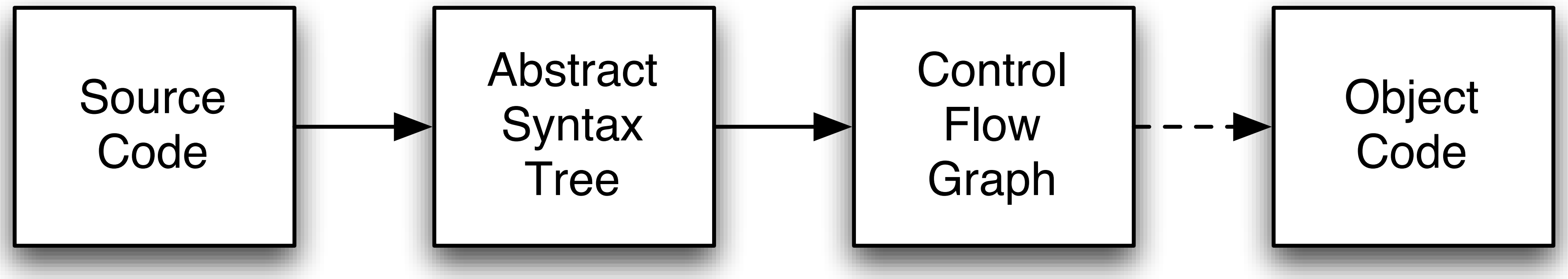
CMSC 631 — Program Analysis and Understanding

Data Flow Analysis

Data Flow Analysis

- A framework for proving facts about programs
- Reasons about lots of little facts
- Little or no interaction between facts
  - Works best on properties about *how* program computes
- Based on all paths through program
  - Including infeasible paths

Compiler Structure



- Source code parsed to produce AST
- AST transformed to CFG
- Data flow analysis operates on control flow graph (and other intermediate representations)
  - Symbolic execution often uses the AST

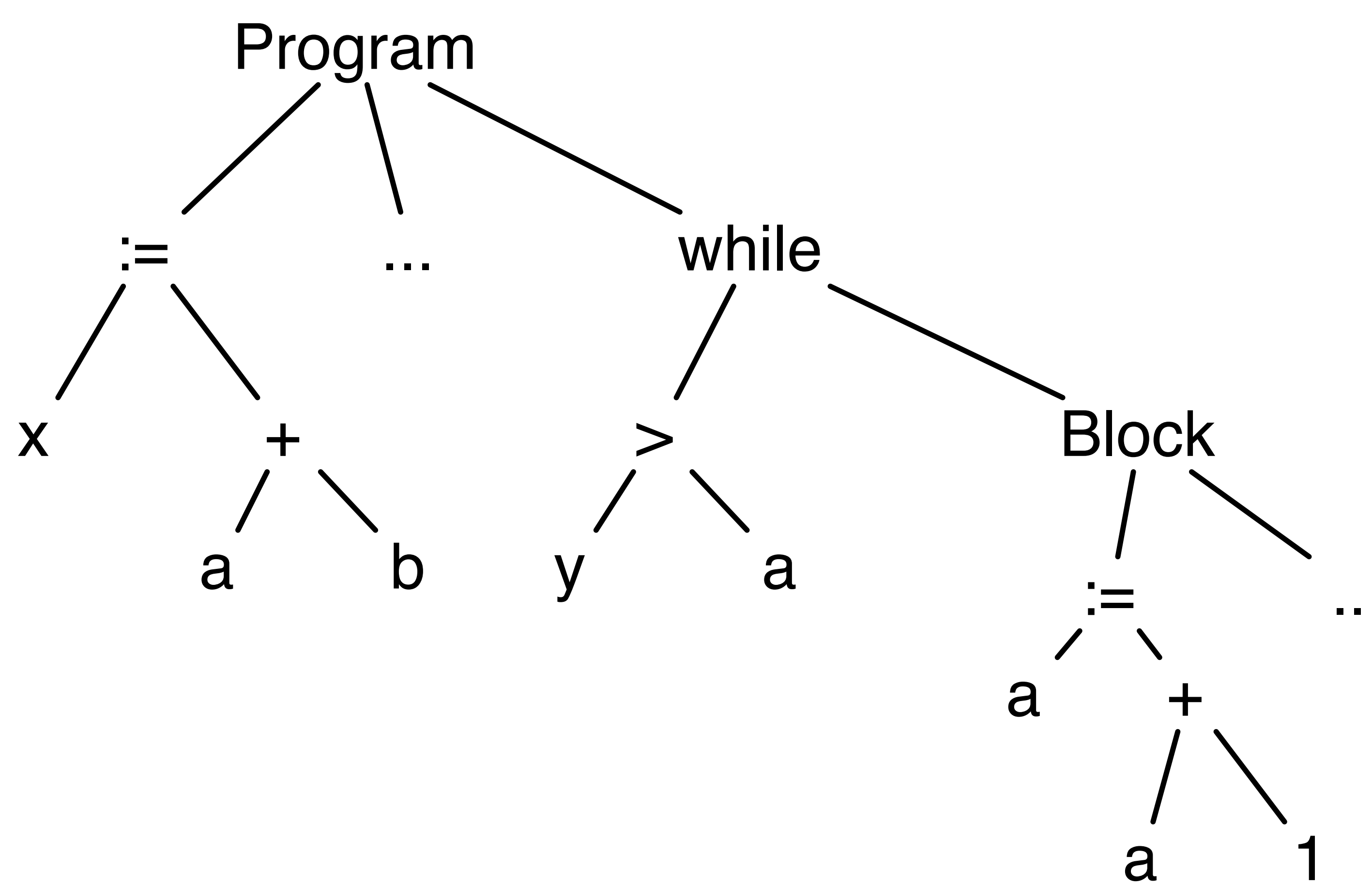
Abstract Syntax Tree (AST)

- Programs are written in text
  - I.e., sequences of characters
  - Awkward to work with

- First step: Convert to structured representation
  - Use lexer (like flex) to recognize *tokens*
    - Sequences of characters that make words in the language
  - Use parser (like bison) to group words structurally
    - And, often, to produce AST

Abstract Syntax Tree Example

```
x := a + b;
y := a * b;
while (y > a) {
    a := a + 1;
    x := a + b
}
```



ASTs

- ASTs are *abstract*
  - They don't contain all information in the program
    - E.g., spacing, comments, brackets, parentheses
  - Any ambiguity has been resolved
    - E.g., a + b + c produces the same AST as (a + b) + c

- For more info, see CMSC 430
  - In this class, we will generally begin at the AST level

Disadvantages of ASTs

- AST has many similar forms
  - E.g., for, while, repeat...until
  - E.g., if, ?:, switch
- Expressions in AST may be complex, nested
  - (42 * y) + (z > 5 ? 12 * z : z + 20)
- Want simpler representation for analysis
  - ...at least, for dataflow analysis

Control-Flow Graph (CFG)

- A directed graph where
  - Each node represents a statement
  - Edges represent control flow

- Statements may be
  - Assignments x := y op z or x := op z
  - Copy statements x := y
  - Branches goto L or if x relop y goto L
  - etc.

Control-Flow Graph Example

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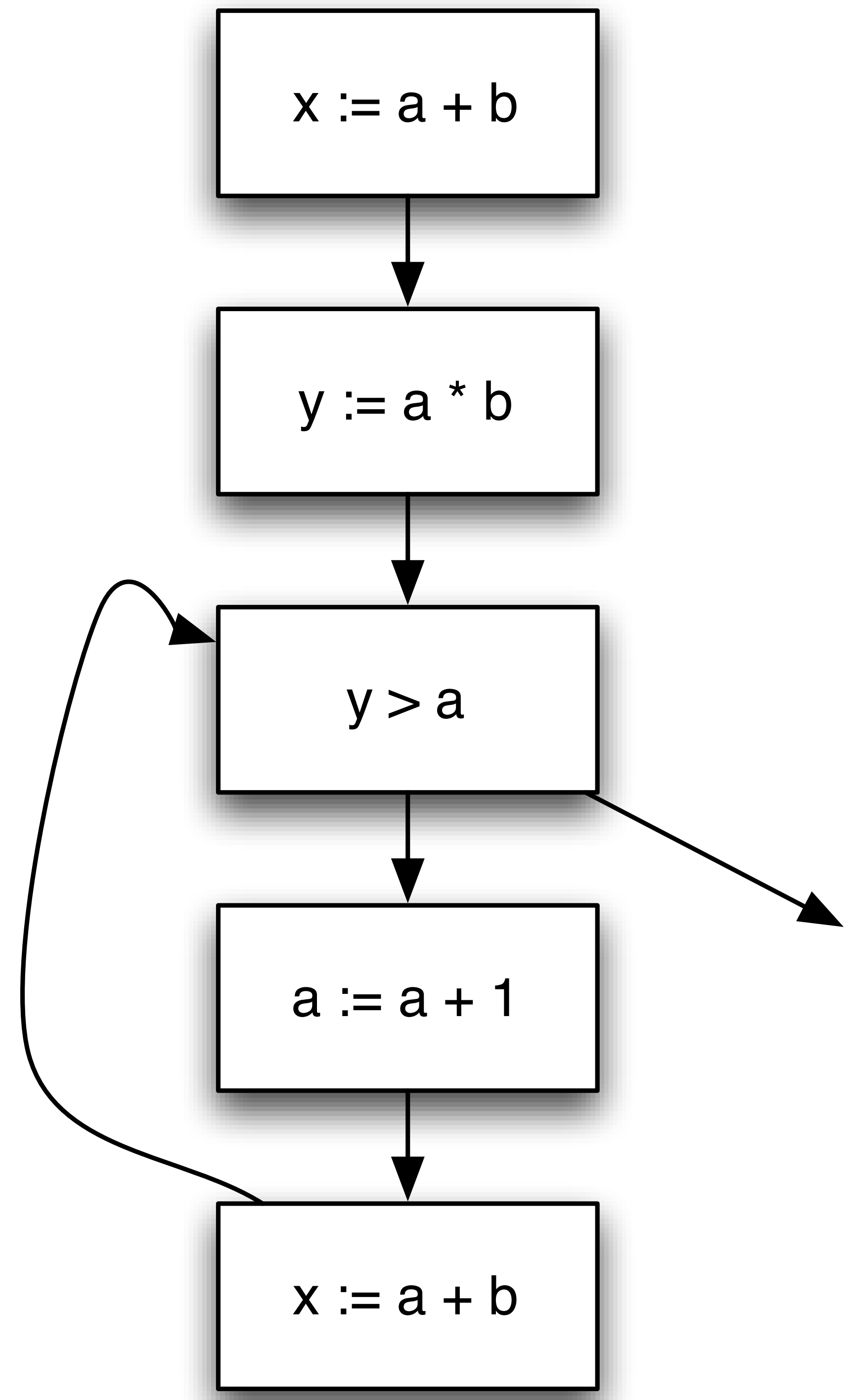
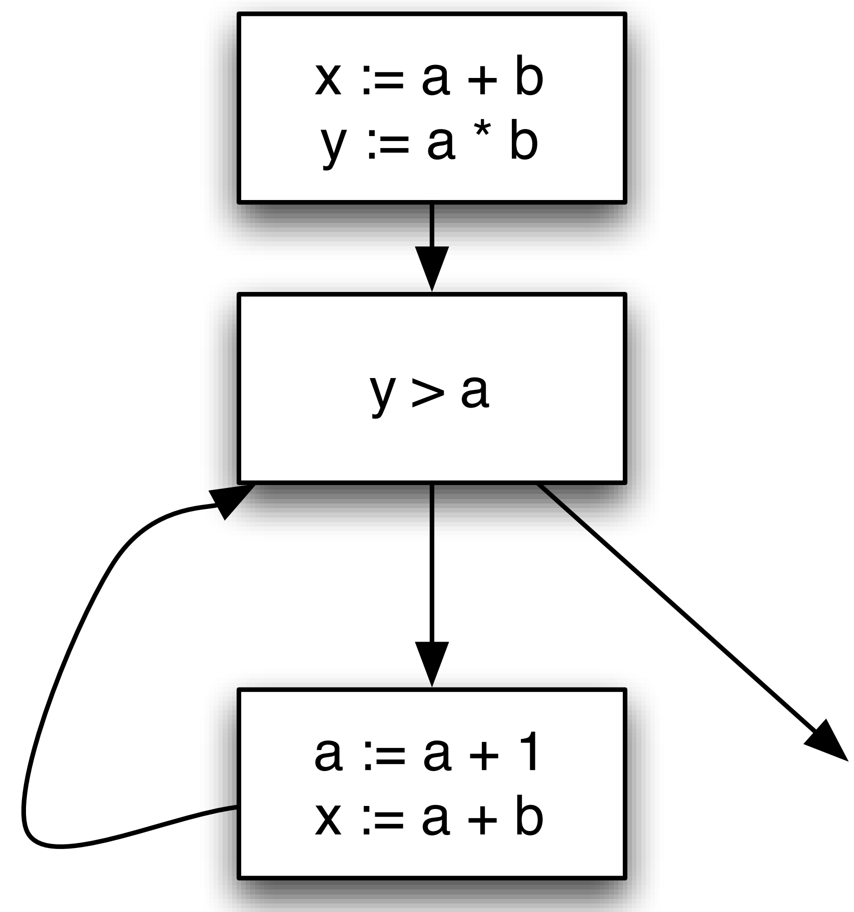


Variations on CFGs

- We usually don’t include declarations (e.g., int x;)
  - But there’s usually something in the implementation
- May want a unique entry and exit node
  - Won’t matter for the examples we give
- May group statements into basic blocks
  - A sequence of instructions with no branches into or out of the block

Control-Flow Graph w/Basic Blocks

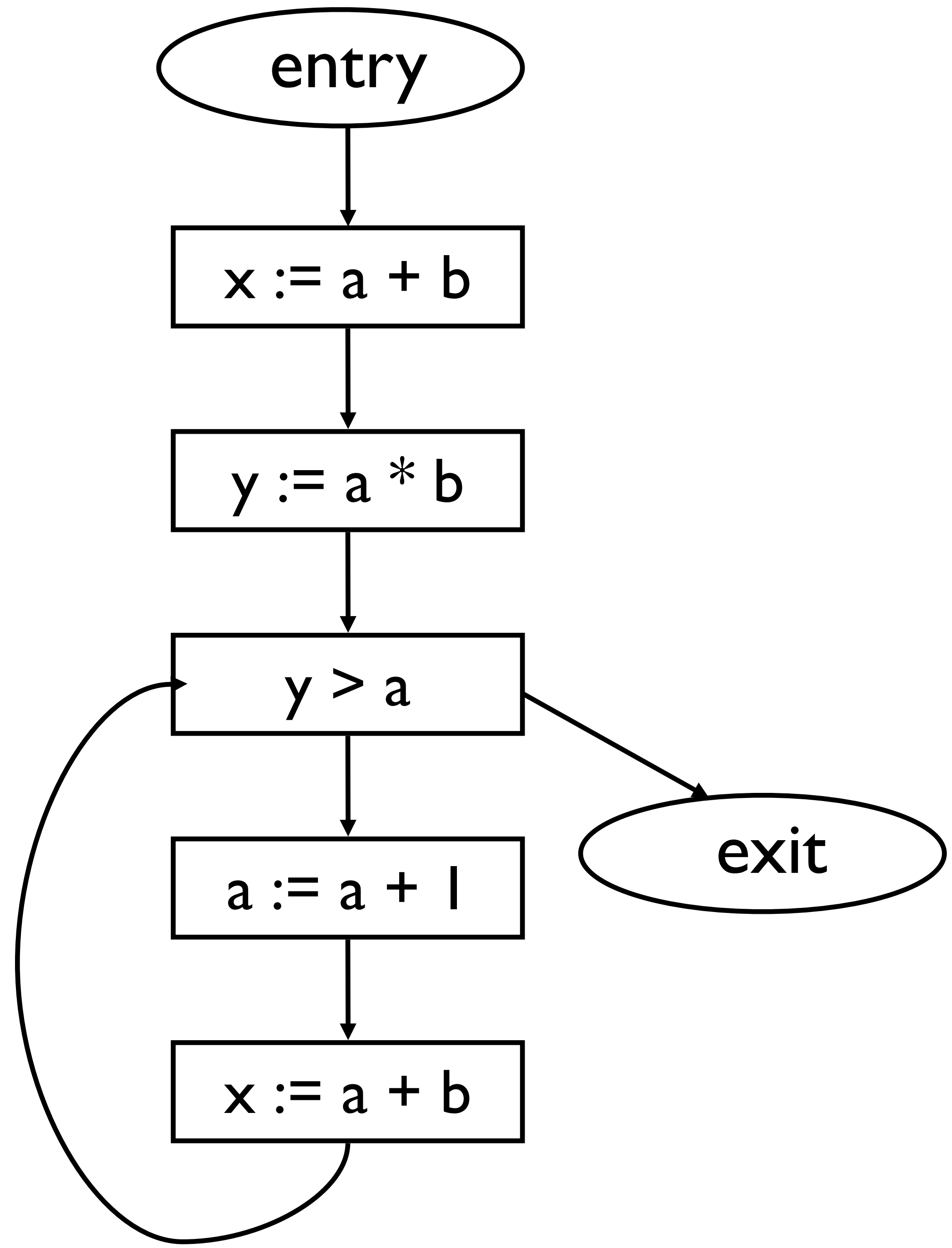
```
x := a + b;
y := a * b;
while (y > a + b) {
   a := a + 1;
   x := a + b
}
```



- Can lead to more efficient implementations
- But more complicated to explain, so...
  - We'll use single-statement blocks in lecture today

Graph Example with Entry and Exit

```
x := a + b;
y := a * b;
while (y > a) {
    a := a + 1;
    x := a + b
}
```



- All nodes without a (normal) predecessor should be pointed to by entry
- All nodes without a successor should point to exit

CFG vs. AST

- CFGs are much simpler than ASTs
  - Fewer forms, less redundancy, only simple expressions
- But...AST is a more faithful representation
  - CFGs introduce temporaries
  - Lose block structure of program
- So for AST,
  - Easier to report errors and other messages
  - Easier to explain to programmer
  - Easier to unparse to produce readable code

Analysis: Available Expressions

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- An expression e is available at program point p if
  - e is computed on every path to p, and
  - the value of e has not changed since the last time e was computed on every path to p

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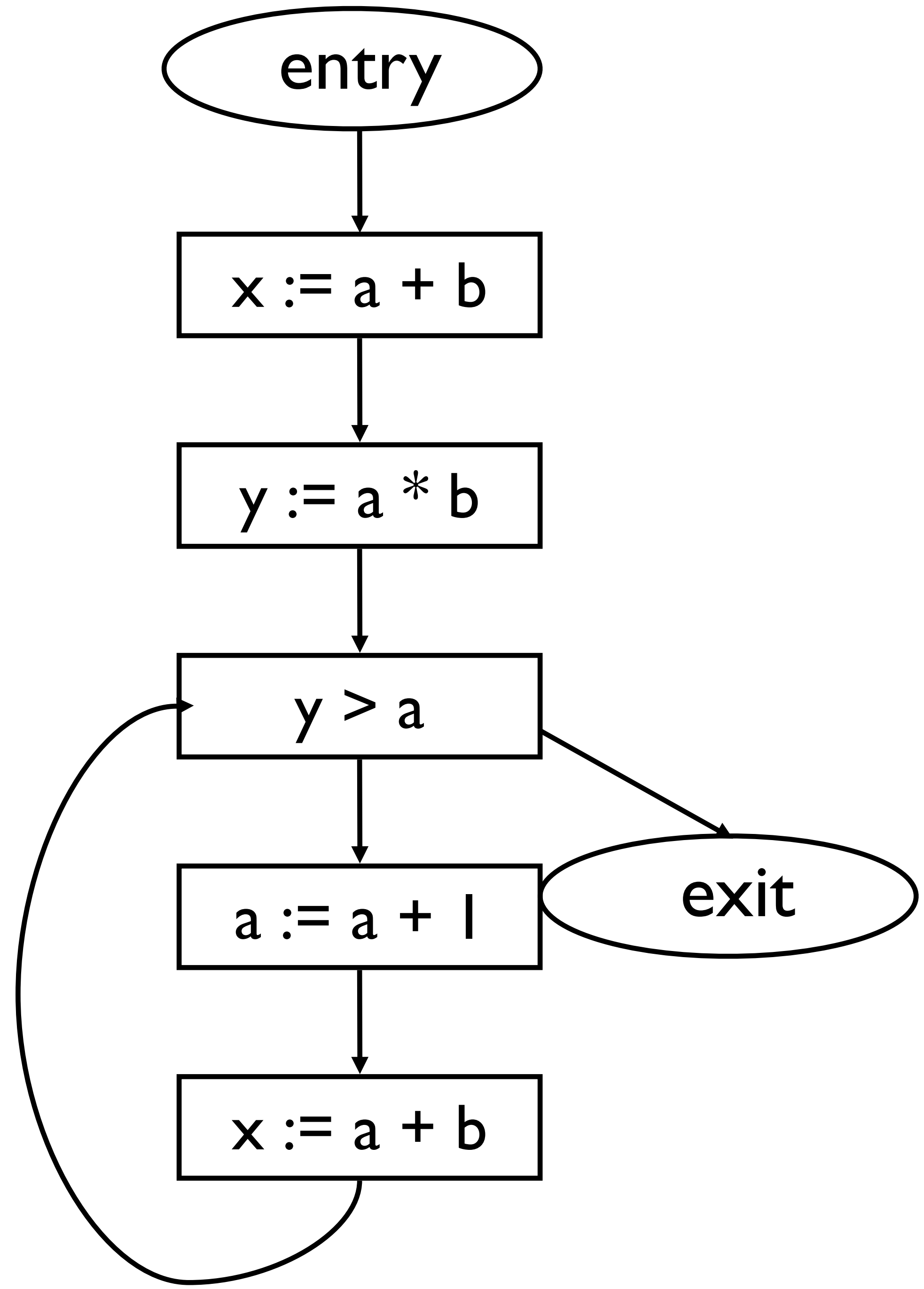
- Optimization
  - If an expression is available, need not be recomputed
    - (At least, if it's still in a register somewhere)

