EECS483 D13: SSA Example

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April 12, 2013

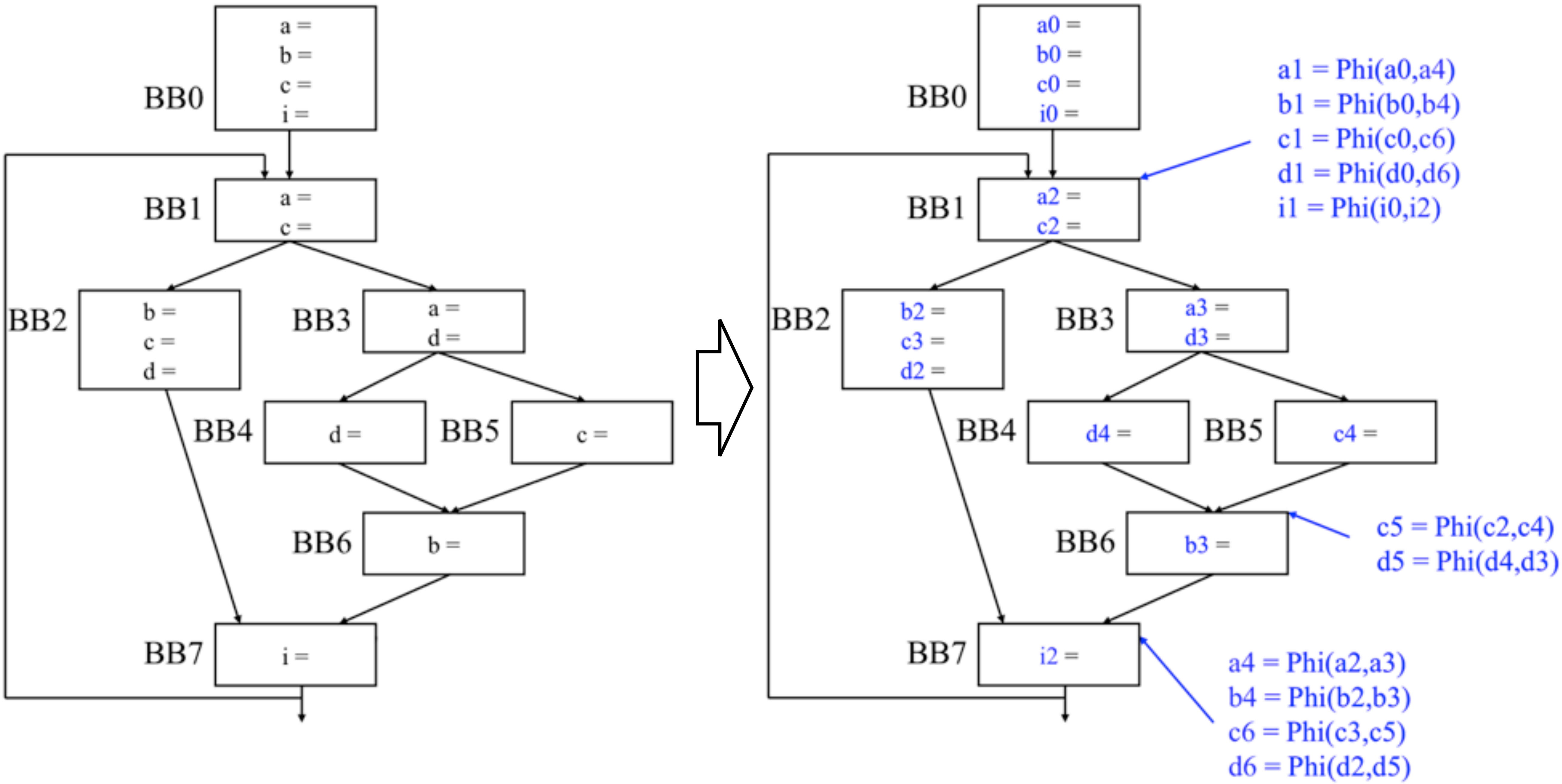
Announcements

- Homework 5 on CTools
  - Due on 4/22

Static Single Assignment Form

- Each variable is given a unique name when it is assigned to a new value
- All of the uses of this assignment are renamed accordingly
- Phi nodes: a special multiplexer that choose a value from its arguments

SSA Conversion (1/2)



a1 = Phi(a0,a4)
b1 = Phi(b0,b4)
c1 = Phi(c0,c6)
d1 = Phi(d0,d6)
i1 = Phi(i0,i2)

c5 = Phi(c2,c4)
d5 = Phi(d4,d3)

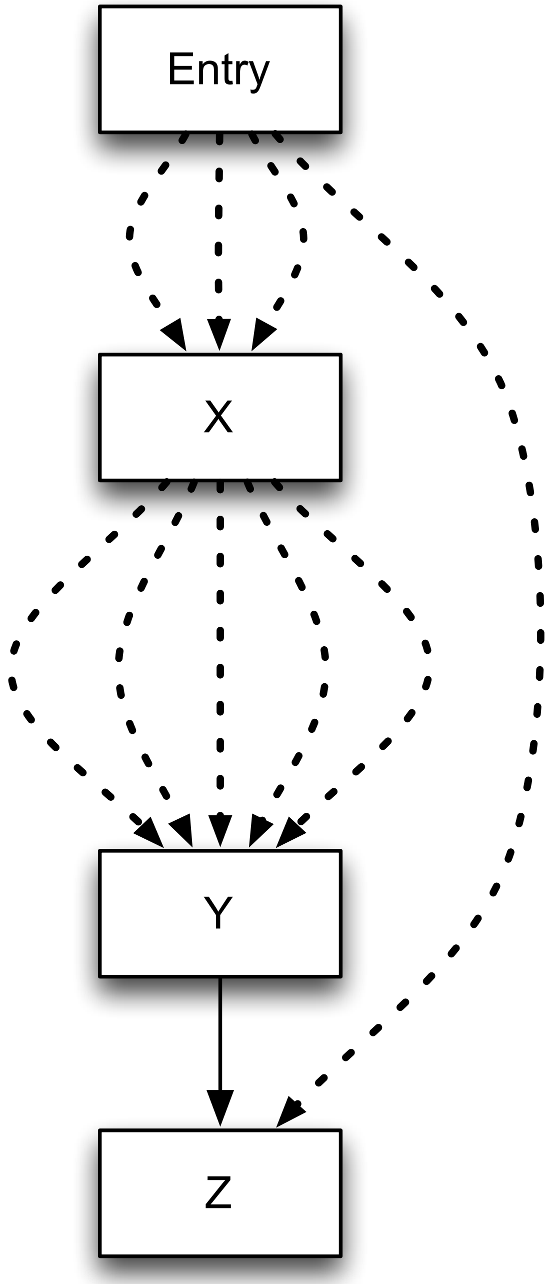
a4 = Phi(a2,a3)
b4 = Phi(b2,b3)
c6 = Phi(c3,c5)
d6 = Phi(d2,d5)

