

CSC D70: Compiler Optimization Static Single Assignment (SSA)

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Winter 2020

*The content of this lecture is adapted from the lectures of
Todd Mowry and Phillip Gibbons*

From Last Lecture

- What is a Loop?
- Dominator Tree
- Natural Loops
- Back Edges

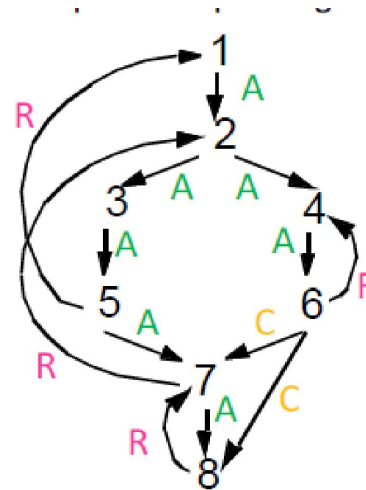
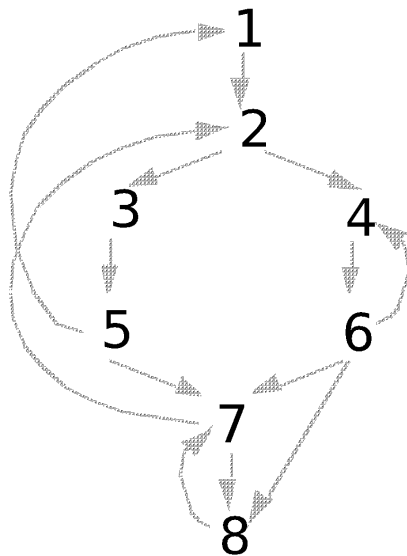
Finding Loops: Summary

- **Define loops in graph theoretic terms**
- **Definitions and algorithms for:**
 - Dominators
 - Back edges
 - Natural loops

Finding Back Edges

- **Depth-first spanning tree**

- Edges traversed in a depth-first search of the flow graph form a depth-first spanning tree

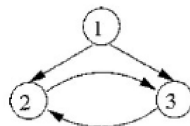


- **Categorizing edges in graph**

- Advancing (A) edges: from ancestor to proper descendant
- Cross (C) edges: from right to left
- Retreating (R) edges: from descendant to ancestor (not necessarily proper)

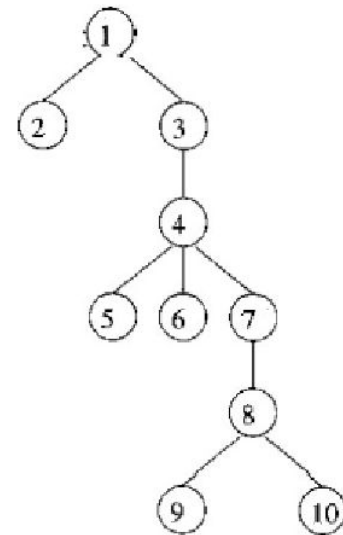
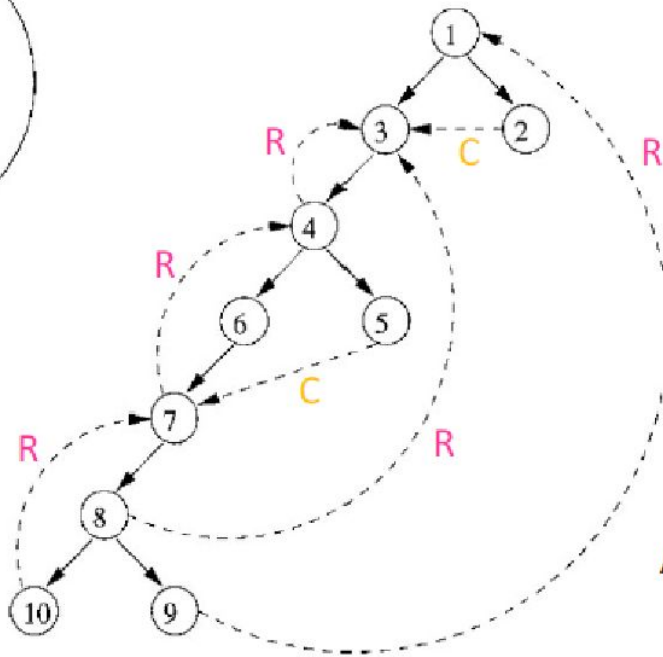
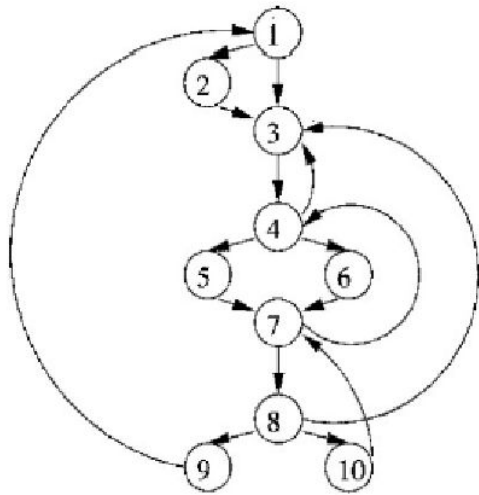
Back Edges

- **Definition**
 - **Back edge**: $t \rightarrow h$, h dominates t
- **Relationships between graph edges and back edges**
- **Algorithm**
 - Perform a depth first search
 - For each retreating edge $t \rightarrow h$, check if h is in t 's dominator list
- **Most programs (all structured code, and most GOTO programs) have **reducible** flow graphs**
 - retreating edges = back edges



A **nonreducible** flow graph

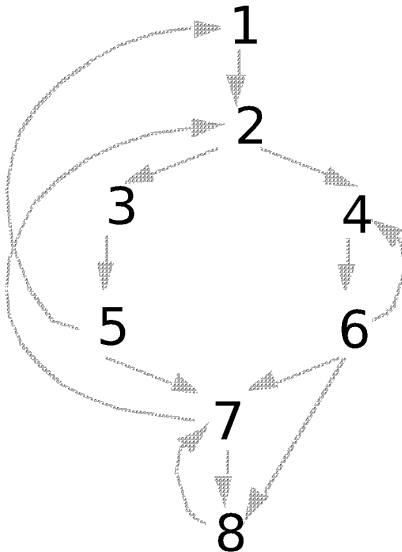
Examples



All the retreating edges
are back edges

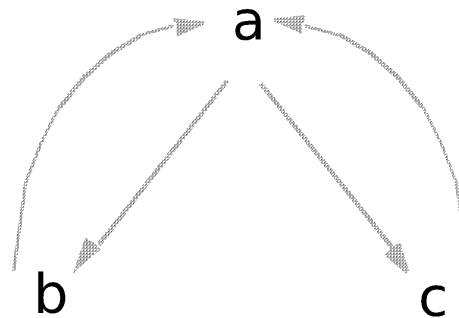
Constructing Natural Loops

- The **natural loop of a back edge** is the smallest set of nodes that includes the head and tail of the back edge, and has no predecessors outside the set, except for the predecessors of the header.
- **Algorithm**
 - delete h from the flow graph
 - find those nodes that can reach t
(those nodes plus h form the natural loop of $t \rightarrow h$)



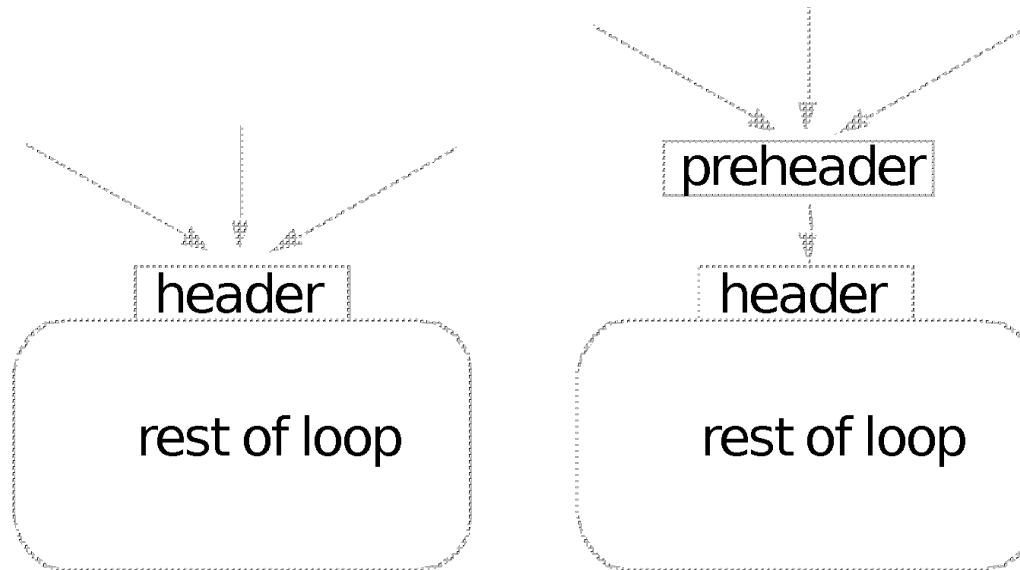
Inner Loops

- **If two loops do not have the same header:**
 - they are either disjoint, or
 - one is entirely contained (nested within) the other
 - inner loop: one that contains no other loop.
- **If two loops share the same header:**
 - Hard to tell which is the inner loop
 - Combine as one



Preheader

- Optimizations often require code to be executed once before the loop
- Create a preheader basic block for every loop



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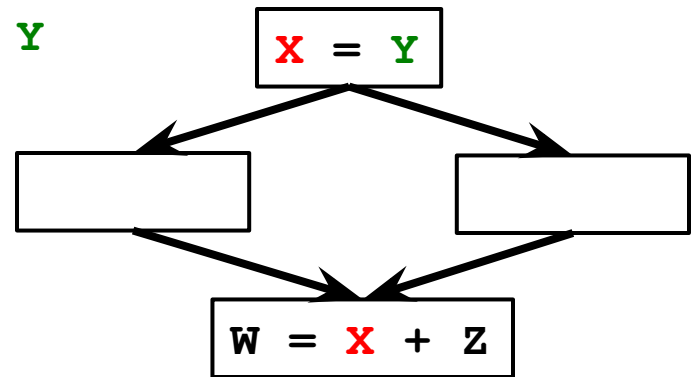
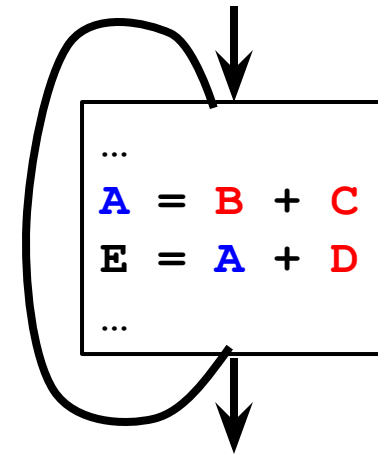
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Where Is a Variable Defined or Used?

- Example: Loop-Invariant Code Motion
 - Are **B**, **C**, and **D** only defined outside the loop?
 - Other definitions of **A** inside the loop?
 - Uses of **A** inside the loop?

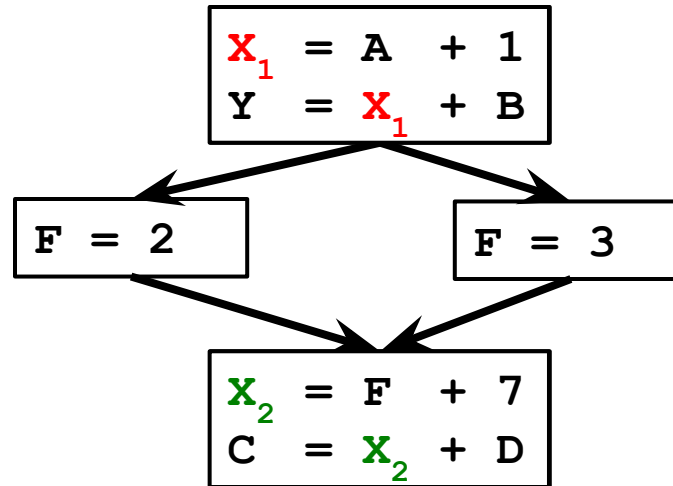
- Example: Copy Propagation

- For a given use of **X**:
 - Are all reaching definitions of **X**:
 - copies from same variable: e.g., **X** = **Y**
 - Where **Y** is not redefined since that copy?
- If so, substitute use of **X** with use of **Y**



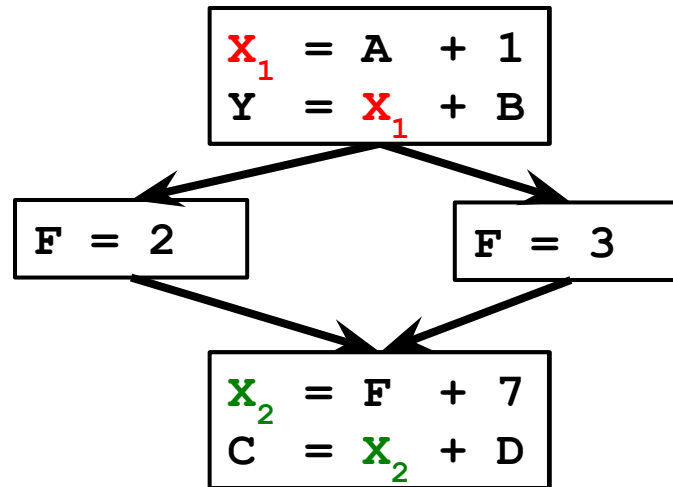
- It would be nice if we could *traverse directly* between related uses and def's
 - this would enable a form of *sparse* code analysis (skip over “don't care” cases)

Appearances of Same Variable Name May Be Unrelated



- The values in reused storage locations may be provably independent
 - in which case the compiler can optimize them as separate values
- Compiler could use renaming to make these different versions more explicit

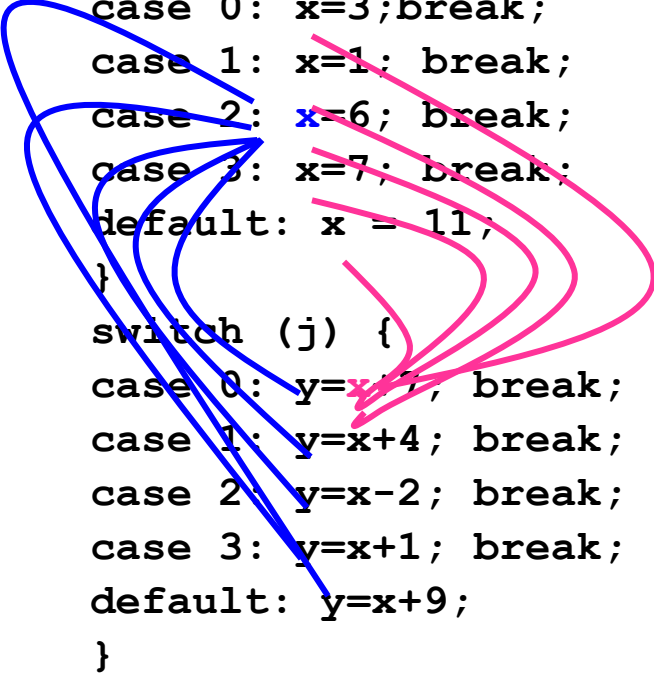
Definition-Use and Use-Definition Chains



- Use-Definition (UD) Chains:
 - for a given definition of a variable X , what are all of its uses?
- Definition-Use (DU) Chains:
 - for a given use of a variable X , what are all of the reaching definitions of X ?

