥) (4 ↦ ⊥) }

# Worklist Algorithms

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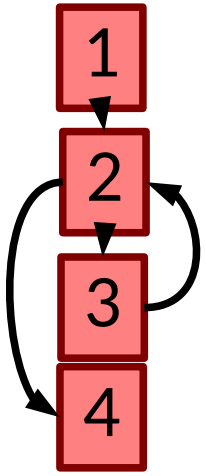
```

unit = 1

old = ⊥

new = sum → 0, i → +




work: 2 3 4

state: { (1 ↦ ⊥) (2 ↦ ⊥) (3 ↦ ⊥) (4 ↦ ⊥) }

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```
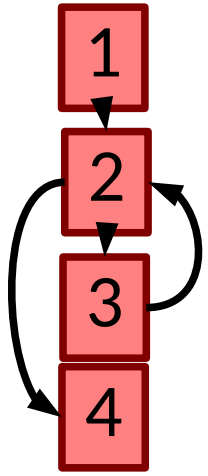

unit = 1

old = ⊥

new = sum → 0, i → +




work: 2 3 4

state: { (1 ↦ sum → 0, i → +) (2 ↦ ⊥) (3 ↦ ⊥) (4 ↦ ⊥) }

# Worklist Algorithms

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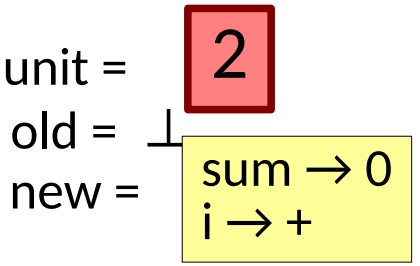


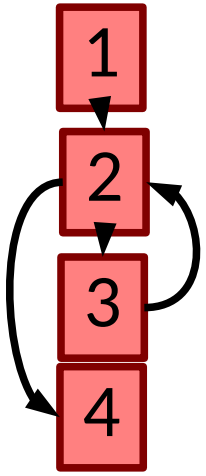


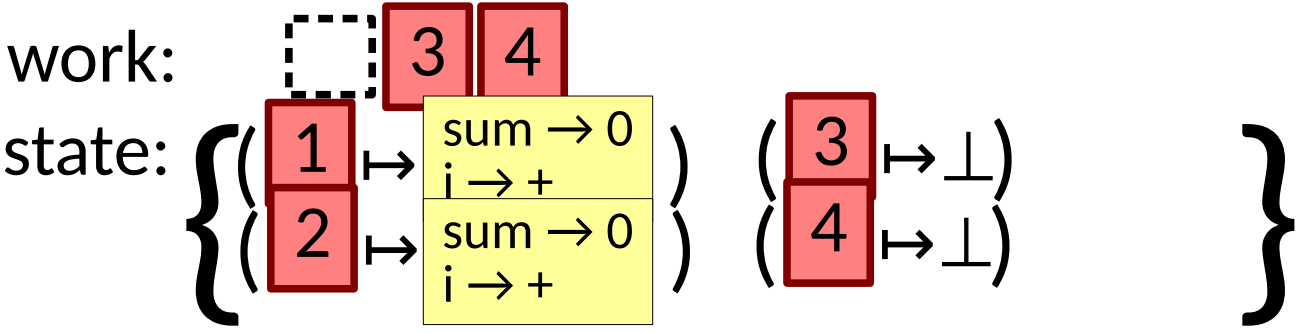

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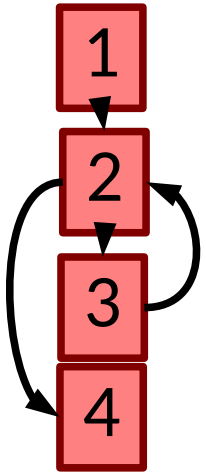
    new = transfer(before, unit)
    if old ≠ after:
        work = work ∪ succs(unit)
        state(unit) = new
```

unit = 3

old = ⊥

new = sum → +, i → +




work: 4 2 ← 2 was added back to the list

state: { (1 ↦ sum → 0, i → +) (2 ↦ sum → 0, i → +) (3 ↦ sum → +, i → +) (4 ↦ ⊥) }

# Worklist Algorithms

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        state(unit) = new
```
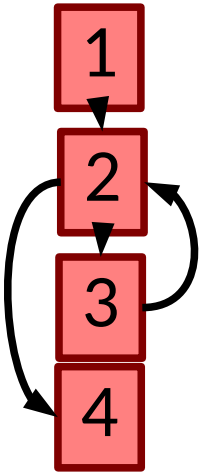

unit = 4

old = ⊥

new = sum → 0, i → +




work: 2

state: { (1 ↦ sum → 0, i → +) (2 ↦ sum → 0, i → +) (3 ↦ sum → +, i → +) (4 ↦ sum → 0, i → +) }

# Worklist Algorithms

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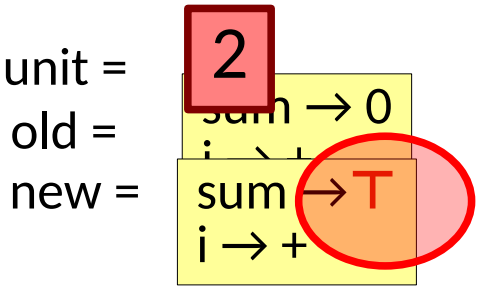
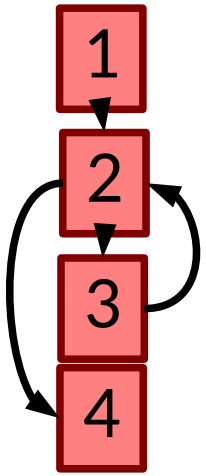
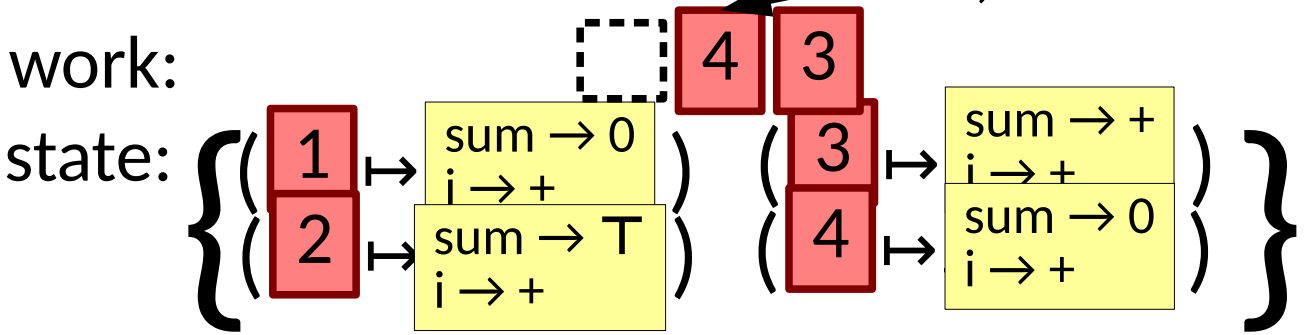



4,3 were added back to the list



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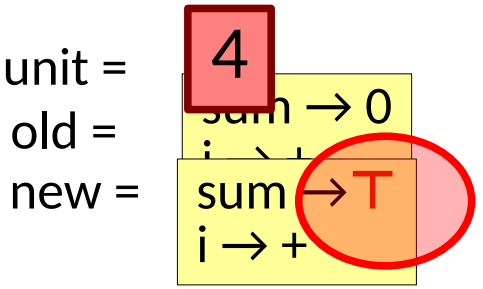
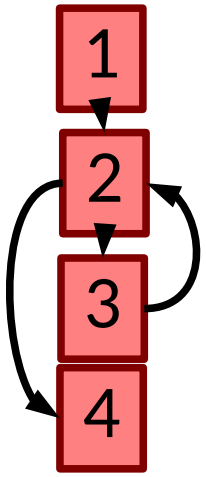
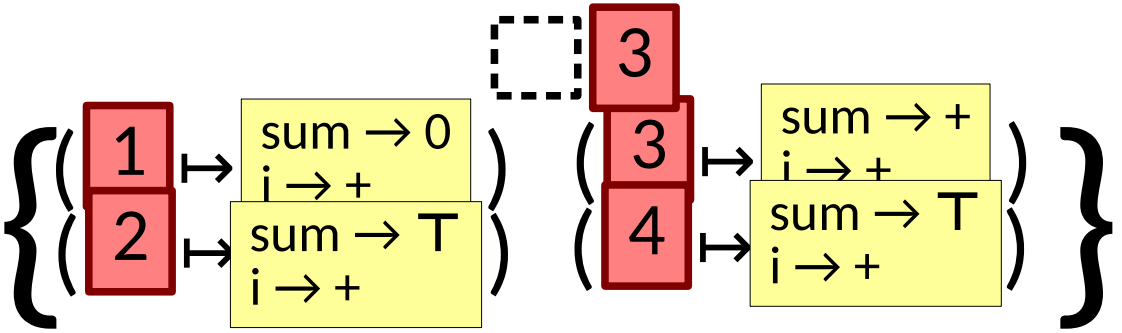



work:

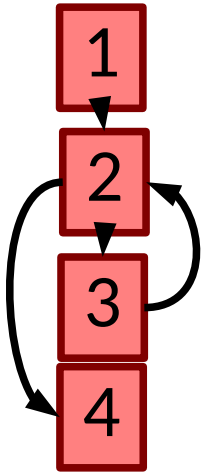
state:



# Worklist Algorithms