SSA Conversion (2/2)

- Dominator analysis
  - Find the dominator frontier set DF(BB) for each basic block BB
- Phi node insertion
  - If variable x is defined in BB, then a Phi node of x is needed in each basic block in DF(BB)
- Variable renaming
  - Rename variables in each assignment (including Phi node) and all their uses

Dominator Analysis (1/2)

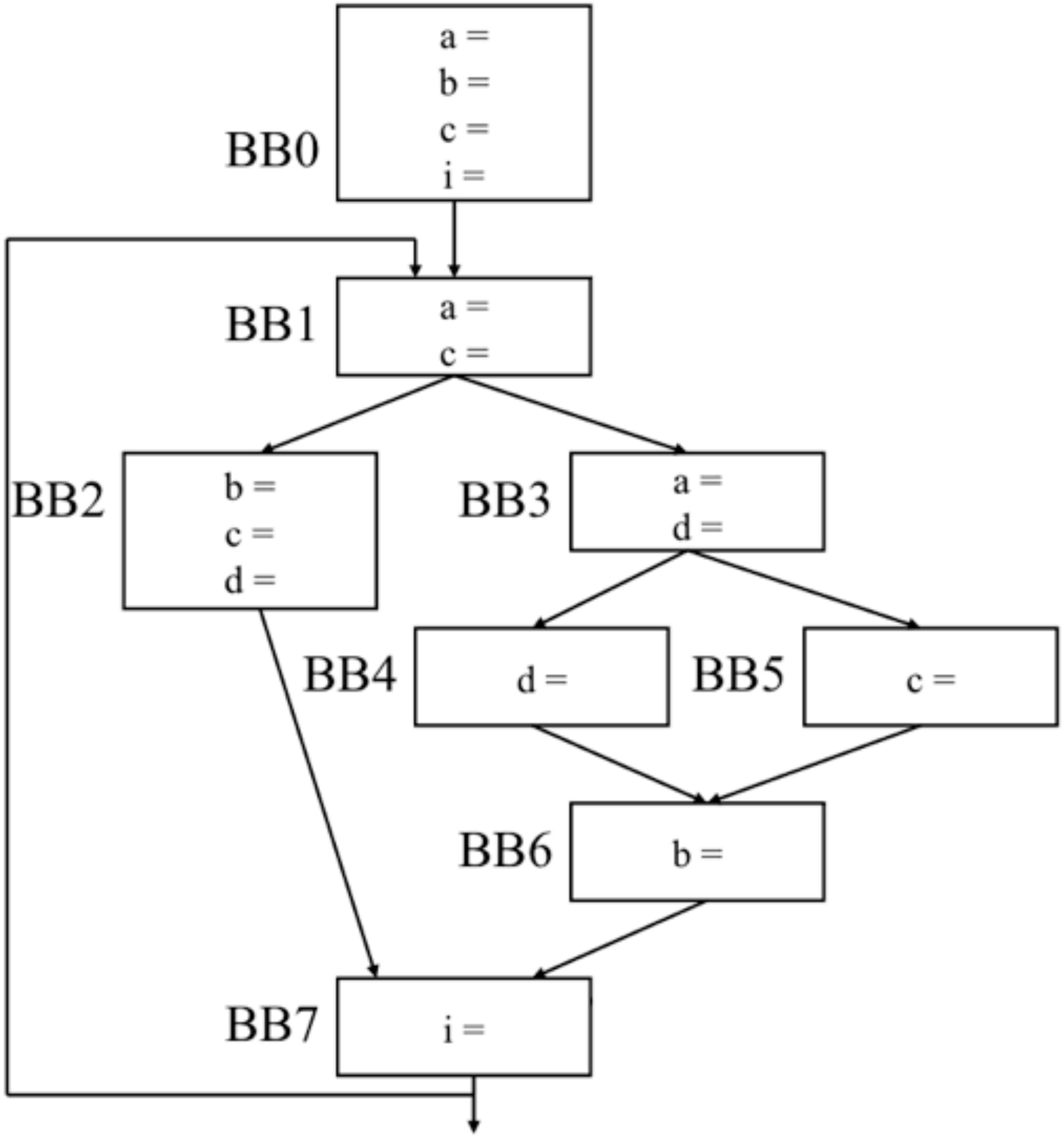
- X dominates Y if every path from entry to Y contains X
  - X dominates X itself
- Z is a dominance frontier of X if X dominates a predecessor Y of Z but not Z
  - The first BB that is not dominated by X
- If variable a is defined in X
  - Uses of a in Y refer to the definition in X
  - Uses of a in Z don't necessary refer to the definition in X
    - Need a Phi node for a!



Dominator Analysis (2/2)

- Dom(X) = Intersection(Dom(predecessors of X))
- Compute dominators
  - Initialization
    - Dom(Entry) = {Entry}
    - Dom(X) = {all nodes} for all other X
  - While(change):
    - Update Dom(X) for each X
- Compute dominance frontiers
  - for each Z
    - for each predecessor Y of Z
      - for each X in Dom(Y) - Dom(Z)
        - » Put Z into DF(X)