DU and UD Chains Can Be Expensive

```
foo(int i, int j) {  
    ...  
    switch (i) {  
    case 0: x=3; break;  
    case 1: x=1; break;  
    case 2: x=6; break;  
    case 3: x=7; break;  
    default: x = 11;  
    }  
    switch (j) {  
    case 0: y=x+7; break;  
    case 1: y=x+4; break;  
    case 2: y=x-2; break;  
    case 3: y=x+1; break;  
    default: y=x+9;  
    }  
    ...  
}
```

The diagram shows two nested switch statements. The first switch statement is for variable 'i' with cases 0, 1, 2, 3, and a default. The second switch statement is for variable 'j' with cases 0, 1, 2, 3, and a default. Blue annotations highlight the definition sites for 'x' (cases 0, 1, 2, 3, and default) and 'y' (cases 0, 1, 2, 3, and default). Pink annotations highlight the use sites for 'x' (cases 0, 1, 2, 3, and default) and 'y' (cases 0, 1, 2, 3, and default). The annotations show that 'x' is defined in the first switch and used in the second, and 'y' is defined in the second switch and used in the first.

In general,

N defs

M uses

$\Rightarrow O(NM)$ space and time

One solution: limit each variable to ONE definition site

DU and UD Chains Can Be Expensive (2)

```
foo(int i, int j) {
```

```
...
```

```
  switch (i) {
```

```
    case 0: x=3; break;
```

```
    case 1: x=1; break;
```

```
    case 2: x=6;
```

```
    case 3: x=7;
```

```
    default: x = 11;
```

```
  }
```

x1 is one of the above x's

```
  switch (j) {
```

```
    case 0: y=x1+7;
```

```
    case 1: y=x1+4;
```

```
    case 2: y=x1-2;
```

```
    case 3: y=x1+1;
```

```
    default: y=x1+9;
```

```
  }
```

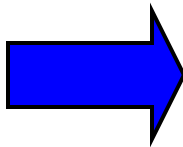
```
...
```

One solution: limit each variable to ONE definition site

Static Single Assignment (SSA)

- Static single assignment is an IR where every variable is assigned a value at most once in the program text
- Easy for a basic block (reminiscent of Value Numbering):
 - Visit each instruction in program order:
 - LHS: assign to a *fresh version* of the variable
 - RHS: use the *most recent version* of each variable

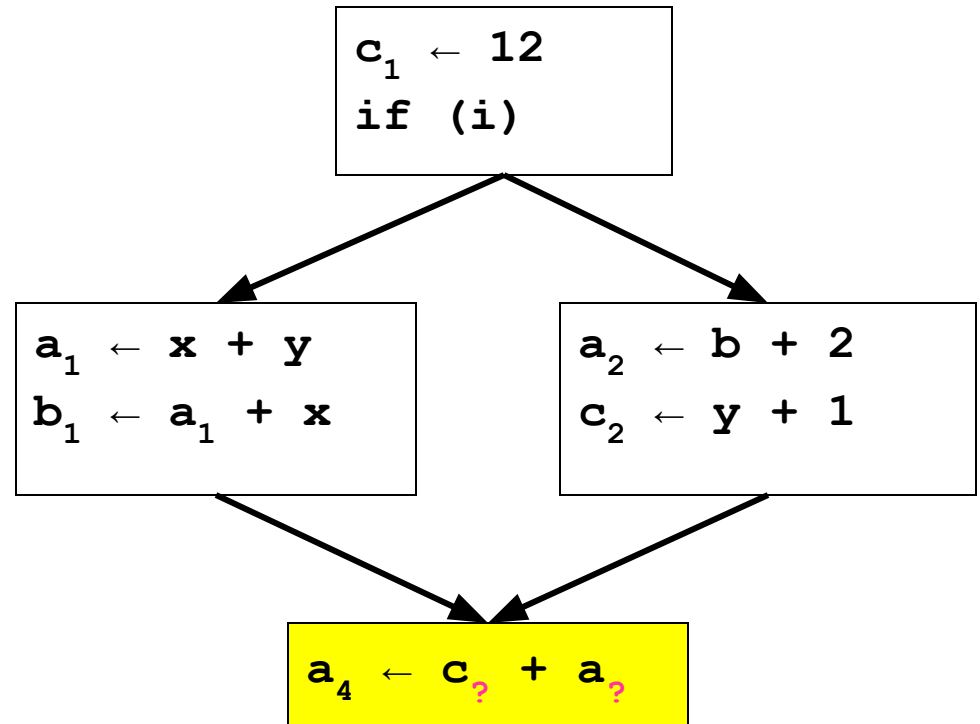
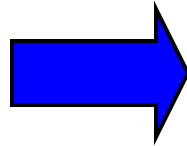
```
a ← x + y
b ← a + x
a ← b + 2
c ← y + 1
a ← c + a
```



```
a1 ← x + y
b1 ← a1 + x
a2 ← b1 + 2
c1 ← y + 1
a3 ← c1 + a2
```

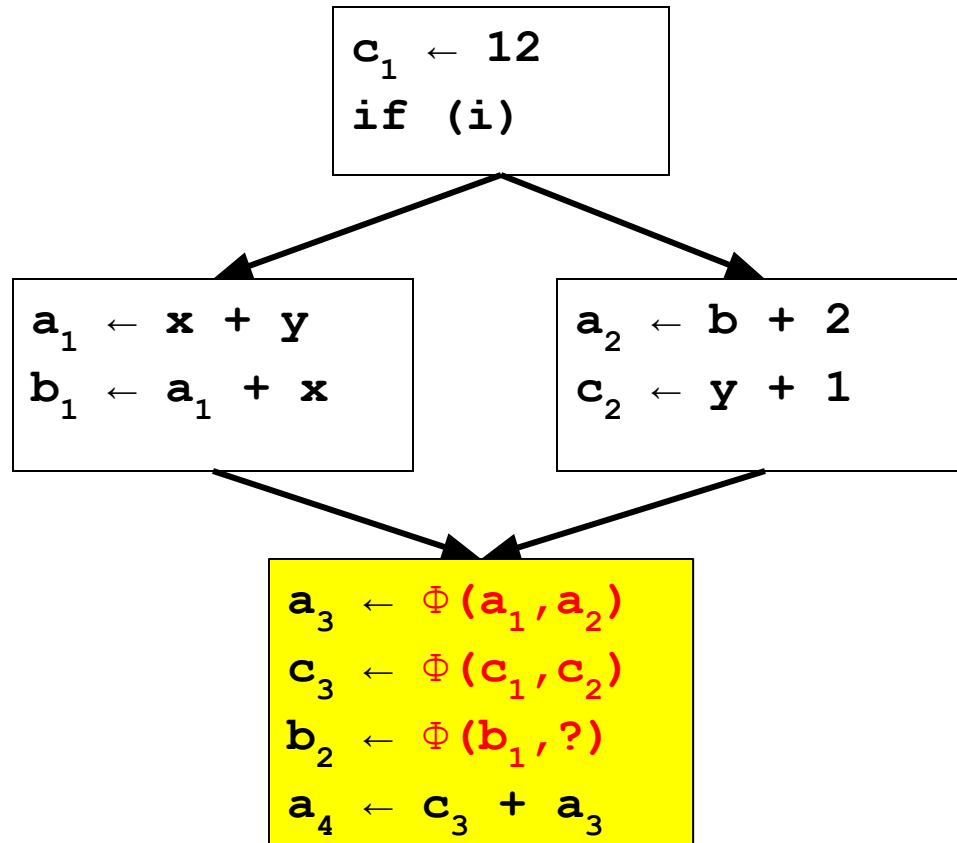

What about Joins in the CFG?

```
c ← 12
if (i) {
  a ← x + y
  b ← a + x
} else {
  a ← b + 2
  c ← y + 1
}
a ← c + a
```



❓ Use a notational fiction: a Φ function

Merging at Joins: the Φ function



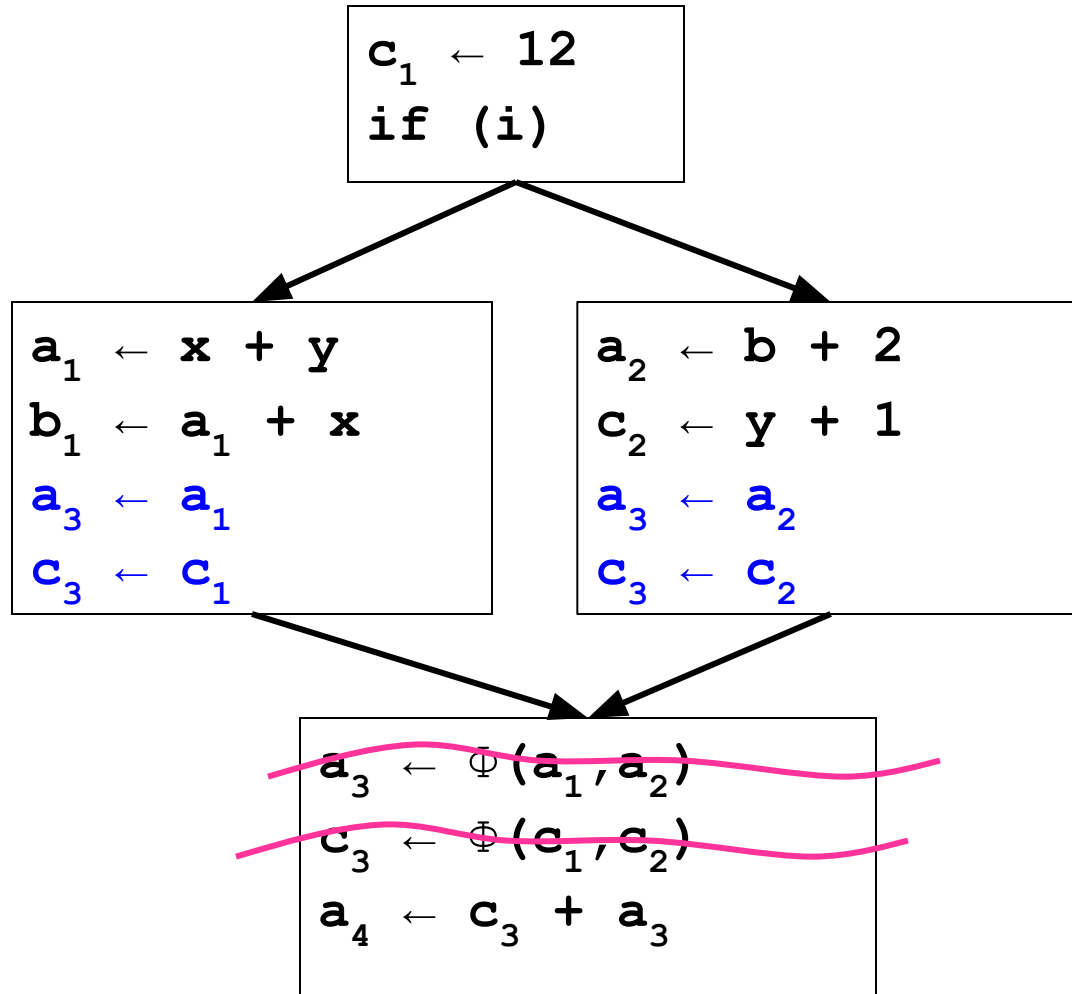
The Φ function

- Φ merges multiple definitions along multiple control paths into a single definition.
- At a basic block with p predecessors, there are p arguments to the Φ function.

$$x_{\text{new}} \leftarrow \Phi(x_1, x_1, x_1, \dots, x_p)$$

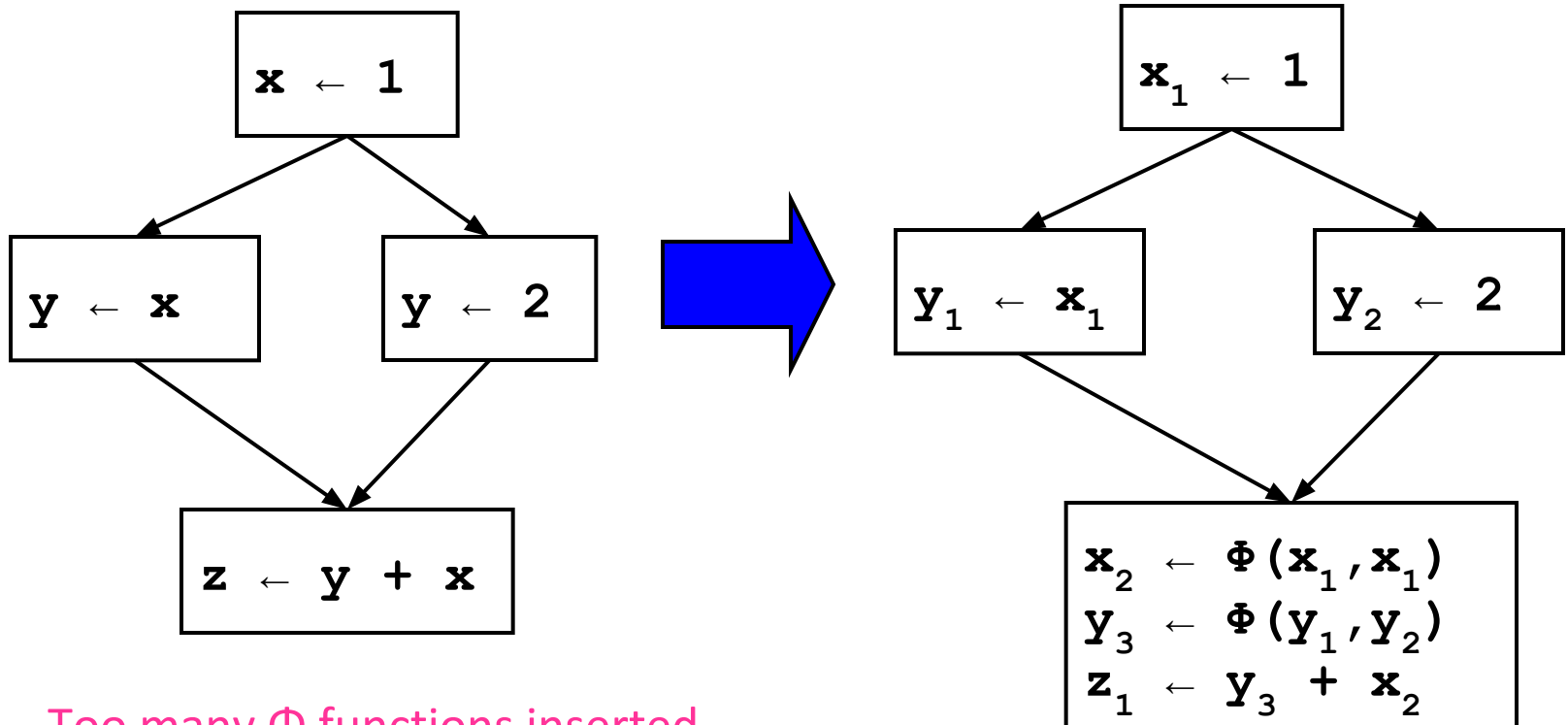
- How do we choose which x_i to use?
 - We don't really care!
 - If we care, use moves on each incoming edge

“Implementing” Φ



Trivial SSA

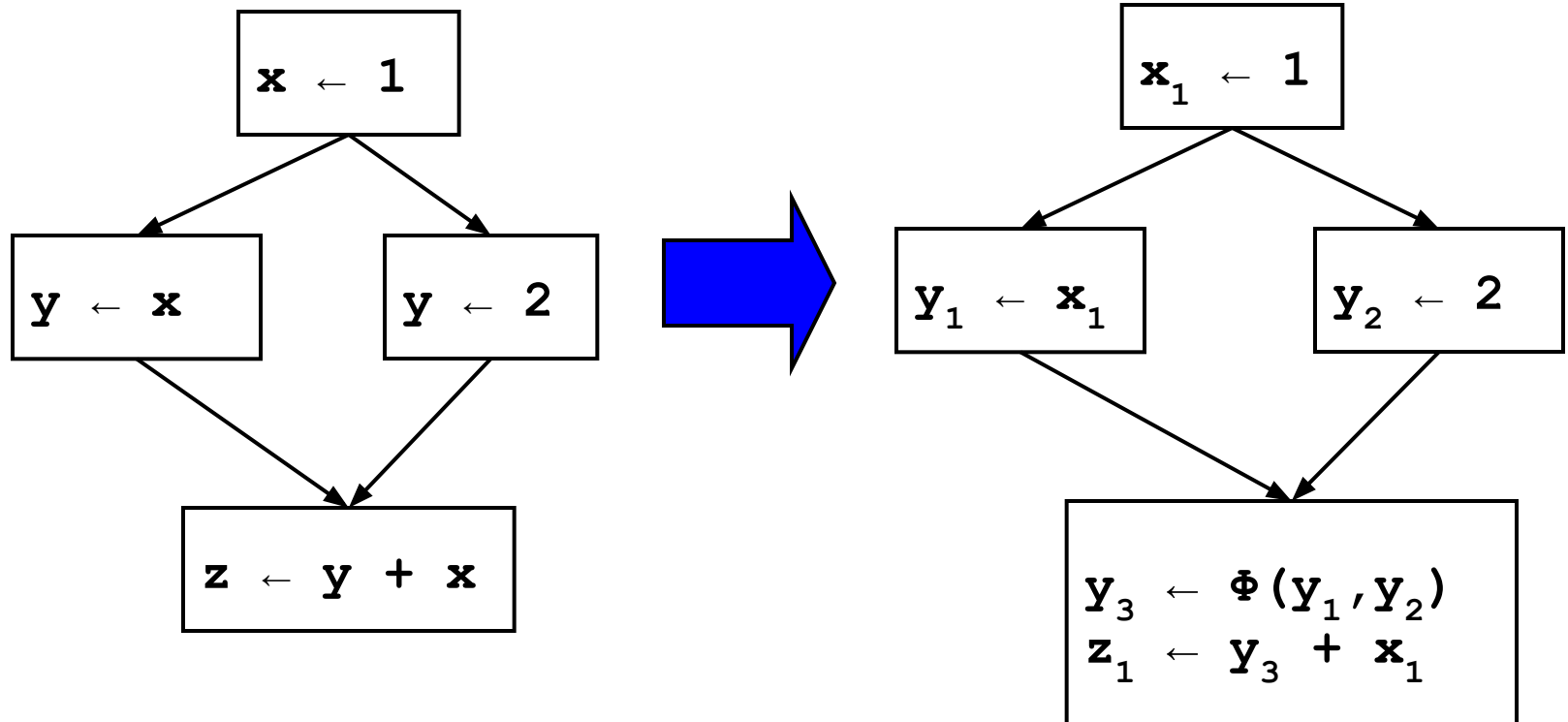
- Each assignment generates a fresh variable.
- At each join point insert Φ functions for **all live variables**.