Data Flow Facts

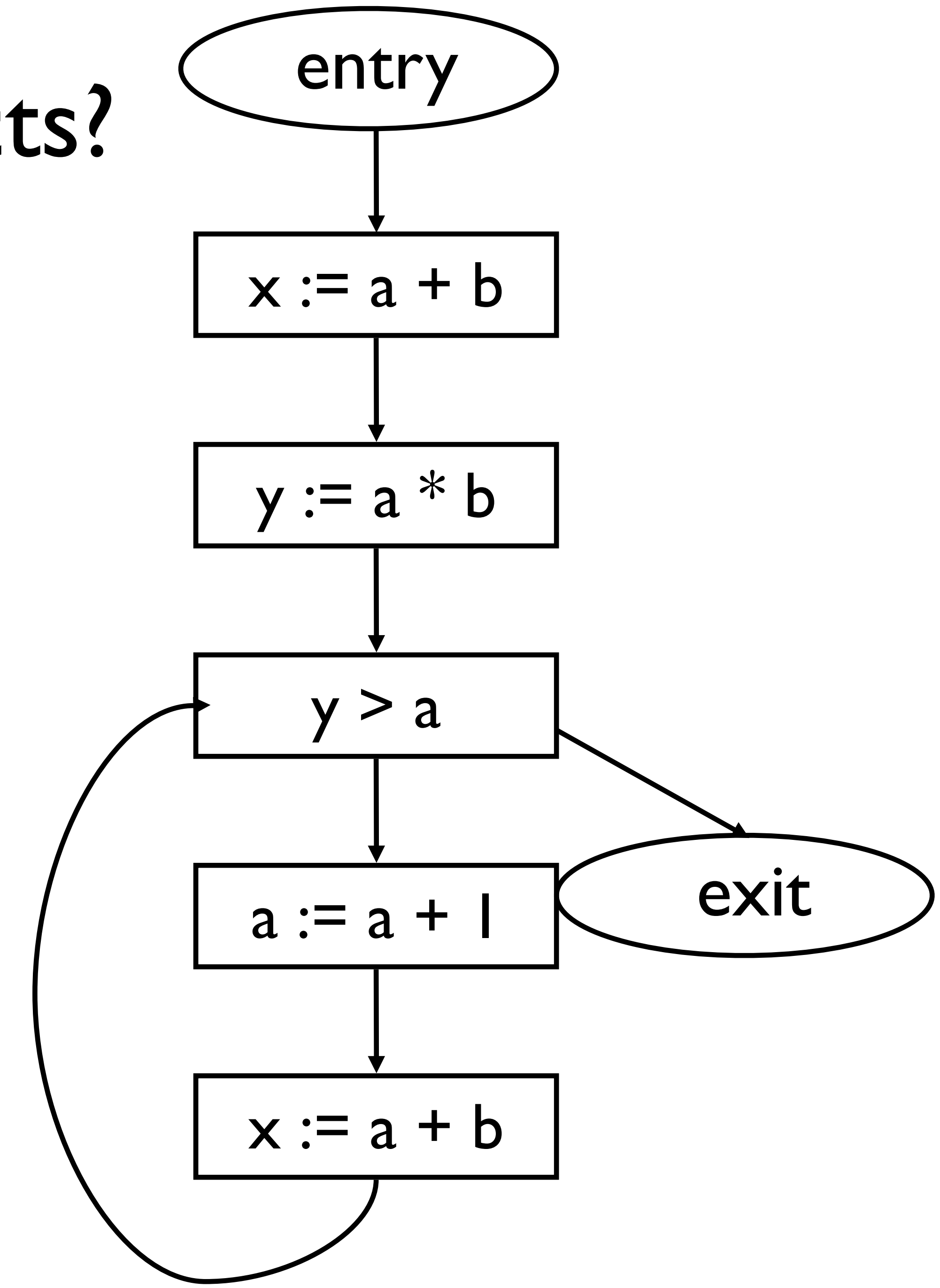
- Is expression e available?
- Facts:
  - a + b is available
  - a * b is available
  - a + 1 is available



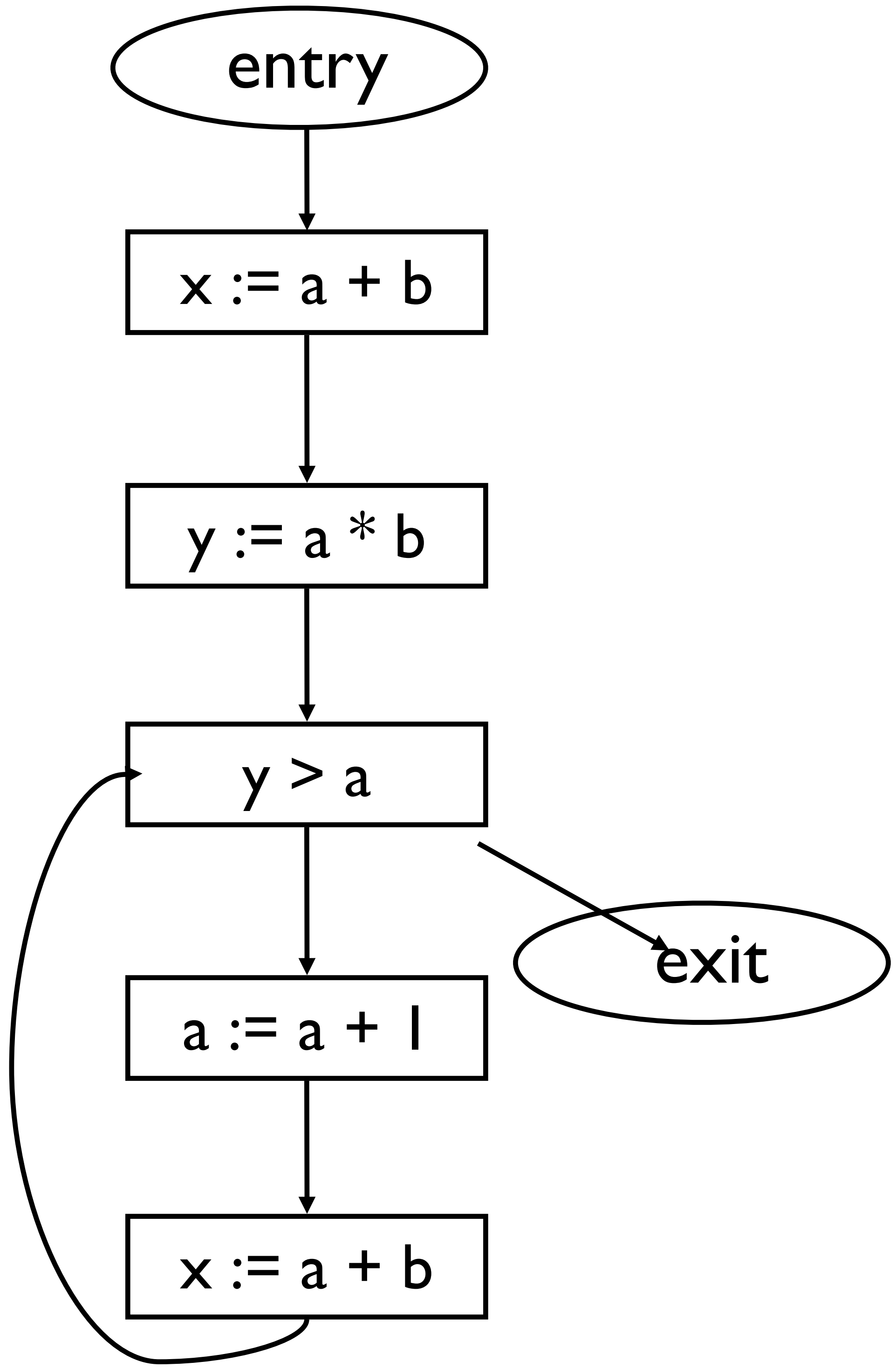
Gen and Kill

- What is the effect of each statement on the set of facts?

Stmt	Gen	Kill
x := a + b	a + b	
y := a * b	a * b	
a := a + 1		a + 1, a + b, a * b



Computing Available Expressions



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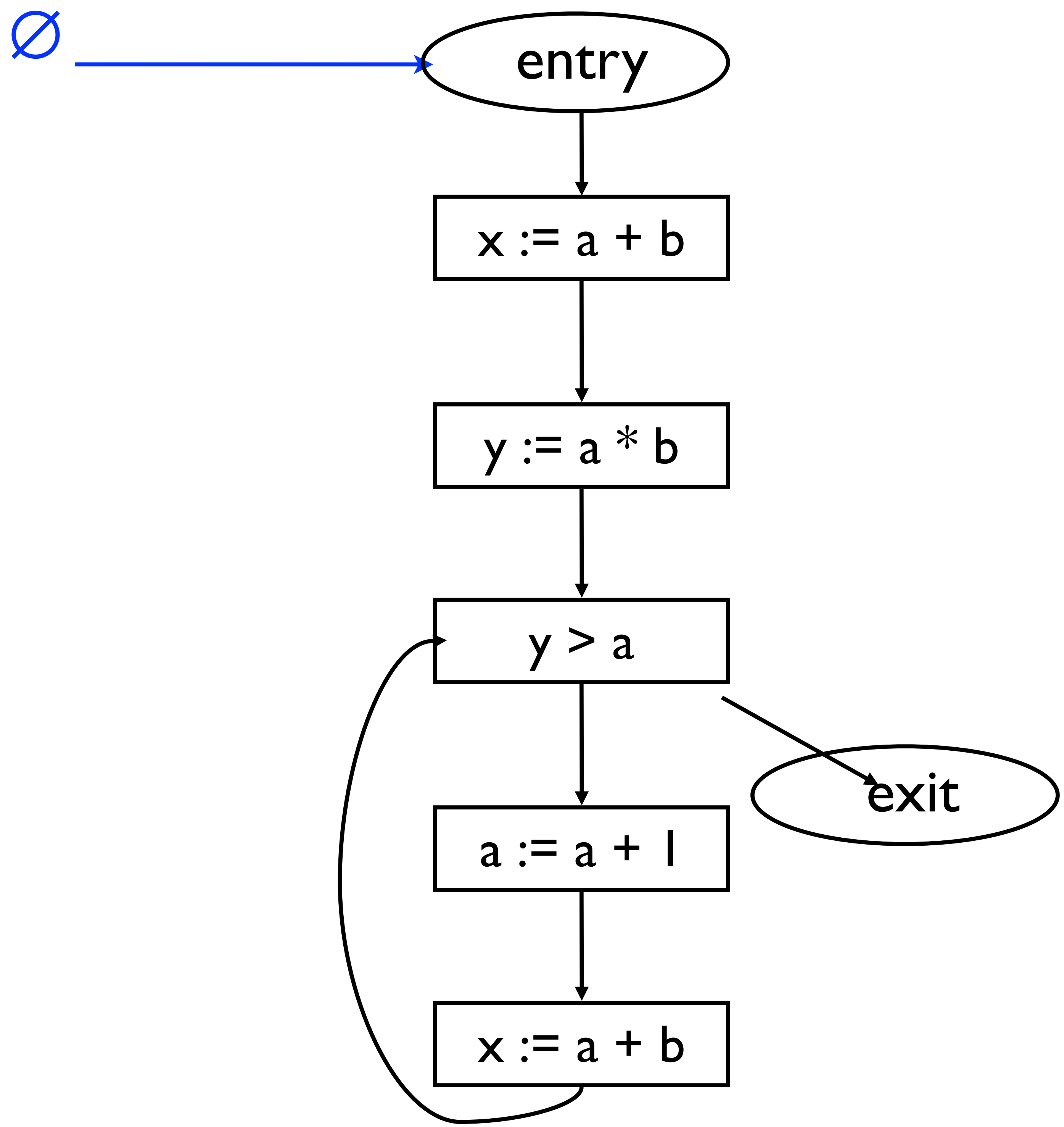

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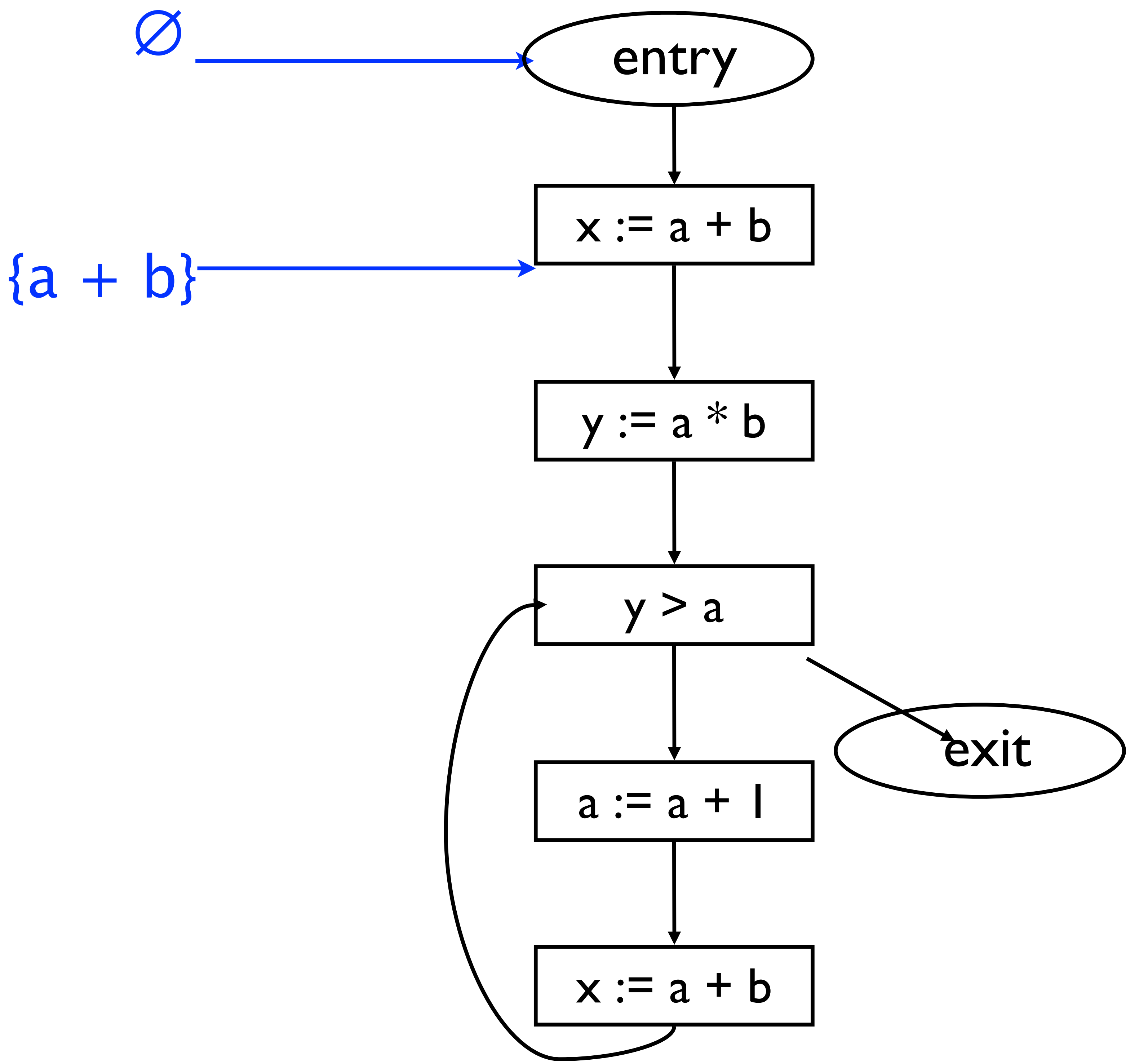

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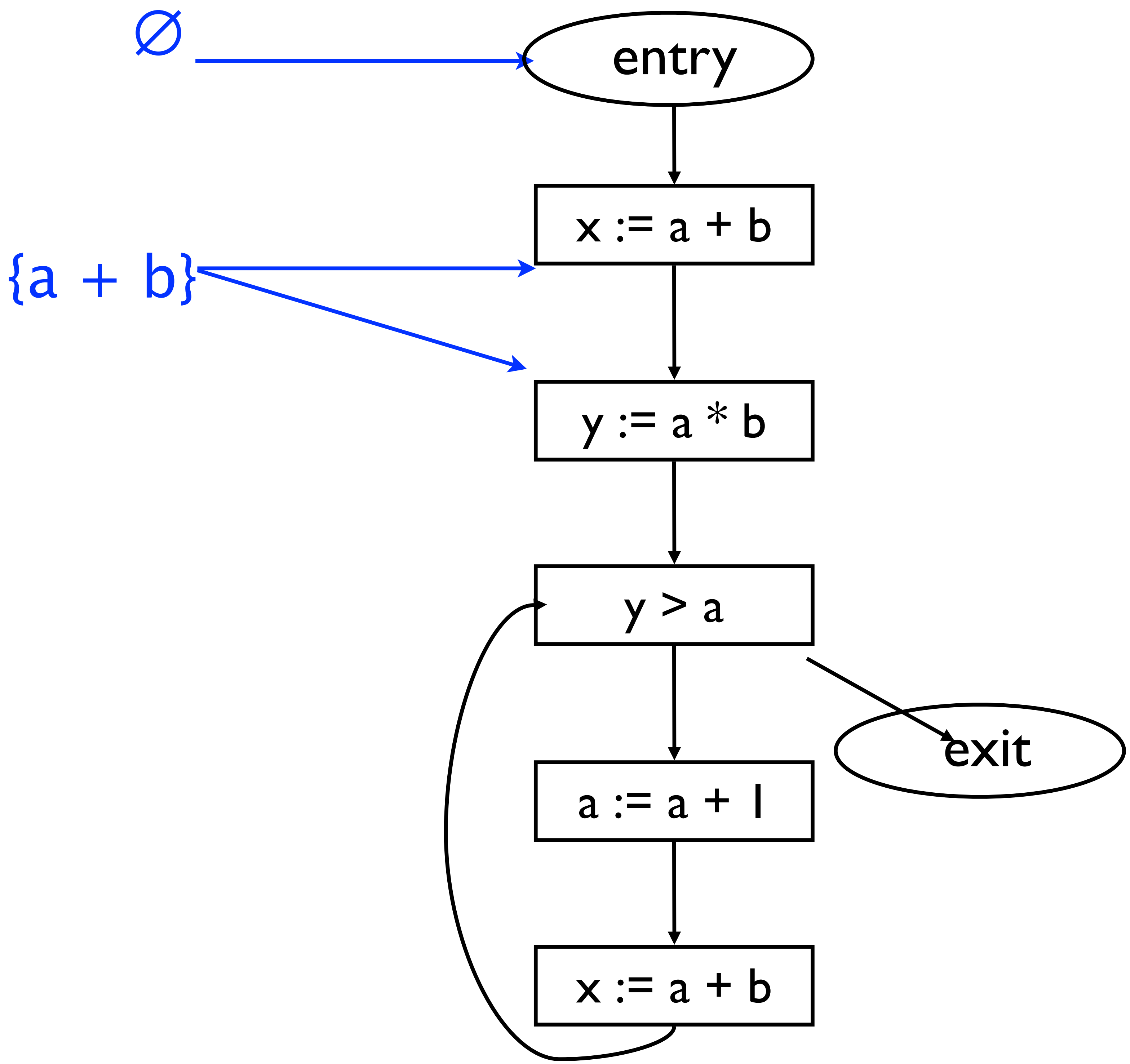

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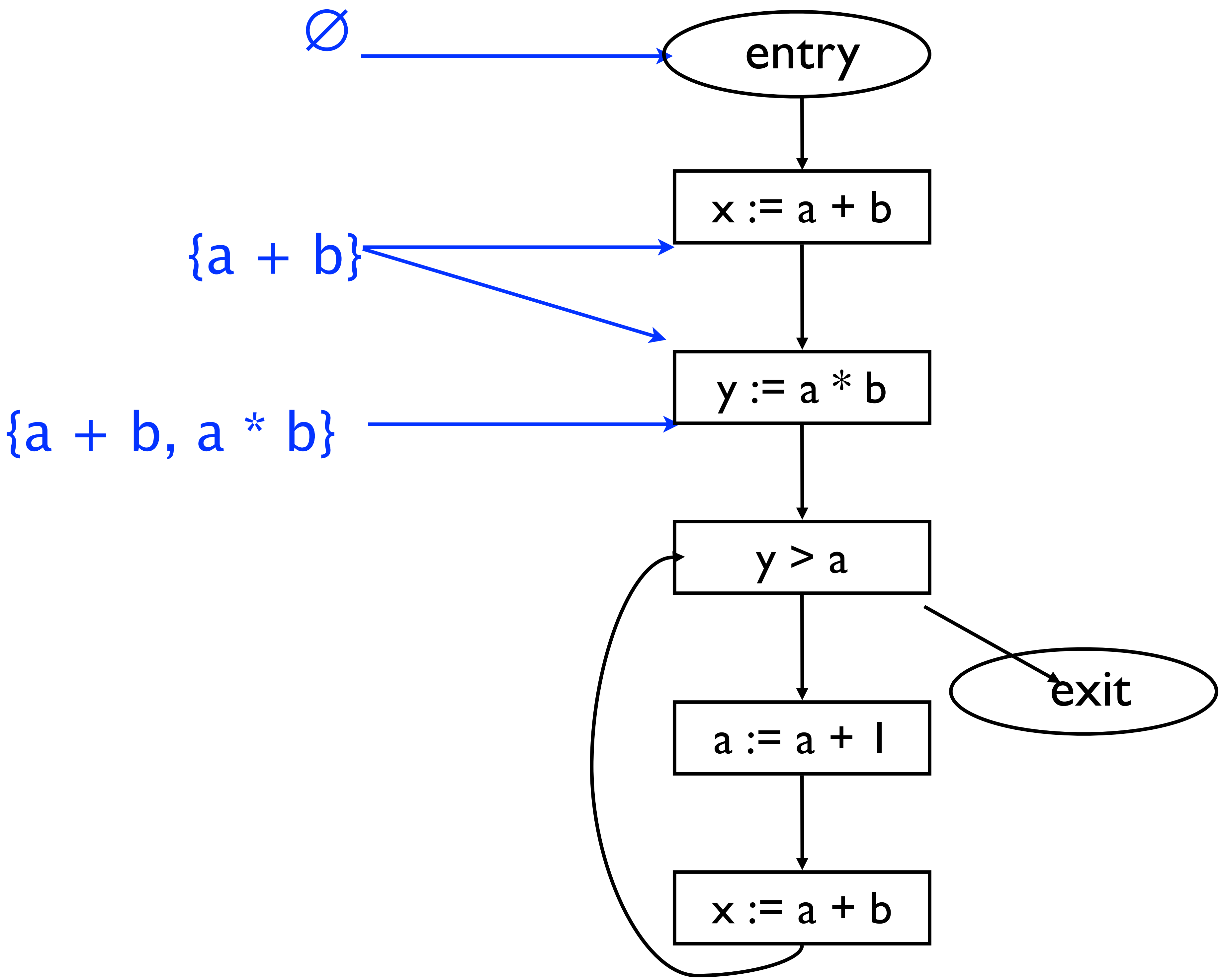