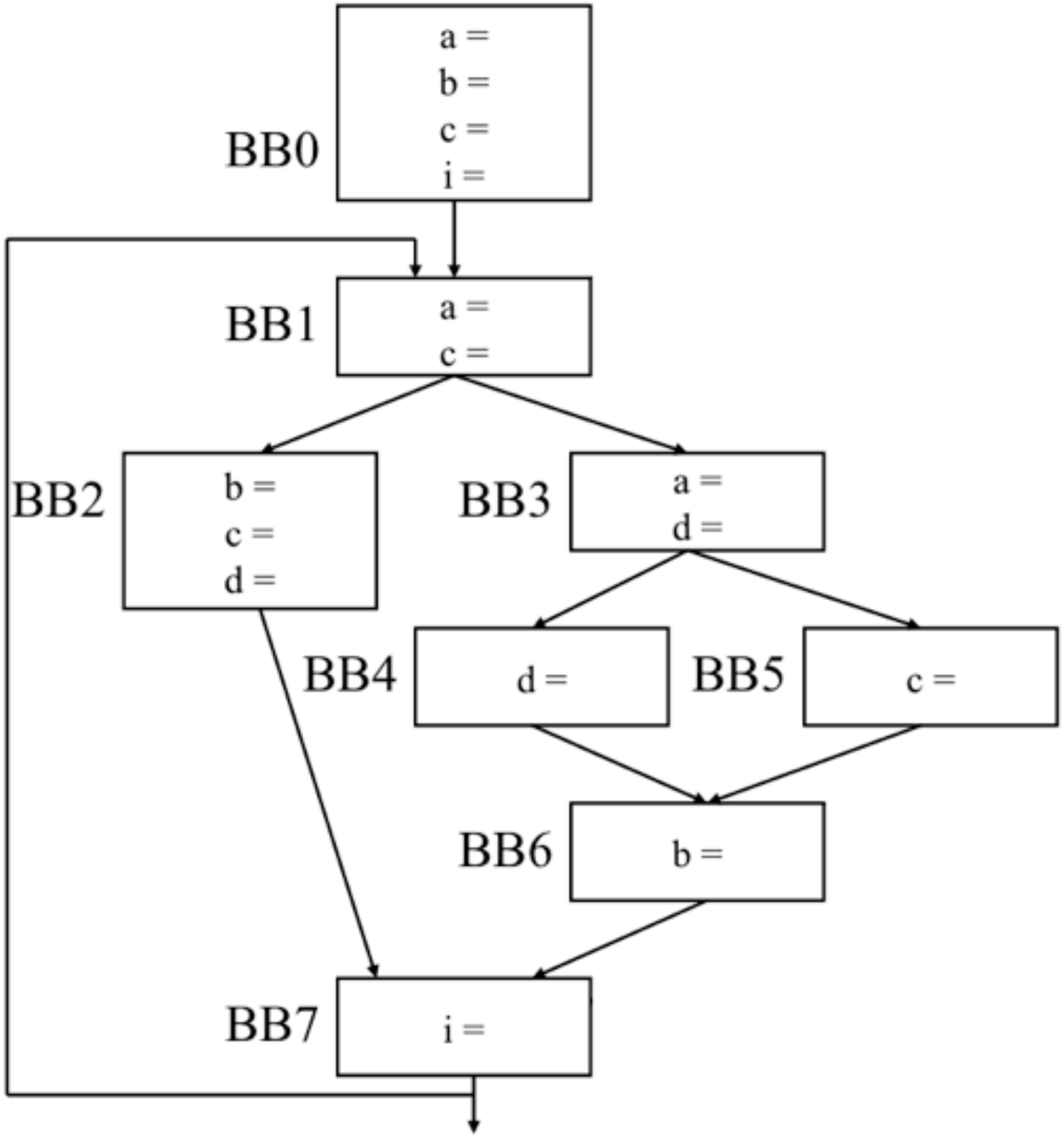
Dominator Analysis: Example



BB	Dom	DF
0		
1		
2		
3		
4		
5		
6		
7		

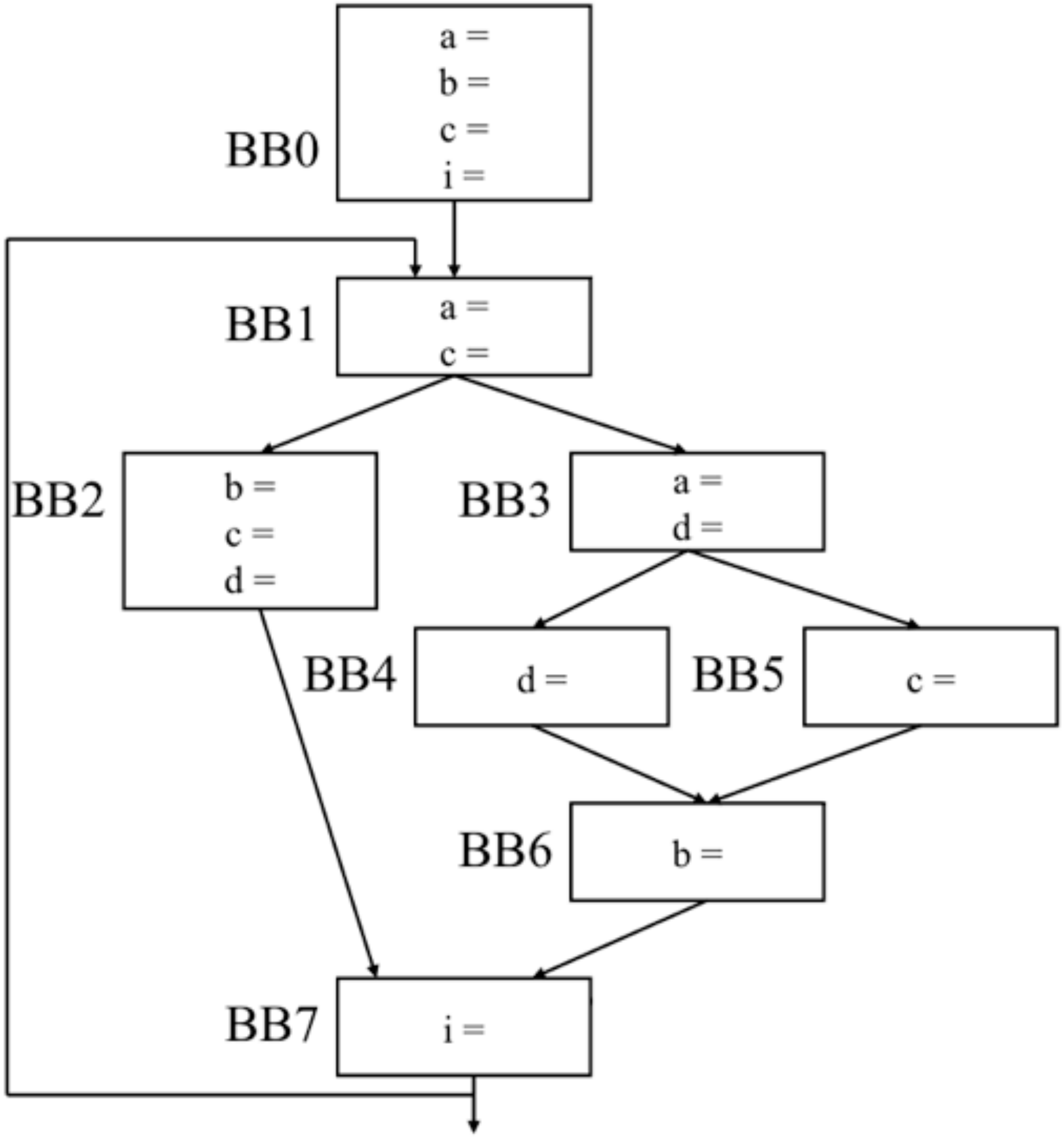
This example comes from Prof. Mahlke's EECS583 slides.

