Static Analysis and Dataflow Analysis

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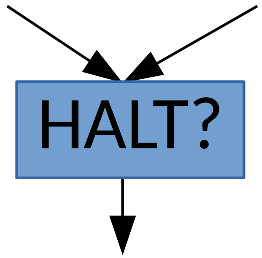

"Does my program terminate?"

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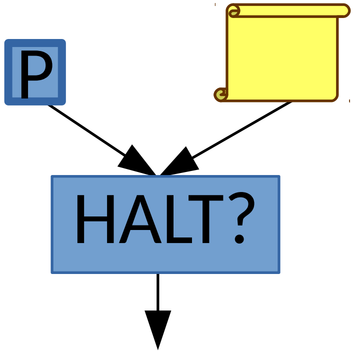

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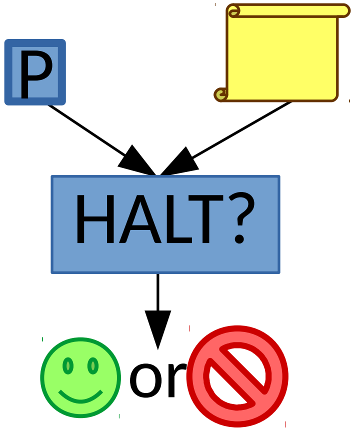

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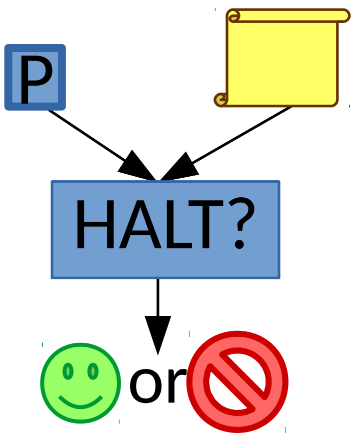

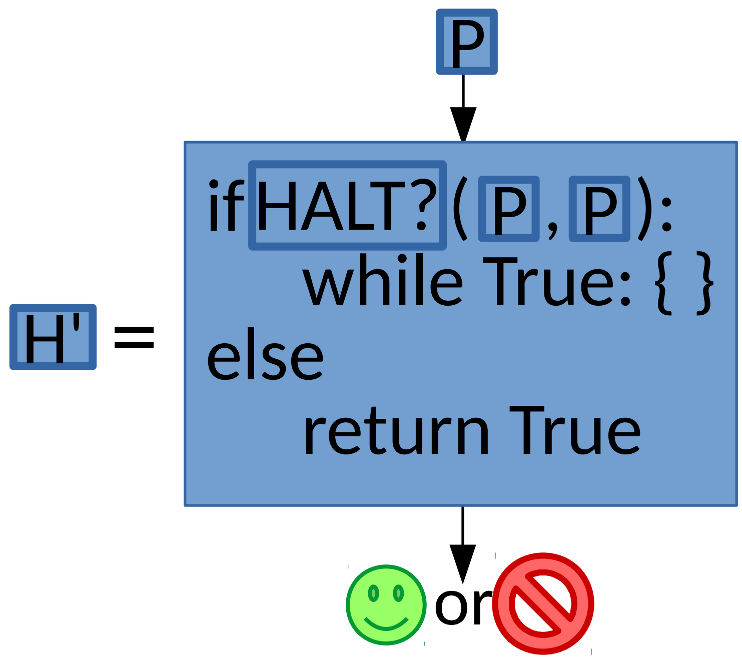

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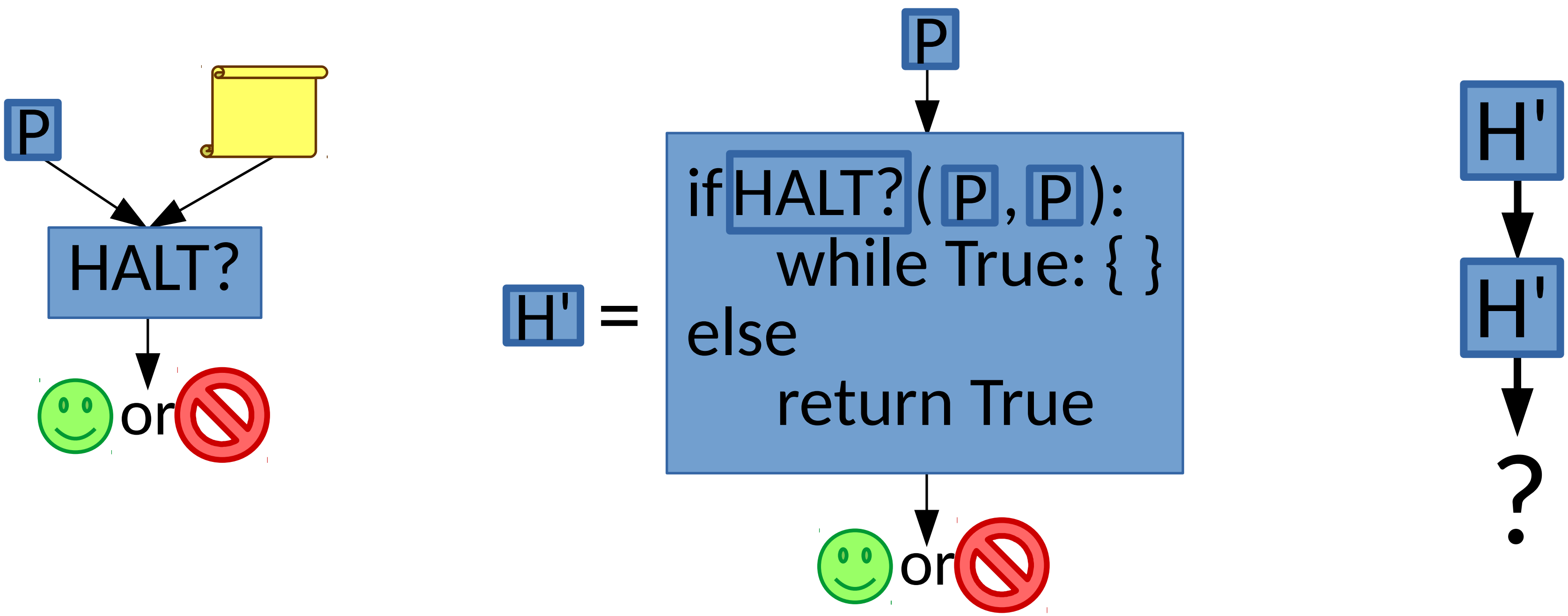

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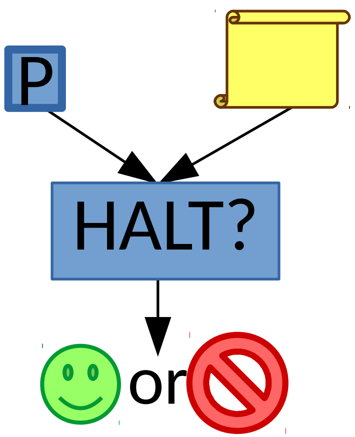

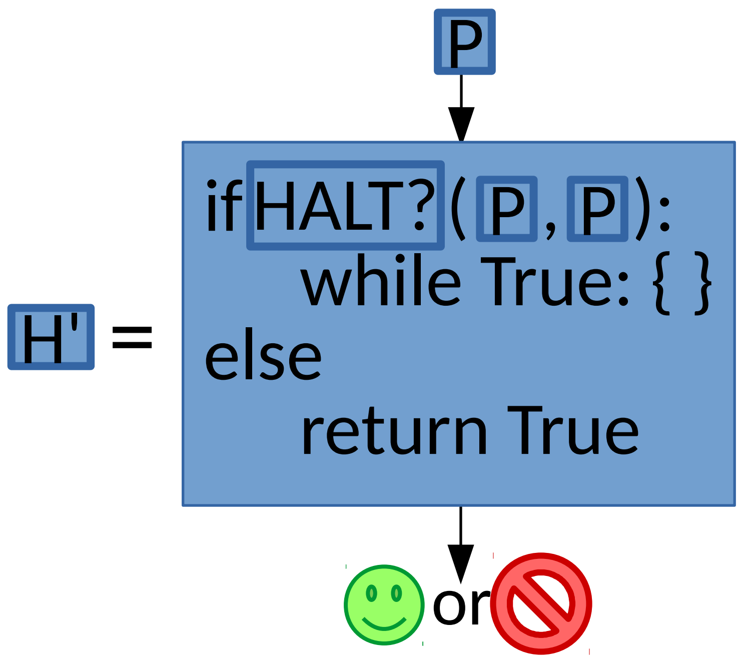

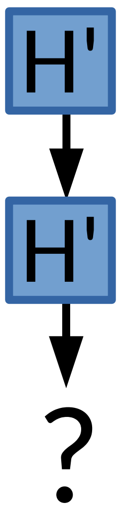

It's a classic paradox!

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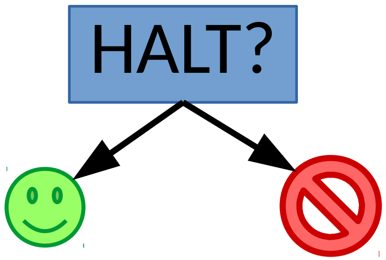

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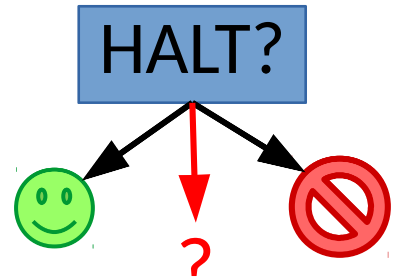

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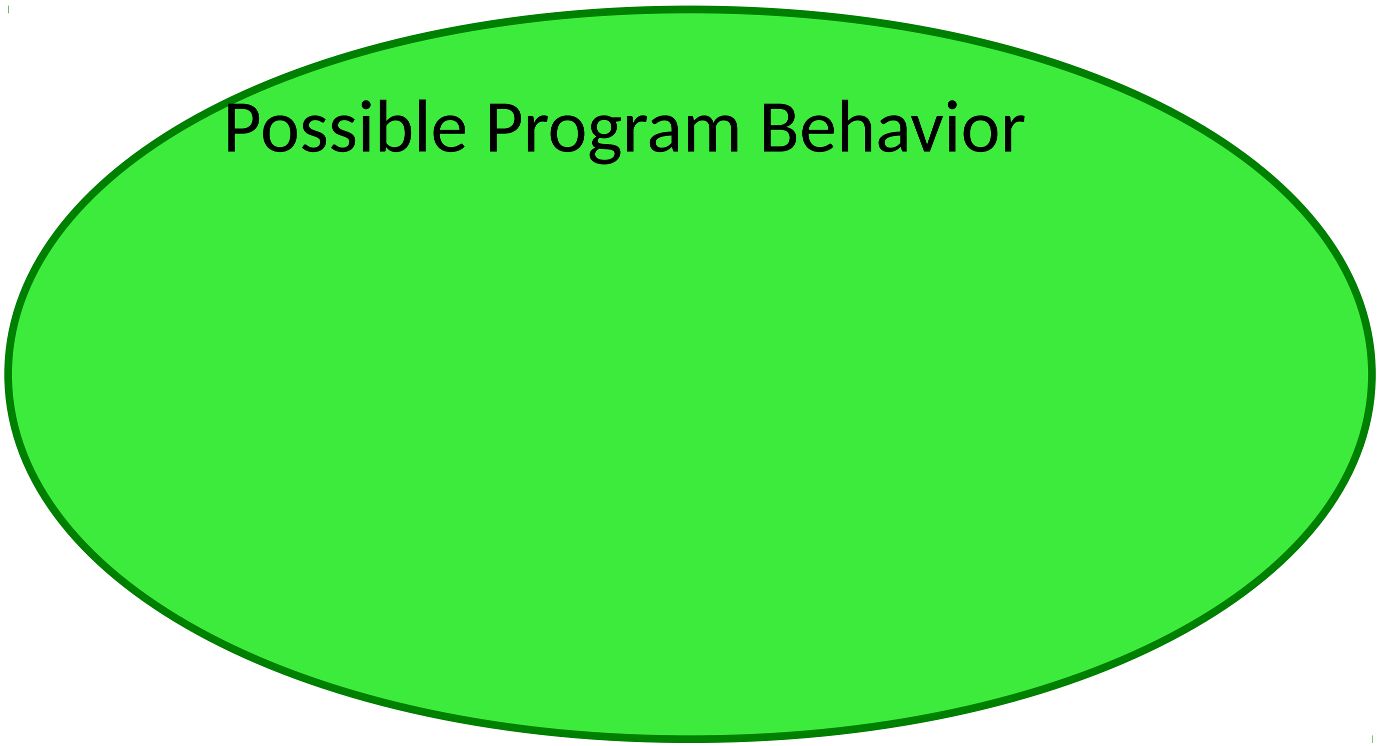
Striking the right balance is key to a useful analysis

Approximation

Modeled program behaviors



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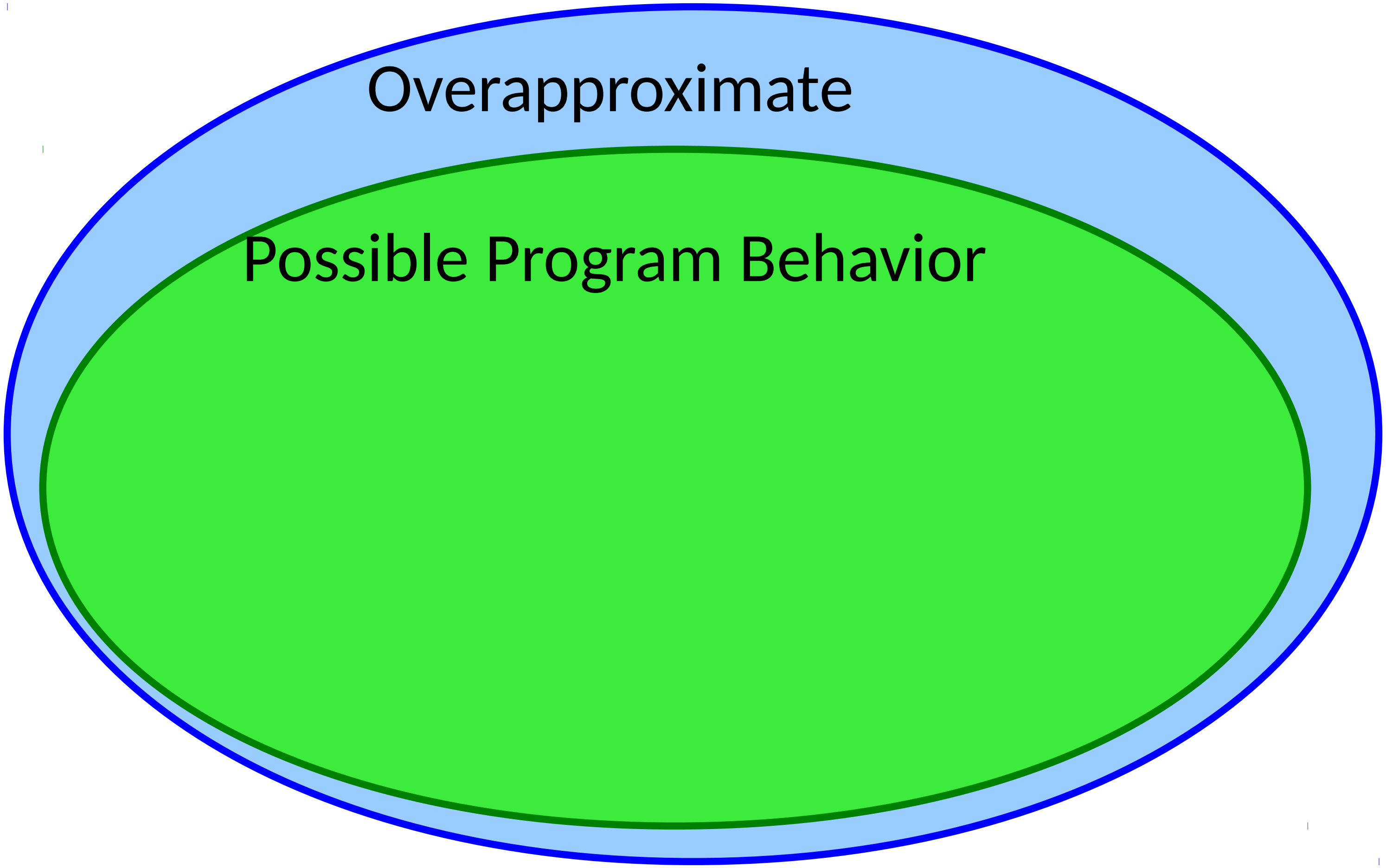

Consider some behaviors possible when they are not.

Approximation

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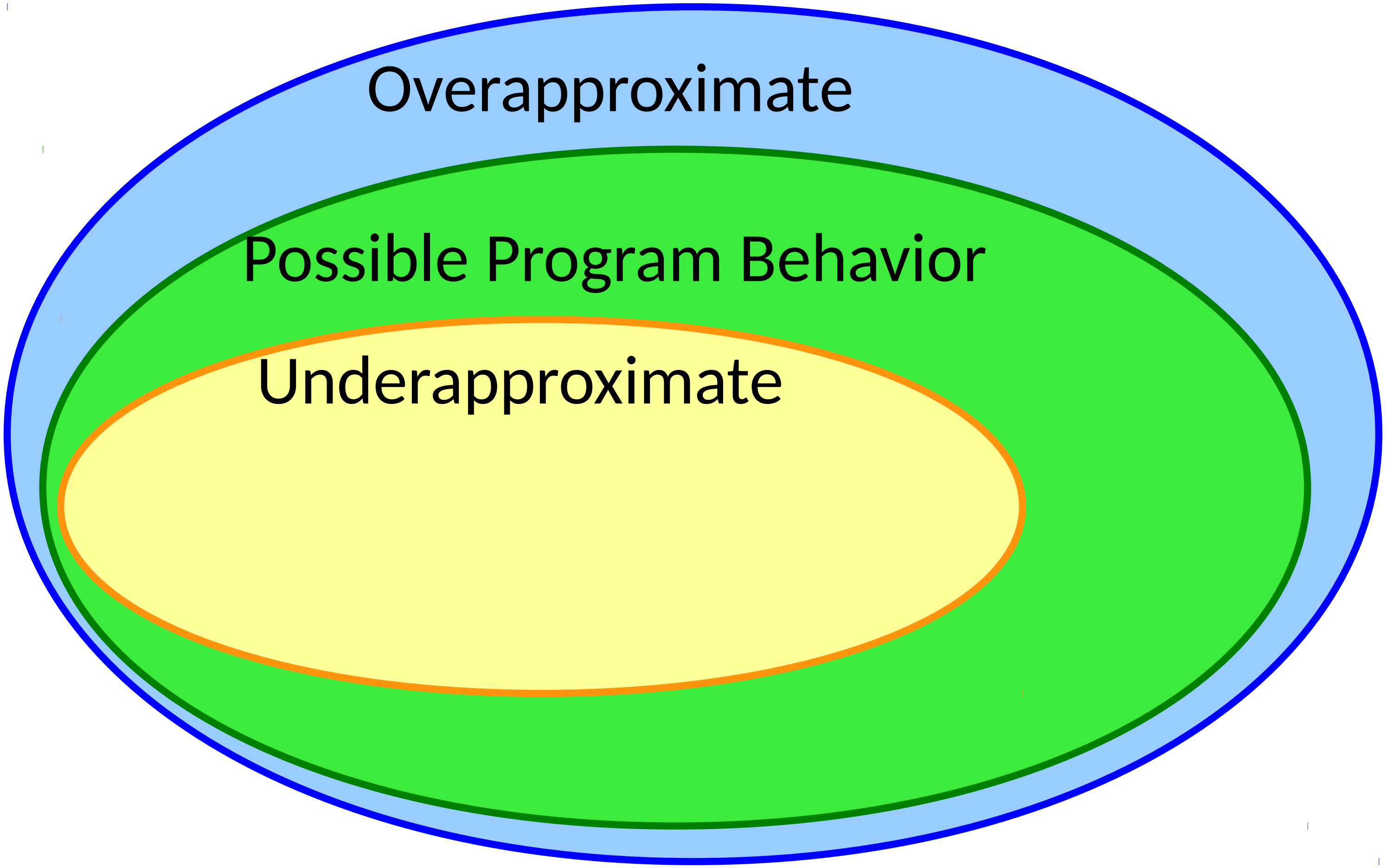
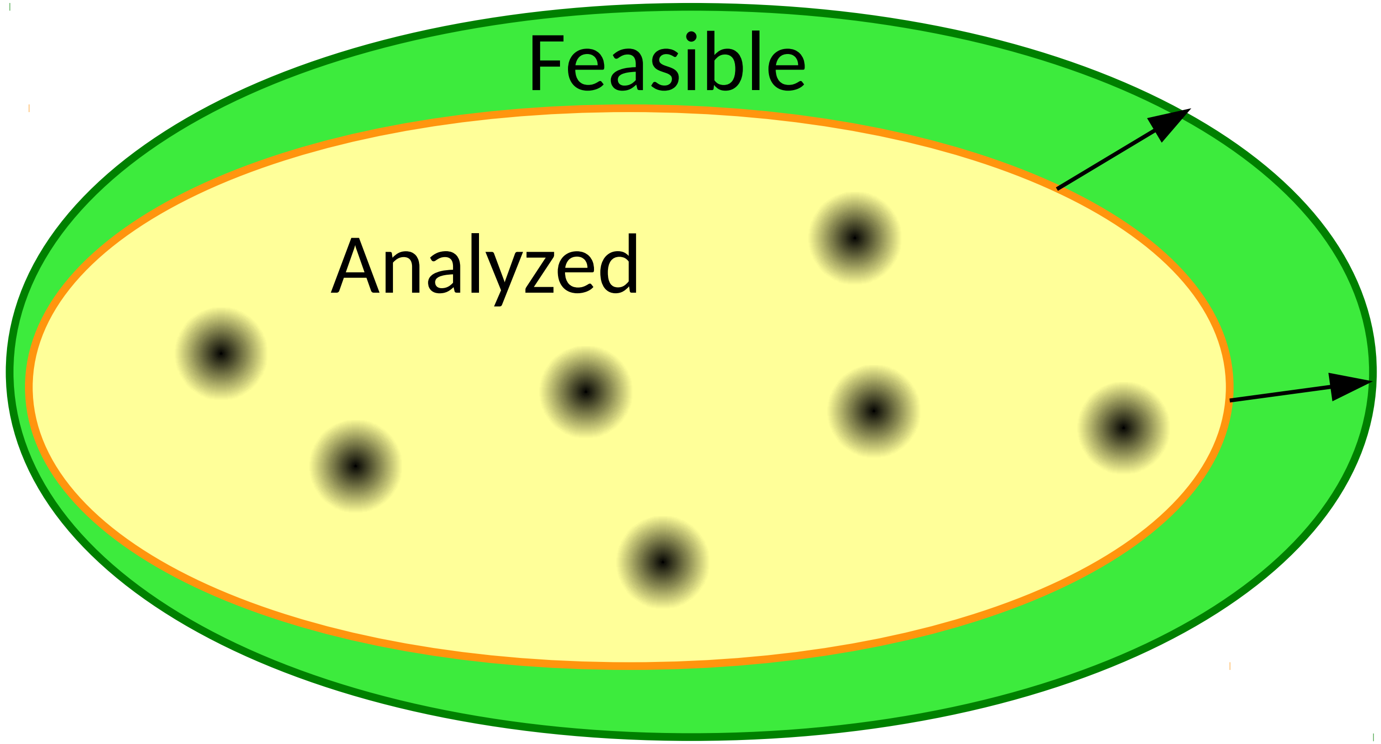


Ignore some behaviors that *are* possible.

Approximation

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



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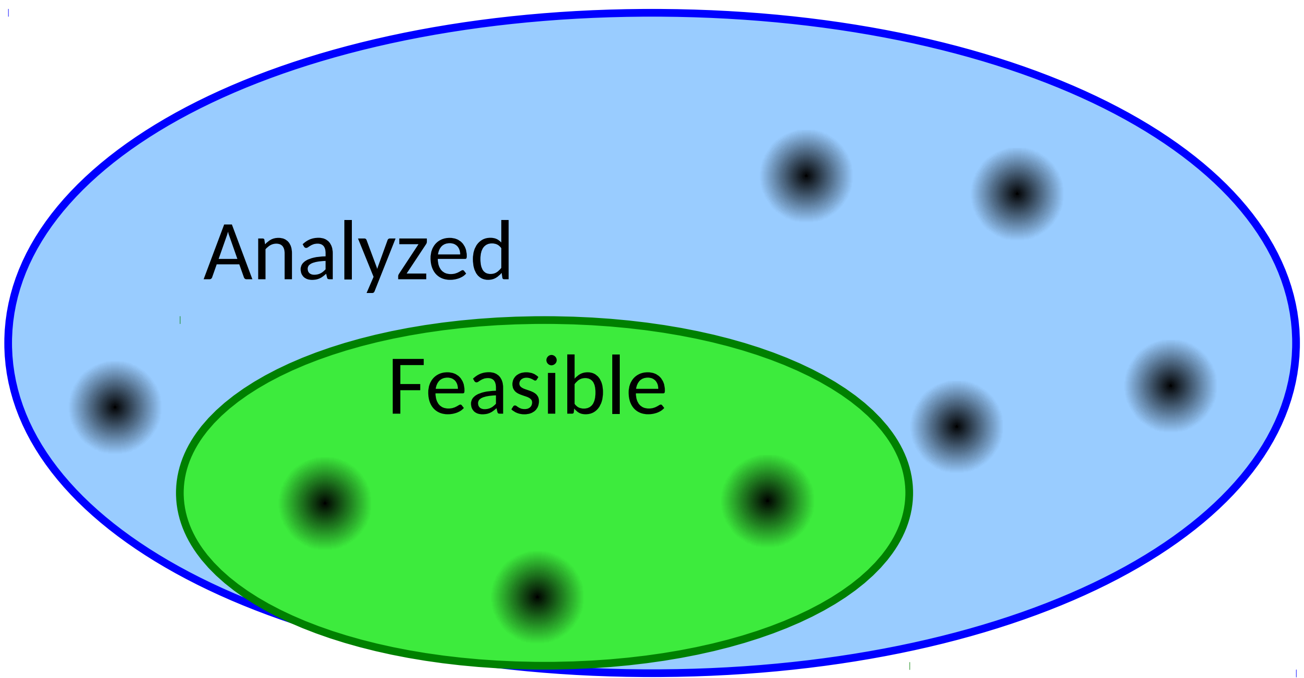

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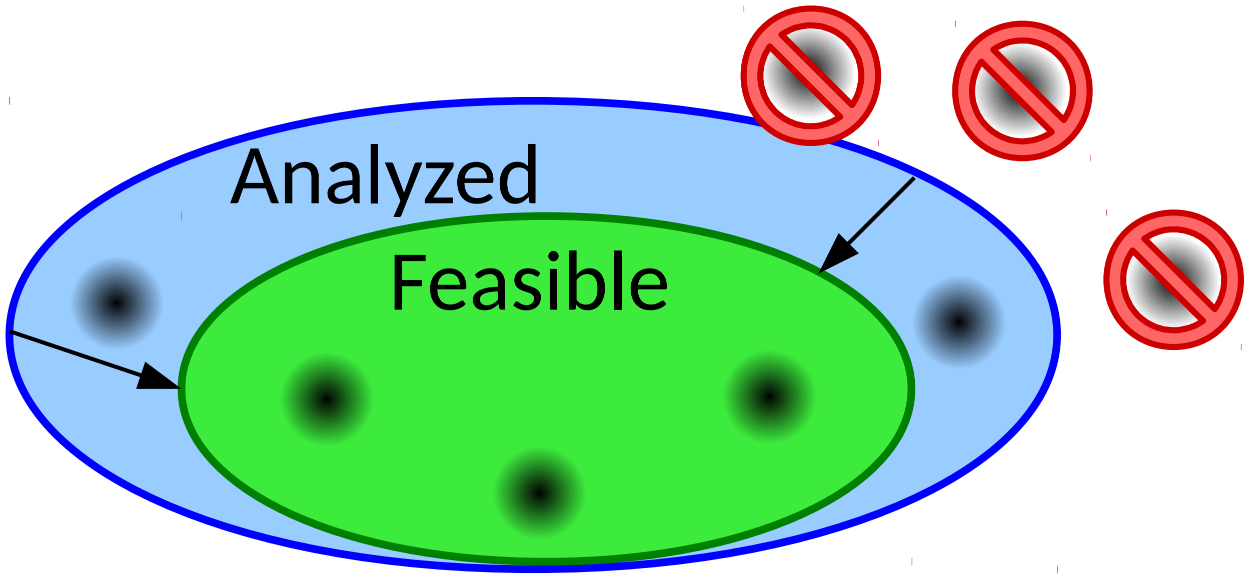

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- The two areas complement each other
  - Static analysis can help generate useful tests
  - Dynamic analysis can help identify infeasibility

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Q: Is a particular number ever negative?

- Might be an offset into invalid memory!

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concrete(x) = 5 $\mapsto$ abstract(x) = +
concrete(y) = -3 $\mapsto$ abstract(y) = -
concrete(z) = 0 $\mapsto$ 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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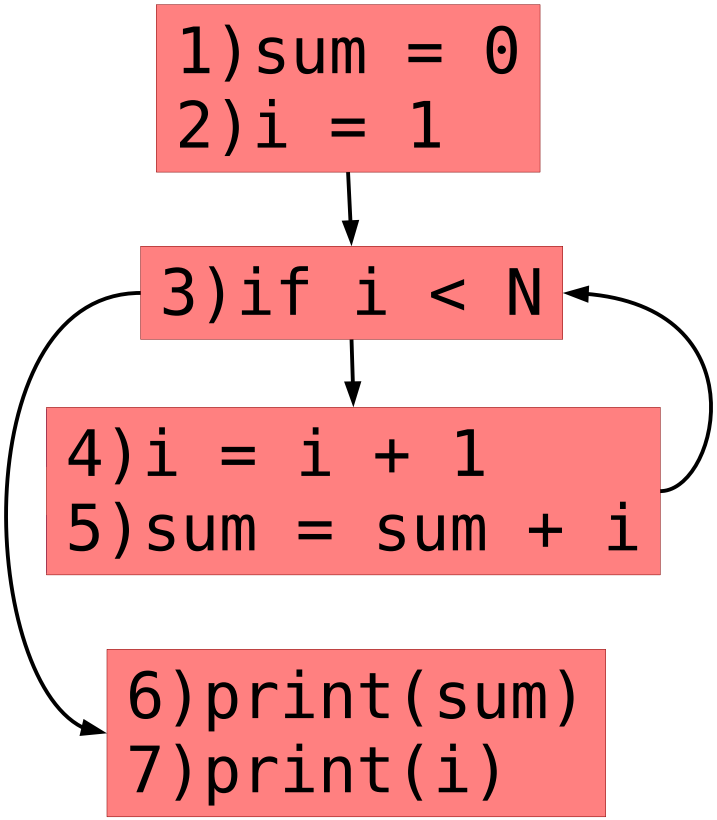

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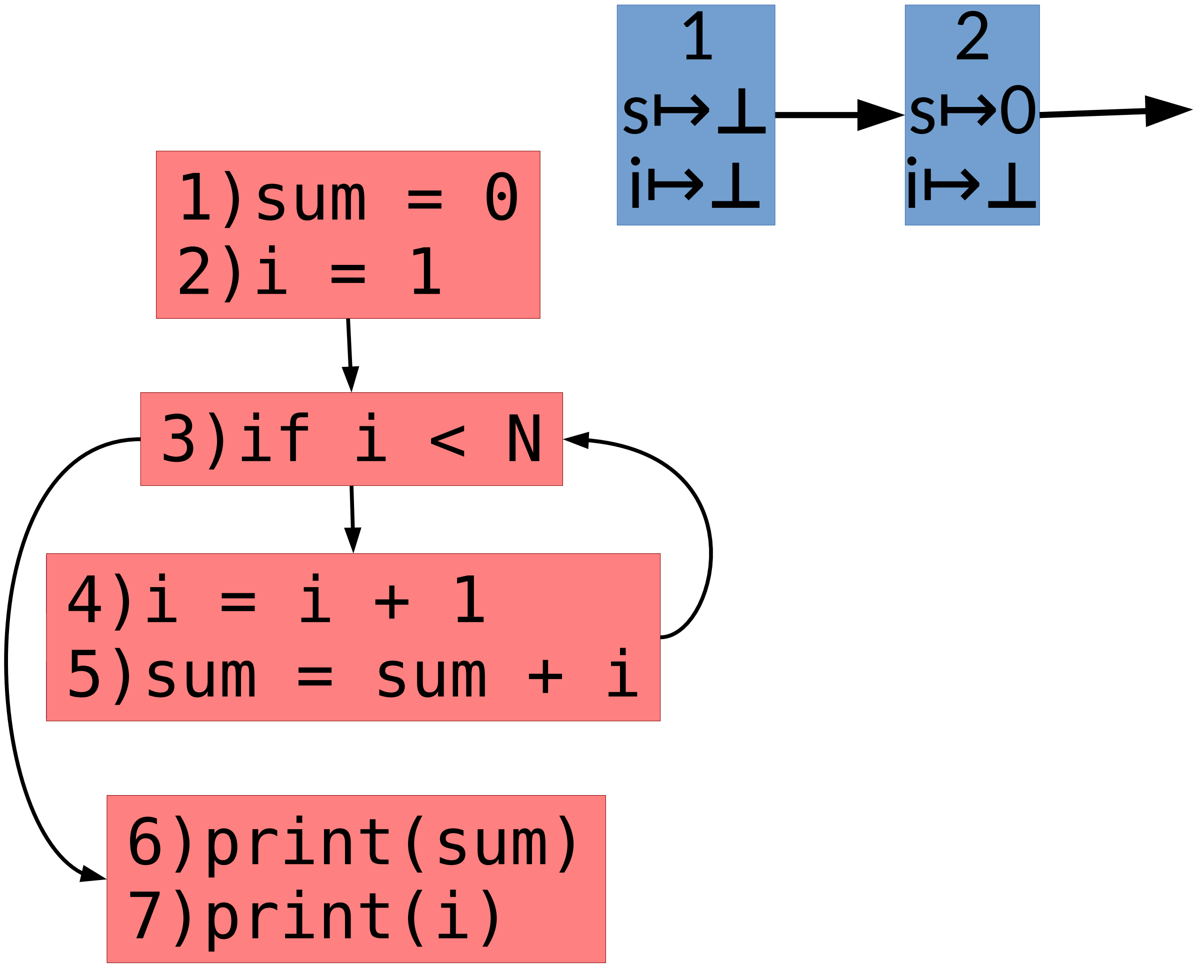