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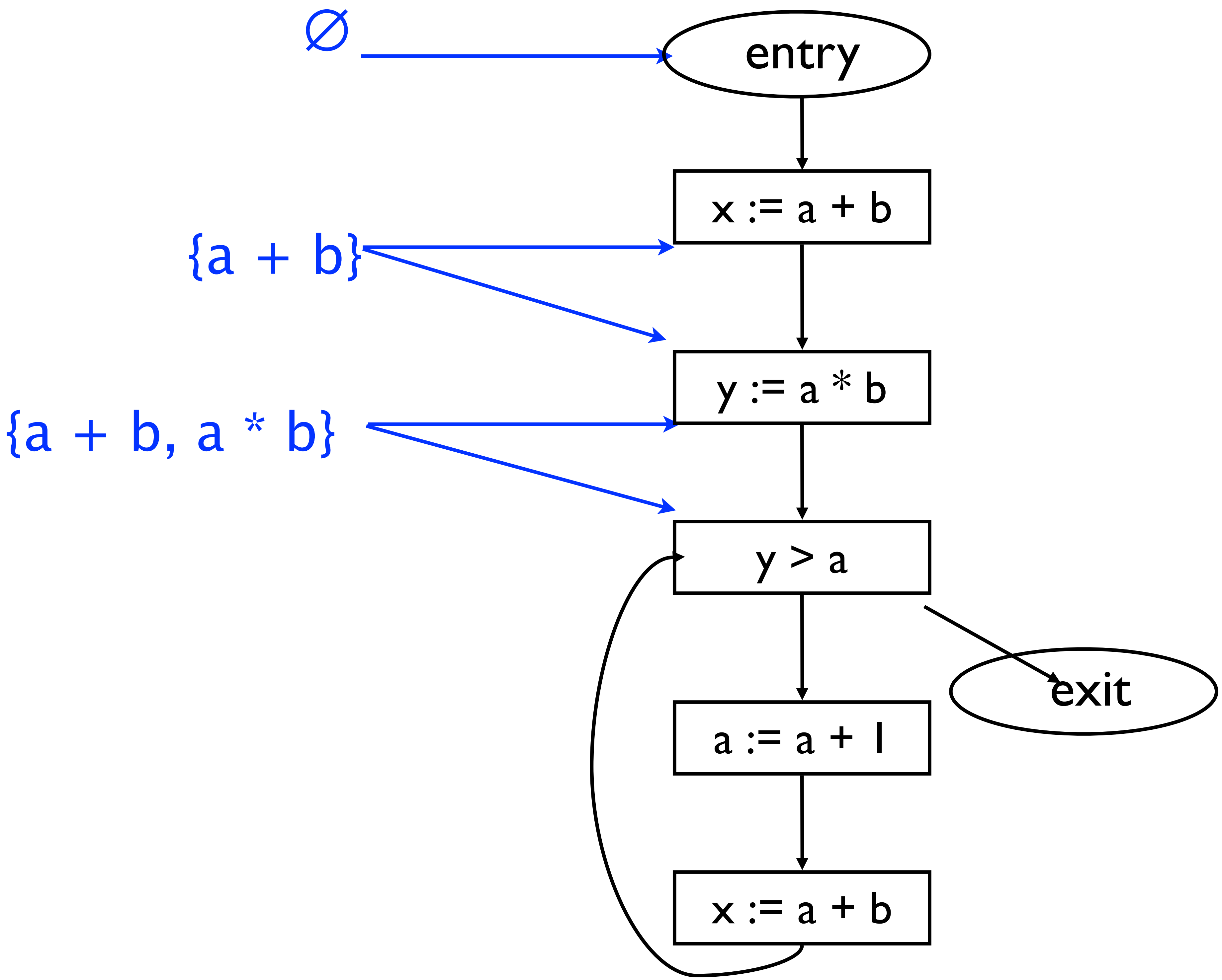

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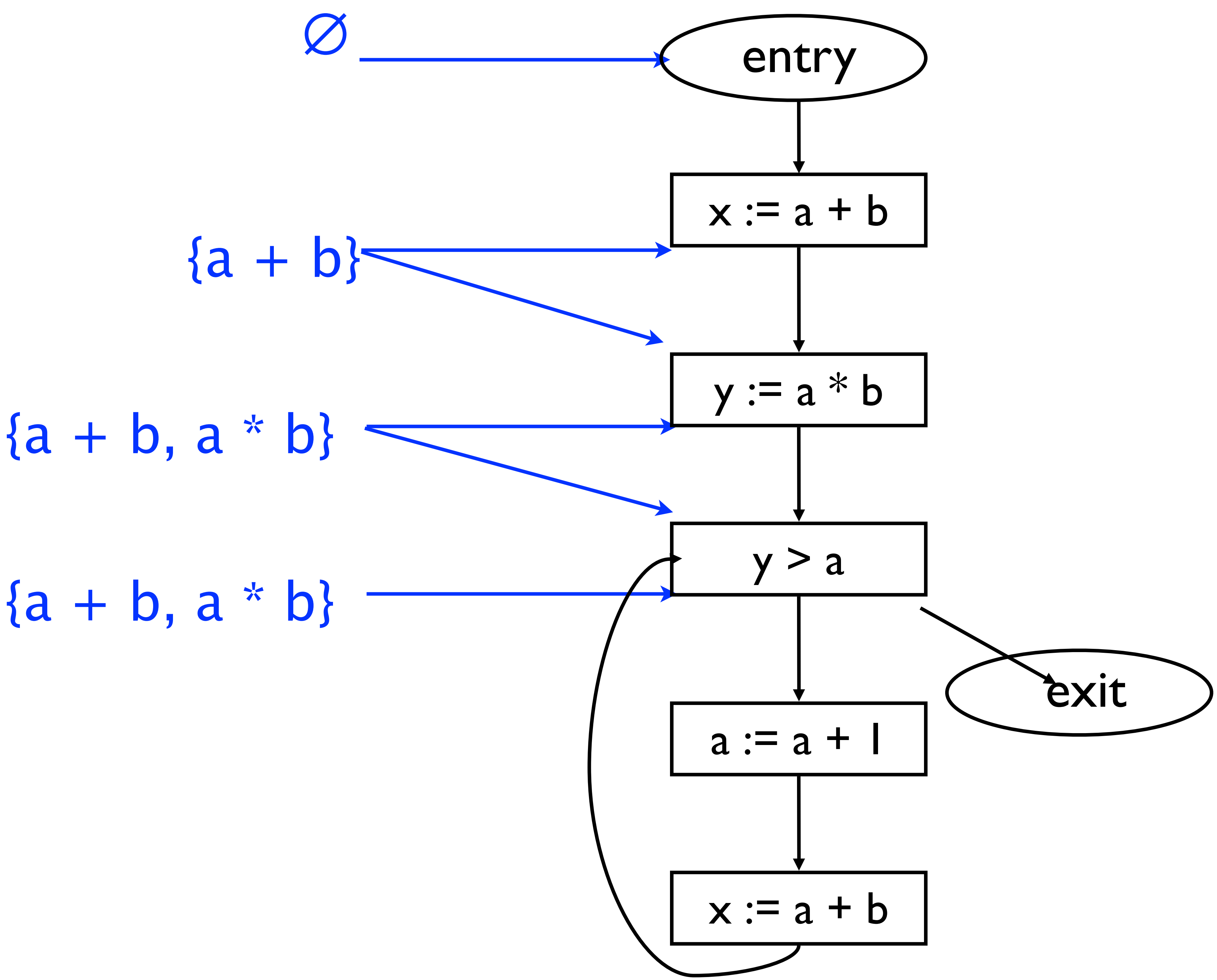

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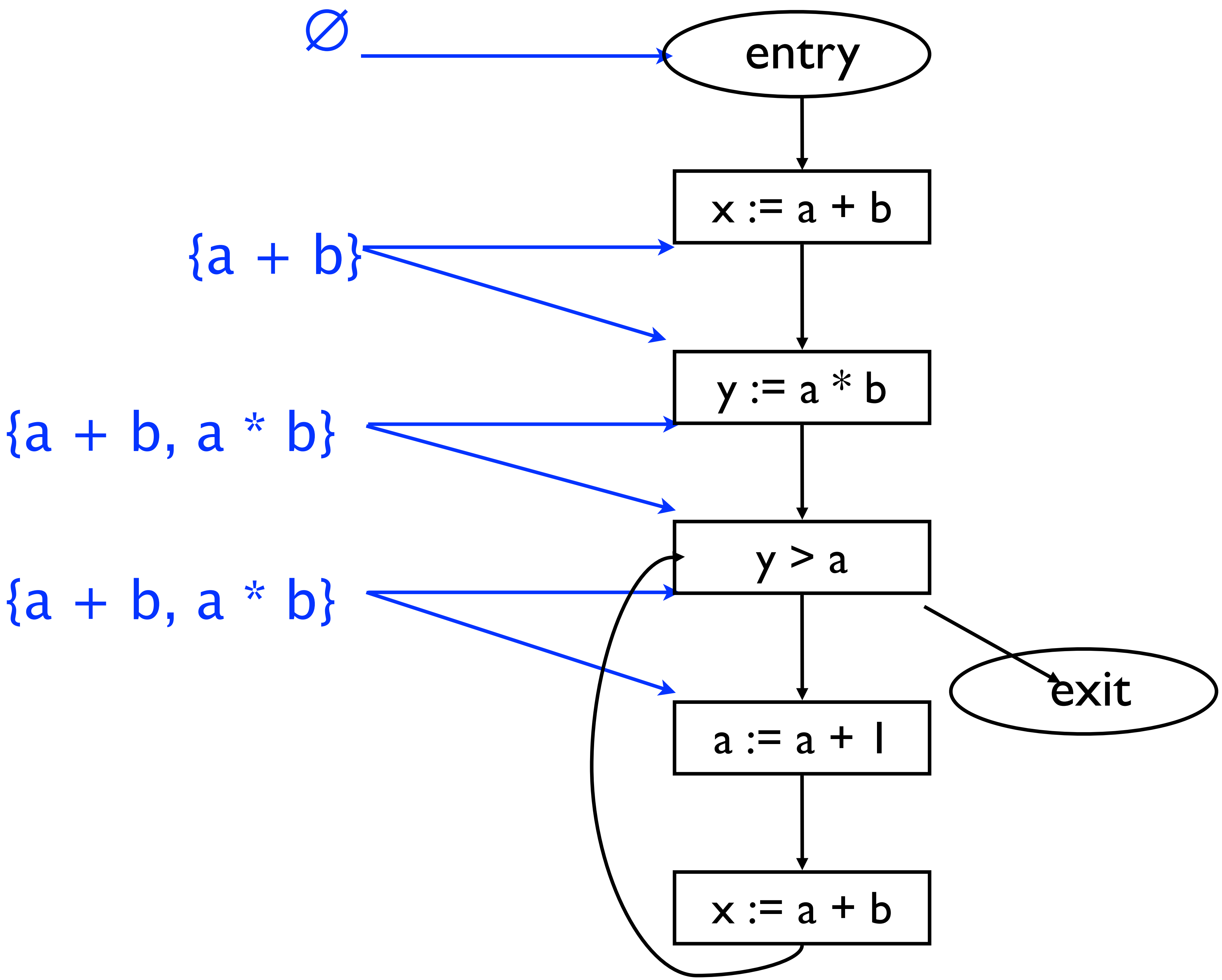

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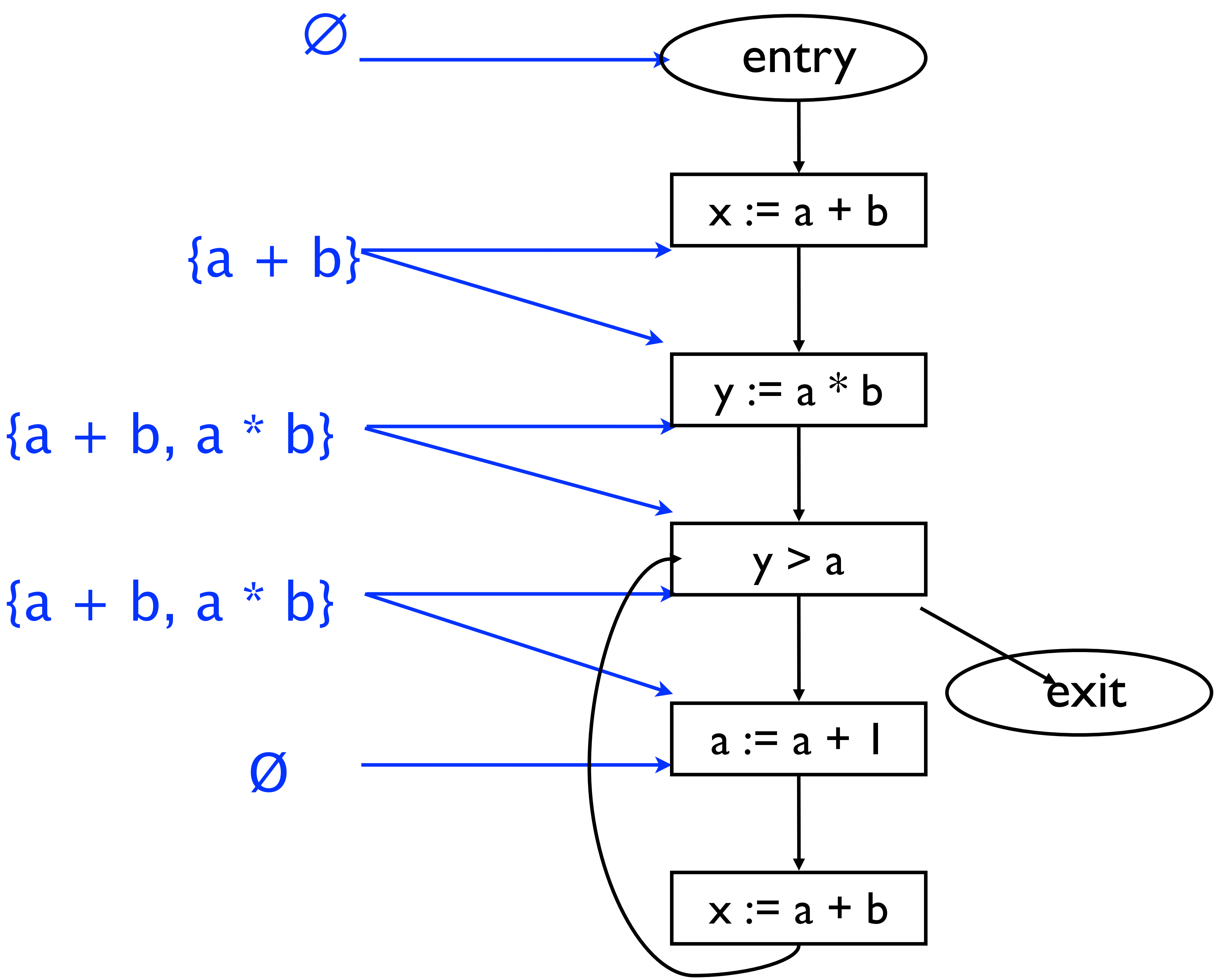

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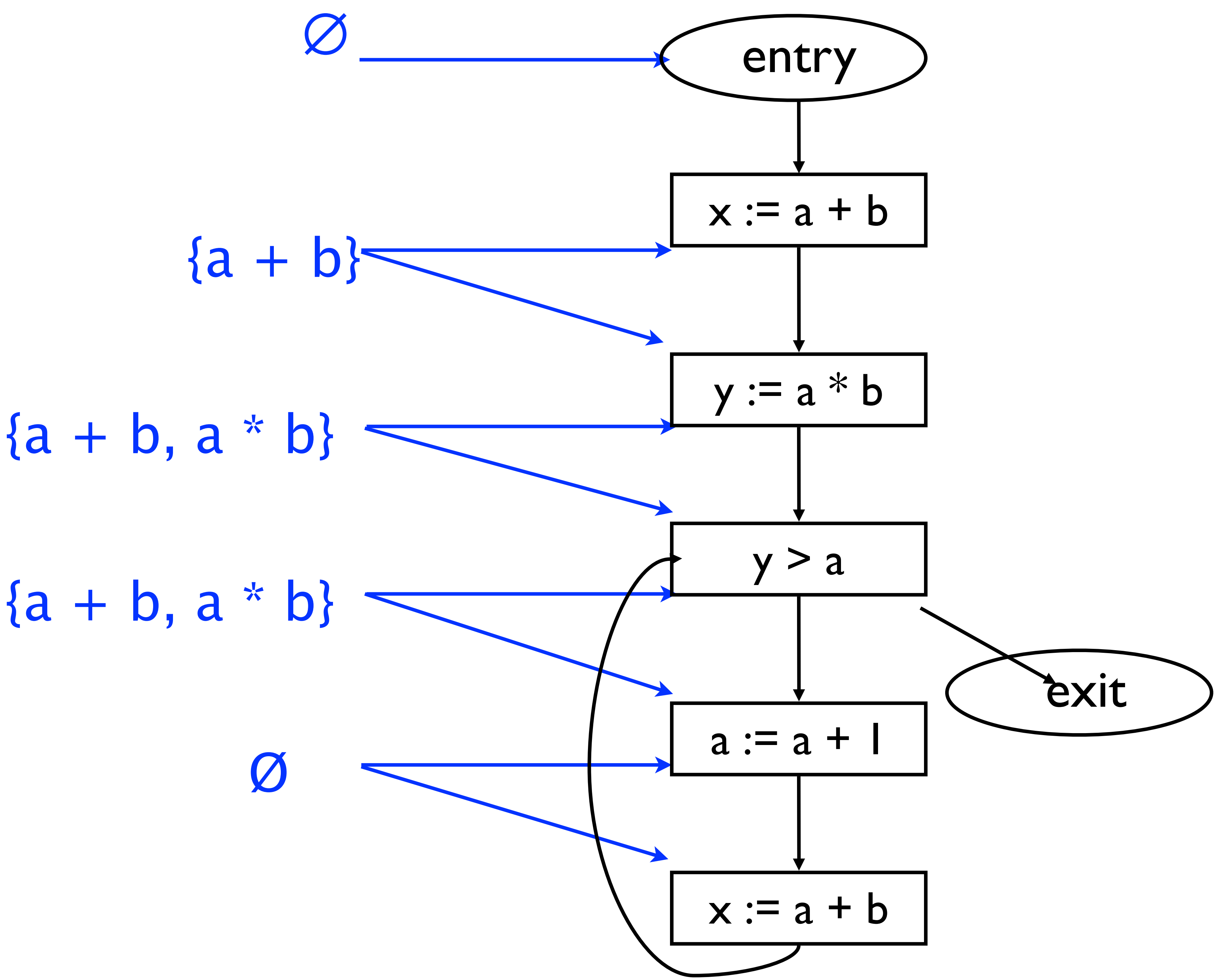

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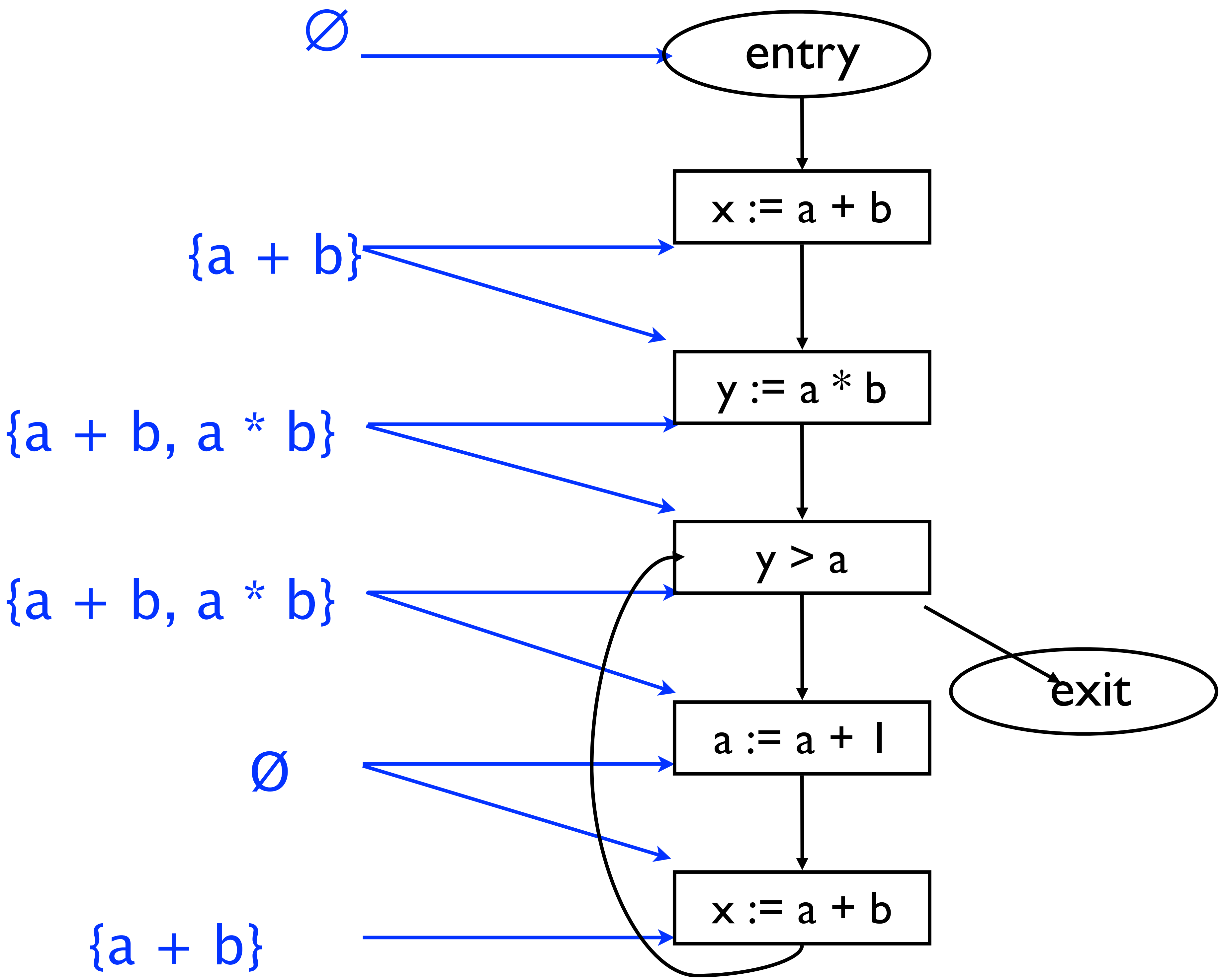