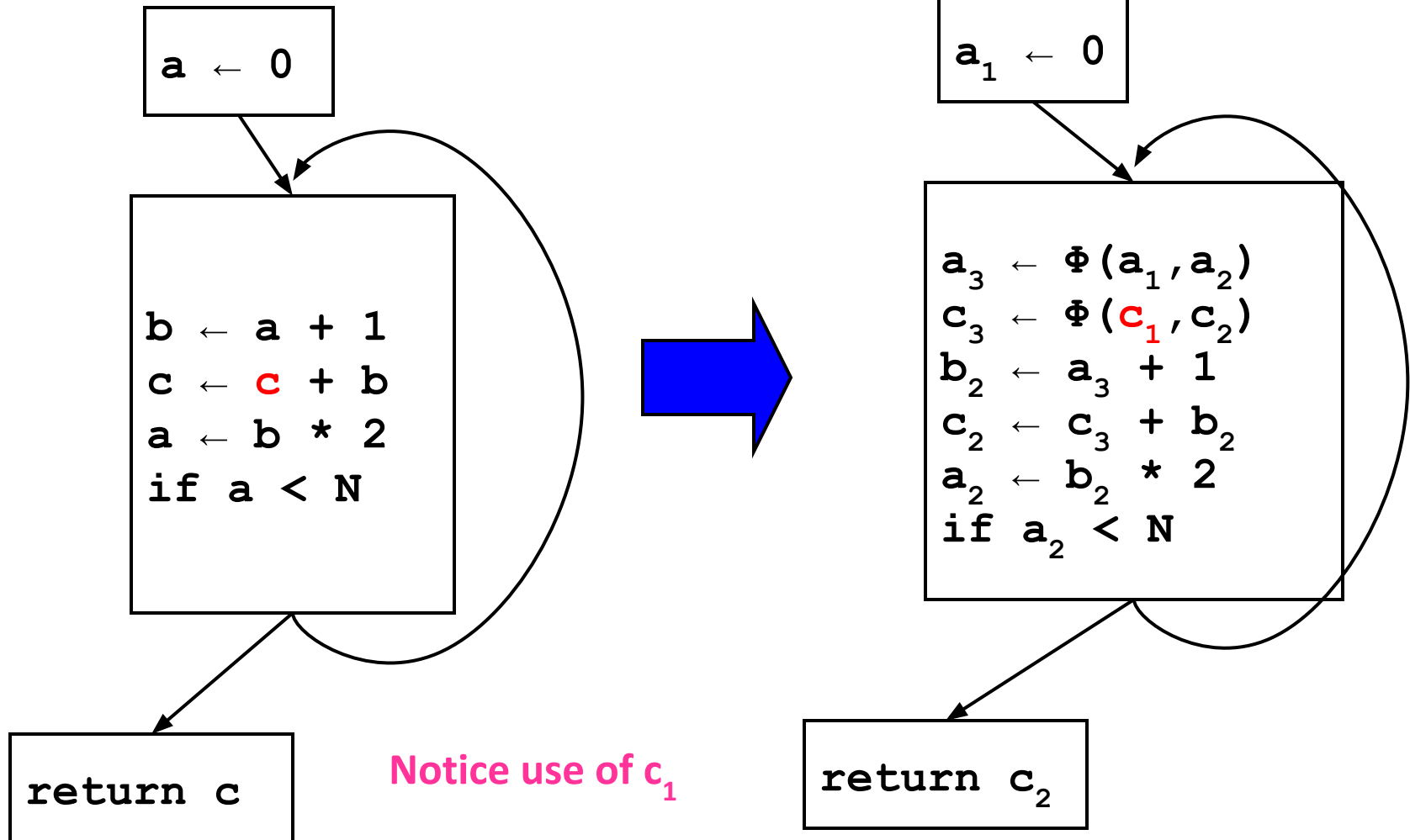
Too many Φ functions inserted.

Minimal SSA

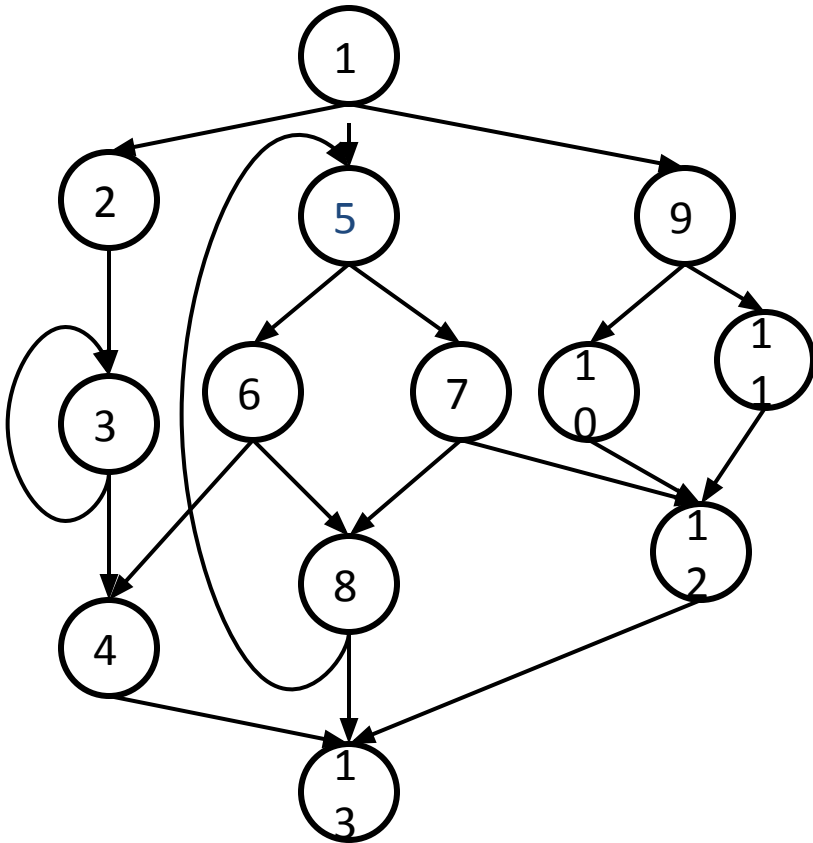
- Each assignment generates a fresh variable.
- At each join point insert Φ functions for **all live variables** with **multiple outstanding defs**.



Another Example



When Do We Insert Φ ?

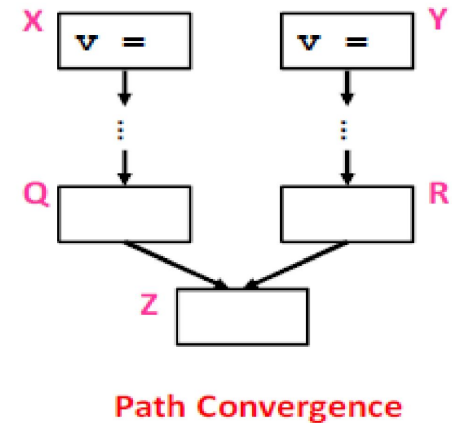


CFG

If there is a def of **a** in block **5**,
which nodes need a $\Phi()$?

When do we insert Φ ?

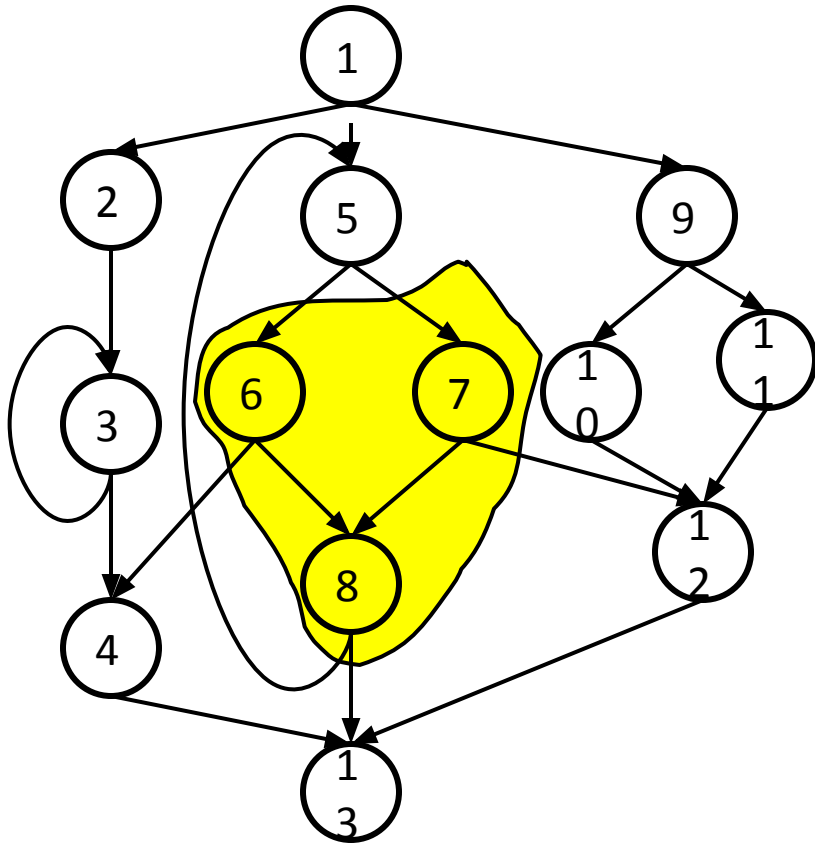
- We insert a Φ function for variable **A** in block **Z** iff:
 - A** was defined more than once before
 - (i.e., **A** defined in **X** and **Y** AND $X \neq Y$)
 - There exists a non-empty path from **x** to **z**, P_{xz} ,
 - and a non-empty path from **y** to **z**, P_{yz} , s.t.
 - $P_{xz} \cap P_{yz} = \{z\}$
 - (Z is only common block along paths)
 - $z \notin P_{xq}$ or $z \notin P_{yr}$ where $P_{xz} = P_{xq} \rightarrow z$ and $P_{yz} = P_{yr} \rightarrow z$
 - (at least one path reaches Z for first time)
- Entry block contains an implicit def of all vars
- Note: $v = \Phi(\dots)$ is a def of **v**



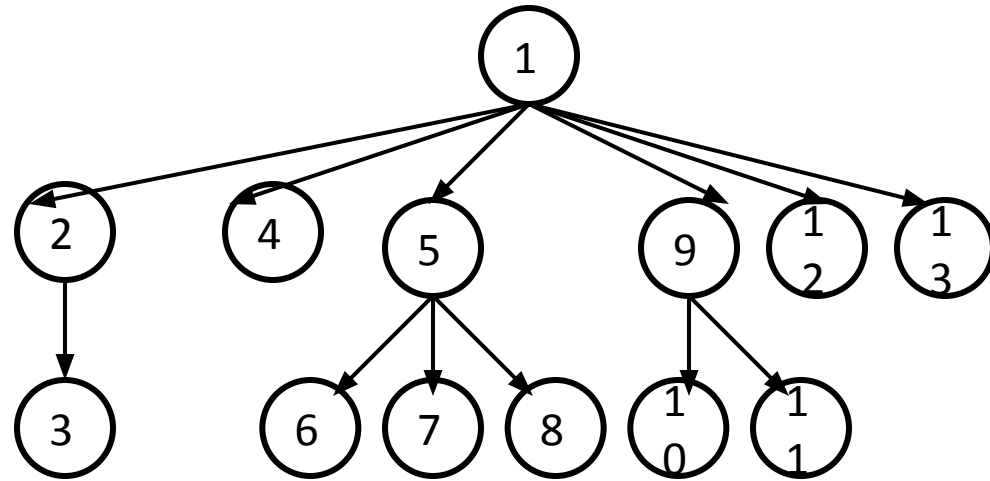
Dominance Property of SSA

- In SSA, definitions dominate uses.
 - If x_i is used in $x \leftarrow \Phi(\dots, x_i, \dots)$, then $\text{BB}(x_i)$ dominates i^{th} predecessor of $\text{BB}(\text{PHI})$
 - If x is used in $y \leftarrow \dots x \dots$, then $\text{BB}(x)$ dominates $\text{BB}(y)$
- We can use this for an efficient algorithm to convert to SSA

