Live Variables Analysis

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Outline

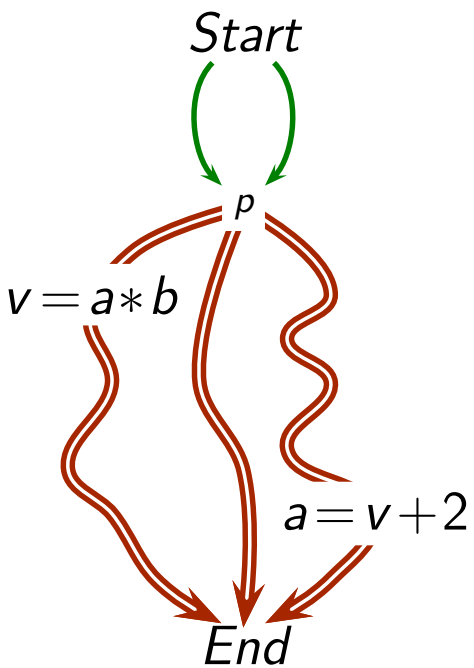
- Live Variables Analysis
- Strongly Live Variables Analysis
- Some Observations

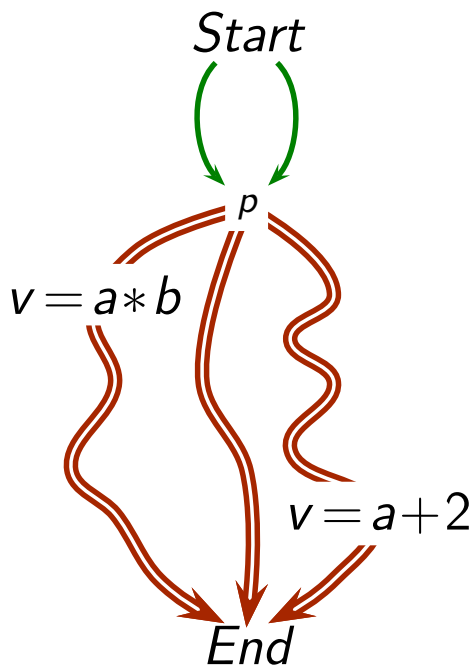
Part 1

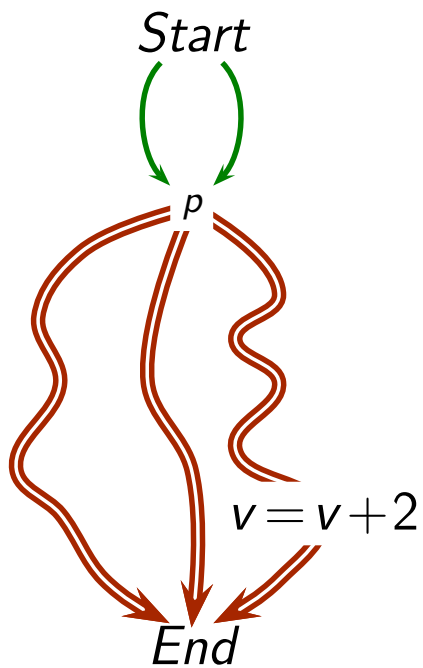
Live Variables Analysis

Defining Live Variables Analysis

A variable v is live at a program point p, if some path from p to program exit contains an r-value occurrence of v which is not preceded by an l-value occurrence of v.







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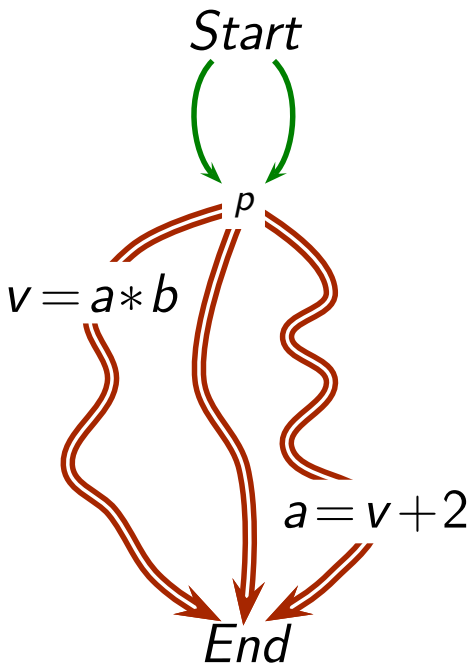
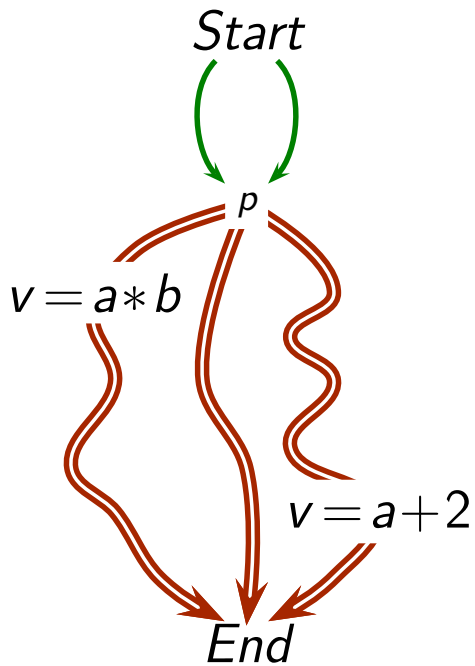
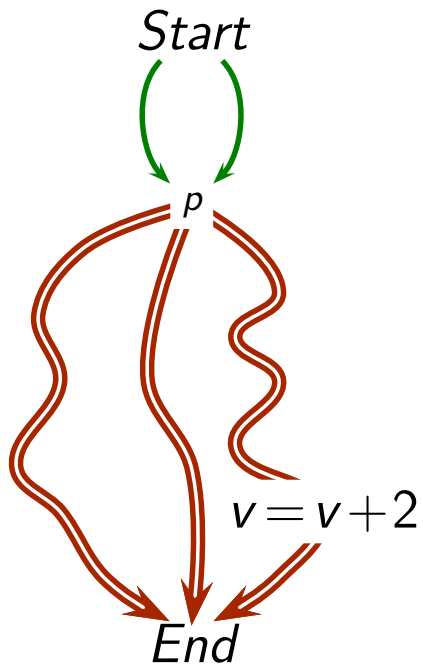
v is live at p







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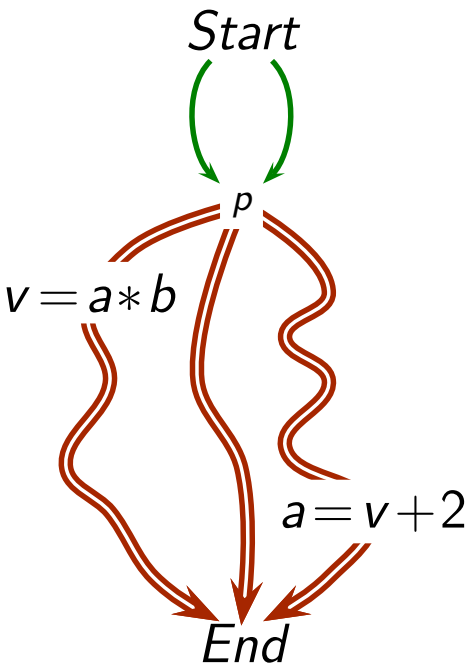
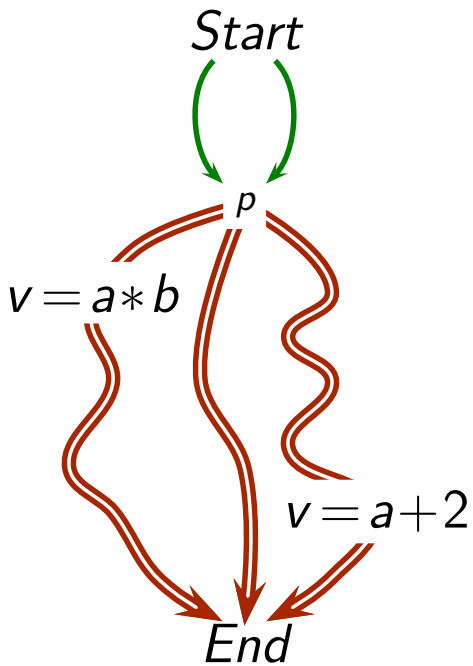
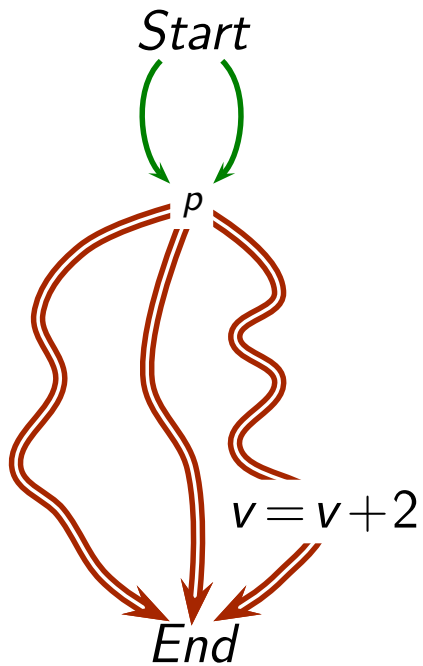


v is not live at p





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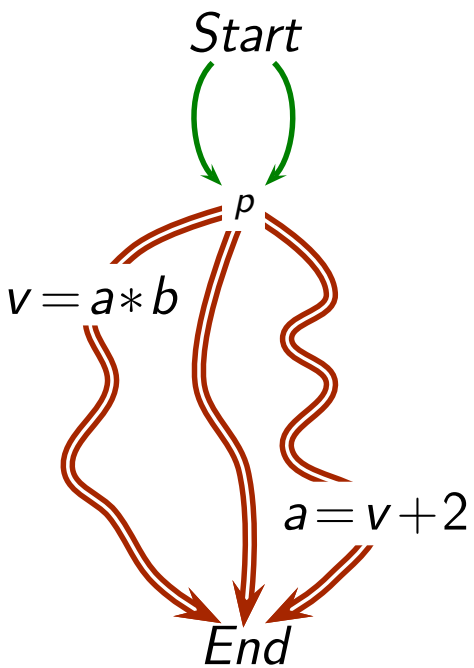

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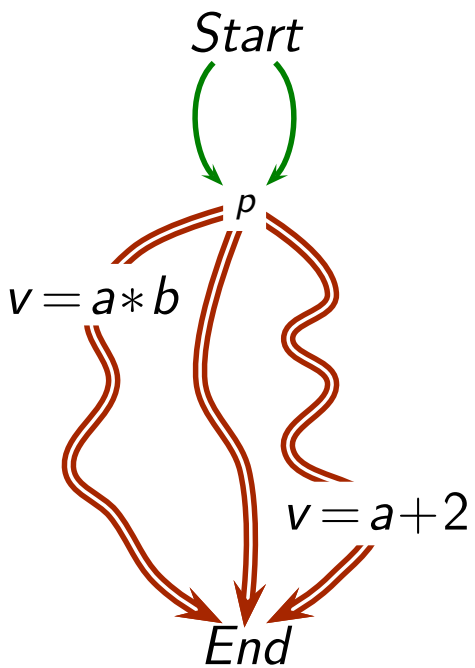

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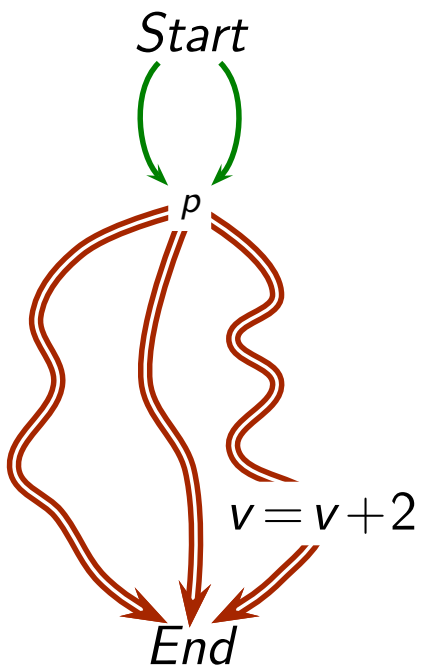

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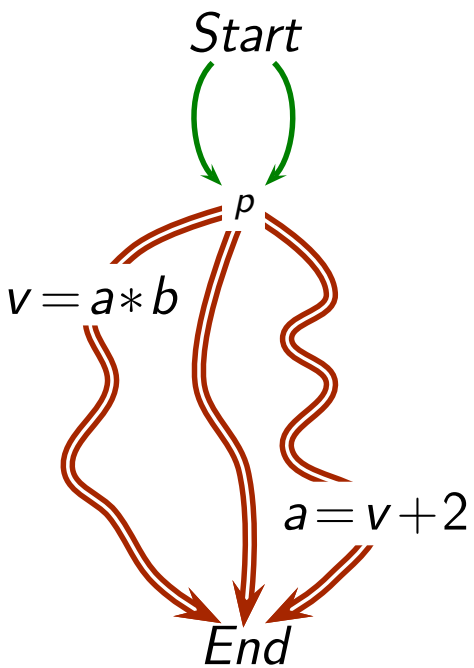
Path based specification

v is live at p



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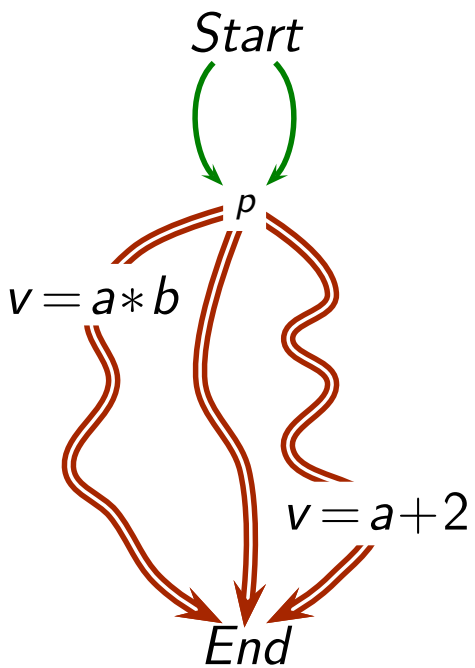

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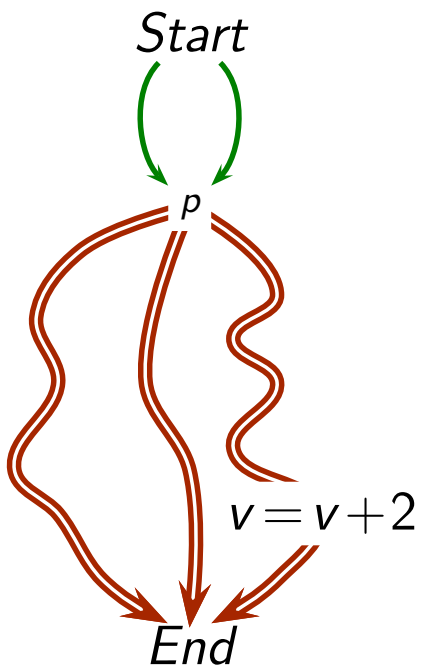

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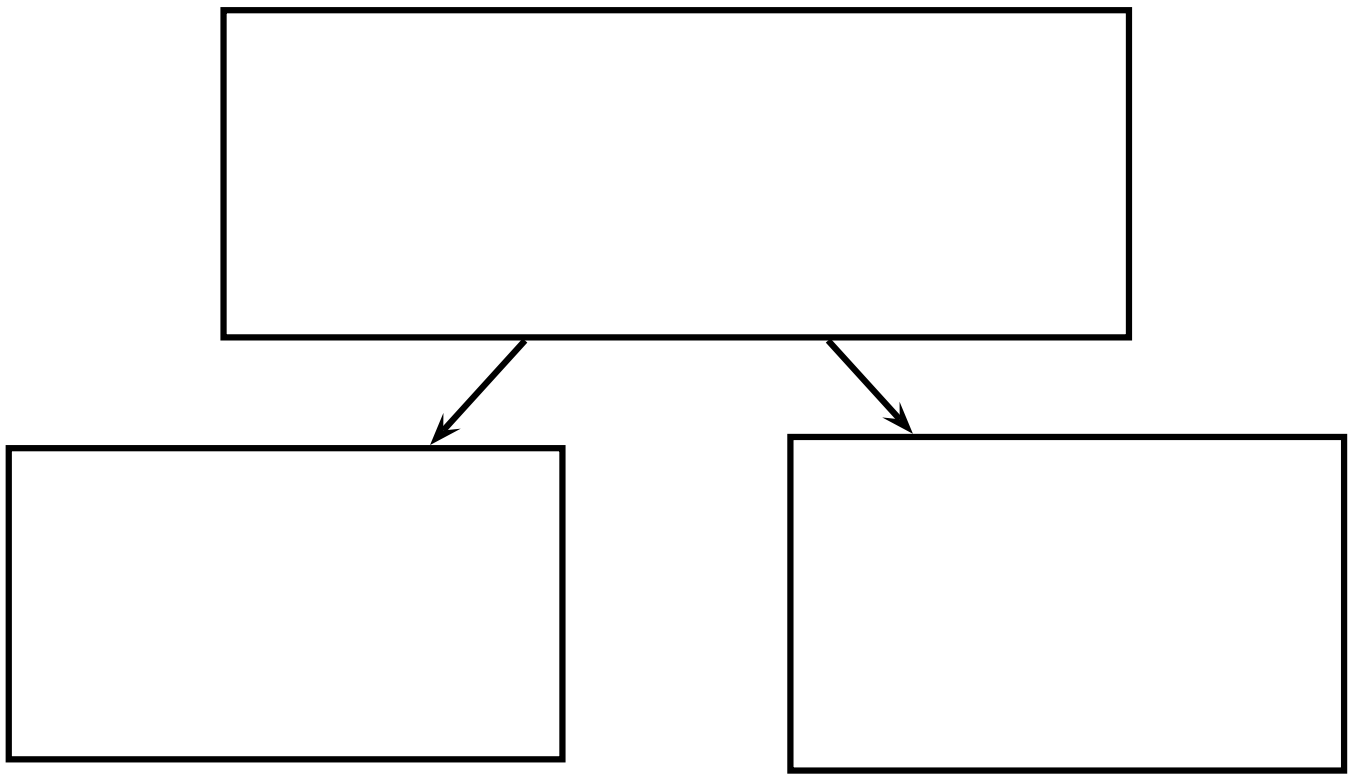

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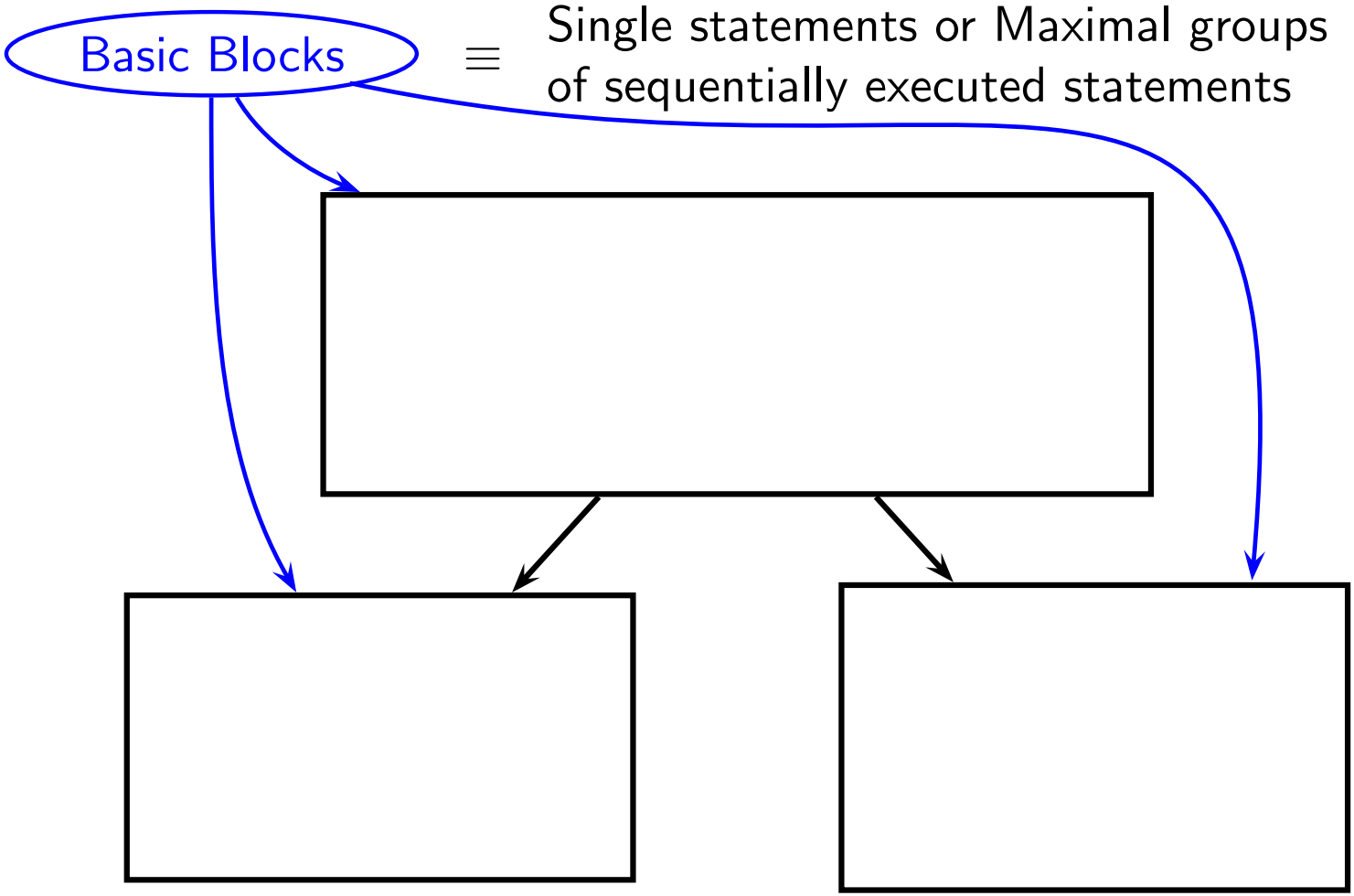

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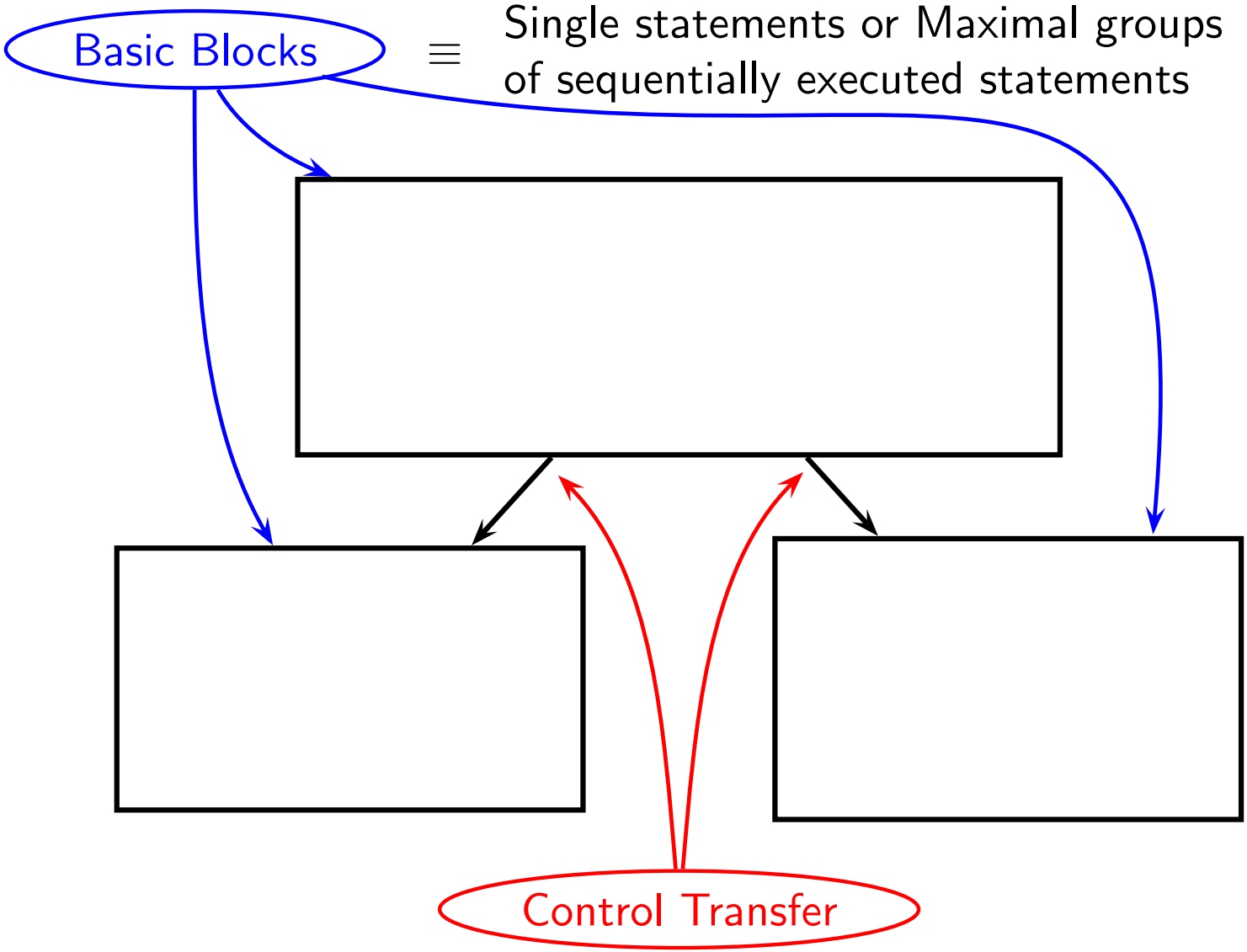