Dominator Analysis: Example



BB	Dom	DF
0	0	
1	0, 1	
2	0, 1, 2	
3	0, 1, 3	
4	0, 1, 3, 4	
5	0, 1, 3, 5	
6	0, 1, 3, 6	
7	0, 1, 7	

Dominator Analysis: Example

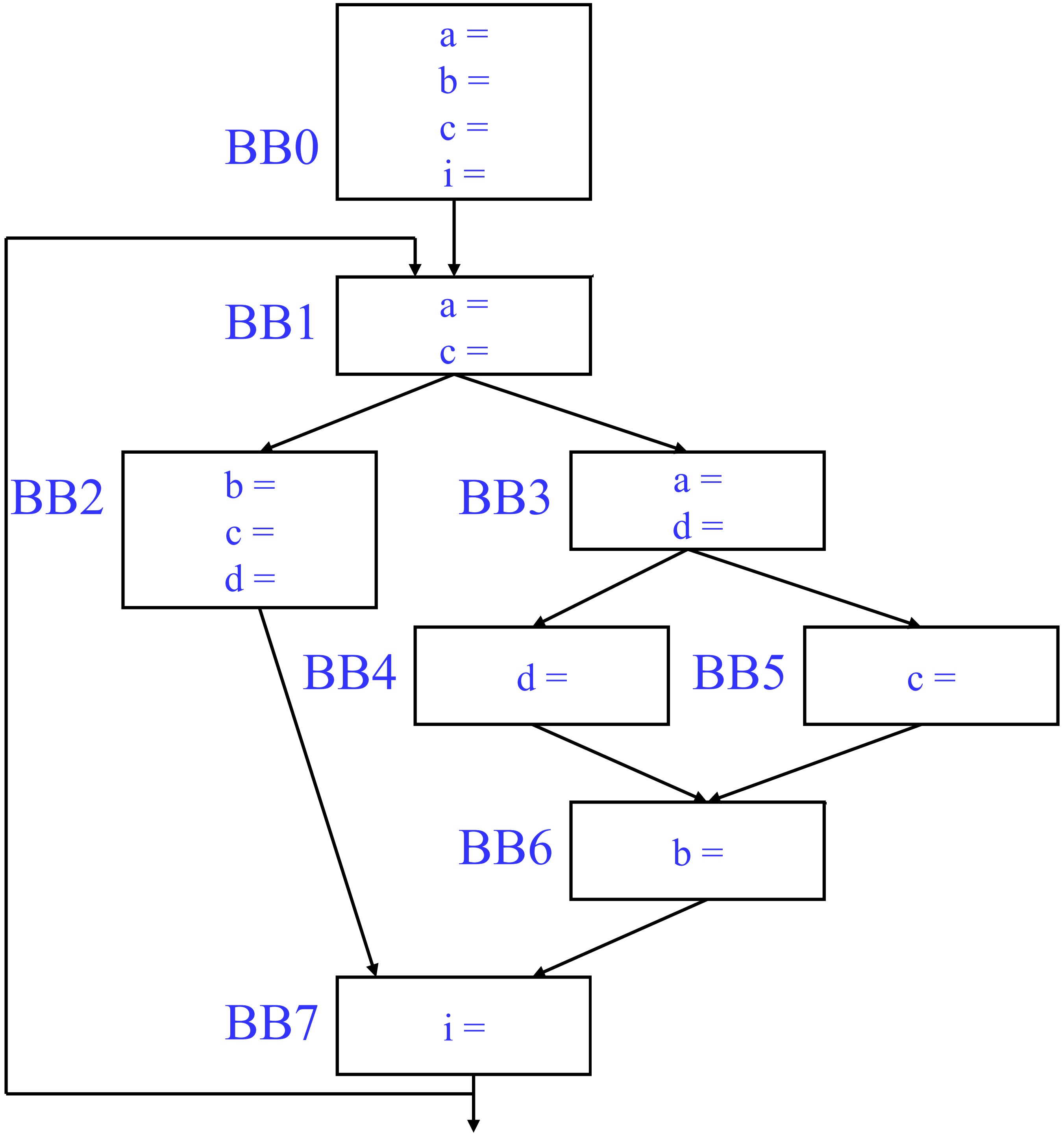


BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

Phi Node Insertion

- Liveness analysis
  - IN(BB): variables used in BB but defined elsewhere
  - KILL(BB): variables defined in BB
- Algorithm
  - for each variable v in IN(BB) for some BB
    - Def(v) = {BB : v ∊ KILL(BB)}
    - for each BB ∊ in Def(v)
      - Insert a Phi node for a in DF(BB)
      - Add BB into Def(v)