Dominance



CFG

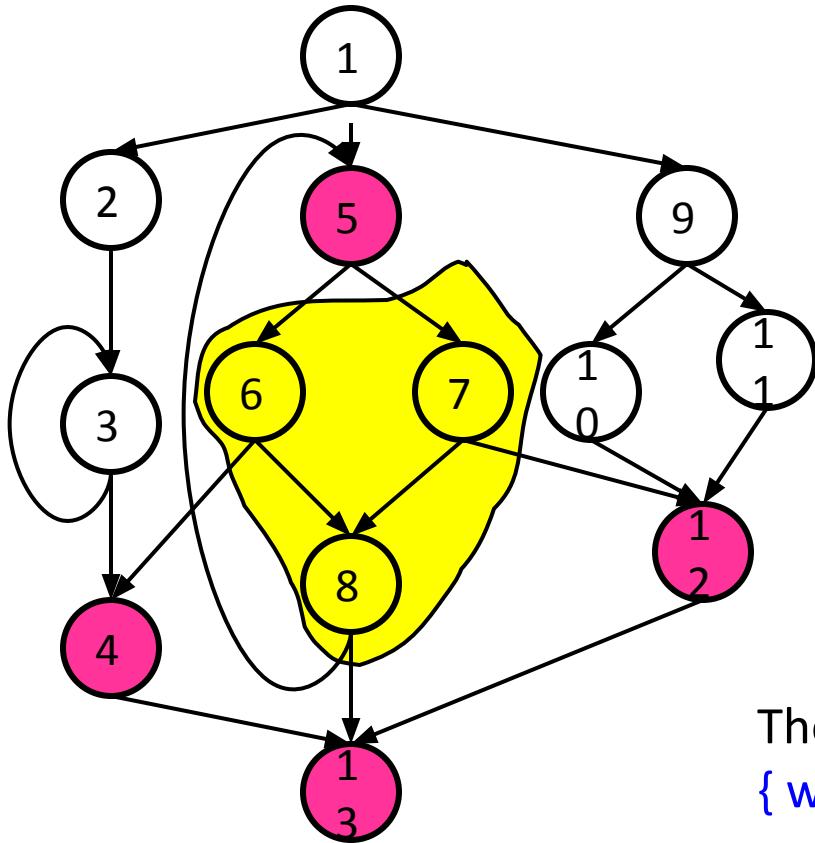


D-Tree

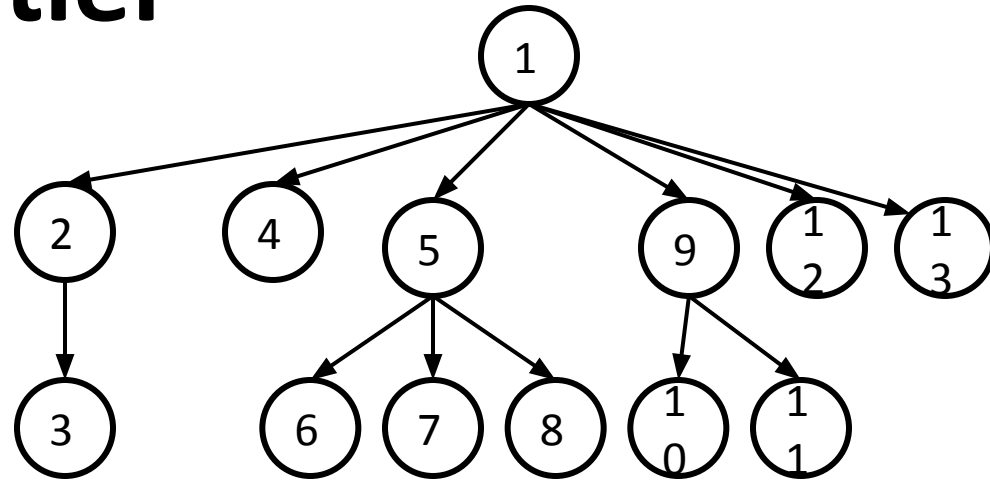
If there is a def of **a** in block **5**,
which nodes need a $\Phi()$?

x strictly dominates **w** ($x \text{ sdom } w$) iff $x \text{ dom } w$ AND $x \neq w$

Dominance Frontier



CFG

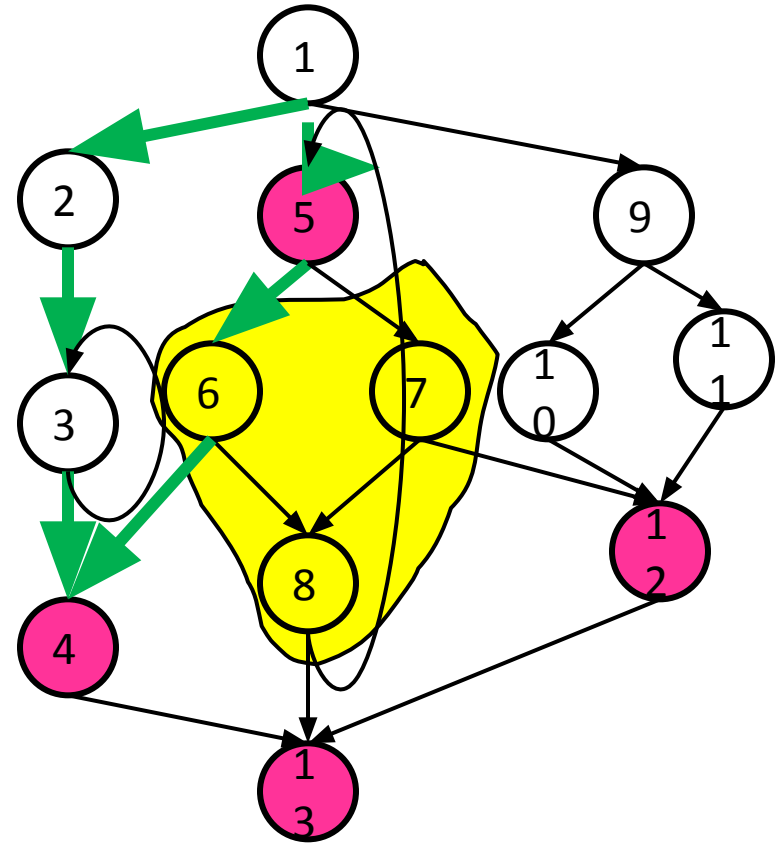
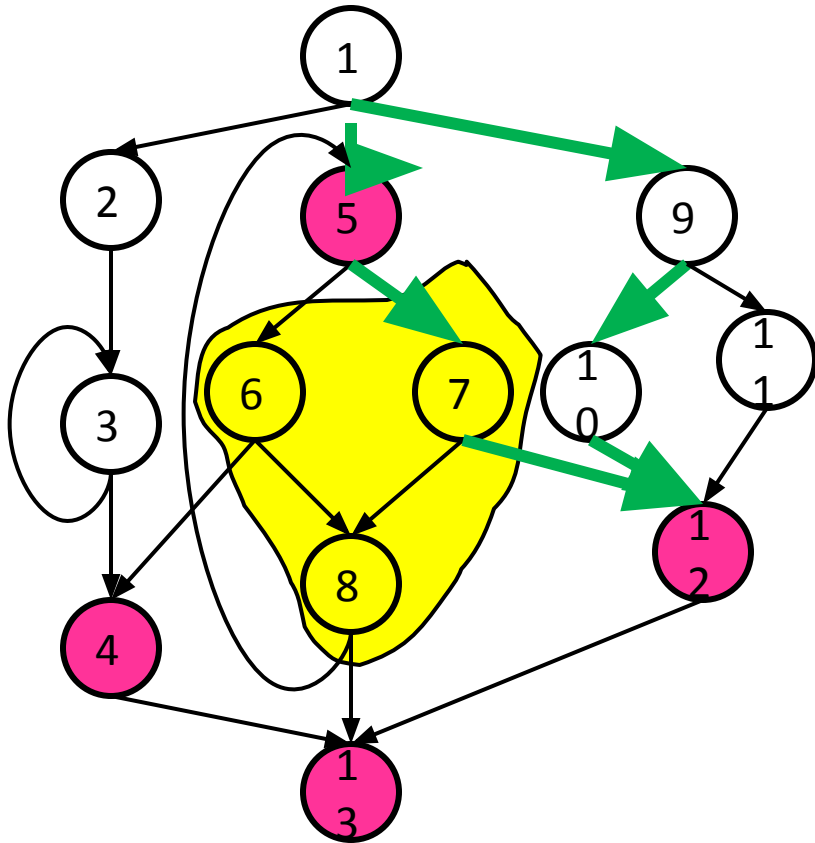


D-Tree

The **Dominance Frontier** of a node $x = \{ w \mid x \text{ dom pred}(w) \text{ AND } \neg(x \text{ sdom } w) \}$

x strictly dominates w ($x \text{ sdom } w$) iff $x \text{ dom } w$ AND $x \neq w$

Dominance Frontier and Path Convergence



If there is a def of **a** in block **5**,
nodes in DF(**5**) need a $\Phi()$ for **a**

Using Dominance Frontier to Compute SSA

- place all $\Phi()$
- Rename all variables

Using Dominance Frontier to Place $\Phi()$

- Gather all the defsites of every variable
- Then, for every variable
 - foreach defsite
 - foreach node in DominanceFrontier(defsite)
 - if we haven't put $\Phi()$ in node, then put one in
 - if this node didn't define the variable before, then add this node to the defsites
- This essentially computes the Iterated Dominance Frontier on the fly, inserting the minimal number of $\Phi()$ necessary

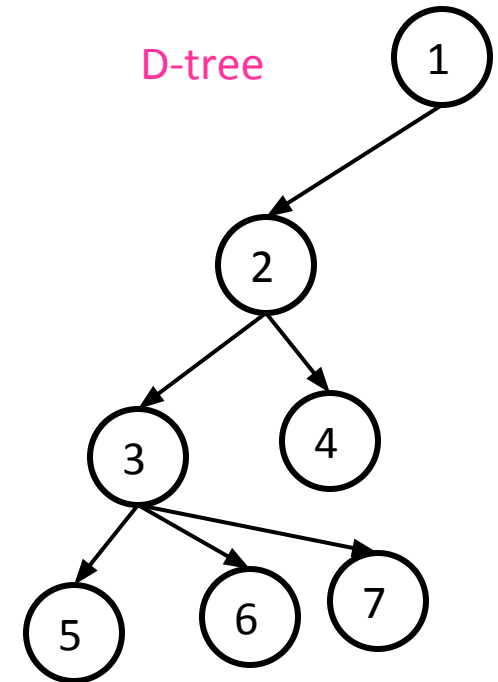
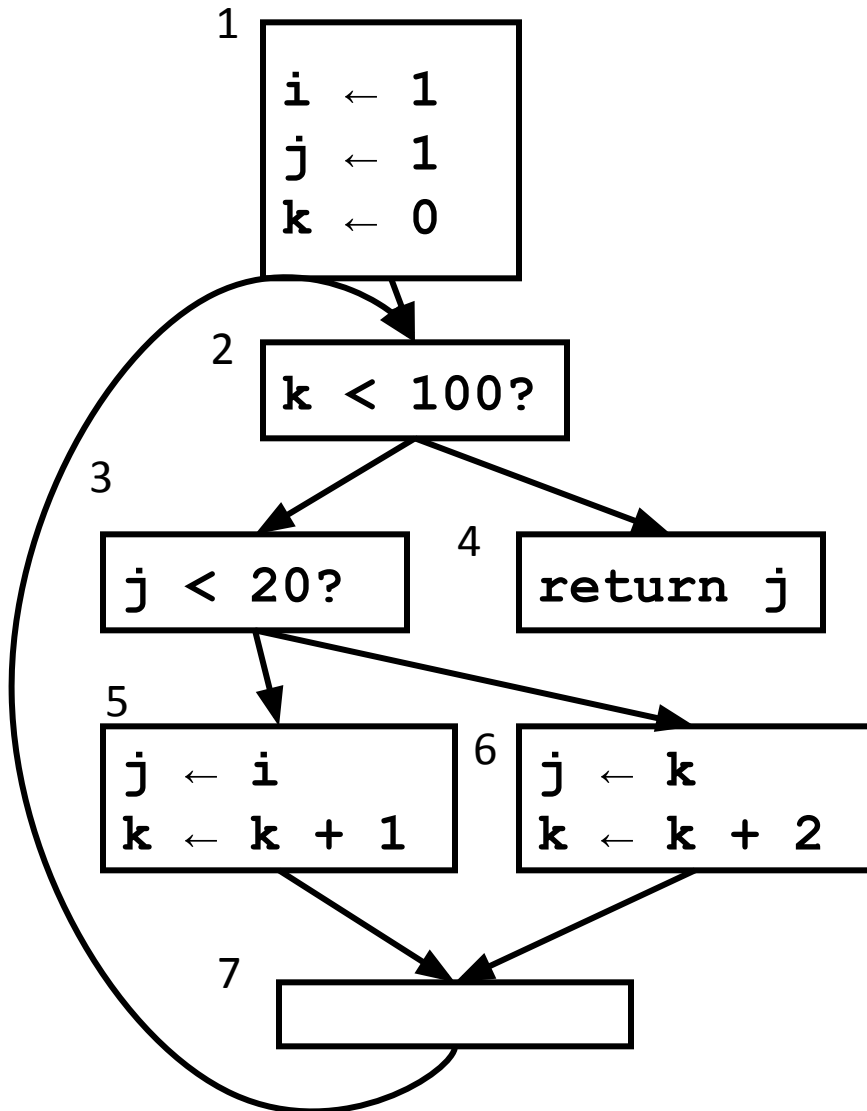
Using Dominance Frontier to Place $\Phi()$

```
foreach node n {
    foreach variable v defined in n {
        orig[n] U= {v}
        defsites[v] U= {n}
    }
}
foreach variable v {
    W = defsites[v]
    while W not empty {
        n = remove node from W
        foreach y in DF[n]
            if y  $\notin$  PHI[v] {
                insert " $v \leftarrow \Phi(v, v, \dots)$ " at top of y
                PHI[v] = PHI[v] U {y}
                if v  $\notin$  orig[y]: W = W U {y}
            }
    }
}
```

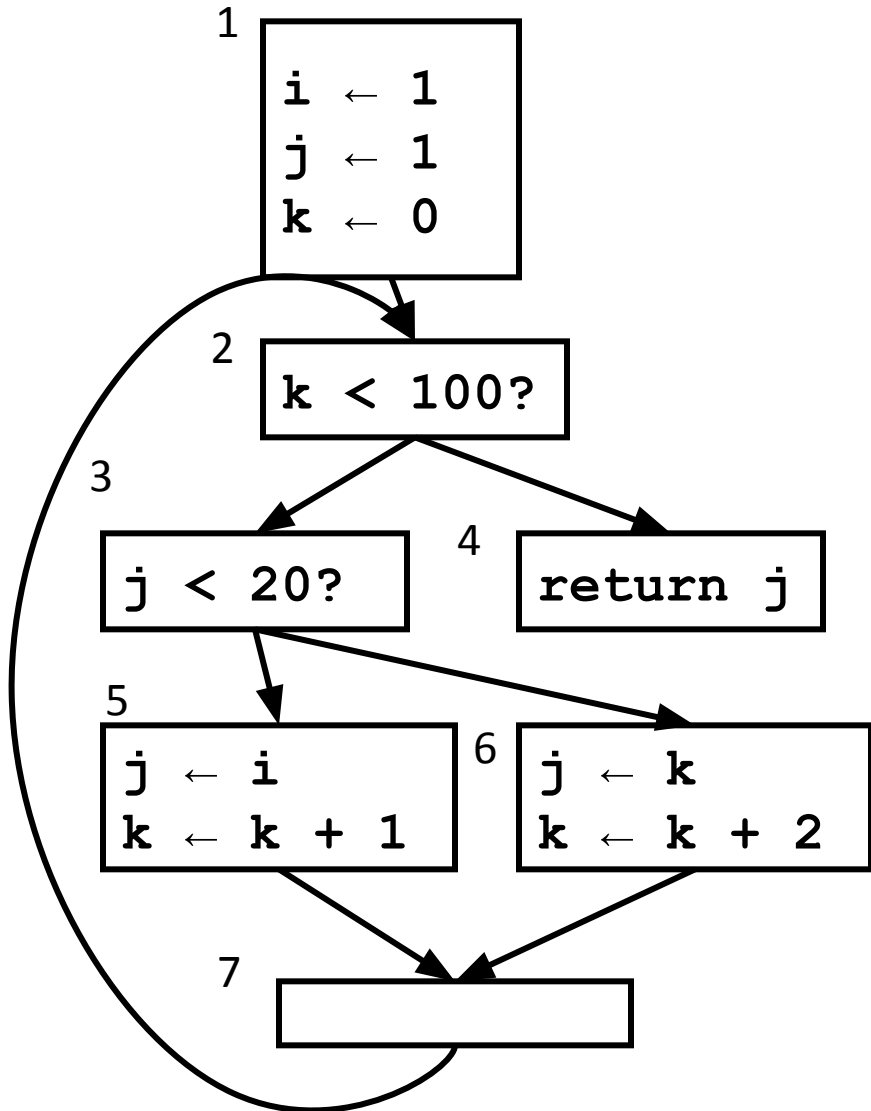

Renaming Variables

- Algorithm:
 - Walk the D-tree, renaming variables as you go
 - Replace uses with more recent renamed def
- For straight-line code this is easy
- What if there are branches and joins?
 - use the **closest def such that the def is above the use in the D-tree**
- Easy implementation:
 - for each var: **rename** (v)
 - **rename**(v):
 - replace uses with top of stack
 - at def: push onto stack
 - call **rename**(v) on all children in D-tree
 - for each def in this block pop from stack