```
work = nodes()
state(n) = ⊥ ∀ n ∈ nodes()
while work ≠ ∅:
    unit = take(work)
    old = state(unit)
    before = ∏state(p)
             ∀ p ∈ preds(unit)
    new = transfer(before, unit)
    if old ≠ after:
        work = work ∪ succs(unit)
        state(unit) = new
```

unit = 3
old = sum → +
new = sum → +
i → +




No change

work:

state: { (1 ↦ sum → 0, i → +) (2 ↦ sum → T, i → +) } { (3 ↦ sum → +, i → +) (4 ↦ sum → T, i → +) }

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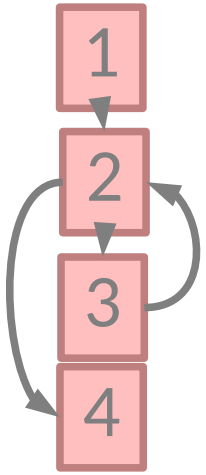
unit = 4

old = sum → 0

new = sum → T

Done!

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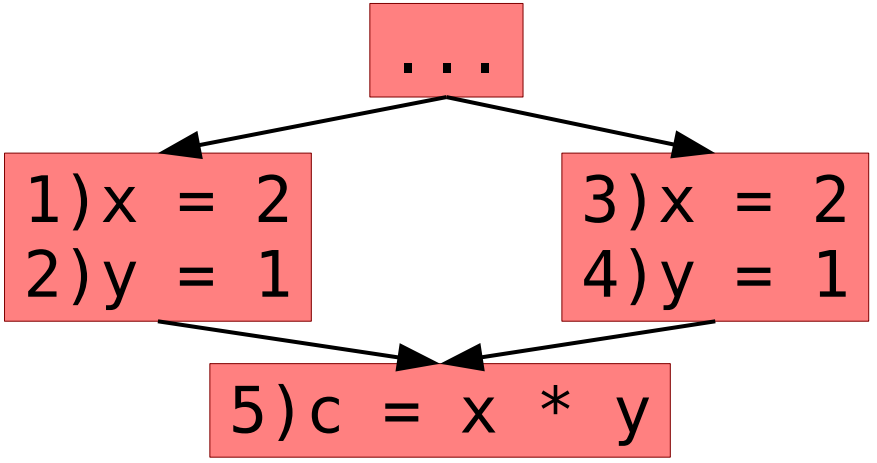

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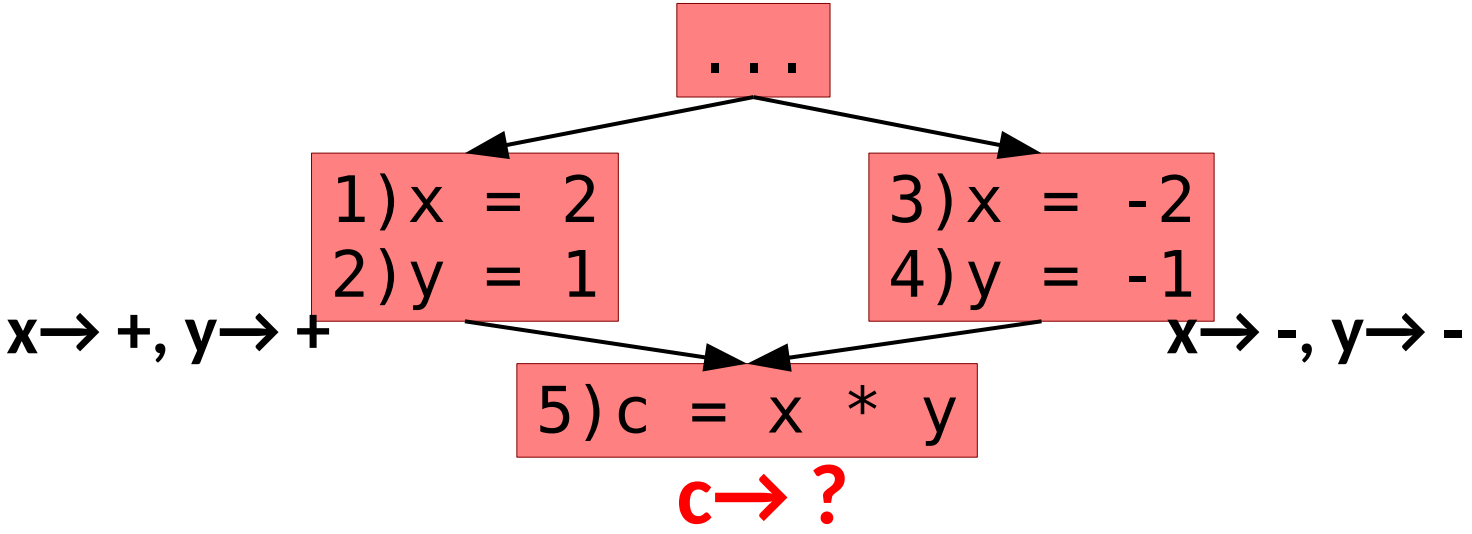

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  - This applies to an important class of problems called *bitvector frameworks*.

# Bitvector Frameworks

- When the property concerns subsets of a finite set, the abstract domain & lattice are easy:
  - Concrete: D = {a, b, c, d, … }
  - Abstract: $\wp$(D) = { {}, {a}, {b}, …, {a, b}, {a, c}, …}
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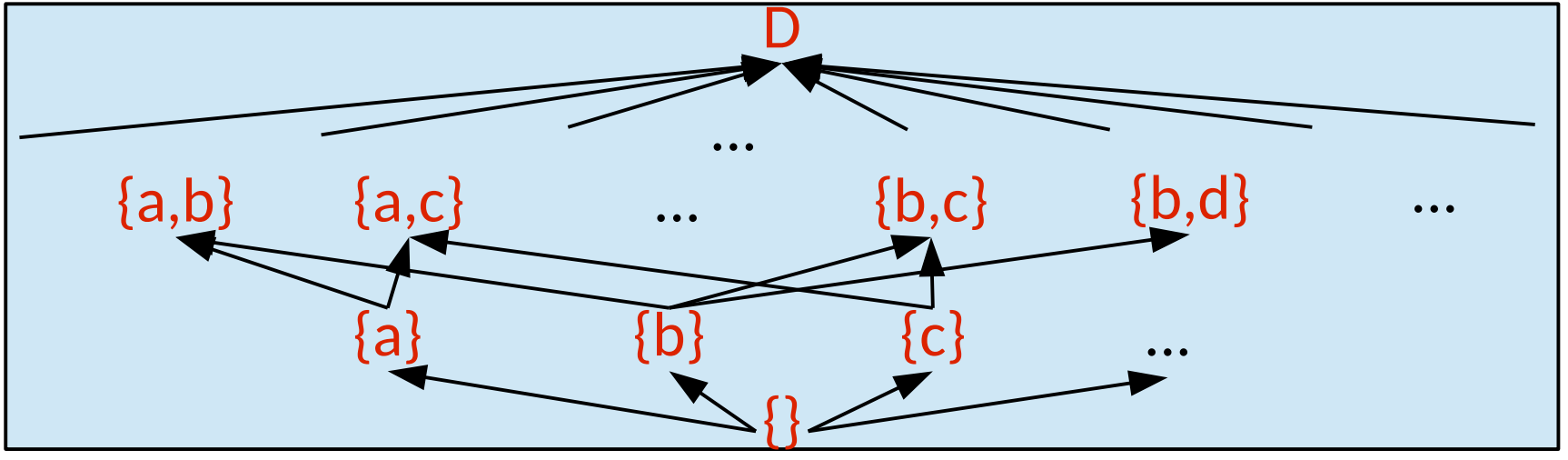

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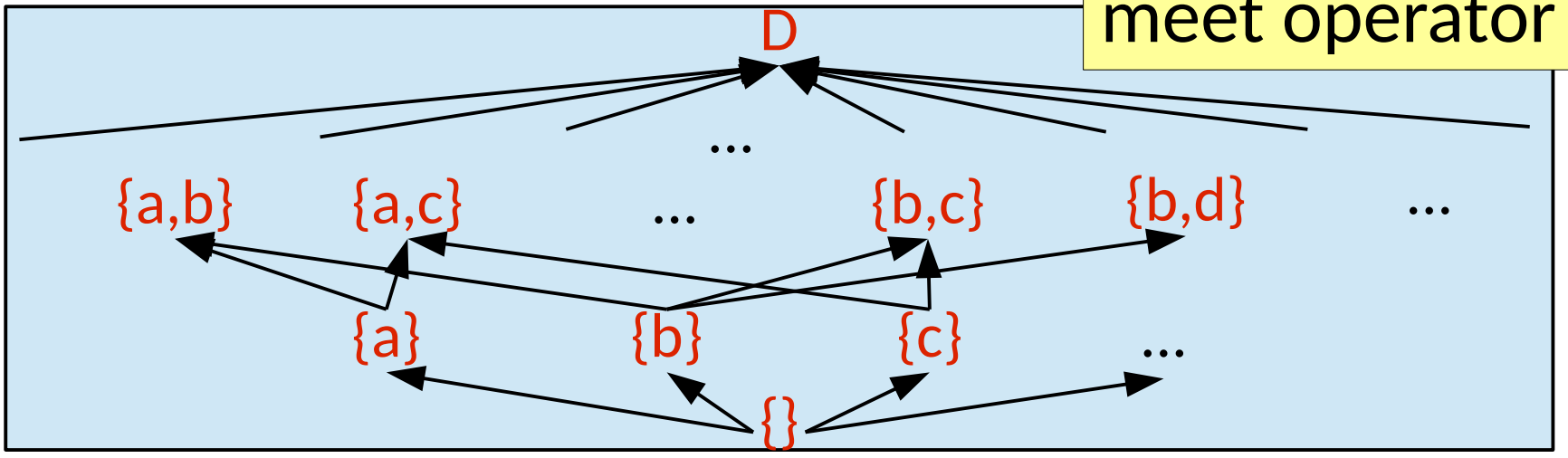
What would the meet operator be?



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  - Hint: ***bitvector*** frameworks
  - X={a,b}, Y={c,d} → X⨆Y = {a,b}∪{c,d} = {a,b,c,d}
  - We can implement the abstract state using efficient bitvectors!

# Effect of Approximation

- If approximation yields imprecise results, why do we do it?

# Recap: Dataflow Analysis

Analyze complex behavior with approximation:

- Abstract domain: e.g. {-,0,+} ⋃ {⊤,⊥}
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- Bounded domain lattice height:
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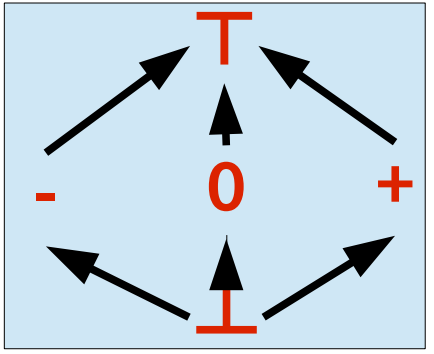

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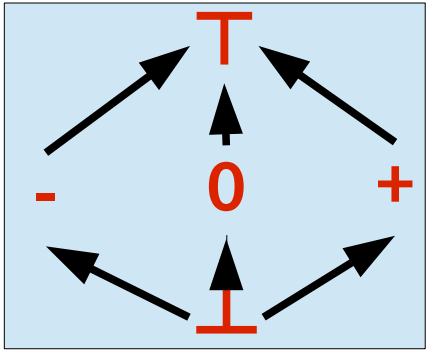


Implementation:

- Computing using work lists
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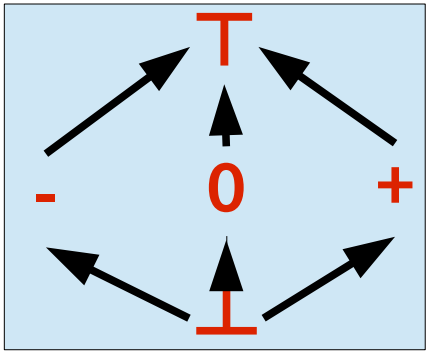


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Let's see an example

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[DEMO]

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  - Usually not beyond 1000s of lines without care
- *Flow insensitive* analyses aggregate into a global state
  - Better scalability
  - Less precision
  - “Does this function modify global variable X?”

# Context Sensitive Analyses

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Can you imagine how to solve this?
What problems might arise?

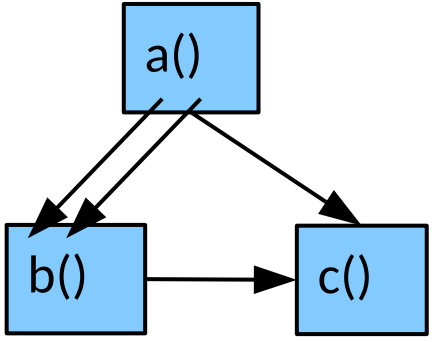
# Context Sensitivity

- Recall that we can extract a call graph
  - Just as you are doing in your first project!