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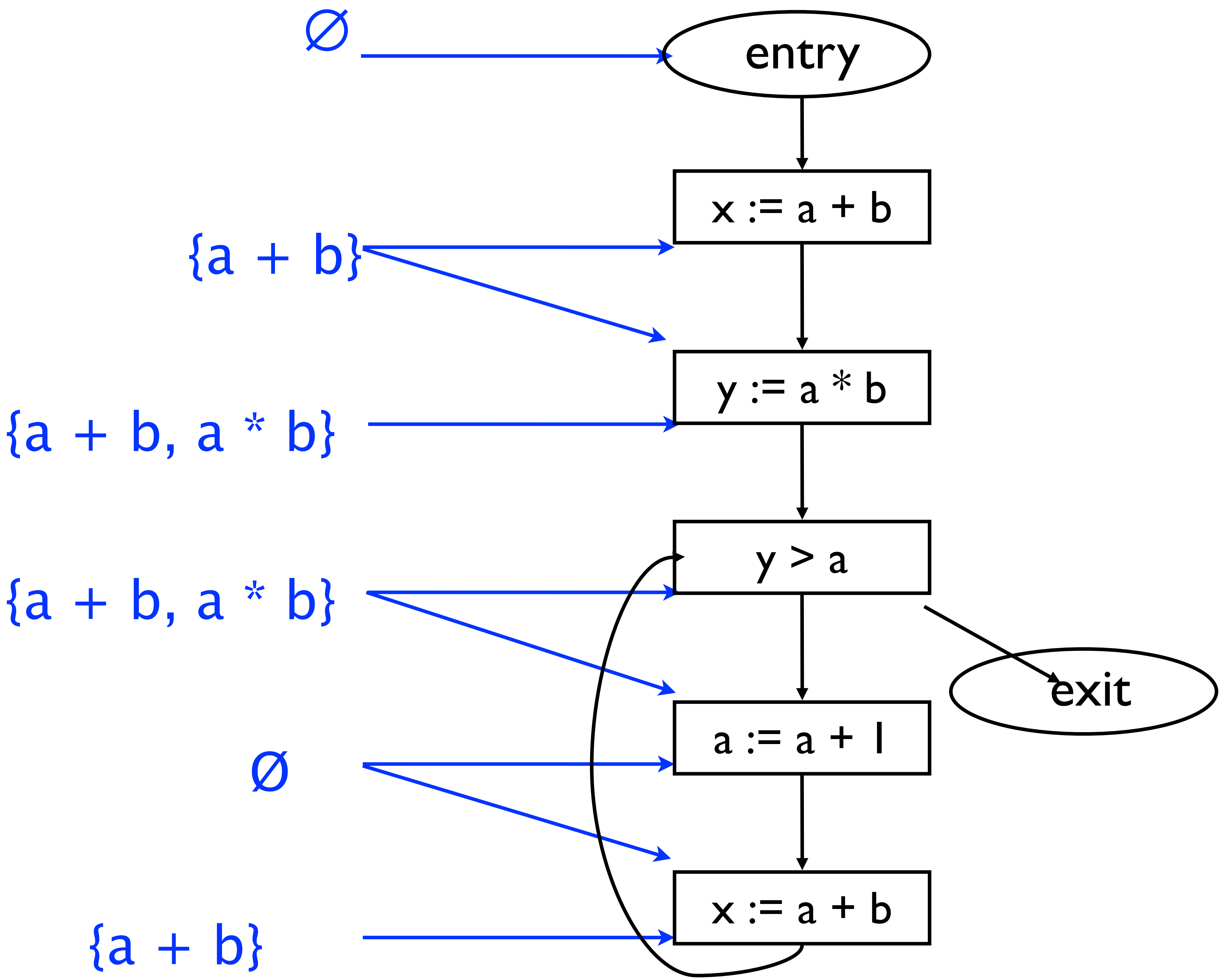

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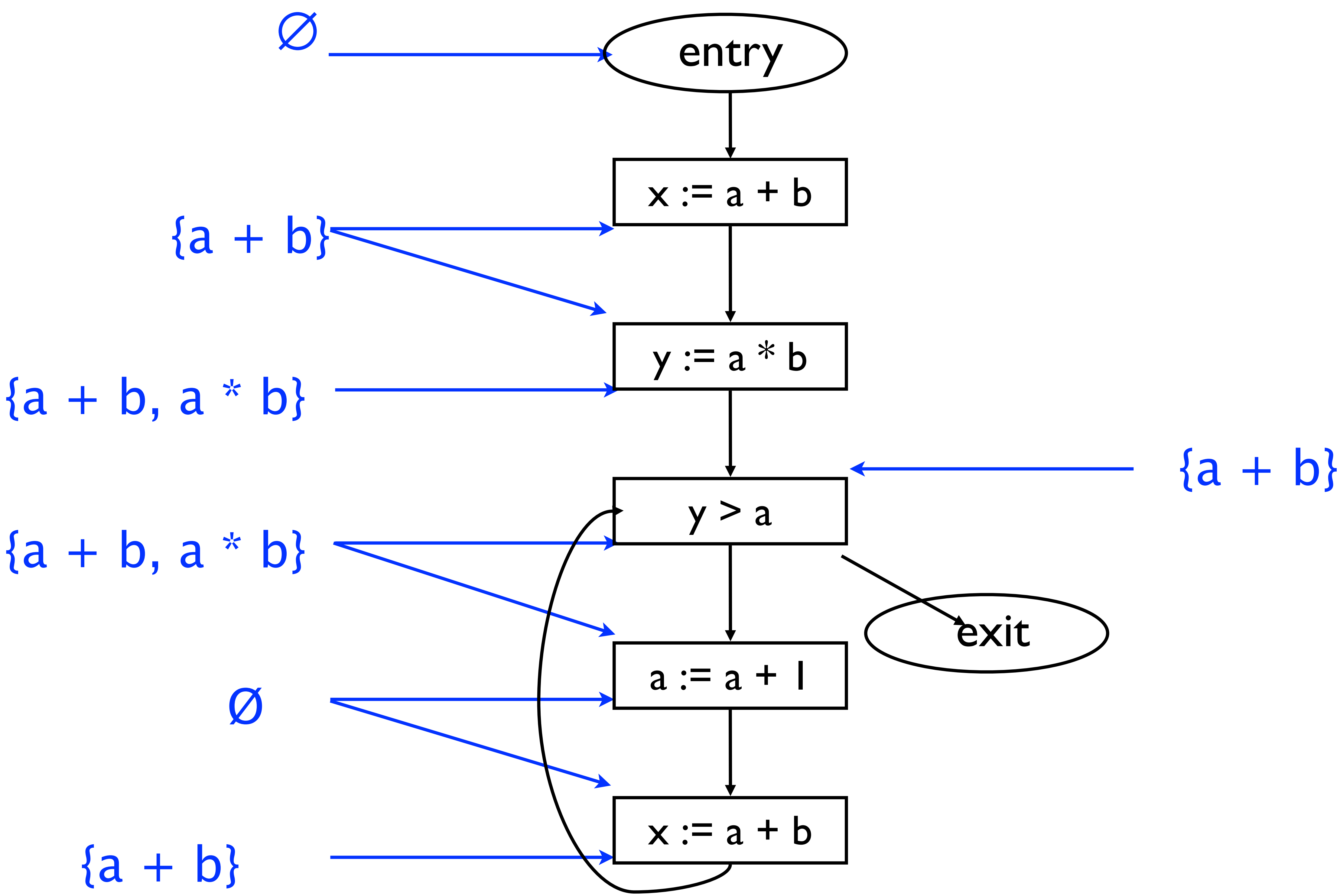

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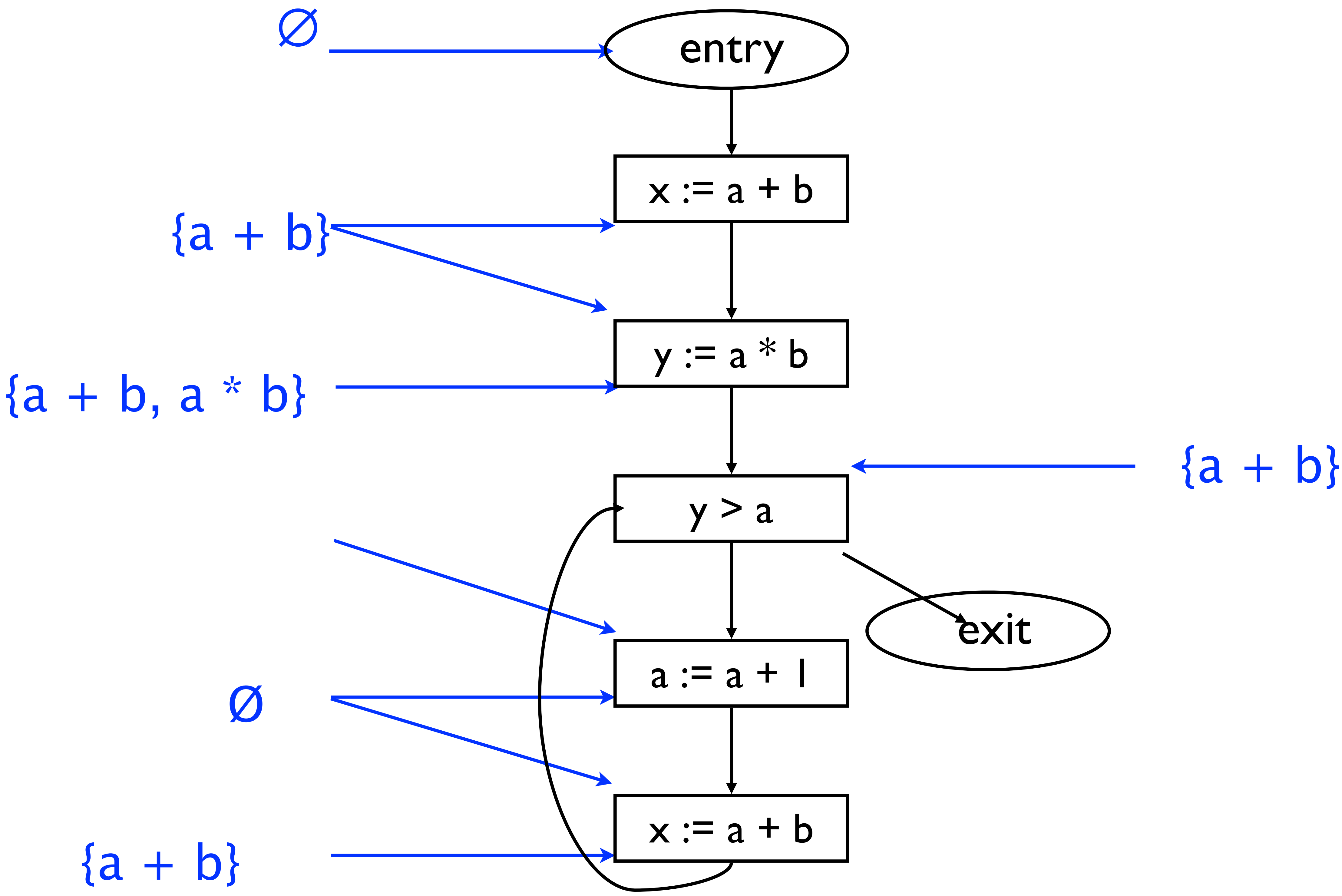

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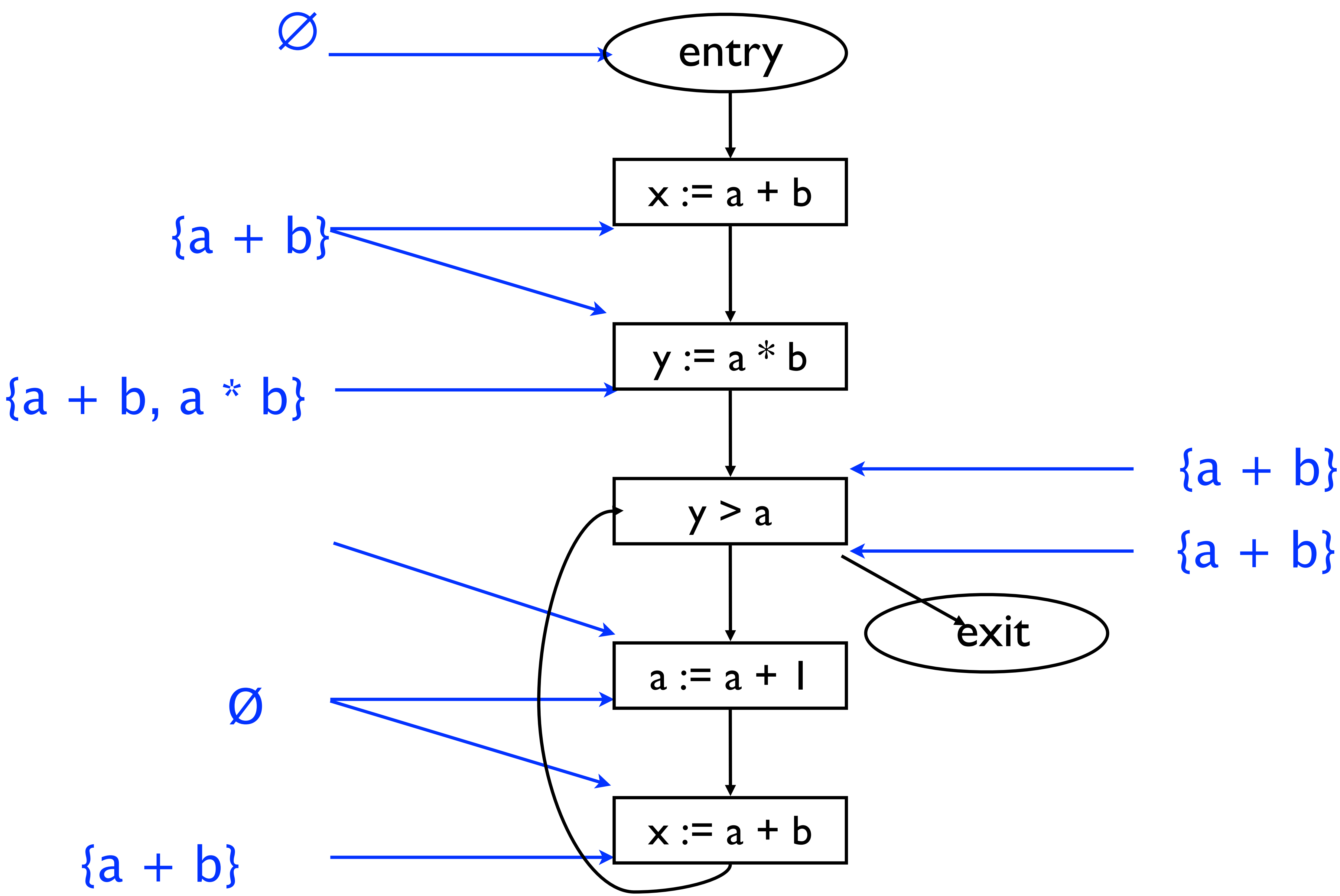

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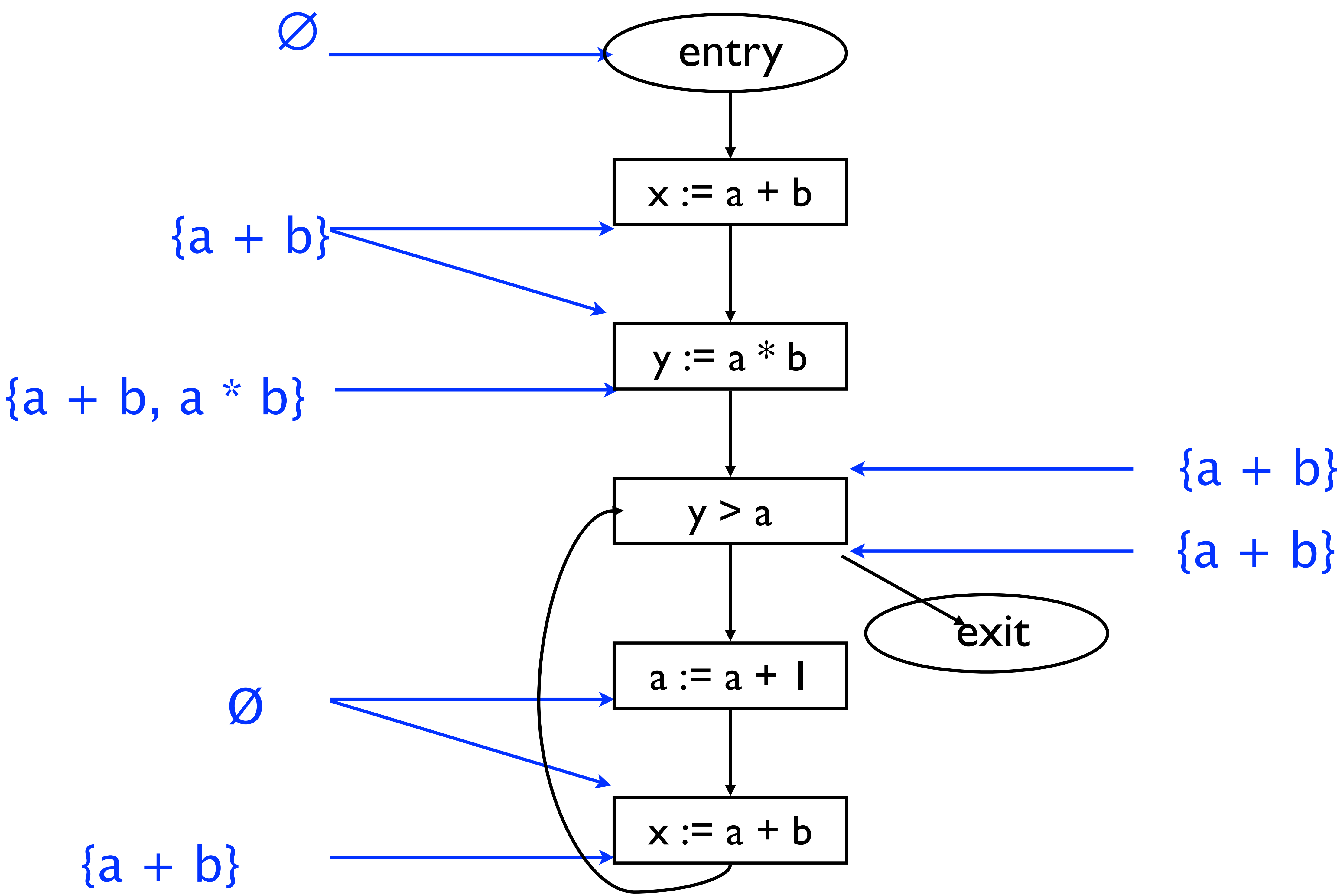

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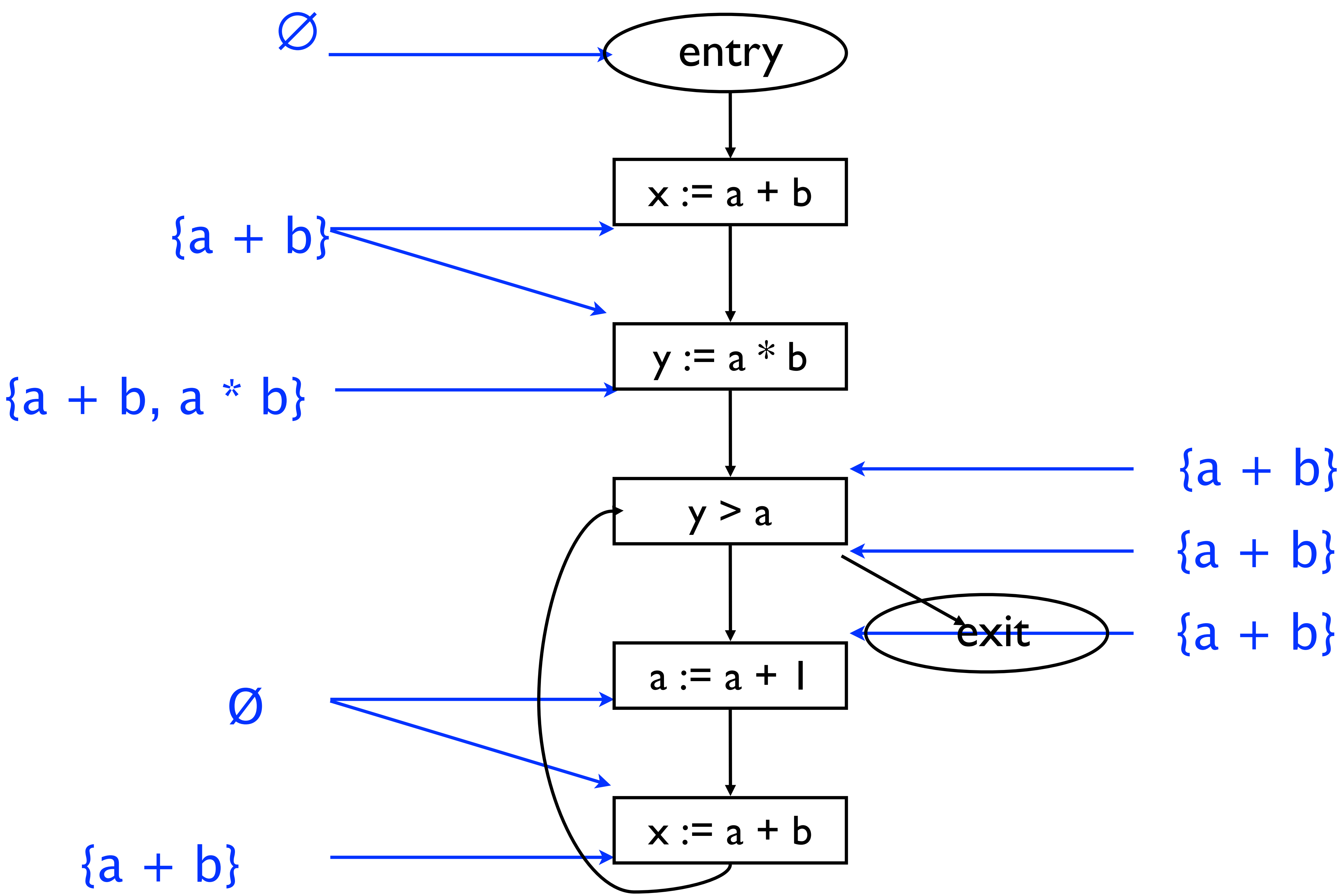

Terminology

- A *join point* is a program point where two branches meet
- Available expressions is a *forward must* problem
  - Forward = Data flow from in to out
  - Must = Property *must* hold on all paths to the join
- Dataflow analysis requires facts that summarize *all paths* to a join point
  - Symbolic execution analyzes each path separately

Data Flow Equations

- Let s be a statement
  - succ(s) = { immediate successor statements of s }
  - pred(s) = { immediate predecessor statements of s}
  - In(s) = program point just before executing s
  - Out(s) = program point just after executing s

- $In(s) = \bigcap_{s' \in pred(s)} Out(s')$

- $Out(s) = Gen(s) \cup (In(s) - Kill(s))$

Liveness Analysis

Liveness Analysis

- A variable v is *live* at program point p if
  - v will be used on some execution path originating from p...
  - before v is overwritten

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- Optimization
  - If a variable is not live, no need to keep it in a register
  - If variable is dead at assignment, can eliminate assignment

Data Flow Equations

- Available expressions is a forward must analysis
  - Data flow propagate in same dir as CFG edges
  - Expr is available only if available on all paths
- Liveness is a *backward may* problem
  - To know if variable live, need to look at future uses
  - Variable is live if used on some path
- $\mathrm{Out}(s) = \bigcup_{s' \in \mathrm{succ}(s)} \mathrm{In}(s')$
- $\mathrm{In}(s) = \mathrm{Gen}(s) \cup (\mathrm{Out}(s) - \mathrm{Kill}(s))$

Gen and Kill

- What is the effect of each statement on the set of facts?