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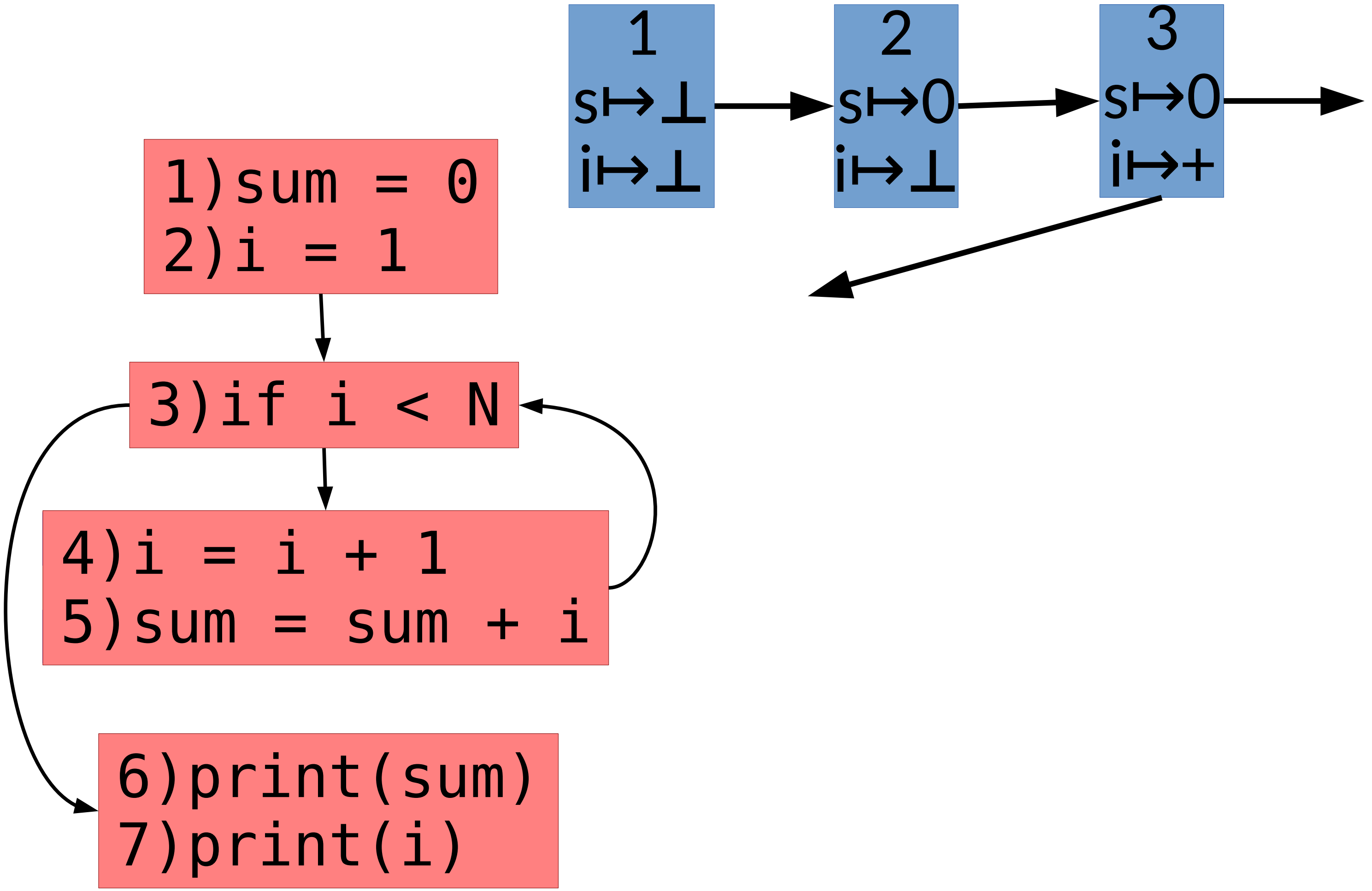

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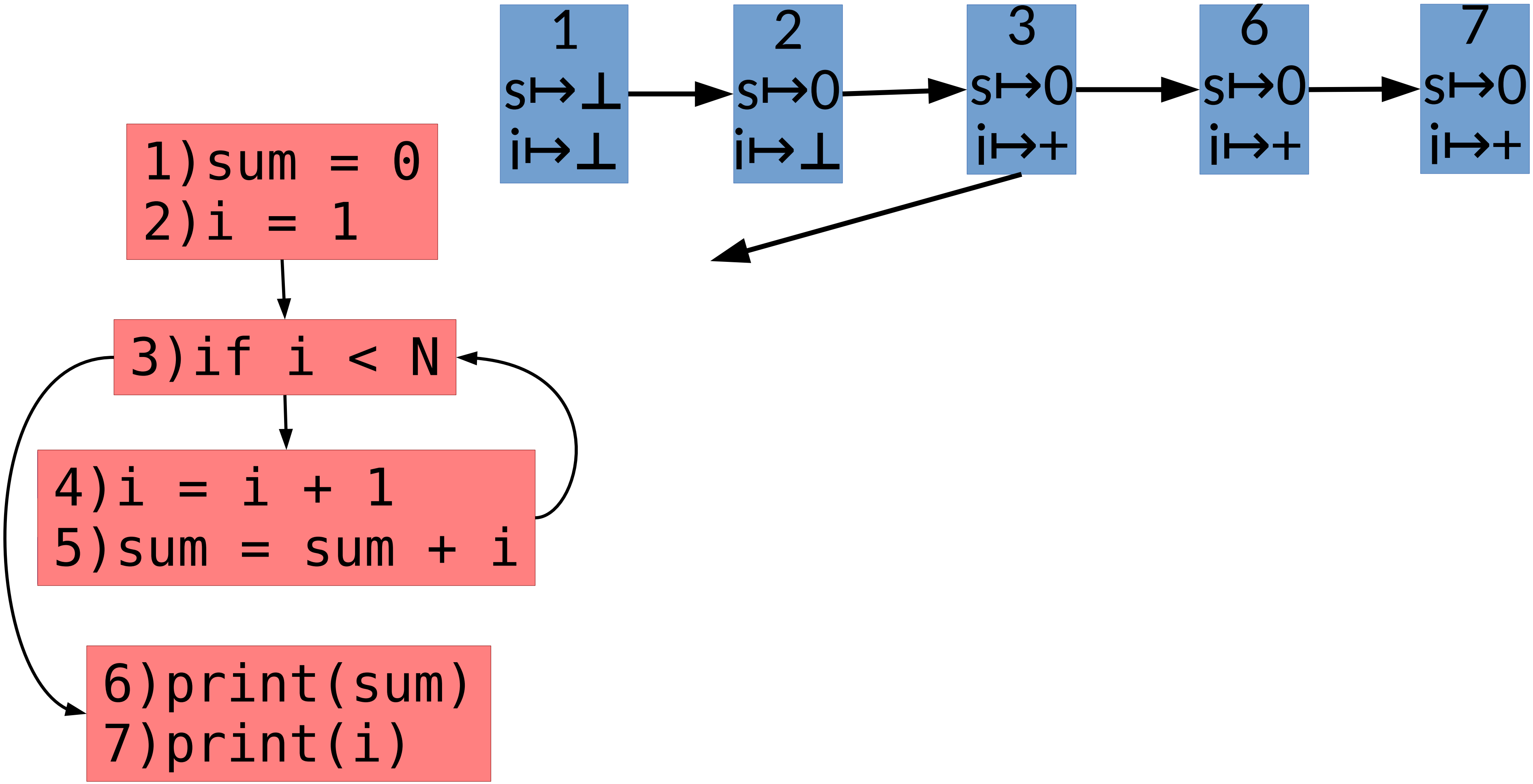

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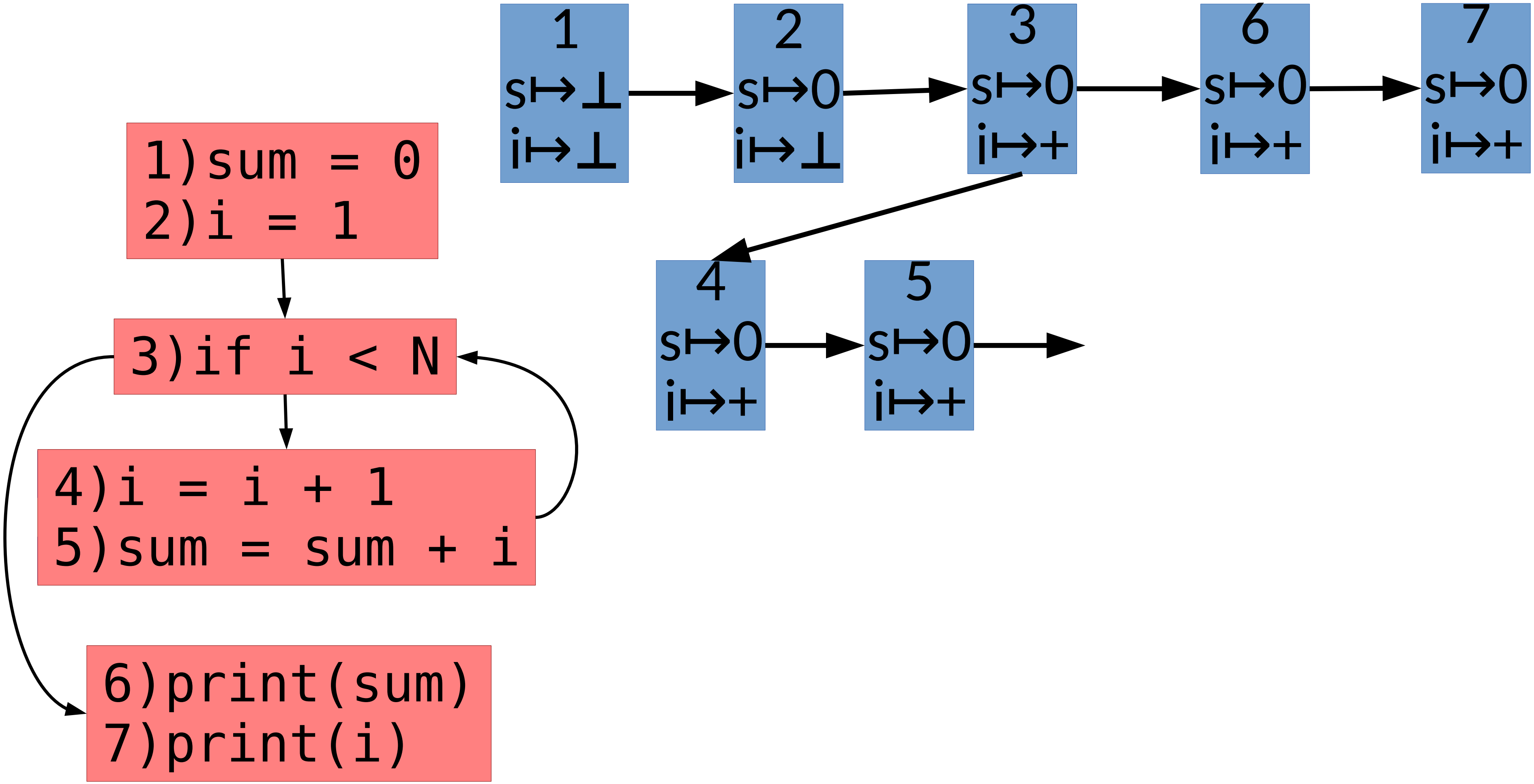

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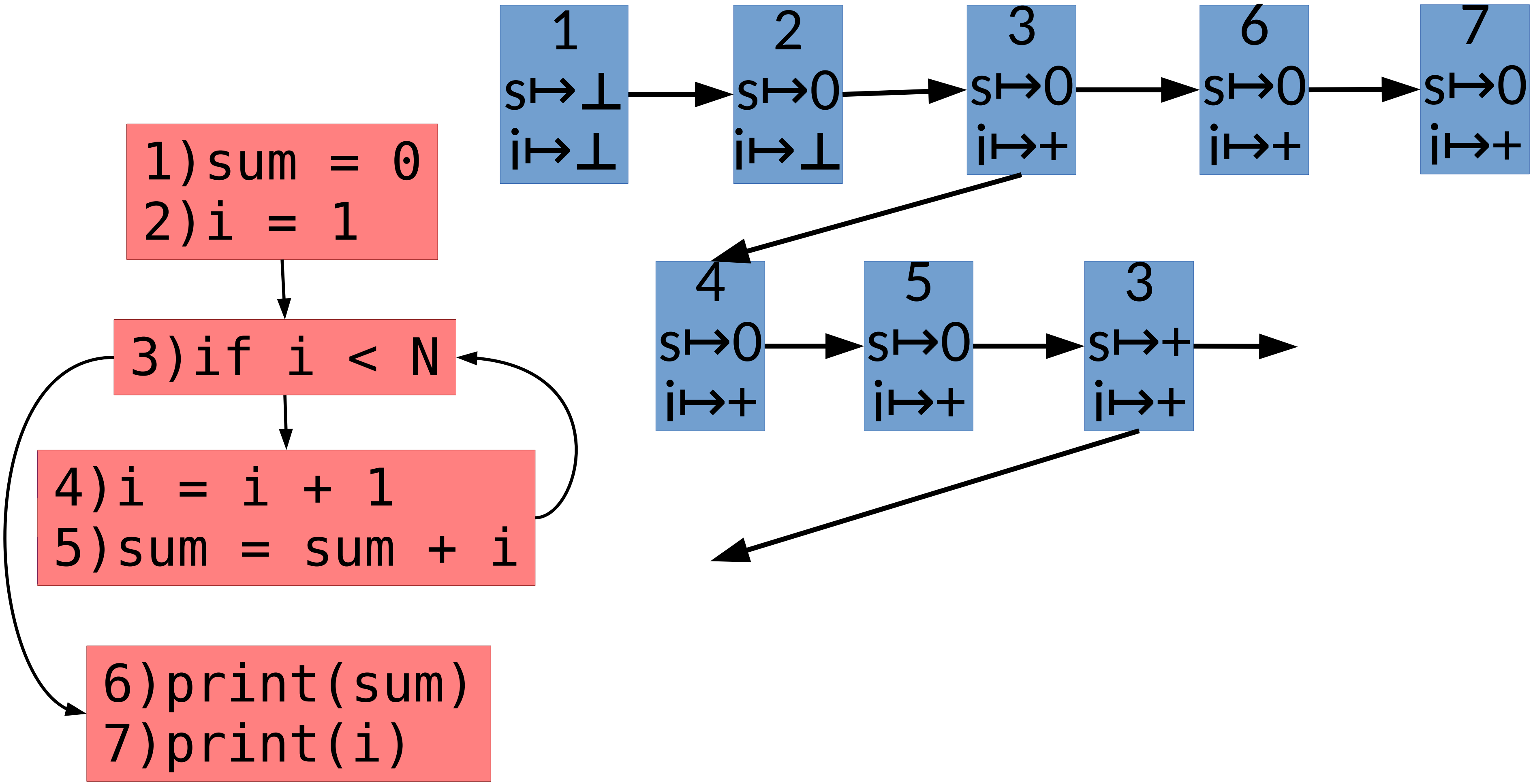

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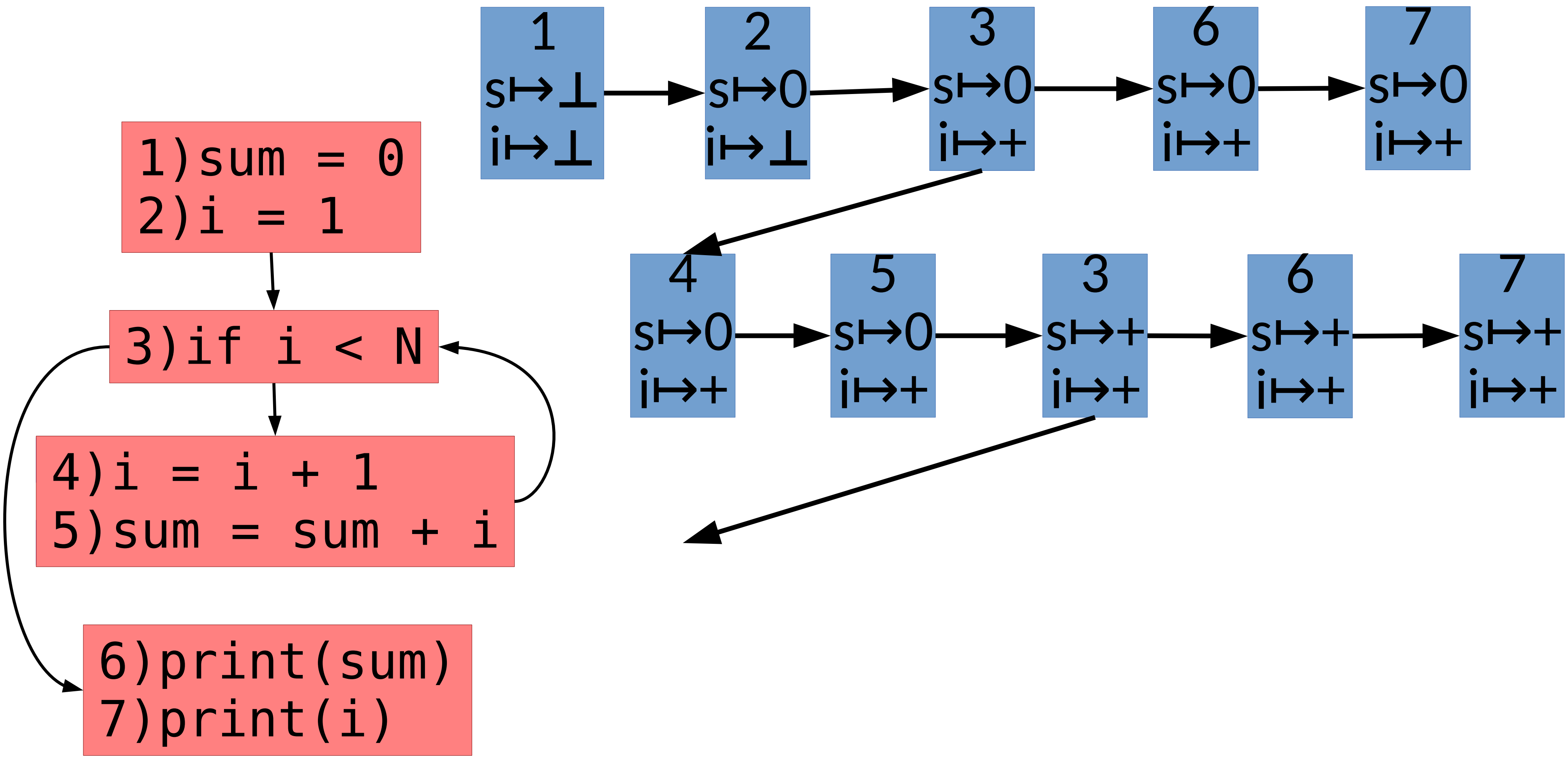

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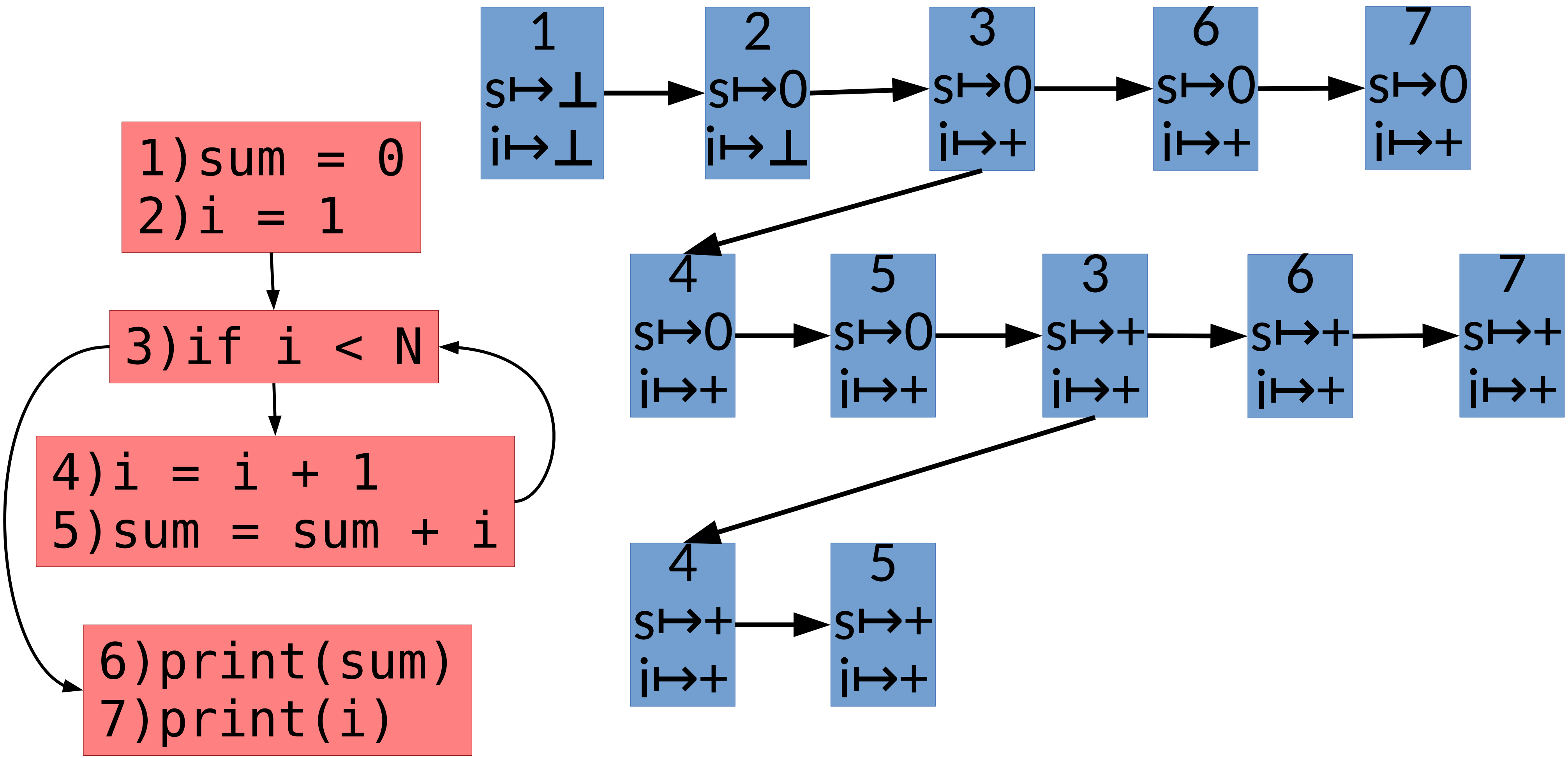

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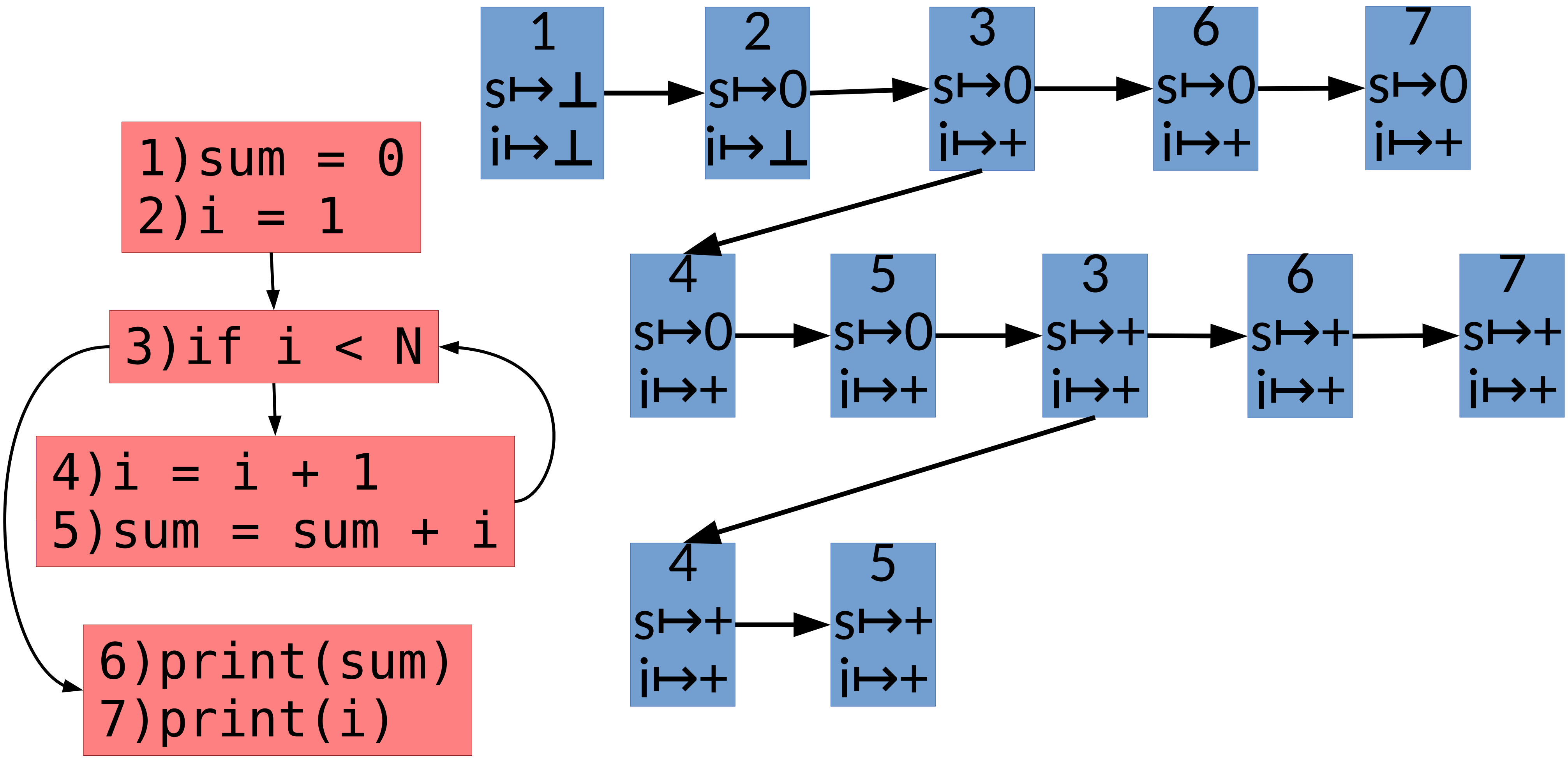

Does the process ever end?

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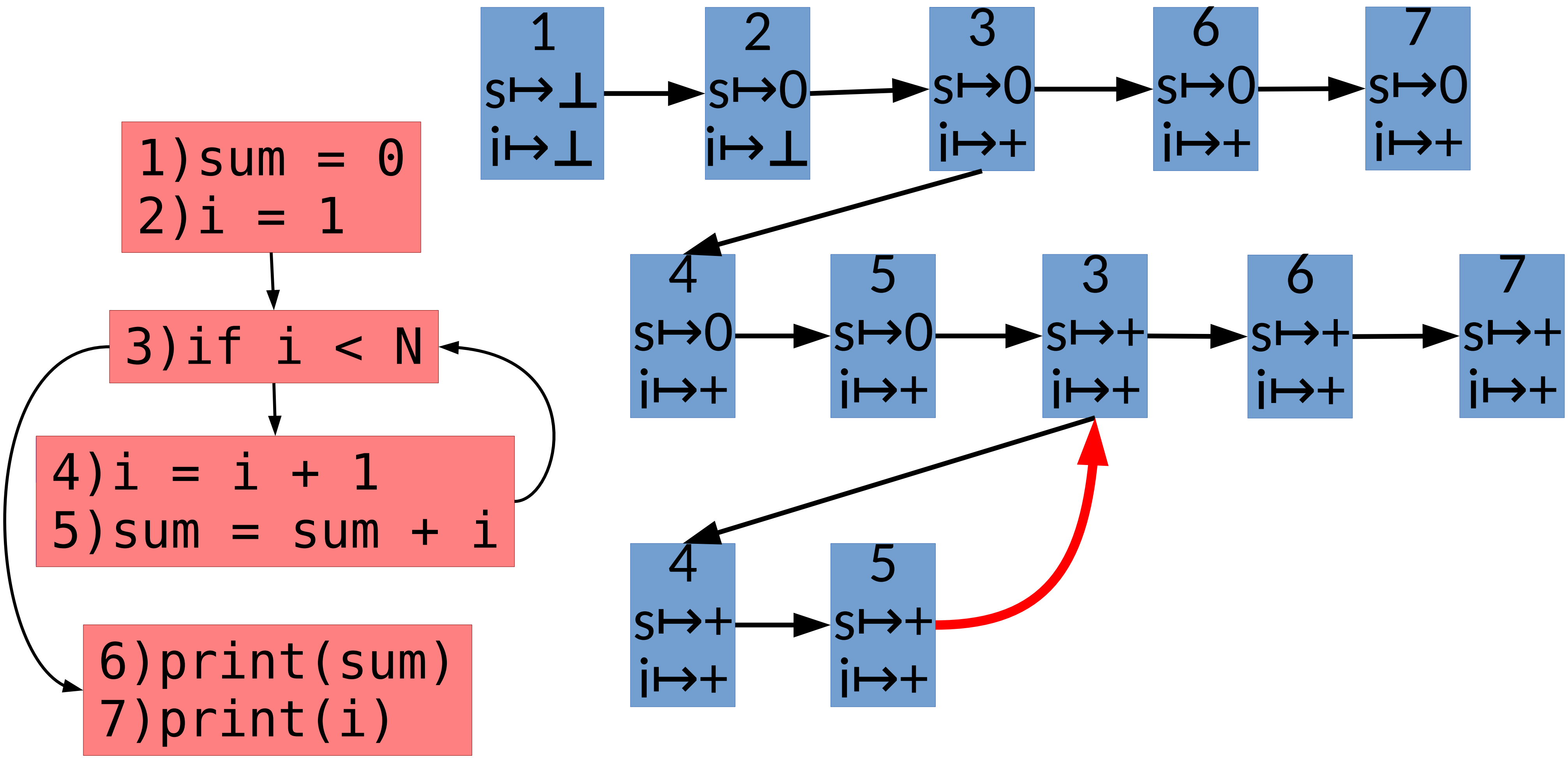

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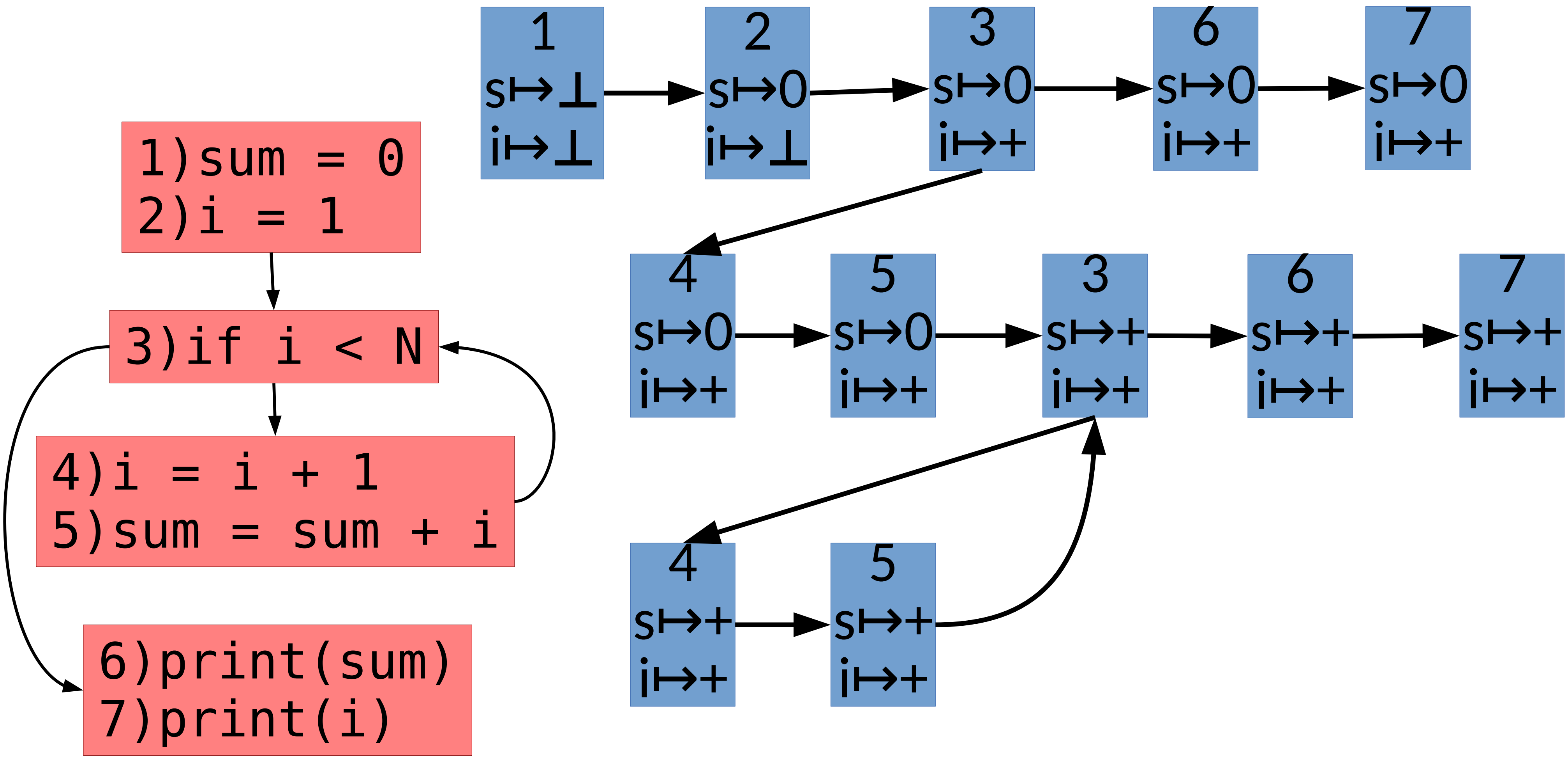

Can the final sum ever be negative?