Compute Dominance Tree

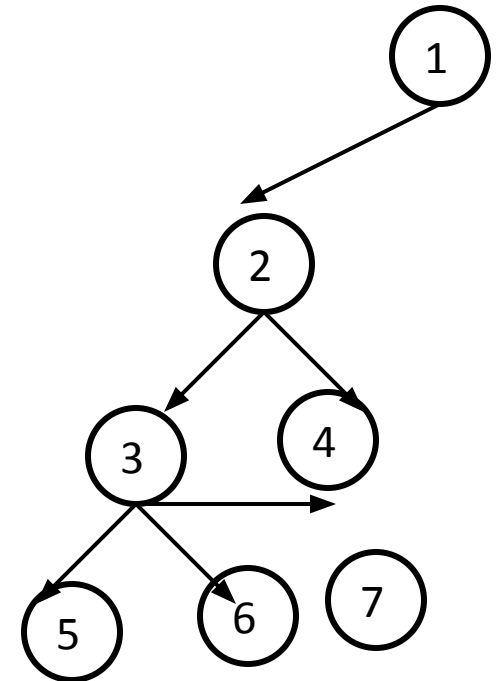


Compute Dominance Frontiers

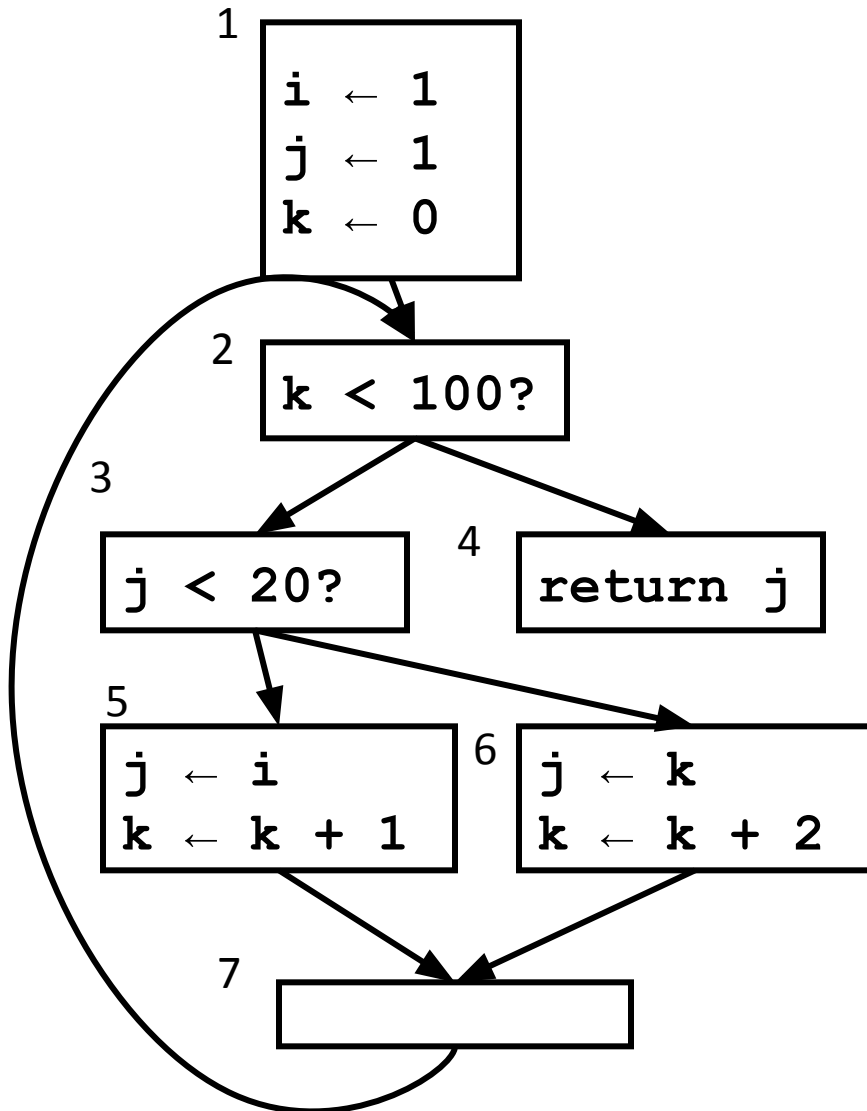


DFs

1	{}
2	{2}
3	{2}
4	{}
5	{7}
6	{7}
7	{2}



Insert $\Phi()$



DFs	orig[n]
1 {}	1 {i,j,k}
2 {2}	2 {}
3 {2}	3 {}
4 {}	4 {}
5 {7}	5 {j,k}
6 {7}	6 {j,k}
7 {2}	7 {}

defsites[v]

i	{1}
j	{1,5,6}
k	{1,5,6}

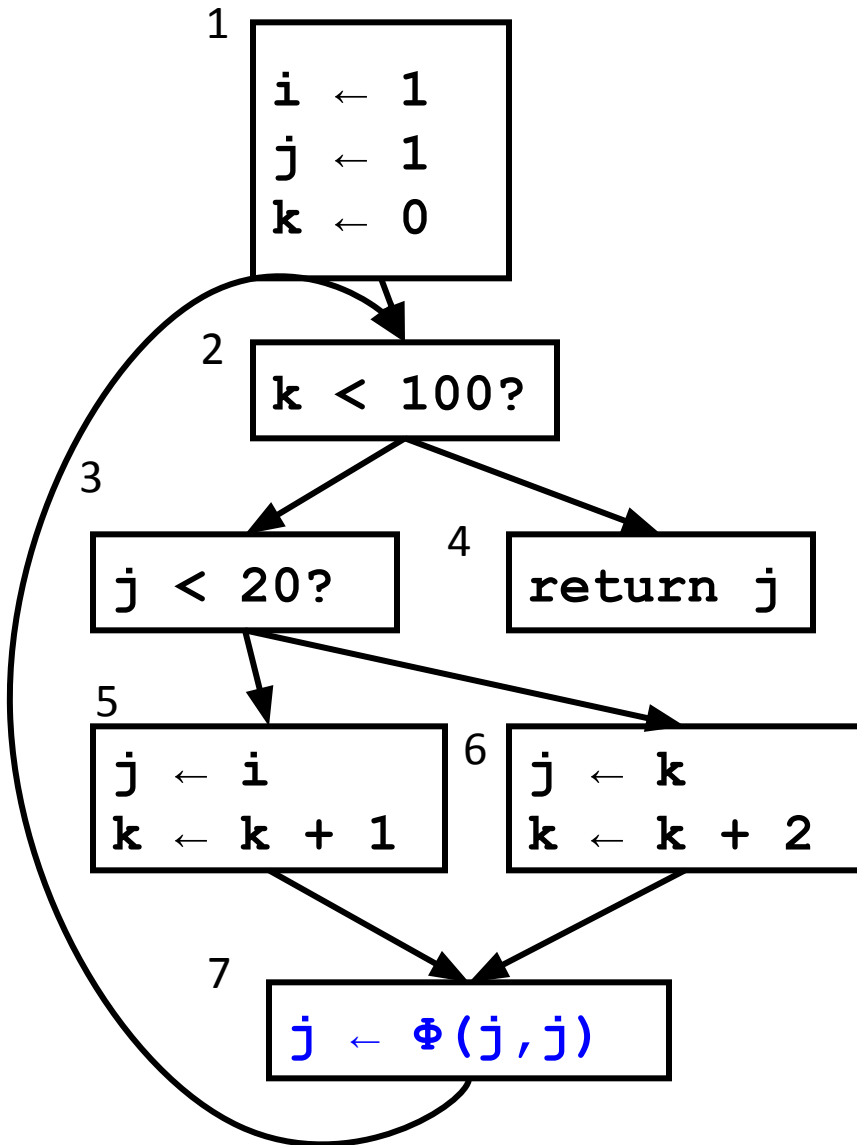
DFs

var i: W={1}

var j: W={1,5,6}

DF{1} DF{5}

Insert $\Phi()$



DFs	orig[n]
1 {}	1 {i,j,k}
2 {2}	2 {}
3 {2}	3 {}
4 {}	4 {}
5 {7}	5 {j,k}
6 {7}	6 {j,k}
7 {2}	7 {}

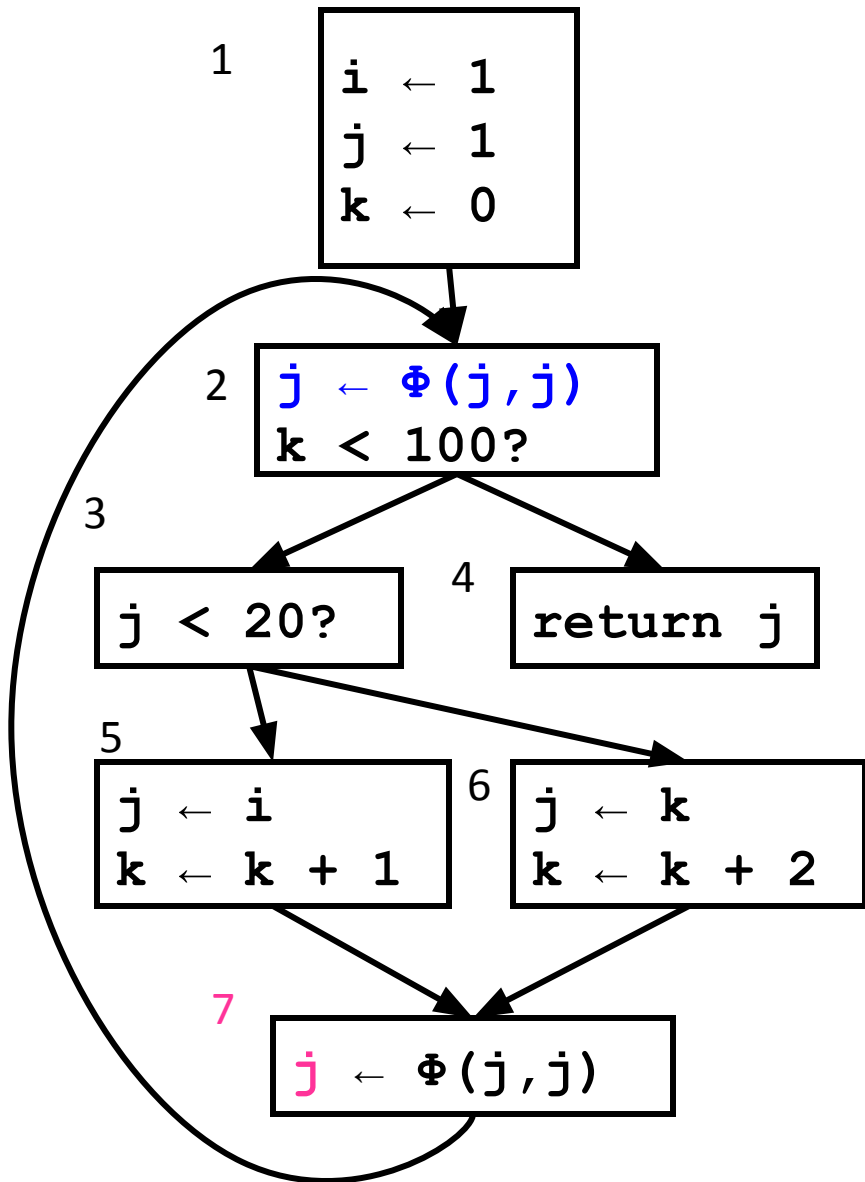
defsites[v]

i	{1}
j	{1,5,6}
k	{1,5,6}

DFs

var j: W={1,5,6}

DF{1} DF{5}



DFs

1	{}
2	{2}
3	{2}
4	{}
5	{7}
6	{7}
7	{2}

orig[n]

1	{i,j,k}
2	{}
3	{}
4	{}
5	{j,k}
6	{j,k}
7	{}

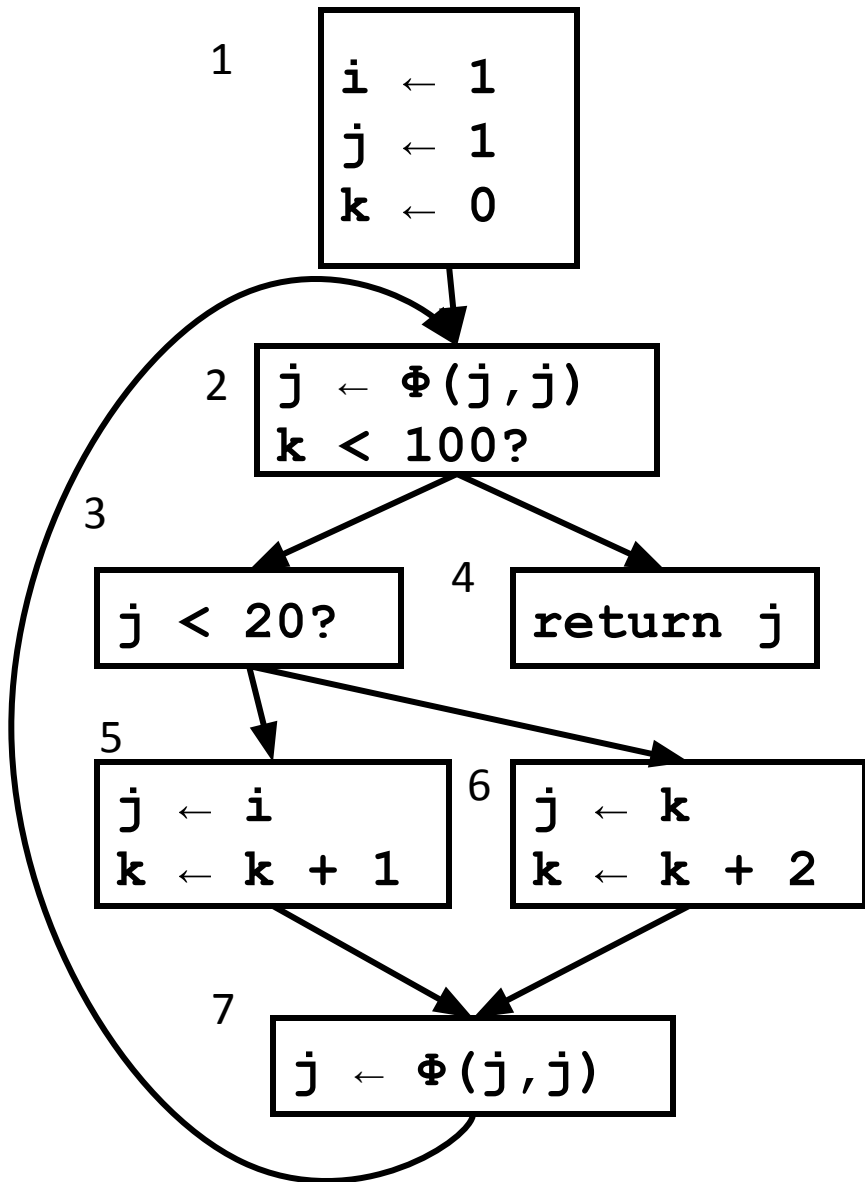
defsites[v]

i	{1}
j	{1,5,6,7}
k	{1,5,6}

DFs

var j: W={1,5,6,7}

DF{1} DF{5} DF{7}



DFs	orig[n]
1 {}	1 {i,j,k}
2 {2}	2 {}
3 {2}	3 {}
4 {}	4 {}
5 {7}	5 {j,k}
6 {7}	6 {j,k}
7 {2}	7 {}