```
def a():
  b()
  …
  b()

def b():
  …
  c()

def c():
  …
```




The behavior of c() could be affected by each "…"

Modeling them can make analysis more precise.

# Context Sensitivity

- Simplest Approach
  - Add edges between call sites & targets
  - Perform data flow on this larger graph

```
def main():
  x = 7
  r = p(x)
  x = r
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```
def p(a):
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main()

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call p(x)
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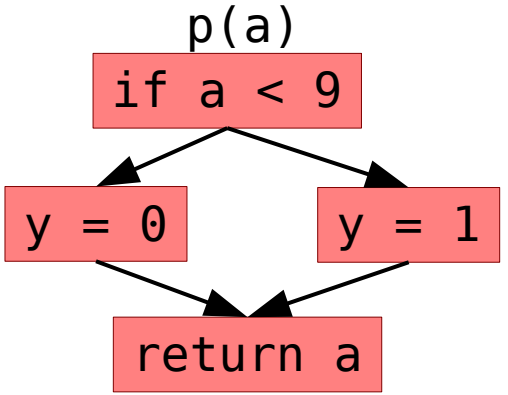




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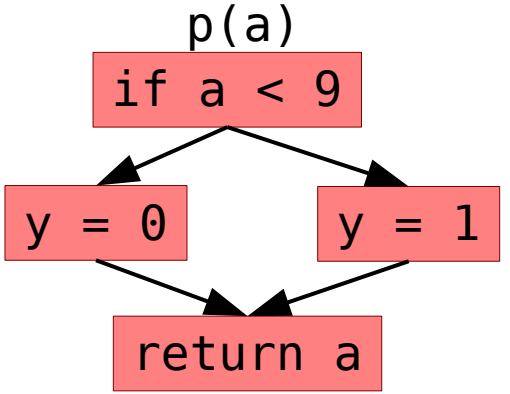




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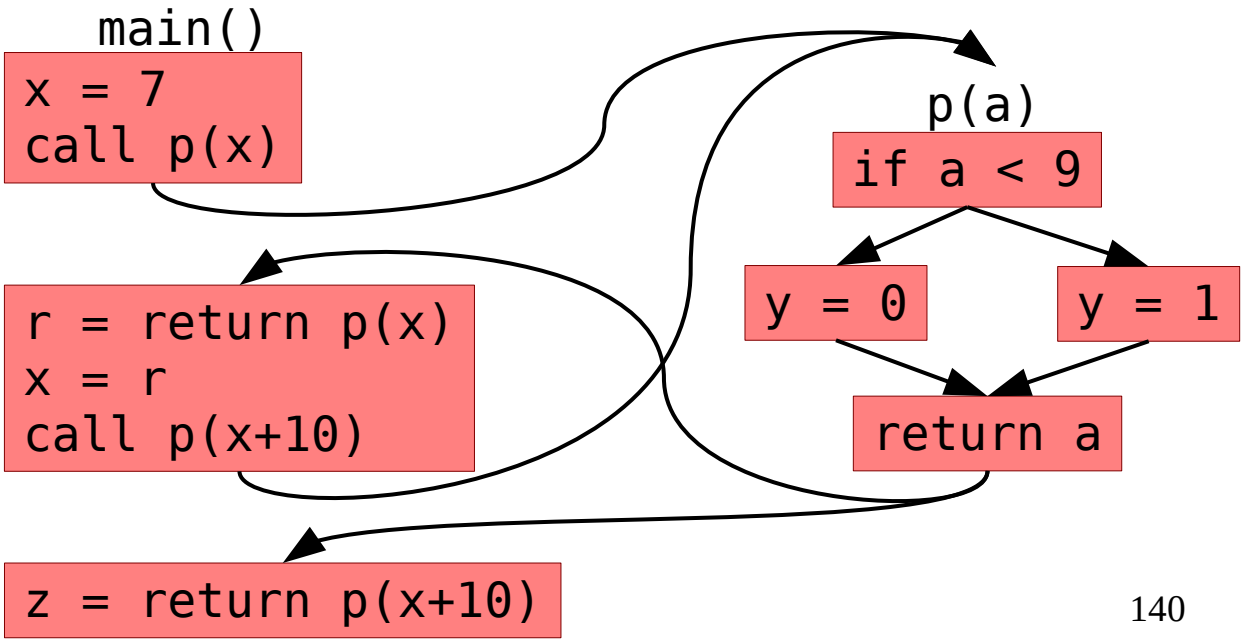


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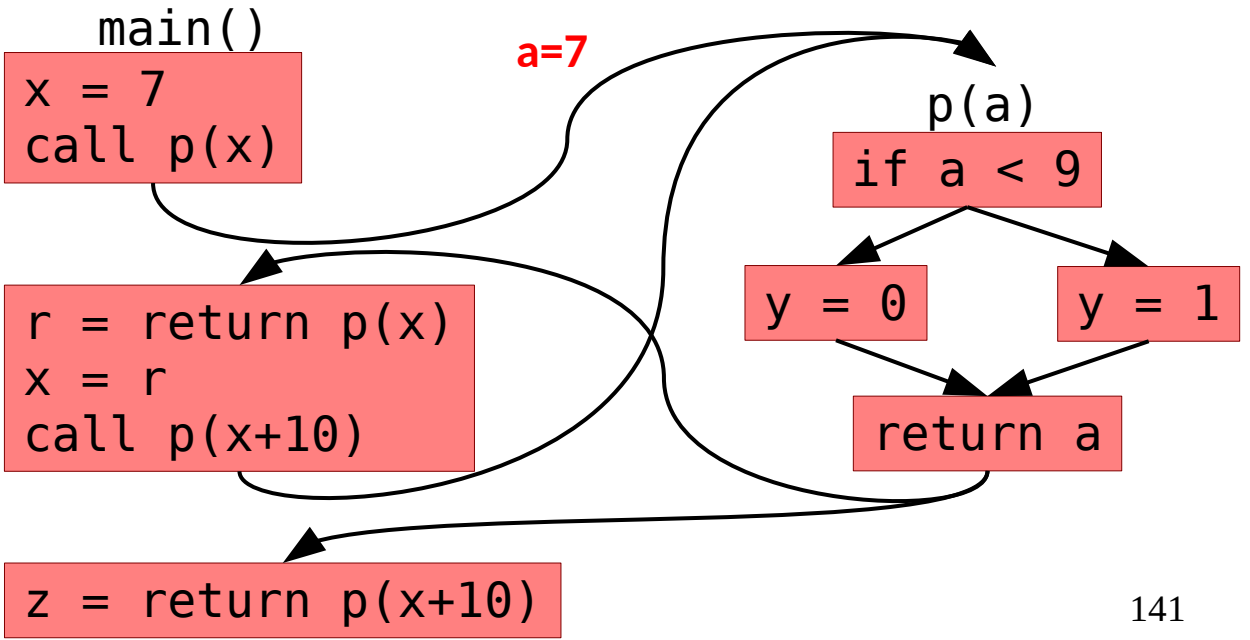


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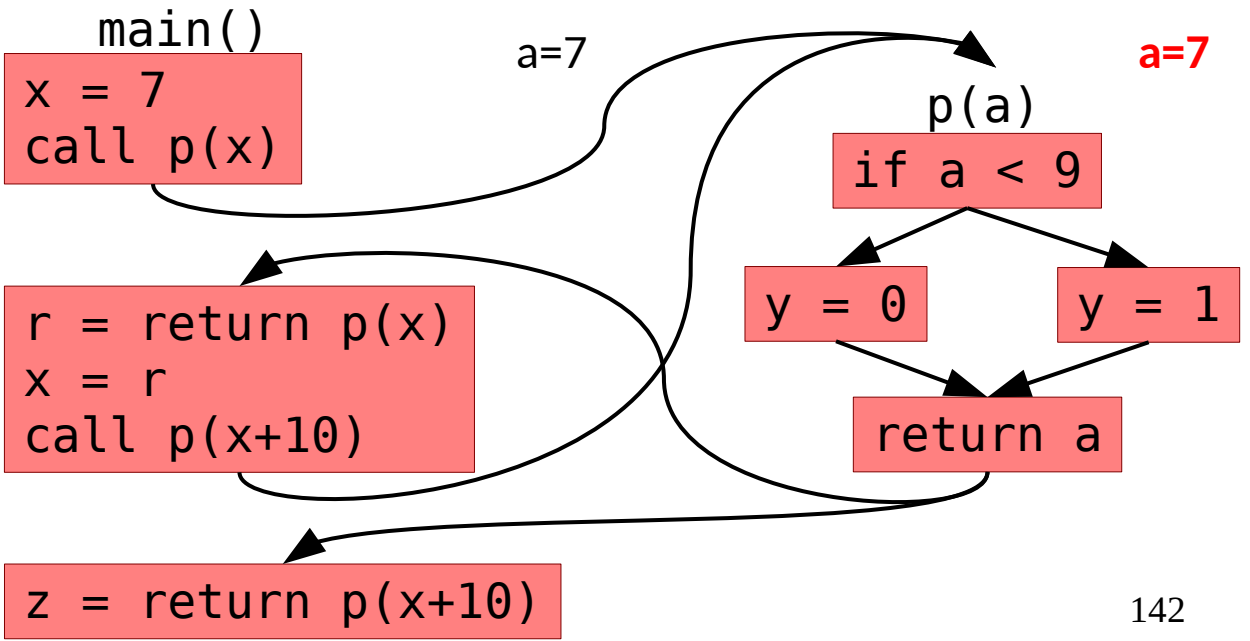


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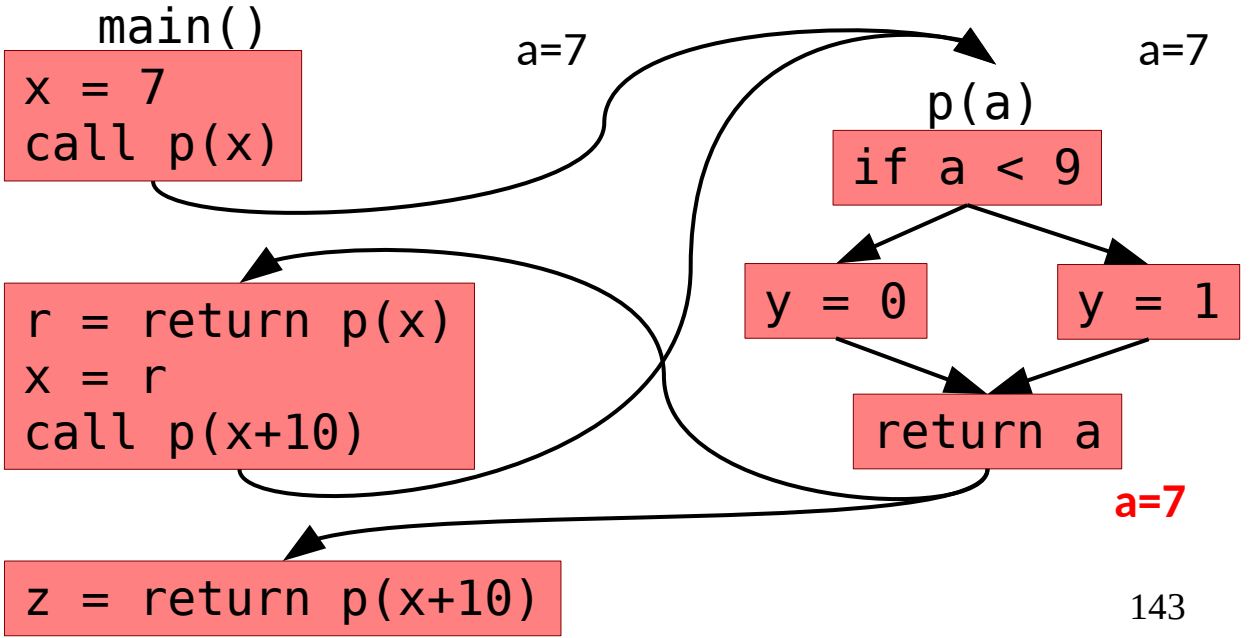


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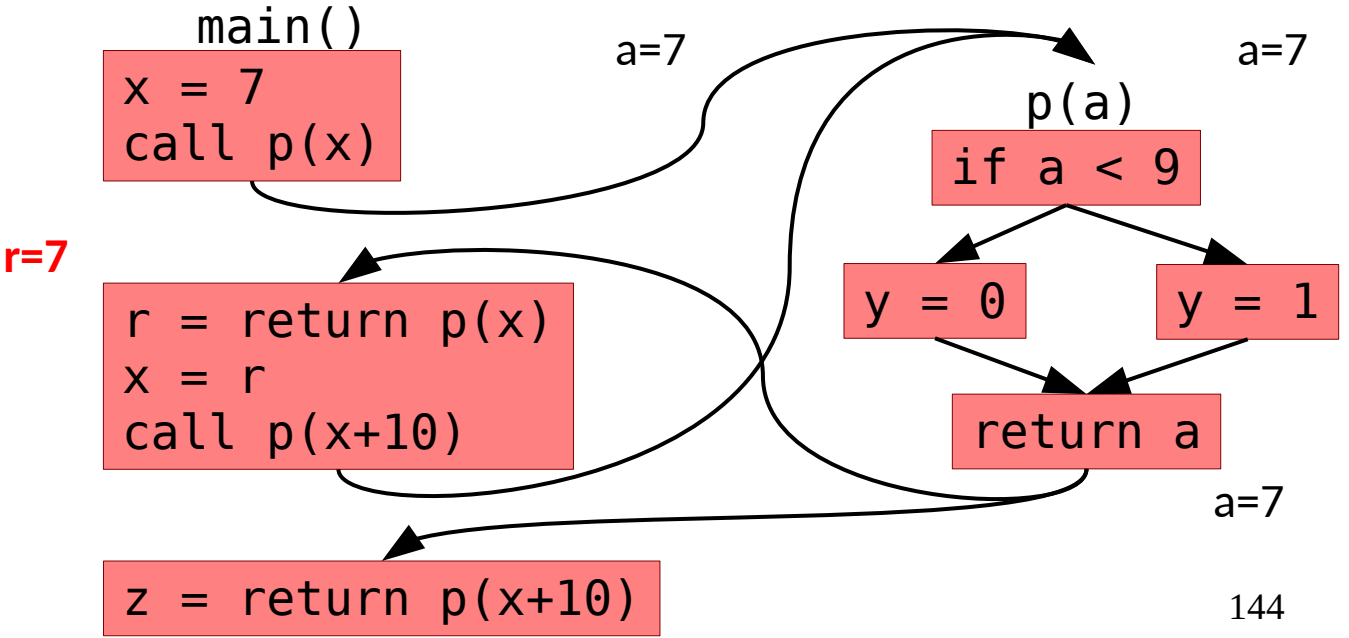