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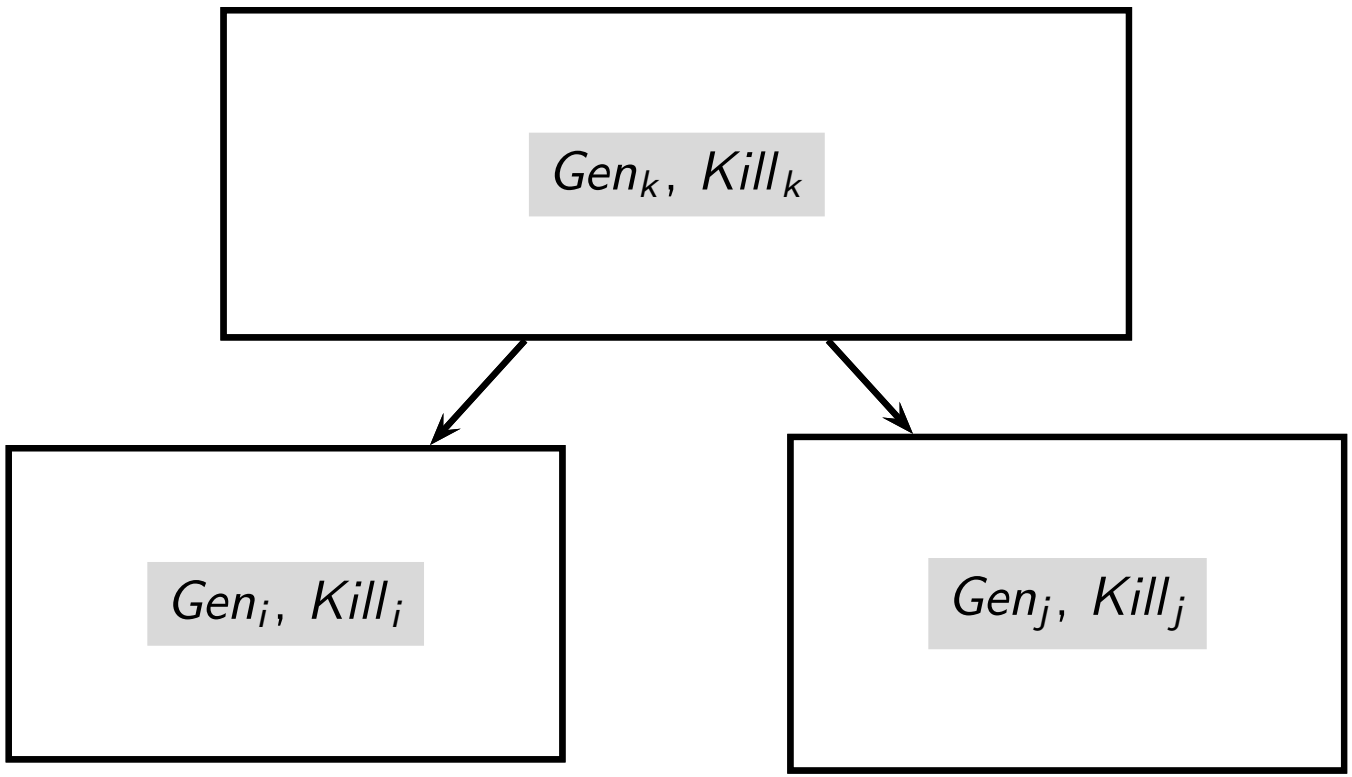

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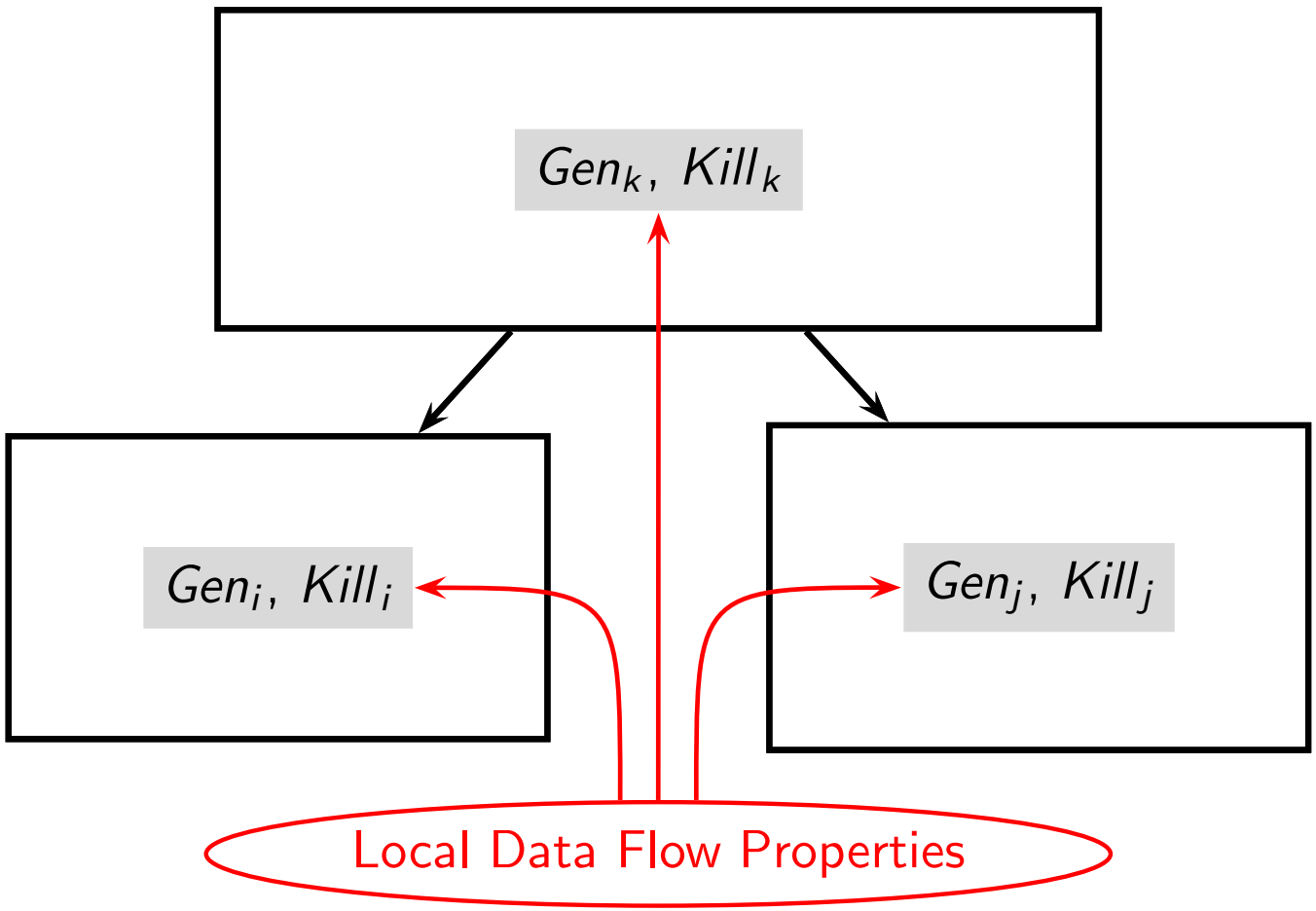

Local Data Flow Properties for Live Variables Analysis

$$
\begin{aligned}
Gen_n &= \{\ v \mid \text{variable } v \text{ is used in basic block } n \text{ and} \\
&\qquad \text{is not preceded by a definition of } v\ \} \\
Kill_n &= \{\ v \mid \text{basic block } n \text{ contains a definition of } v\ \}
\end{aligned}
$$

Local Data Flow Properties for Live Variables Analysis

r-value occurrence

Value is only read, e.g. x,y,z in

x.sum = y.data + z.data

$$Gen_n = \{ v \mid \text{variable } v \text{ is used in basic block } n \text{ and is not preceded by a definition of } v \}$$

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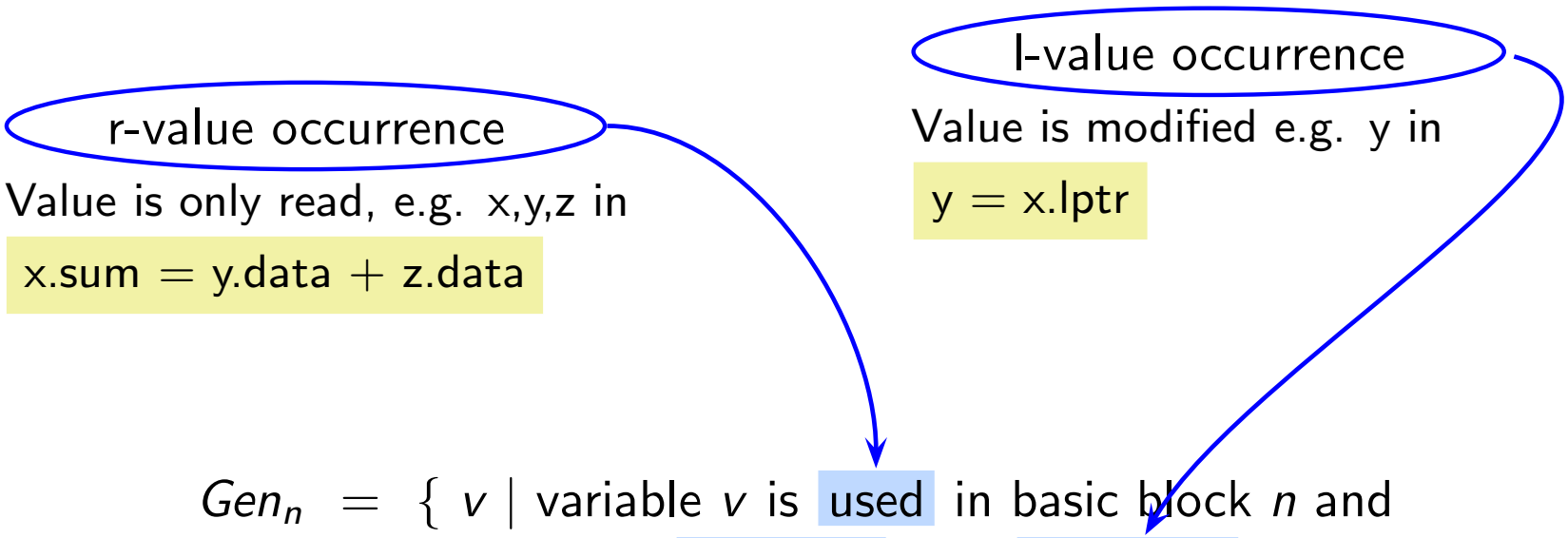

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Local Data Flow Properties for Live Variables Analysis

r-value occurrence

Value is only read, e.g. x,y,z in

x.sum = y.data + z.data

l-value occurrence

Value is modified e.g. y in

y = x.lptr

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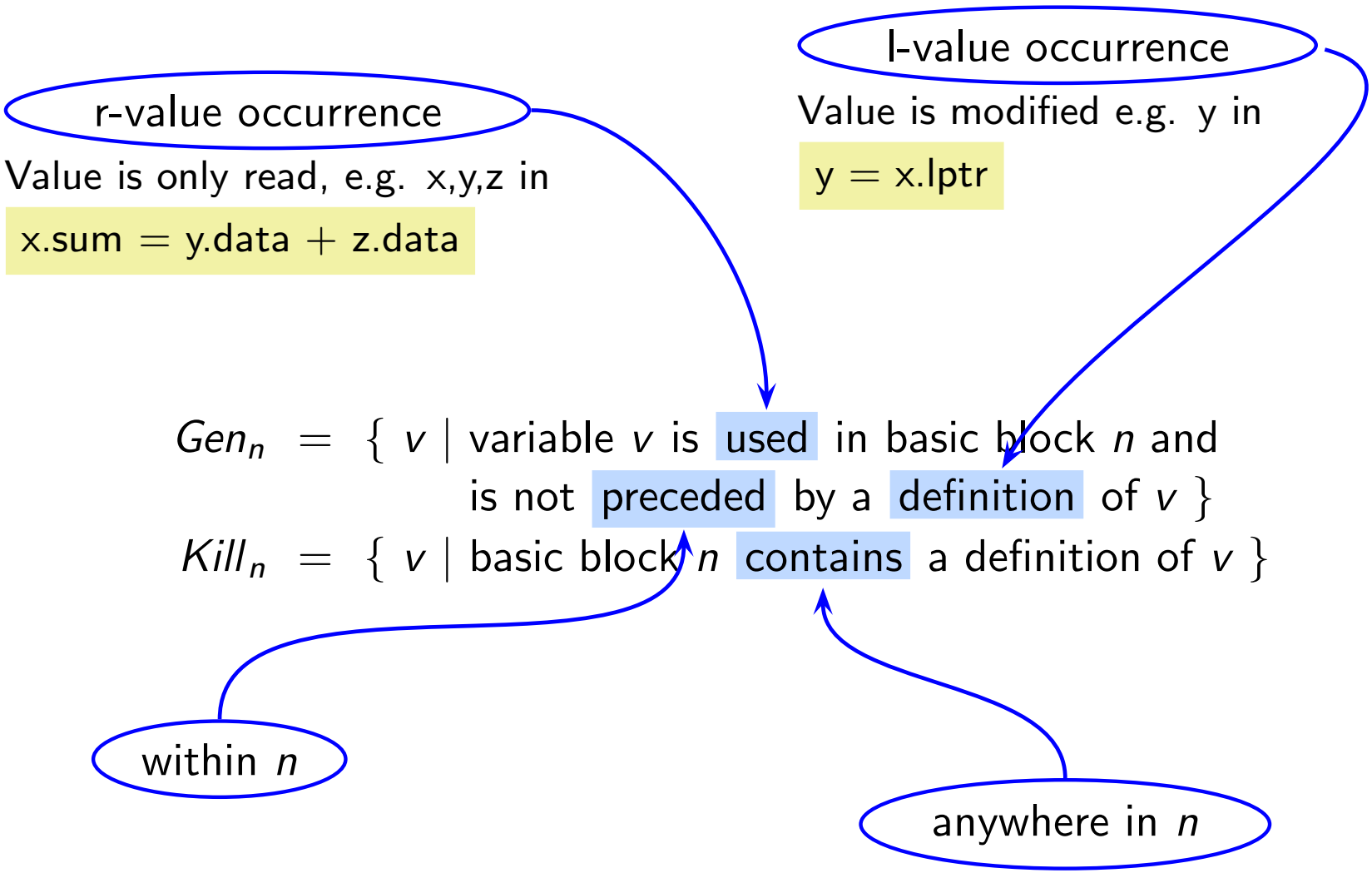
within n

Local Data Flow Properties for Live Variables Analysis



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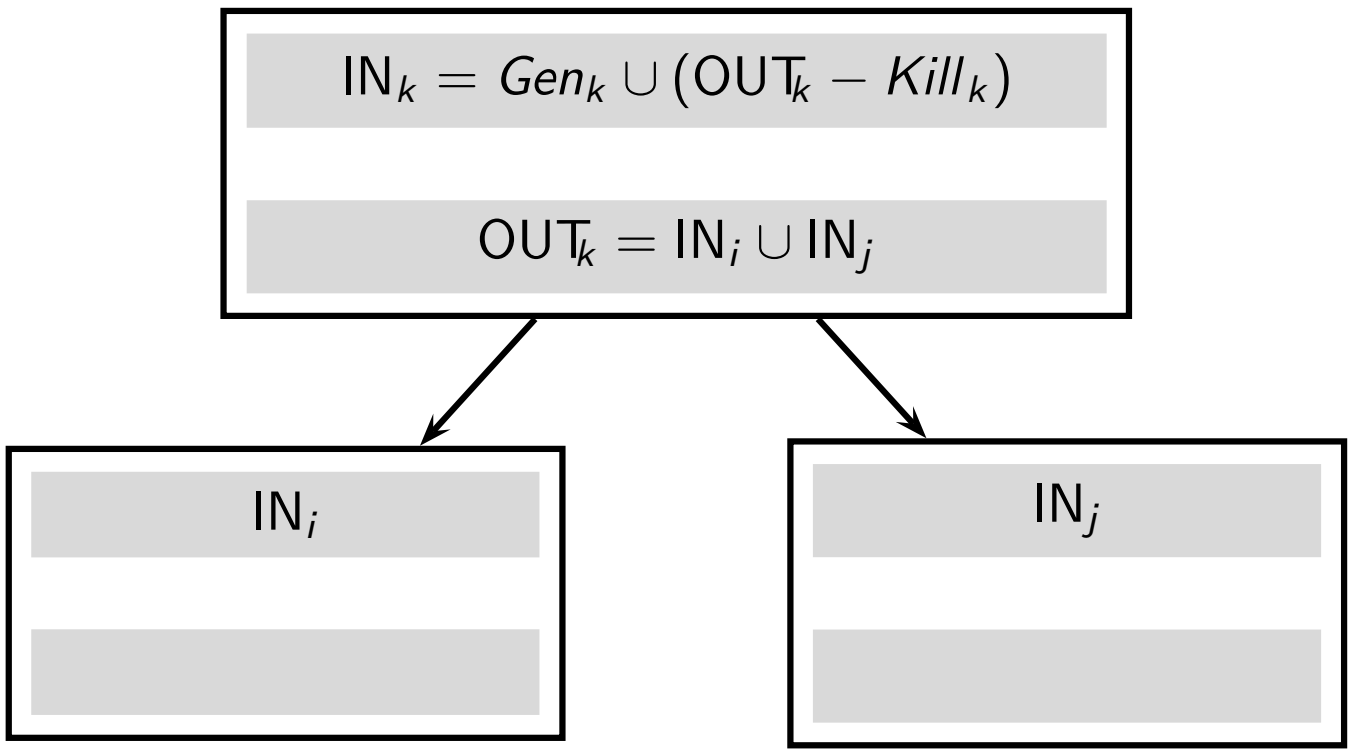

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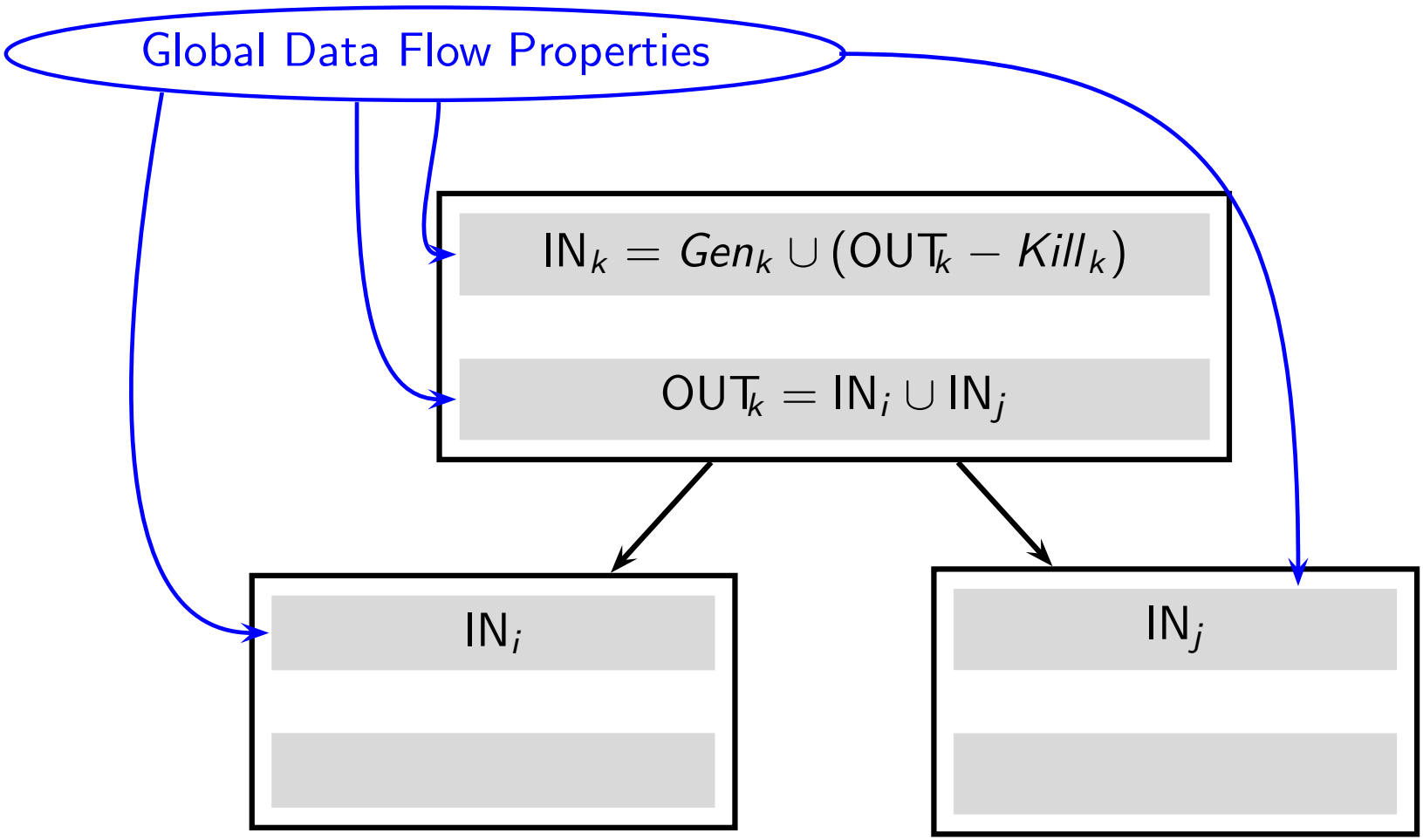

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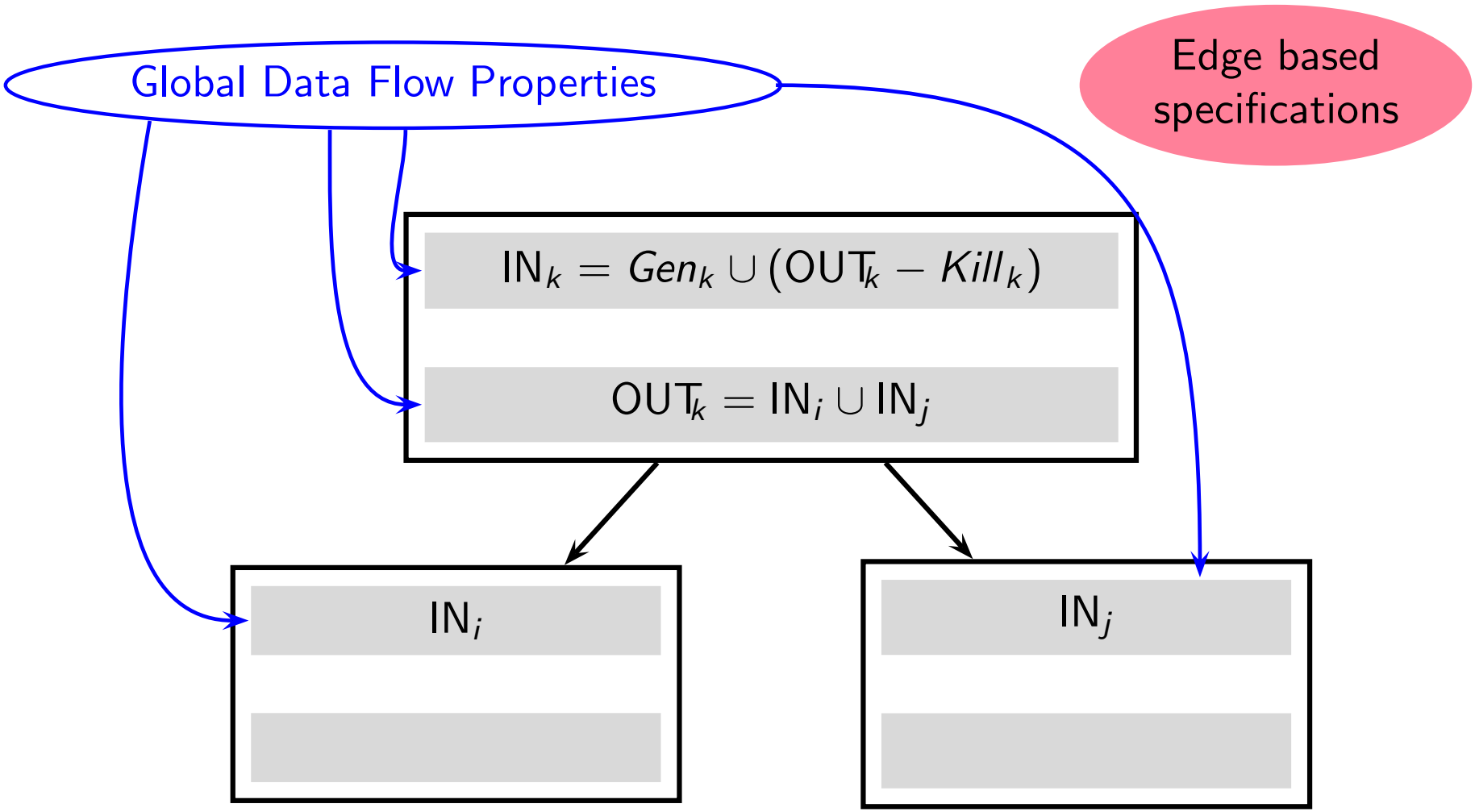

Data Flow Equations For Live Variables Analysis

$$\text{IN}_n = (\text{OUT}_n - \mathit{Kill}_n) \cup \mathit{Gen}_n$$

$$\text{OUT}_n = \begin{cases} \mathit{BI} & n \text{ is } \mathit{End} \text{ block} \\ \bigcup_{s \in succ(n)} \text{IN}_s & \text{otherwise} \end{cases}$$

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- IN_n and OUT_n are sets of variables