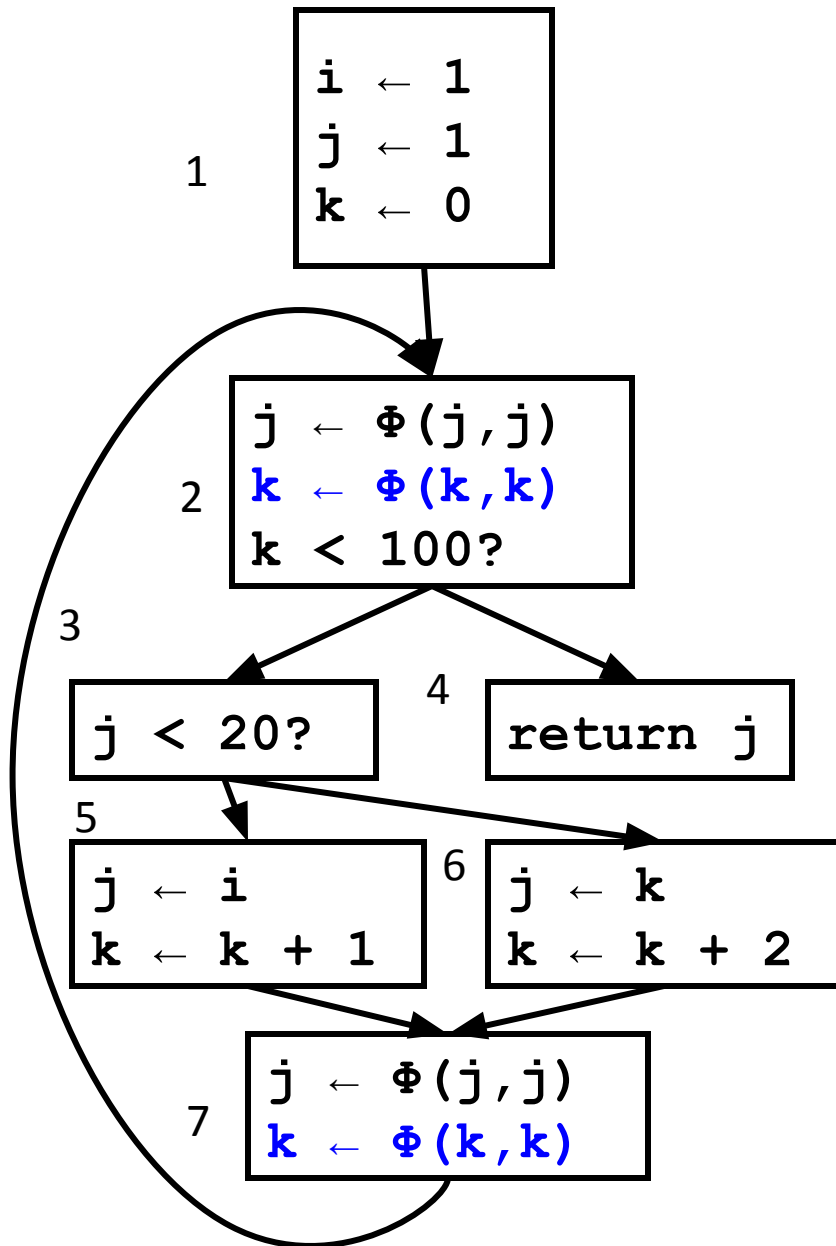
defsites[v]

i	{1}
j	{1,5,6}
k	{1,5,6}

DFs

var j: W={1,5,6,7}

DF{1} DF{5} DF{7} DF{6}



	DFs		orig[n]
1	{}	1	{i,j,k}
2	{2}	2	{}
3	{2}	3	{}
4	{}	4	{}
5	{7}	5	{j,k}
6	{7}	6	{j,k}
7	{2}	7	{}

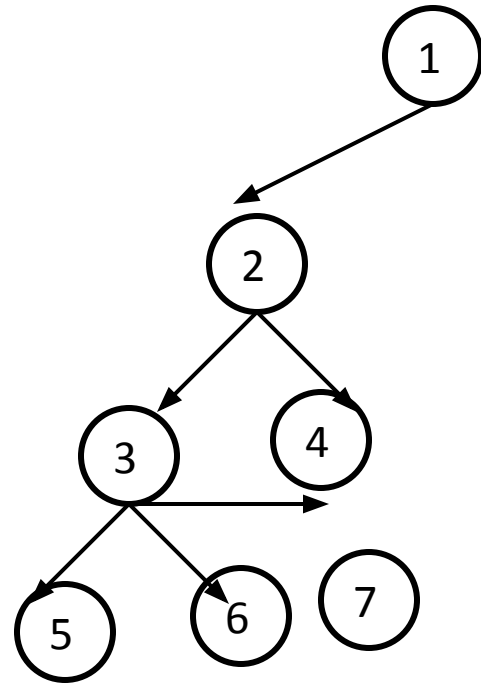
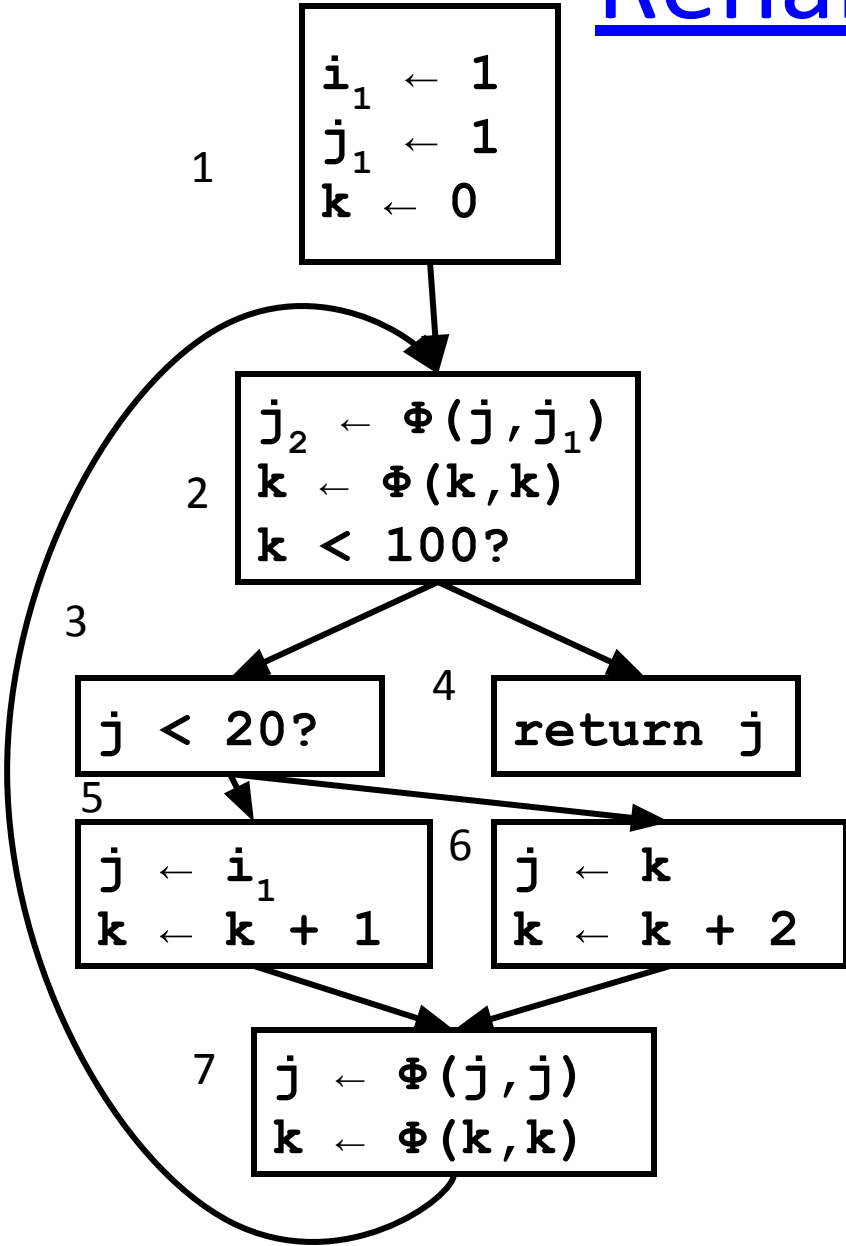
Def sites[v]

i	{1}
j	{1,5,6}
k	{1,5,6}

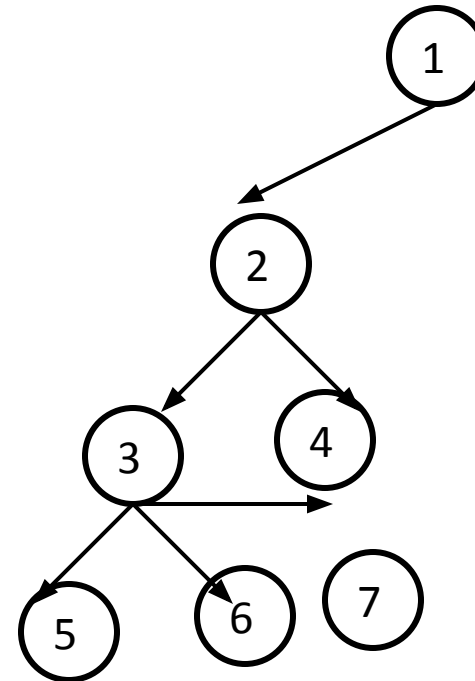
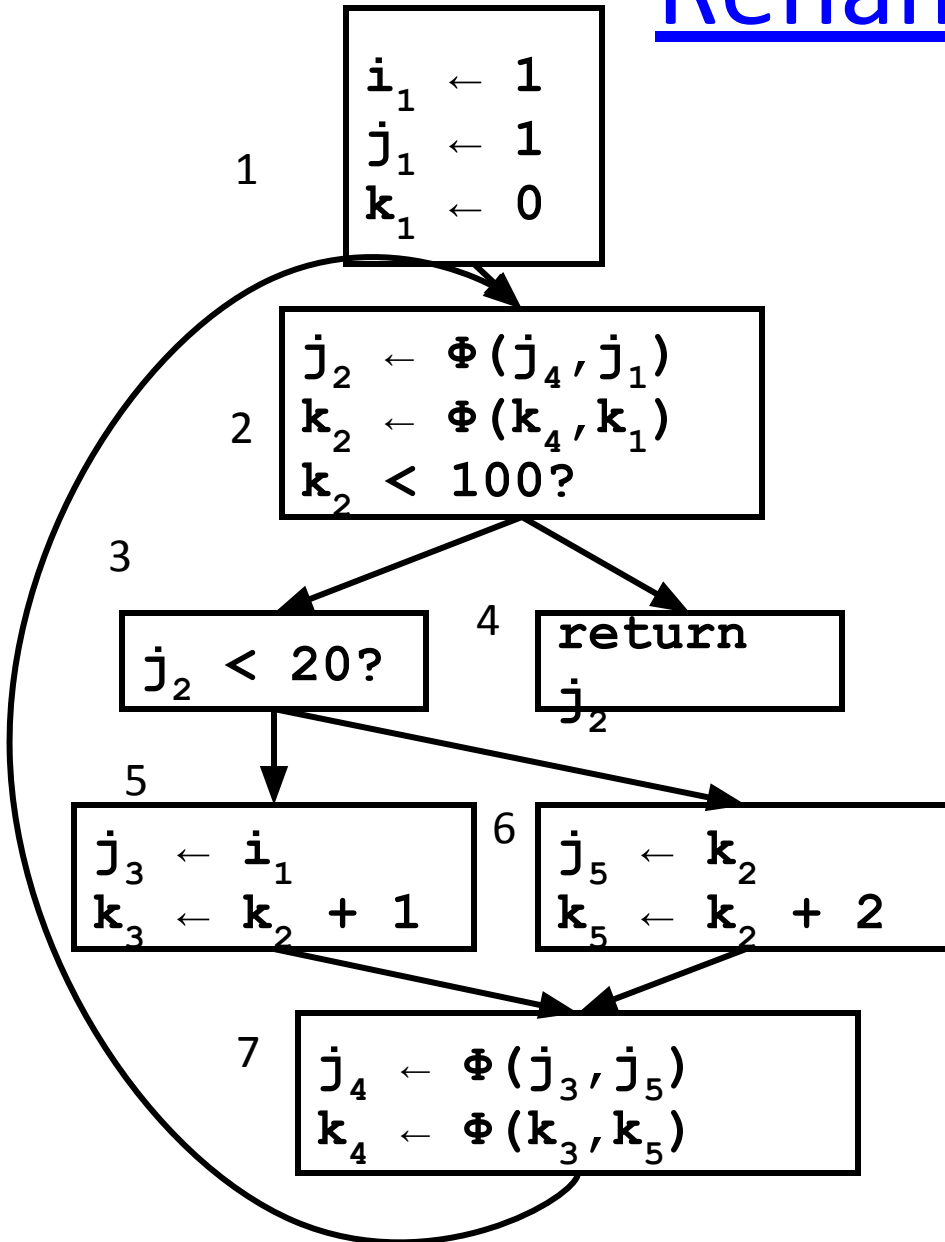
DFs

var k: W={1,5,6}

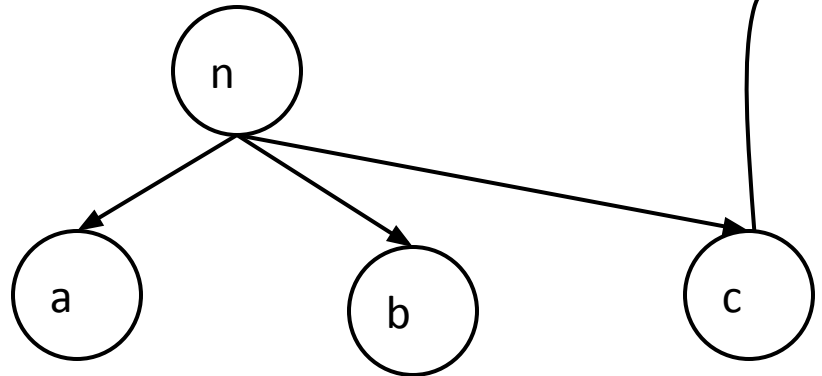
Rename Vars



Rename Vars

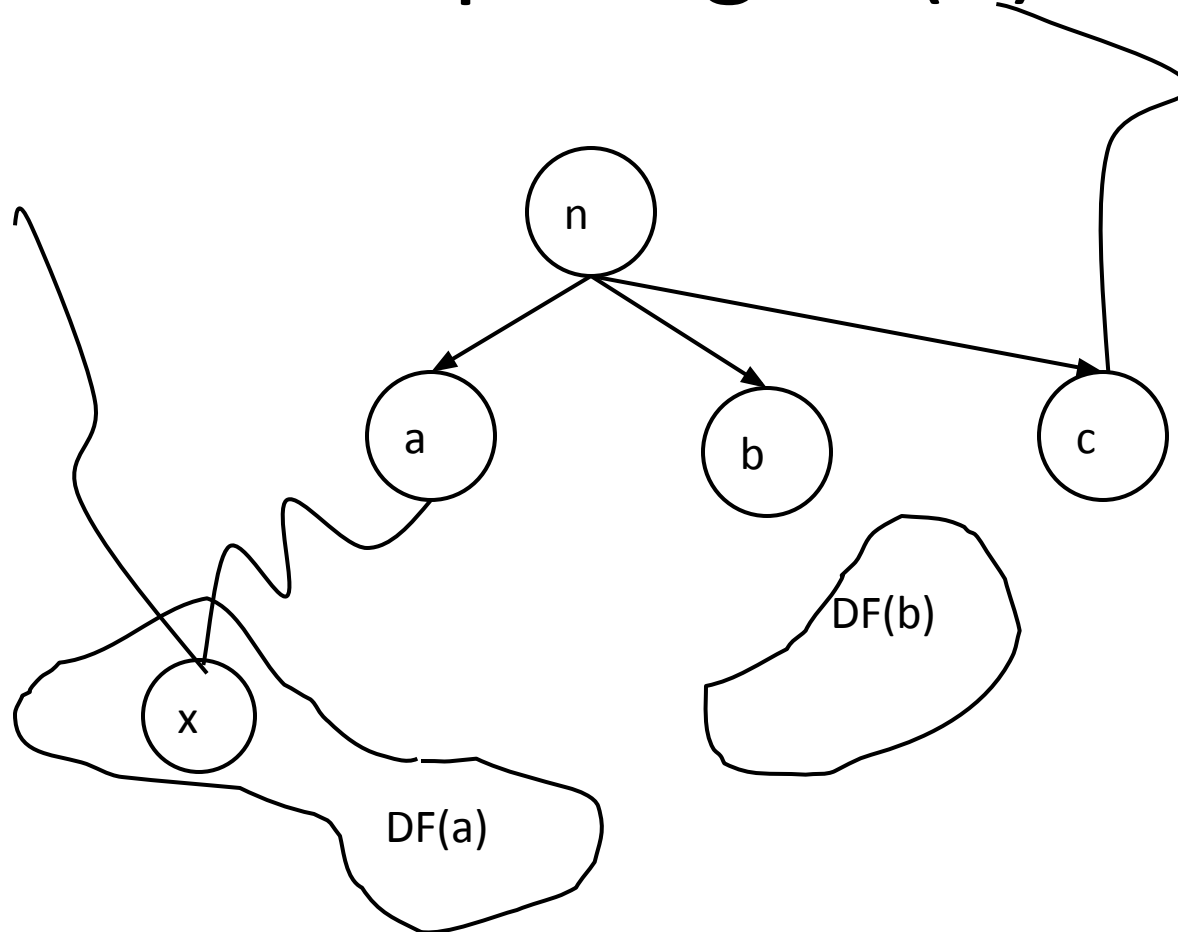


Computing DF(n)



n dom a
n dom b
!n dom c

Computing DF(n)