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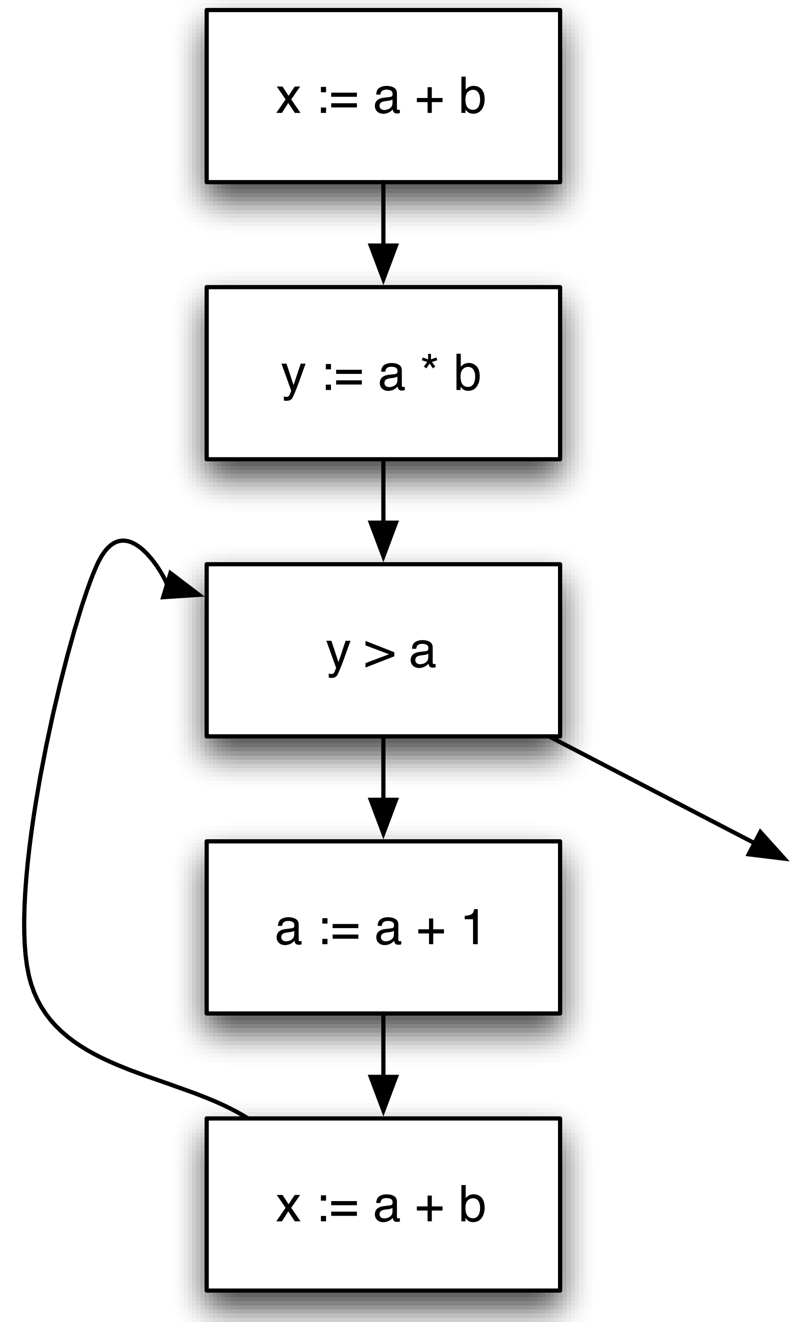

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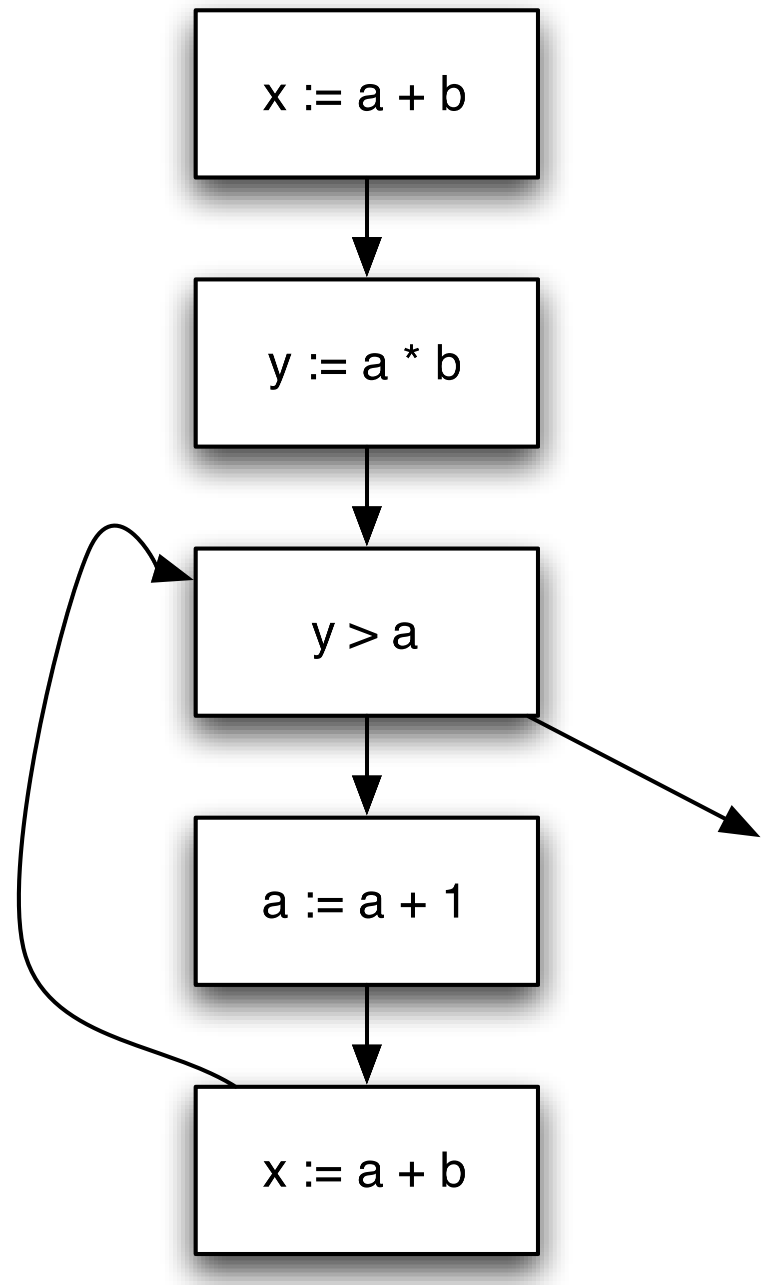

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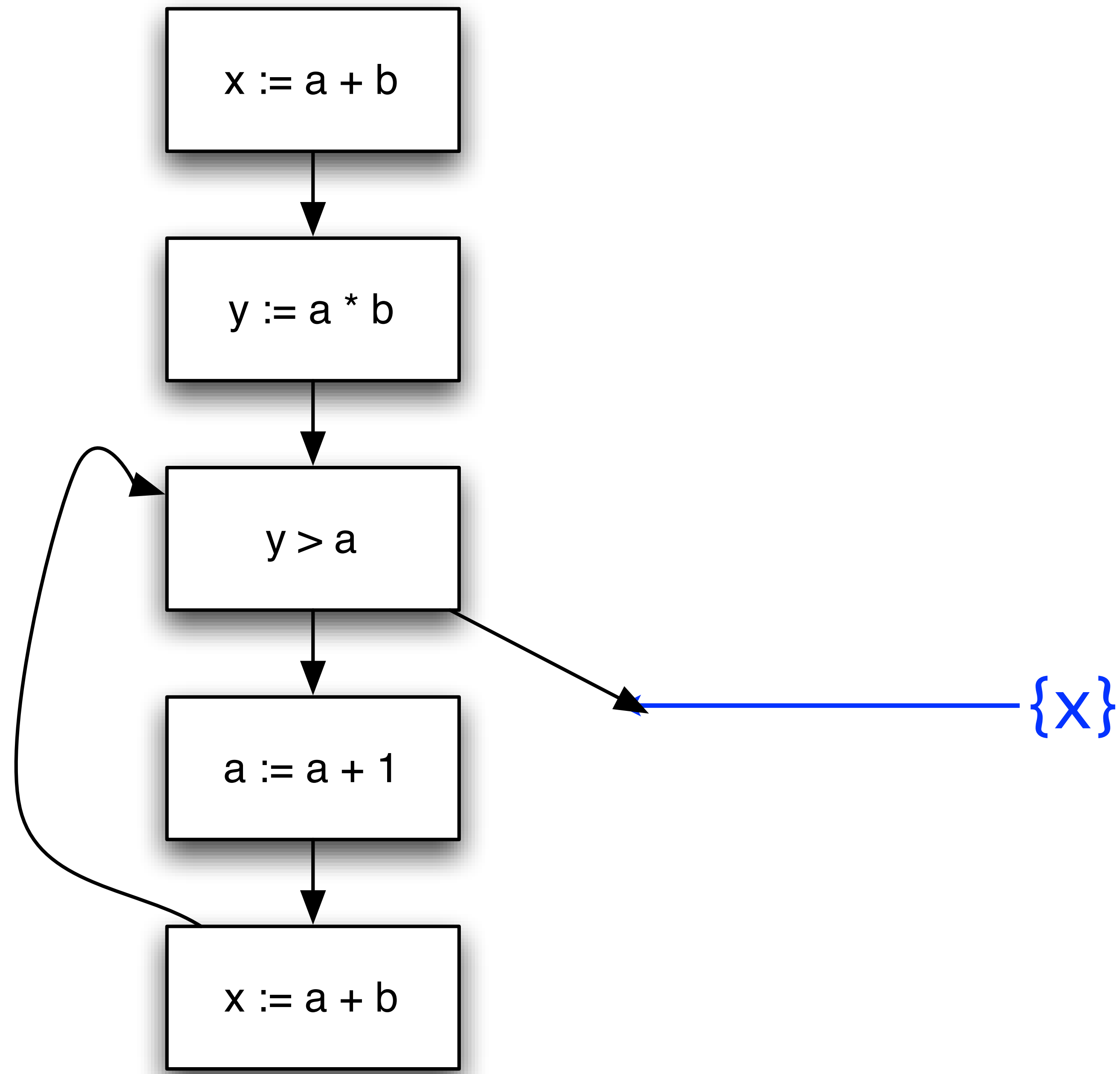

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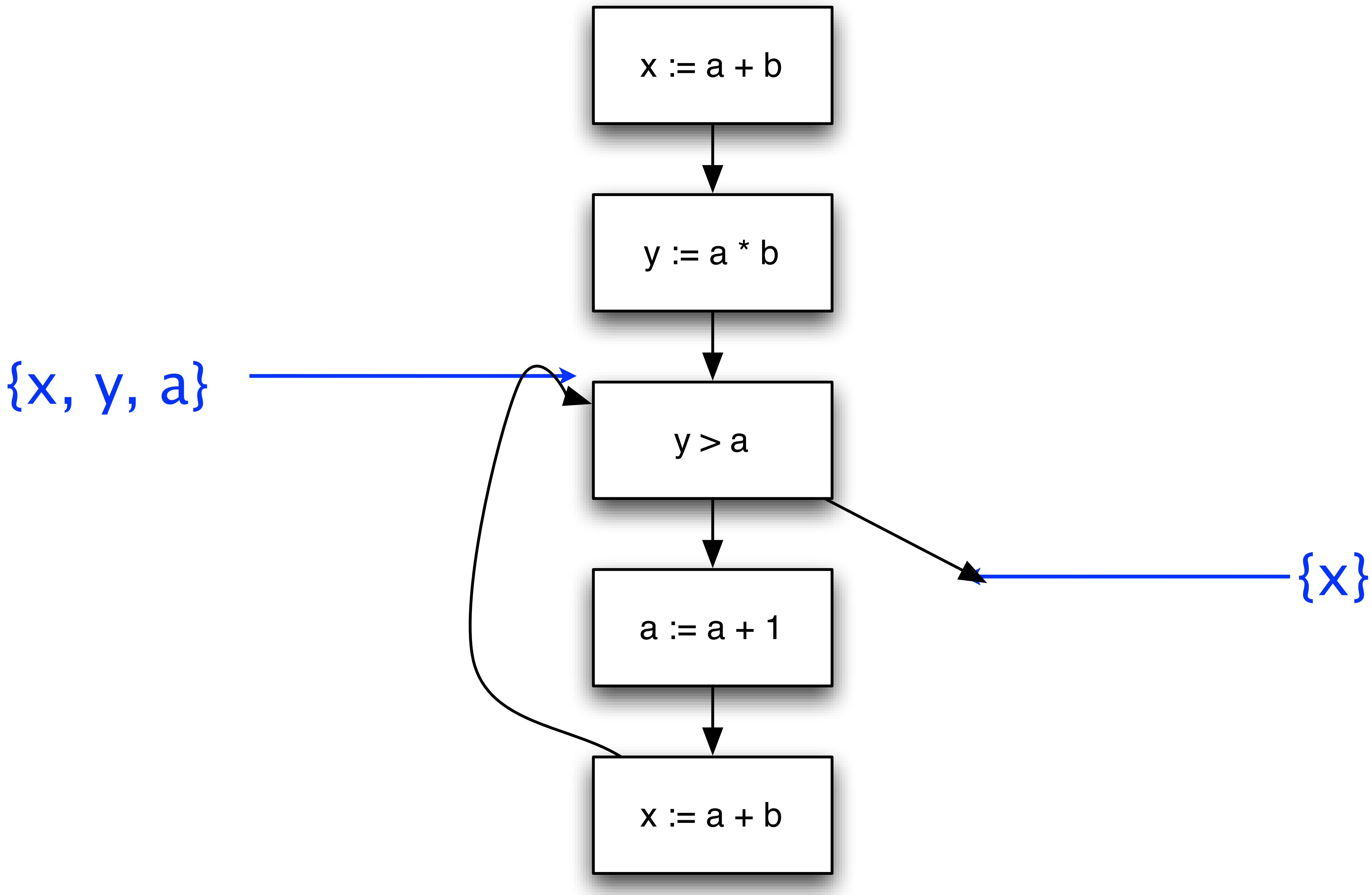

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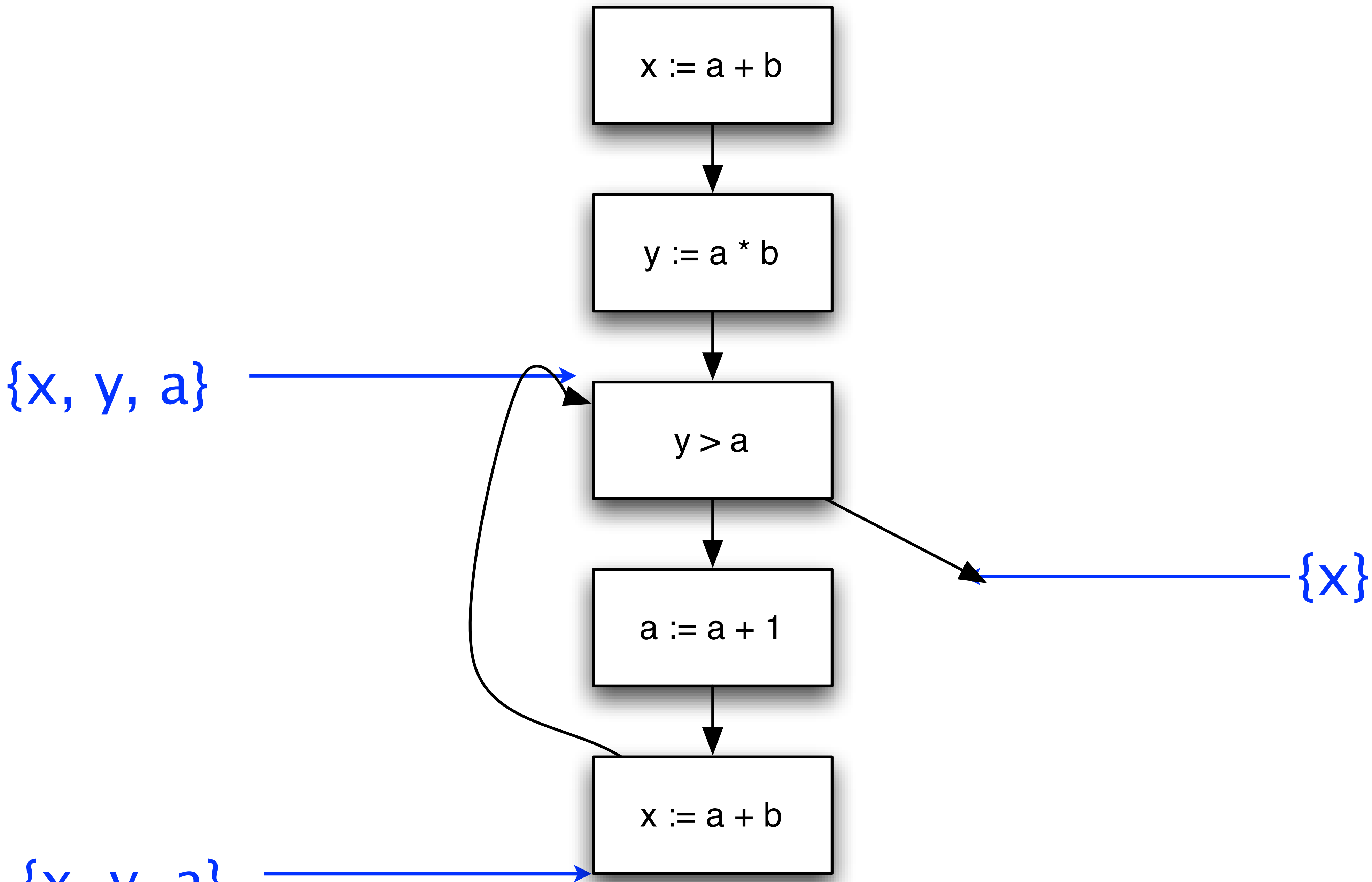