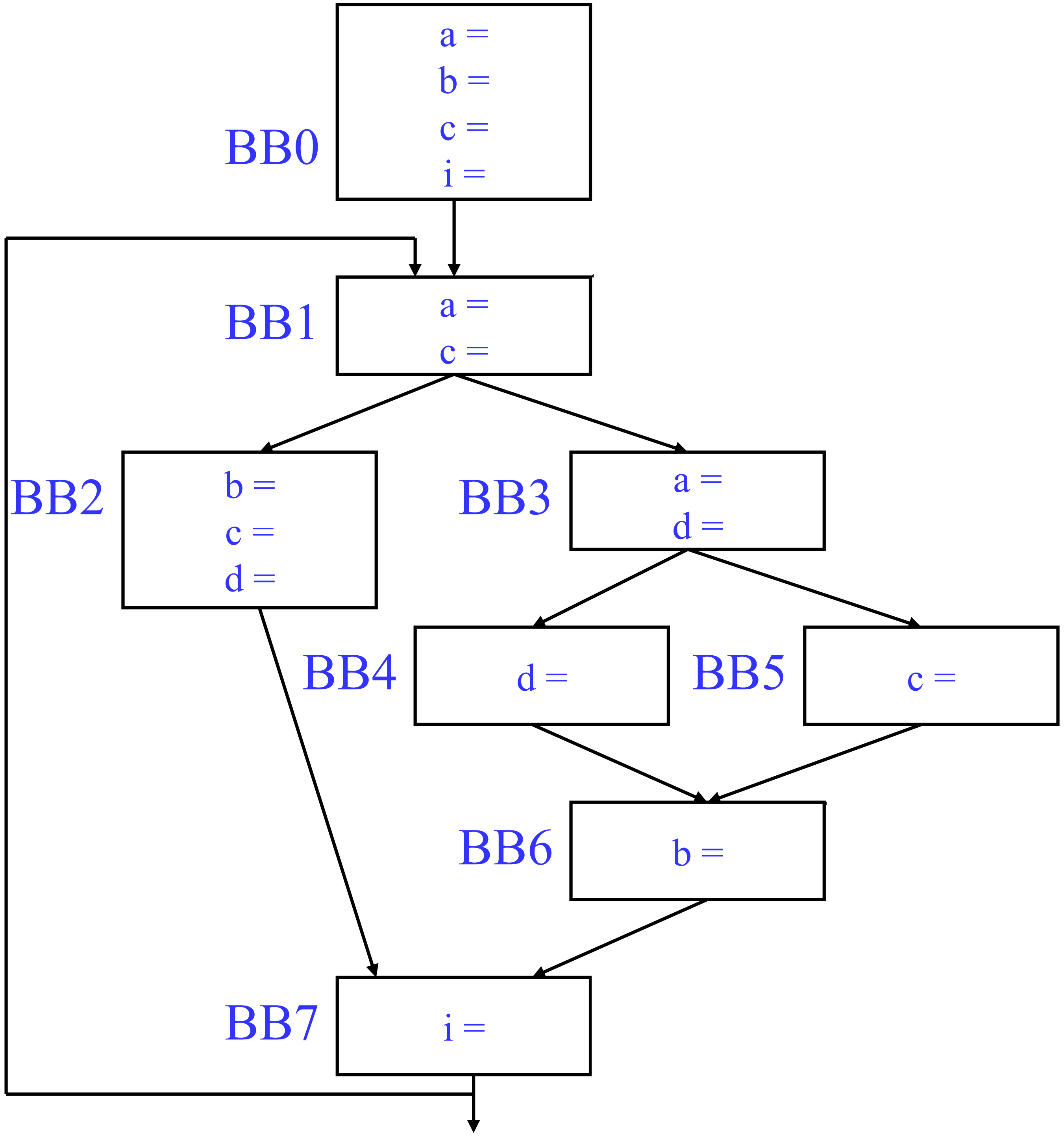
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	
b	
c	
d	
i	

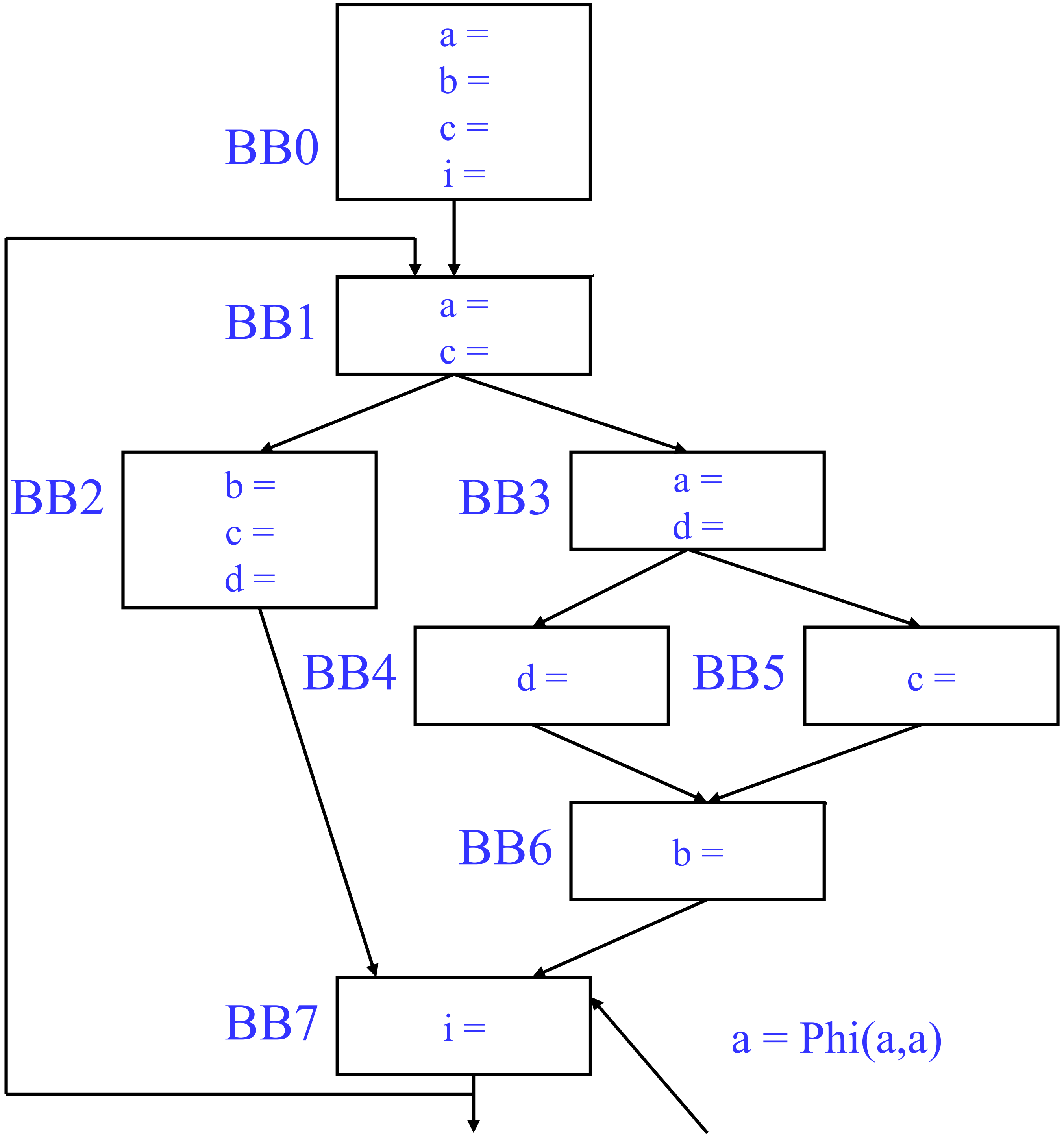
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3
b	
c	
d	
i	