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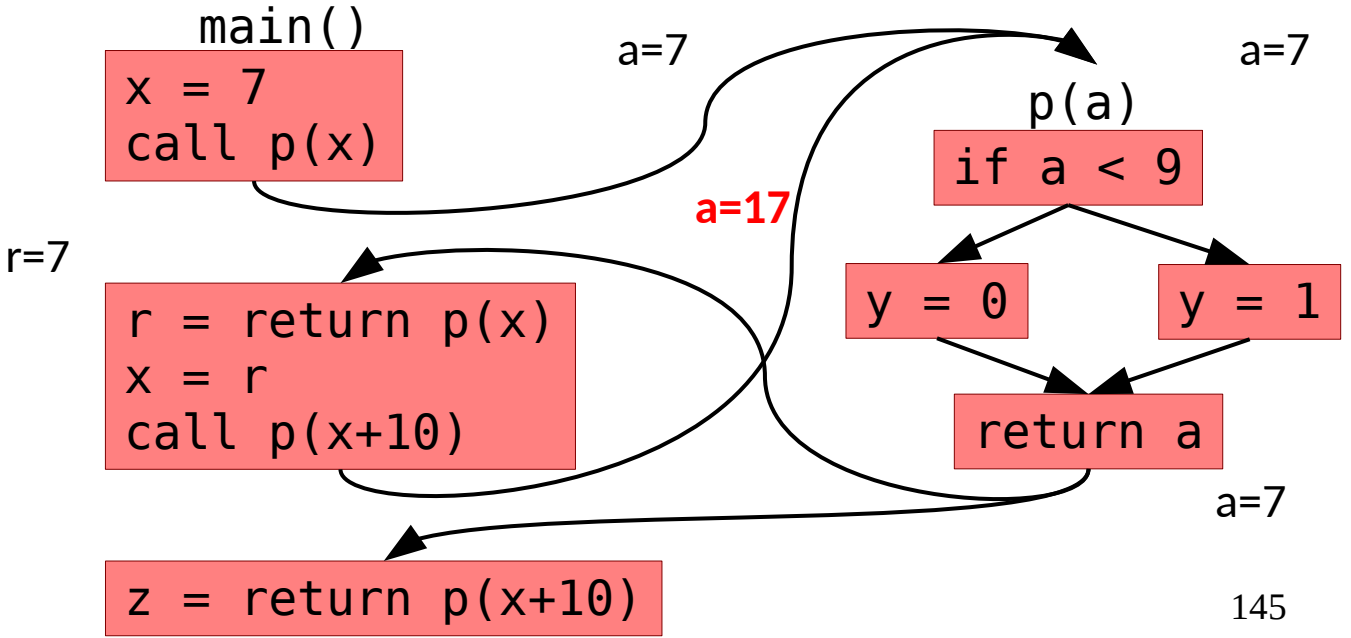




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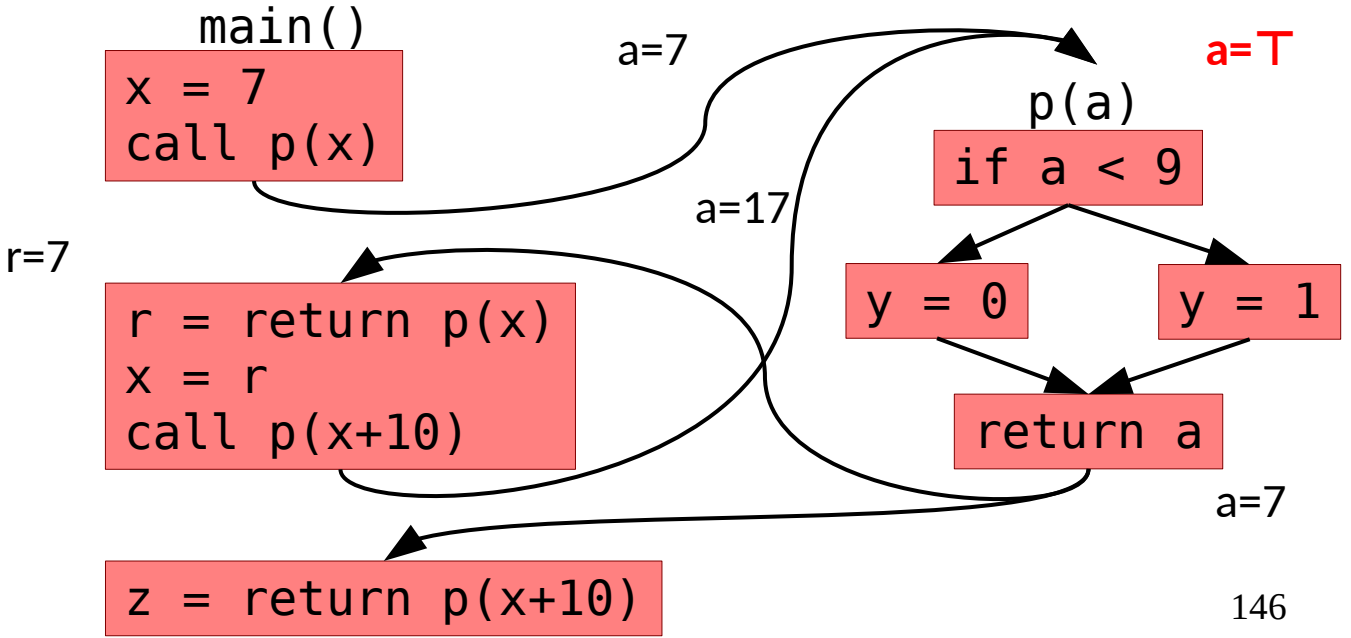


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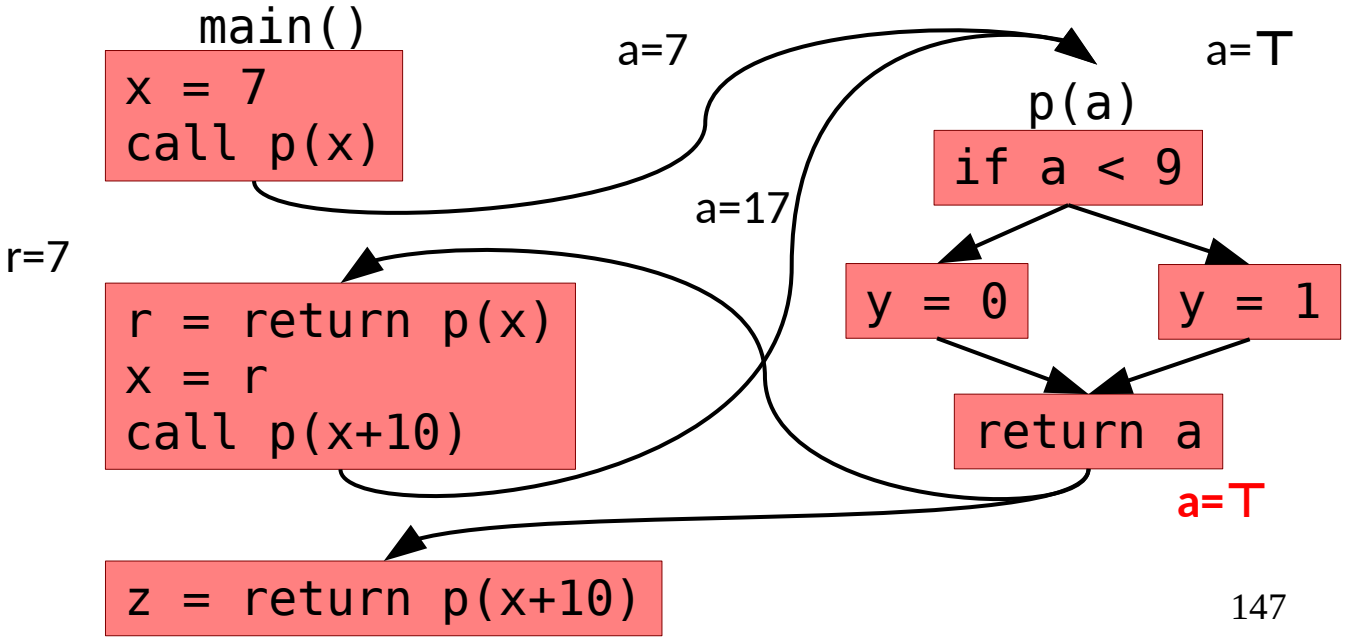




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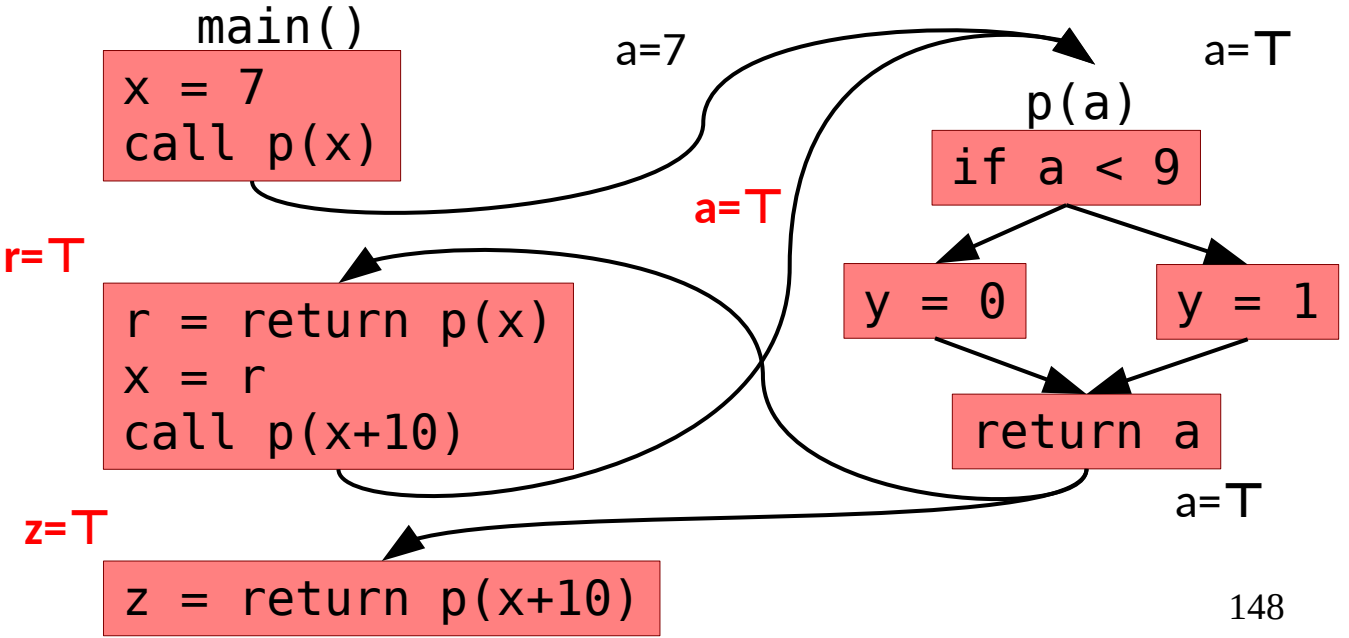