Computing the Dominance Frontier

compute-DF(n)

$S = \{\}$

foreach node y in succ[n]

if idom(y) $\neq n$

$S = S \cup \{y\}$

foreach child of n , c , in D-tree

compute-DF(c)

foreach w in DF[c]

if ! n dom w

$S = S \cup \{w\}$

DF[n] = S

The **Dominance Frontier** of a node x =
 $\{ w \mid x \text{ dom pred}(w) \text{ AND } !(x \text{ sdom } w) \}$

SSA Properties

- Only 1 assignment per variable
- Definitions dominate uses

Constant Propagation

- If “ $v = c$ ”, replace all uses of v with c
- If “ $v = \Phi(c,c,c)$ ” (each input is the same constant), replace all uses of v with c

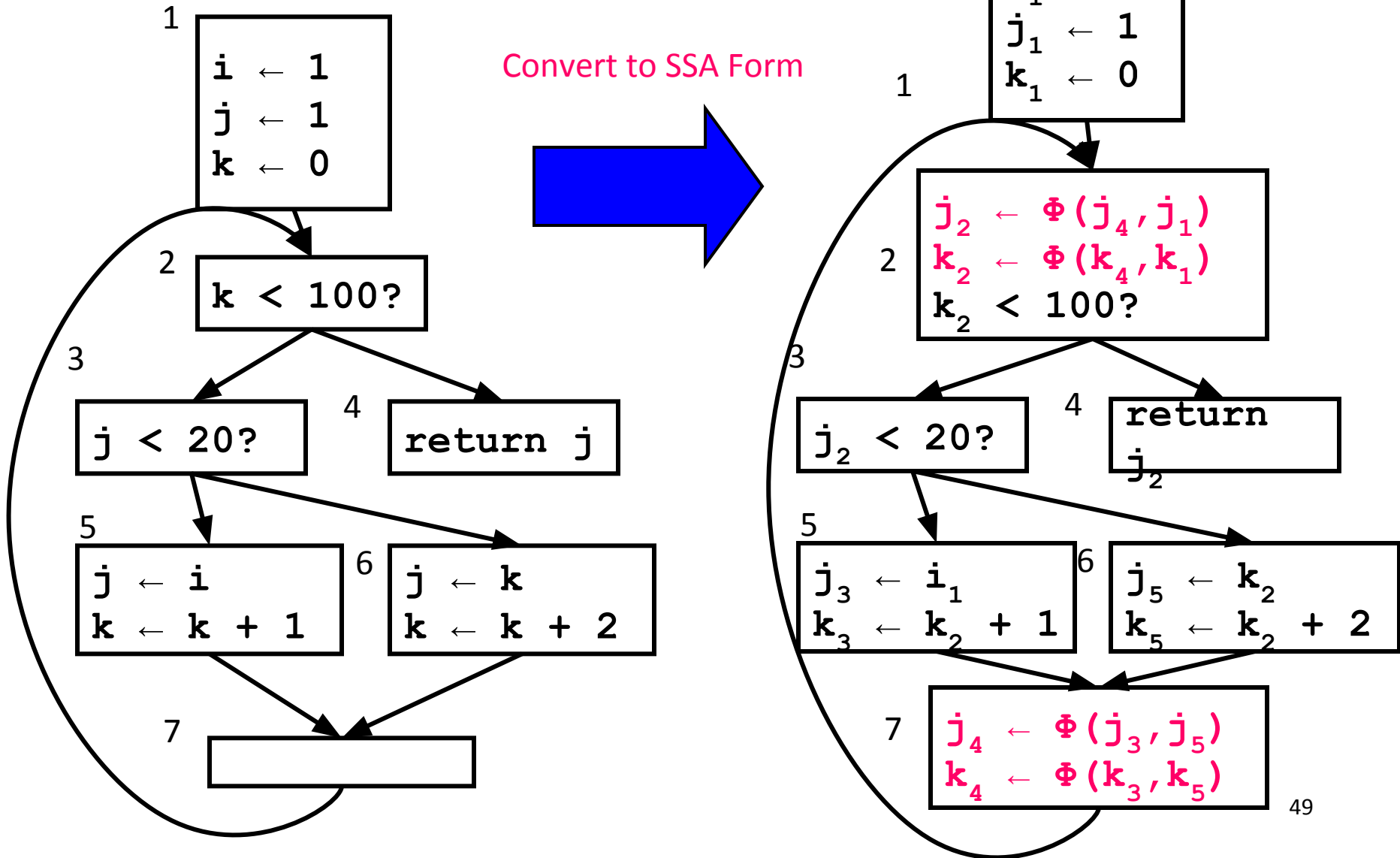
W = list of all defs

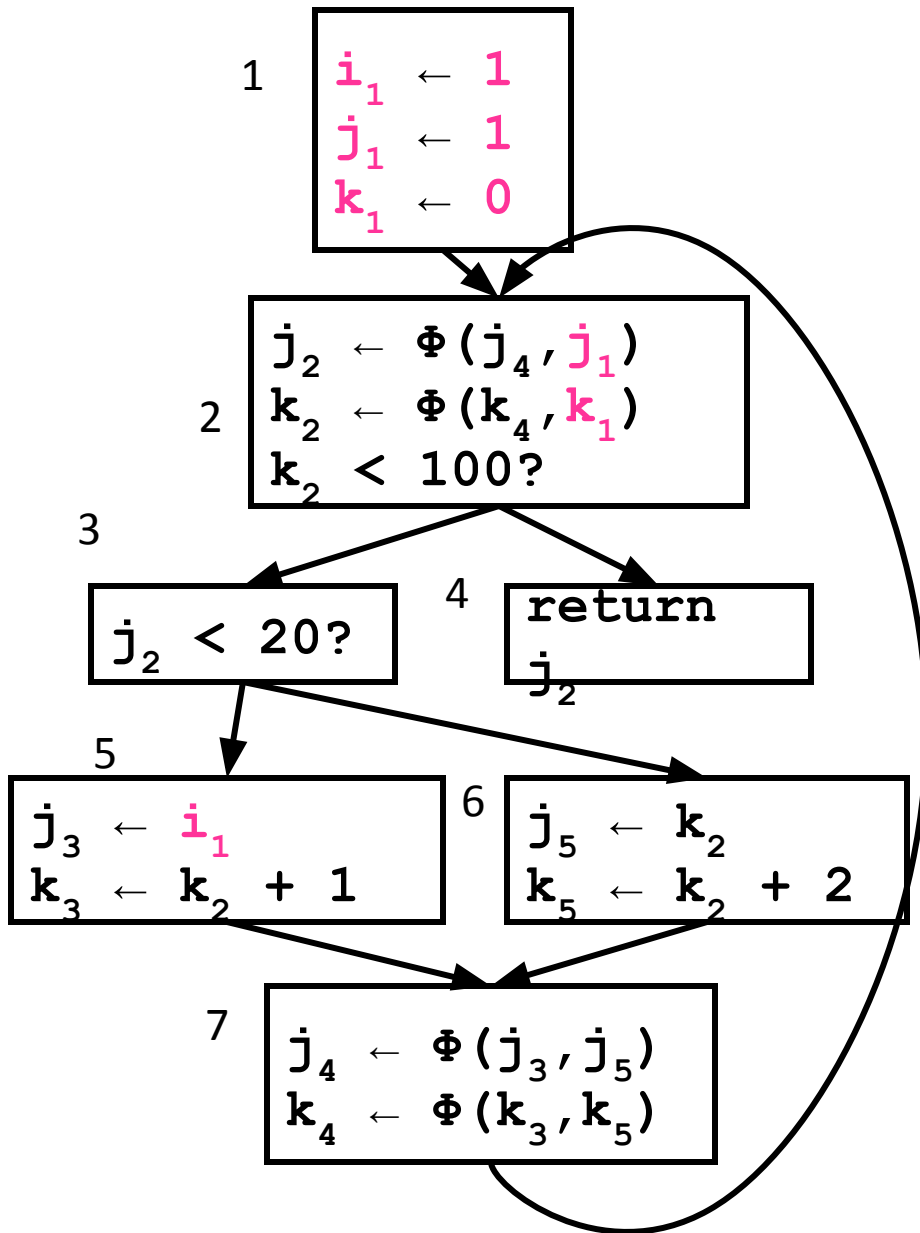
```
while !W.isEmpty {
  Stmt S = W.removeOne
  if ((S has form " $v = c$ ") ||
      (S has form " $v = \Phi(c, \dots, c)$ ")) then {
    delete S
    foreach stmt U that uses v {
      replace v with c in U
    }
    W.add(U)
  }
}
```

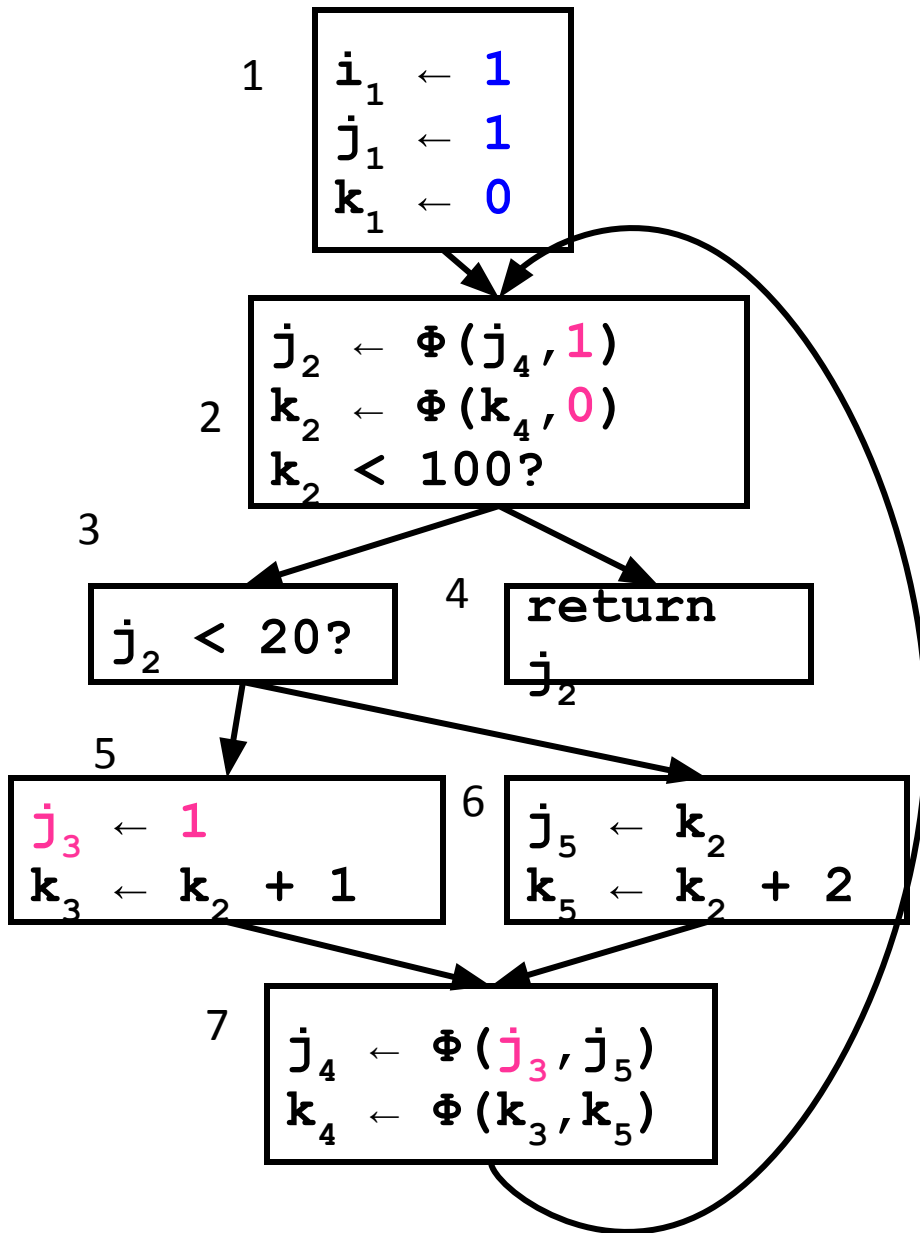
Other Optimizations with SSA

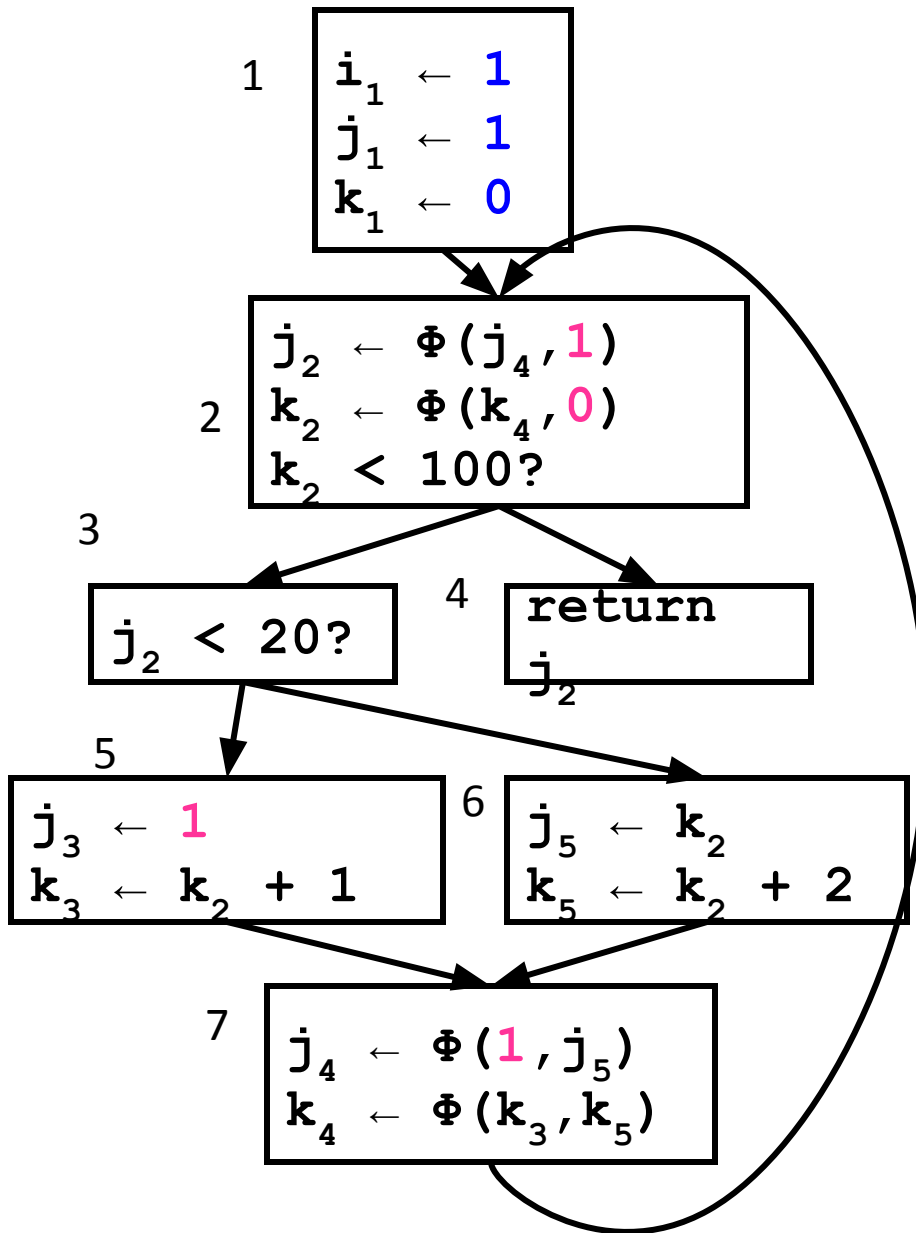
- Copy propagation
 - delete “ $x \stackrel{?}{=} \Phi(y,y,y)$ ” and replace all x with y
 - delete “ $x \stackrel{?}{=} y$ ” and replace all x with y
- Constant Folding
 - (Also, constant conditions too!)