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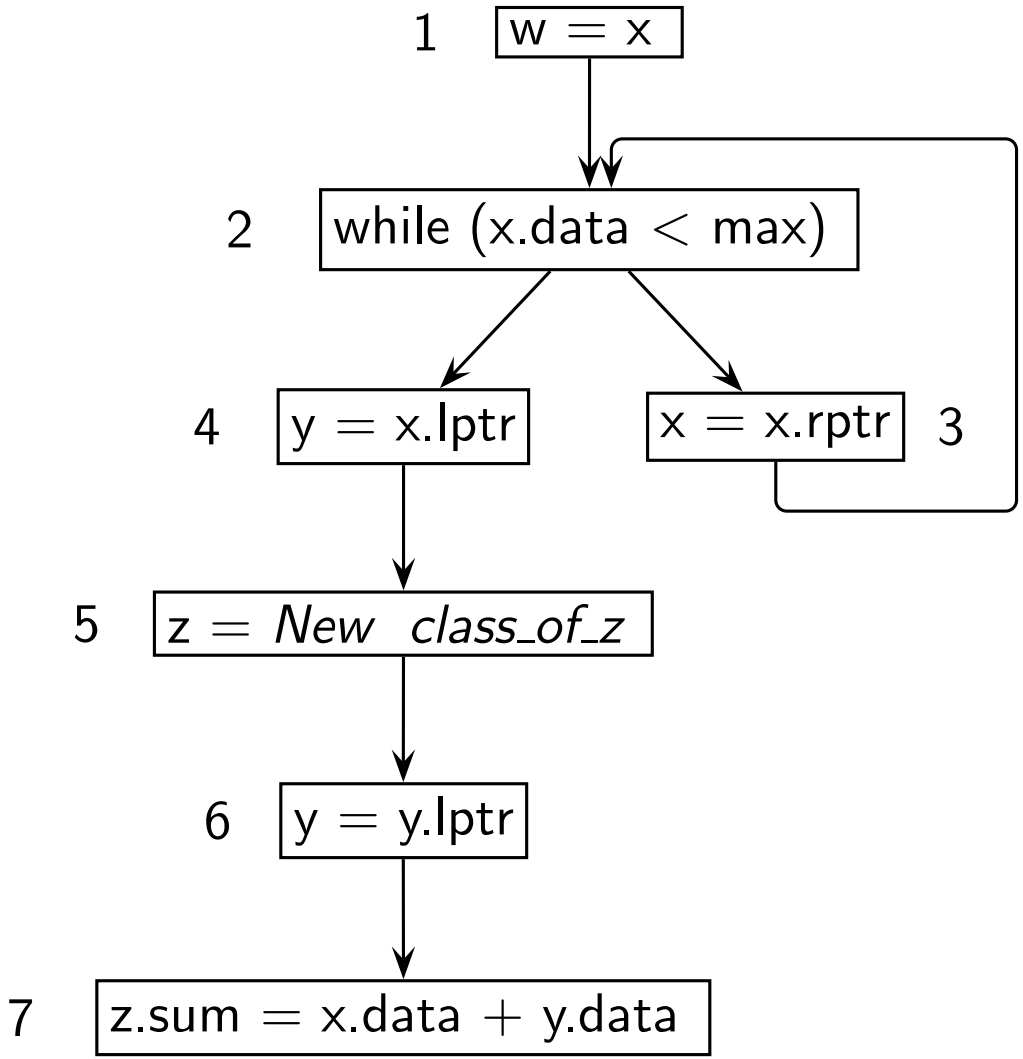
- IN_n and OUT_n are sets of variables
- *BI* is boundary information representing the effect of calling contexts
  - $\emptyset$ for local variables except for the values being returned
  - set of global variables used further in any calling context (can be safely approximated by the set of all global variables)

Data Flow Equations for Our Example



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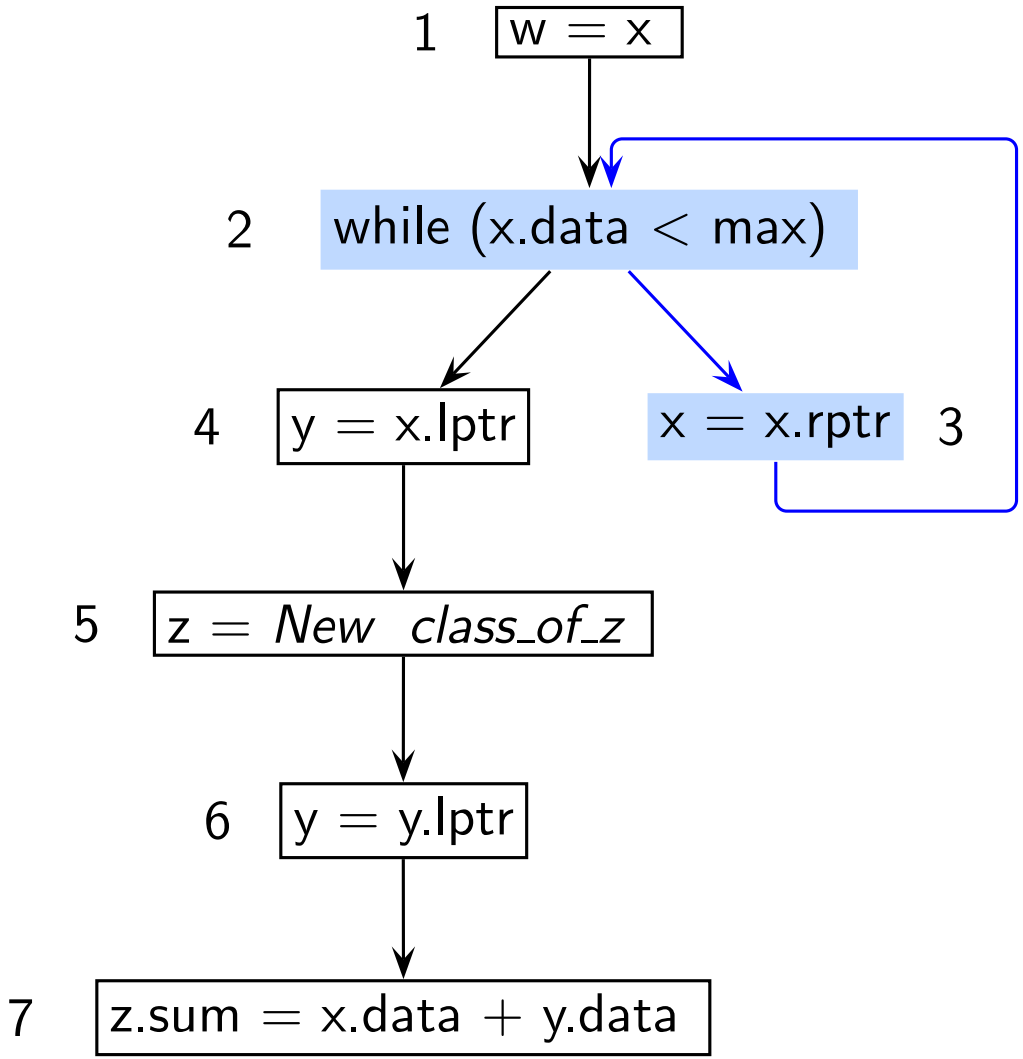

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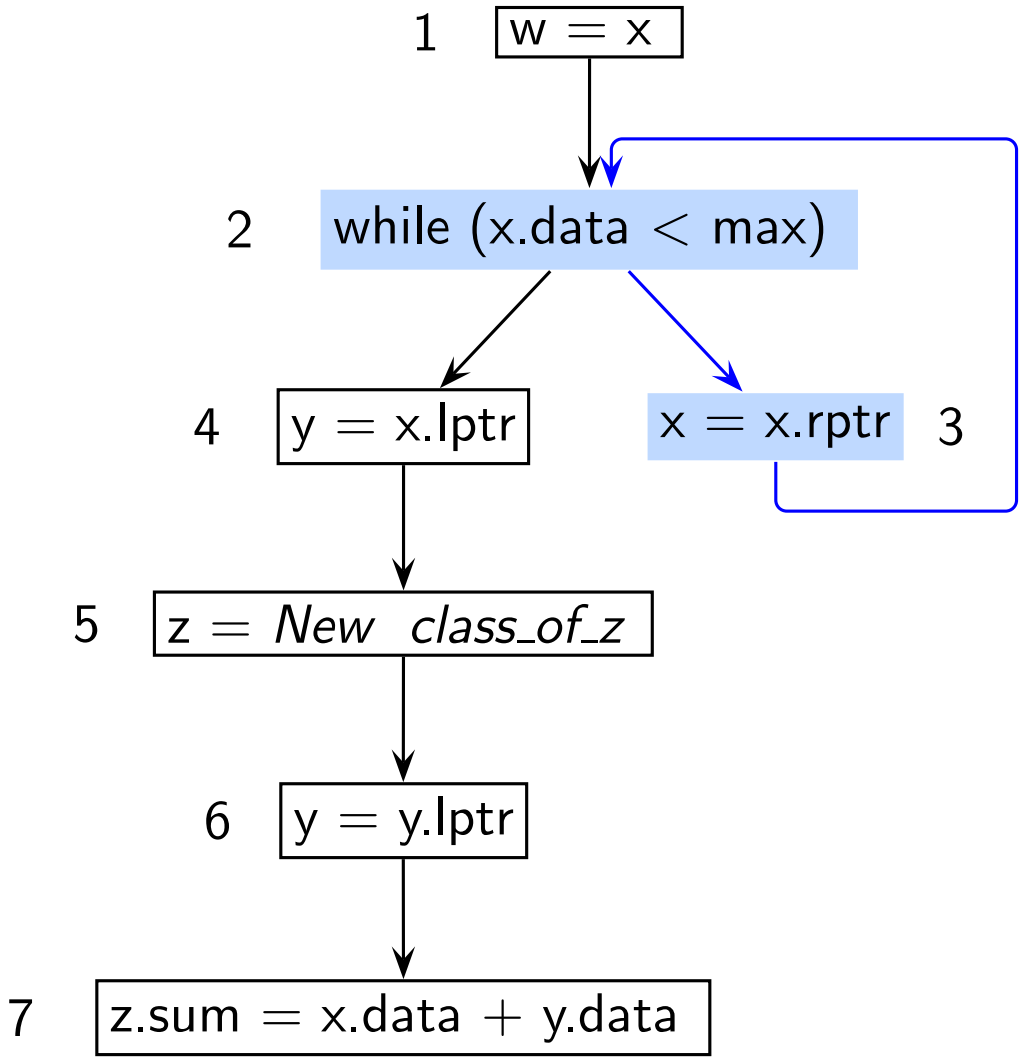

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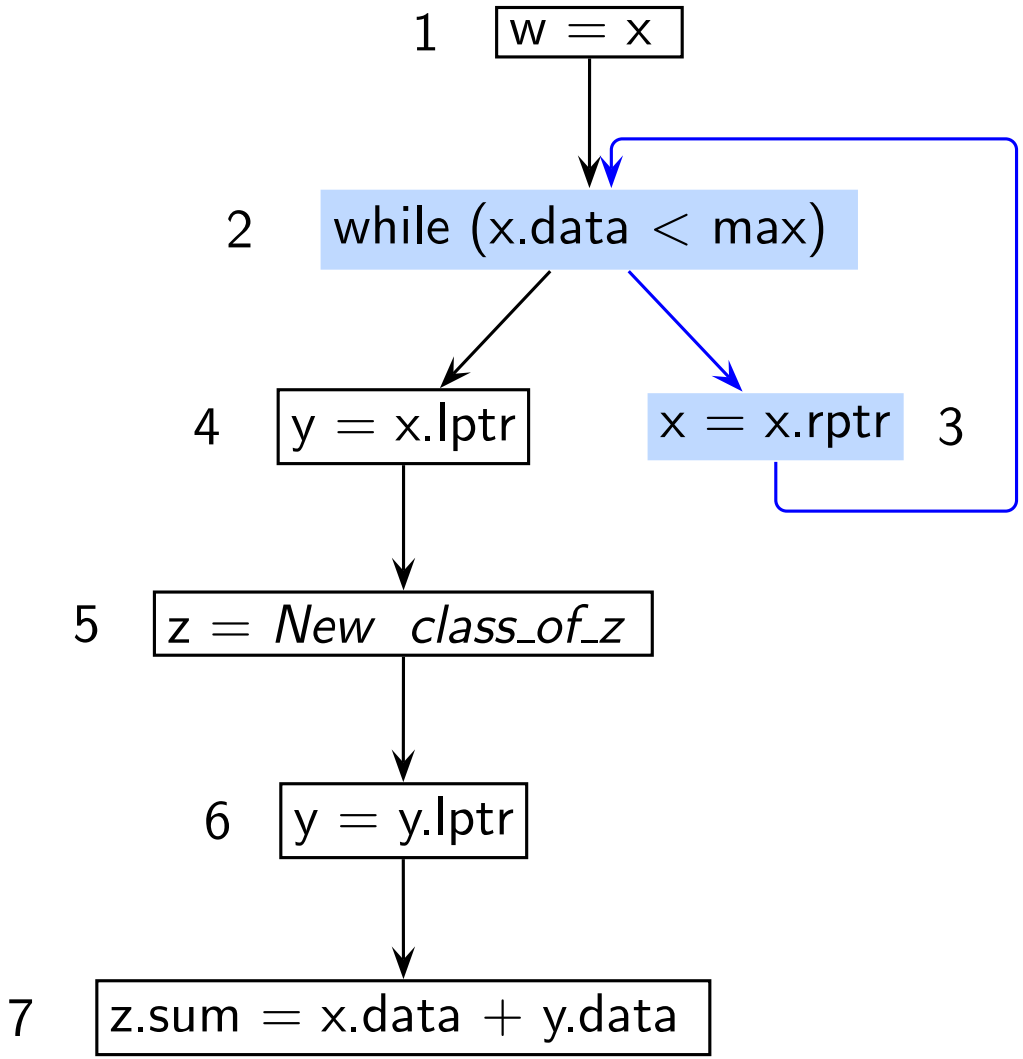

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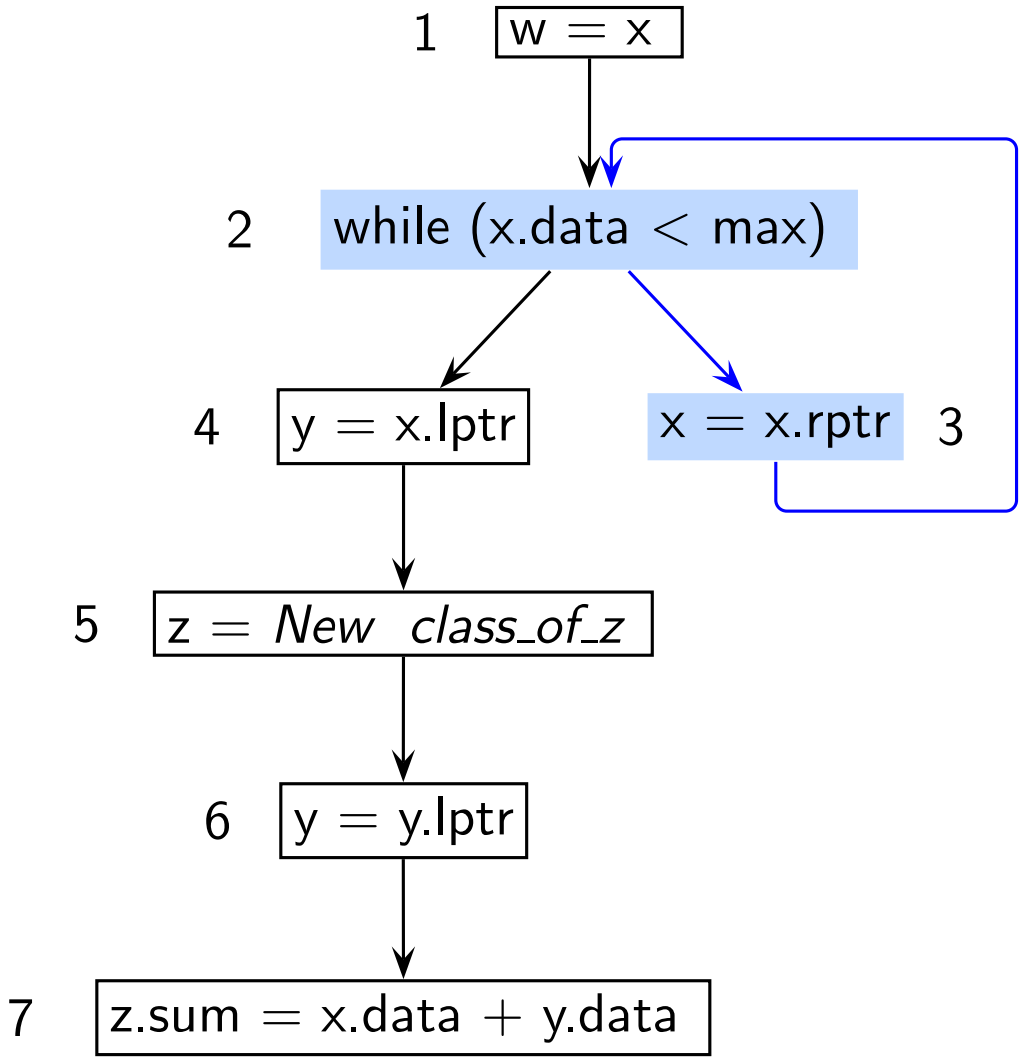

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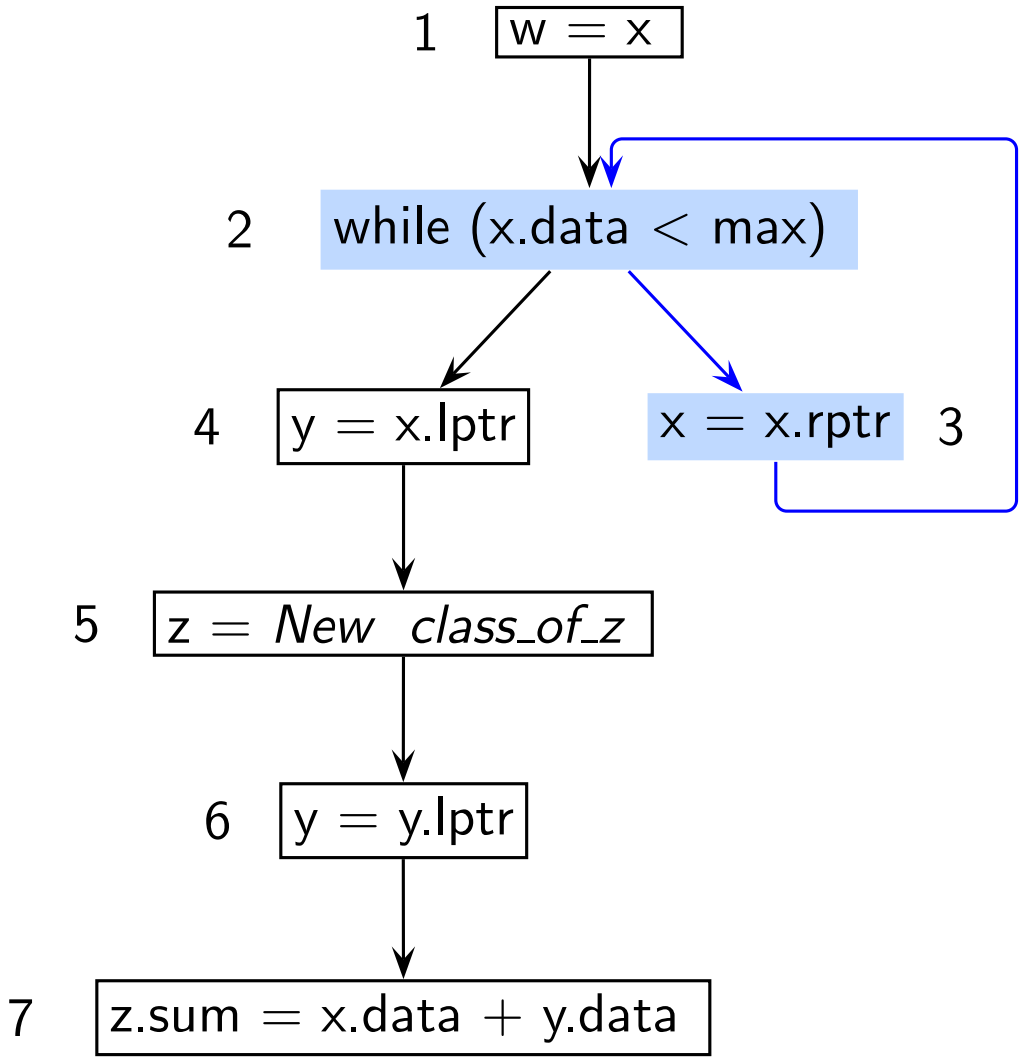

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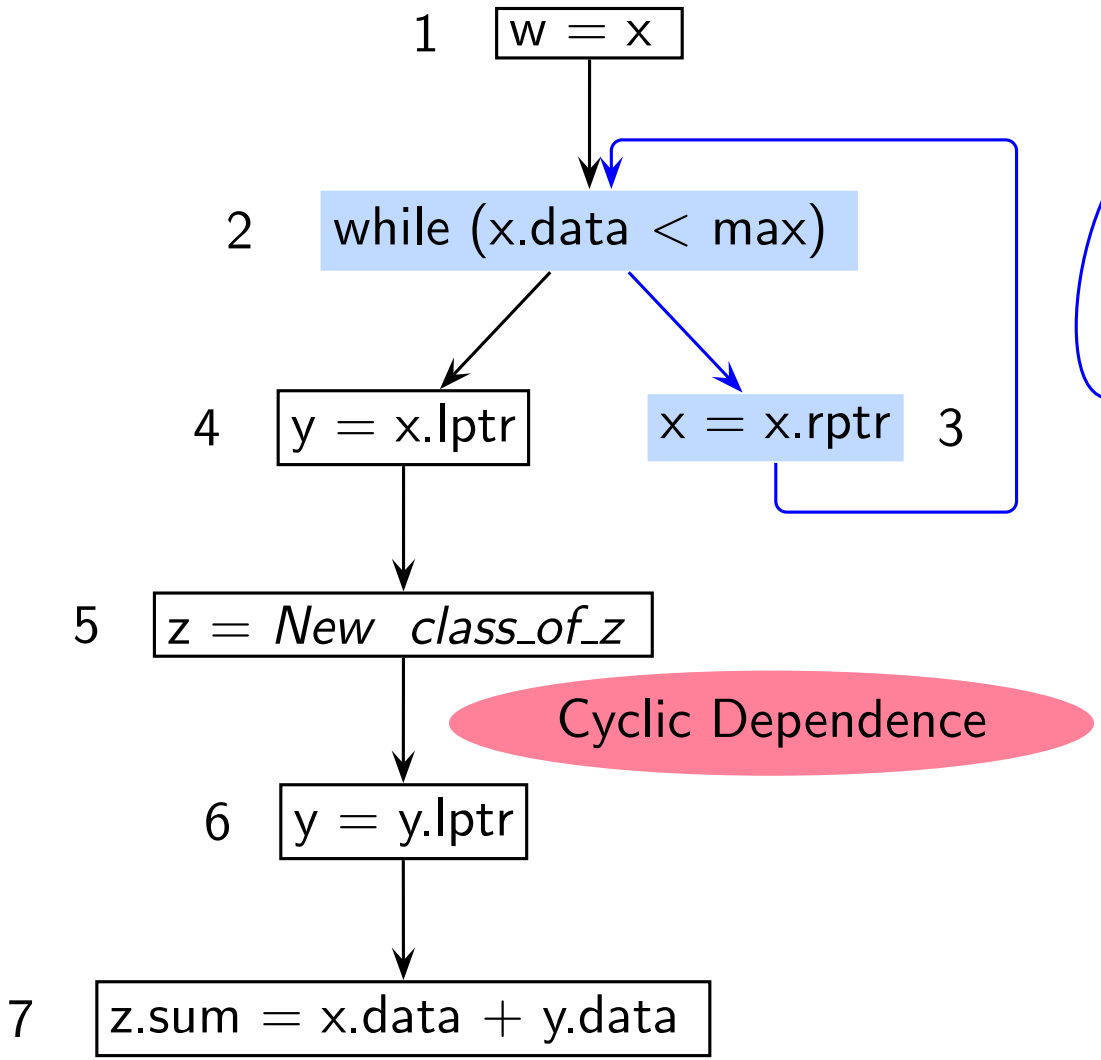

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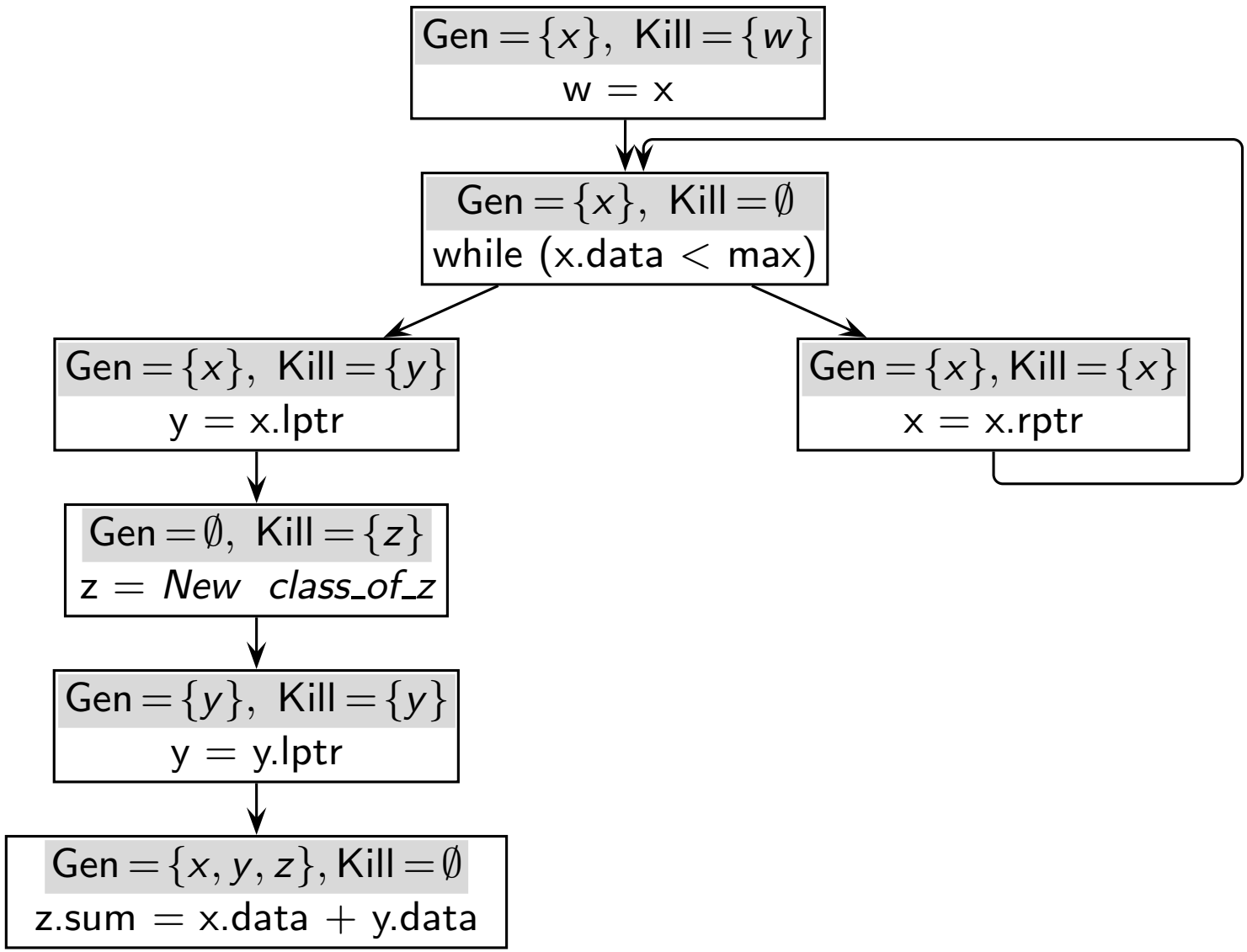
Performing Live Variables Analysis