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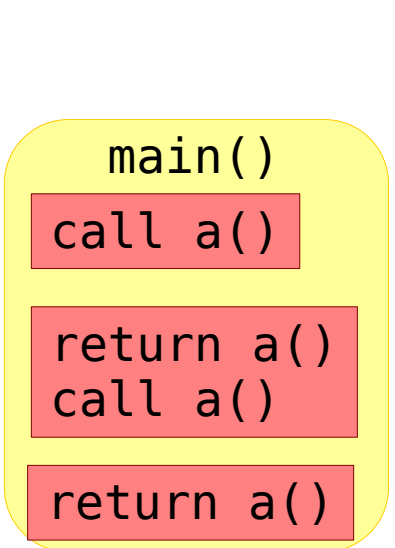


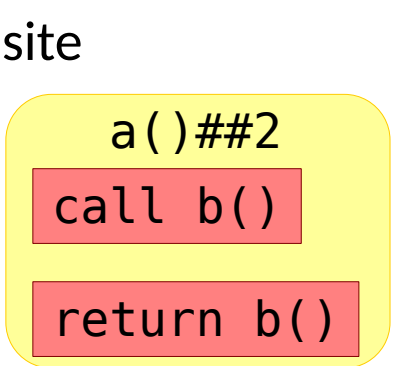


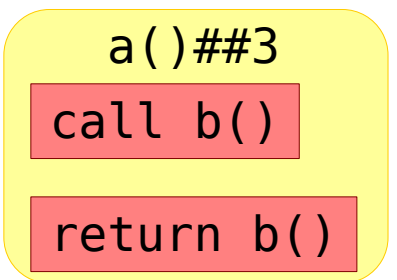


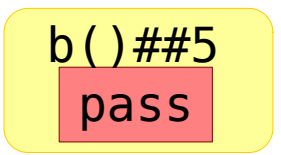

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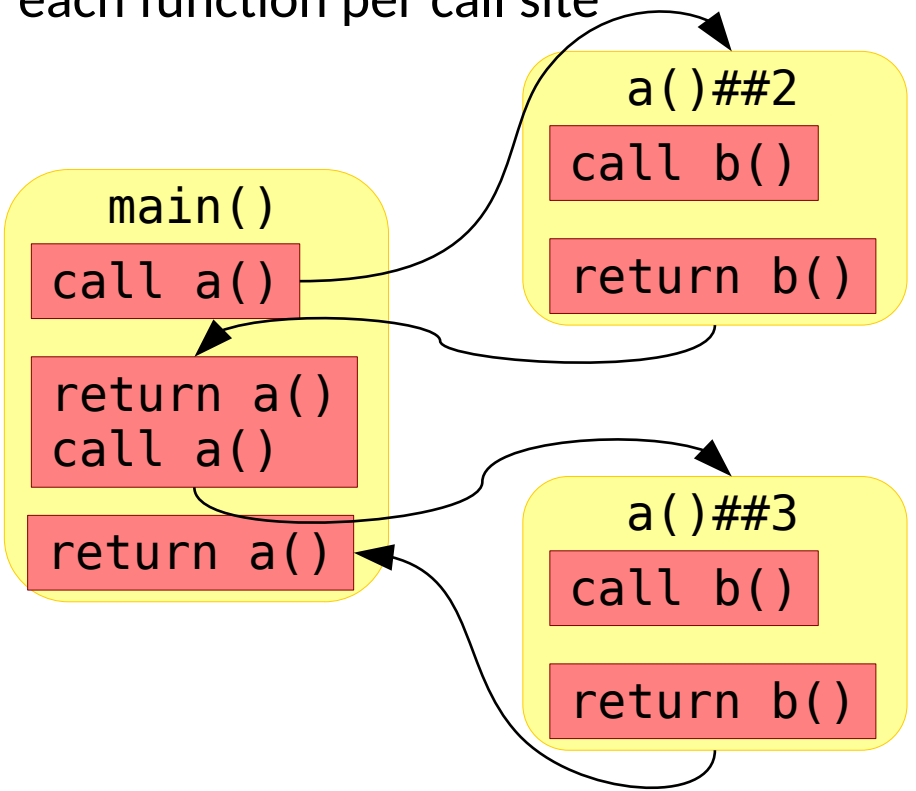


So far, so good

b()##5
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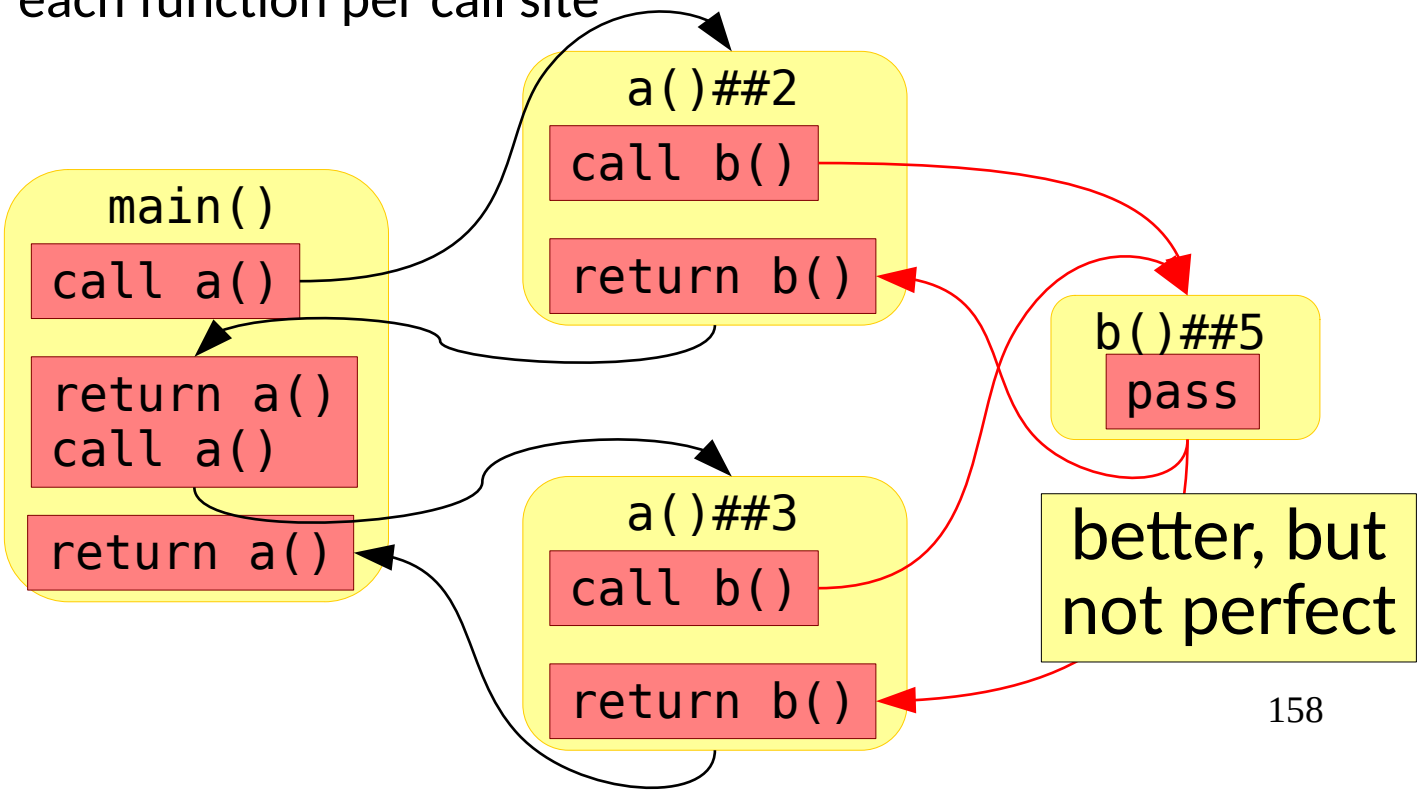


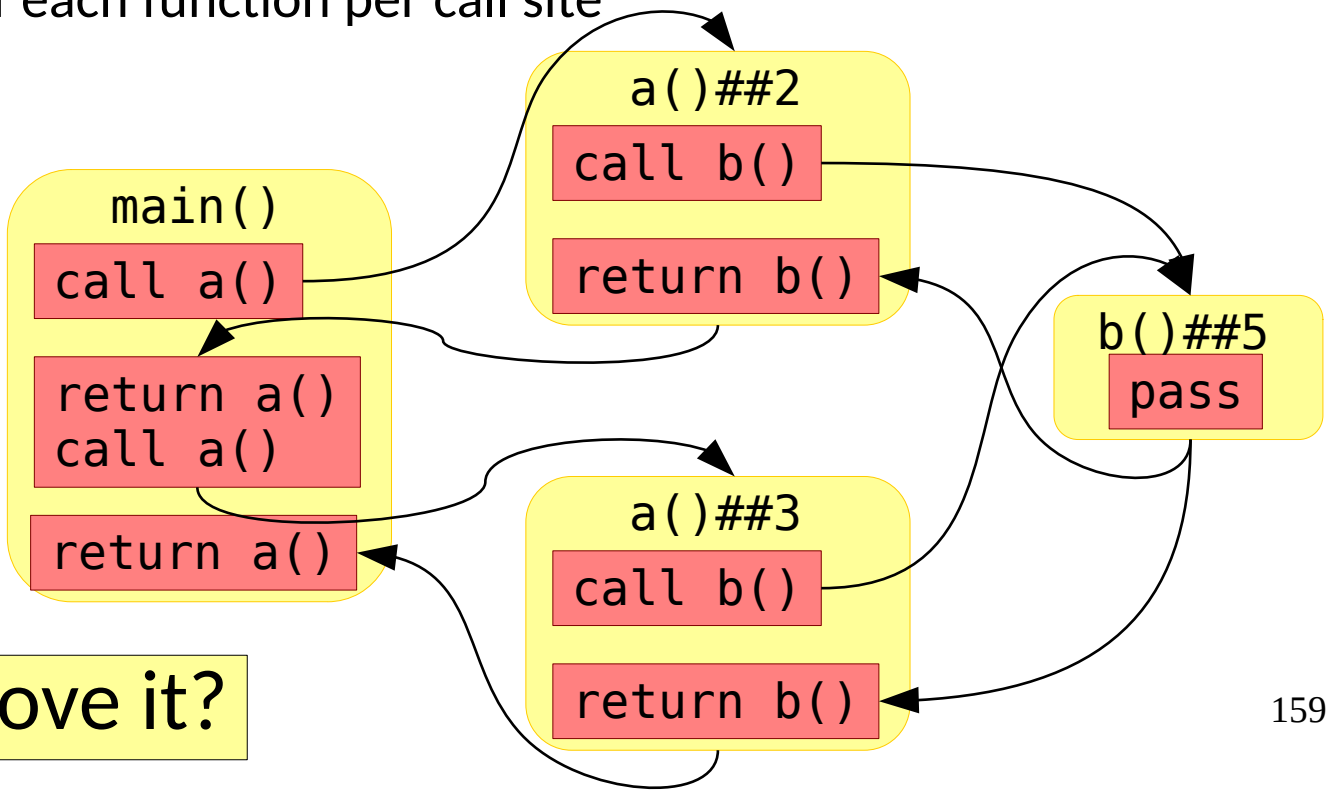
# Context Sensitivity

- Solution 3: Make a Copy
  - Make one copy of each function per call site

```
1) def main():
2)   a()
3)   a()
```

```
4) def a():
5)   b()
```

```
6) def b():
7)   pass
```




How can we improve it?