Constant Propagation



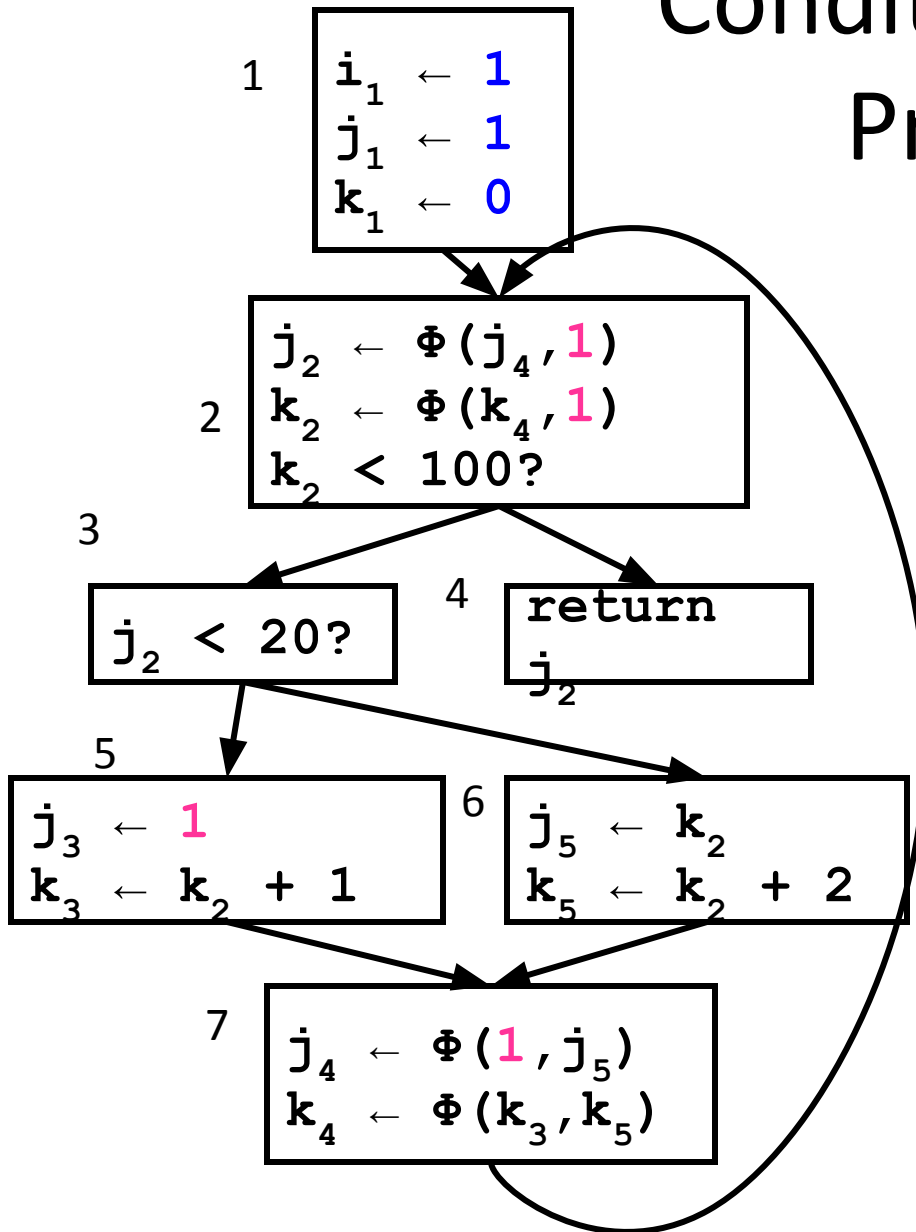






Not a very exciting result (yet)...

Conditional Constant Propagation

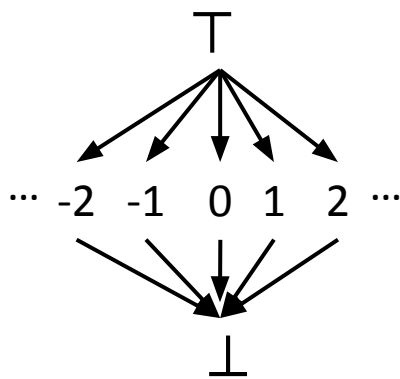


- Does block 6 ever execute?
- Simple Constant Propagation can't tell
- But “Conditional Const. Prop.” *can* tell:
 - Assumes **blocks don't execute until proven otherwise**
 - Assumes **values are constants until proven otherwise**

Conditional Constant Propagation Algorithm

Keeps track of:

- **Blocks**
 - assume unexecuted until proven otherwise
- **Variables**
 - assume not executed (only with proof of assignments of a non-constant value do we assume not constant)
 - Lattice for representing variables:

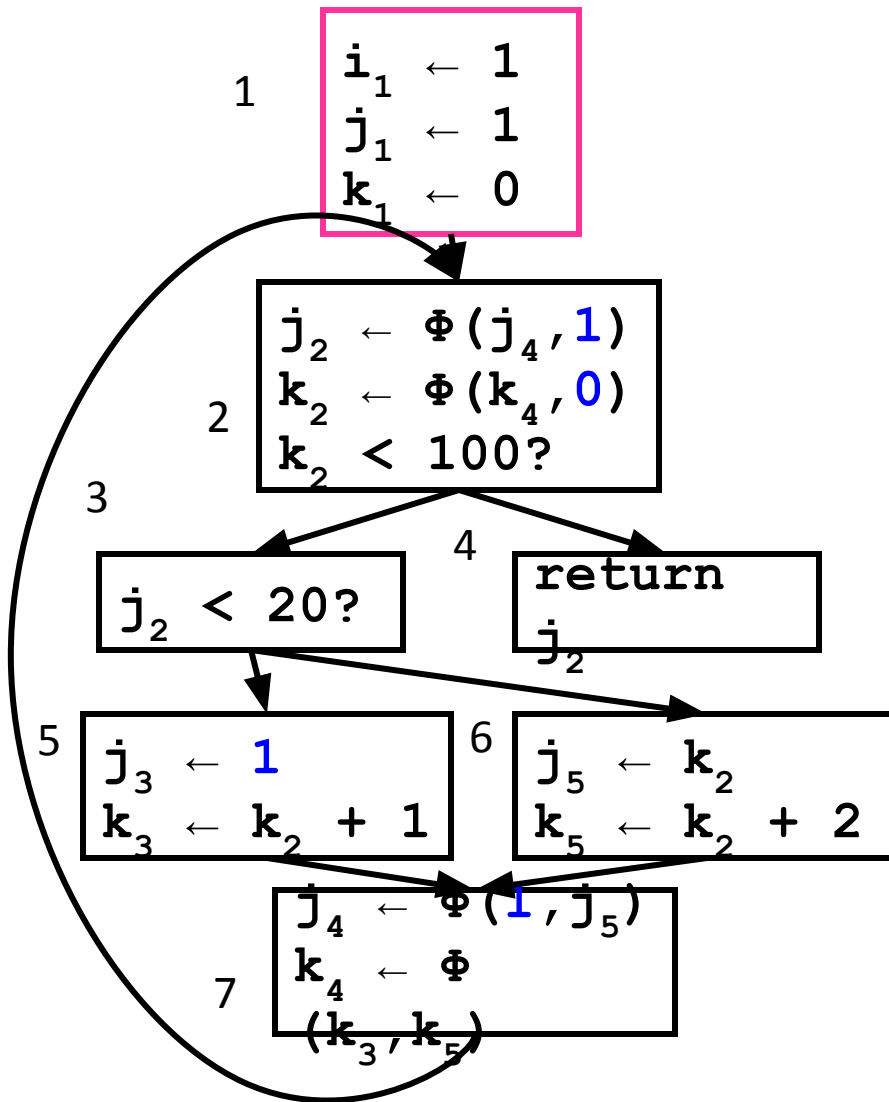


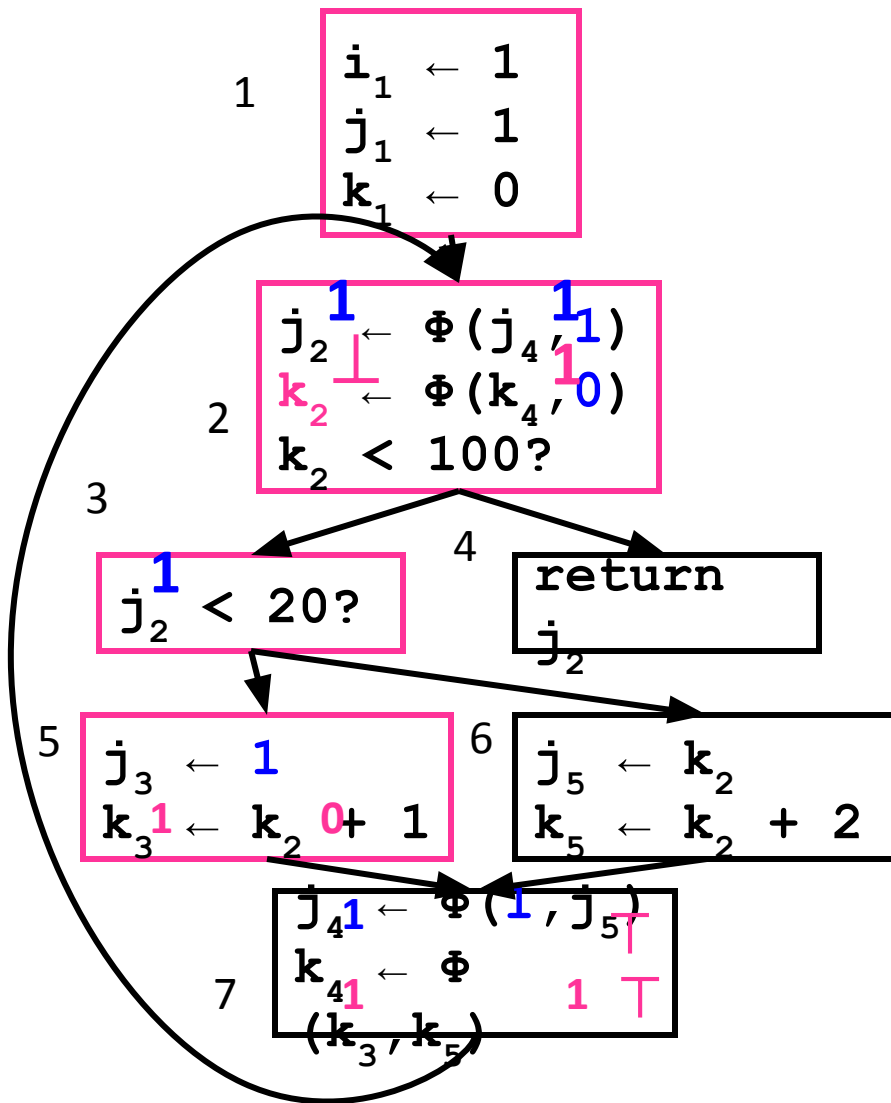
not executed

we have seen **evidence** that the variable has been **assigned a constant** with the value

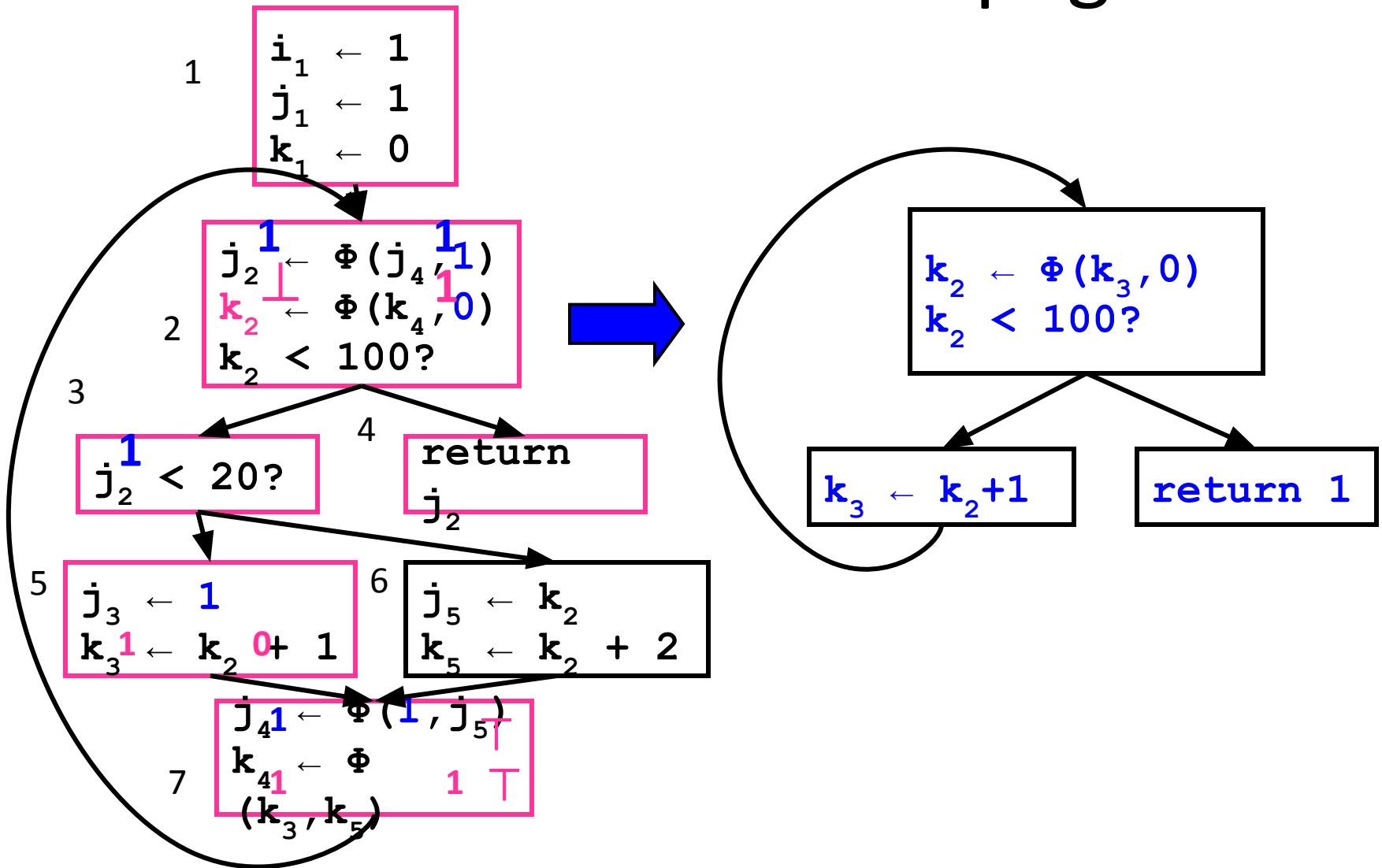
we have seen **evidence** that the variable **can hold different values** at different times

Conditional Constant Propagation





Conditional Constant Propagation



CSC D70: Compiler Optimization Static Single Assignment (SSA)

Prof. Gennady Pekhimenko

University of Toronto

Winter 2020

*The content of this lecture is adapted from the lectures of
Todd Mowry and Phillip Gibbons*

Backup Slides