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  Loosely: <CFG, Transfer Function, Lattice Abstraction>

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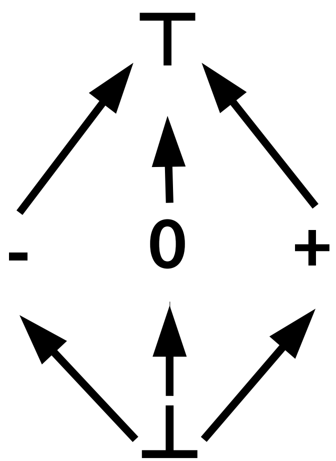

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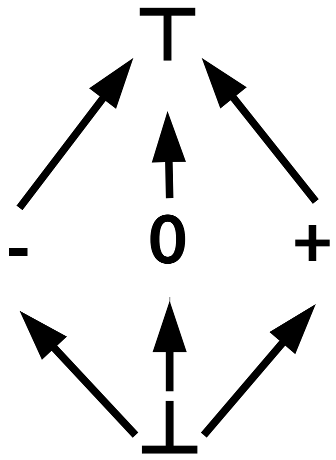

Why does this specific example terminate?

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- But in theory a lattice need not be finite!

  (ranges/intervals, linear constraints, …)

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  - Widening operators can still make it feasible (e.g., heuristically raise to $\top$)

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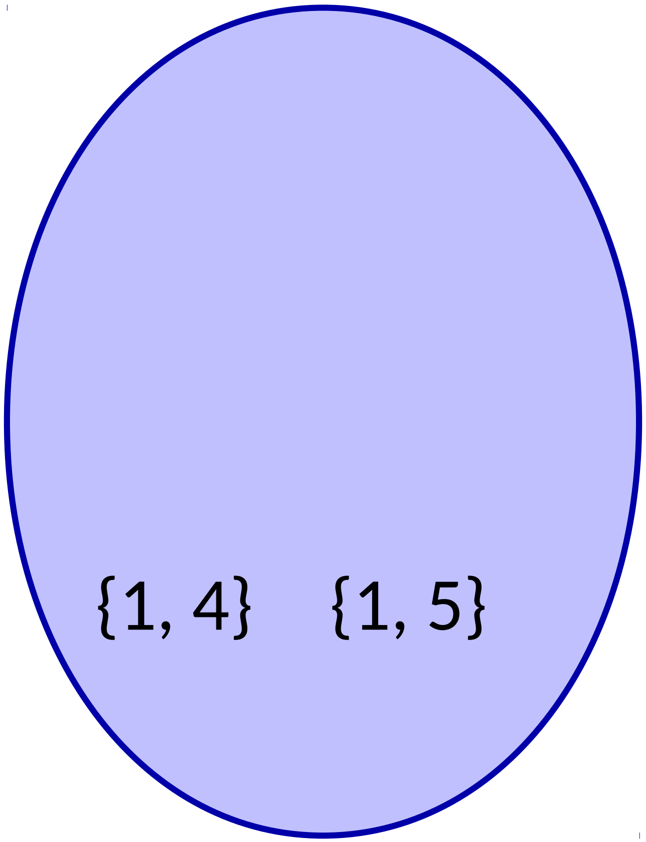

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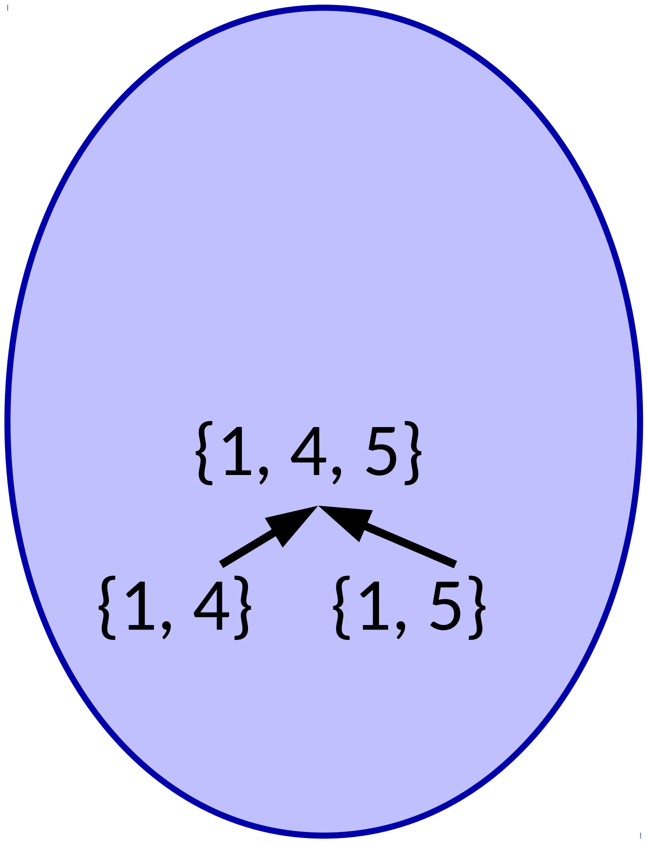

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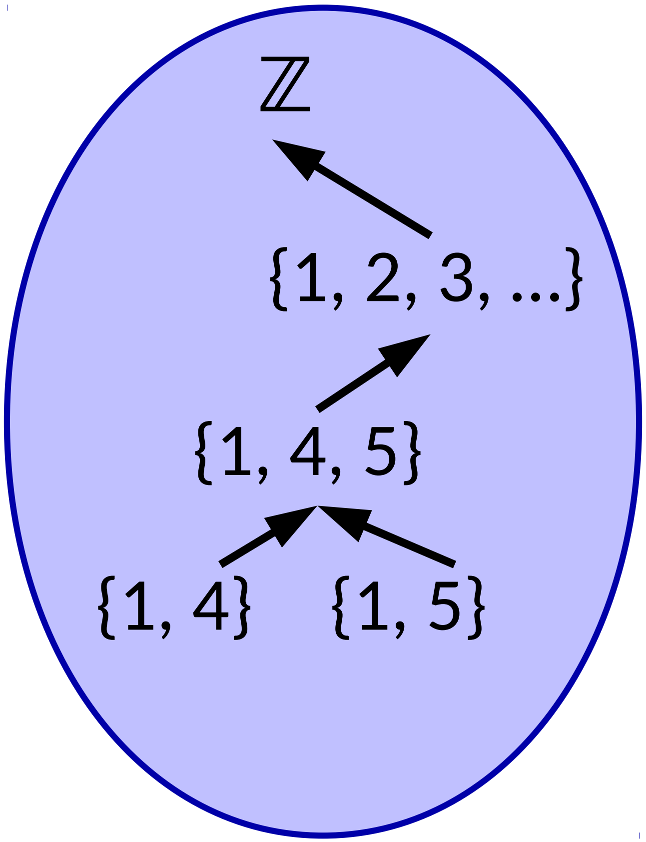

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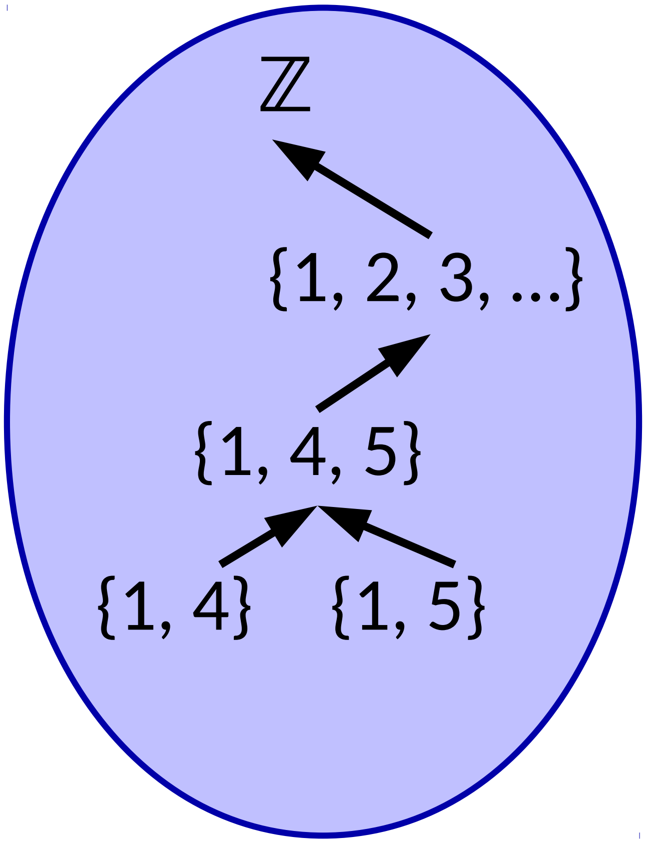

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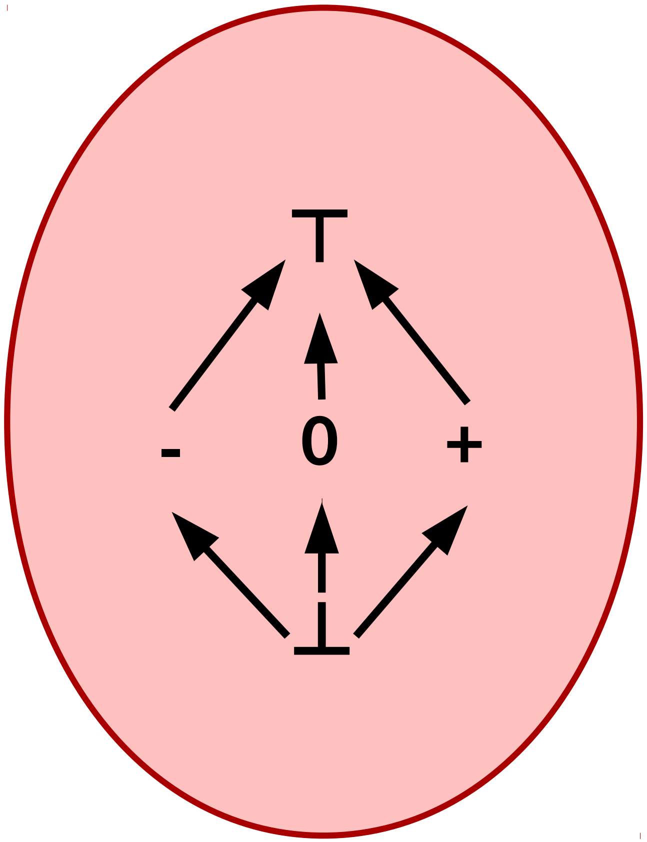

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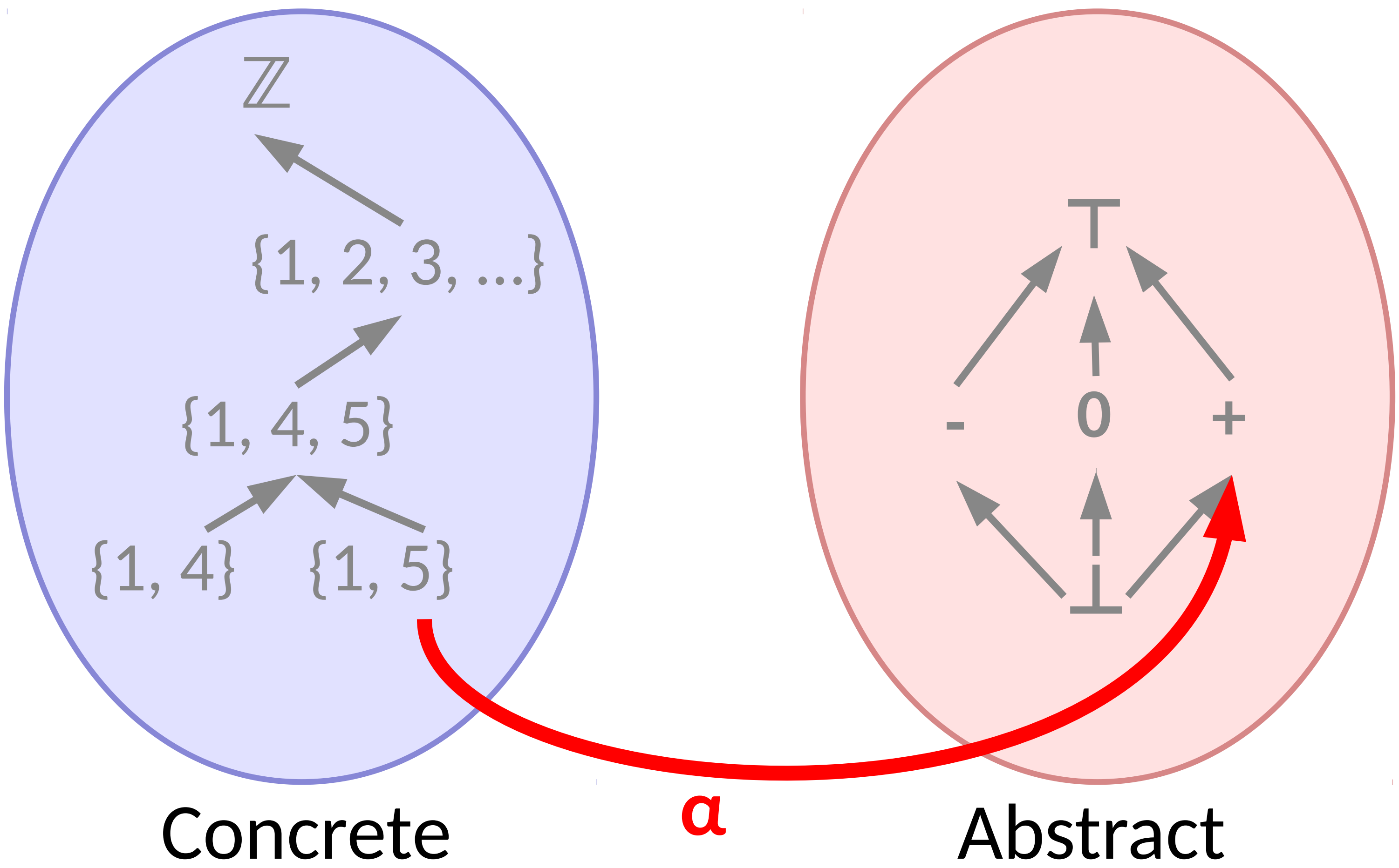

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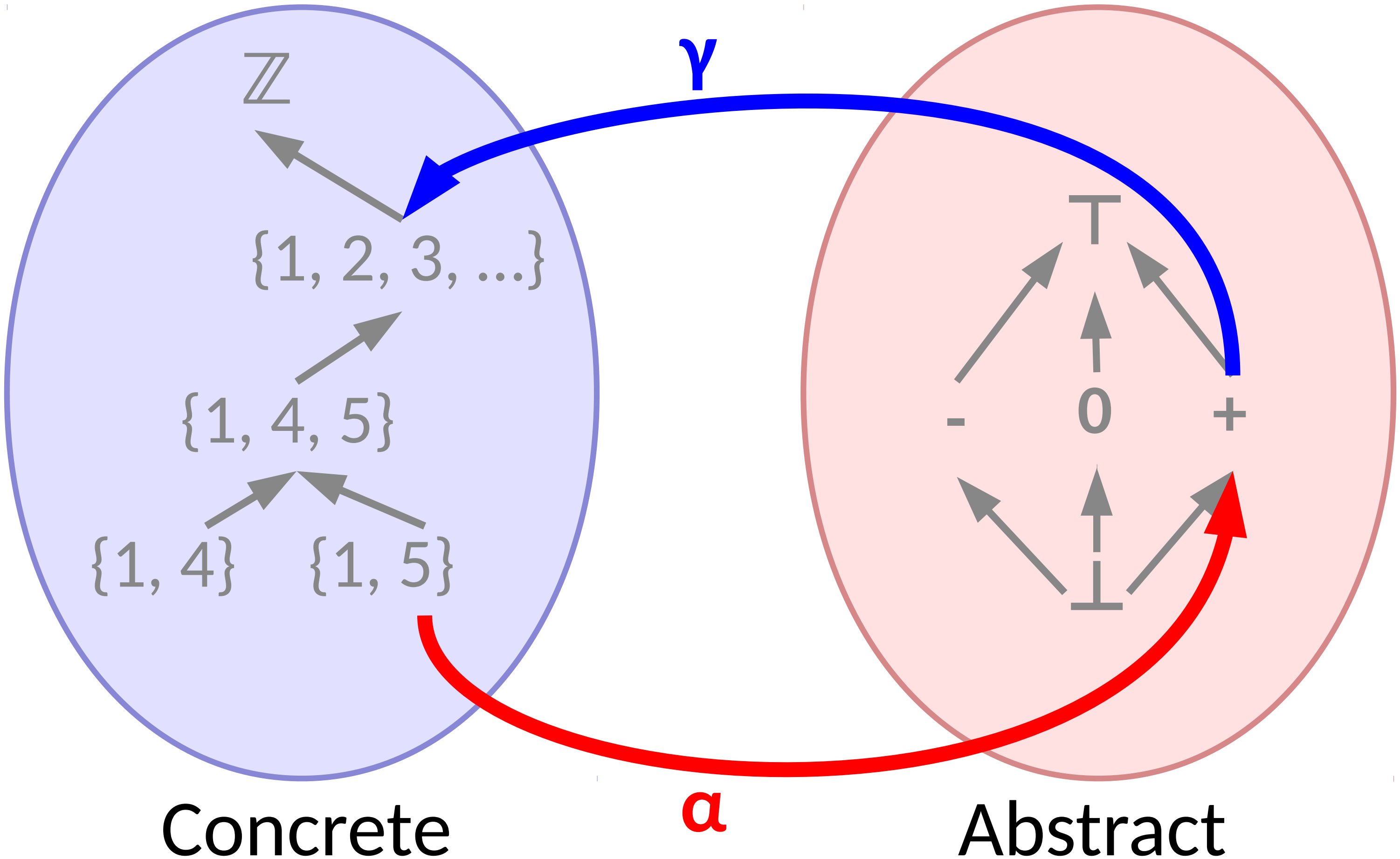

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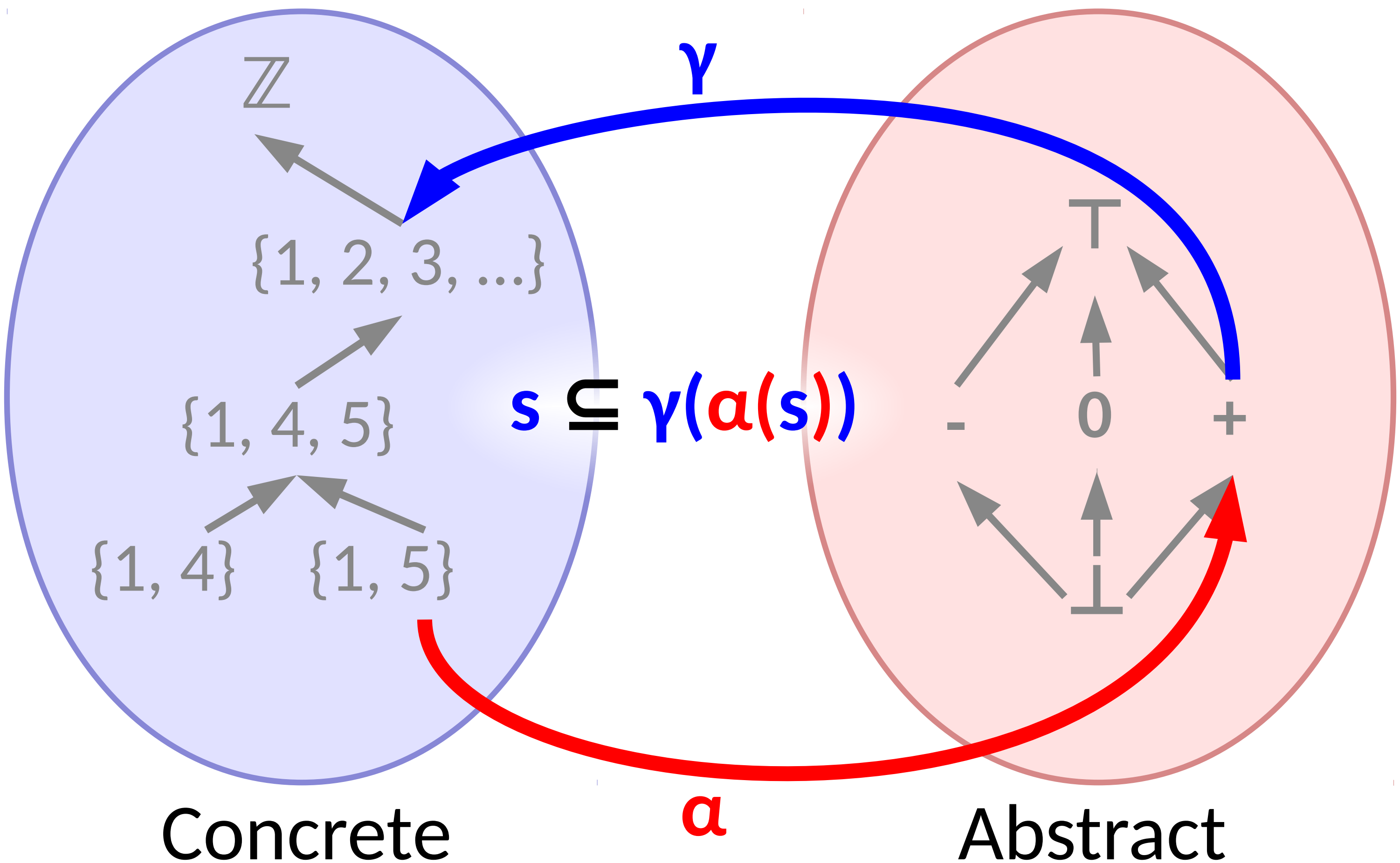

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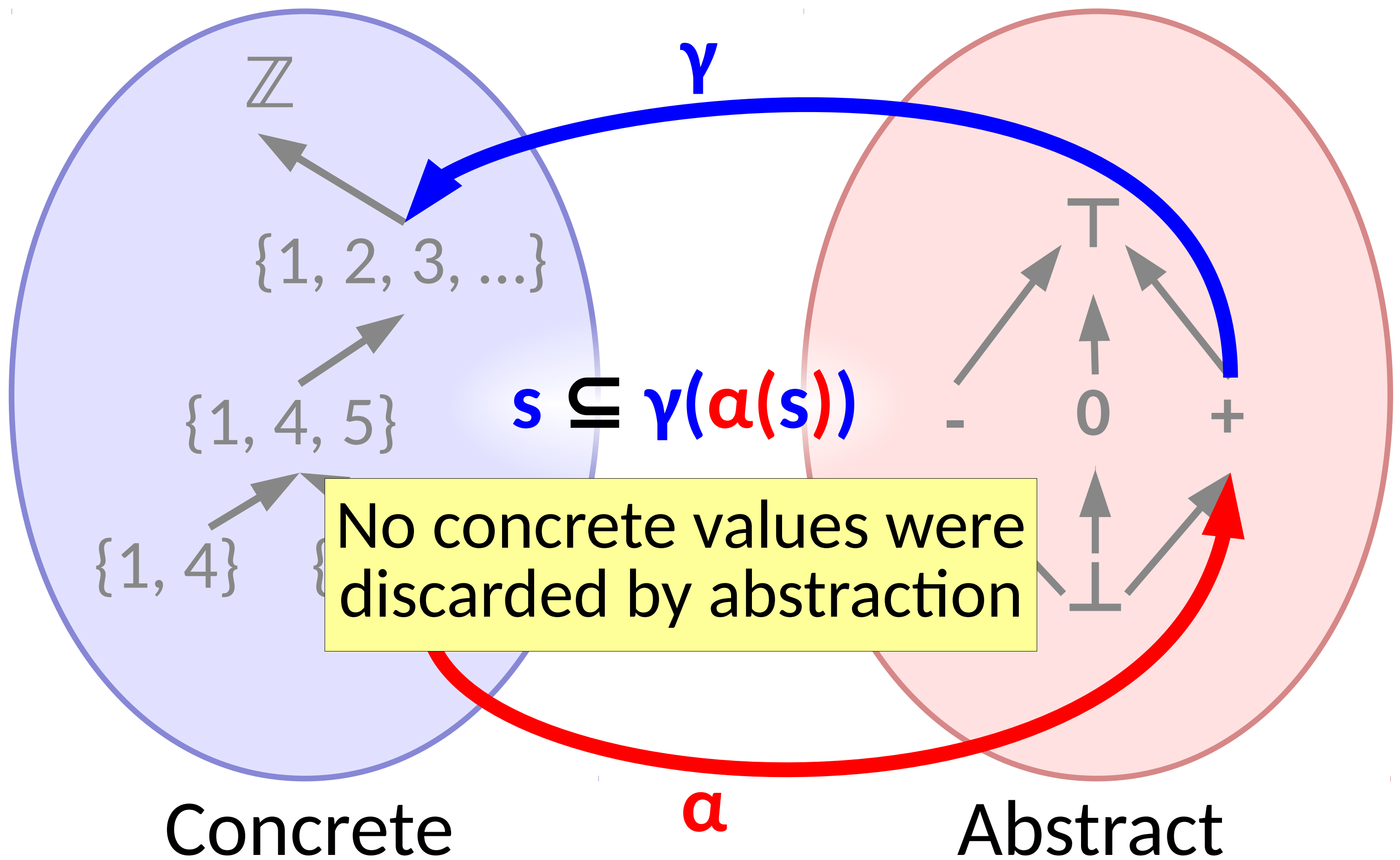

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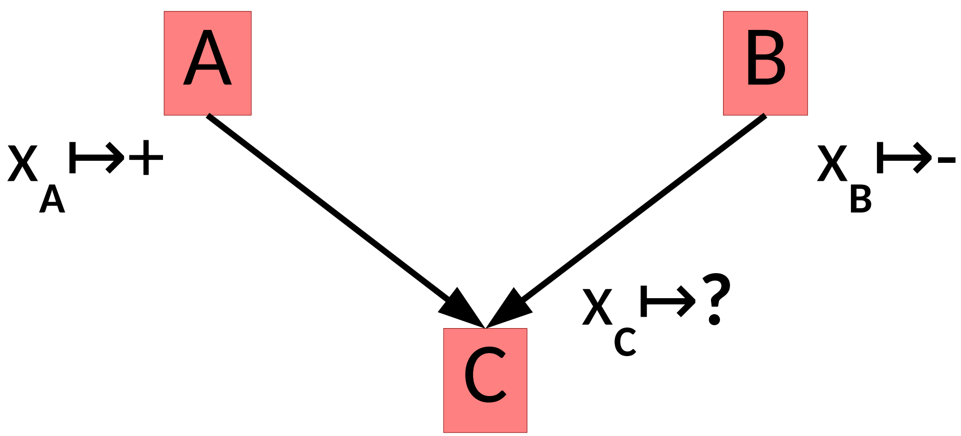

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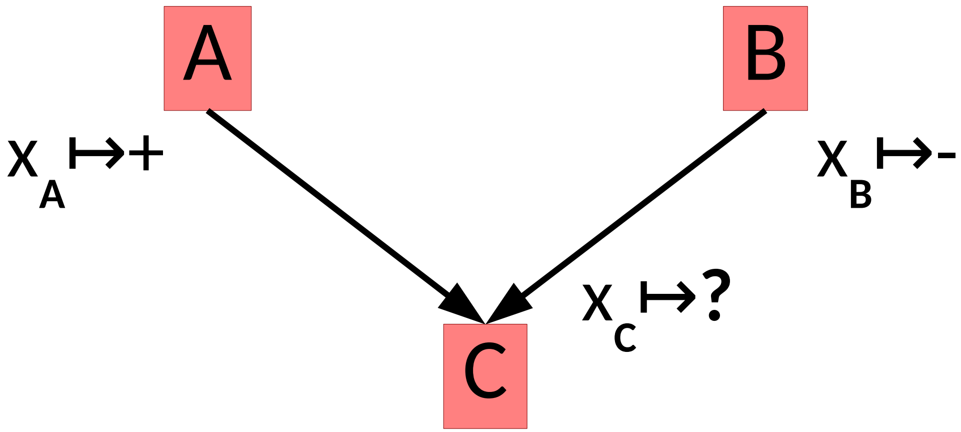

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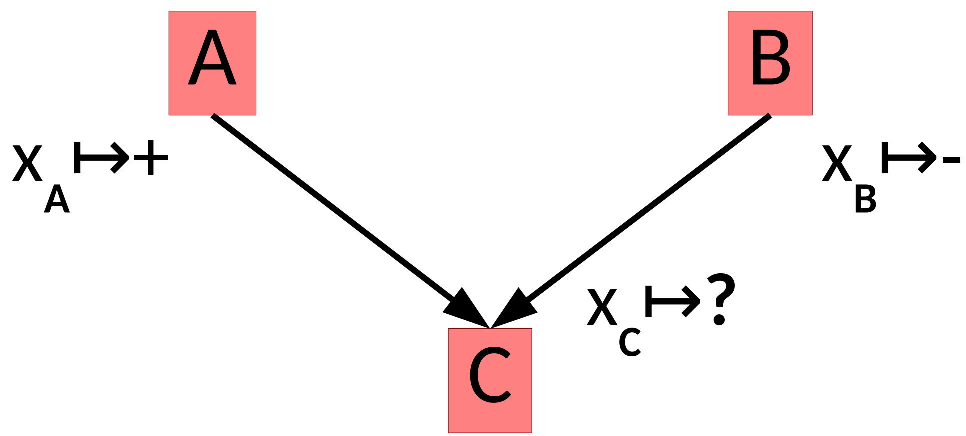

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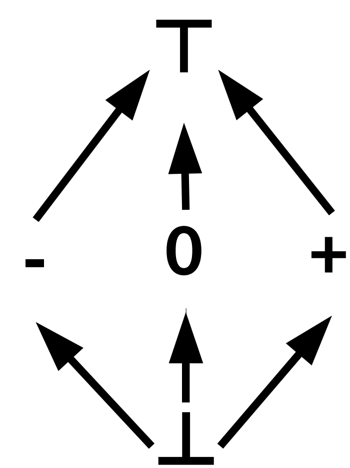

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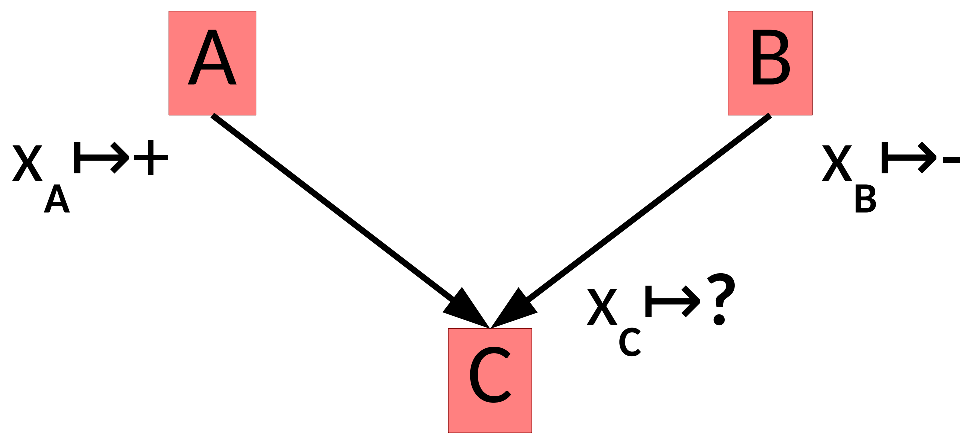

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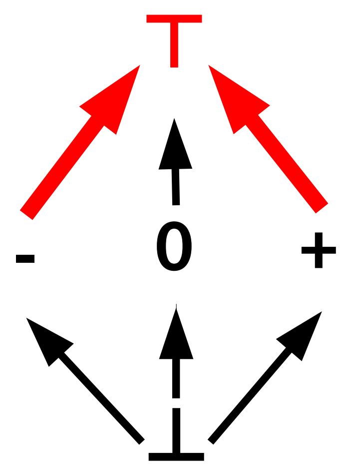

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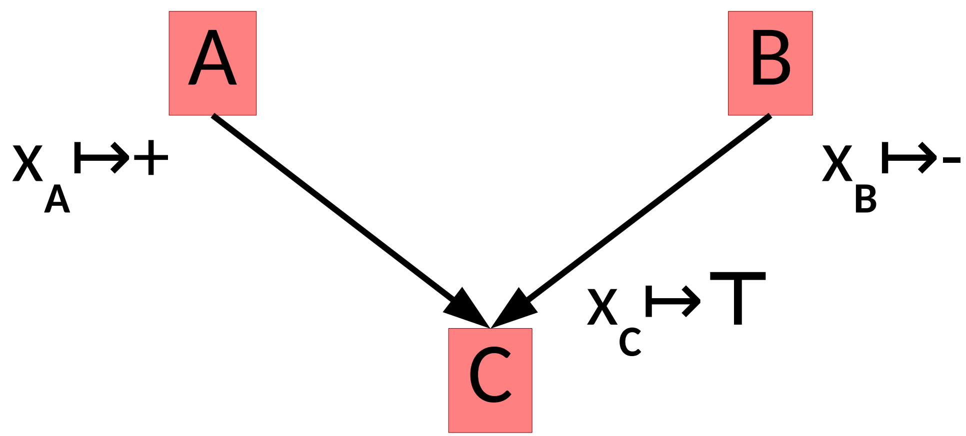

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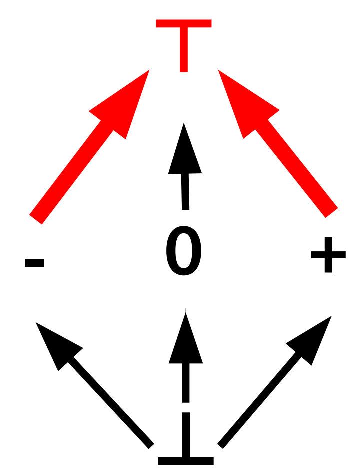