# Context Sensitivity

Generalized:

- Make a bounded number of copies

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- Make a bounded number of copies
- Choose a key/feature that determines which copy to use
  - Bounded calling context/call stack (*call site sensitivity*)
  - Allocation sites of objects (*object sensitivity*)

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    If the result changes, reprocess all callers of (foo,C)

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(**I**nterprocedural **F**inite **D**istributive **S**ubsets)

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b = a

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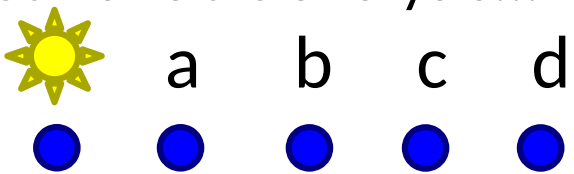


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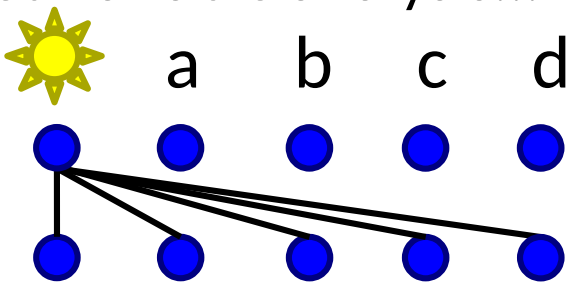


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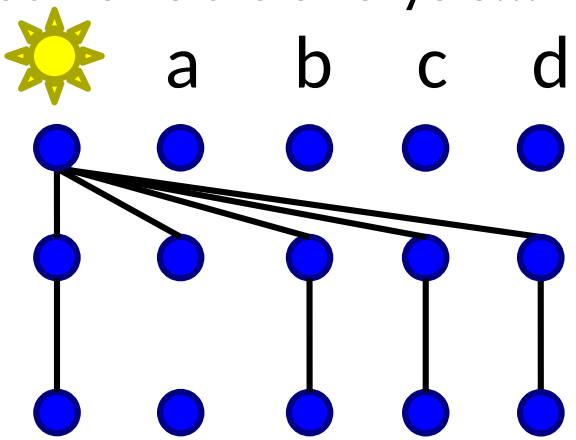


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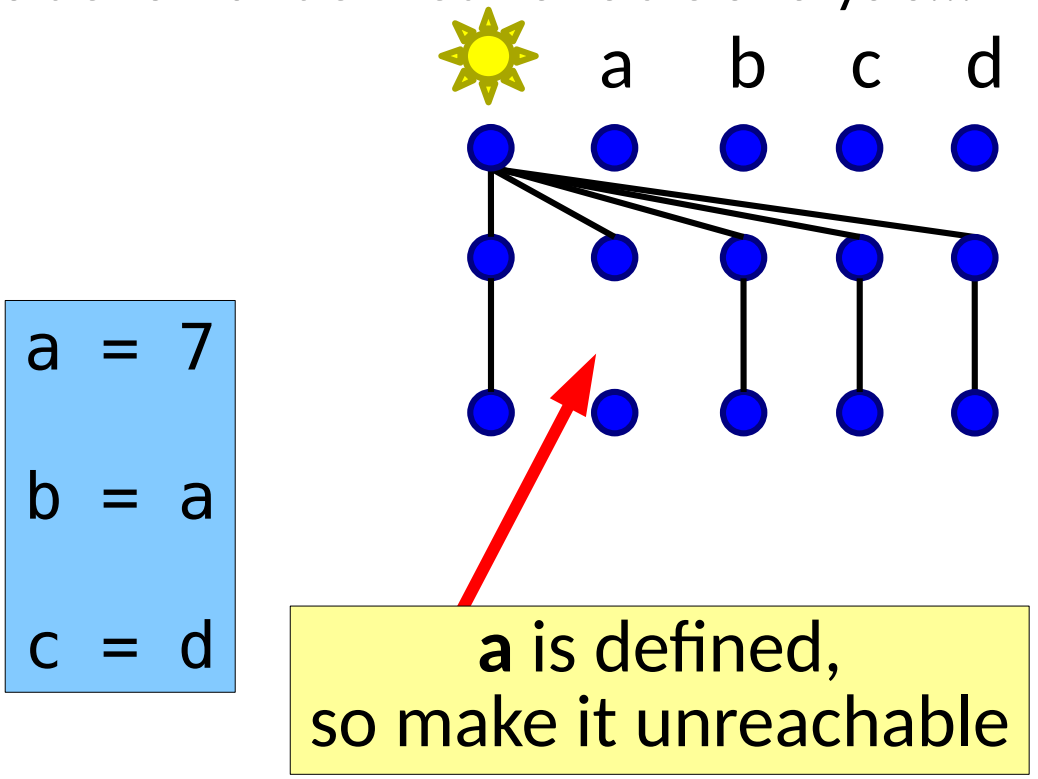

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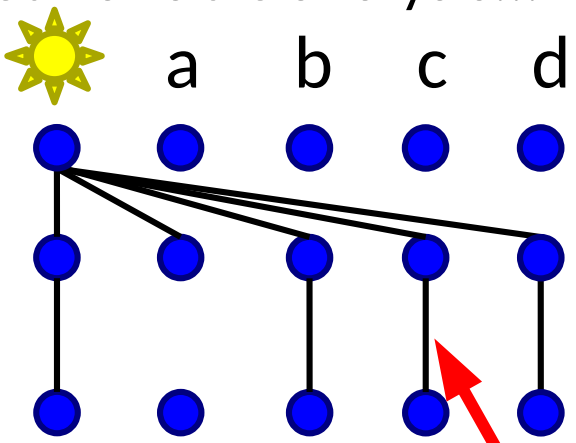


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**c** is unchanged,
so propagate its reachability

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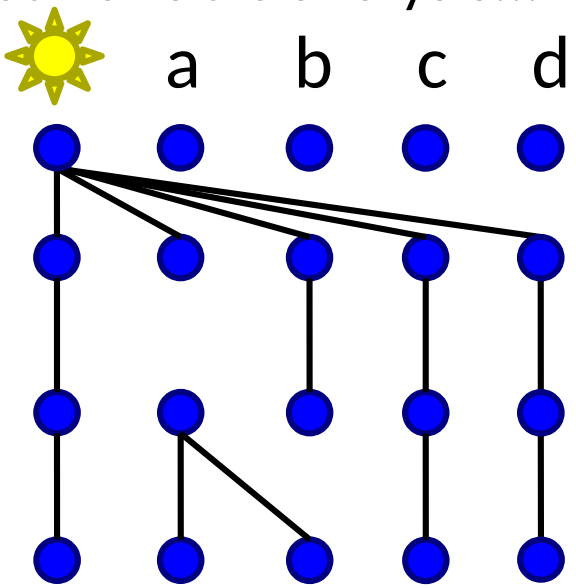

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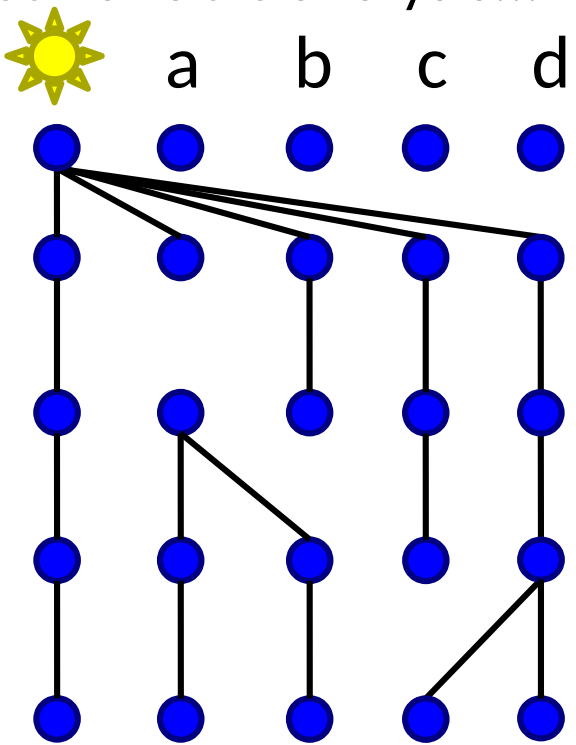

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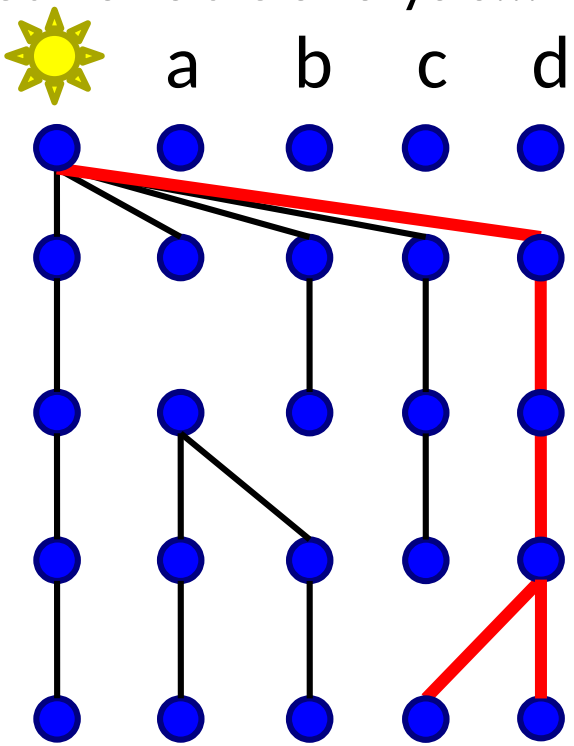


**c** and **d** are reachable here.
They are undefined at this point.

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- Consider an undefined variable analysis…

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def main():
  x = 7
  r = p(x)
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def p(a):
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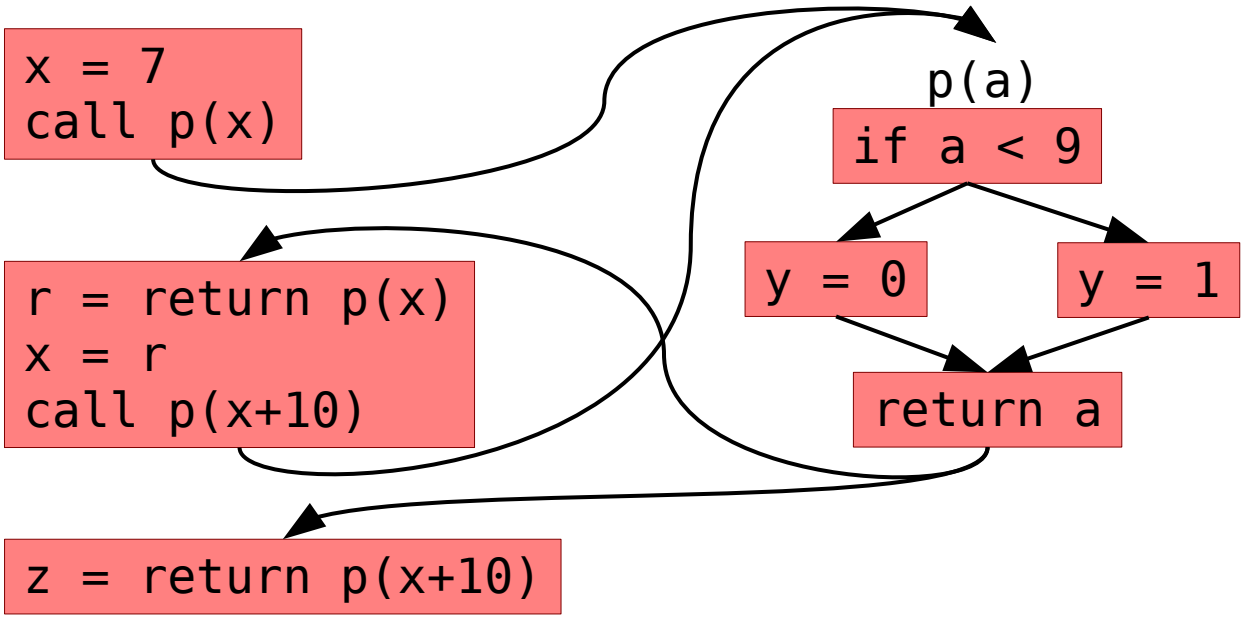