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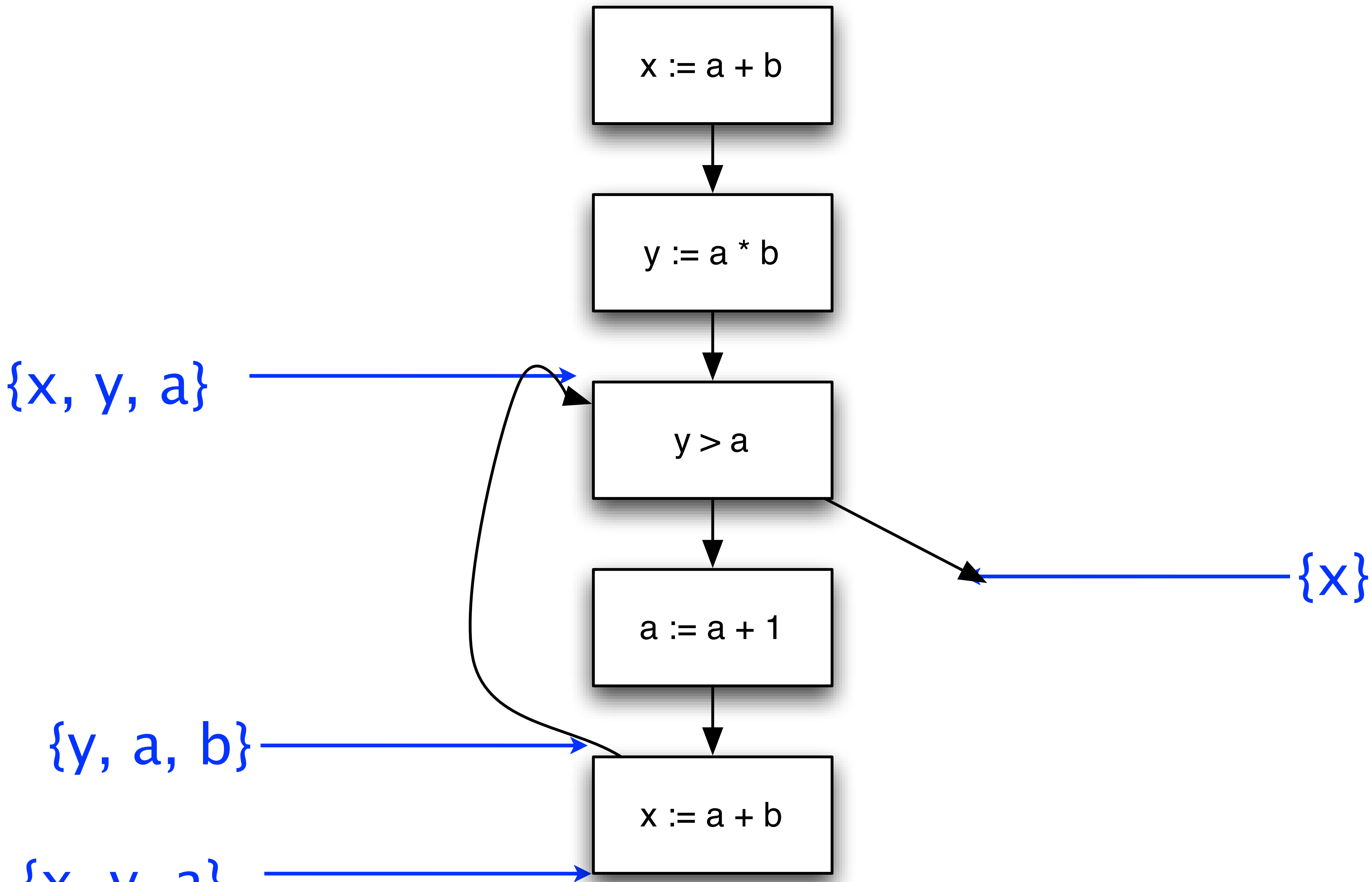

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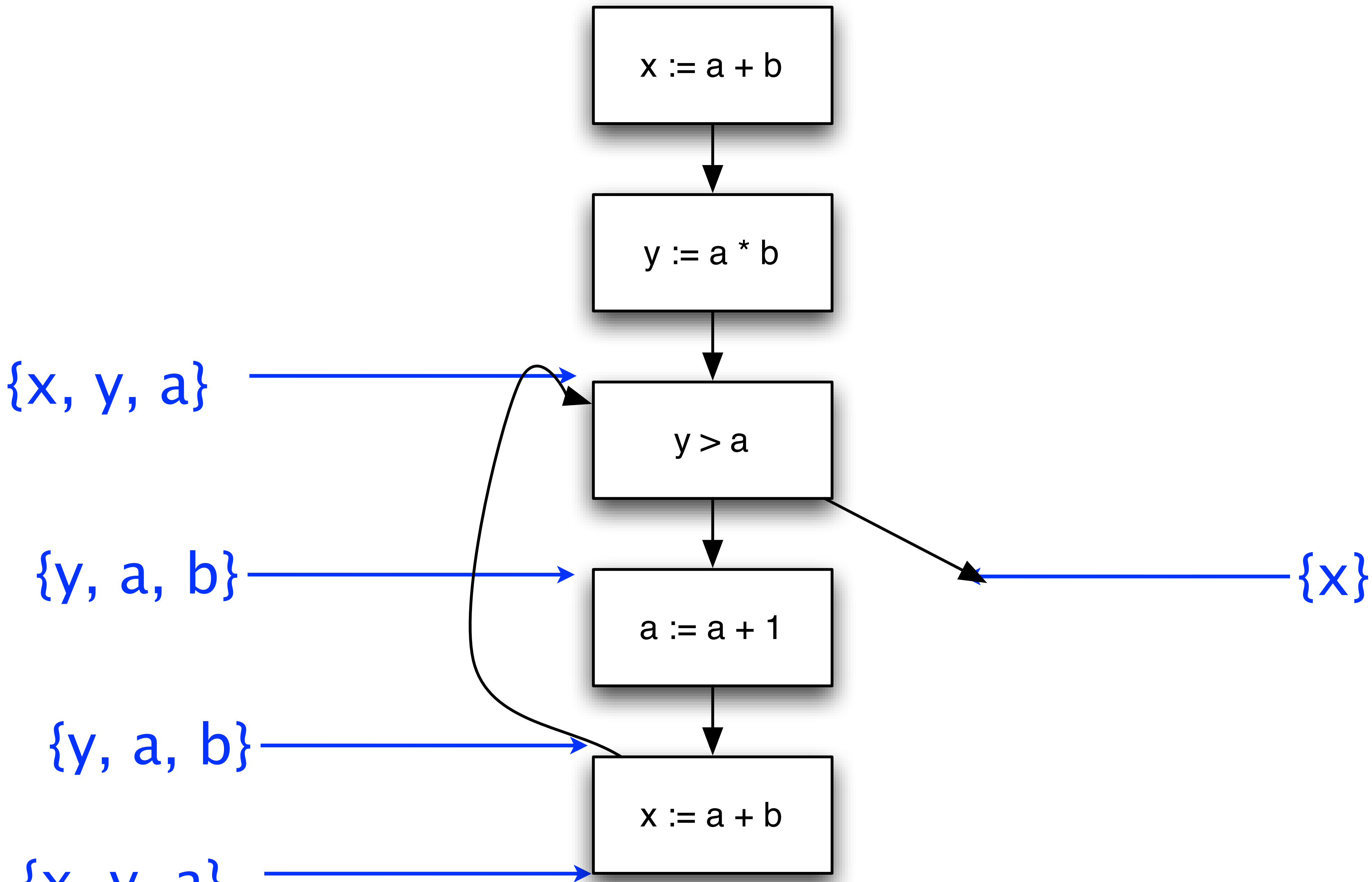

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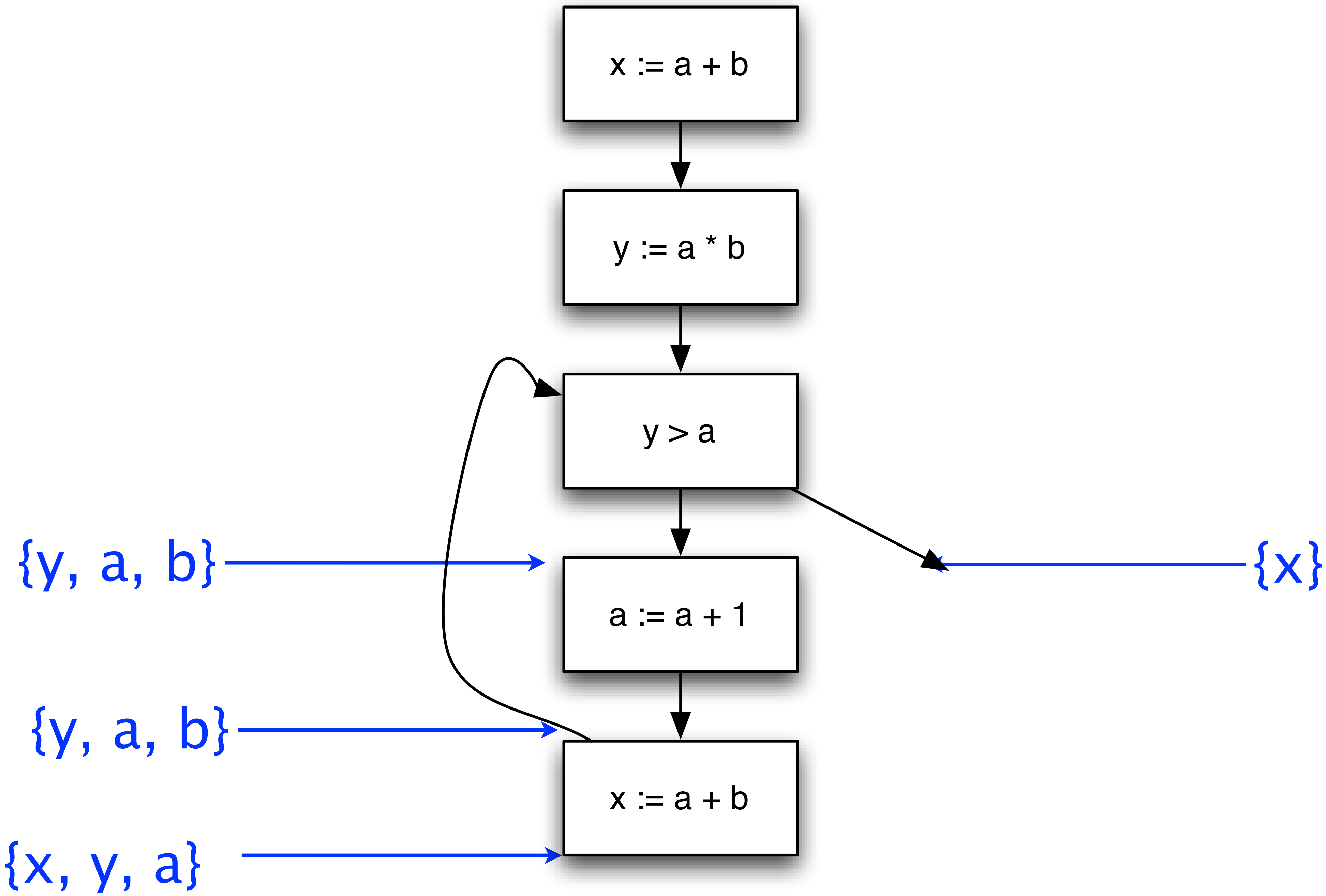

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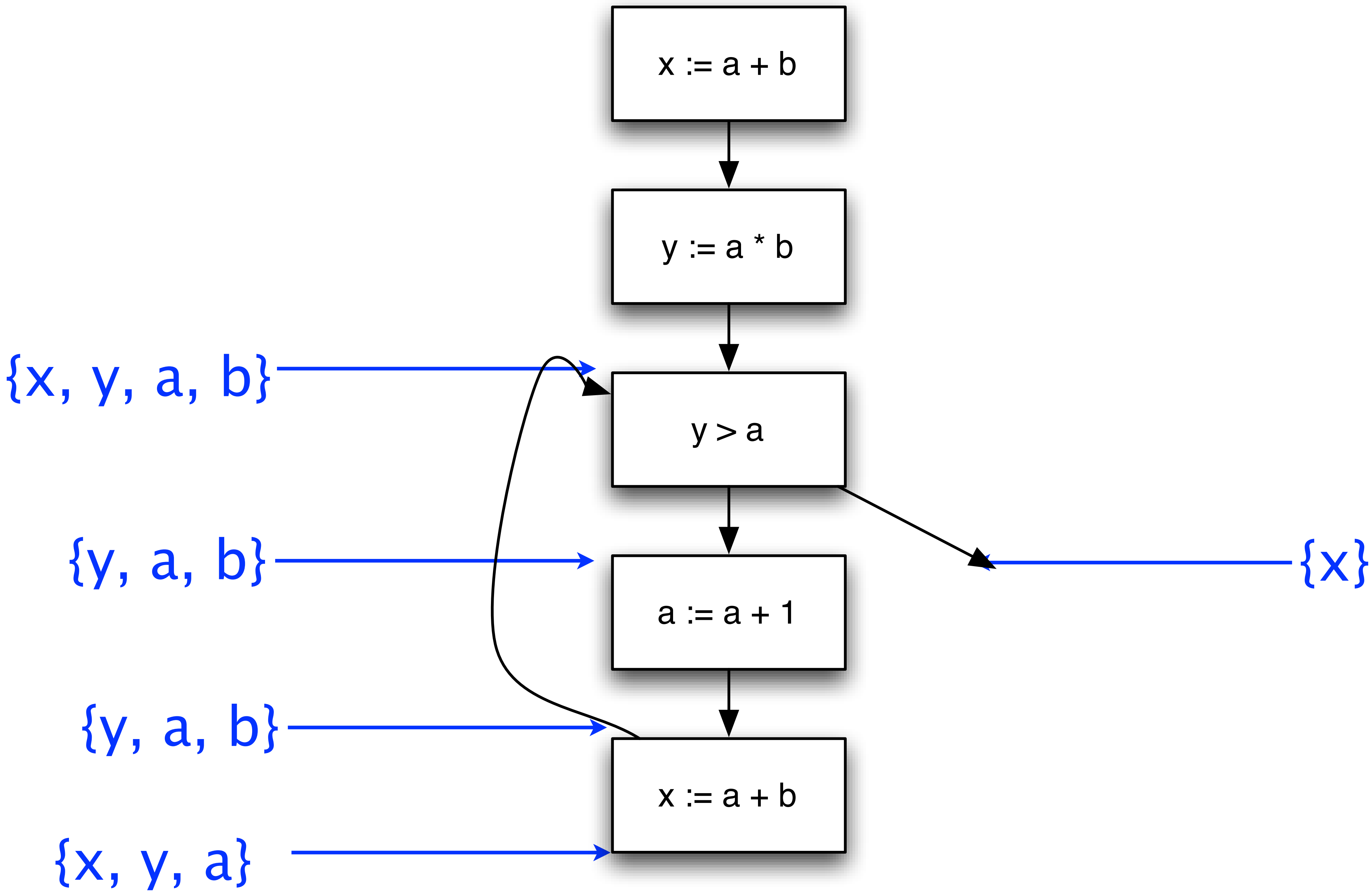

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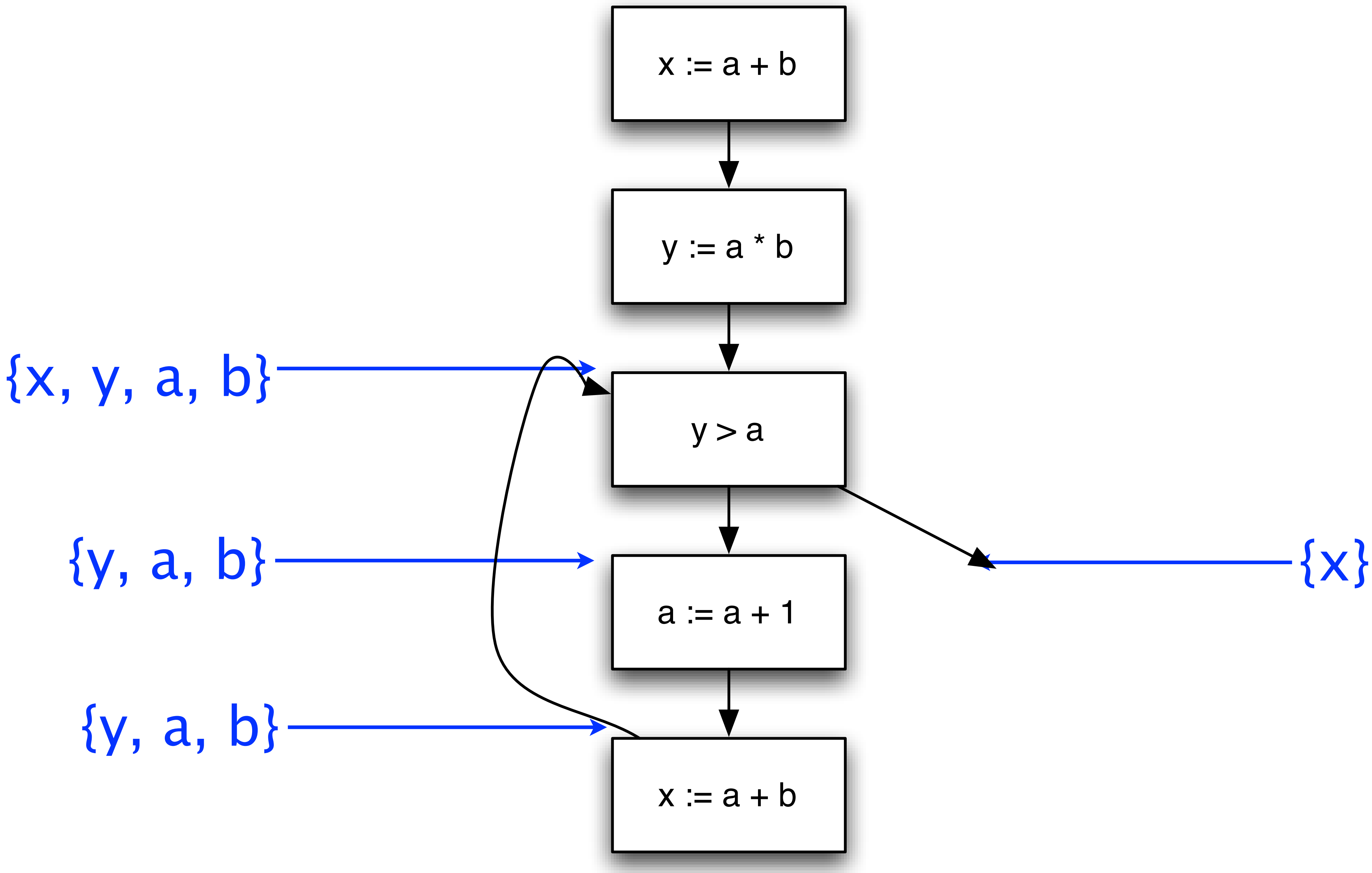

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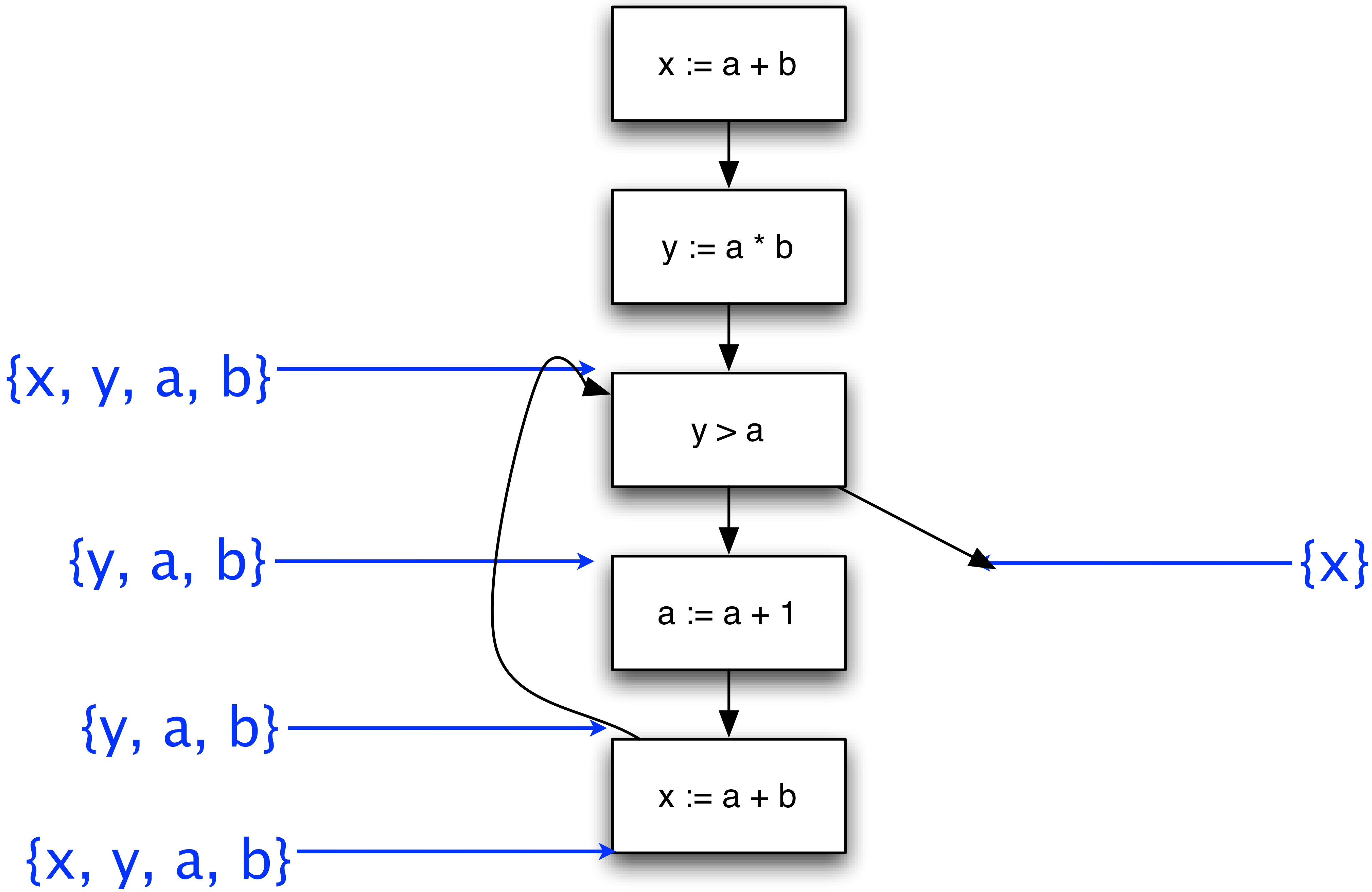