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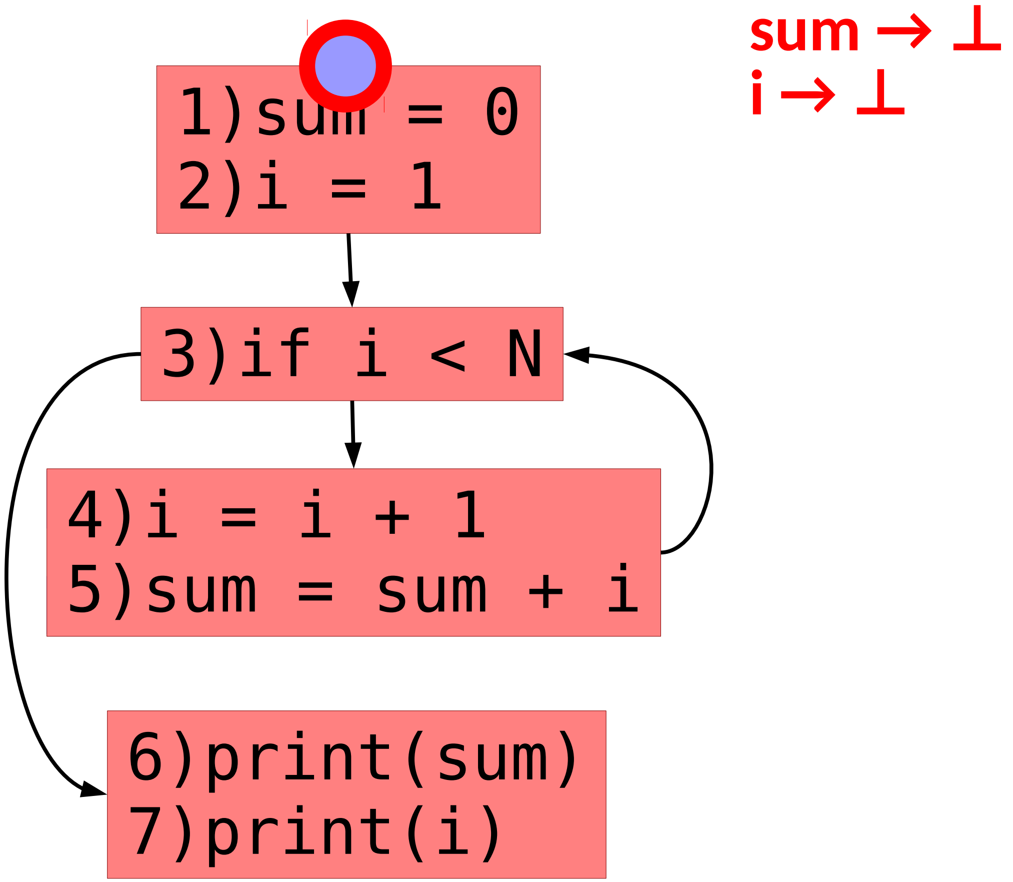

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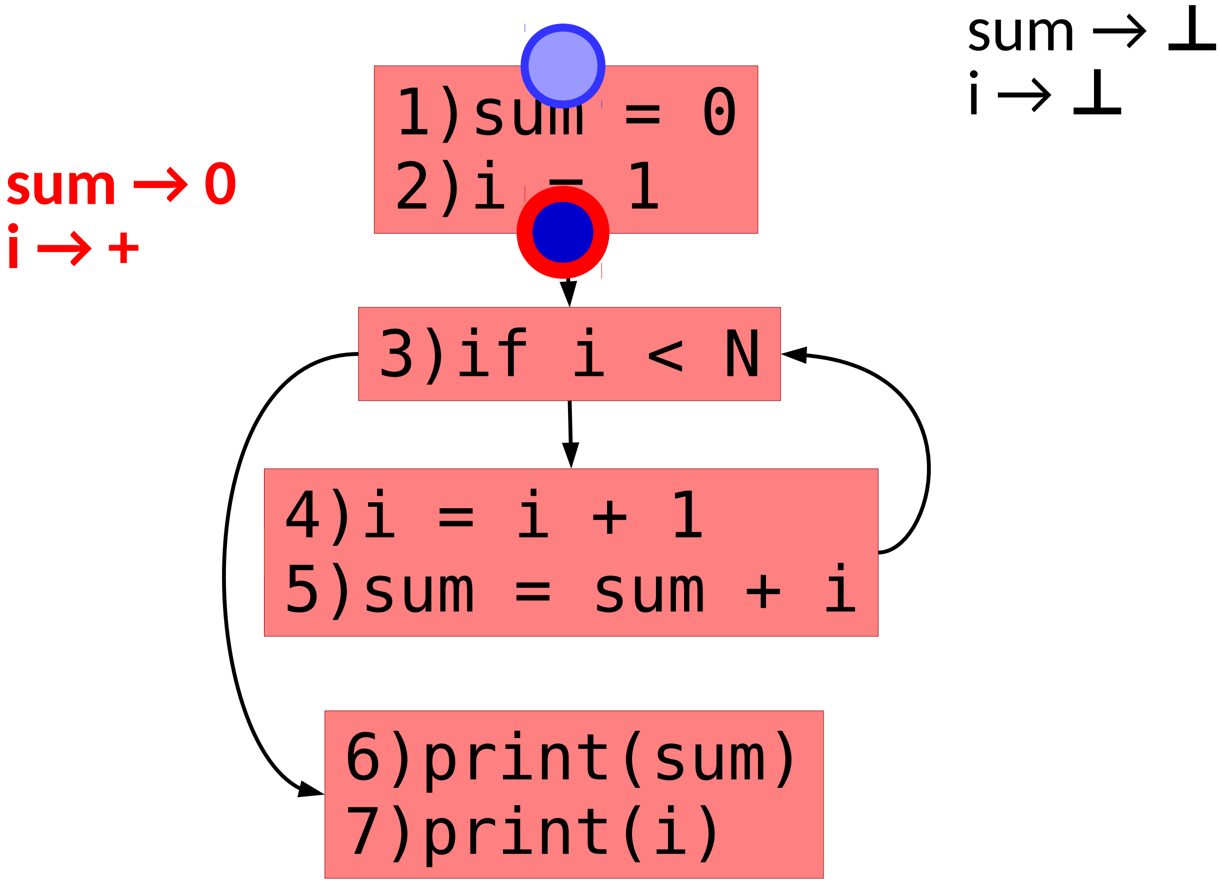

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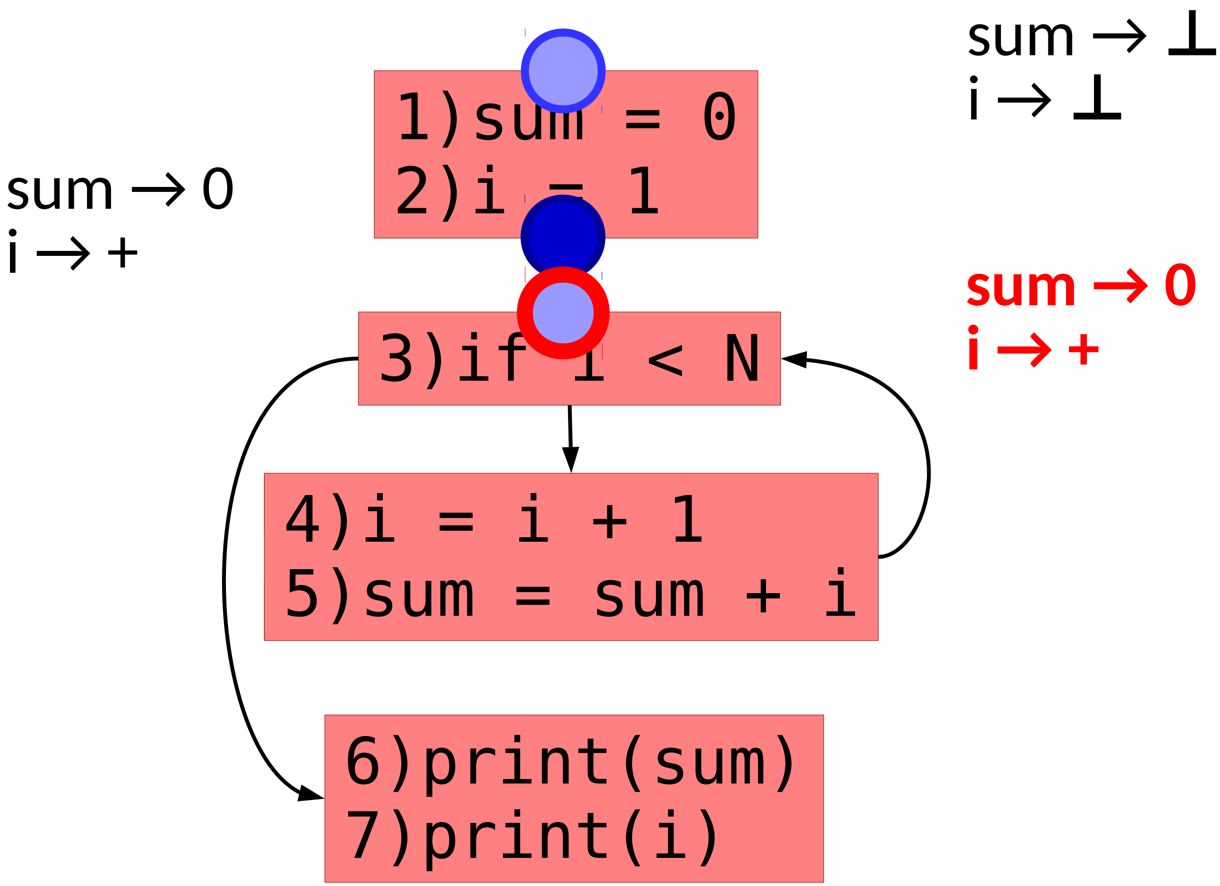

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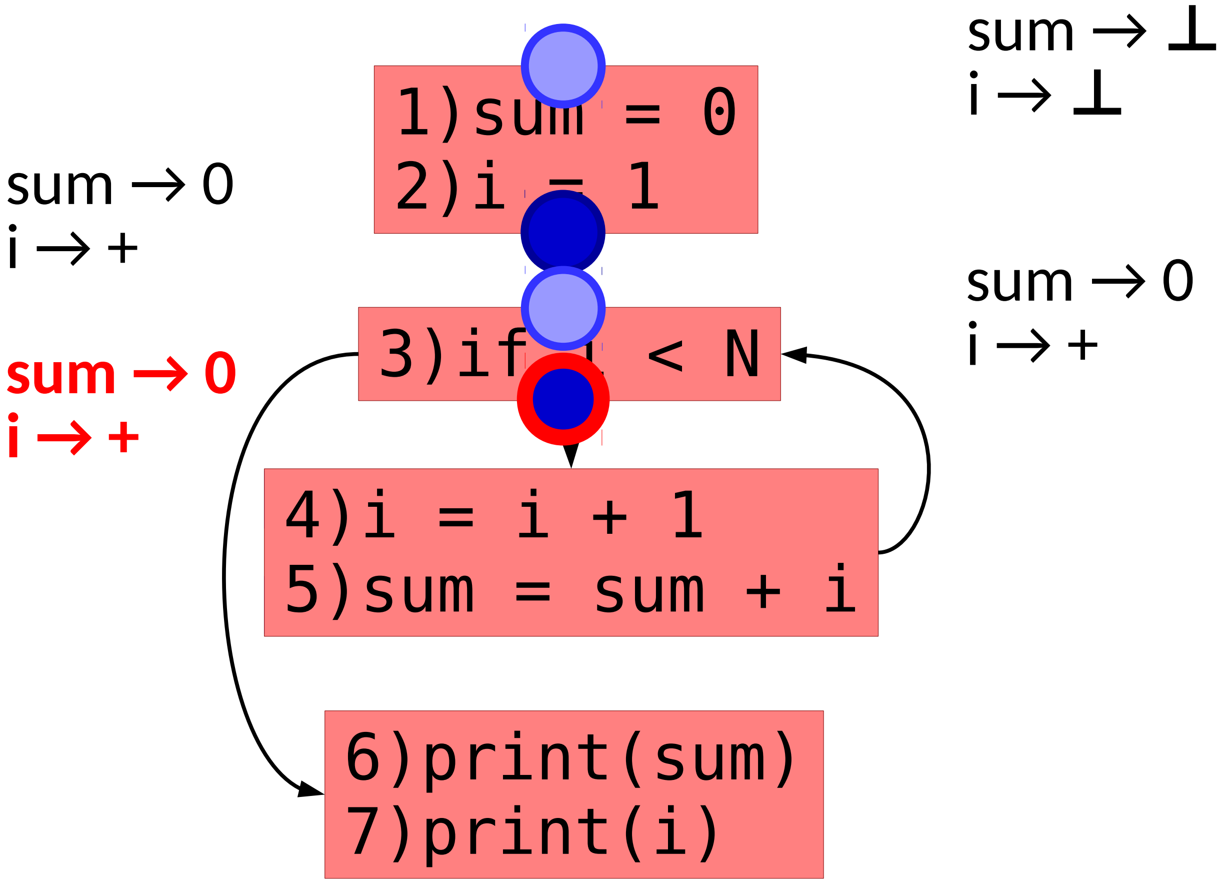

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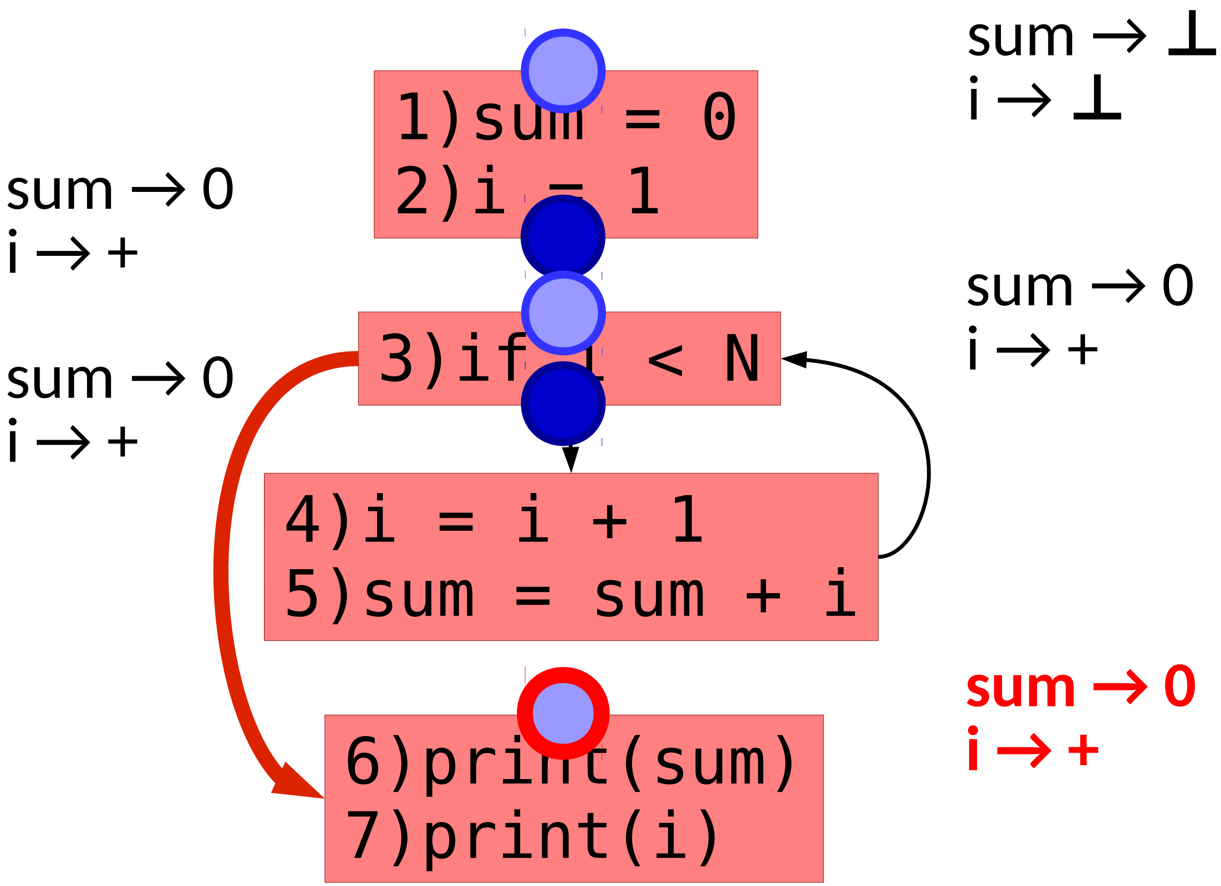

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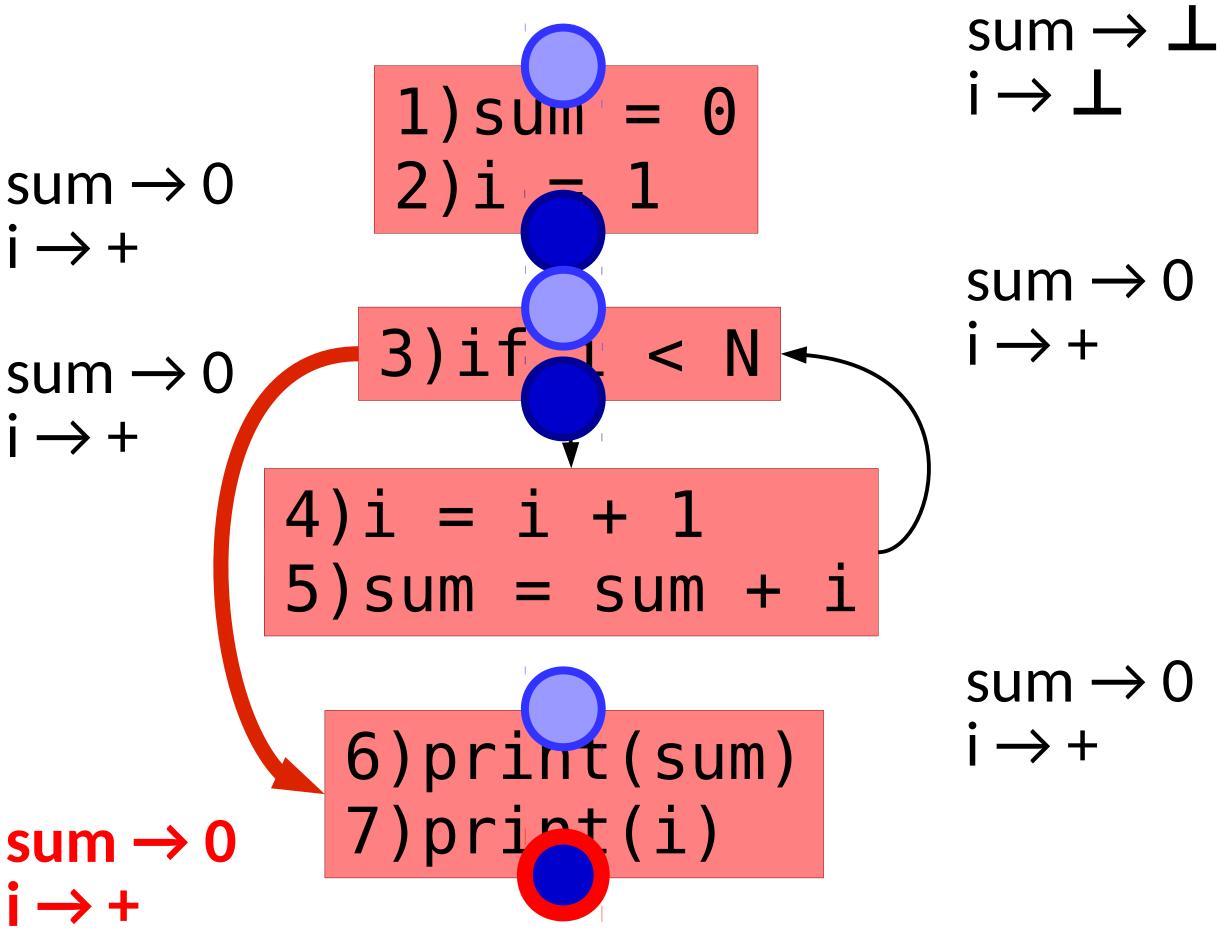

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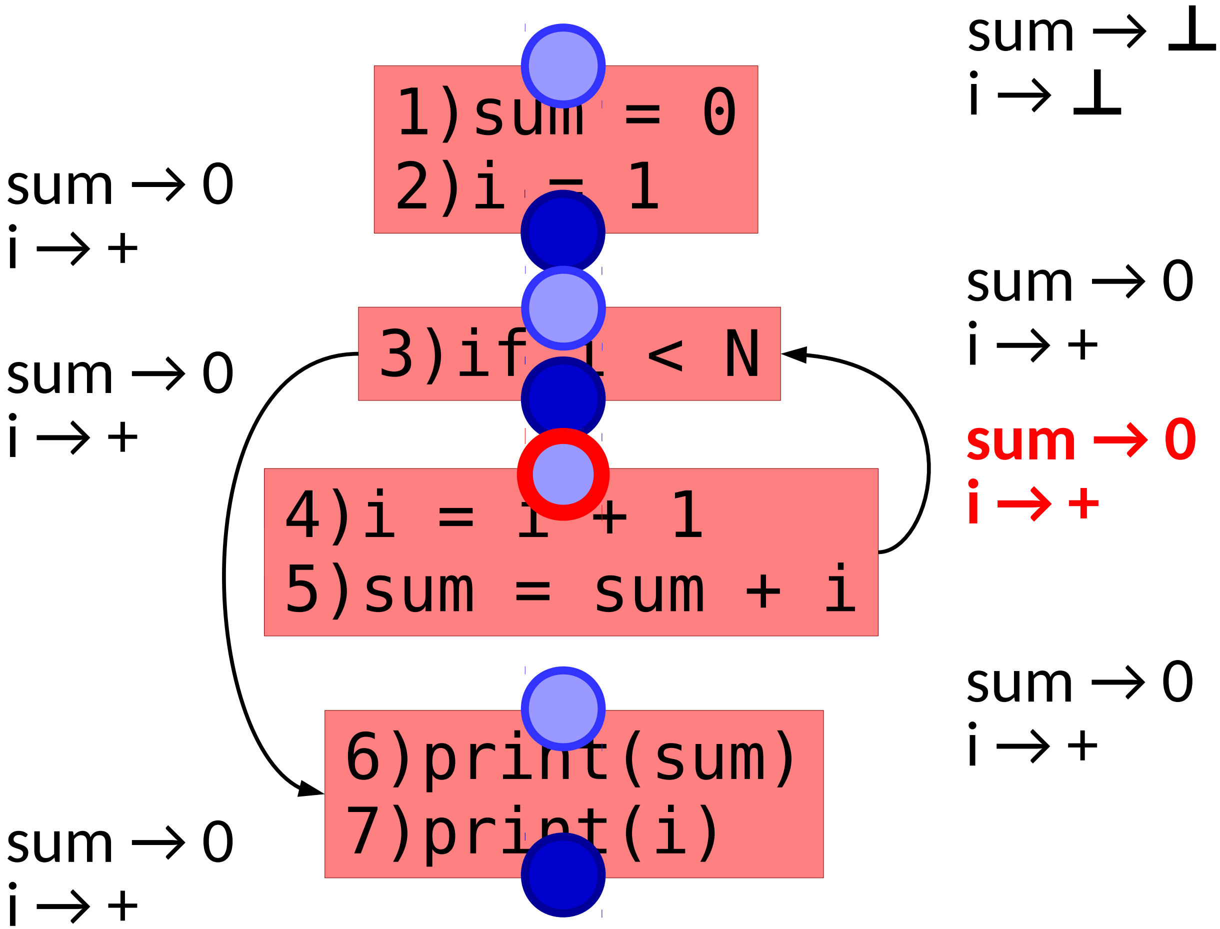

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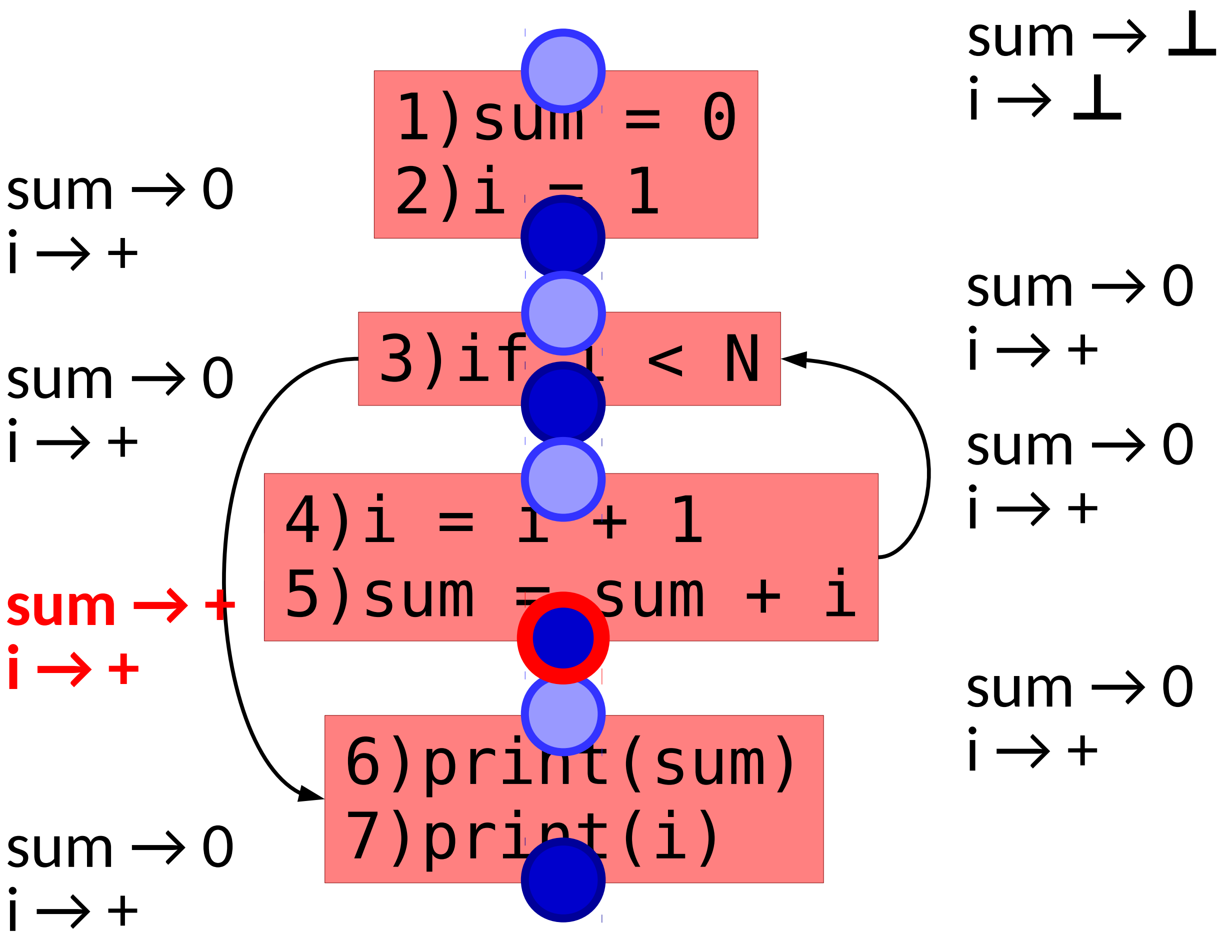

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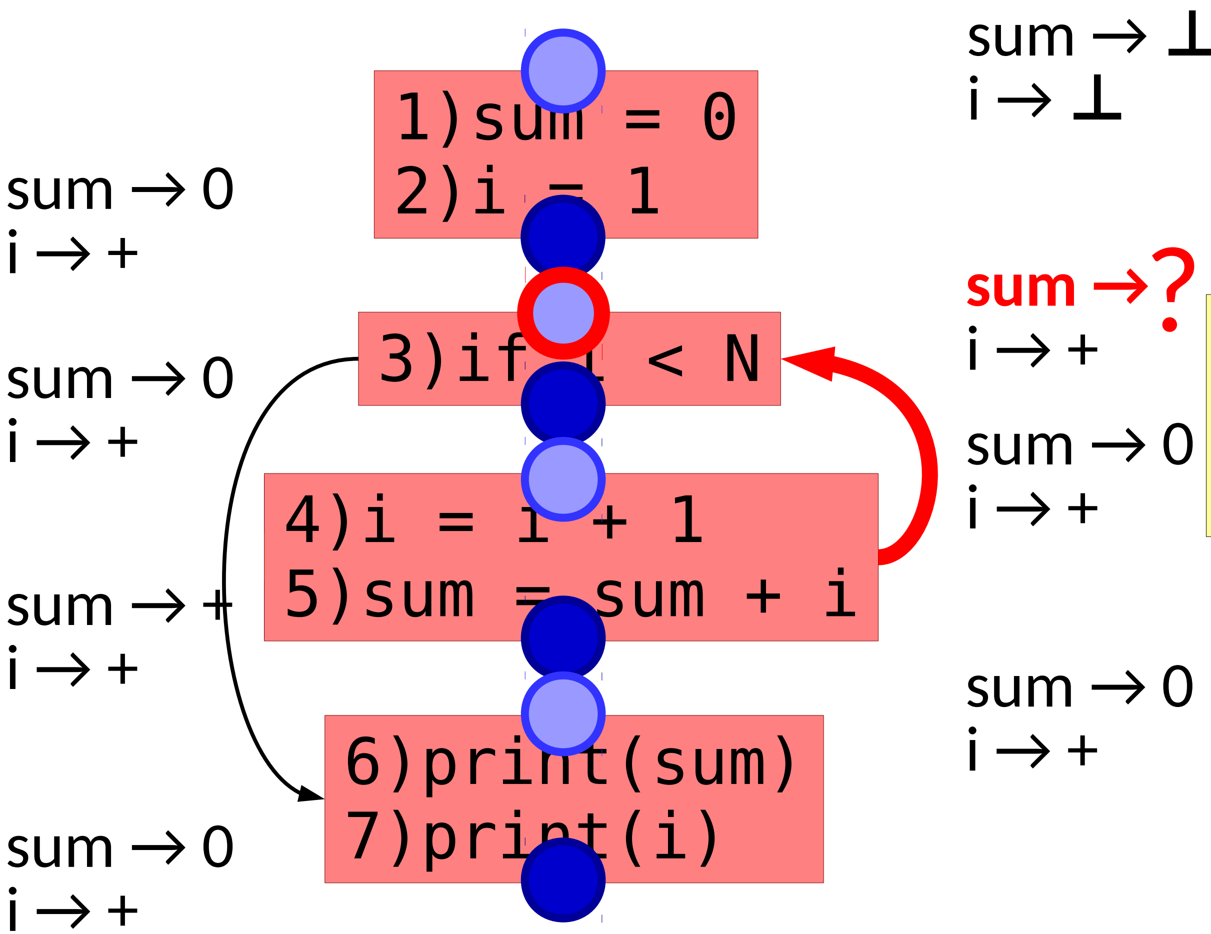
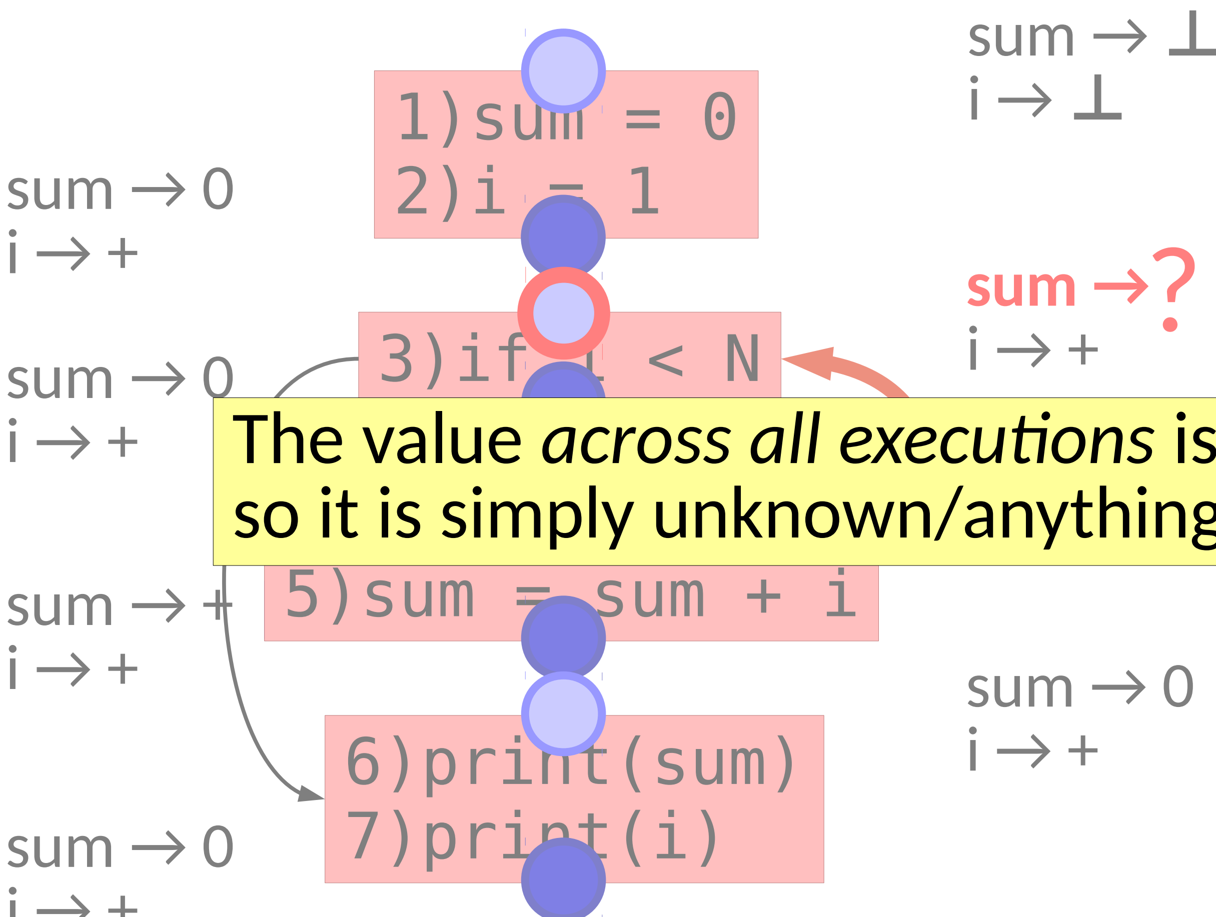


Meet Operator
sum was 0, but what should it be now?