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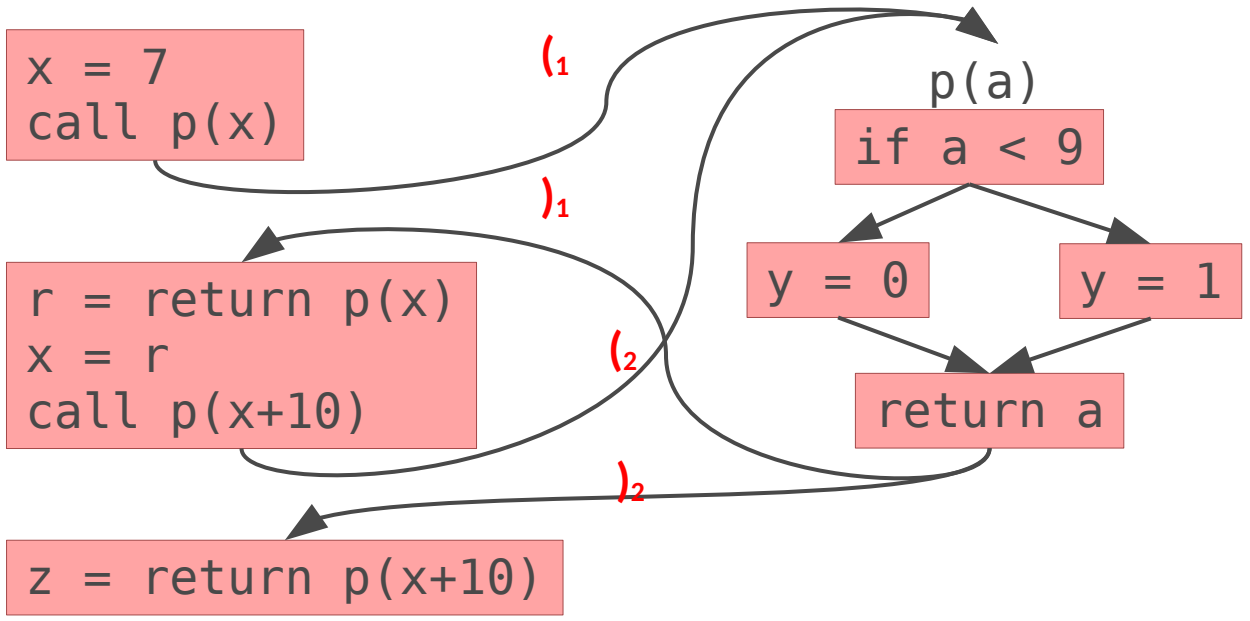

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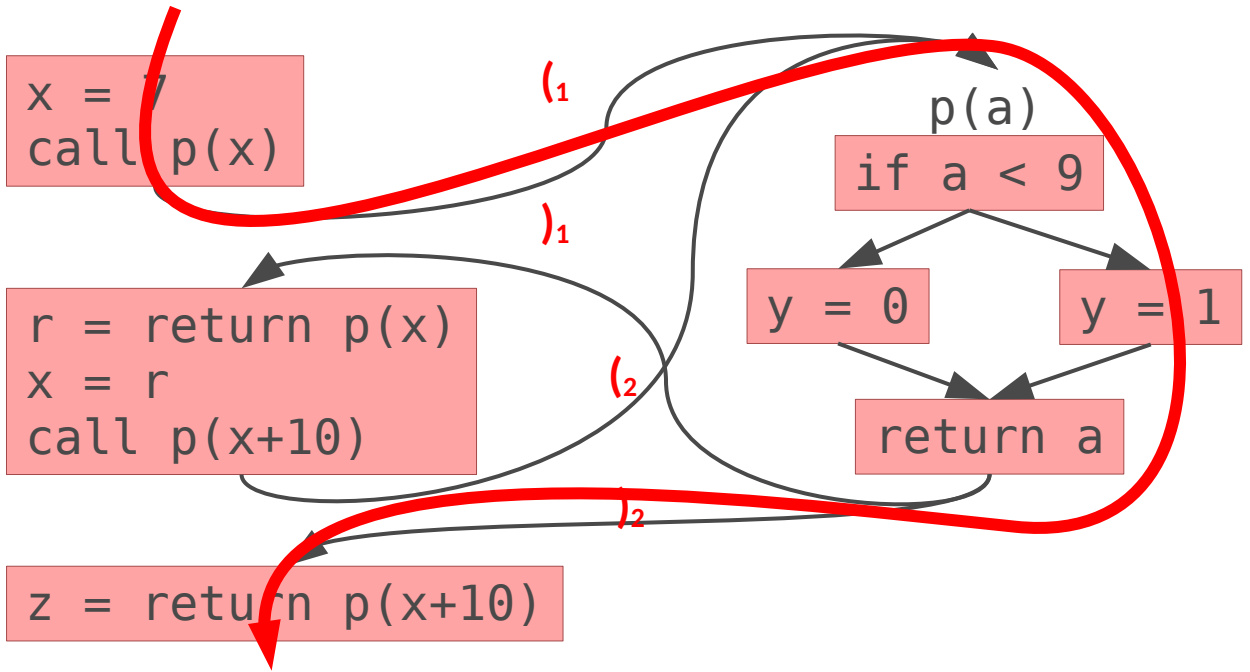


string: $(_1\ )_2$

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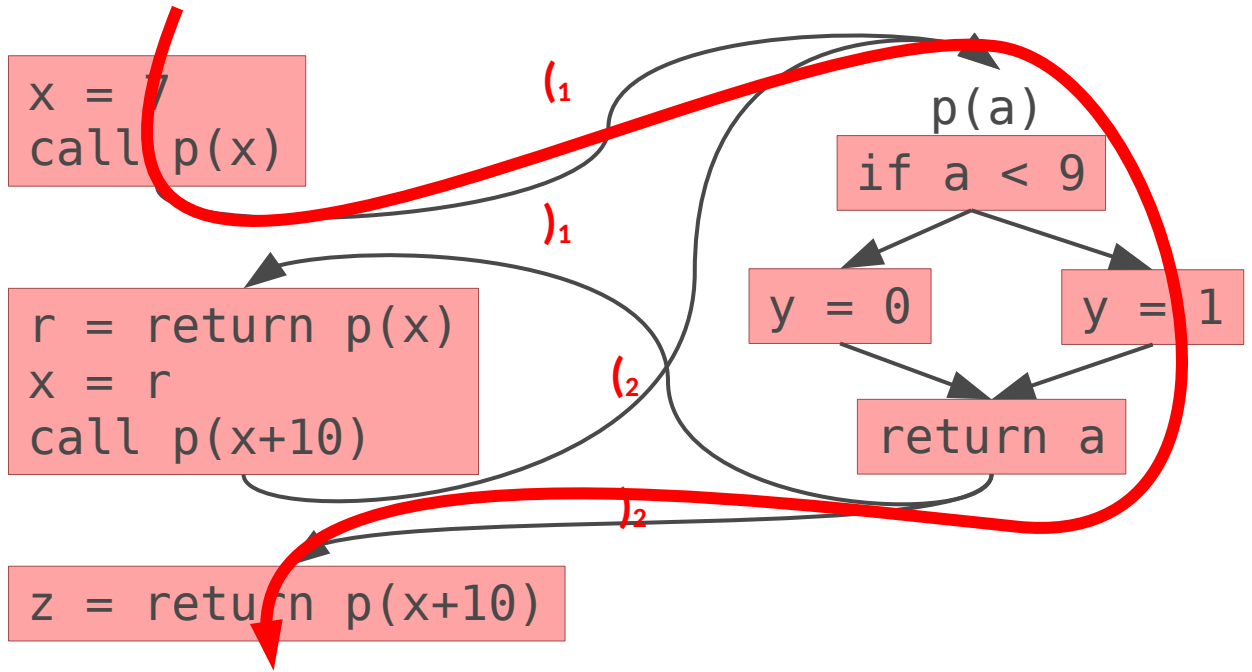


string: $(_1\ )_2$ unreachable

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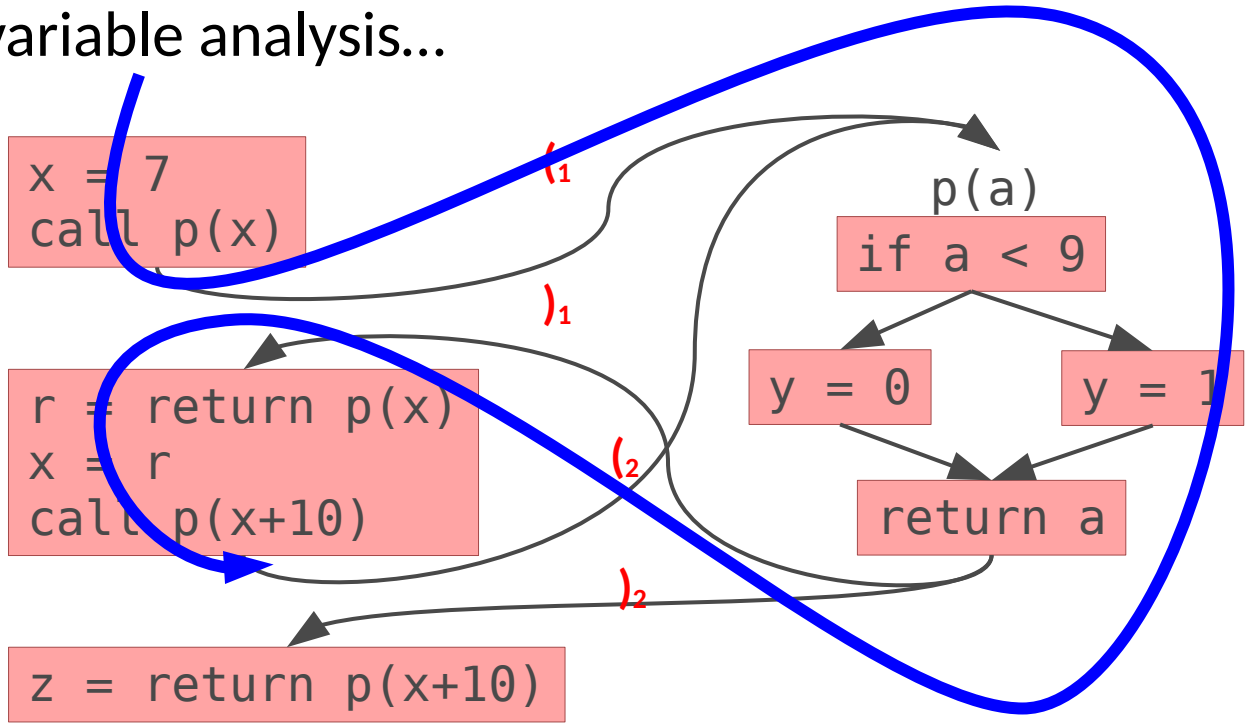