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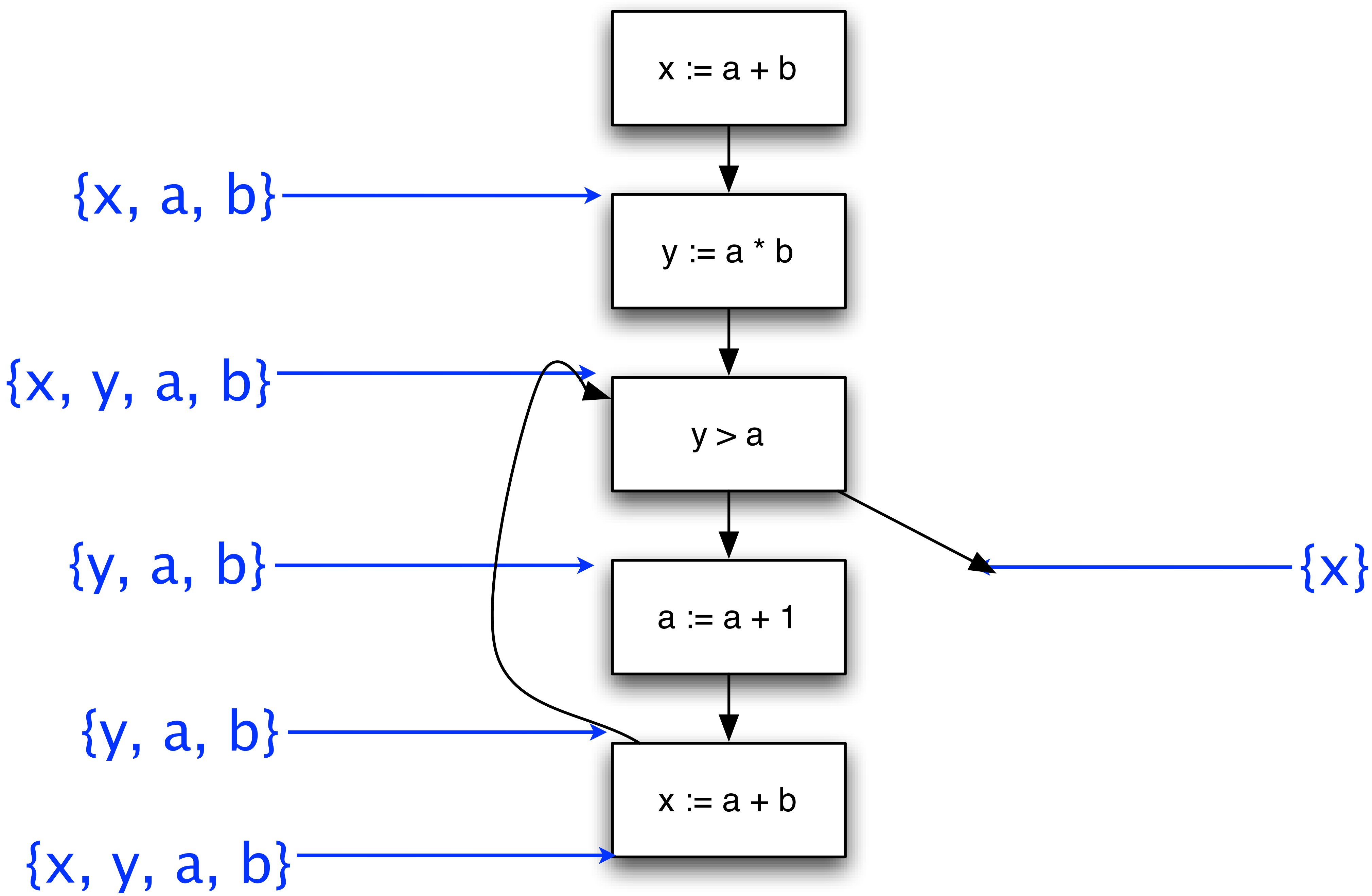

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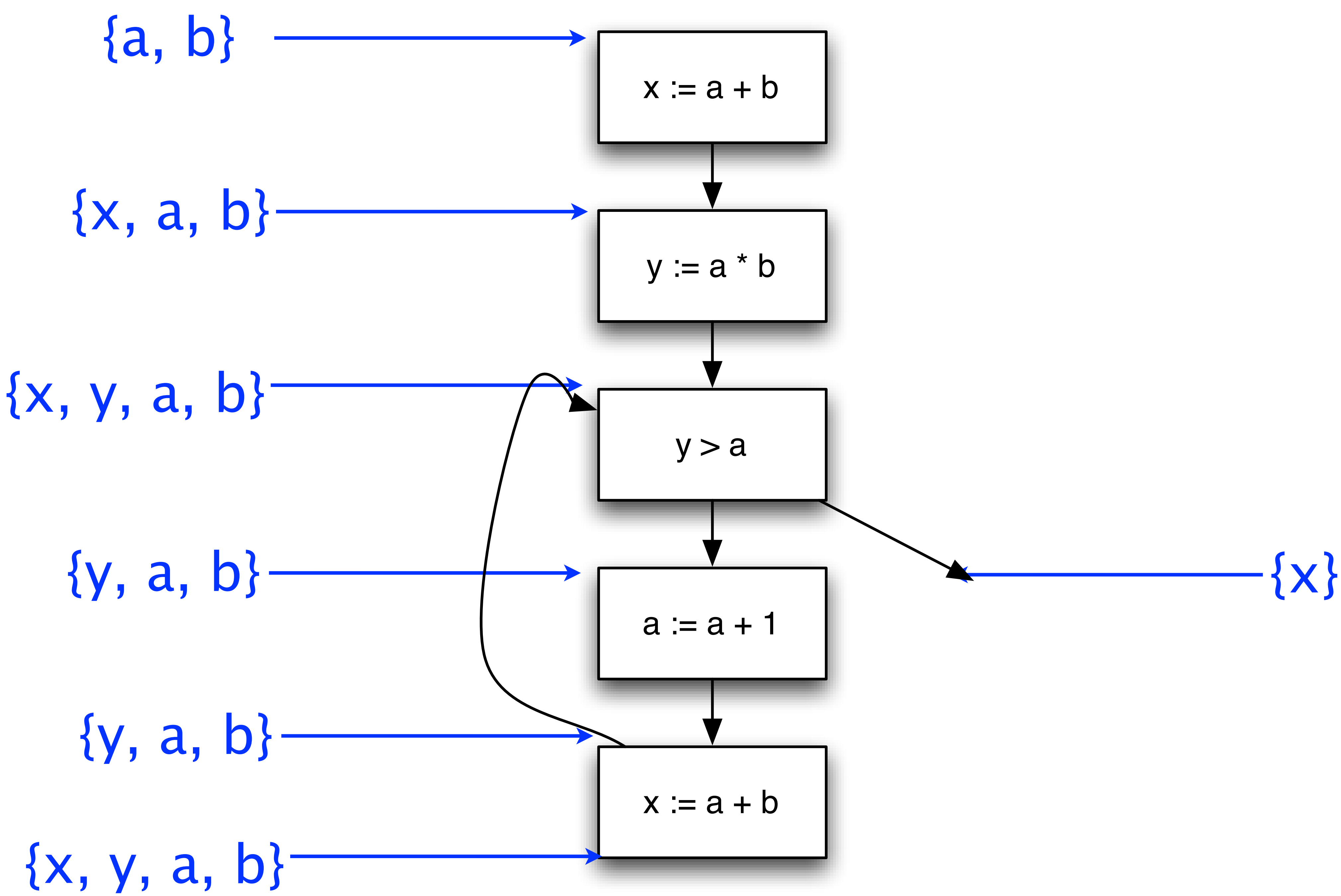

Very Busy Expressions

- An expression e is *very busy* at point p if
  - On every path from p, expression e is evaluated before the value of e is changed
- Optimization
  - Can hoist very busy expression computation
- What kind of problem?
  - Forward or backward?
  - May or must?

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Reaching Definitions

- A *definition* of a variable v is an assignment to v
- A definition of variable v reaches point p if
  - There is no intervening assignment to v
- Also called def-use information
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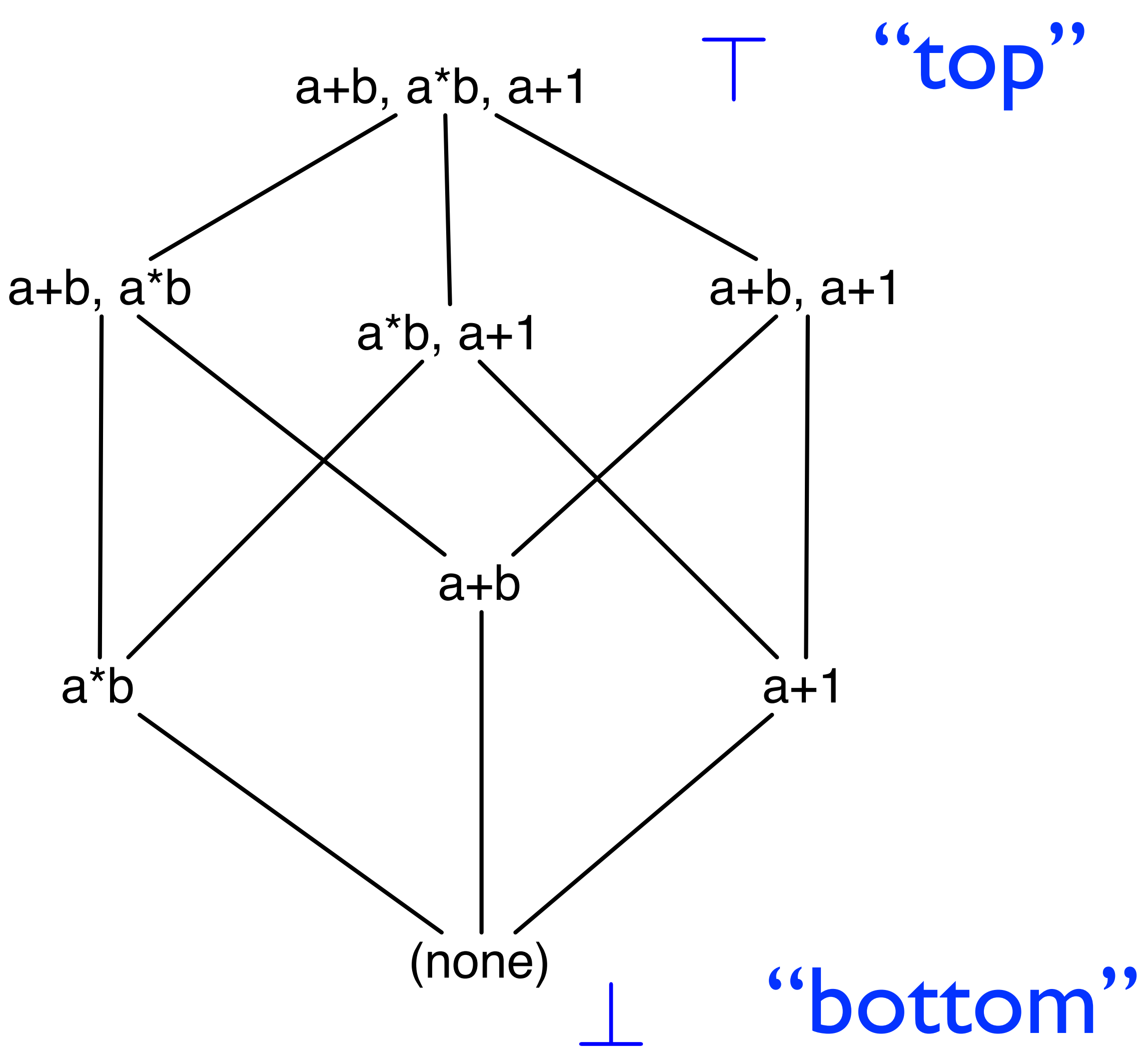
Space of Data Flow Analyses

	May	Must
Forward	Reaching definitions	Available expressions
Backward	Live variables	Very busy expressions

- Most data flow analyses can be classified this way
  - A few don’t fit: bidirectional analysis
- Lots of literature on data flow analysis

Data Flow Facts and Lattices

- Typically, data flow facts form a lattice
  - Example: Available expressions



Partial Orders

- A partial order is a pair $(P, \leq)$ such that
  - $\leq \subseteq P \times P$
  - $\leq$ is reflexive: $x \leq x$
  - $\leq$ is anti-symmetric: $x \leq y$ and $y \leq x \Rightarrow x = y$
  - $\leq$ is transitive: $x \leq y$ and $y \leq z \Rightarrow x \leq z$

Lattices

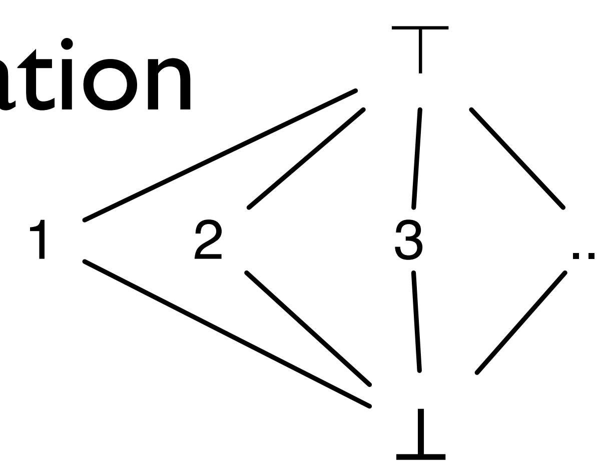
- A partial order is a lattice if $\sqcap$ and $\sqcup$ are defined on any set:
  - $\sqcap$ is the *meet* or *greatest lower bound* operation:
    - $x \sqcap y \leq x$ and $x \sqcap y \leq y$
    - if $z \leq x$ and $z \leq y$, then $z \leq x \sqcap y$
  - $\sqcup$ is the *join* or *least upper bound* operation:
    - $x \leq x \sqcup y$ and $y \leq x \sqcup y$
    - if $x \leq z$ and $y \leq z$, then $x \sqcup y \leq z$

Lattices (cont'd)

- A finite partial order is a lattice if meet and join exist for every pair of elements
- A lattice has unique elements $\perp$ and $\top$ such that
  - $x \sqcap \perp = \perp \qquad x \sqcup \perp = x$
  - $x \sqcap \top = x \qquad x \sqcup \top = \top$
- In a lattice, $x \leq y \text{ iff } x \sqcap y = x$
  $x \leq y \text{ iff } x \sqcup y = y$
- A partial order is a *complete lattice* if meet and join are defined on any set $S \subseteq P$

Useful Lattices

- $(2^S, \subseteq)$ forms a lattice for any set S
  - 2^S is the powerset of S (set of all subsets)
- If $(S, \leq)$ is a lattice, so is $(S, \geq)$
  - I.e., lattices can be flipped
- The lattice for constant propagation



Forward Must Data Flow Algorithm

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Out(s) = *Top* for all statements s

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// Slight acceleration: Could set Out(s) = Gen(s) U (*Top* - Kill(s))

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W := { all statements }   (worklist)

Forward Must Data Flow Algorithm

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W := { all statements }   (worklist)

repeat

Forward Must Data Flow Algorithm

Out(s) = *Top* for all statements s

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W := { all statements }   (worklist)

repeat

Take s from W

Forward Must Data Flow Algorithm

Out(s) = *Top* for all statements s

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W := { all statements } (worklist)

repeat

Take s from W

In(s) := $\cap_{s' \in \text{pred}(s)}$ Out(s')

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W := { all statements }   (worklist)

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Take s from W

In(s) := $\cap_{s' \in \text{pred}(s)}$ Out(s')

temp := Gen(s) ∪ (In(s) - Kill(s))

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Take s from W

In(s) := $\cap_{s' \in \text{pred}(s)}$ Out(s')

temp := Gen(s) ∪ (In(s) - Kill(s))

if (temp != Out(s)) {

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W := { all statements }   (worklist)

repeat

  Take s from W

  In(s) := $\cap_{s' \in \text{pred}(s)}$ Out(s')

  temp := Gen(s) ∪ (In(s) - Kill(s))

  if (temp != Out(s)) {

    Out(s) := temp

    W := W ∪ succ(s)

Forward Must Data Flow Algorithm

Out(s) = *Top* for all statements s

// Slight acceleration: Could set Out(s) = Gen(s) ∪ (*Top* - Kill(s))

W := { all statements }   (worklist)

repeat

Take s from W

In(s) := $\cap_{s' \in \text{pred}(s)}$ Out(s')

temp := Gen(s) ∪ (In(s) - Kill(s))

if (temp != Out(s)) {

Out(s) := temp

W := W ∪ succ(s)

}

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until W = ∅

Monotonicity

- A function f on a partial order is *monotonic* if

$$x \leq y \Rightarrow f(x) \leq f(y)$$

- Easy to check that operations to compute In and Out are monotonic
  - $\mathrm{In}(s) := \cap_{s' \in \mathrm{pred}(s)} \mathrm{Out}(s')$
  - $\mathrm{temp} := \mathrm{Gen}(s) \cup (\mathrm{In}(s) - \mathrm{Kill}(s))$
- Putting these two together,
  - temp := $f_s(\sqcap_{s' \in \mathrm{pred}(s)} Out(s'))$

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a function f_s(In(s))

- Putting these two together,
  - temp := $f_s(\sqcap_{s' \in \mathrm{pred}(s)} Out(s'))$

Termination

- We know the algorithm terminates because
  - The lattice has finite height
  - The operations to compute In and Out are monotonic
  - On every iteration, we remove a statement from the worklist and/or move down the lattice

Forward Data Flow, Again

Out(s) = *Top*   for all statements s

W := { all statements }   (worklist)

repeat

  Take s from W

  temp := $f_s(\sqcap_{s' \in pred(s)} Out(s'))$ (f_s monotonic *transfer fn*)

  if (temp != Out(s)) {

    Out(s) := temp

    W := W ∪ succ(s)

  }

until W = ∅

Lattices (P, ≤)

Lattices (P, ≤)

- Available expressions

Lattices (P, $\leq$)

- Available expressions
  - P = sets of expressions

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  - P = sets of expressions
  - $S1 \sqcap S2 = S1 \cap S2$

Lattices (P, ≤)

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  - P = sets of expressions
  - S1 ⊓ S2 = S1 ∩ S2
  - *Top* = set of all expressions

Lattices (P, ≤)

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  - P = sets of expressions
  - S1 $\sqcap$ S2 = S1 $\cap$ S2
  - *Top* = set of all expressions
- Reaching Definitions

Lattices (P, ≤)

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  - P = sets of expressions
  - S1 ⊓ S2 = S1 ∩ S2
  - *Top* = set of all expressions
- Reaching Definitions
  - P = set of definitions (assignment statements)

Lattices (P, $\leq$)

- Available expressions
  - P = sets of expressions
  - $S1 \sqcap S2 = S1 \cap S2$
  - *Top* = set of all expressions
- Reaching Definitions
  - P = set of definitions (assignment statements)
  - $S1 \sqcap S2 = S1 \cup S2$

Lattices (P, ≤)

- Available expressions
  - P = sets of expressions
  - $S1 \sqcap S2 = S1 \cap S2$
  - *Top* = set of all expressions
- Reaching Definitions
  - P = set of definitions (assignment statements)
  - $S1 \sqcap S2 = S1 \cup S2$
  - *Top* = empty set

Fixpoints

- We always start with *Top*
  - Every expression is available, no defns reach this point
  - Strongest possible hypothesis
    - = true of fewest number of states

- Revise as we encounter contradictions
  - Always move down in the lattice (with meet)

- Result: A greatest fixpoint

Lattices (P, ≤), cont'd

Lattices (P, ≤), cont'd

- Live variables

Lattices (P, ≤), cont'd

- Live variables
  - P = sets of variables

Lattices (P, ≤), cont'd

- Live variables
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Lattices (P, ≤), cont'd

- Live variables
  - P = sets of variables
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Lattices (P, ≤), cont'd

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  - $S1 \sqcap S2 = S1 \cup S2$
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Lattices (P, ≤), cont'd

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  - P = sets of variables
  - S1 ⊓ S2 = S1 ∪ S2
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- Very busy expressions

Lattices (P, $\leq$), cont'd

- Live variables
  - P = sets of variables
  - S1 $\sqcap$ S2 = S1 $\cup$ S2
  - Top = empty set
- Very busy expressions
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Lattices (P, ≤), cont'd

- Live variables
  - P = sets of variables
  - $S1 \sqcap S2 = S1 \cup S2$
  - Top = empty set
- Very busy expressions
  - P = set of expressions
  - $S1 \sqcap S2 = S1 \cap S2$

Lattices (P, ≤), cont'd

- Live variables
  - P = sets of variables
  - $S1 \sqcap S2 = S1 \cup S2$
  - Top = empty set
- Very busy expressions
  - P = set of expressions
  - $S1 \sqcap S2 = S1 \cap S2$
  - Top = set of all expressions

Forward vs. Backward

Out(s) = *Top* for all s
W := { all statements }
repeat
  Take s from W
  temp := $f_s(\sqcap_{s' \in pred(s)} Out(s'))$
  if (temp != Out(s)) {
    Out(s) := temp
    W := W ∪ succ(s)
  }
until W = ∅

In(s) = *Top* for all s
W := { all statements }
repeat
  Take s from W
  temp := $f_s(\sqcap_{s' \in succ(s)} In(s'))$
  if (temp != In(s)) {
    In(s) := temp
    W := W ∪ pred(s)
  }
until W = ∅

Termination Revisited

- How many times can we apply this step:

  $temp := f_s(\sqcap_{s' \in pred(s)} Out(s'))$

  if (temp != Out(s)) { ... }

  - Claim: Out(s) only shrinks
    - Proof: Out(s) starts out as *Top*
      - So temp must be $\leq$ than *Top* after first step
    - Assume Out(s′) shrinks for all predecessors s′ of s
    - Then $\sqcap_{s' \in pred(s)} Out(s')$ shrinks
    - Since f_s monotonic, $f_s(\sqcap_{s' \in pred(s)} Out(s'))$ shrinks

Termination Revisited (cont'd)

- A *descending chain* in a lattice is a sequence
  - $x0 \sqsupset x1 \sqsupset x2 \sqsupset \ldots$
- The *height* of a lattice is the length of the longest descending chain in the lattice
- Then, dataflow must terminate in $O(nk)$ time
  - n = # of statements in program
  - k = height of lattice
  - assumes meet operation takes $O(1)$ time