Dataflow Analysis

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



The value *across all executions* is not -, 0, or +, so it is simply unknown/anything. (⊤)

Dataflow Analysis

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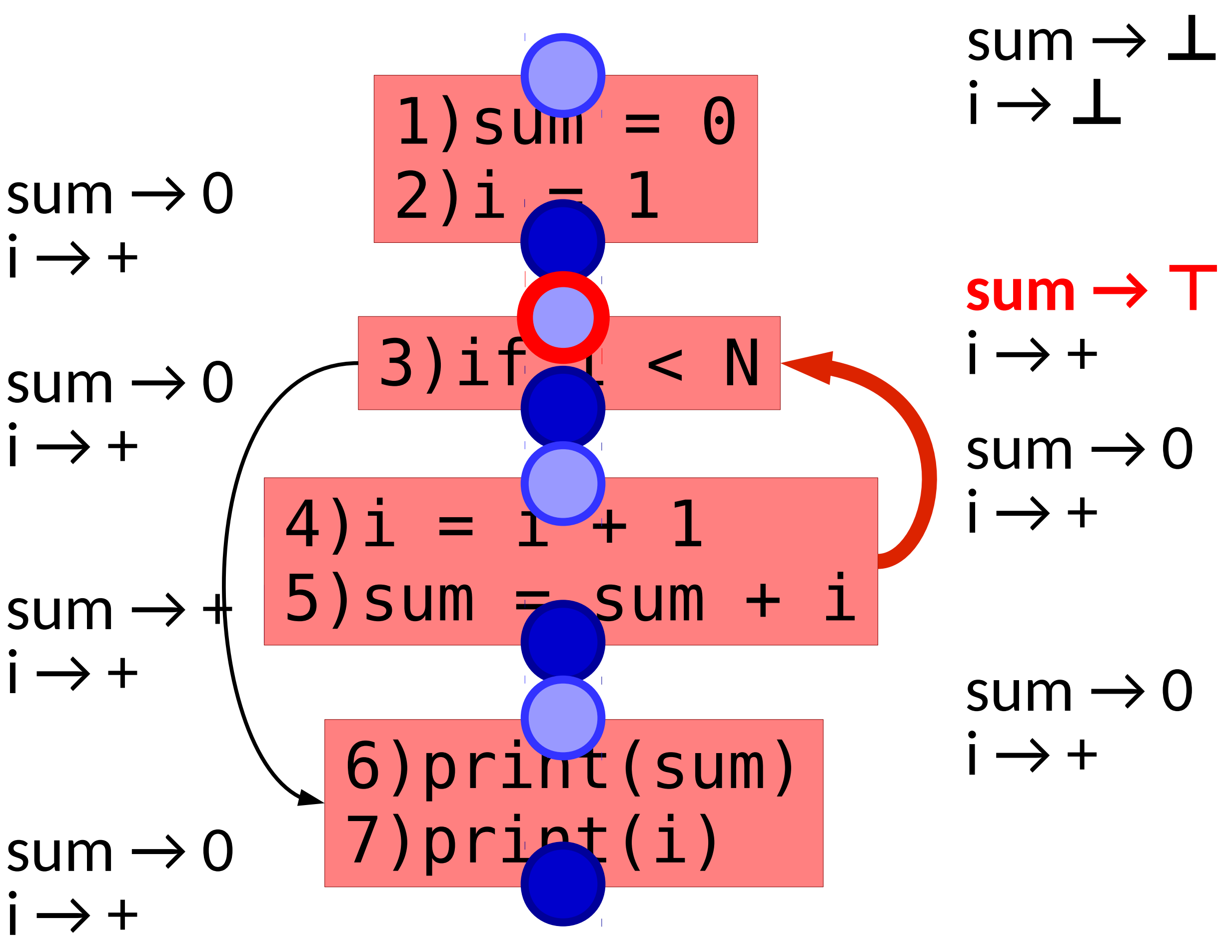

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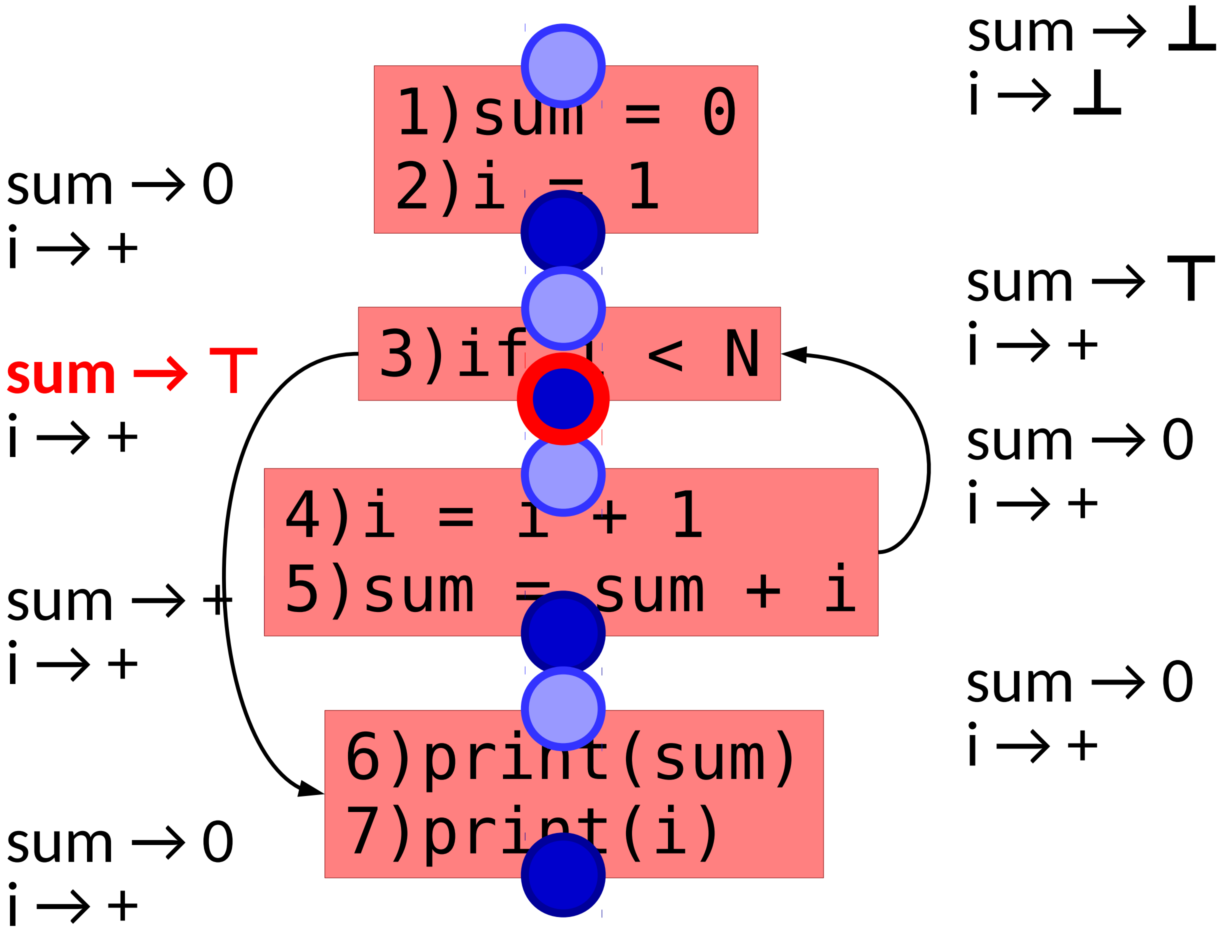

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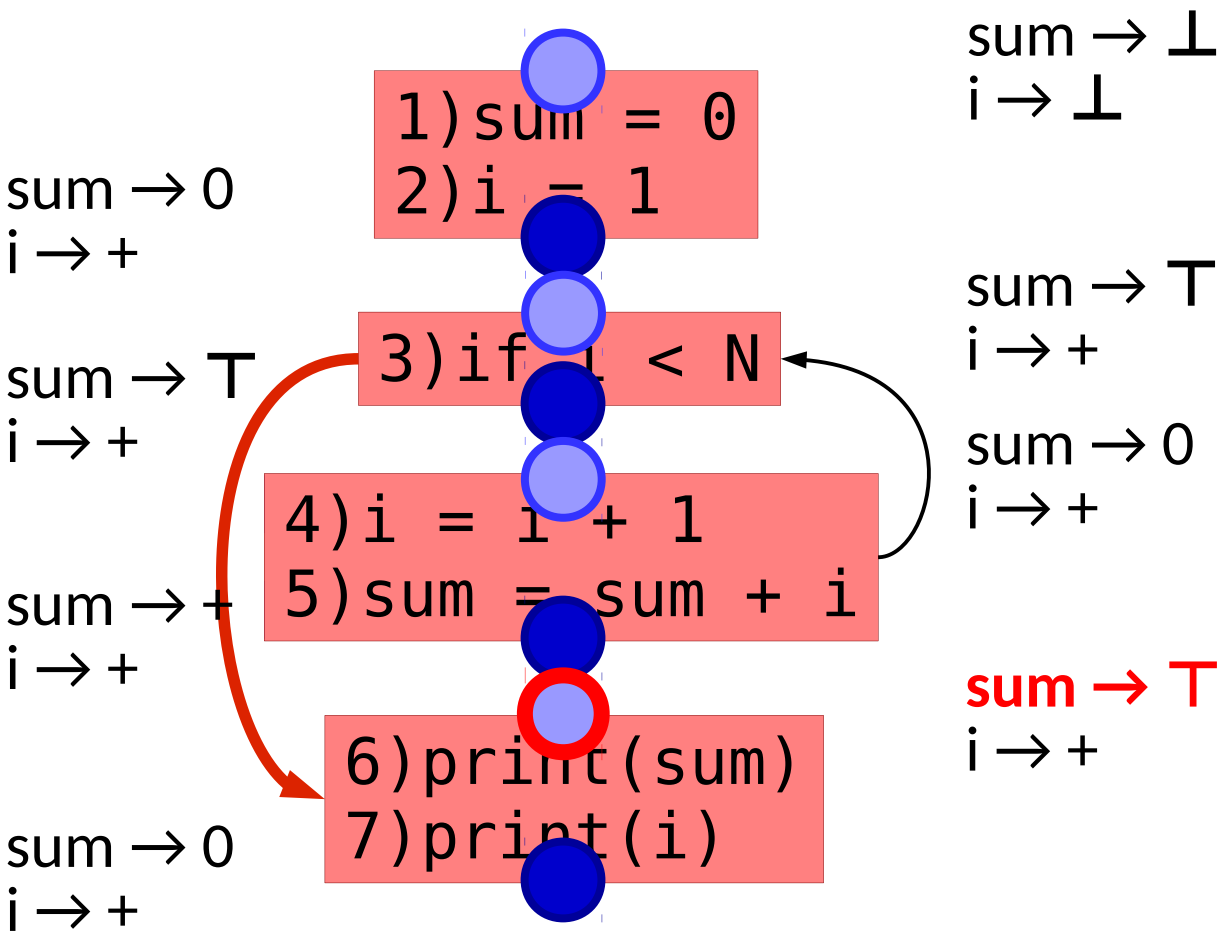

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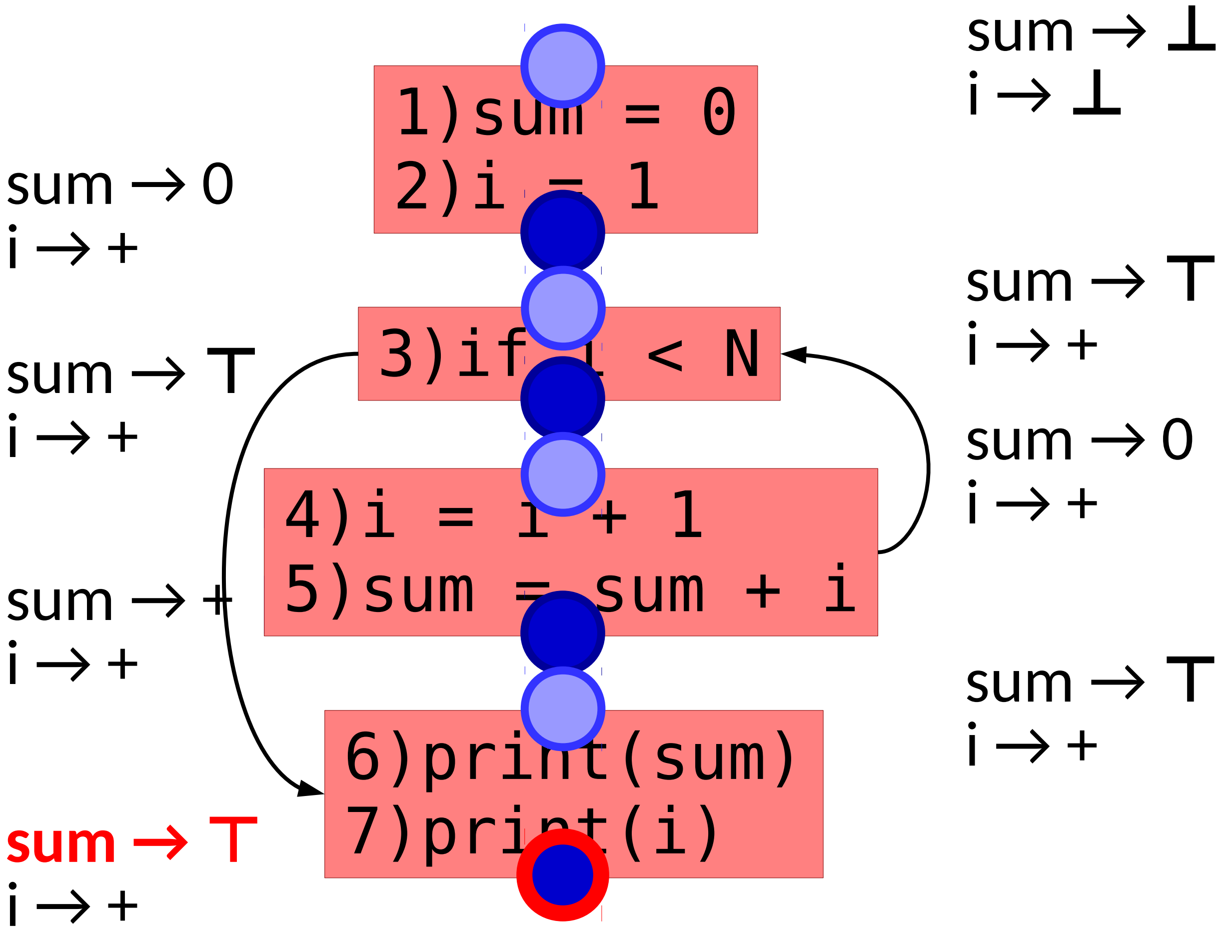

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- Now model the abstract program state and propagate through the CFG.
  - Continue until we reach a fixed point

    (No more changes)

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    (No more changes)
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    - (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)
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    before = ∏state(p)
              ∀ p ∈ preds(unit)
    new = transfer(before, unit)
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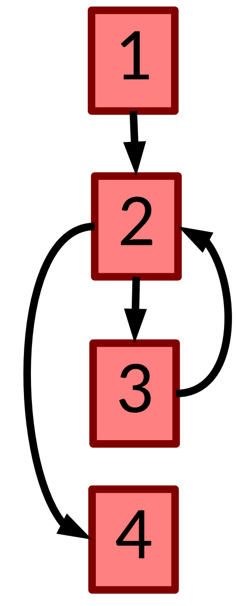

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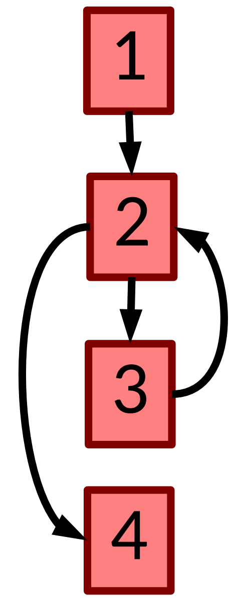

work: 1 2 3 4

state: $\{(1 \mapsto \bot)\ (2 \mapsto \bot)\ (3 \mapsto \bot)\ (4 \mapsto \bot)\}$

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```
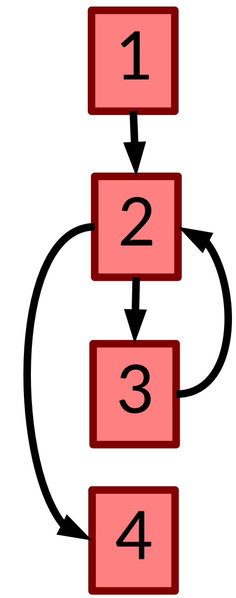

unit = 1



work: [ ] 2 3 4

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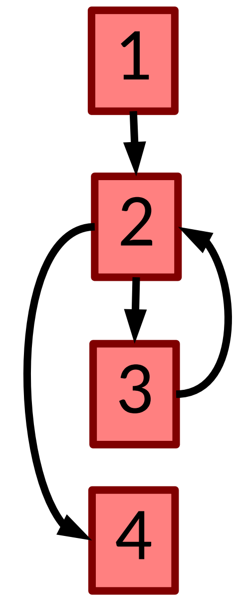
```

unit = 1

old = ⊥



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```

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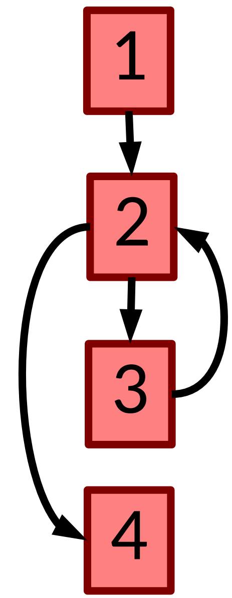
old = ⊥

new =

sum → 0
i → +



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state: { (1 ↦ ⊥) (3 ↦ ⊥)
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```

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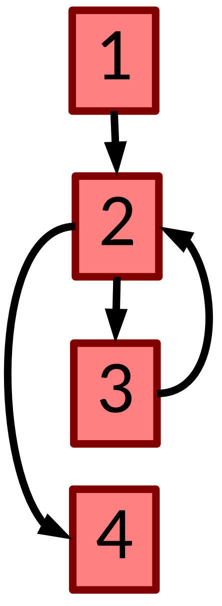
old = ⊥

new = sum → 0, i → +



work: 2 3 4

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```
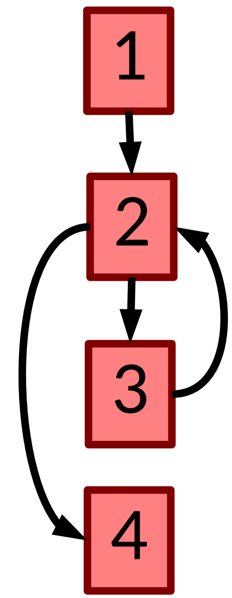

unit = 2

old = ⊥

new =
sum → 0
i → +



work: [ ] 3 4

state: { (1 ↦ sum → 0, i → +) (3 ↦ ⊥)
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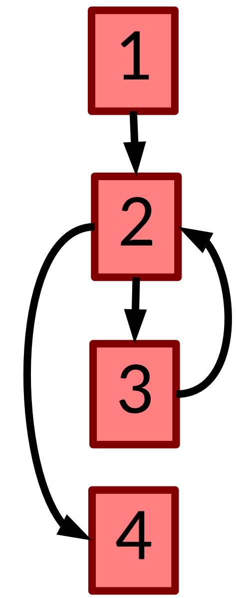
```

unit = 3

old = ⊥

new = sum → +, i → +



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

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

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```
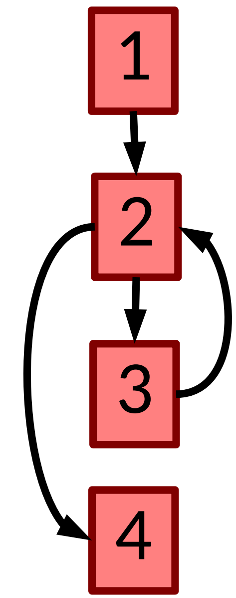