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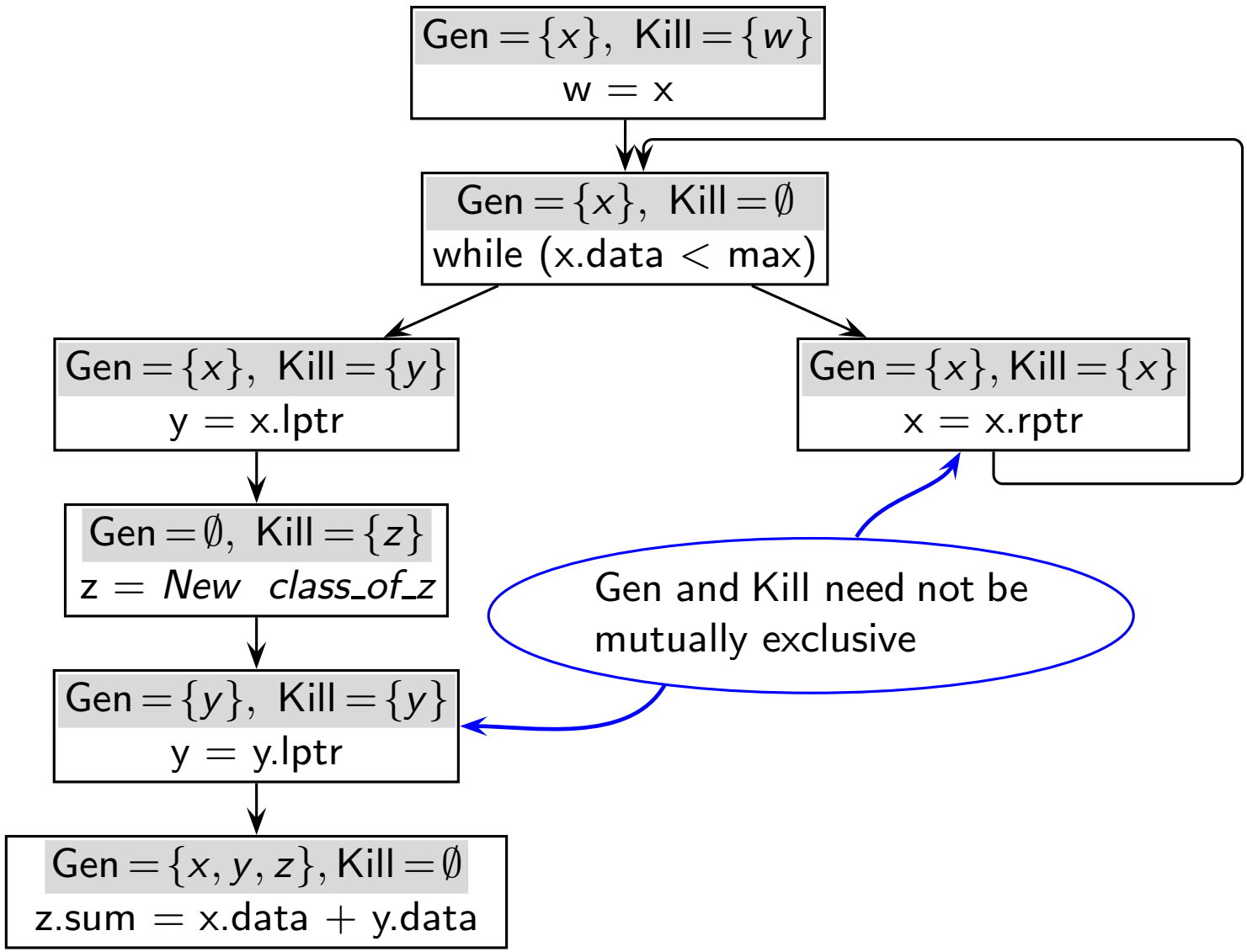

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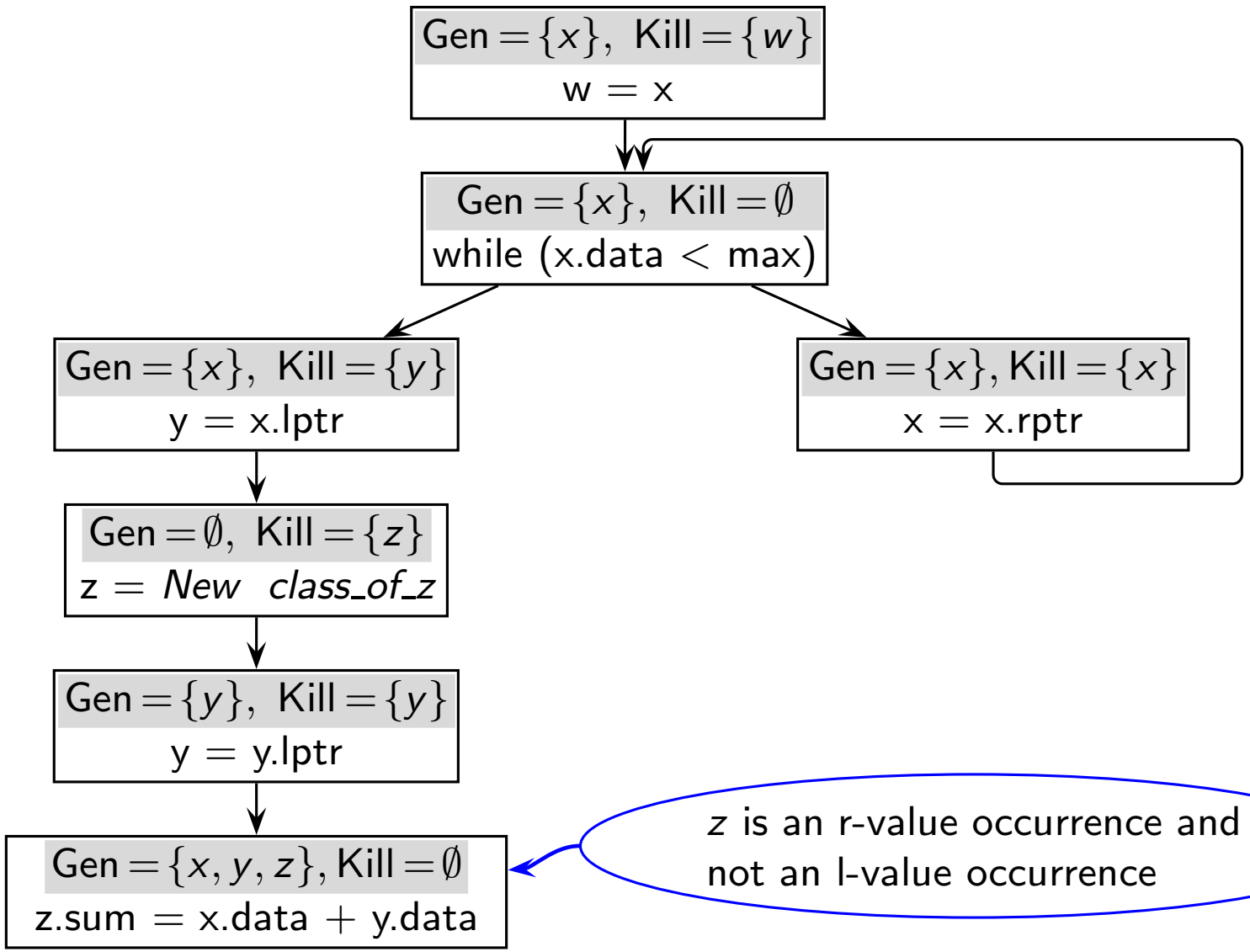

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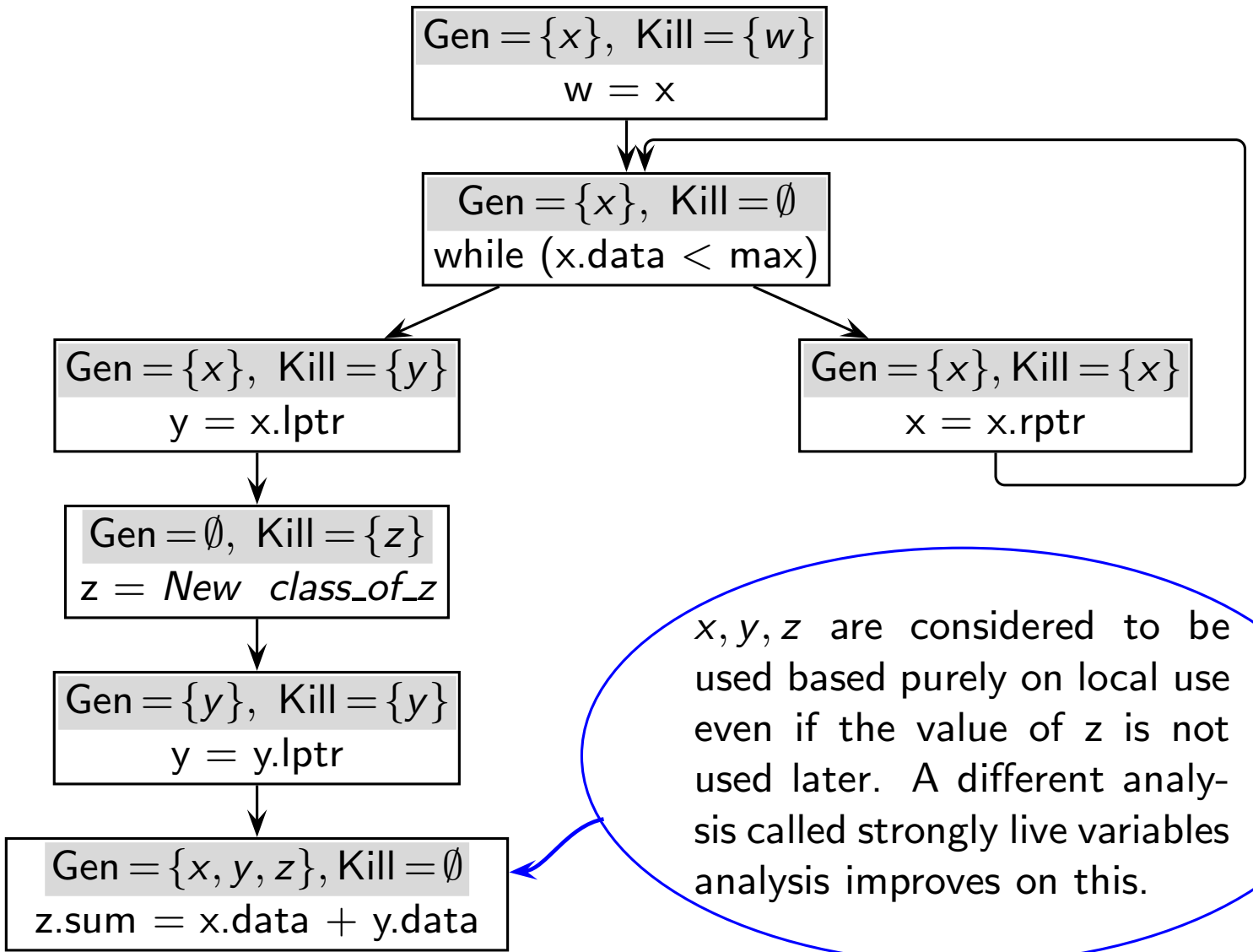

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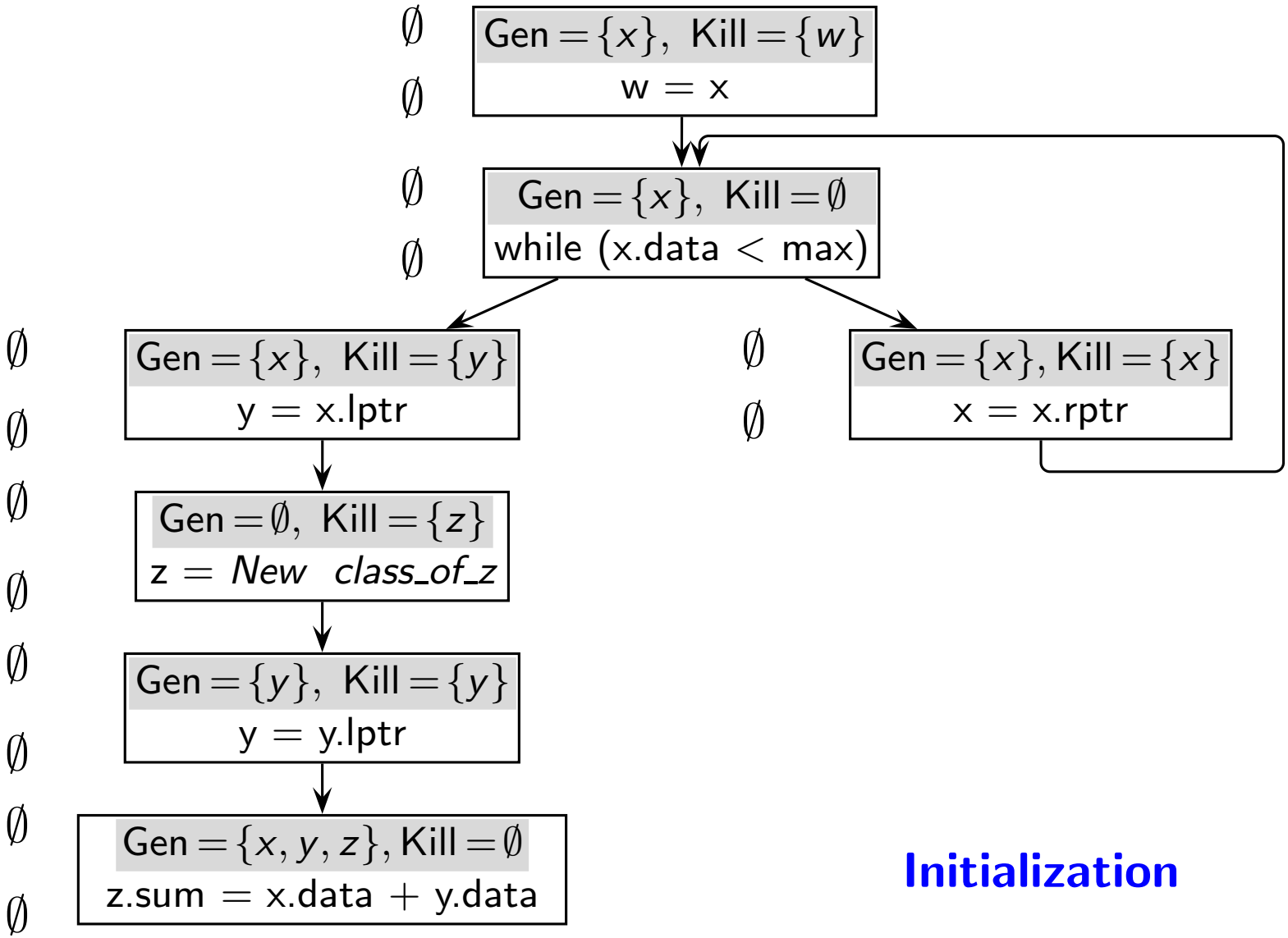
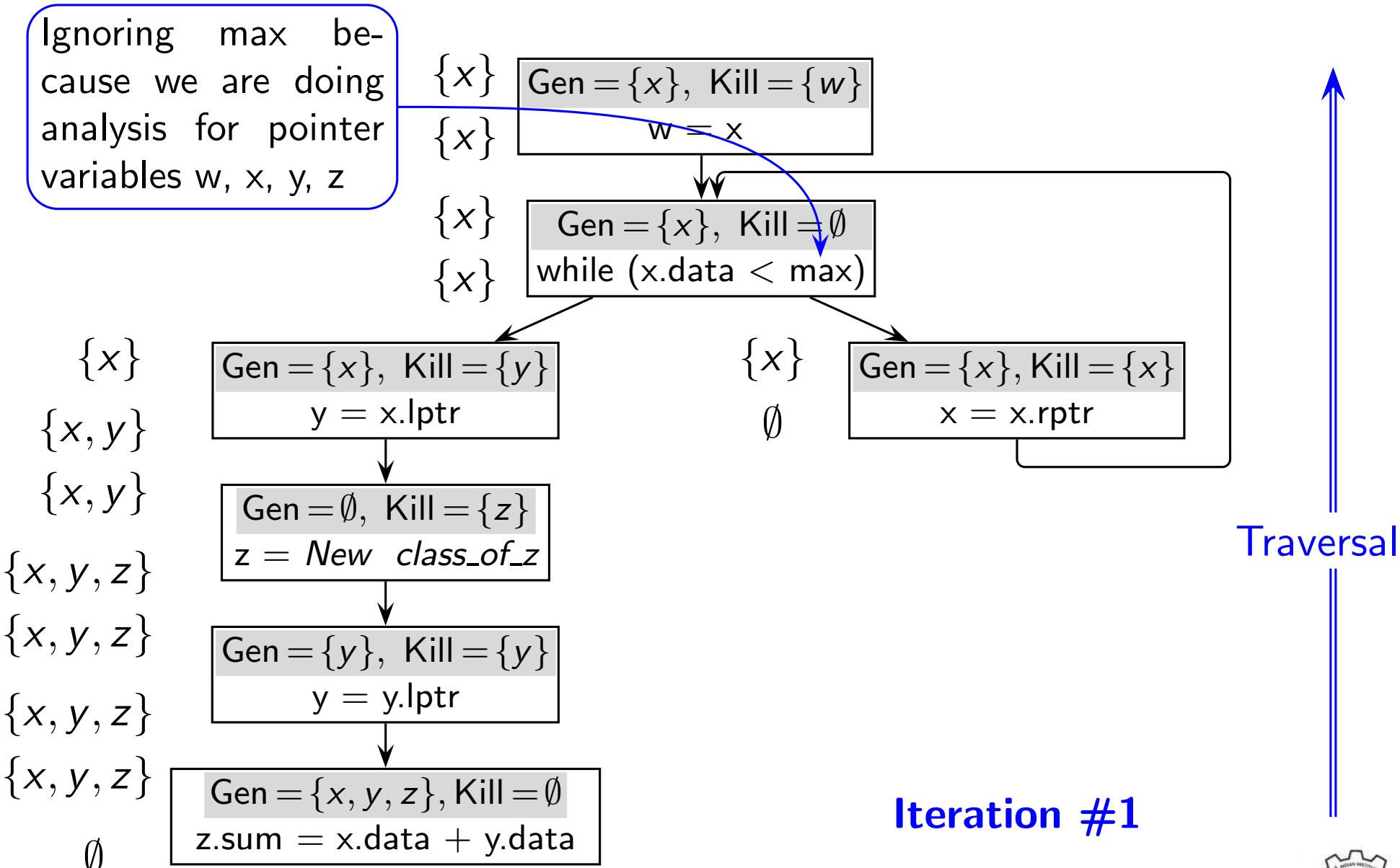
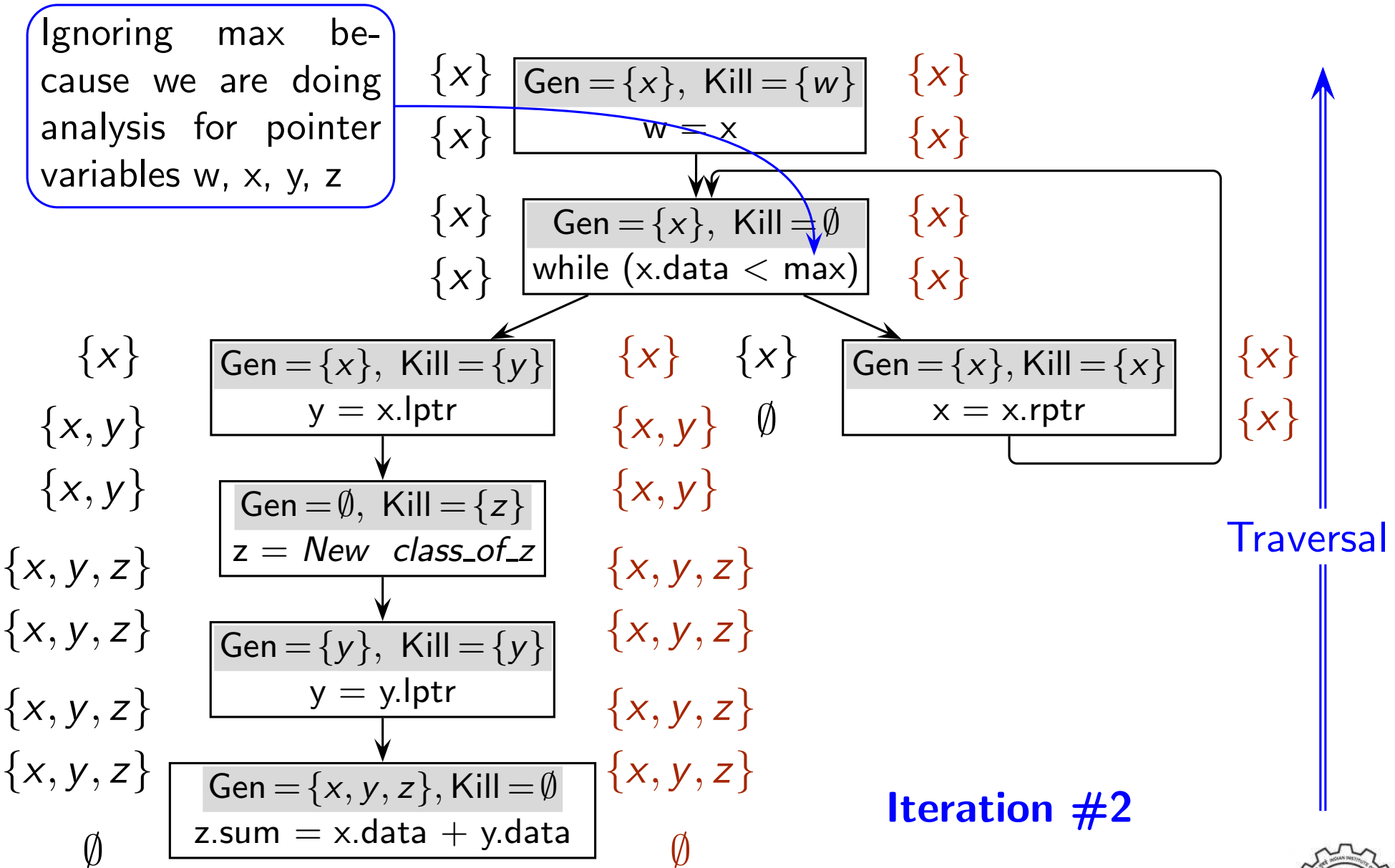


Initialization

Performing Live Variables Analysis

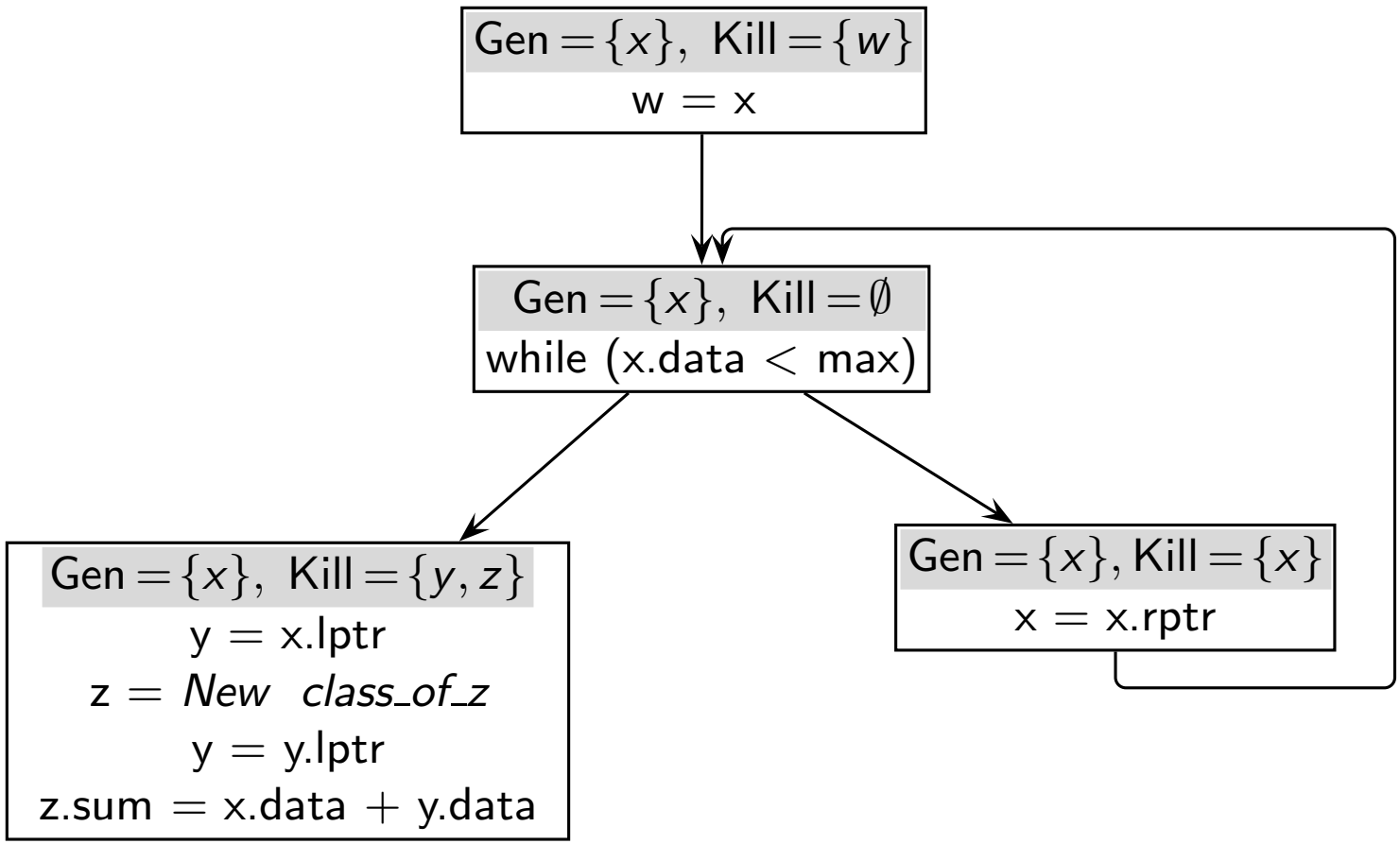


Performing Live Variables Analysis



Performing Live Variables Analysis

Local data flow properties when basic blocks contain multiple statements



Local Data Flow Properties for Live Variables Analysis

$$\text{IN}_n = \mathit{Gen}_n \cup (\text{OUT}_n - \mathit{Kill}_n)$$

- Gen_n : Use not preceded by definition
- Kill_n : Definition anywhere in a block