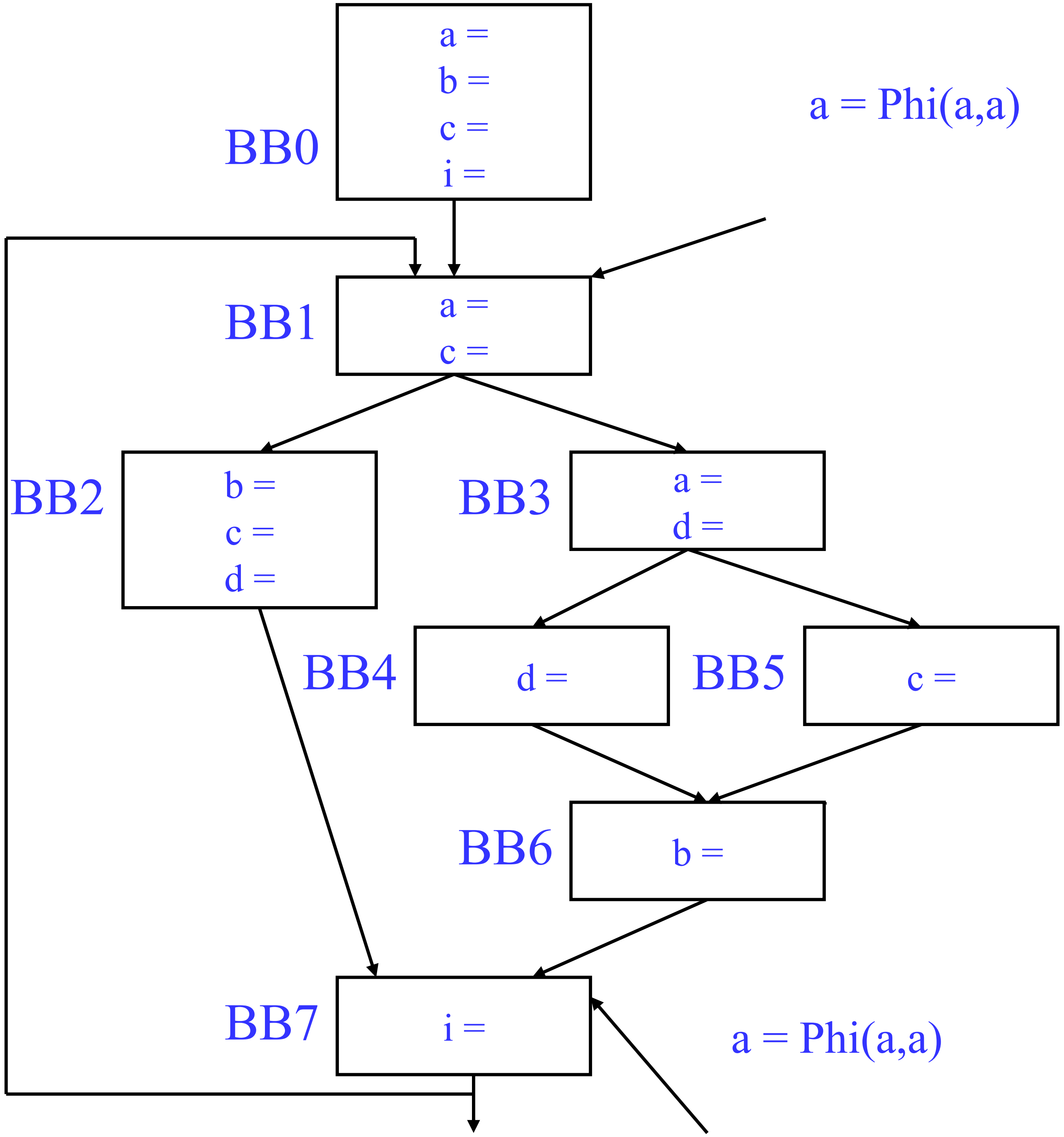
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	
c	
d	
i	

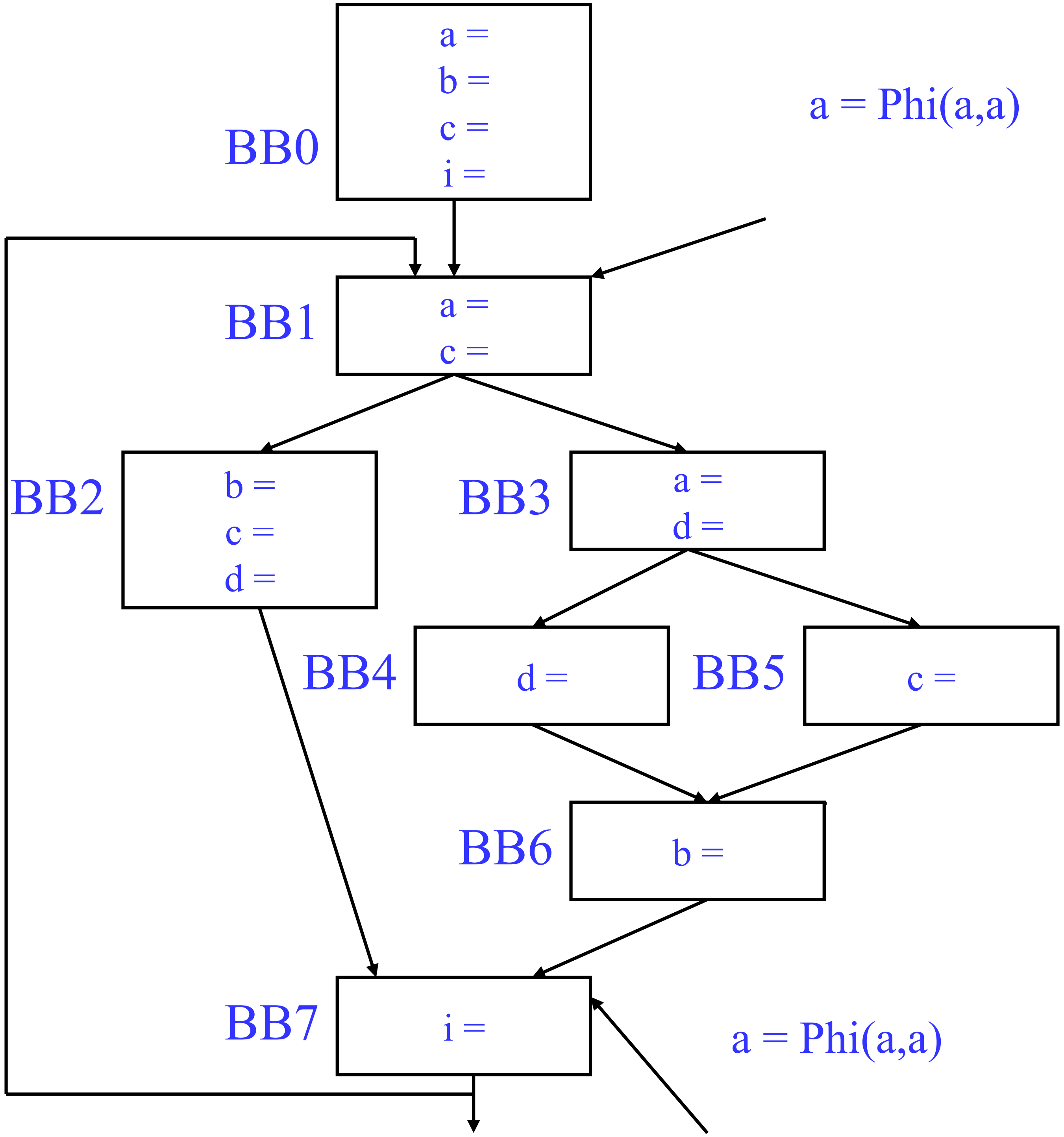
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	
c	
d	
i	