unit = 4

old = ⊥

new =
sum → 0
i → +



work: 2

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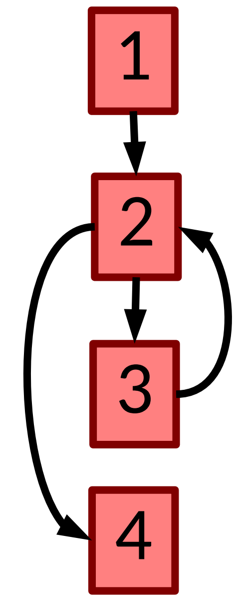
```

unit = 2

old = sum → 0, i → +

new = sum → ⊤, i → +



4,3 were added back to the list

work: [ ] 4 3

state: { (1 ↦ sum → 0, i → +) (3 ↦ sum → +, i → +)
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```
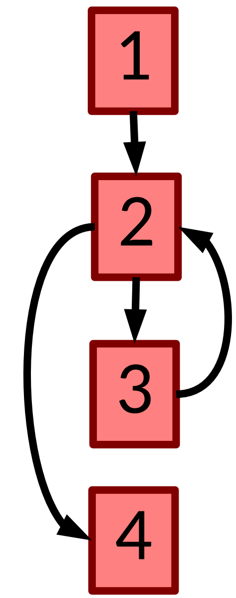

unit = 4

old = sum → 0, i → +

new = sum → T, i → +



work: 3

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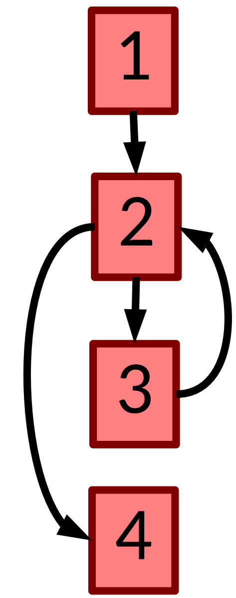
old = sum → +, i → +

new = sum → +, i → +

No change



work:

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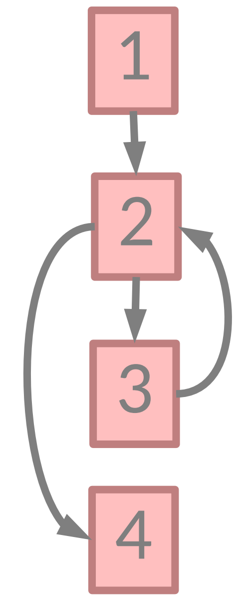
old = sum → 0, i → +

new = sum → ⊤

Done!



work:

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- There are several possible sources of imprecision

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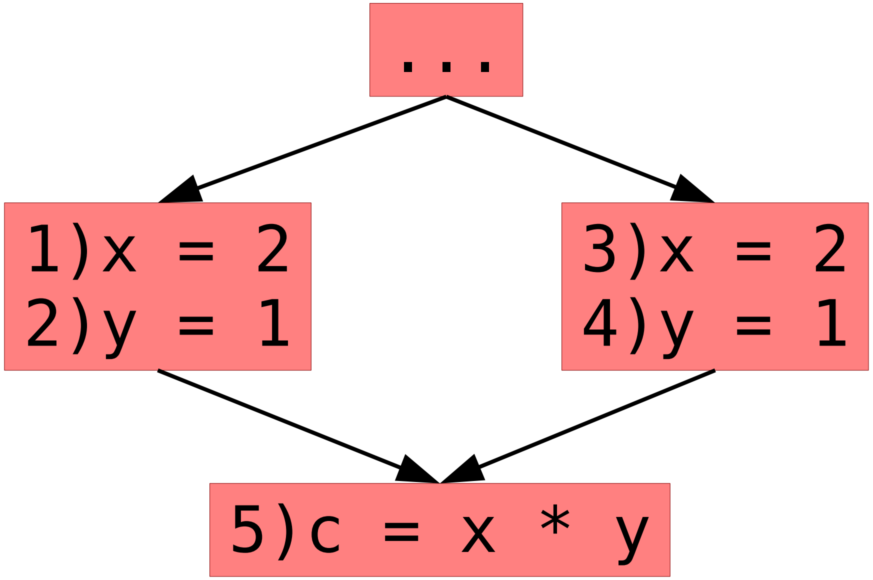

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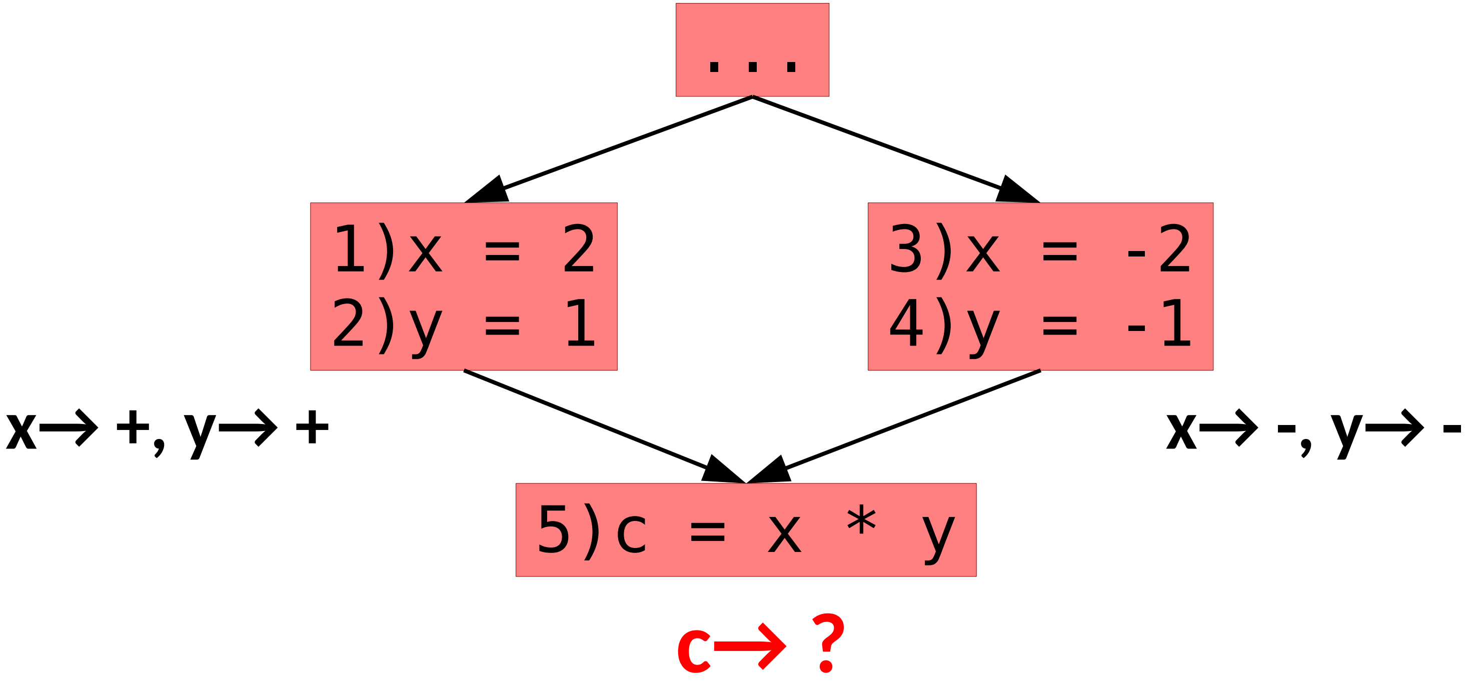

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- 2 Key sources are
  - Control flow
    - Many different paths are summarized together
  - Abstraction
    - Deliberately throwing away information
    - Granularity of program state affects correlations across variables

Effect of Approximation

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For all paths p: $\sqcap_p f_p(\bot)$

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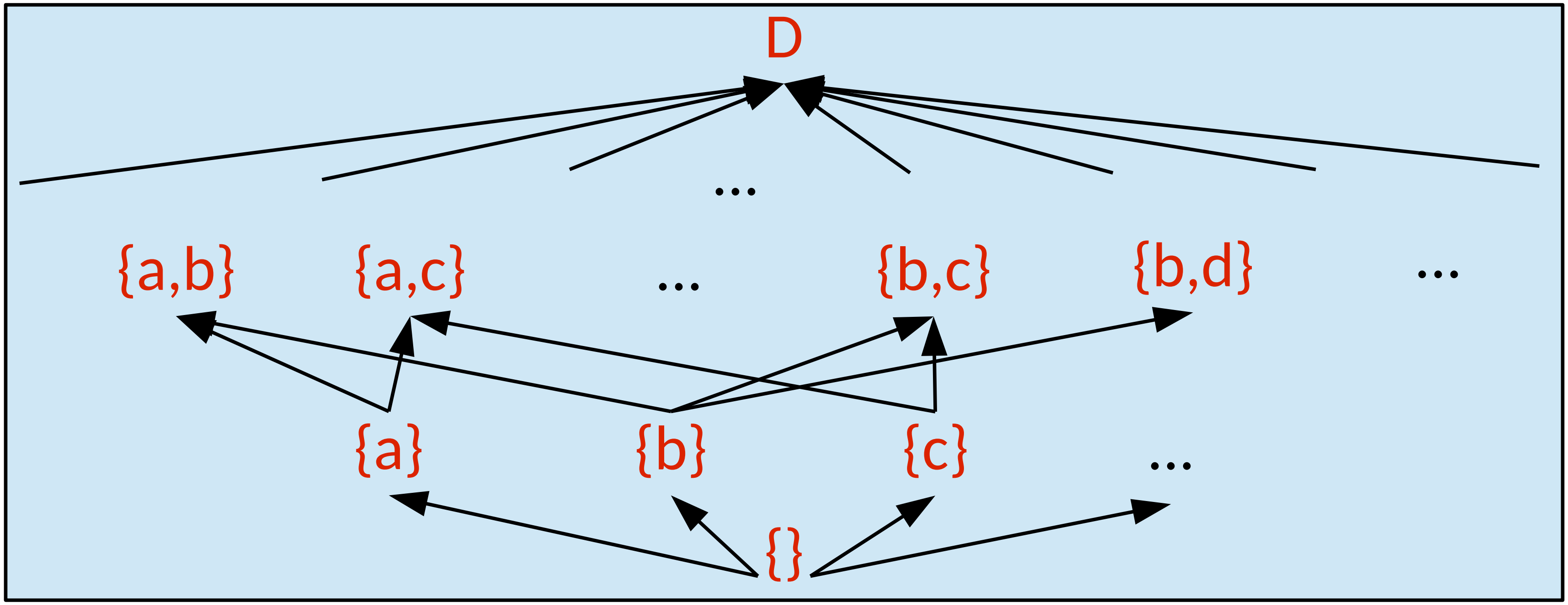
    $f(x \sqcap y \sqcap z) = f(x) \sqcap f(y) \sqcap f(z)$
  - This applies to an important class of problems called *bitvector frameworks*.

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}, …}
  - Lattice: Defined by subset relation:



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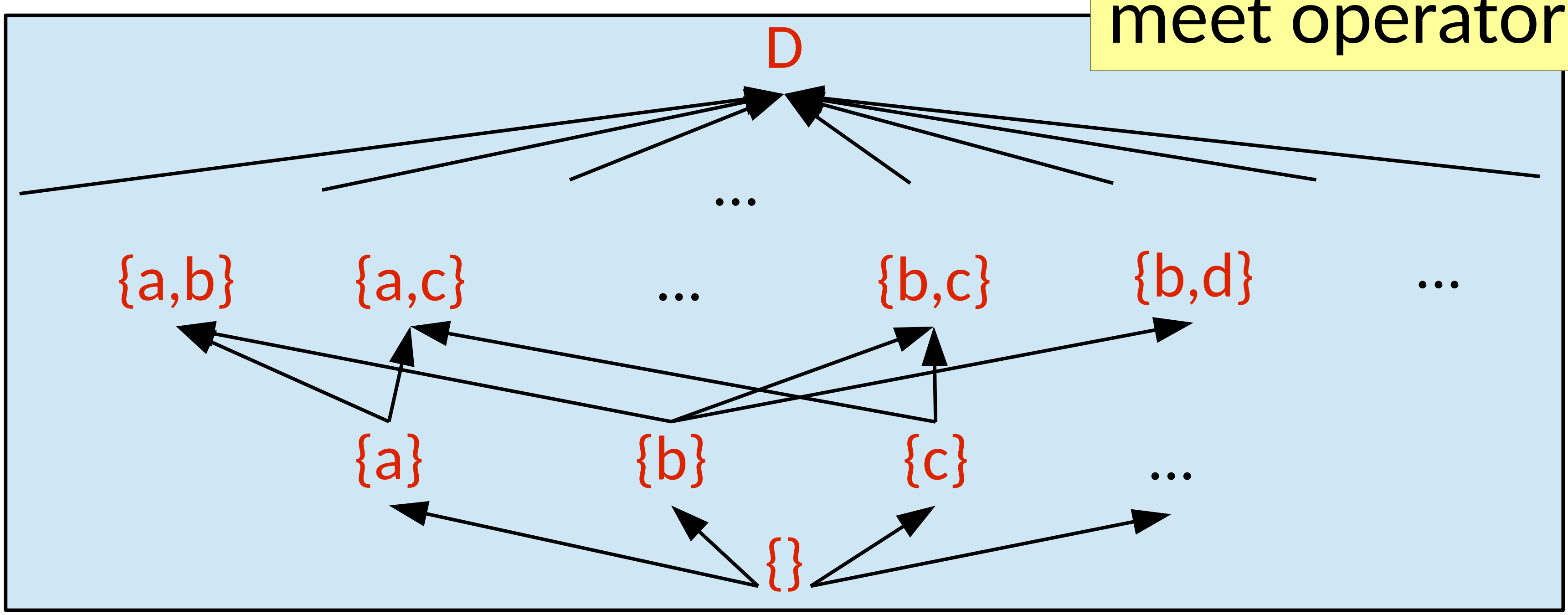
What would the meet operator be?



Bitvector Frameworks

- Why is this convenient?
  - Hint: ***bitvector*** frameworks

Bitvector Frameworks

- Why is this convenient?
  - 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!

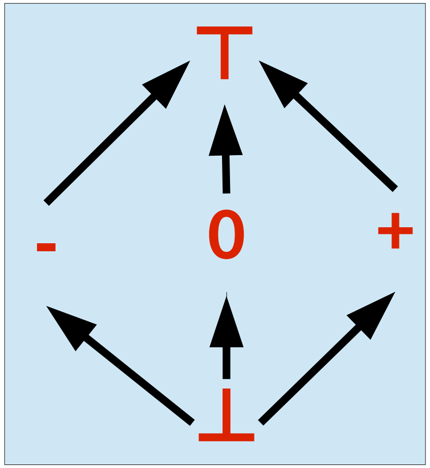
Effect of Approximation

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

Recap: Dataflow Analysis

Analyze complex behavior with approximation:

- Abstract domain: e.g. {**-**,**0**,**+**} ⋃ {⊤,⊥}
- Transfer functions: **-** + **+** → ⊤
- Bounded domain lattice height:
- Concern for false + & -



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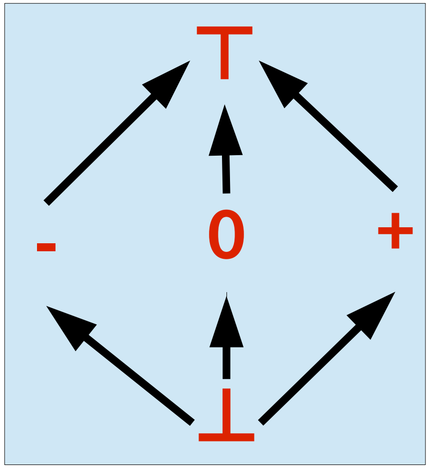

Implementation:

- Computing using work lists
- Speeding up by sorting CFG nodes

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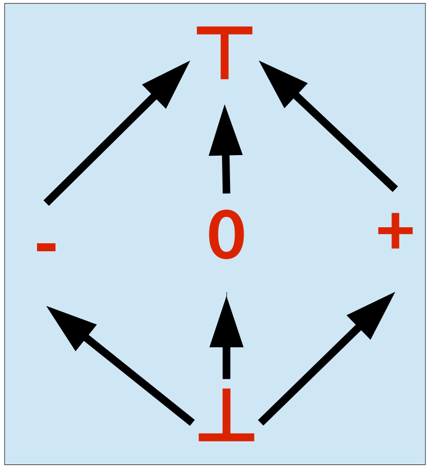

Implementation:

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Let's see an example

File Policy Analysis

Goal: Identify potential misuses of open/closed files

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e.g. read, write, print, flush, close, …

File Policy Analysis

Goal: Identify potential misuses of open/closed files

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- Many operations may only occur on open files

e.g. read, write, print, flush, close, …

What should our design actually be?

- Abstract domain?
- Transfer functions?
- Lattice?

File Policy Analysis

Goal: Identify potential misuses of open/closed files
- Files may be open or closed
- Many operations may only occur on open files

e.g. read, write, print, flush, close, …

What should our design actually be?
- Abstract domain?
- Transfer functions?
- Lattice?

[DEMO]

Flow Insensitive Analysis

- Saw *flow sensitive* analysis
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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

- Program behavior may be dependent on the call stack / calling context.
  - "If bar() is called by foo(), then it is exception free."
  - Can enable more precise *interprocedural* analyses

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

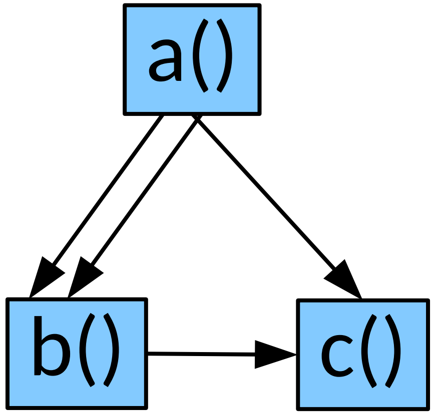
Context Sensitivity

- 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):
  if a < 9:
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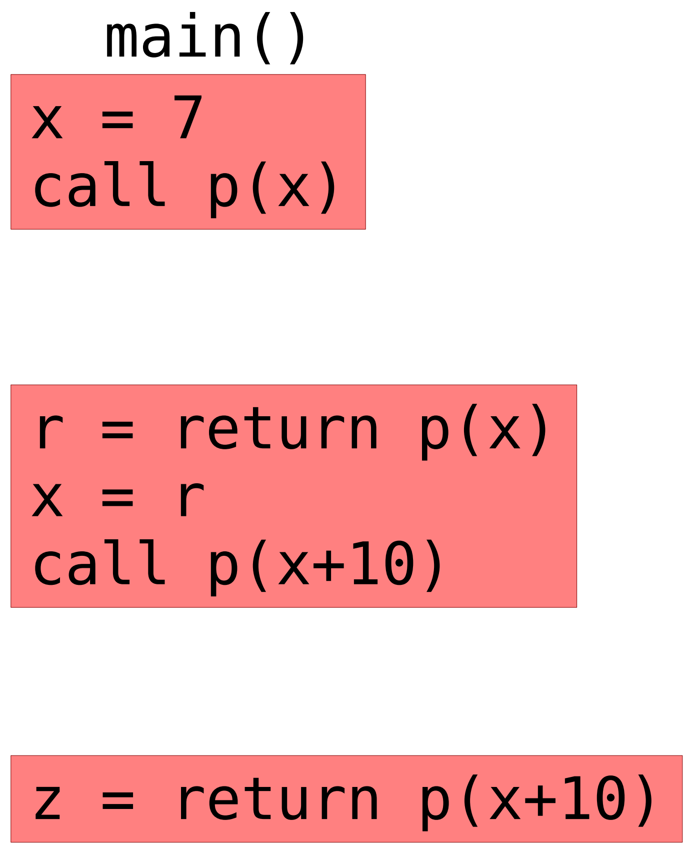

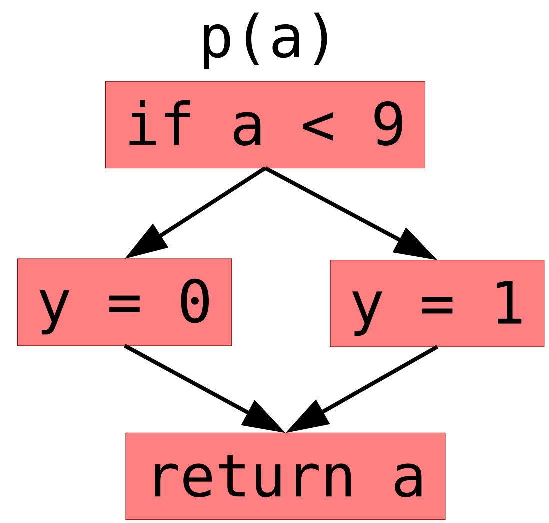

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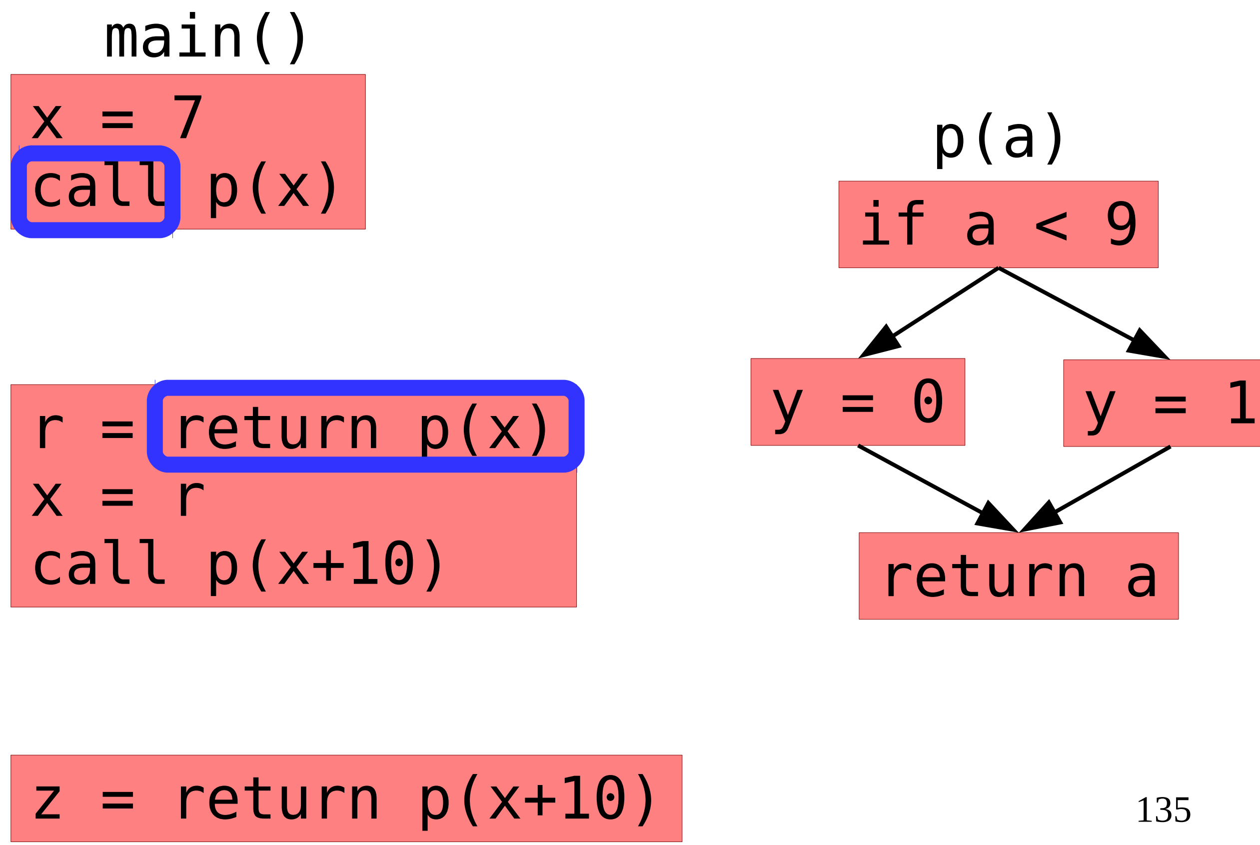

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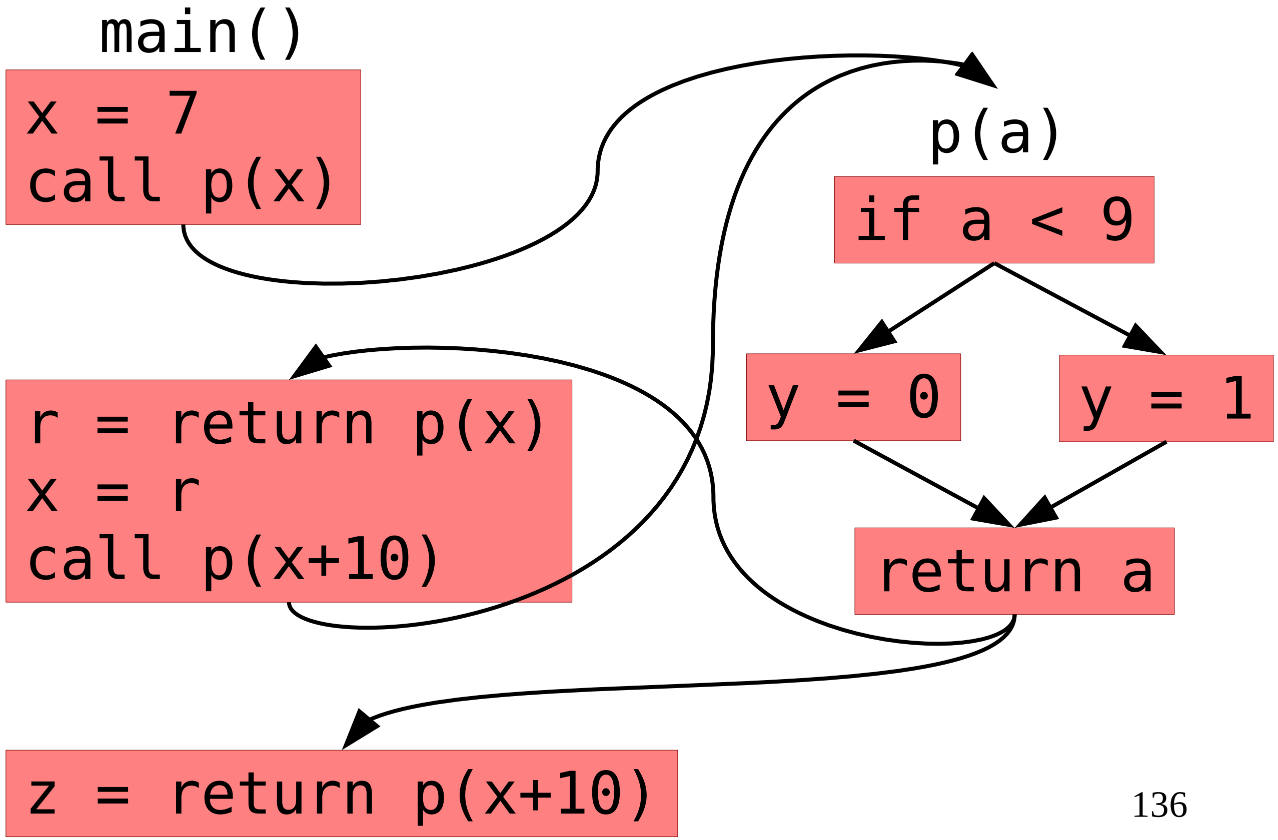

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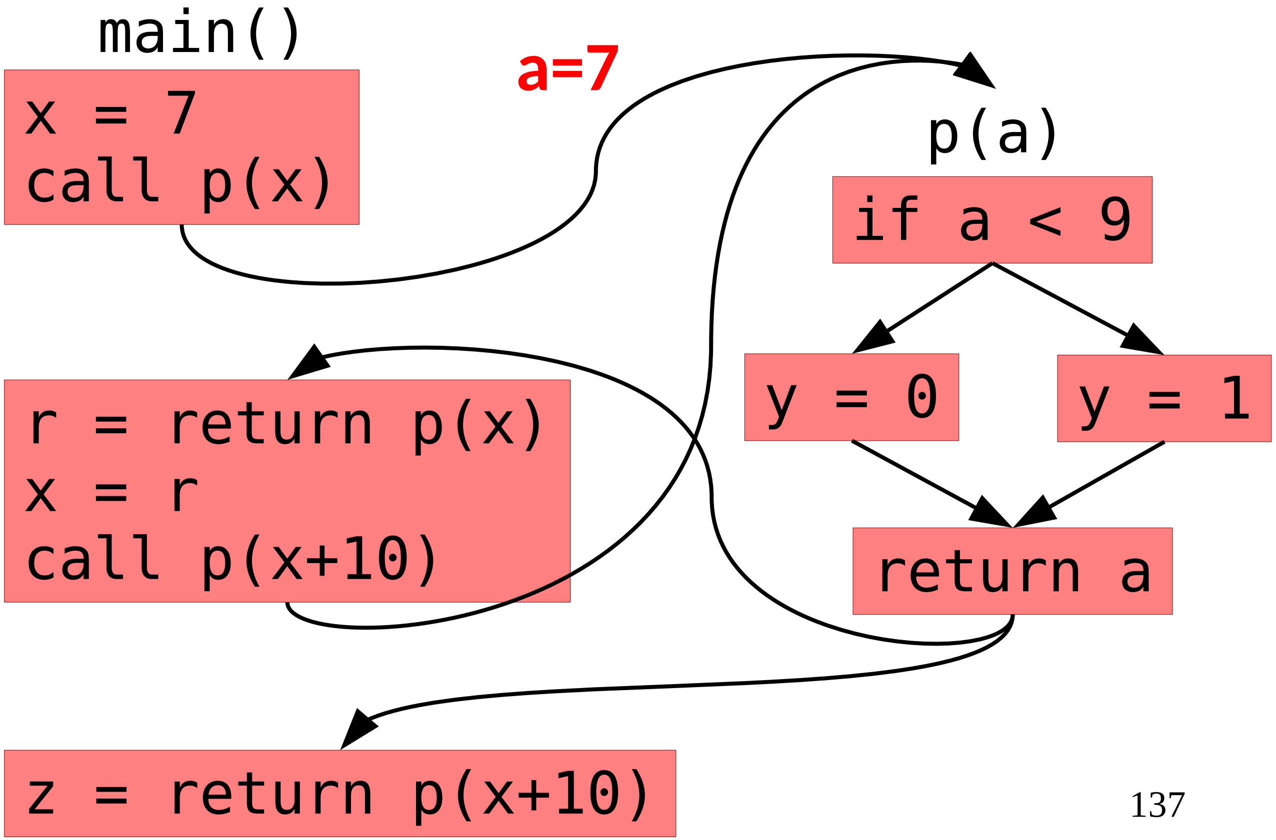

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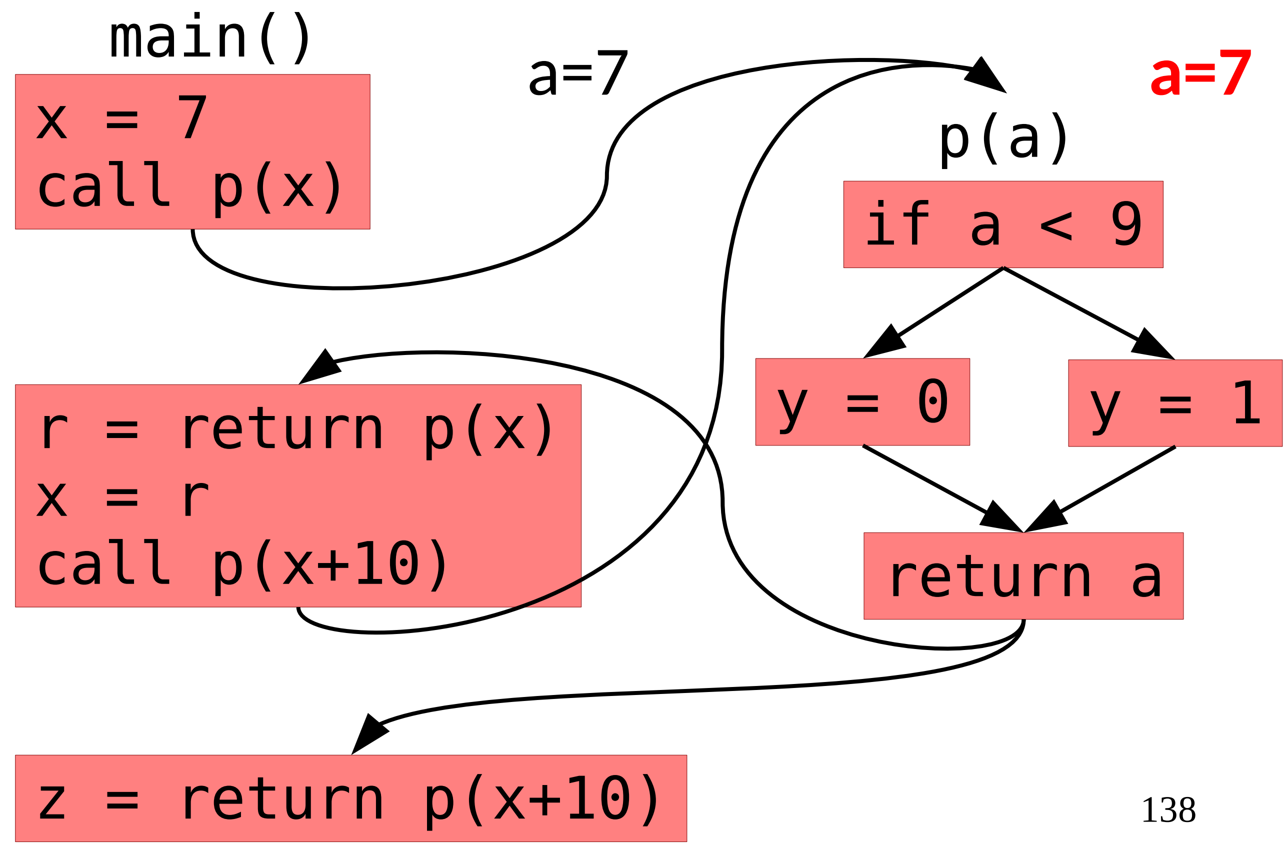

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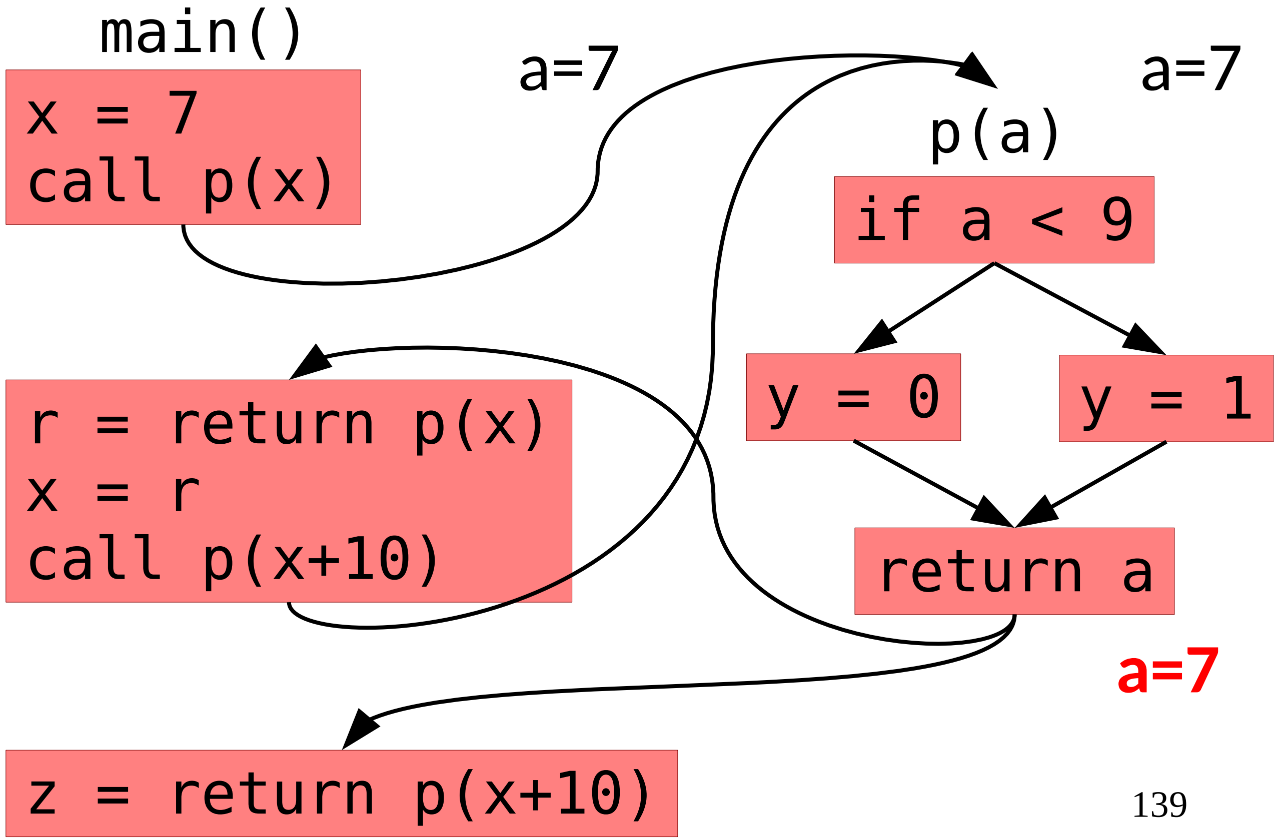

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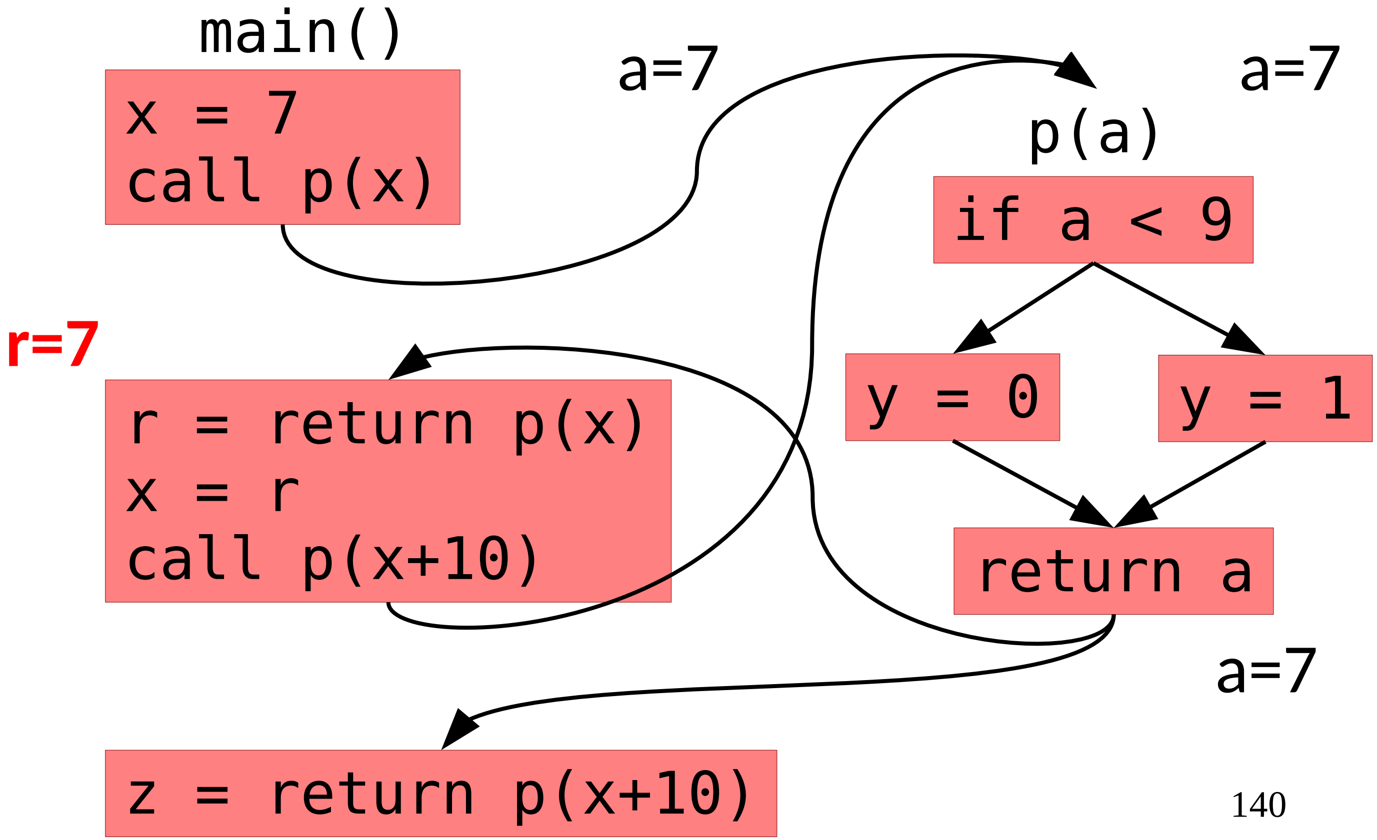

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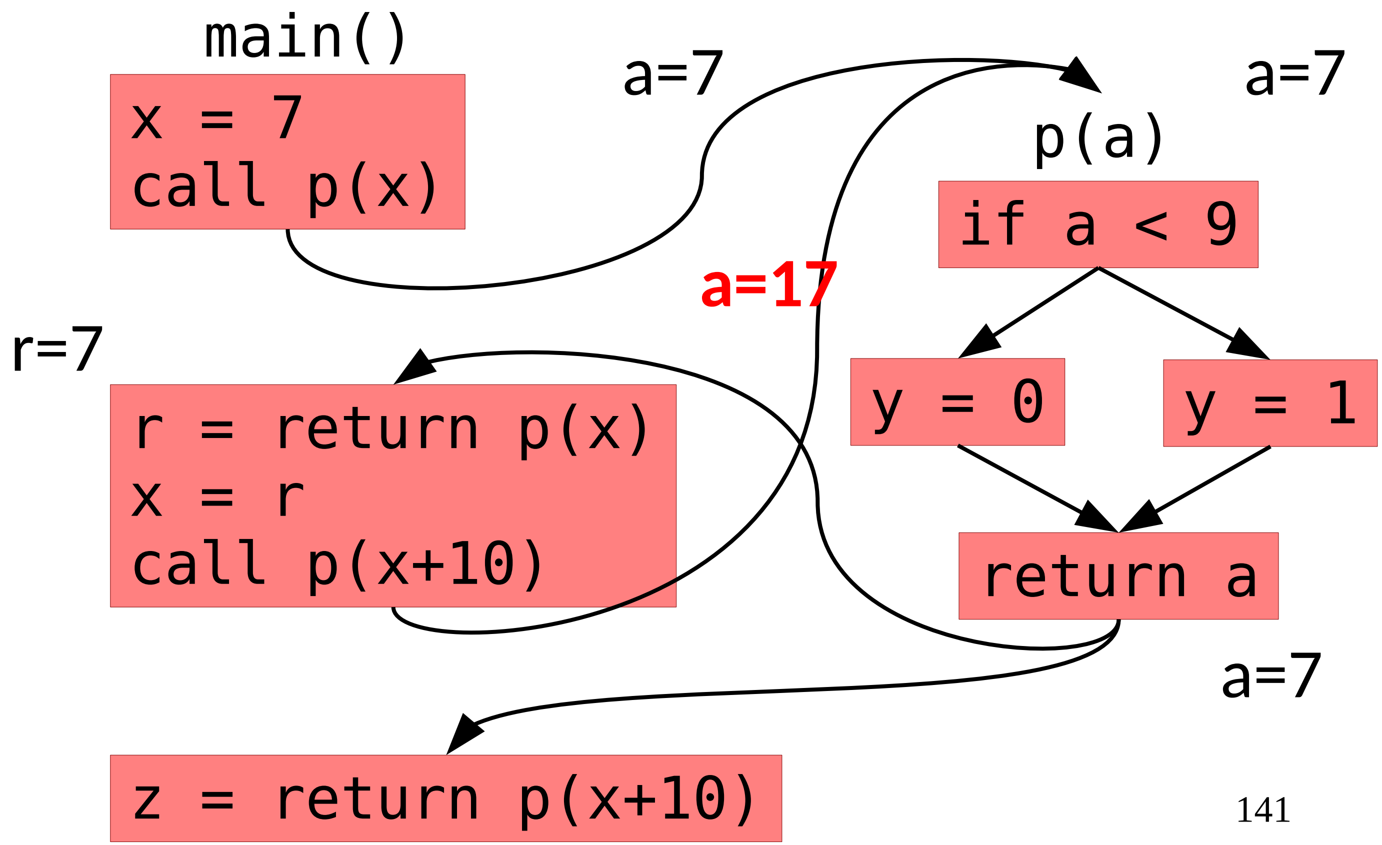

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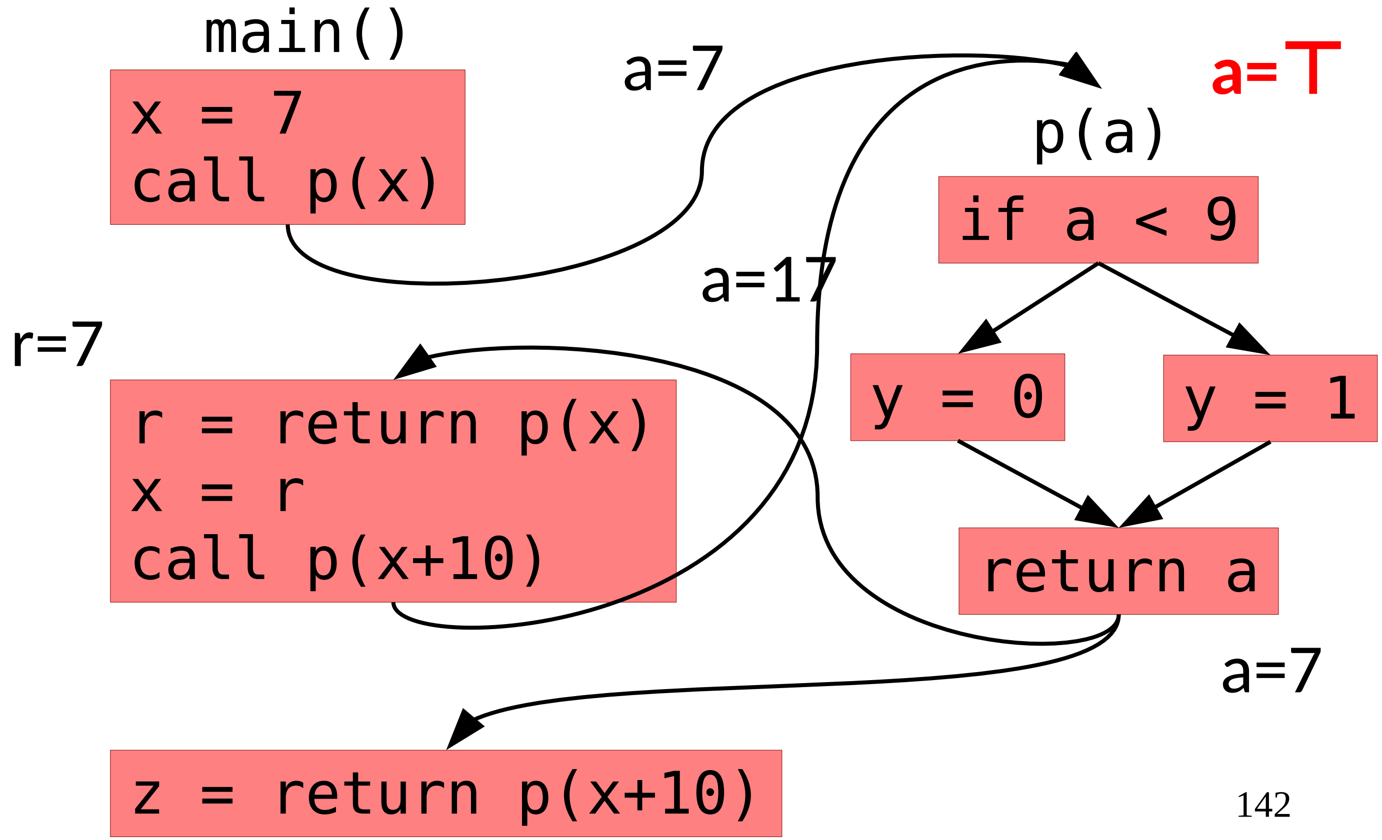

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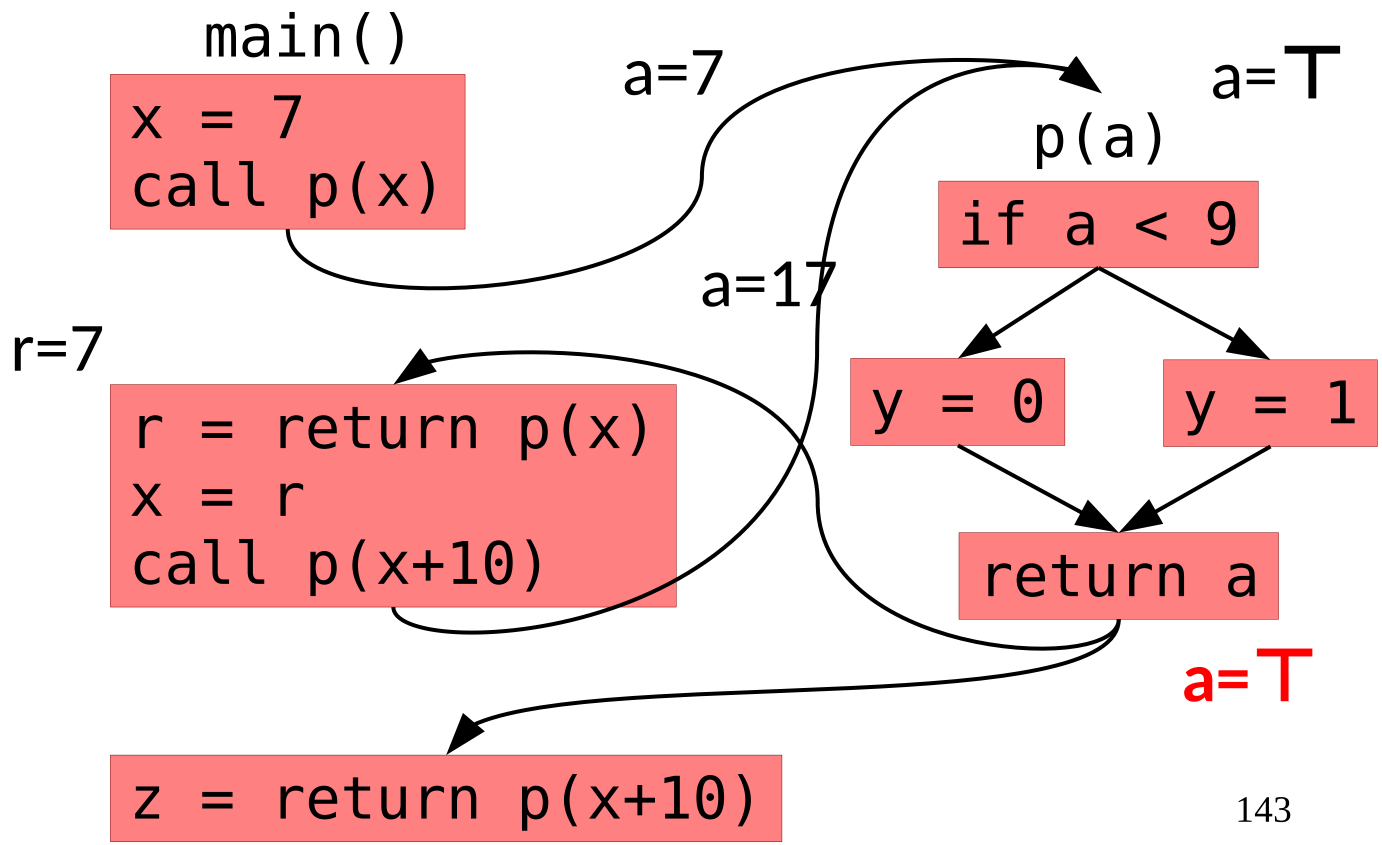

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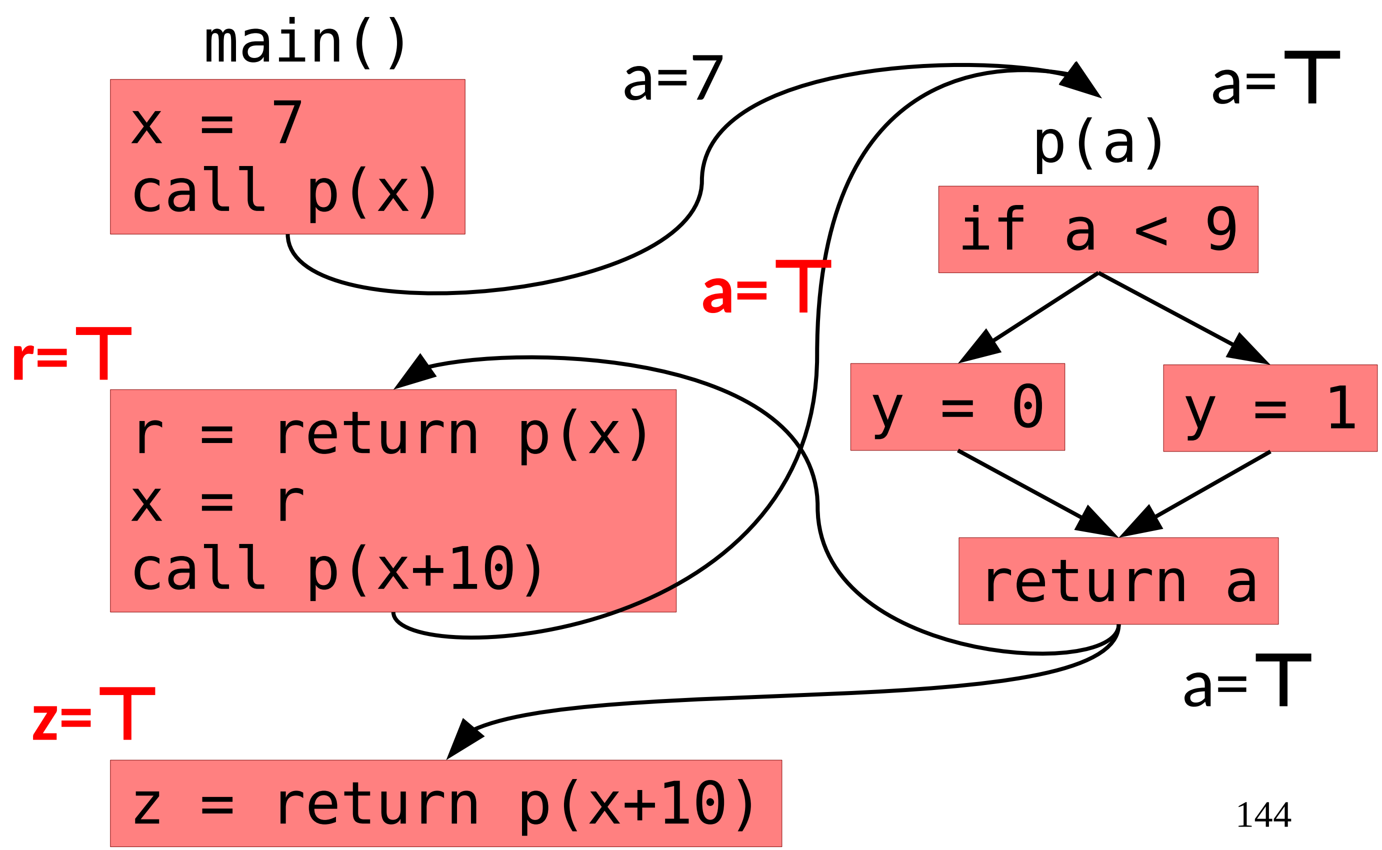

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- How could we address it?

Context Sensitivity

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- What problems arise?
- What other strategies can we use?

Context Sensitivity

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```
def main():
  a()
  a()
```

```
def a():
  b()
```

```
def b():
  pass
```