Local Data Flow Properties for Live Variables Analysis

$$\text{IN}_n = \mathit{Gen}_n \cup (\text{OUT}_n - \mathit{Kill}_n)$$

- Gen_n : Use not preceded by definition

  Upwards exposed use

- Kill_n : Definition anywhere in a block

  Stop the effect from being propagated across a block

Using Data Flow Information of Live Variables Analysis

- Used for register allocation

  If variable x is live in a basic block b, it is a potential candidate for register allocation

Using Data Flow Information of Live Variables Analysis

- Used for register allocation

  If variable x is live in a basic block b, it is a potential candidate for register allocation

- Used for dead code elimination

  If variable x is not live after an assignment $x = \ldots$, then the assignment is redundant and can be deleted as dead code

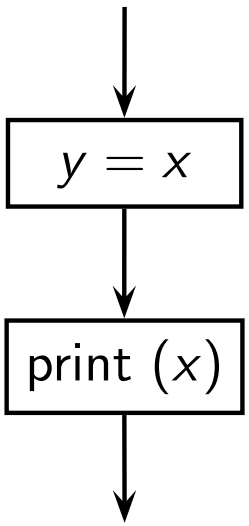
Part 2

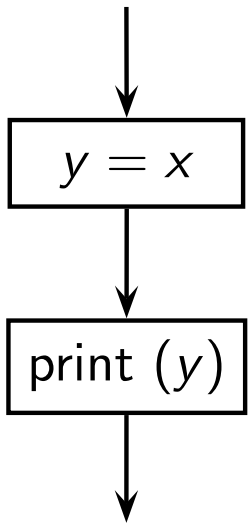
Strongly Live Variables Analysis

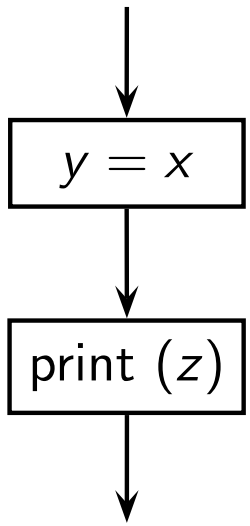
Strongly Live Variables Analysis

- A variable is strongly live if
  - it is used in a statement other than assignment statement, or (same as simple liveness)
  - it is used in an assignment statement defining a variable that is strongly live
    (different from simple liveness)
- Killing: An assignment statement, an input statement, or BI
  (this is same as killing in simple liveness)
- Generation: A direct use or a use for defining values that are strongly live
  (this is different from generation in simple liveness)

Understanding Strong Liveness

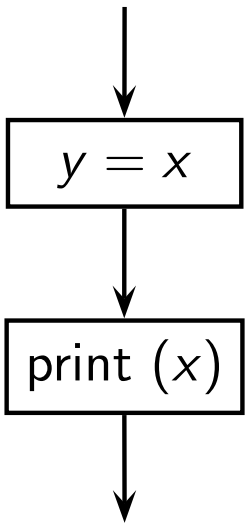


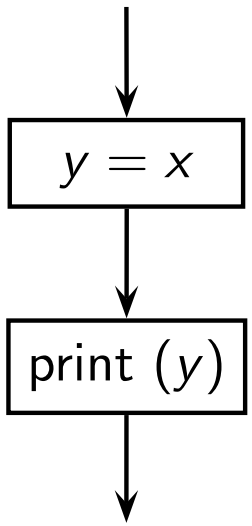


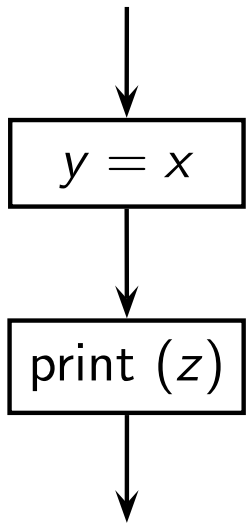


Understanding Strong Liveness

Strong Liveness







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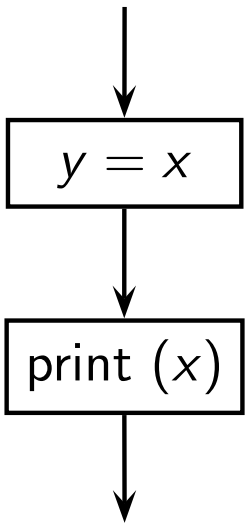
Strong Liveness



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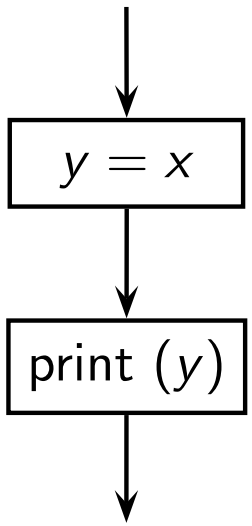

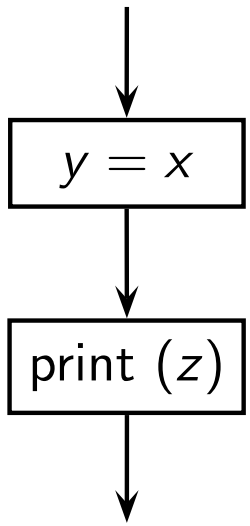

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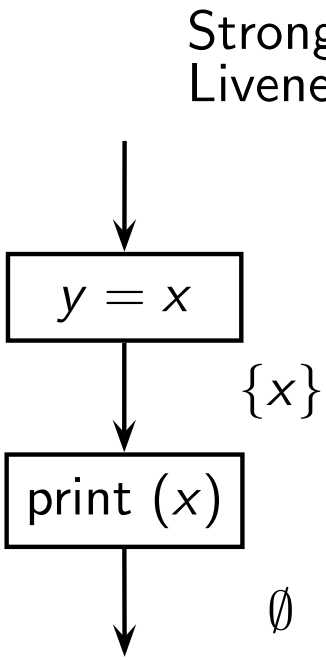

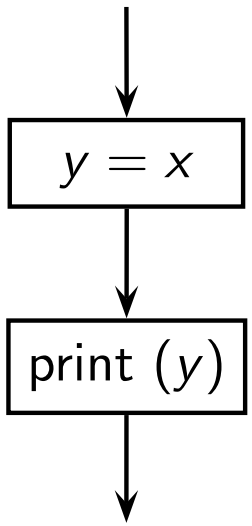

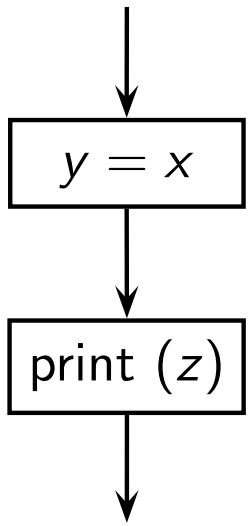

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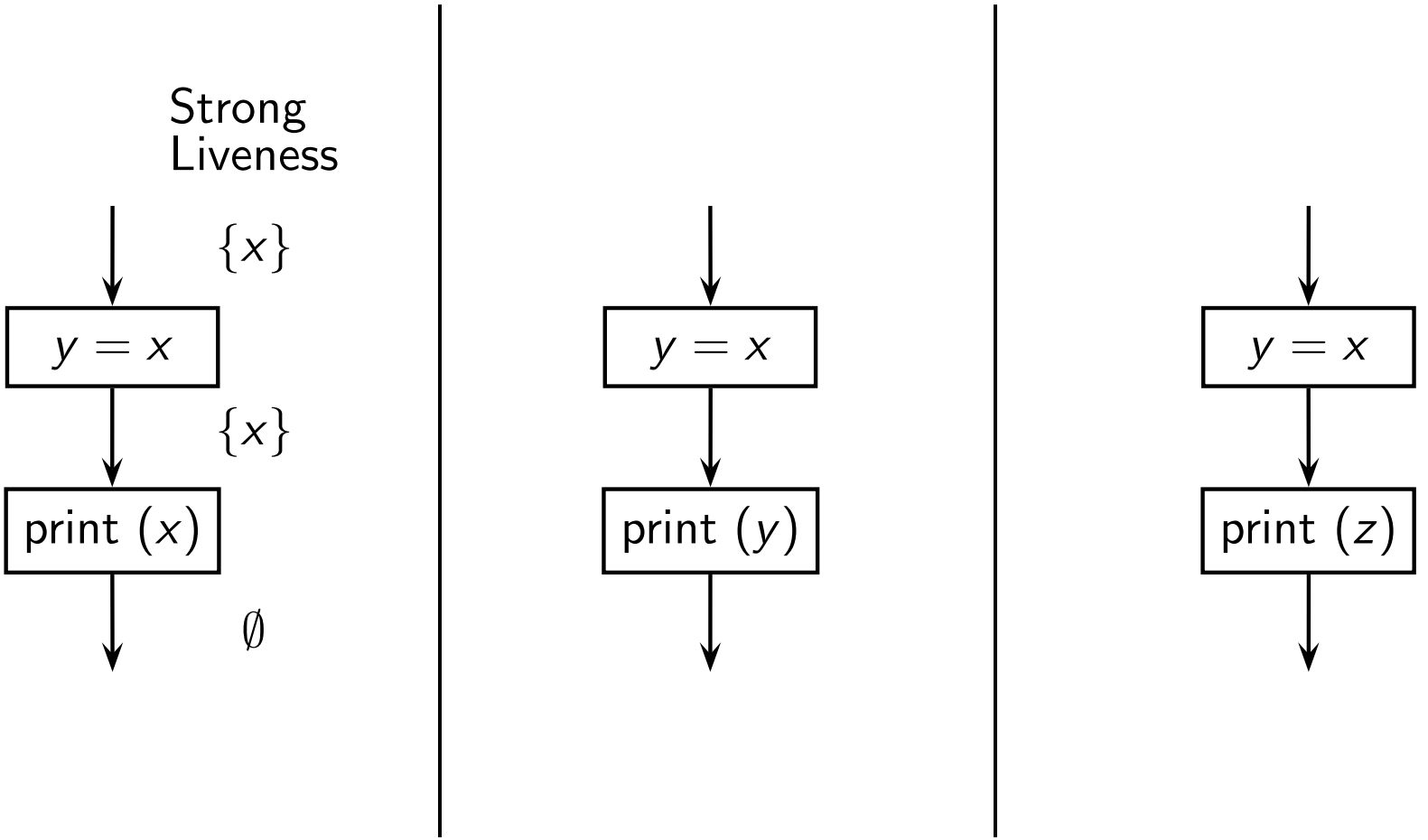

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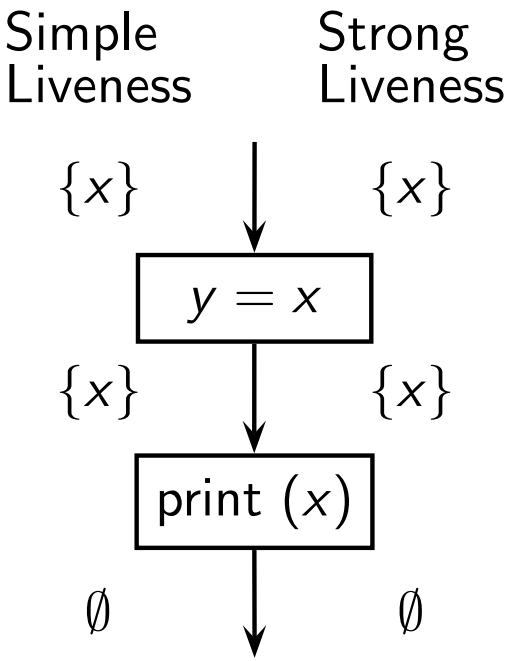

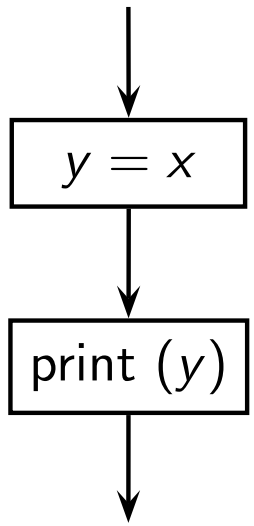

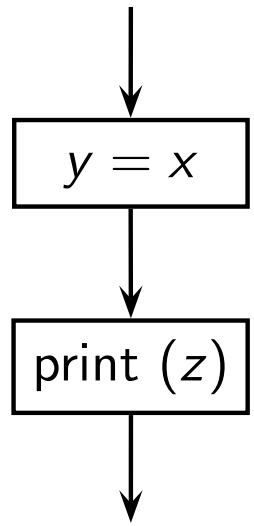

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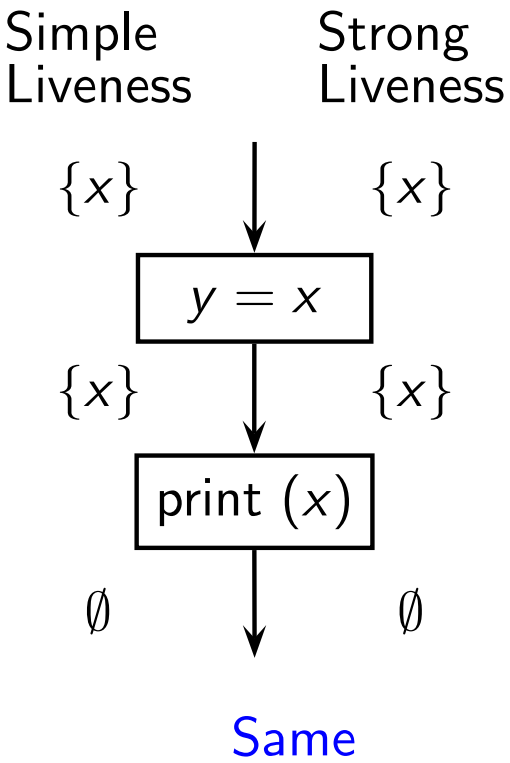

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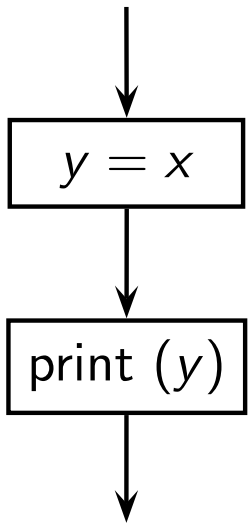

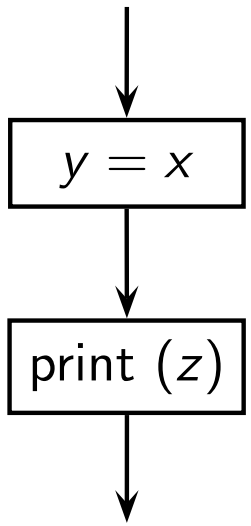

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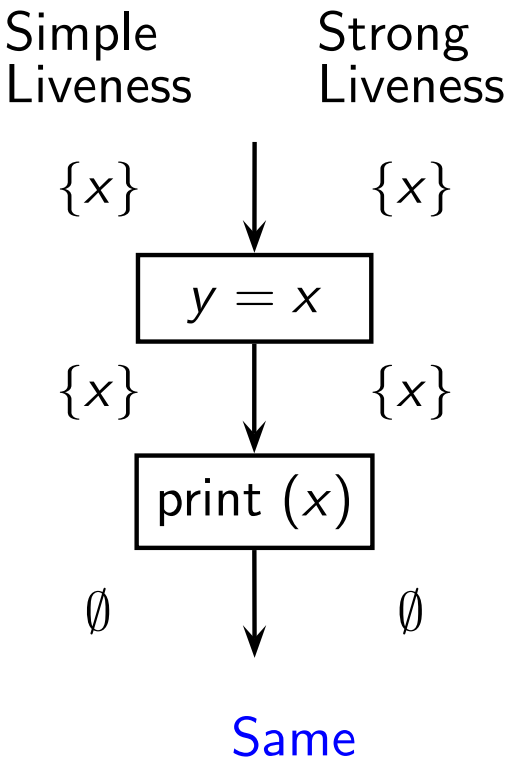

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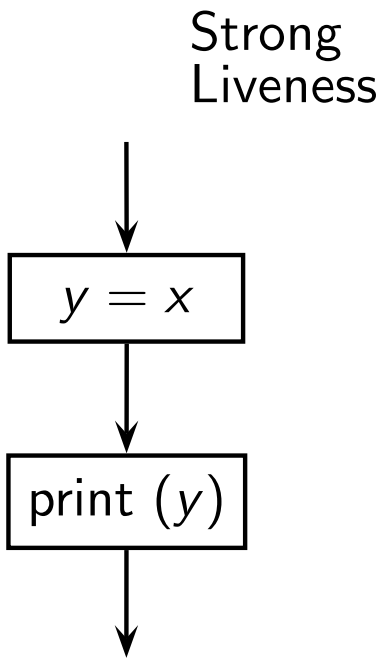

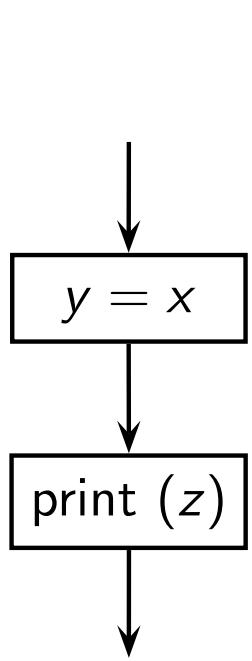

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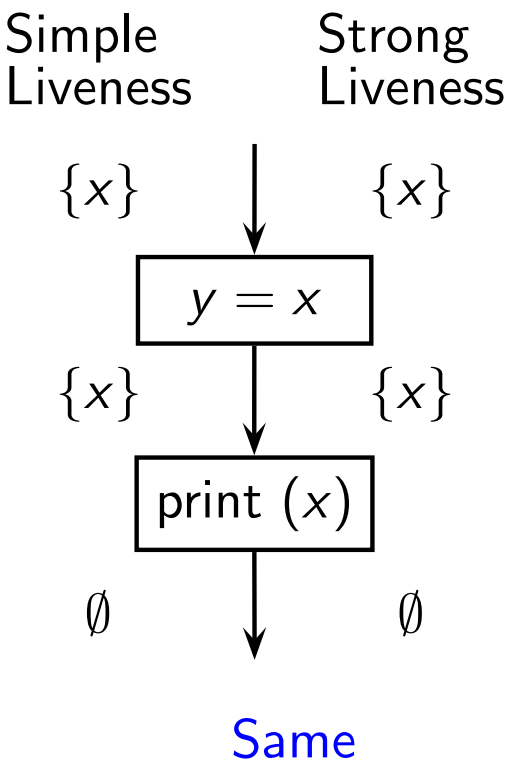

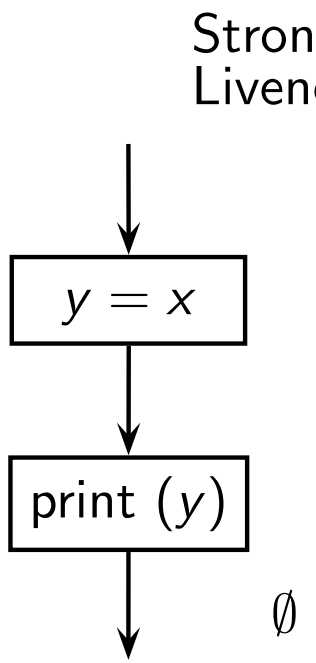

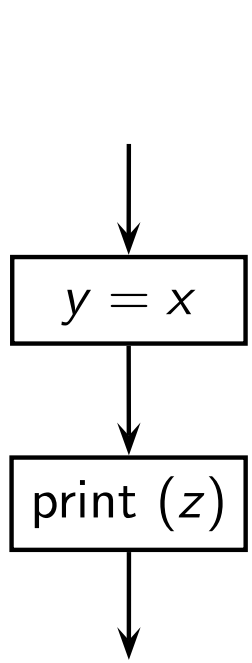

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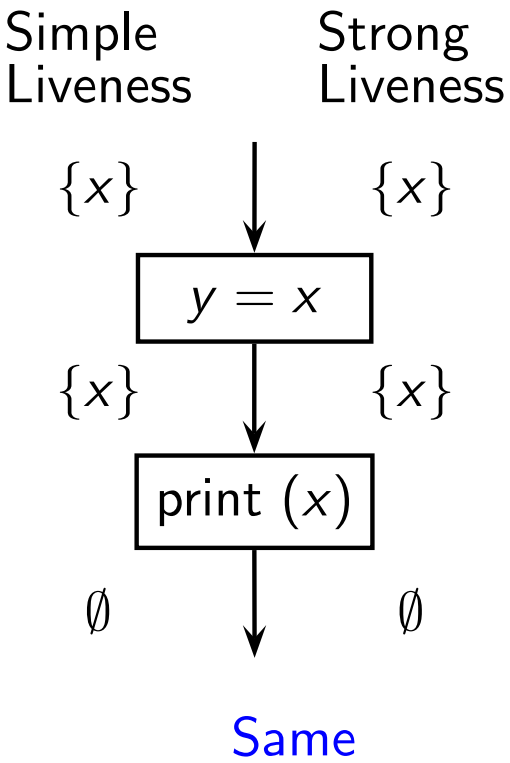

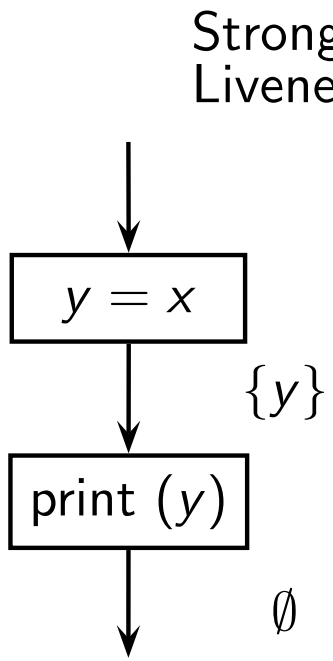

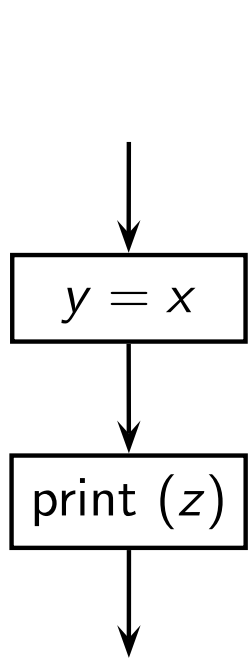

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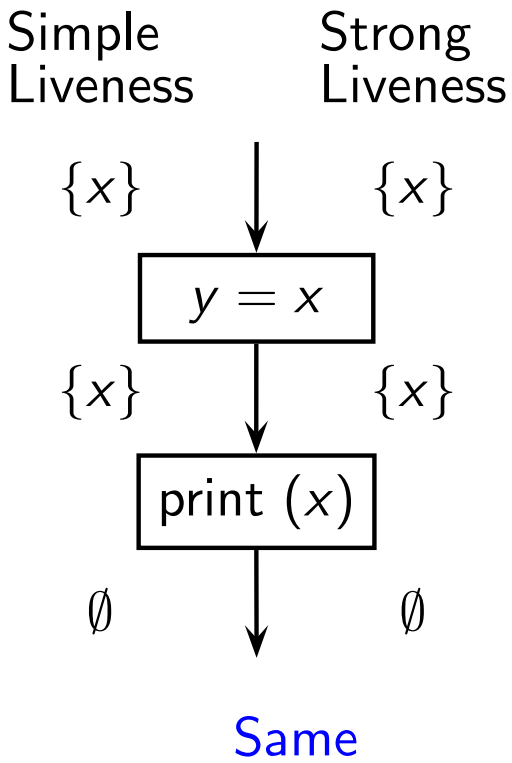

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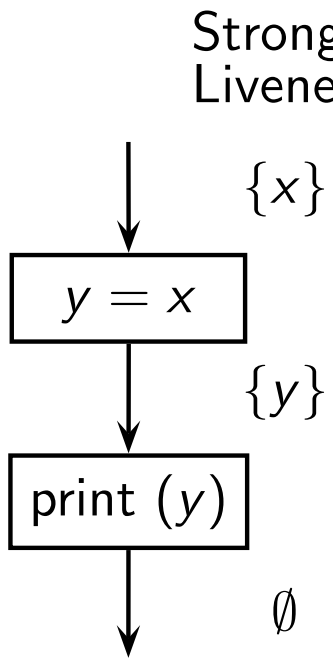

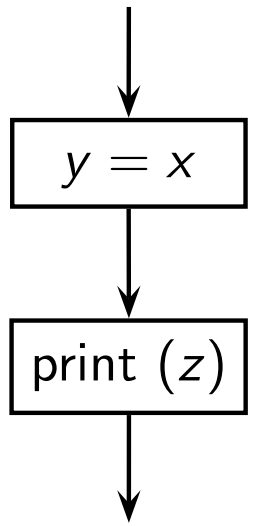

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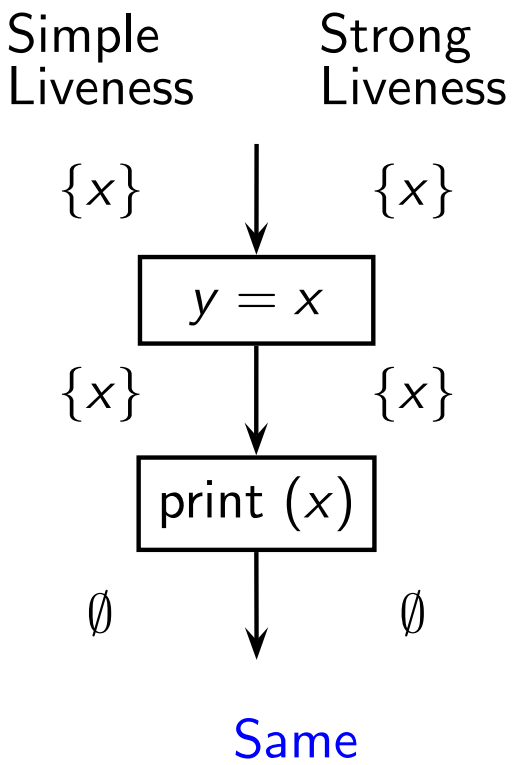

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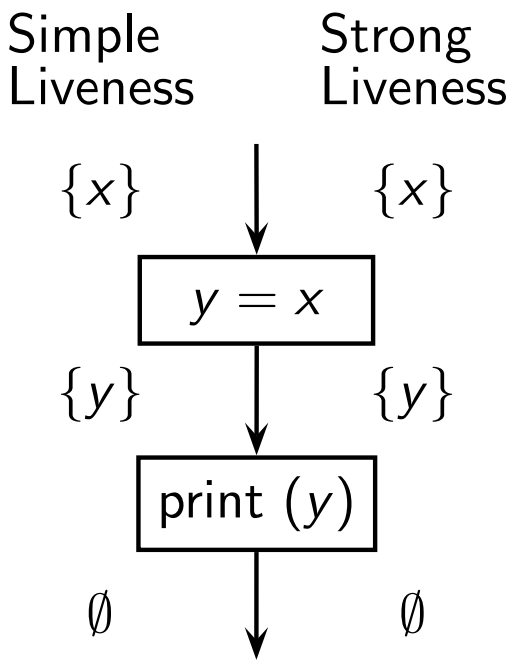