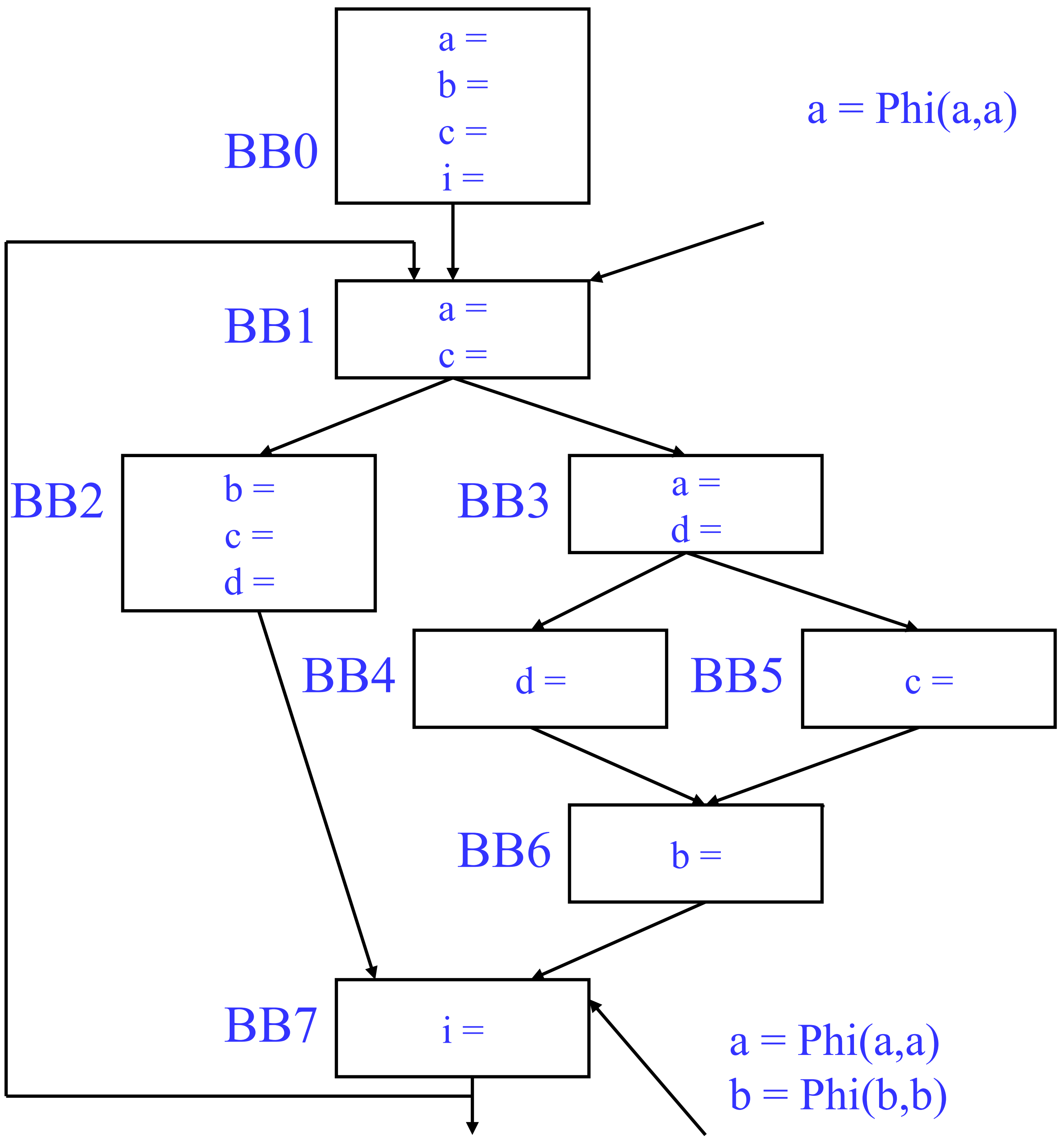
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6
c	
d	
i	