Context Sensitivity

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

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1) def main():
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```
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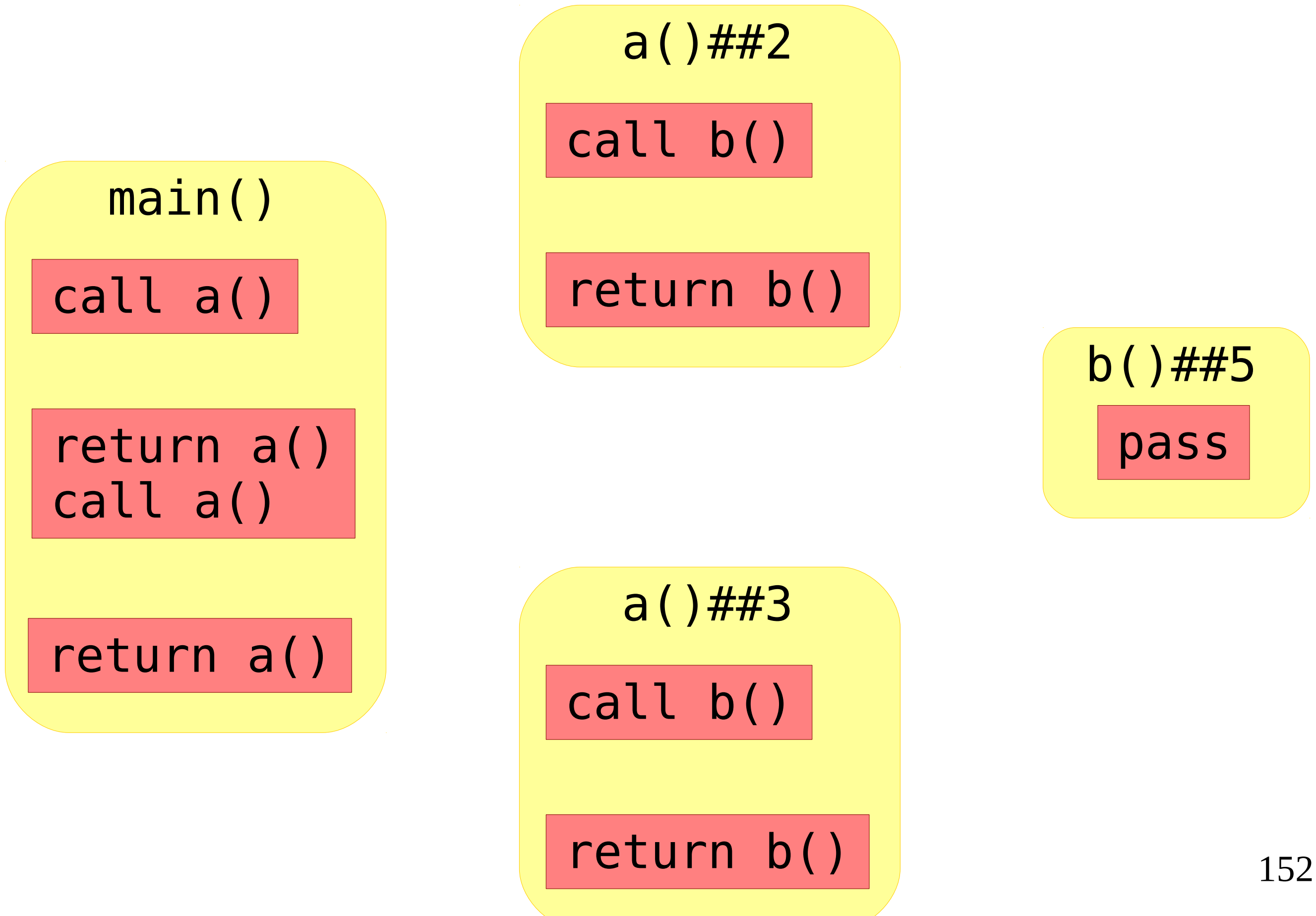

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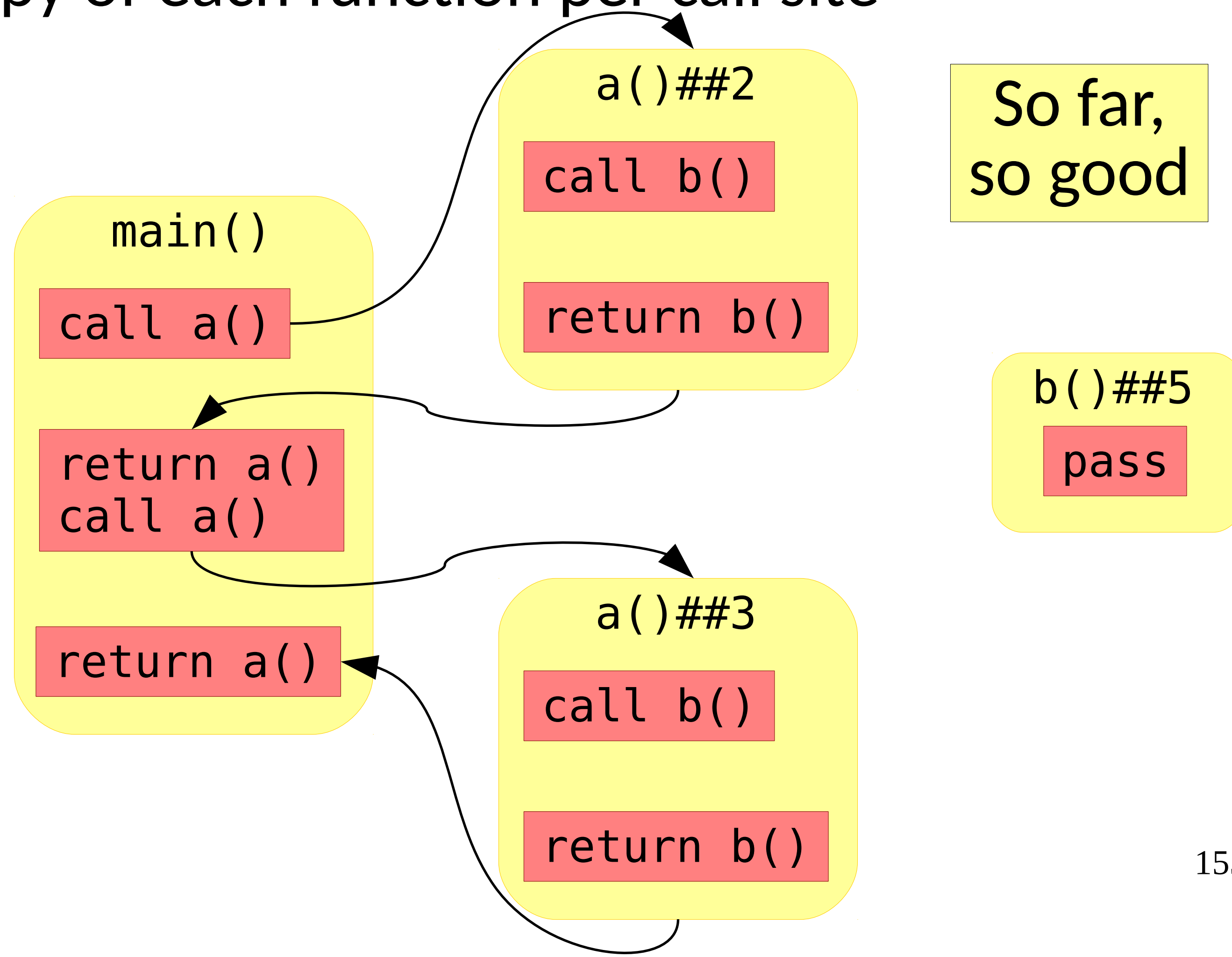

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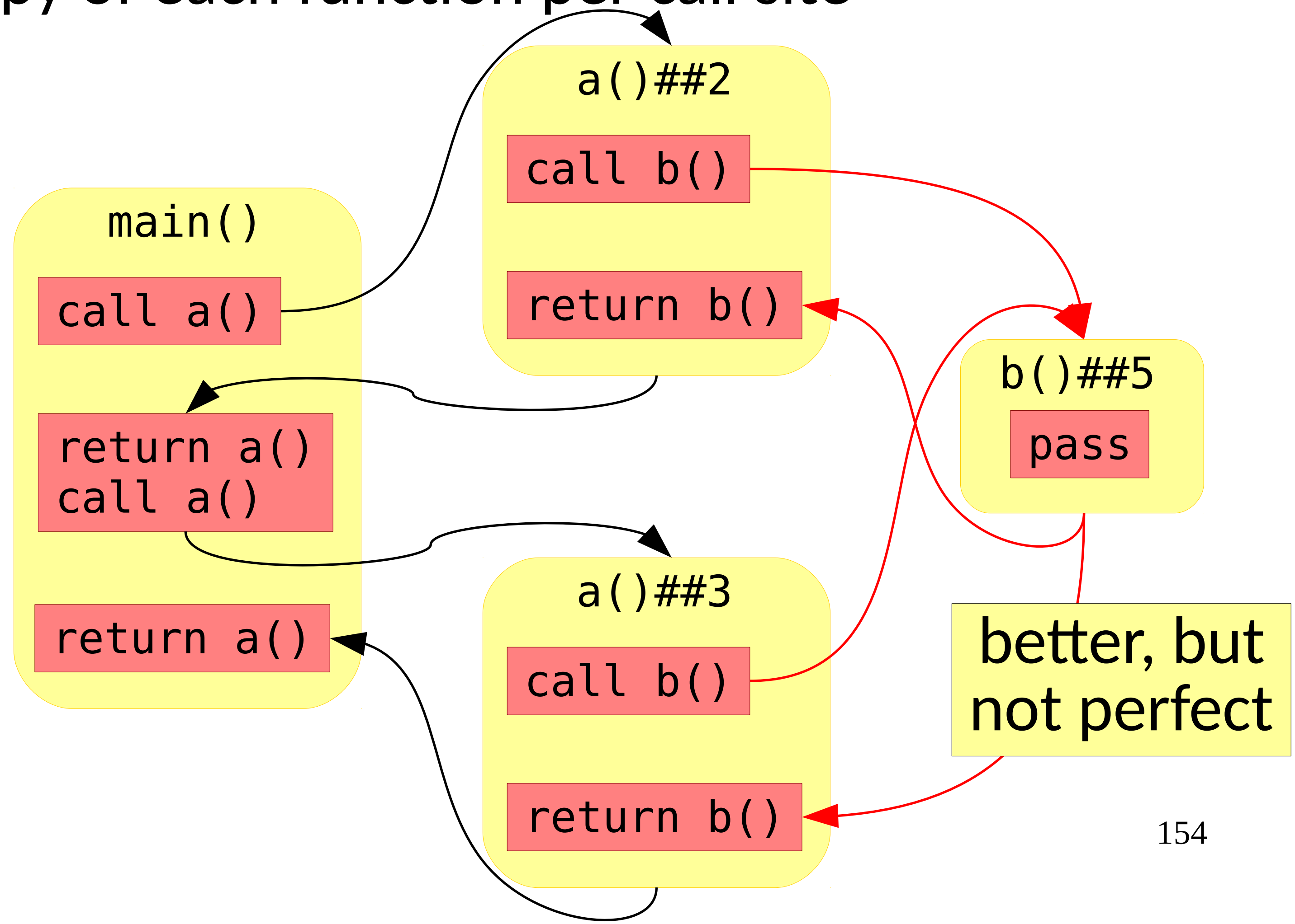

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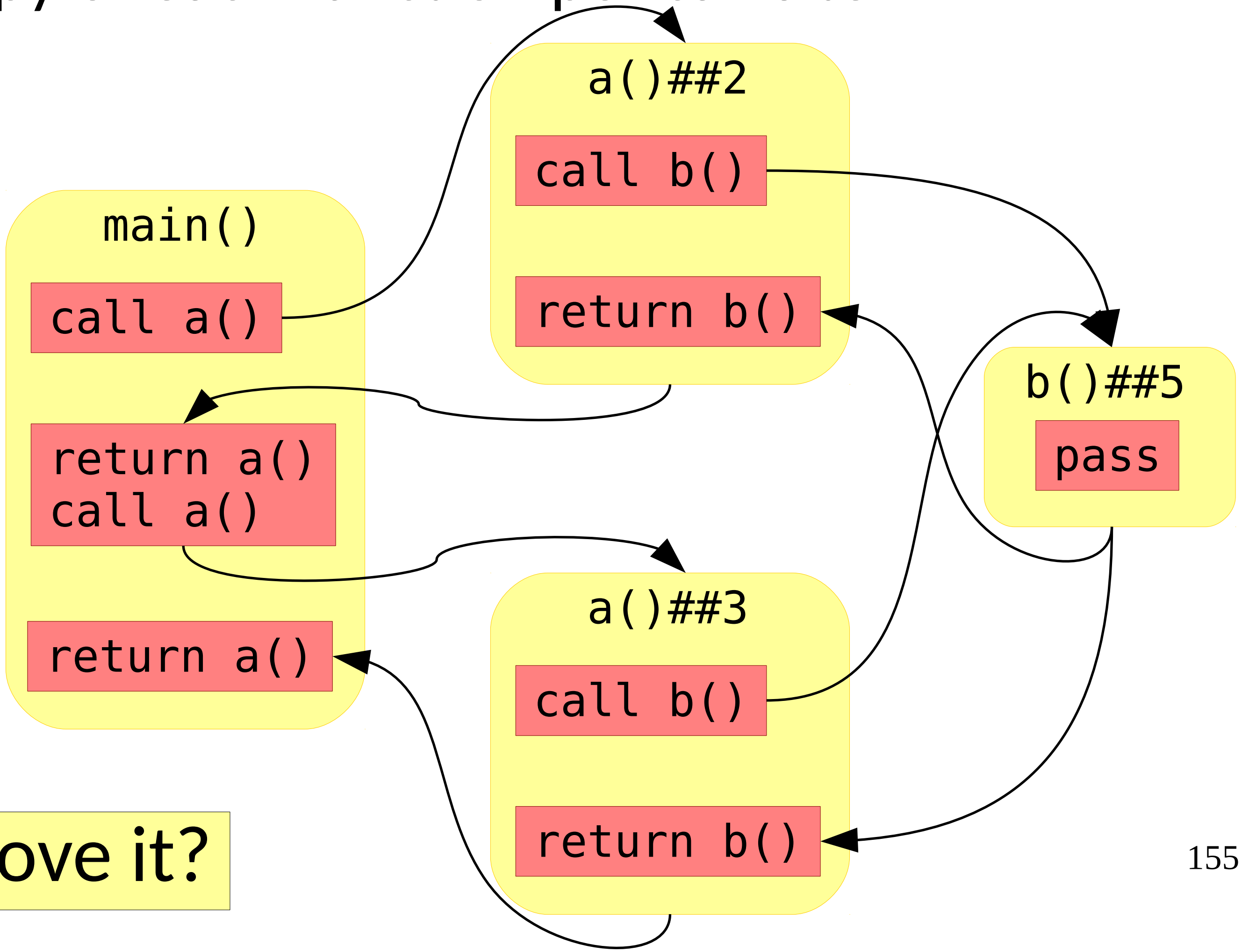

How can we improve it?

Context Sensitivity

Generalized:

- Make a bounded number of copies

Context Sensitivity

Generalized:

- 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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    On `foo(in)` with context C:

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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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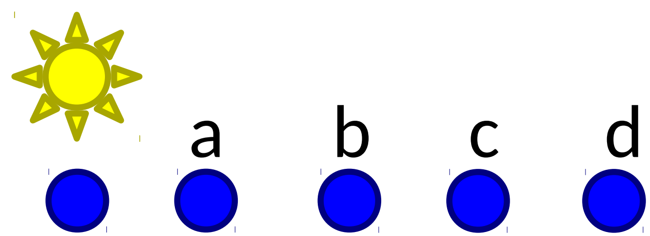


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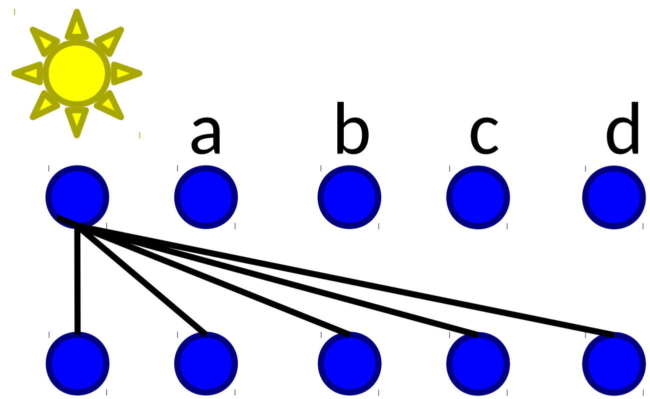


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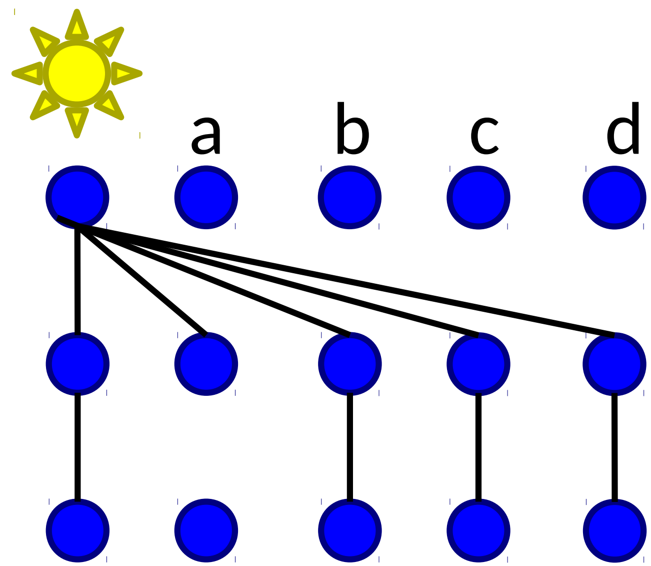

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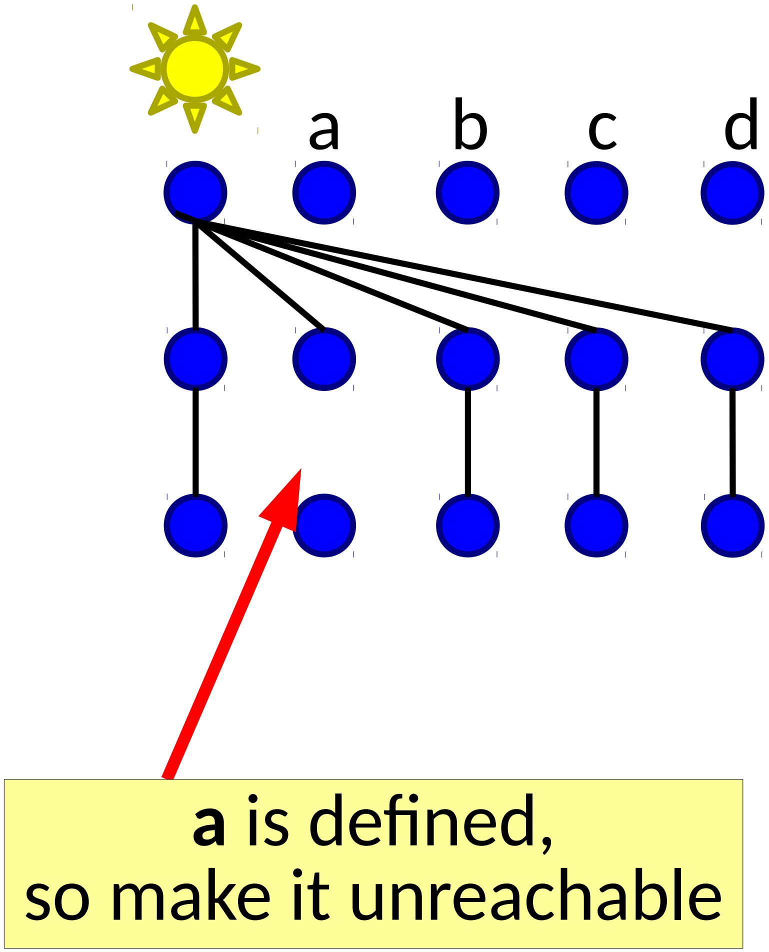

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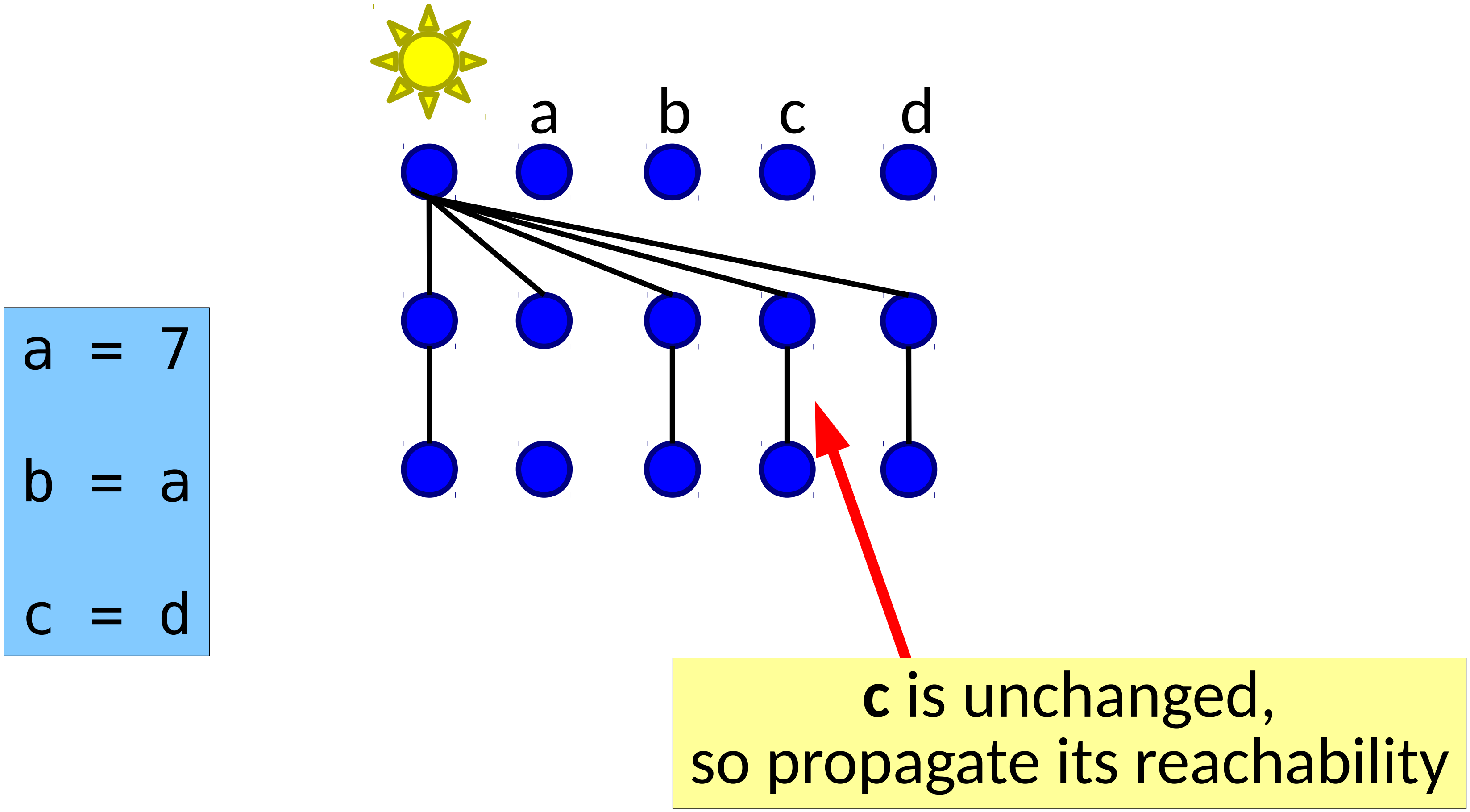

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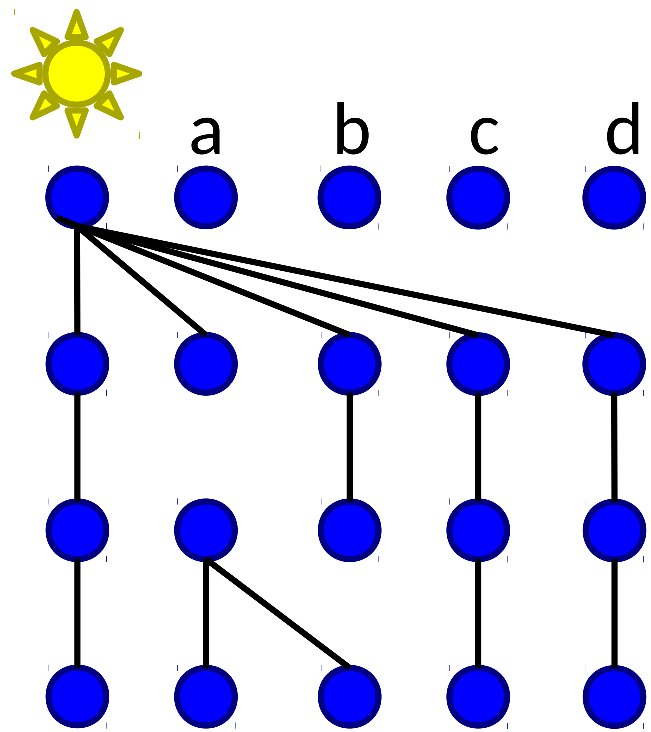

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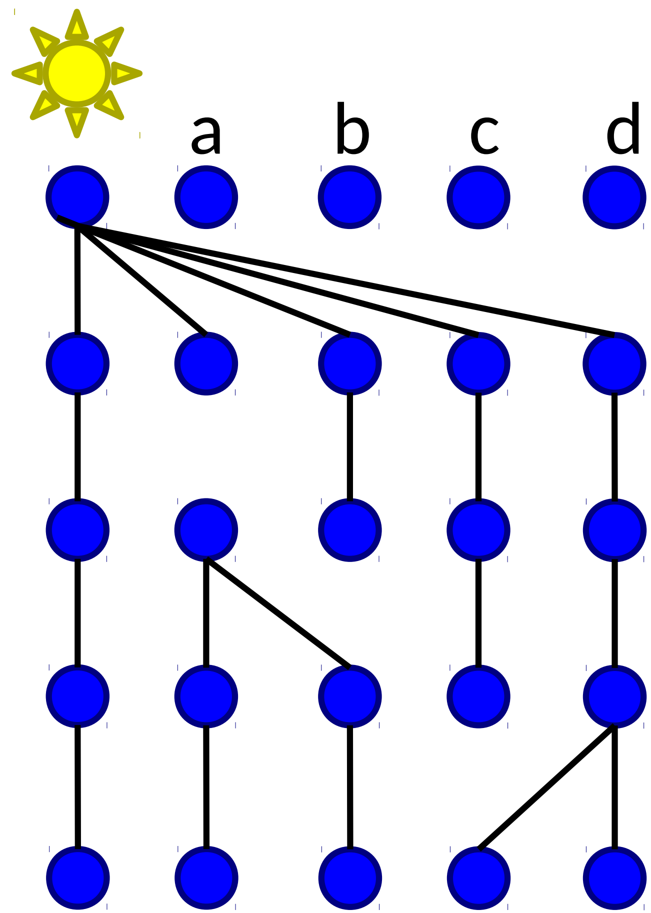

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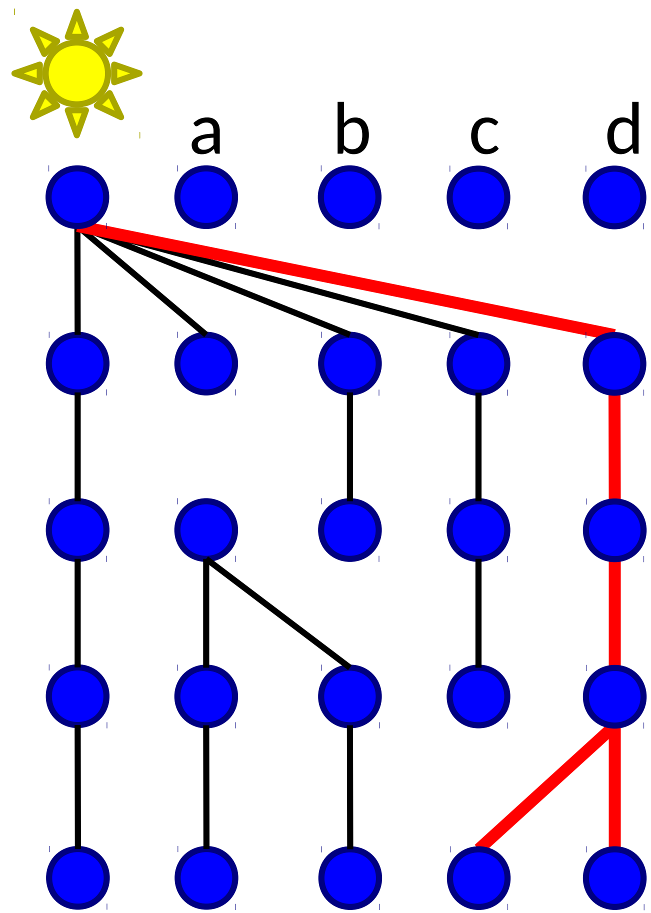

c and **d** are reachable here.
They are undefined at this point.