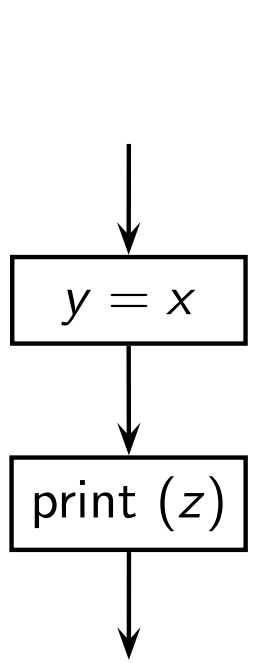

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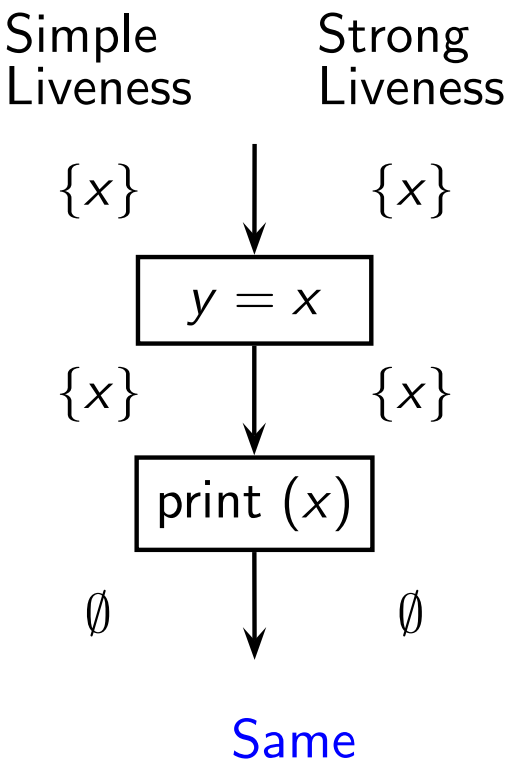

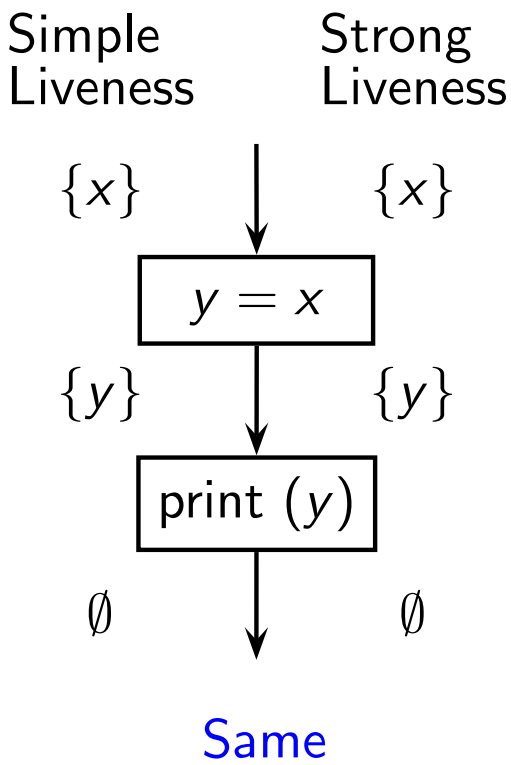

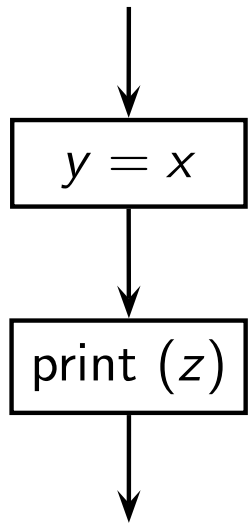

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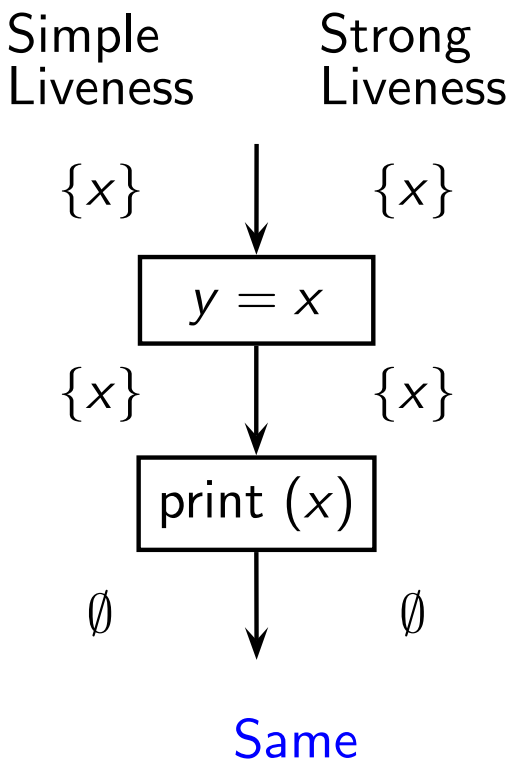

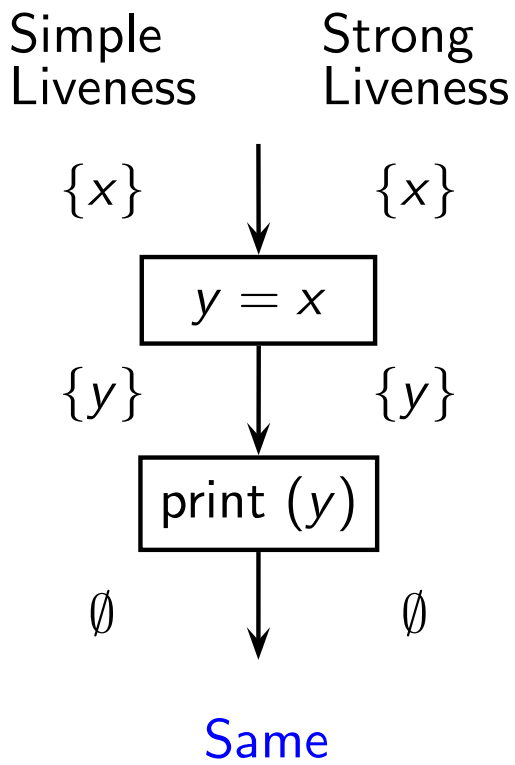

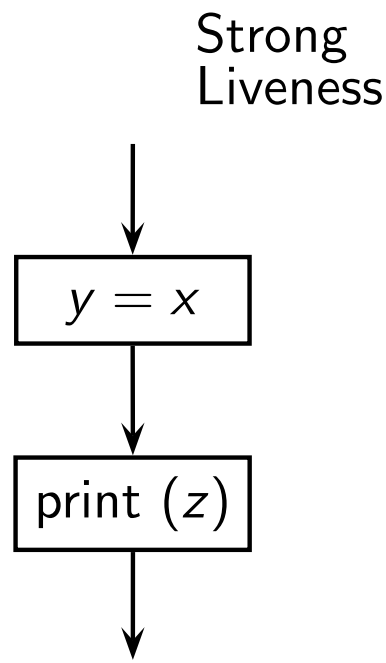

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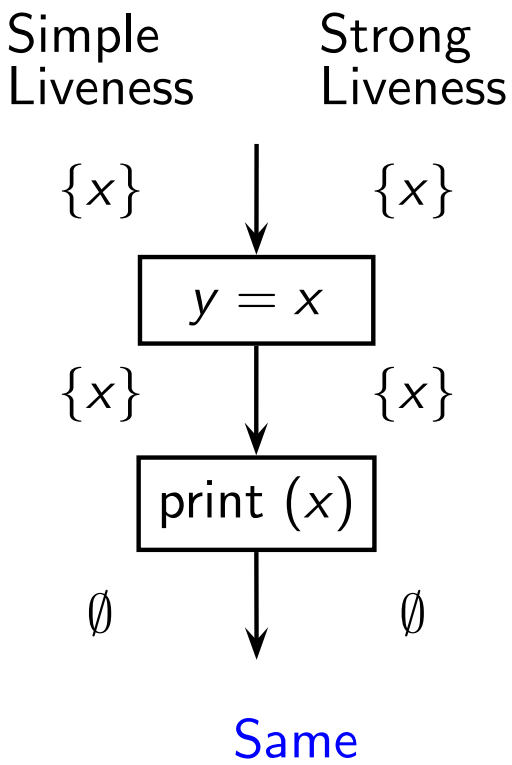

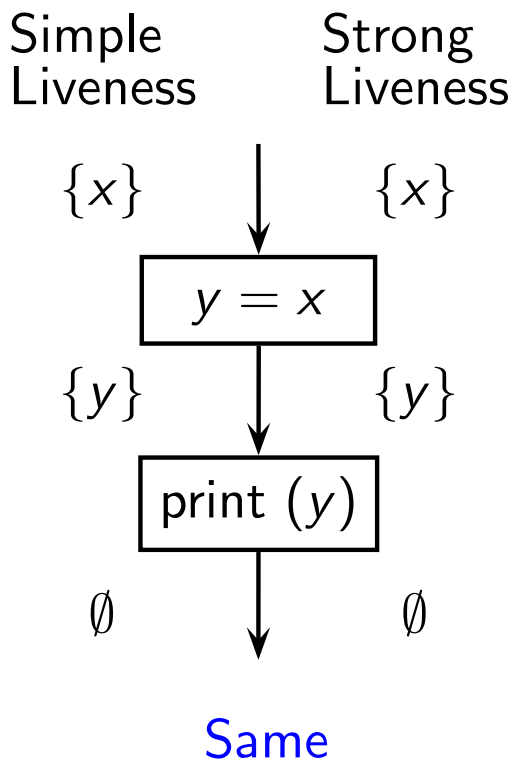

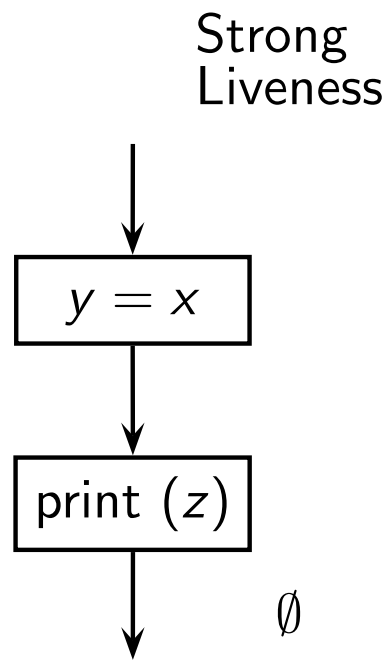

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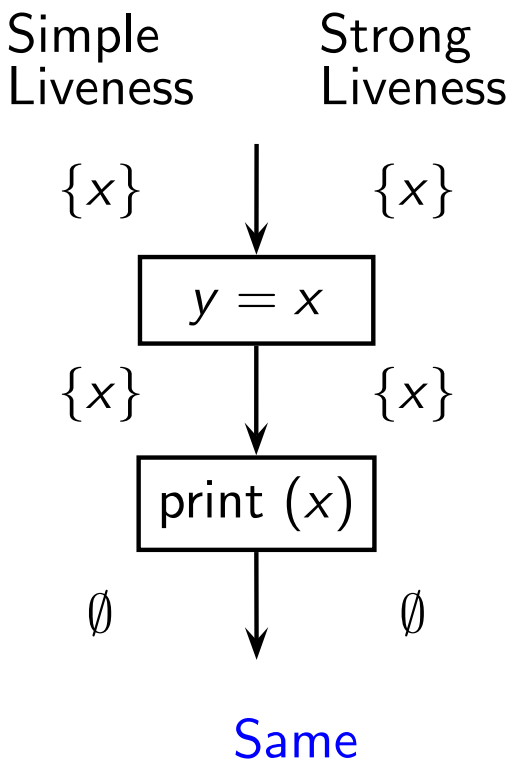

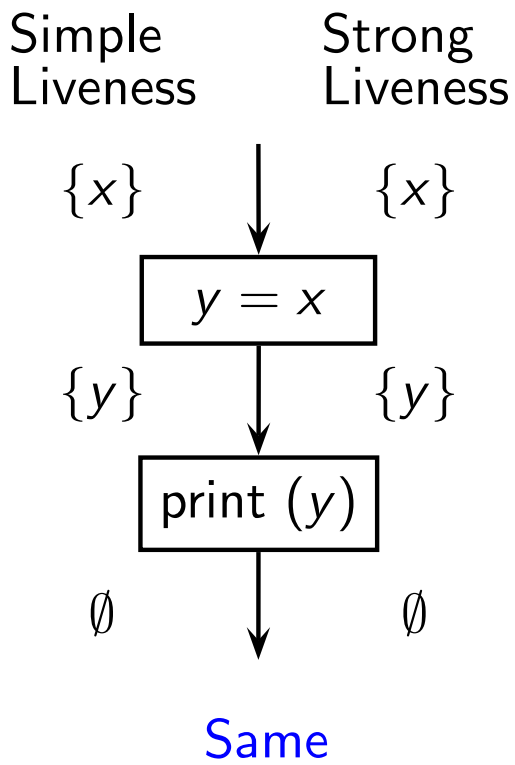

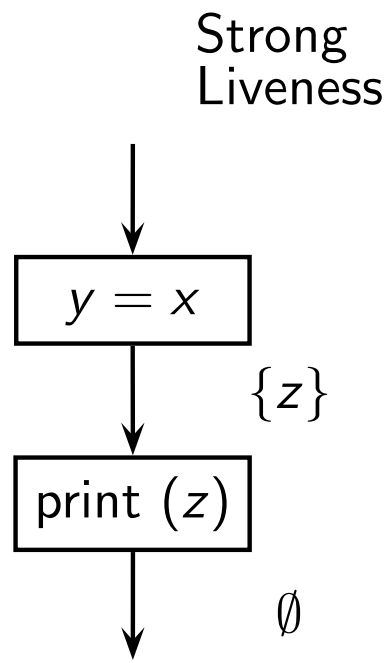

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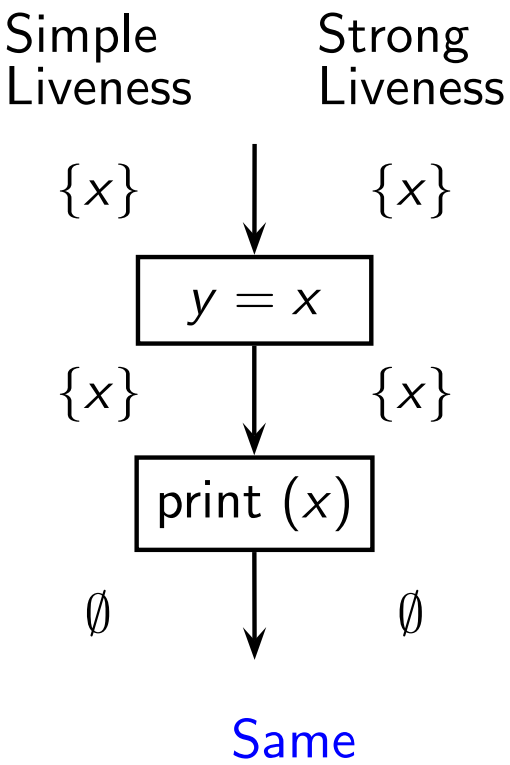

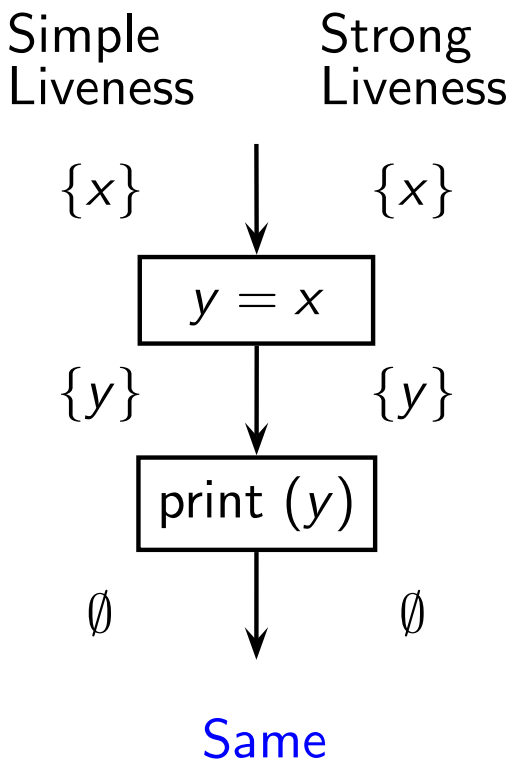

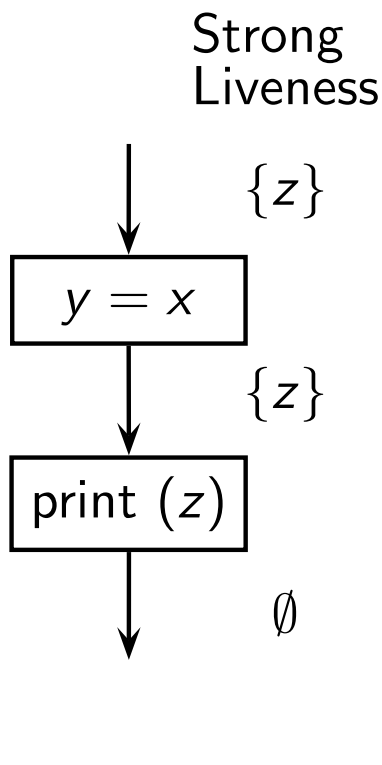

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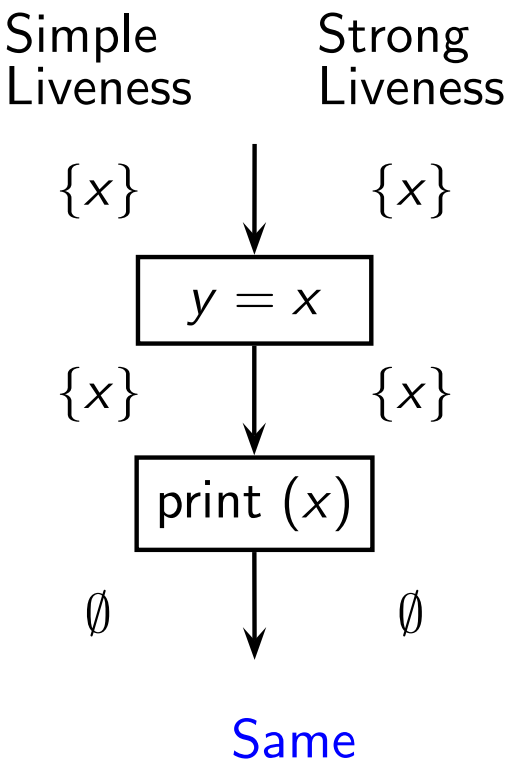

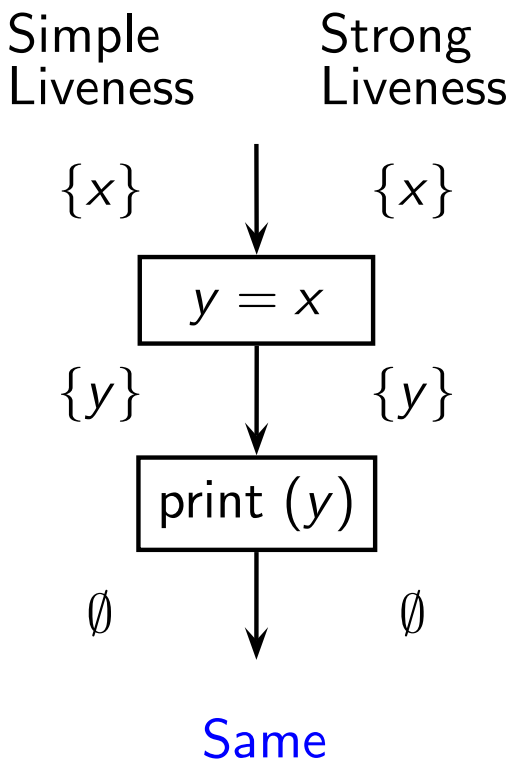

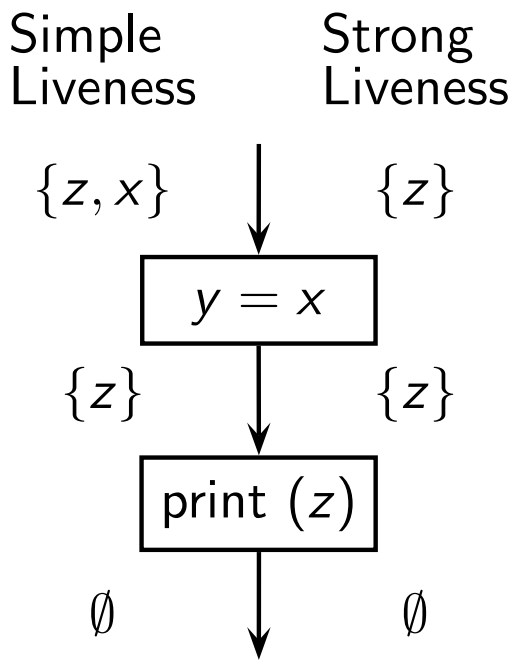

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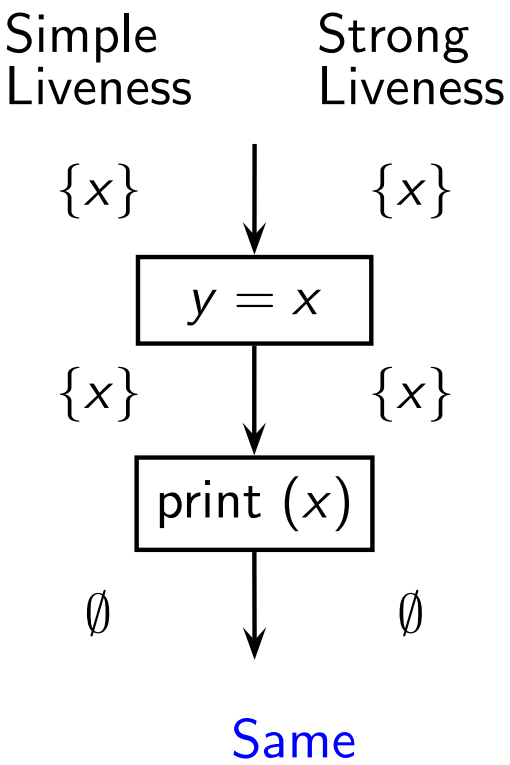

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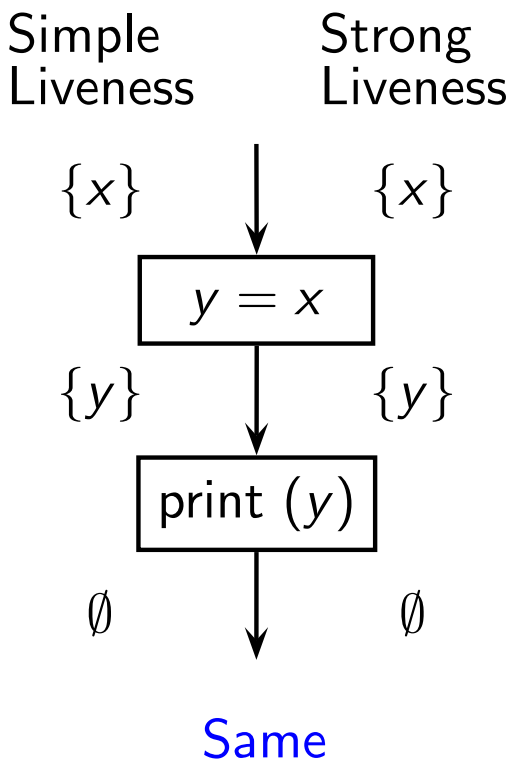

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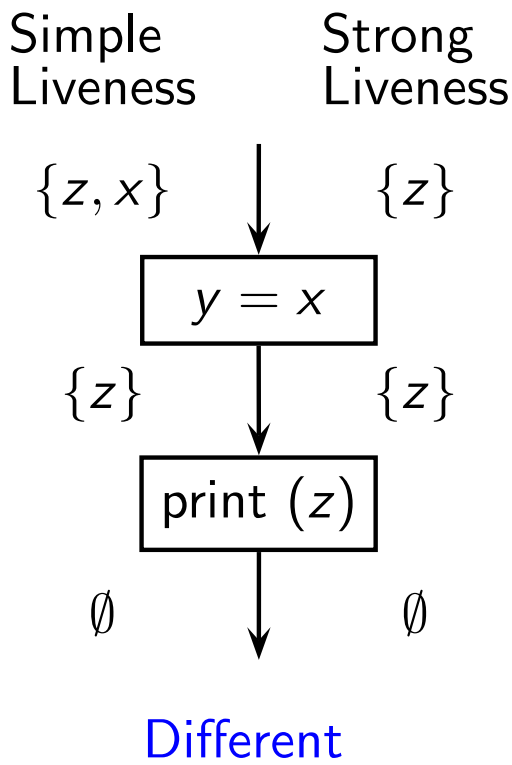

Different

Live Variables Analysis: Simple and Strong Liveness

- A variable is live at a program point if its current value is likely to be used later

Live Variables Analysis: Simple and Strong Liveness

- A variable is live at a program point if its current value is likely to be used later
- We want to compute the smallest set of variables that are live