string: $(_1\ )_1$

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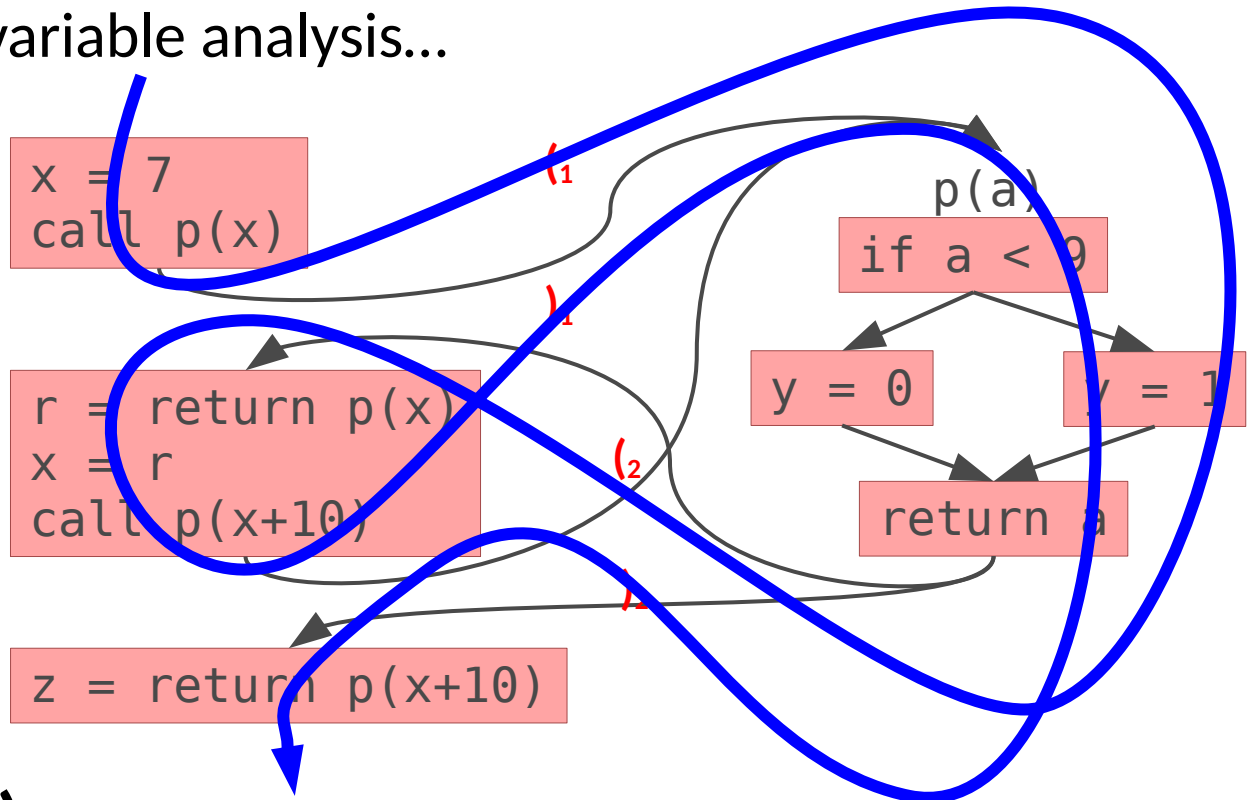


string: $(_1\ )_1(_2)_2$

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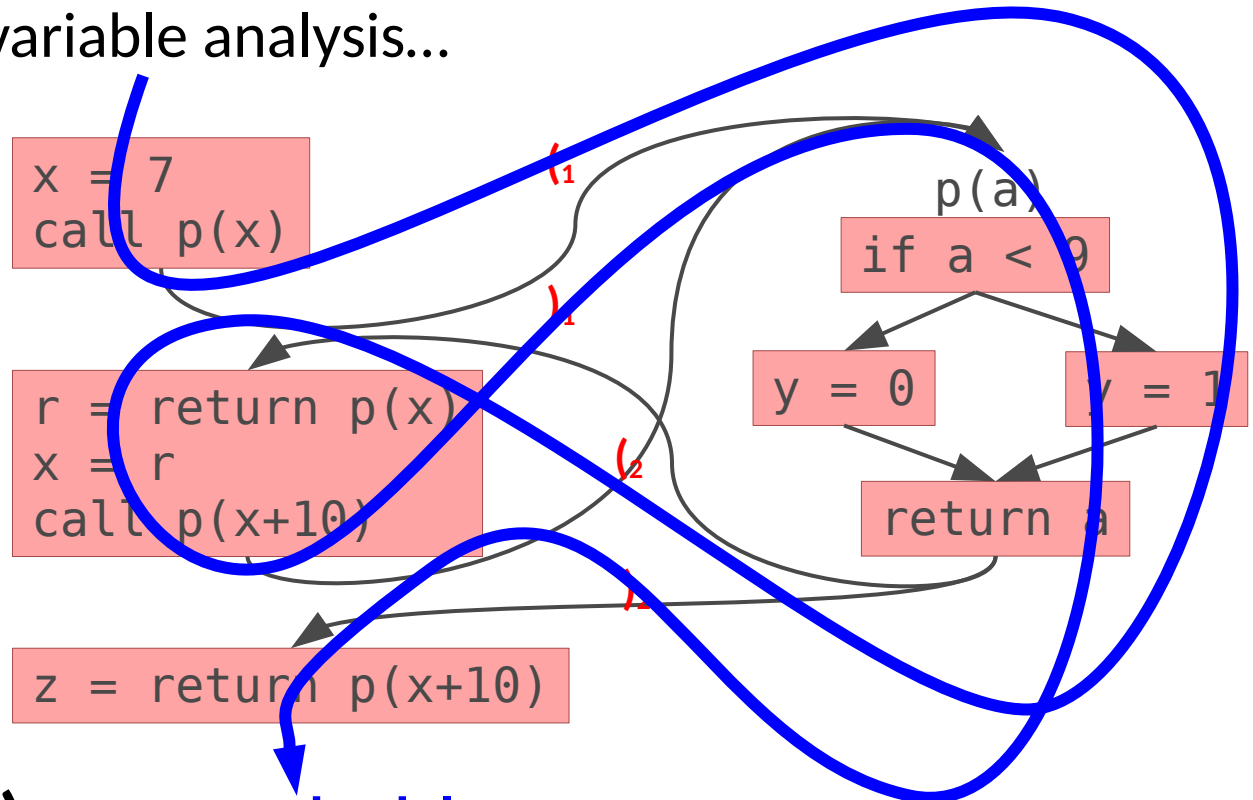


string: $(_1\ )_1(_2)_2$ reachable

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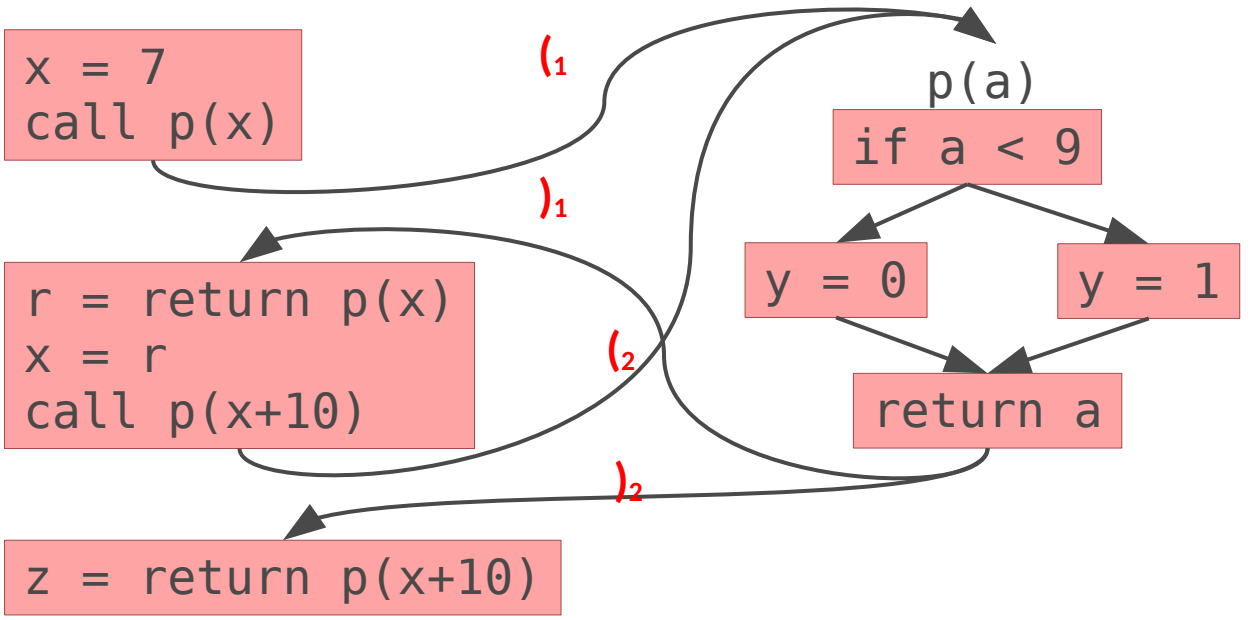
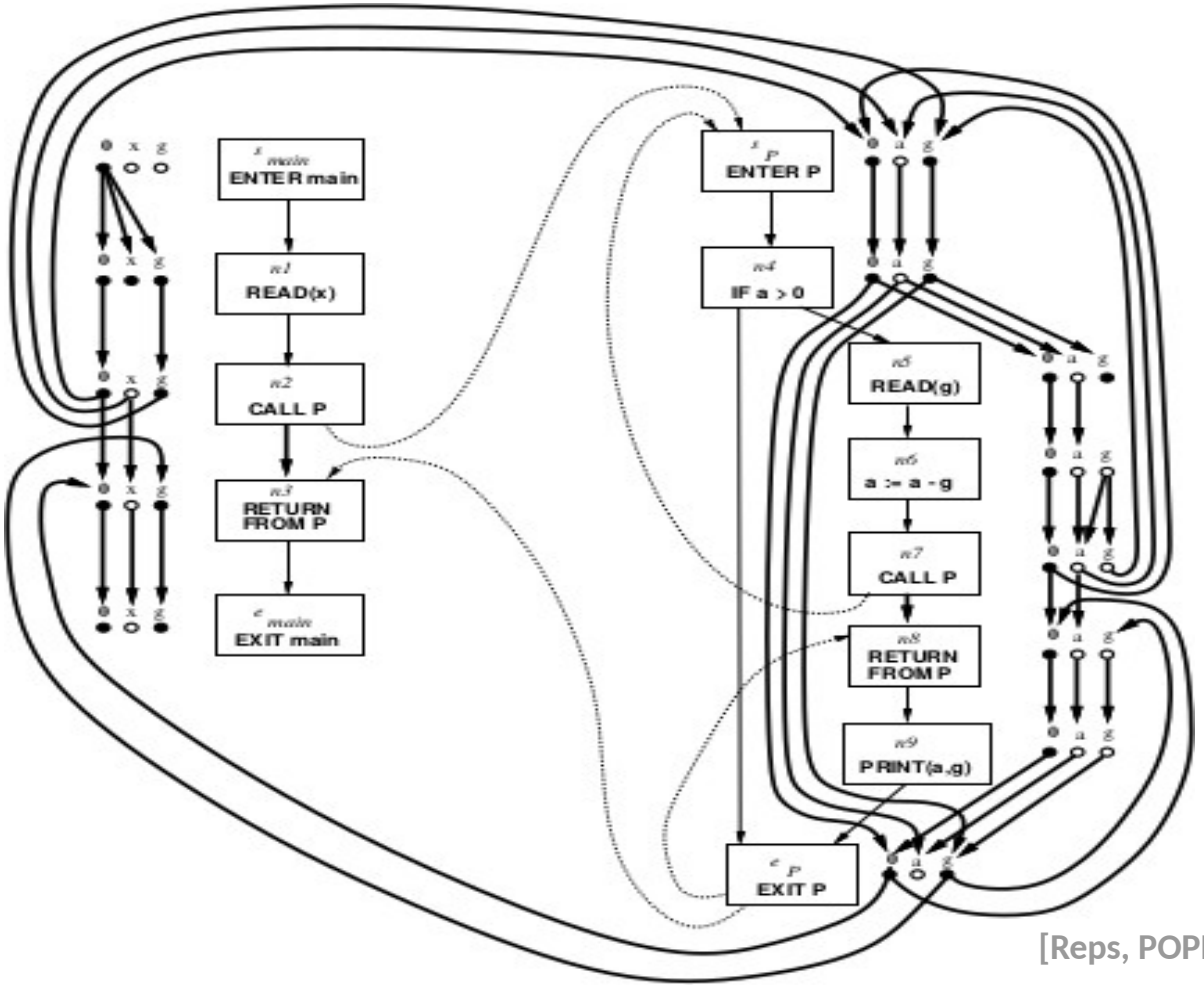



- A fact f holds before a node if f is *CFL-Reachable* in a language of matched parentheses

# Context Sensitivity - IFDS




[Reps, POPL 1995]

# Context Sensitivity - IFDS

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- Can you think of ways that it could be made to fit into IFDS?

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The configuration is ultimately driven by the property/problem of interest

# Static Analysis

- We've already seen a few static analyses:
  - Call graph construction
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  - Points-to graph construction (What are MAY/MUST?)
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- The choices for approximation are why these analyses are imprecise.

# Other (Traditionally) Static Approaches

- Type based analyses
- Bounded state exploration
- Symbolic execution
- Model checking

Many of these have been integrated into *dynamic* analyses, as we shall see over the semester.

# Static Analysis Summary

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- Dataflow analysis is one common form of static analysis