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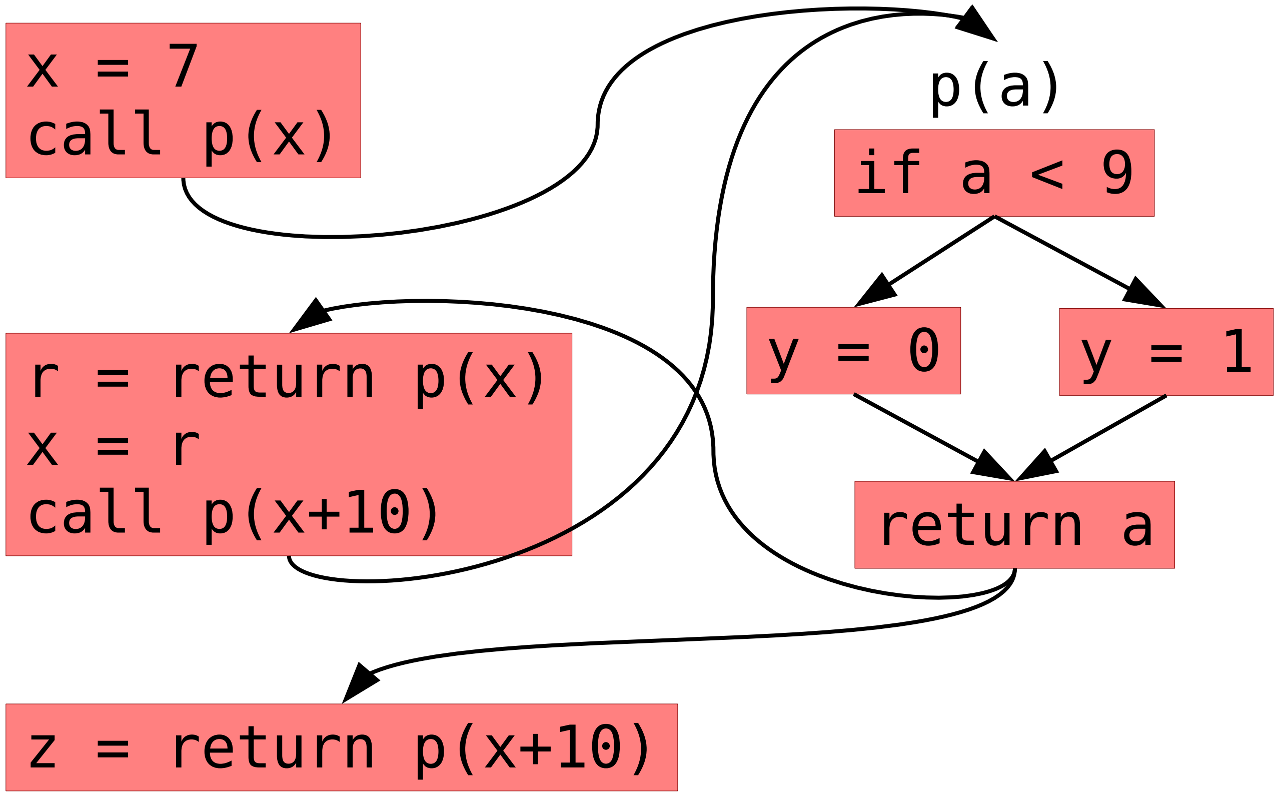

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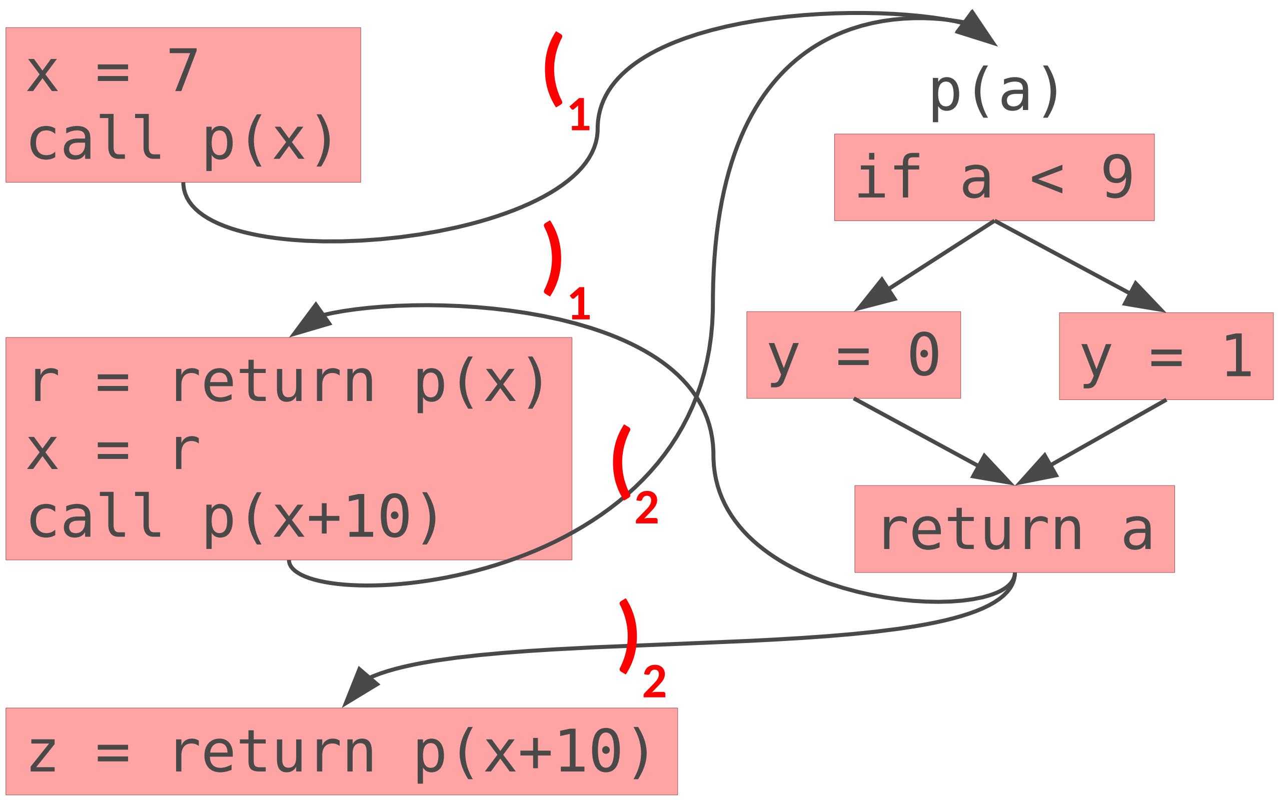

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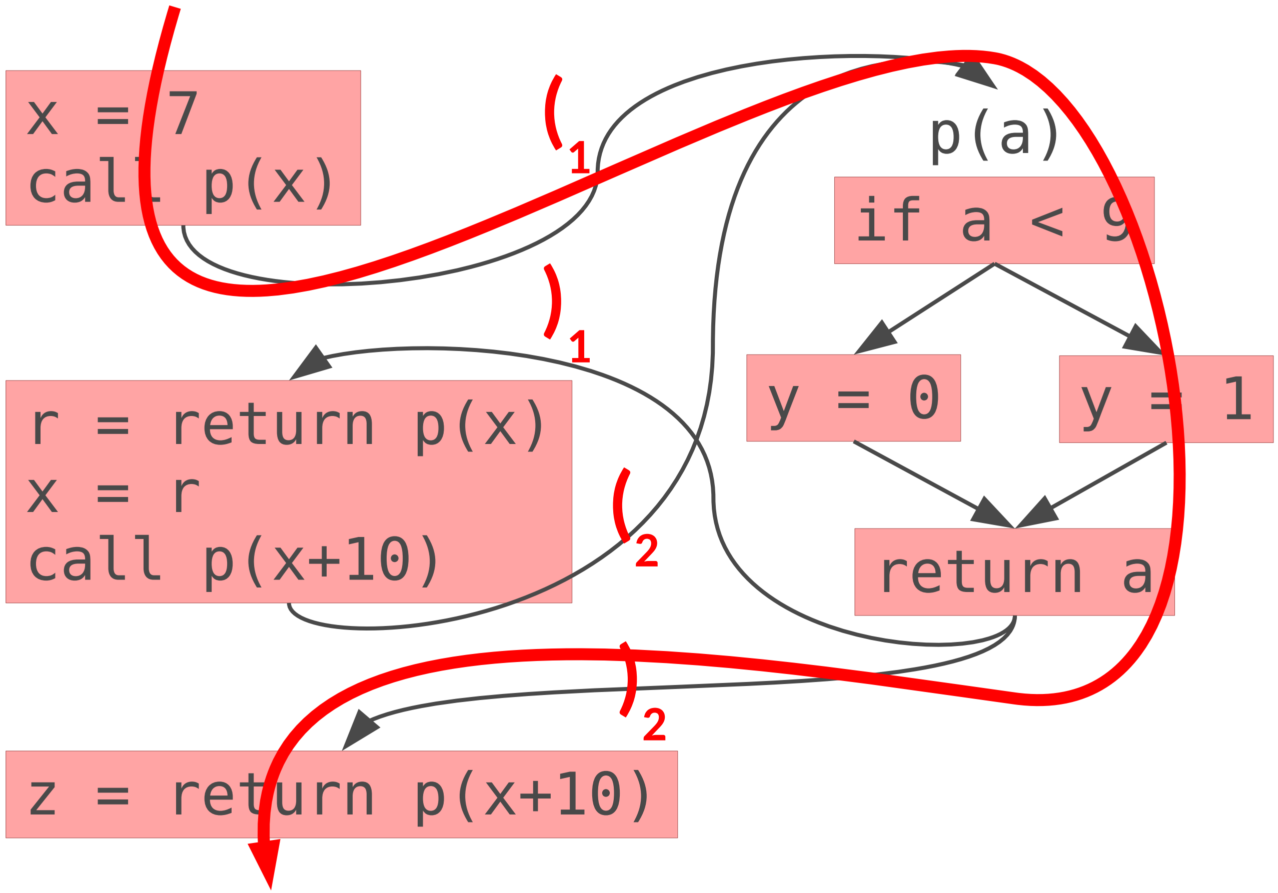

string: $(_1\ )_2$

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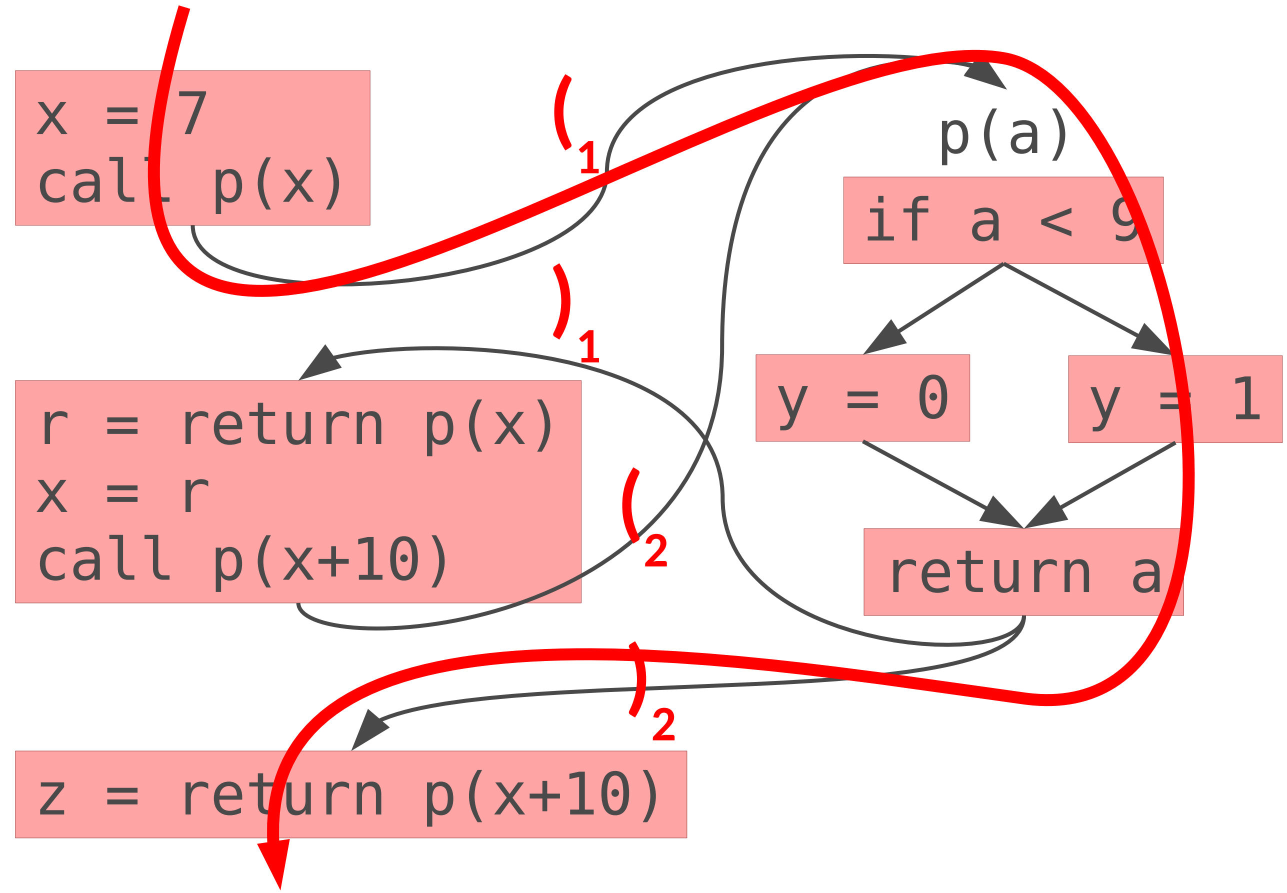

string: $(_1\ )_2$ unreachable

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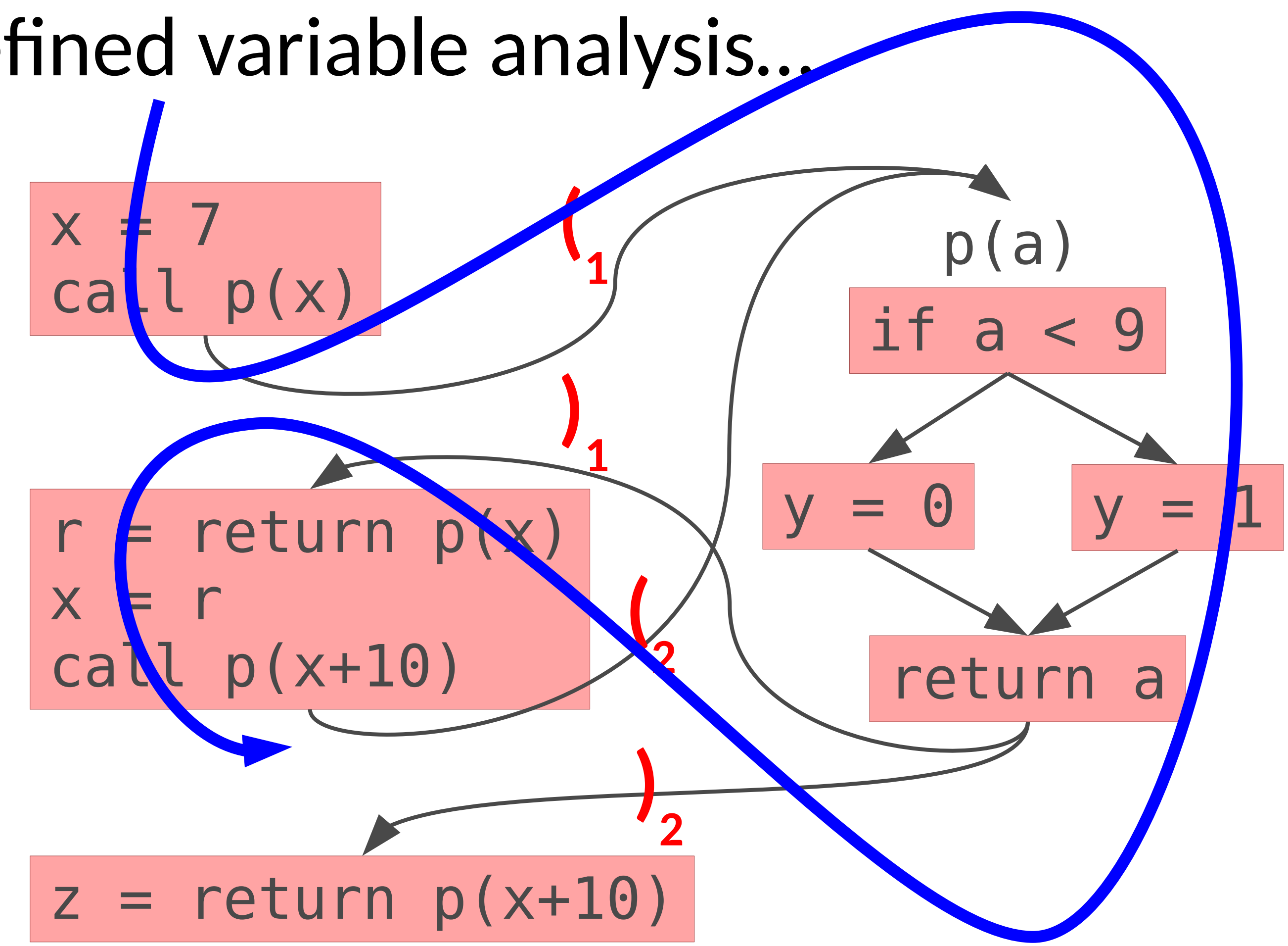

string: $(_1\ )_1$

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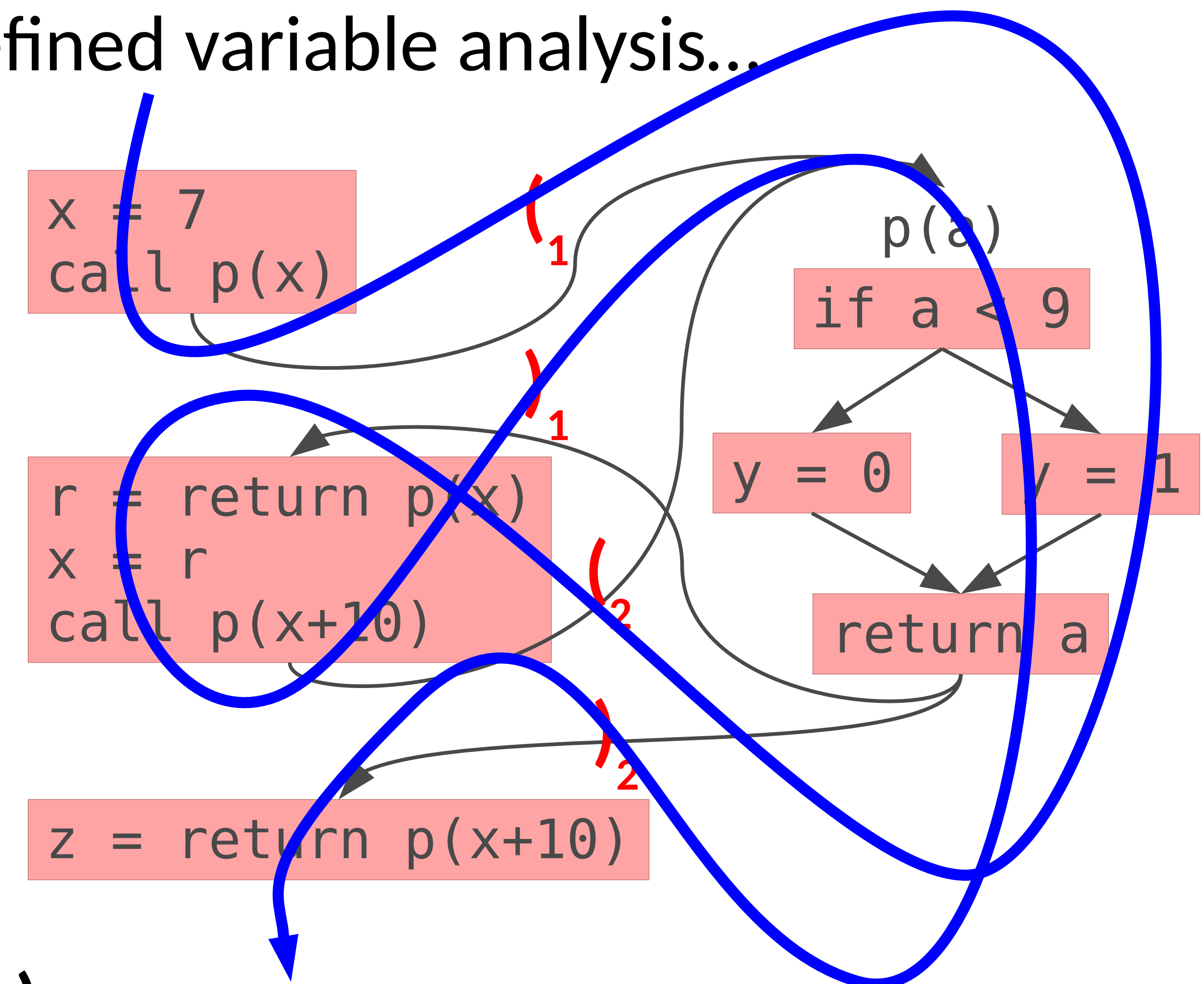

string: $(_1\ )_1(_2)_2$

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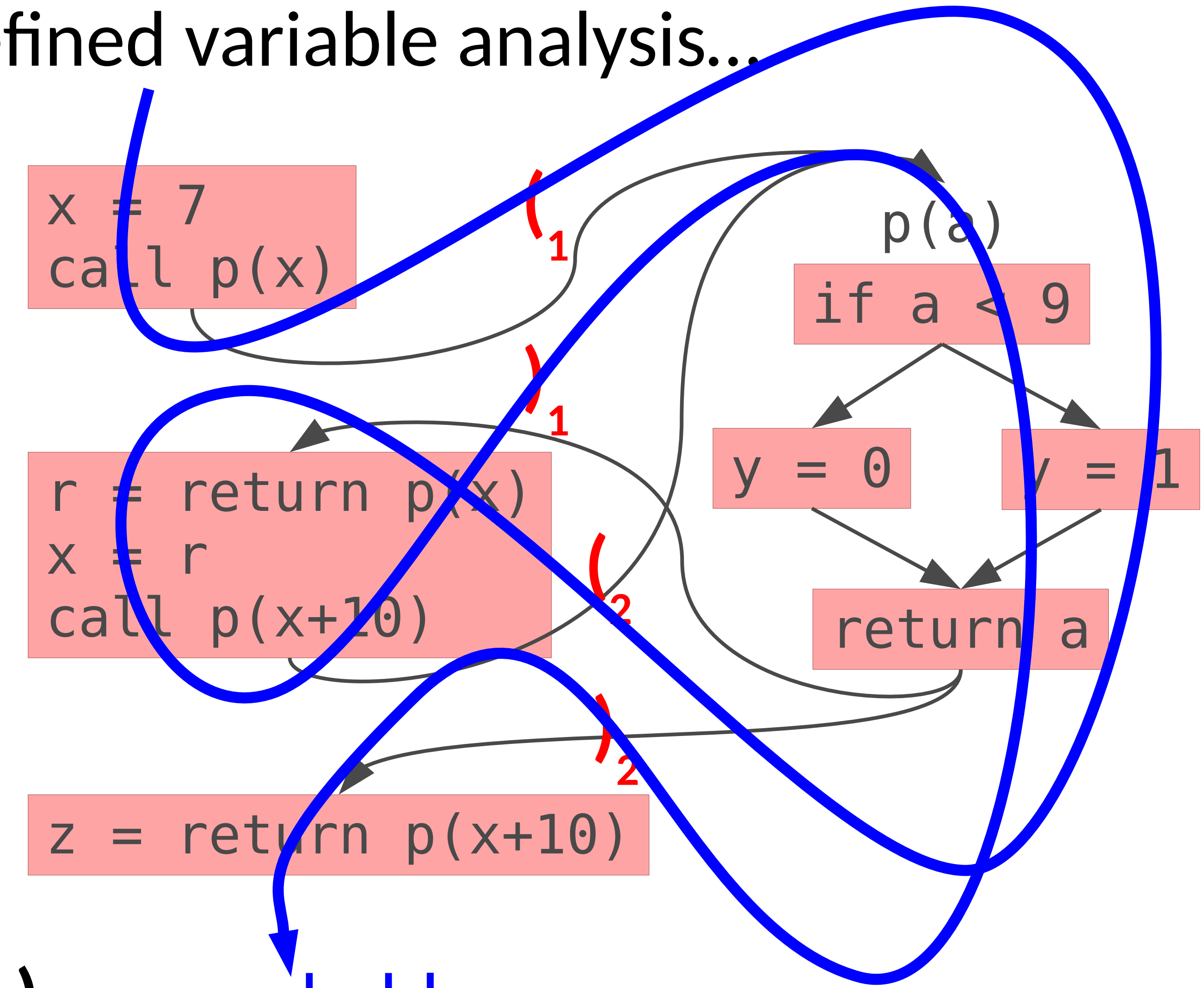

string: $(_1\ )_1(_2\ )_2$ reachable

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    y = 1
```
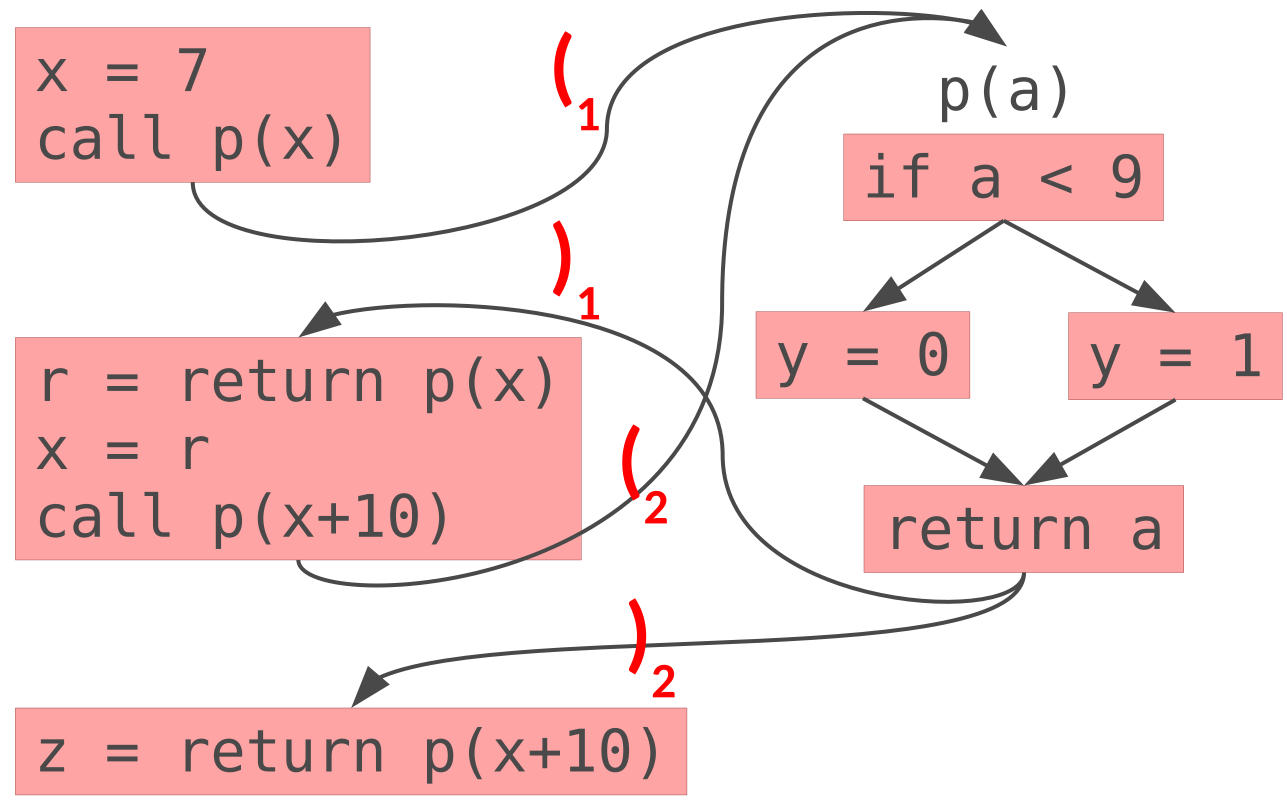
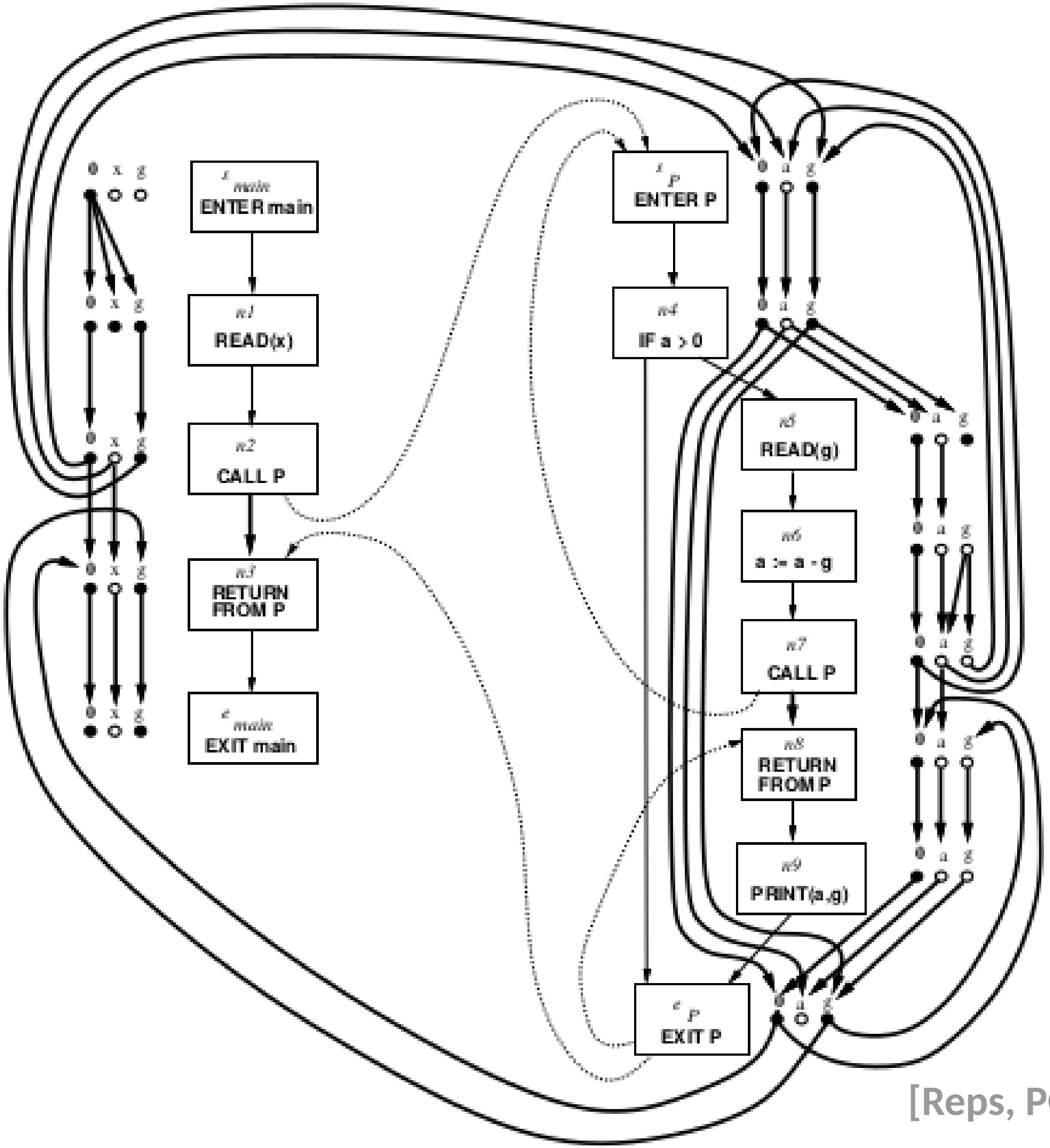



- A fact f holds before a node if f is *CFL-Reachable* in a language of matched parentheses

Context Sensitivity - IFDS



[Reps, POPL 1995]

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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

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- 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.

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  - May my program ever …?
- Dataflow analysis is one common form of static analysis