Live Variables Analysis: Simple and Strong Liveness

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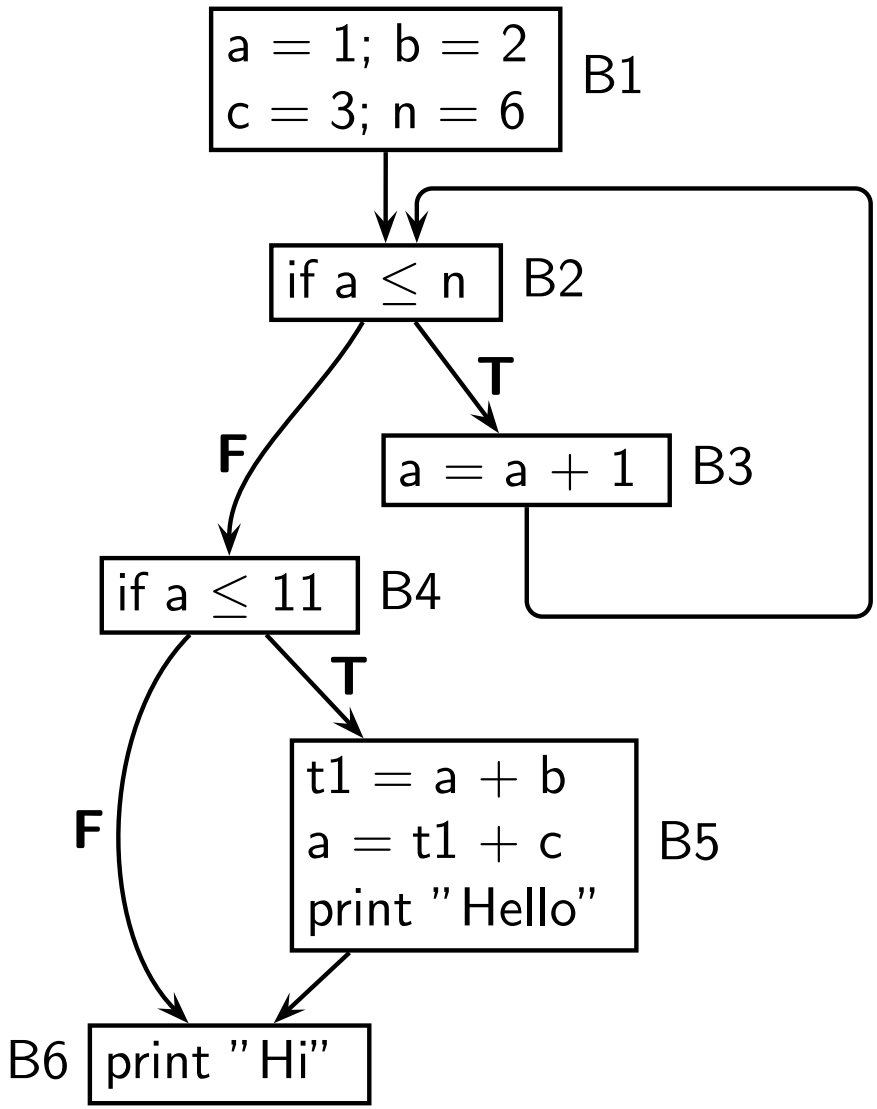

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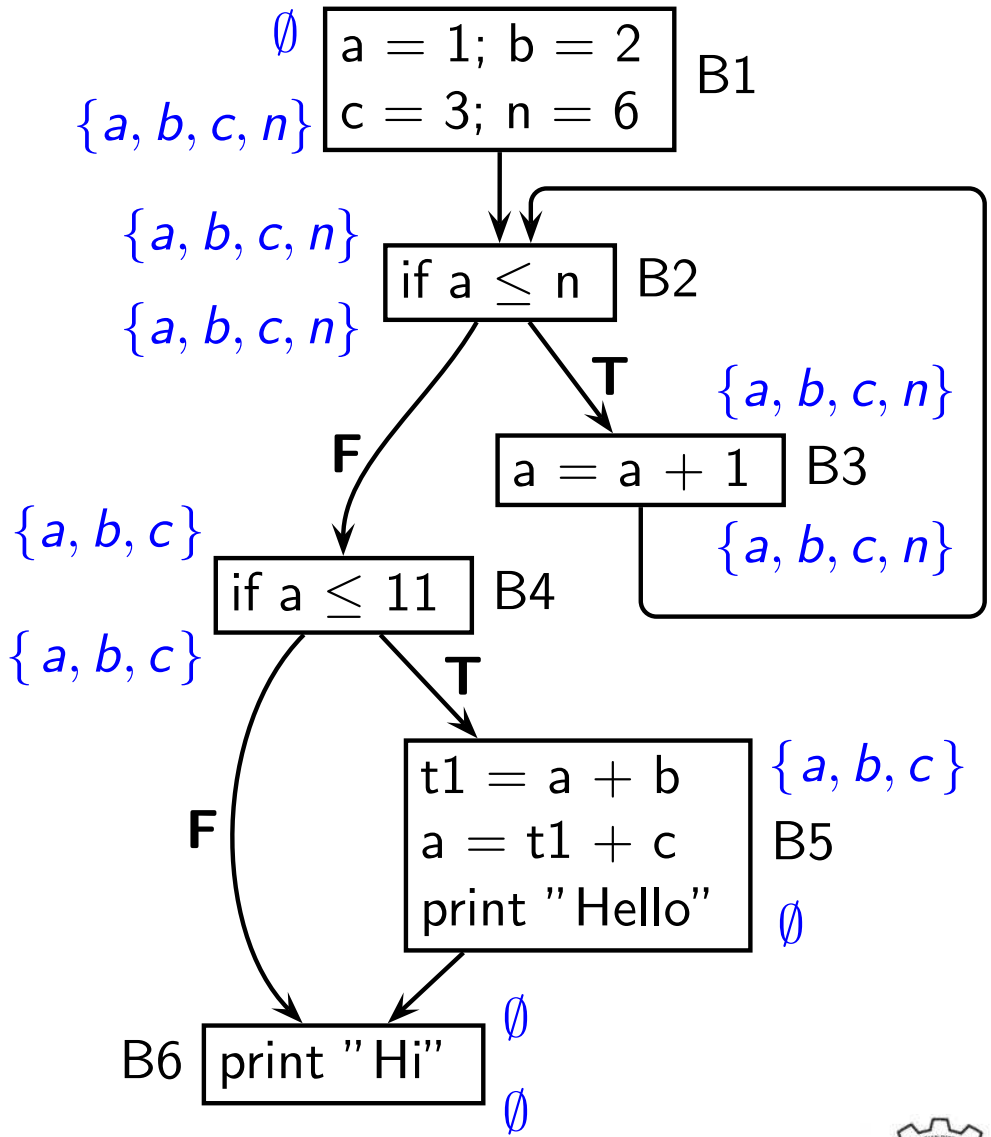

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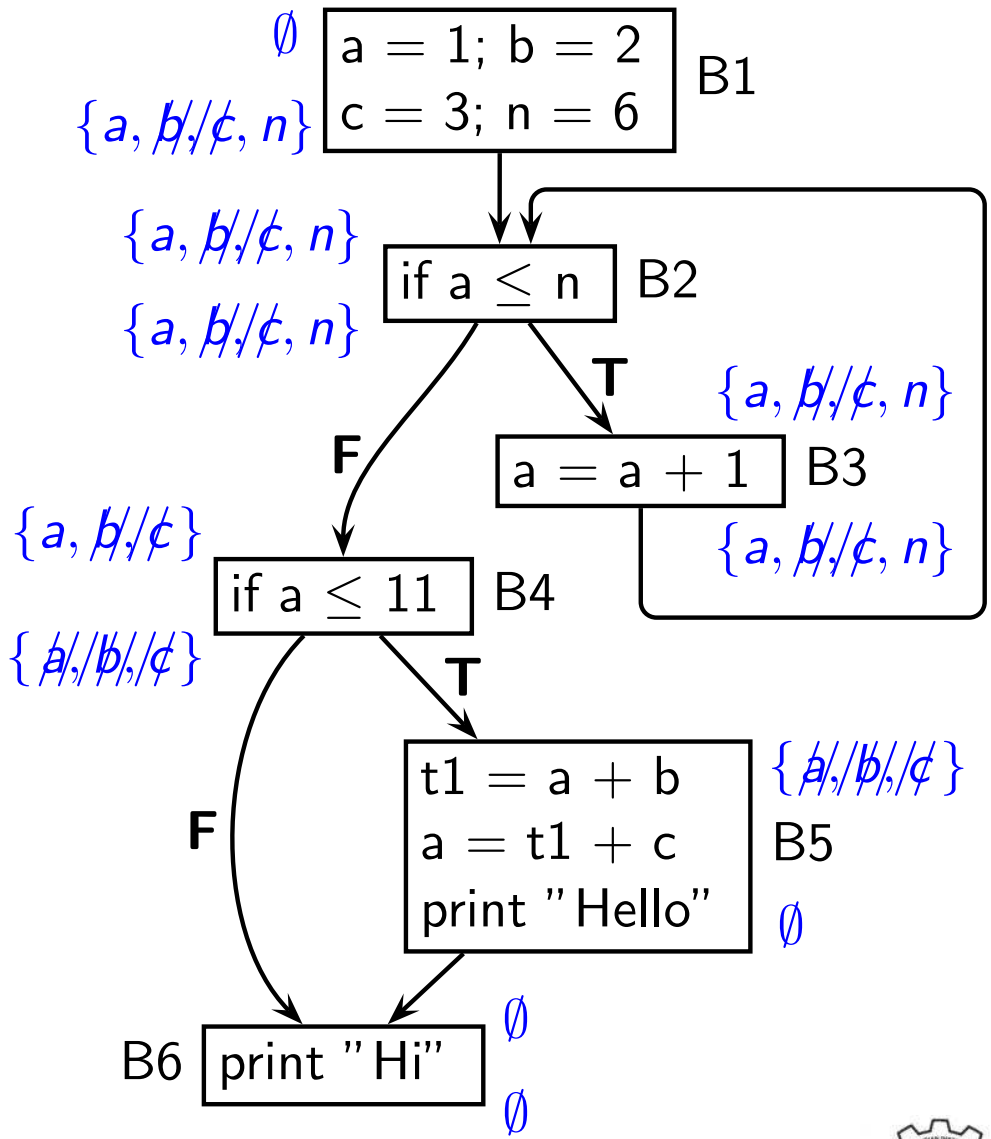

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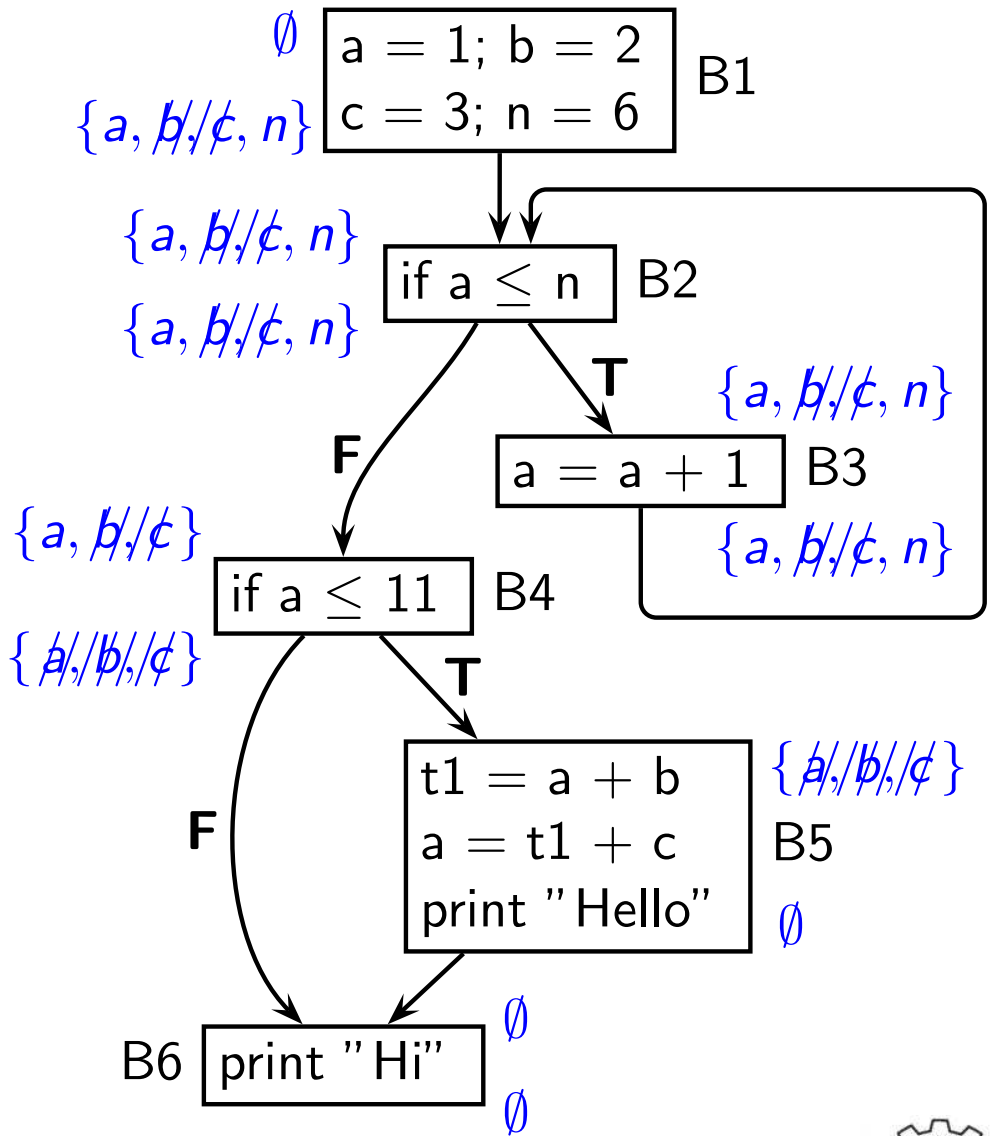
- Strong liveness is more precise than simple liveness



Data Flow Equations for Strongly Live Variables Analysis

$$\mathsf{IN}_n = f_n(\mathsf{OUT}_n)$$

$$\mathsf{OUT}_n = \begin{cases} BI & n \text{ is } End \\ \bigcup_{s \in succ(n)} \mathsf{IN}_s & \text{otherwise} \end{cases}$$

where,

$$f_n(X) = \begin{cases} (X - \{y\}) \cup (Opd(e) \cap \mathbb{V}\text{ar}) & n \text{ is } y = e, e \in \mathbb{E}\text{xpr}, \ y \in X \\ X - \{y\} & n \text{ is } input(y) \\ X \cup \{y\} & n \text{ is } use(y) \\ X & \text{otherwise} \end{cases}$$

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If y is not strongly live, the assignment is skipped using the "otherwise" clause

Part 3

Some Observations

What Does Data Flow Analysis Involve?

- Defining the analysis.
- Formulating the analysis.
- Performing the analysis.

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  - Linear simultaneous equations on sets rather than numbers
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- Performing the analysis. Solve data flow equations for the given program flow graph
- Many unanswered questions

  Initial value? Termination? Complexity? Properties of Solutions?

Iterative Solution of Linear Simultaneous Equations

- Simultaneous equations represented in the form of the product of a matrix of coefficients (**A**) with the vector of unknowns (**x**)

$$\mathbf{Ax} = \mathbf{b}$$

- Start with approximate values
- Compute new values repeatedly from old values
- Two classical methods
  - Gauss-Seidel Method (Gauss: 1823, 1826), (Seidel: 1874)
  - Jacobi Method (Jacobi: 1845)

Our Method of Performing Data Flow Analysis

- Round robin iteration
- Essentially Jacobi method
- Unknowns are the data flow variables IN_i and OUT_i
- Domain of values is not numbers
- Computation in a fixed order
  - either forward (reverse post order) traversal, or
  - backward (post order) traversal

  over the control flow graph

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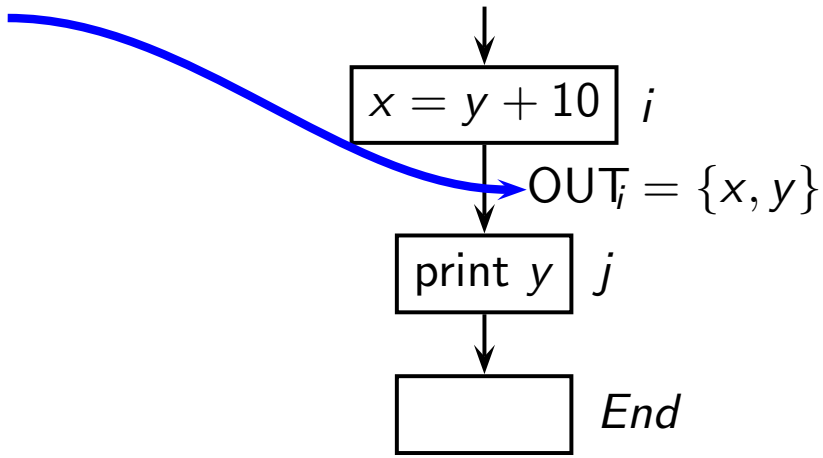

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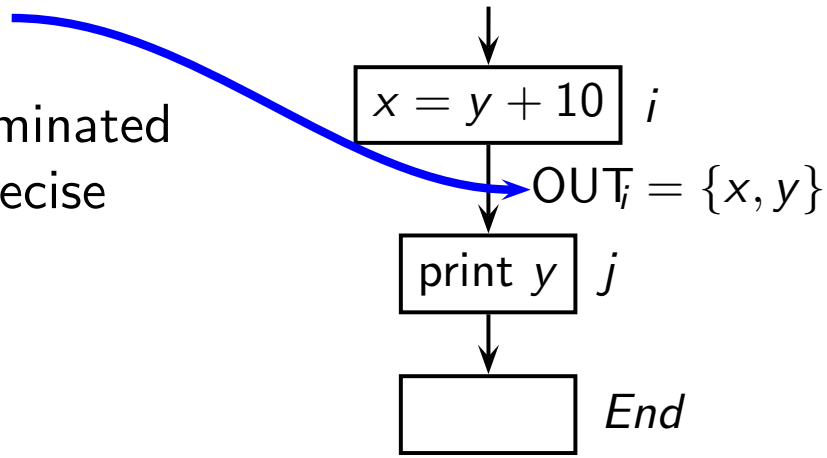

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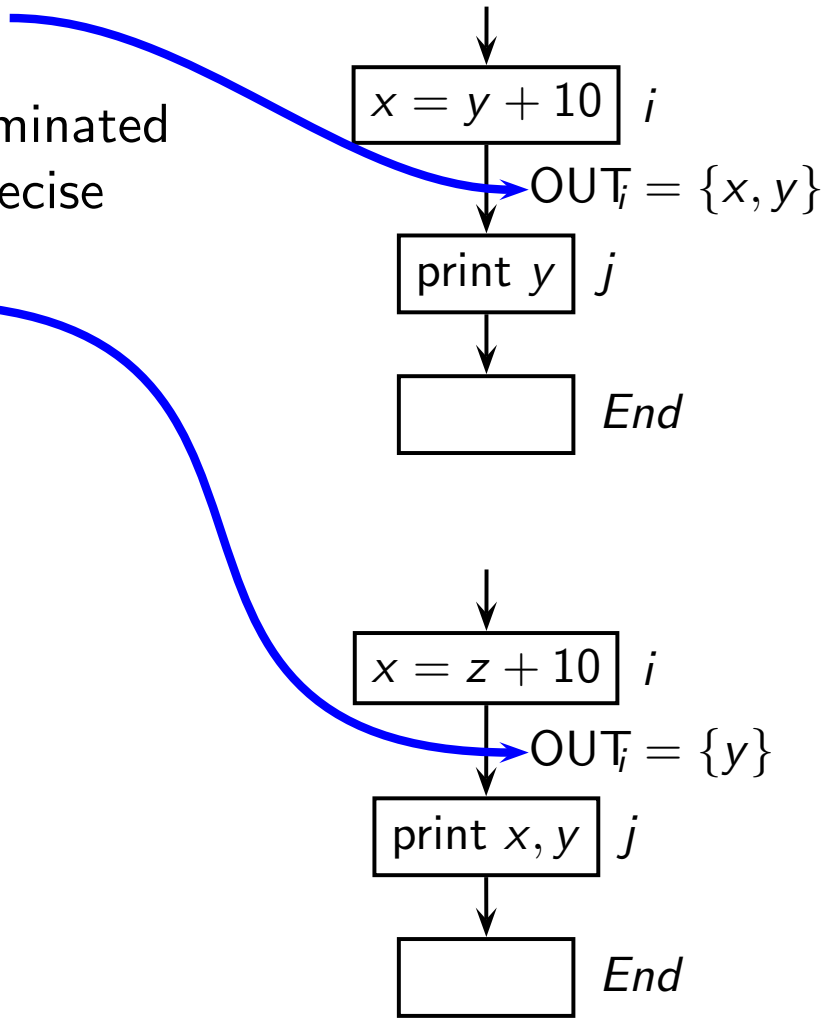

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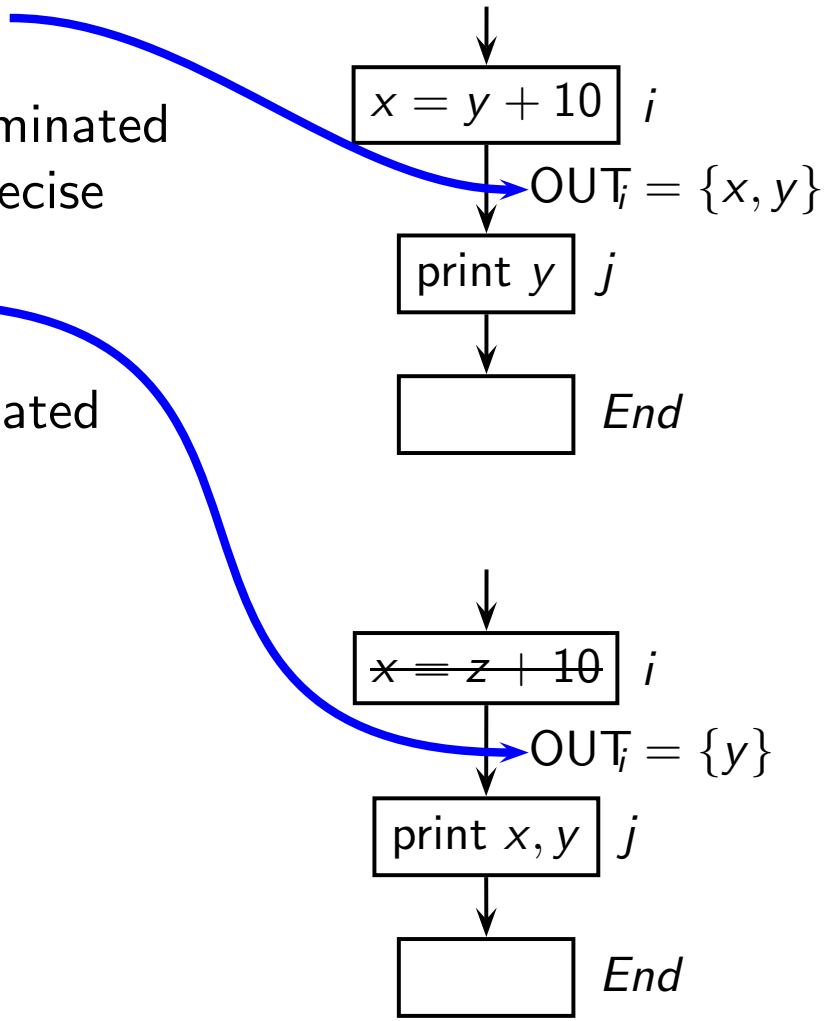

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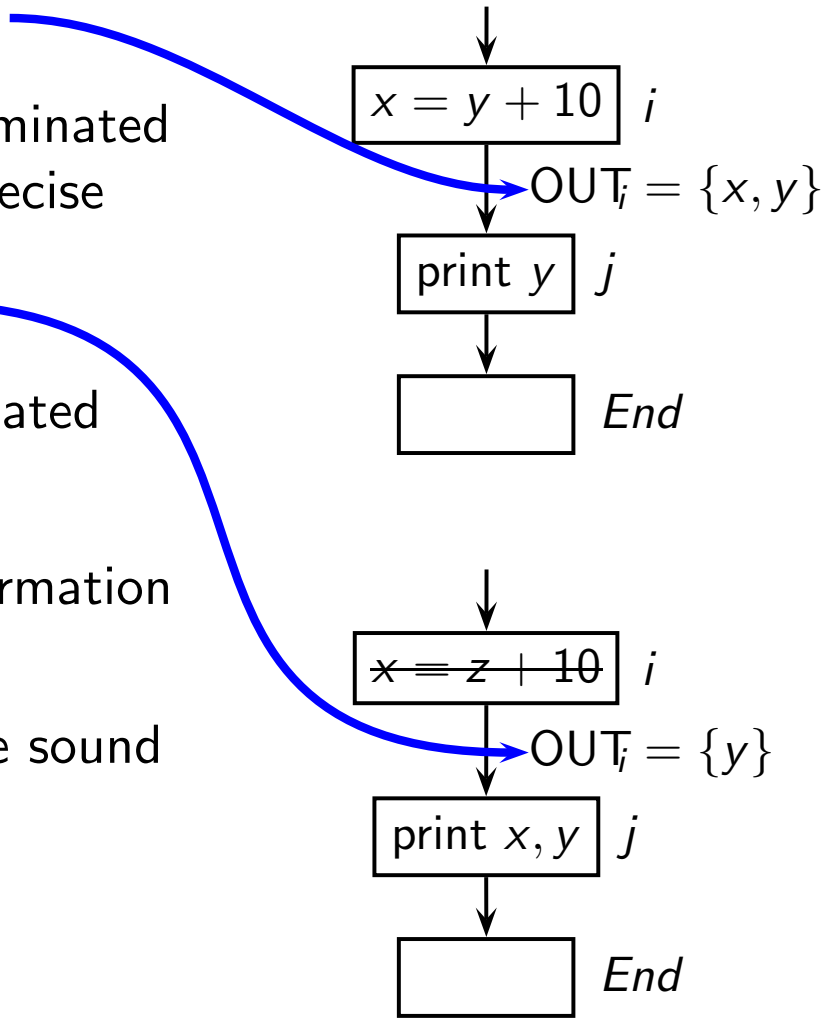

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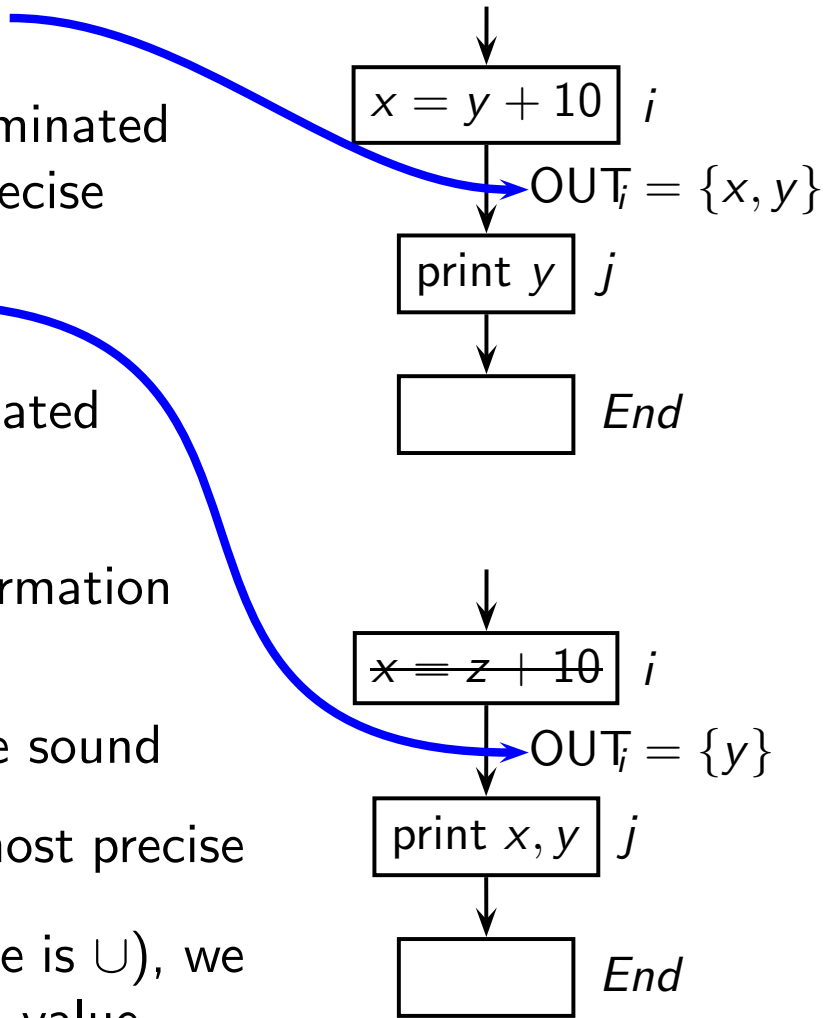
- The smallest set of all live variables is most precise
  - Since liveness sets grow (confluence is $\cup$), we choose $\emptyset$ as the initial conservative value



Termination, Convergence, and Complexity

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  - The set of all variables is finite, and
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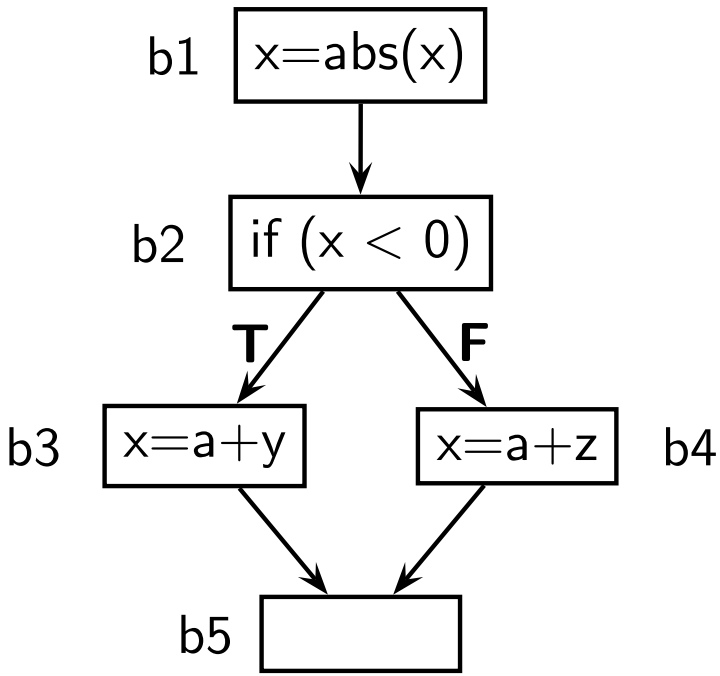
- Since initial value is $\emptyset$, live variables analysis converges on the smallest set
- How many iterations do we need for reaching the convergence?
- Going beyond live variables analysis
  - Do the sets always grow for other data flow frameworks?
  - What is the complexity of round robin analysis for other analyses?