Least vs. Greatest Fixpoints

- Dataflow tradition: Start with *Top*, use *meet*
  - To do this, we need a *meet semilattice with top*
    - complete meet semilattice = meets defined for any set
    - finite height ensures termination
  - Computes greatest fixpoint
- Denotational semantics tradition: Start with *Bottom*, use *join*
  - Computes least fixpoint

Distributive Data Flow Problems

- By monotonicity, we also have

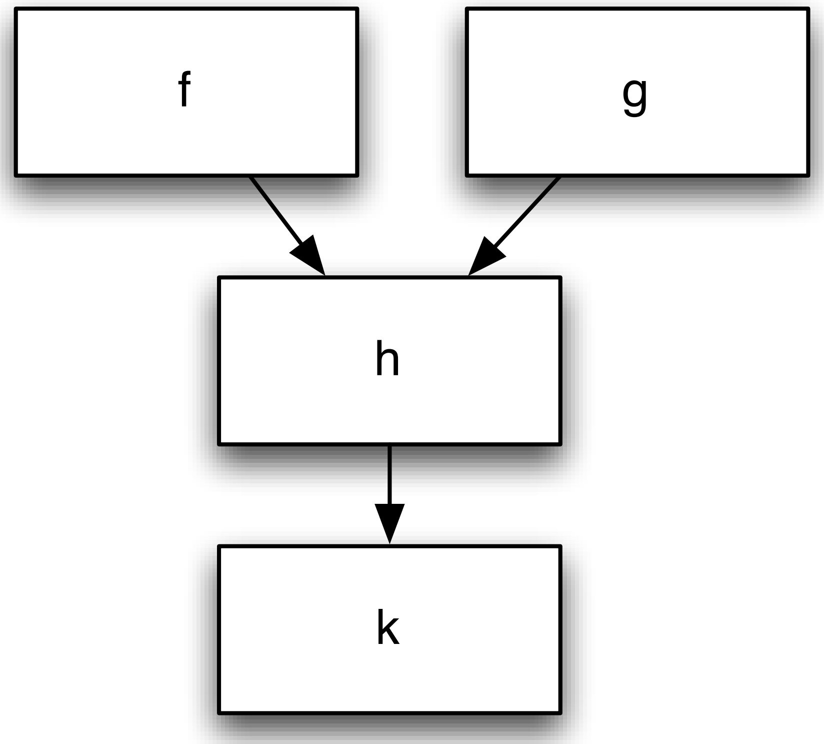
$$f(x \sqcap y) \leq f(x) \sqcap f(y)$$

- A function f is distributive if

$$f(x \sqcap y) = f(x) \sqcap f(y)$$

Benefit of Distributivity

- Joins lose no information



$$k(h(f(\top) \sqcap g(\top))) =$$
$$k(h(f(\top)) \sqcap h(g(\top))) =$$
$$k(h(f(\top))) \sqcap k(h(g(\top)))$$

Accuracy of Data Flow Analysis

- Ideally, we would like to compute the meet over all paths (MOP) solution:
  - Let f_s be the transfer function for statement s
  - If p is a path $\{s_1, ..., s_n\}$, let $f_p = f_n;...;f_1$
  - Let path(s) be the set of paths from the entry to s

$$\mathrm{MOP}(s) = \sqcap_{p \in \mathrm{path}(s)} f_p(\top)$$

- If a data flow problem is distributive, then solving the data flow equations in the standard way yields the MOP solution

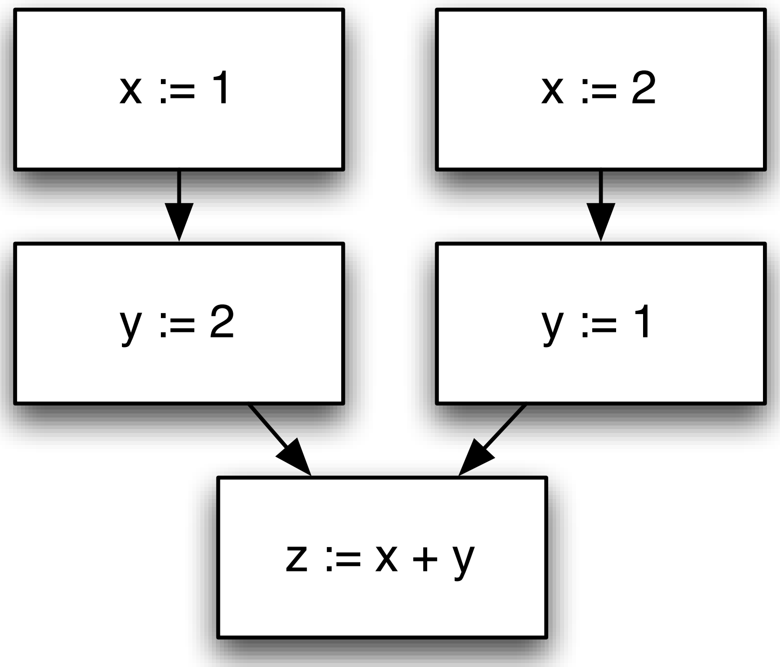
What Problems are Distributive?

- Analyses of *how* the program computes
  - Live variables
  - Available expressions
  - Reaching definitions
  - Very busy expressions

- All Gen/Kill problems are distributive

A Non-Distributive Example

- Constant propagation



- In general, analysis of *what* the program computes in not distributive
  - Symbolic execution more accurate for nondistributive problems

Practical Implementation

- Data flow facts = assertions that are true or false at a program point
- Represent set of facts as bit vector
  - $Fact_i$ represented by bit i
  - Intersection = bitwise and, union = bitwise or, etc
- "Only" a constant factor speedup
  - But very useful in practice

Basic Blocks

- A *basic block* is a sequence of statements s.t.
  - No statement except the last in a branch
  - There are no branches to any statement in the block except the first

- In practical data flow implementations,
  - Compute Gen/Kill for each basic block
    - Compose transfer functions
  - Store only In/Out for each basic block
  - Typical basic block ~5 statements

Order Matters

- Assume forward data flow problem
  - Let G = (V, E) be the CFG
  - Let k be the height of the lattice
- If G acyclic, visit in topological order
  - Visit head before tail of edge
- Running time O(|E|)
  - No matter what size the lattice

Order Matters — Cycles

- If G has cycles, visit in reverse postorder
  - Order from depth-first search
- Let Q = max # back edges on cycle-free path
  - Nesting depth
  - Back edge is from node to ancestor on DFS tree
- Then if $\forall x . f(x) \leq x$ (sufficient, but not necessary)
  - Running time is $O((Q+1)|E|)$
    - Note direction of req't depends on top vs. bottom

Flow-Sensitivity

- Data flow analysis is *flow-sensitive*
  - The order of statements is taken into account
  - I.e., we keep track of facts per program point

- Alternative: *Flow-insensitive* analysis
  - Analysis the same regardless of statement order
  - Standard example: types
    - /* x : int */ x := ... /* x : int */

Terminology Review

- Must vs. May
  - (Not always followed in literature)
- Forwards vs. Backwards
- Flow-sensitive vs. Flow-insensitive
- Distributive vs. Non-distributive

Data Flow Analysis and Functions

- What happens at a function call?
  - Lots of proposed solutions in data flow analysis literature
- In practice, only analyze one procedure at a time
- Consequences
  - Call to function kills all data flow facts
  - May be able to improve depending on language, e.g., function call may not affect locals

More Terminology

- An analysis that models only a single function at a time is *intraprocedural*
- An analysis that takes multiple functions into account is *interprocedural*
- An analysis that takes the whole program into account is...guess?

- Note: *global* analysis means "more than one basic block," but still within a function

Data Flow Analysis and The Heap

- Data Flow is good at analyzing local variables
  - But what about values stored in the heap?
  - Not modeled in traditional data flow

- In practice: *x := e
  - Assume all data flow facts killed (!)
  - Or, assume write through x may affect any variable whose address has been taken

- In general, hard to analyze pointers

Data Flow Analysis and Optimization

Data Flow Analysis and Optimization

- Moore's Law: Hardware advances double computing power every 18 months.

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Data Flow Analysis and Optimization

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- Proebsting's Law: Compiler advances double computing power every 18 *years*.

  - Not so much bang for the buck!

DF Analysis and Defect Detection

- LCLint - Evans et al. (UVa)
- METAL - Engler et al. (Stanford, now Coverity)
- ESP - Das et al. (MSR)
- FindBugs - Hovemeyer, Pugh (Maryland)
  - For Java. The first three are for C.
- Many other one-shot projects
  - Memory leak detection
  - Security vulnerability checking (tainting, info. leaks)

Appendix: Elimination

- Recall using one transfer function per basic block

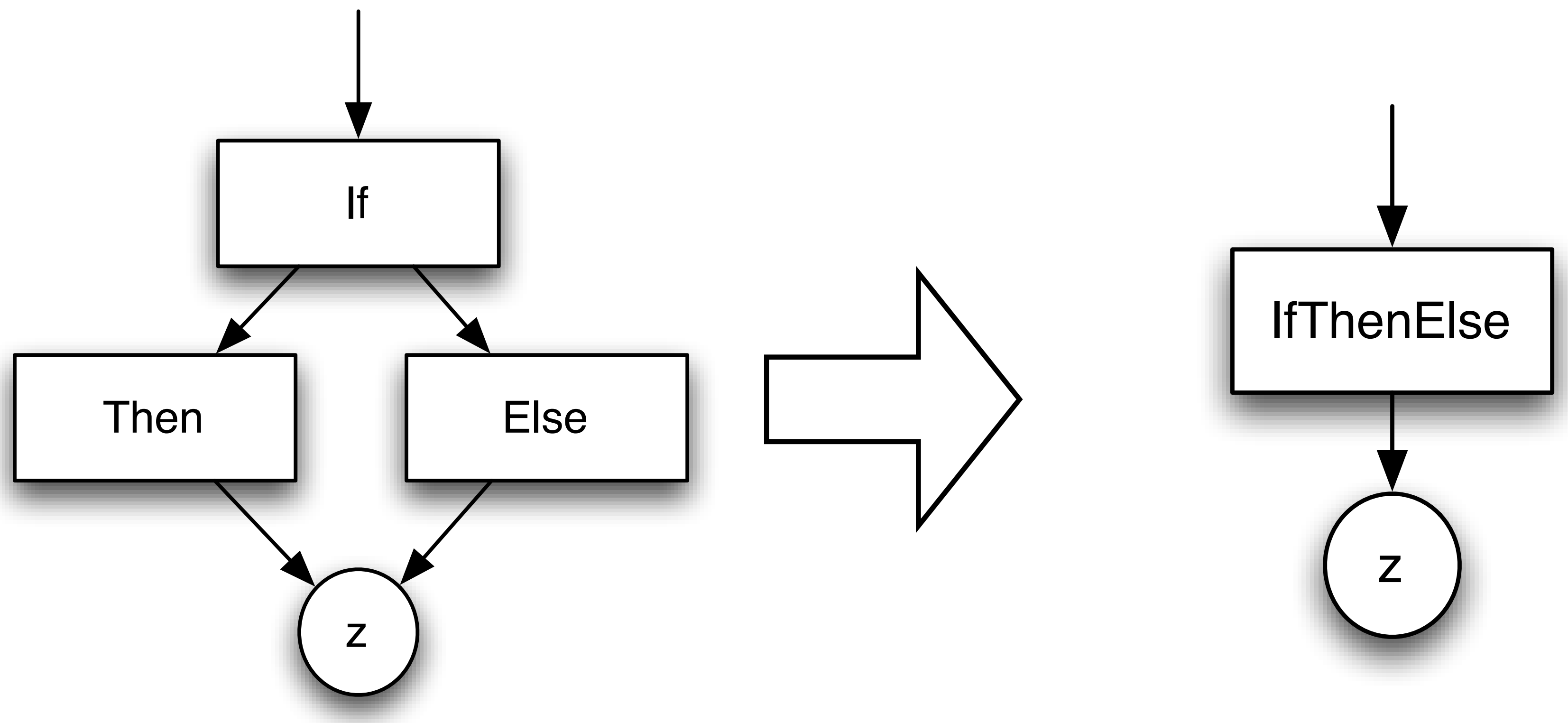
- Why not generalize this idea beyond a basic block?
  - "Collapse" larger constructs into smaller ones, combining data flow equations
  - Eventually program collapsed into a single node!
  - "Expand out" back to original constructs, rebuilding information

Lattices of Functions

- Let $(P, \leq)$ be a lattice
- Let M be the set of monotonic functions on P
- Define $f \leq_f g$ if for all x, $f(x) \leq g(x)$
- Define the function $f \sqcap g$ as
  - $(f \sqcap g)(x) = f(x) \sqcap g(x)$

- Claim: $(M, \leq_f)$ forms a lattice

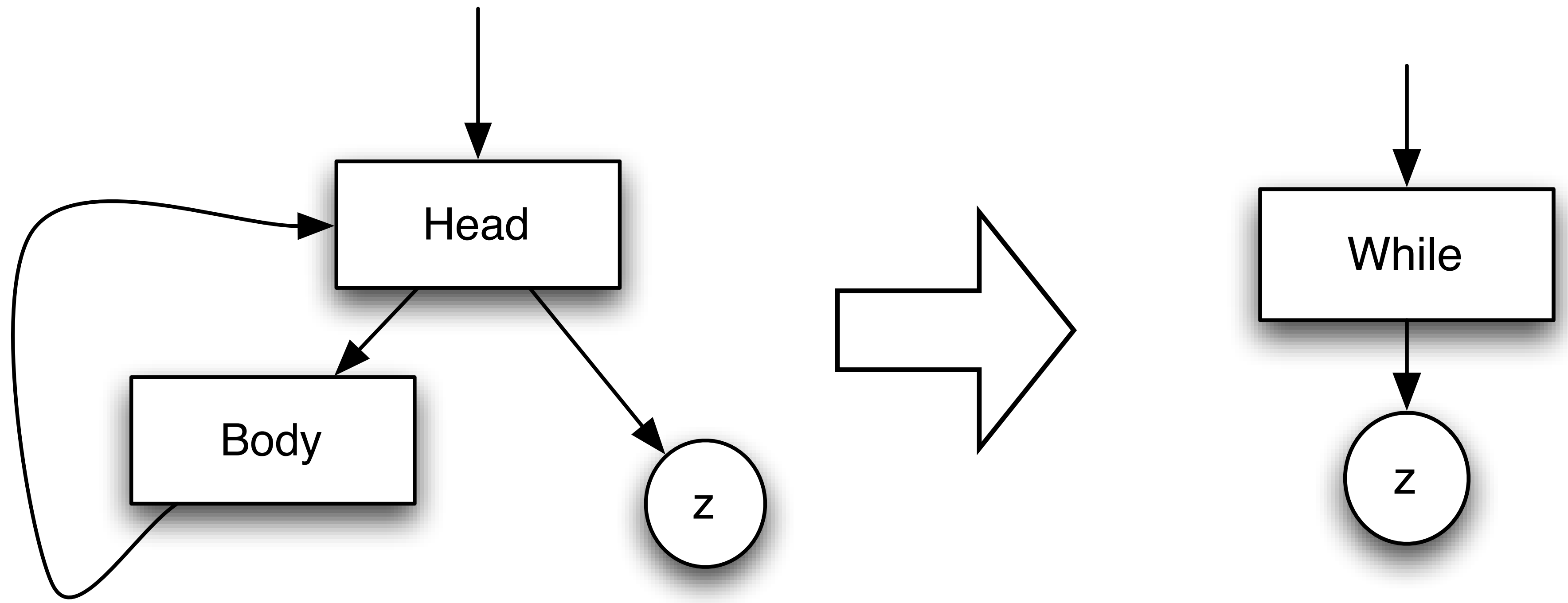
Elimination Methods: Conditionals



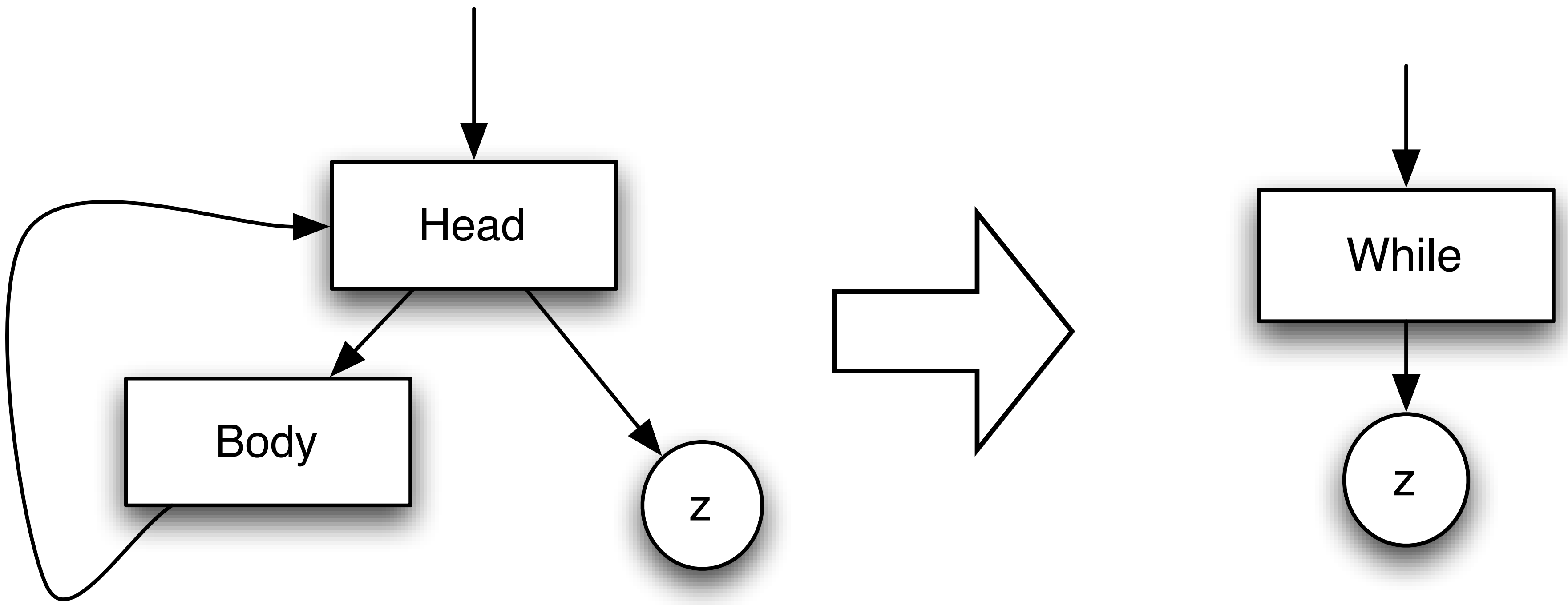
$$f_{\mathrm{ite}} = (f_{\mathrm{then}} \circ f_{\mathrm{if}}) \sqcap (f_{\mathrm{else}} \circ f_{\mathrm{if}})$$

$$\begin{aligned}
\mathrm{Out(if)} &= f_{\mathrm{if}}(\mathrm{In(ite)})) \\
\mathrm{Out(then)} &= (f_{\mathrm{then}} \circ f_{\mathrm{if}})(\mathrm{In(ite)})) \\
\mathrm{Out(else)} &= (f_{\mathrm{else}} \circ f_{\mathrm{if}})(\mathrm{In(ite)}))
\end{aligned}$$

Elimination Methods: Loops



Elimination Methods: Loops



$$
\begin{aligned}
f_{\text{while}} \quad = \quad & f_{\text{head}} \sqcap \\
& f_{\text{head}} \circ f_{\text{body}} \circ f_{\text{head}} \sqcap \\
& f_{\text{head}} \circ f_{\text{body}} \circ f_{\text{head}} \circ f_{\text{body}} \circ f_{\text{head}} \sqcap \cdots
\end{aligned}
$$

Elimination Methods: Loops (cont'd)

- Let $f^i = f \circ f \circ \ldots \circ f$ (i times)
  - $f^0 = id$
- Let
  $$g(j) = \sqcap_{i \in [0..j]} (f_{\text{head}} \circ f_{\text{body}})^i \circ f_{\text{head}}$$
- Need to compute limit as j goes to infinity
  - Does such a thing exist?
- Observe: $g(j+1) \leq g(j)$

Height of Function Lattice

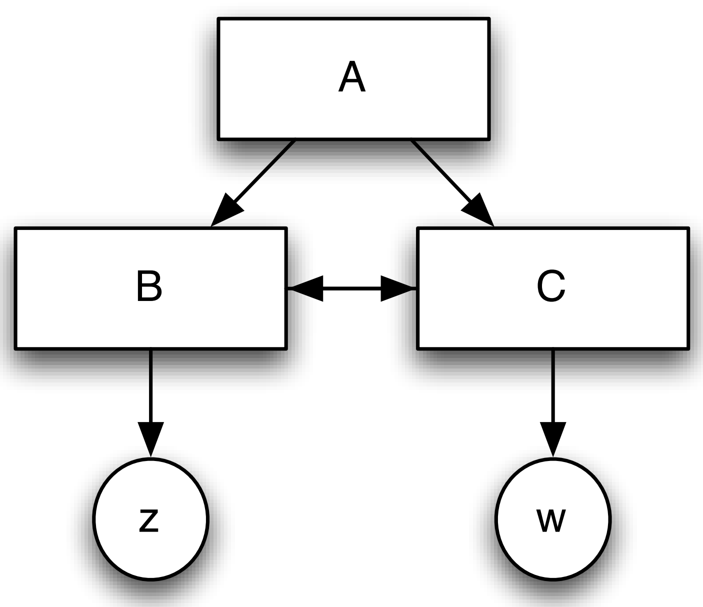
- Assume underlying lattice $(P, \leq)$ has finite height
  - What is height of lattice of monotonic functions?
  - Claim: finite (can you prove this?)

- Therefore, $g(j)$ converges

Non-Reducible Flow Graphs

- Elimination methods usually only applied to *reducible* flow graphs
  - Ones that can be collapsed
  - Standard constructs yield only reducible flow graphs

- Unrestricted goto can yield non-reducible graphs



Comments

- Can also do backwards elimination
  - Not quite as nice (regions are usually single *entry* but often not single *exit*)
- For bit-vector problems, elimination efficient
  - Easy to compose functions, compute meet, etc.
- Elimination originally seemed like it might be faster than iteration
  - Not really the case