Conservative Nature of Analysis (1)



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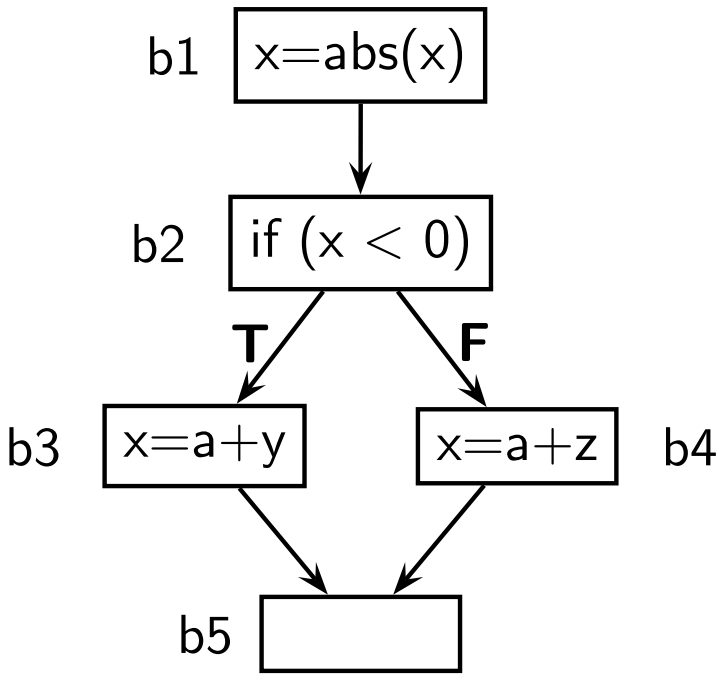

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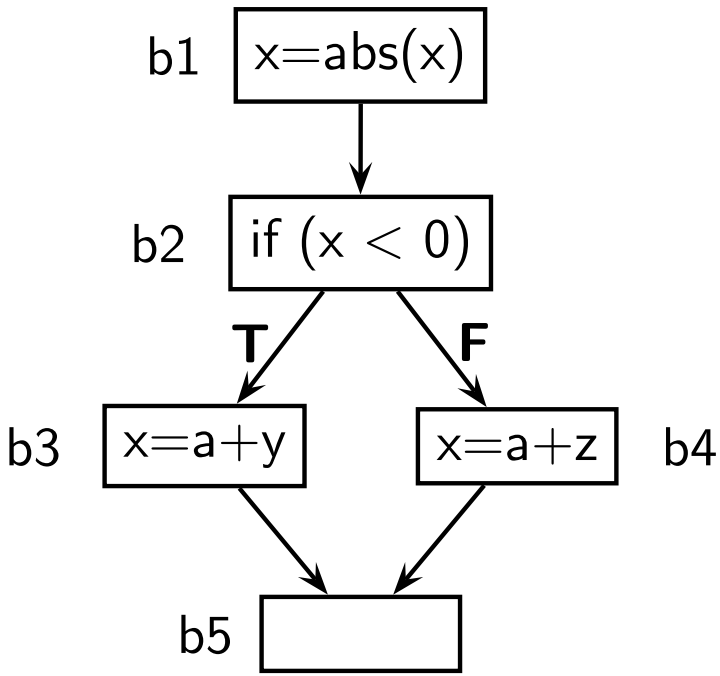

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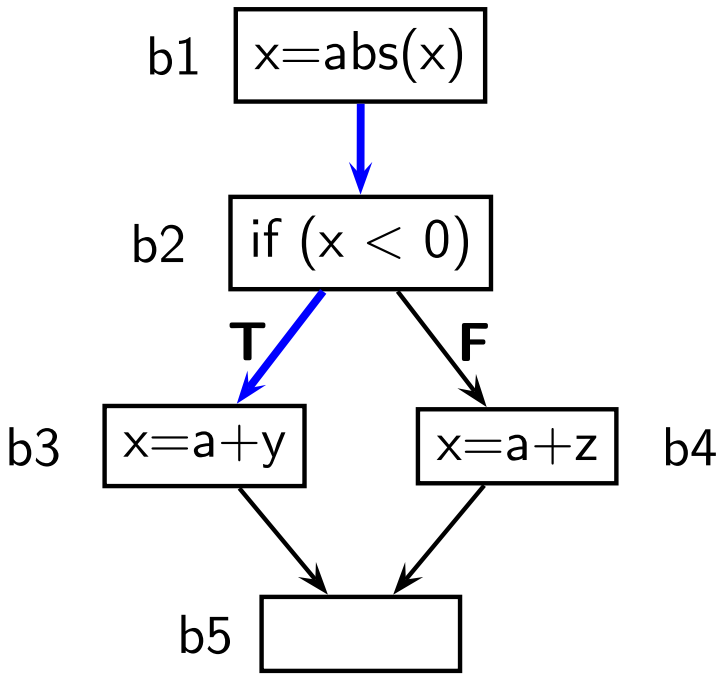

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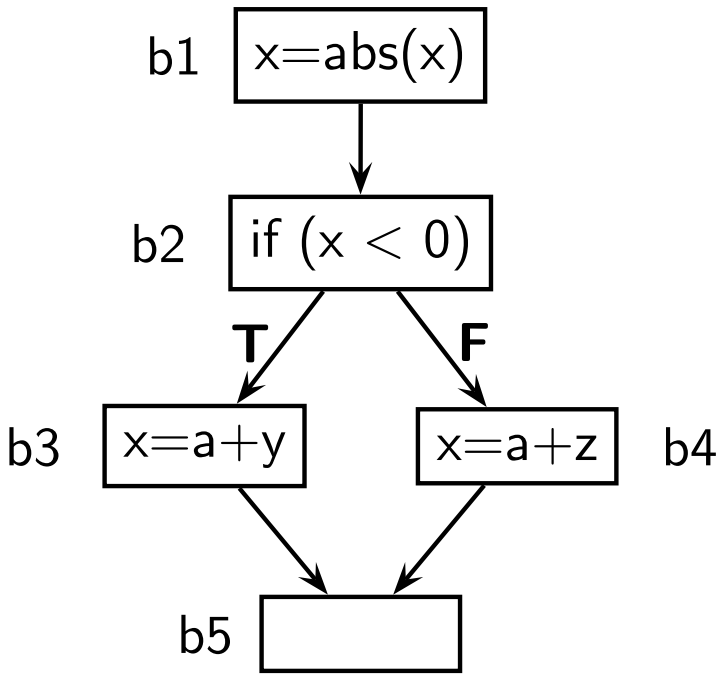

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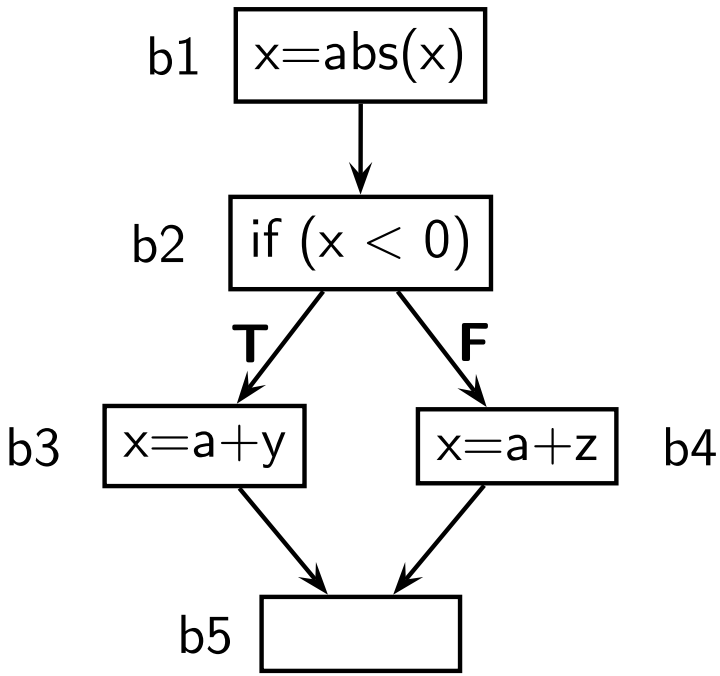

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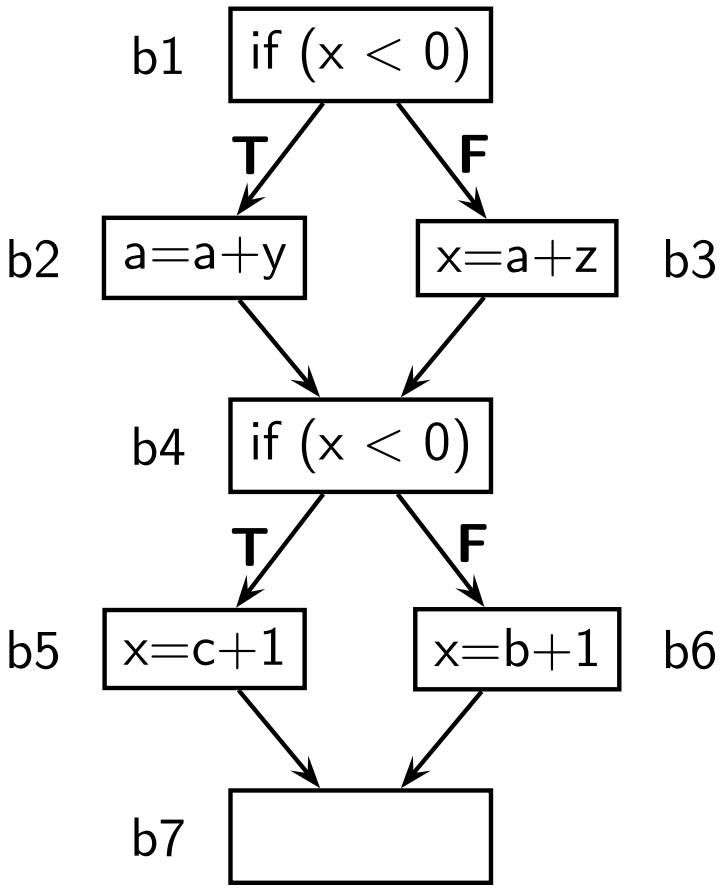

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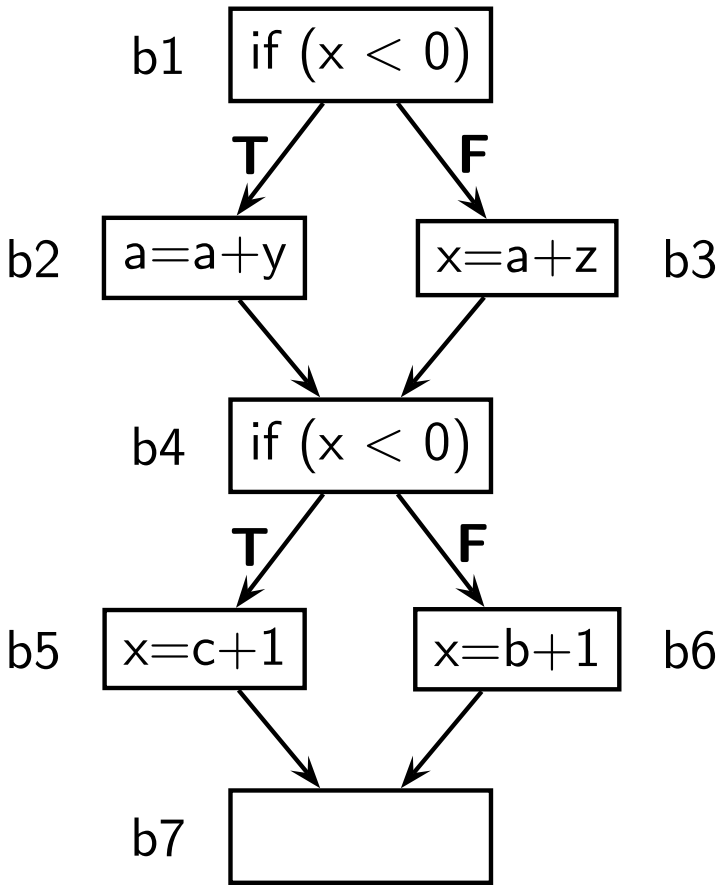

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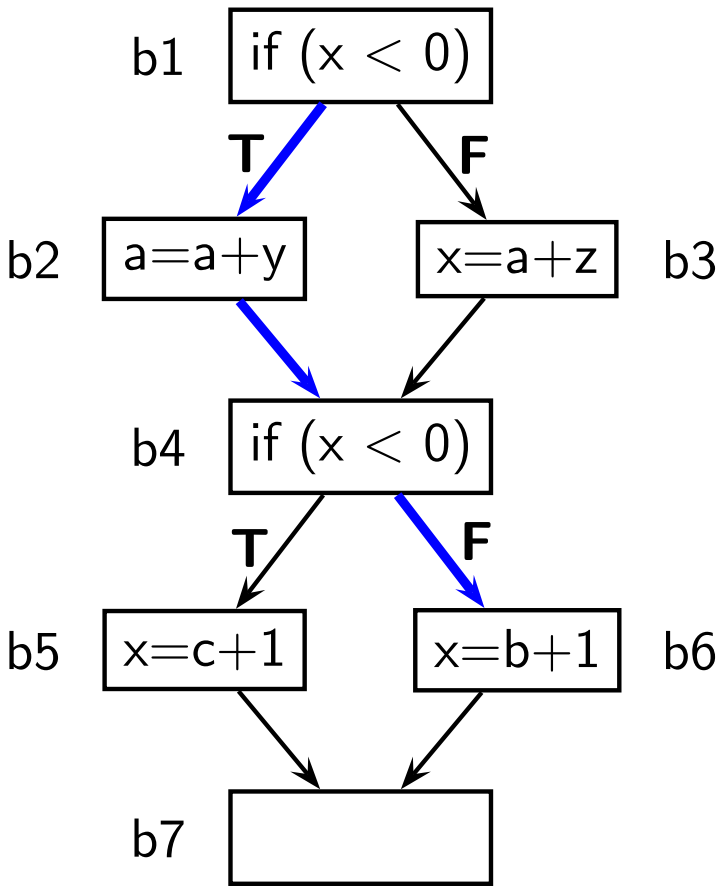

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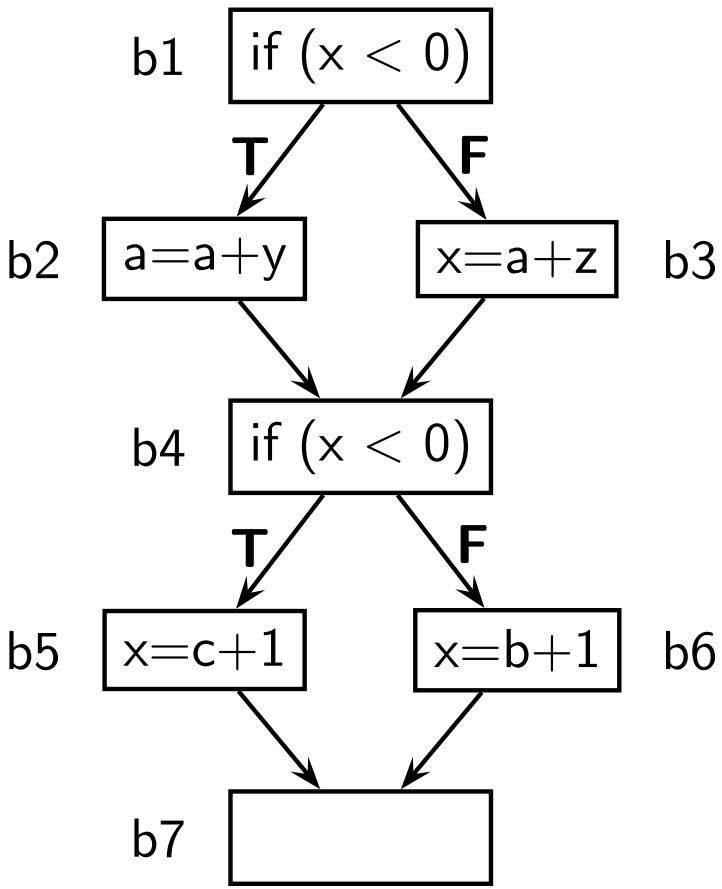

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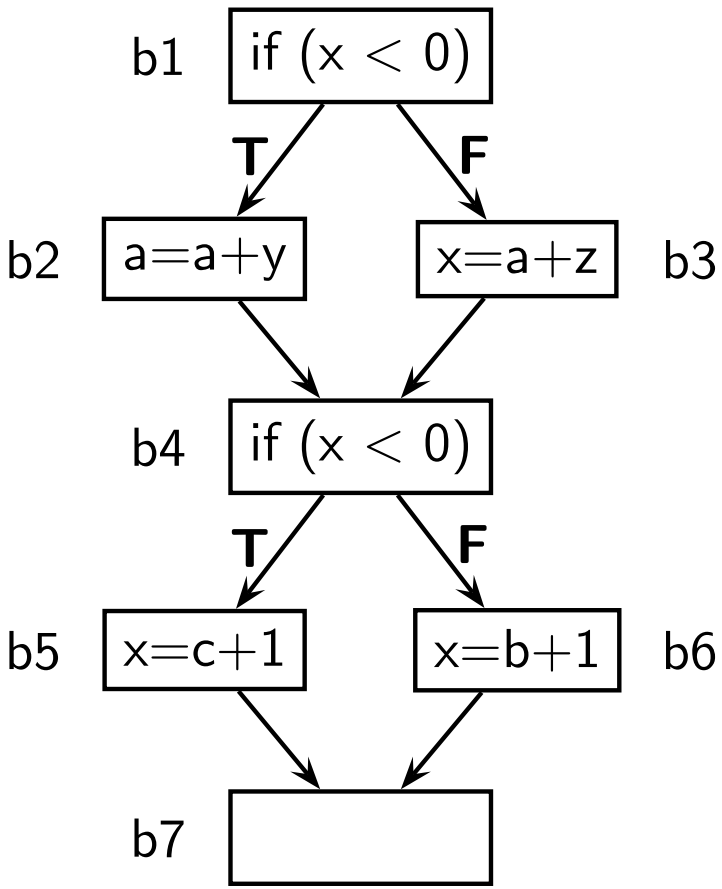

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  Note: It is *flow sensitive* (i.e. information is computed for every control flow points)

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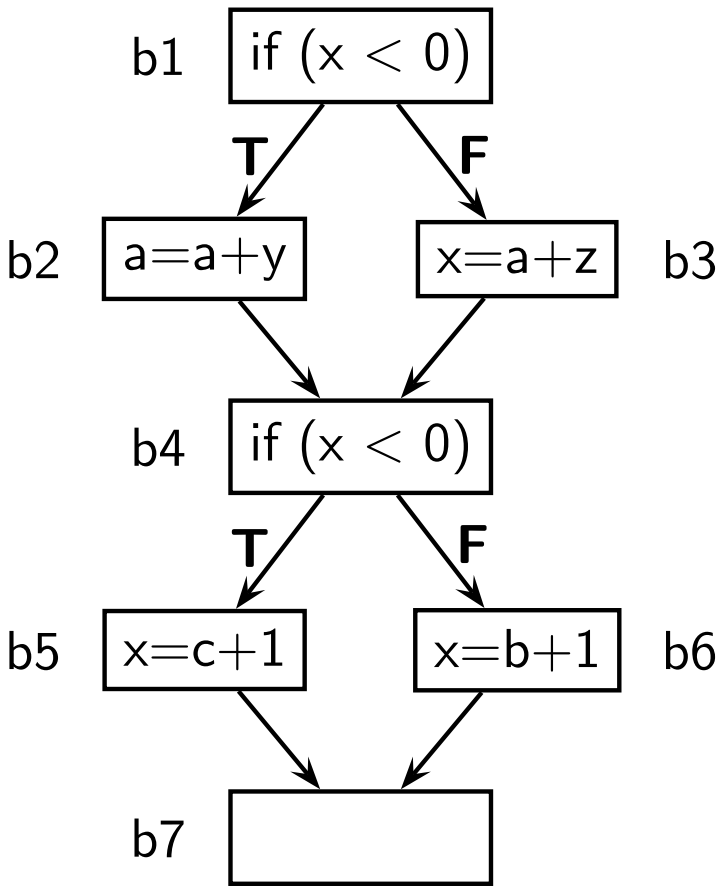

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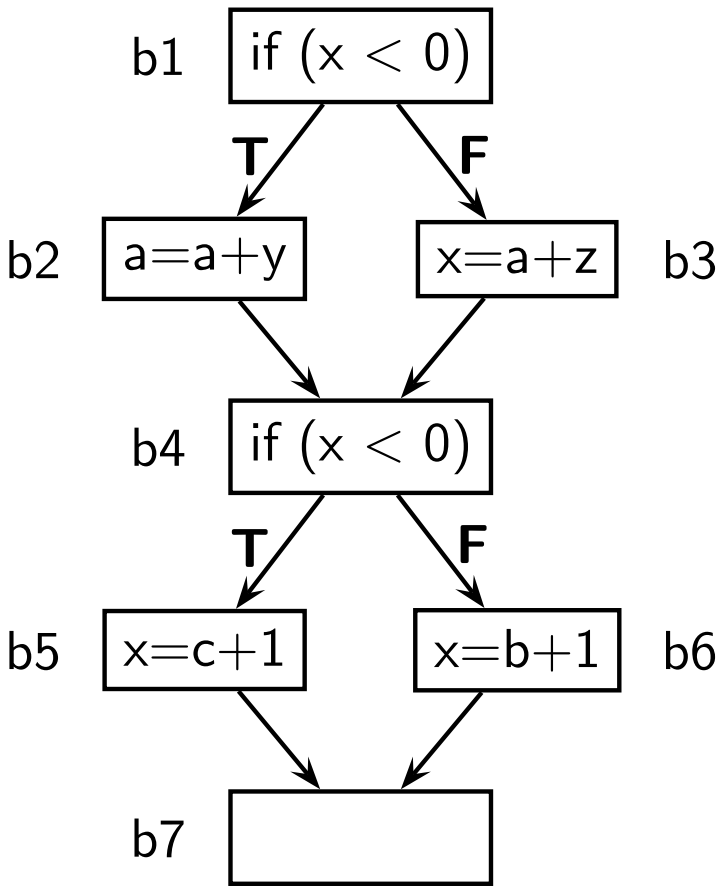

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- Is c live at the entry of b3?

Conservative Nature of Analysis at Intraprocedural Level

- We assume that all paths are potentially executable
- Our analysis is path insensitive
  - The data flow information at a program point p is path insensitive
    - information at p is merged along all paths reaching p
  - The data flow information reaching p is computed path insensitively
    - information is merged at all shared points in paths reaching p
    - may generate spurious information due to non-distributive flow functions

Conservative Nature of Analysis at Interprocedural Level

- Context insensitivity
  - Merges of information across all calling contexts
- Flow insensitivity
  - Disregards the control flow

More about it later

Looking Ahead

The exciting word of pointer analysis beckons us ☺