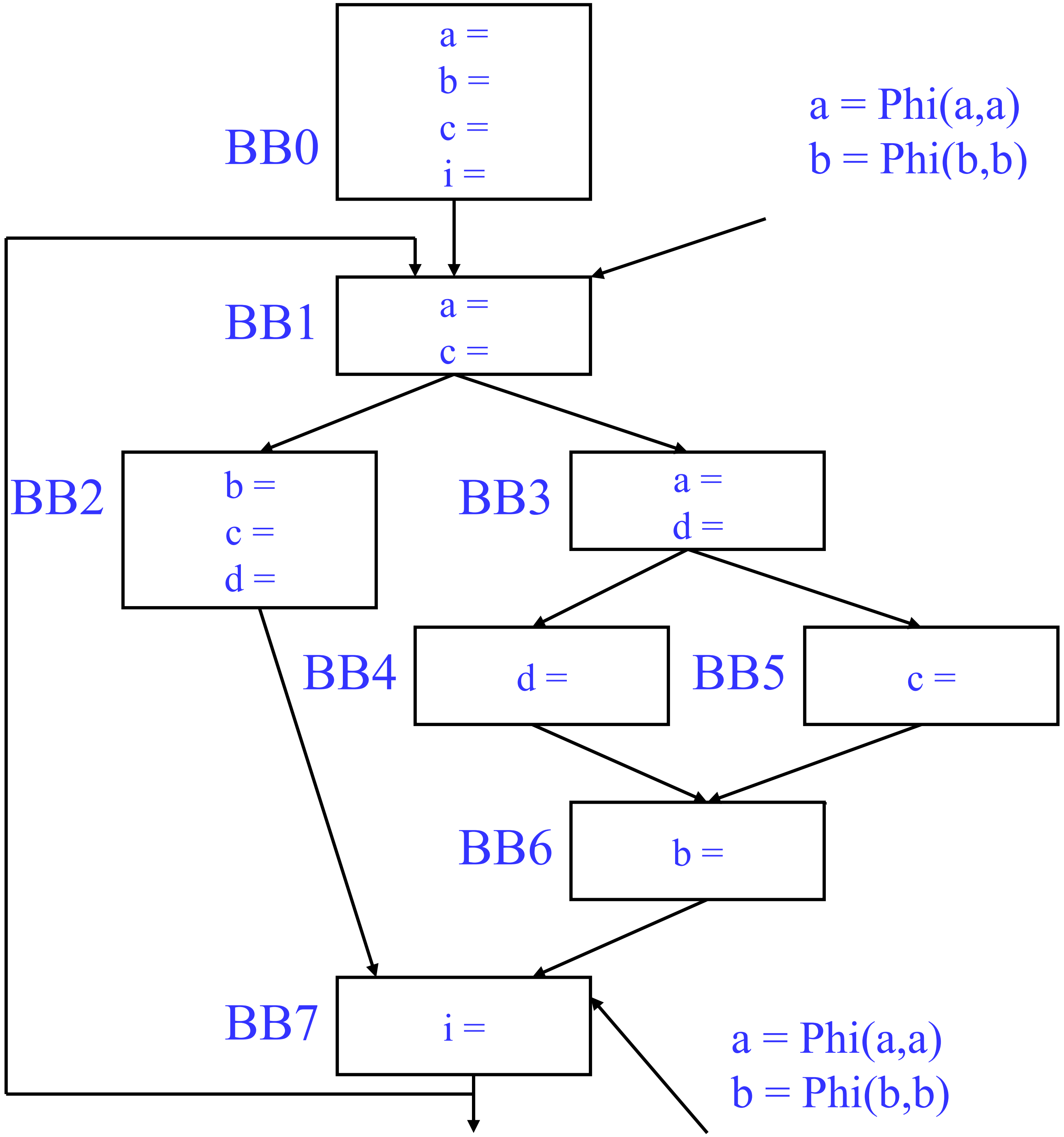
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6, 7
c	
d	
i	

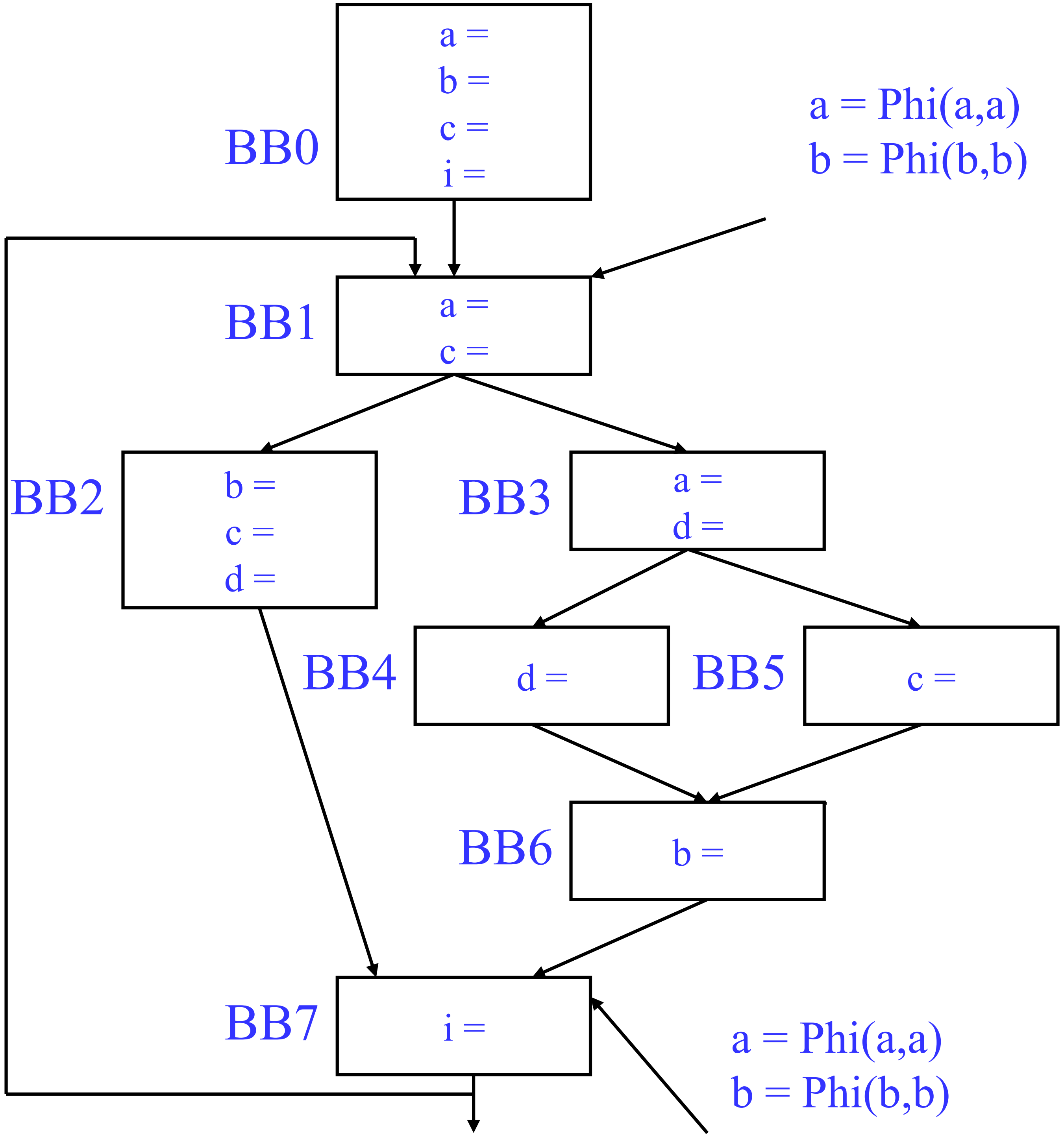
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6, 7, 1
c	
d	
i	

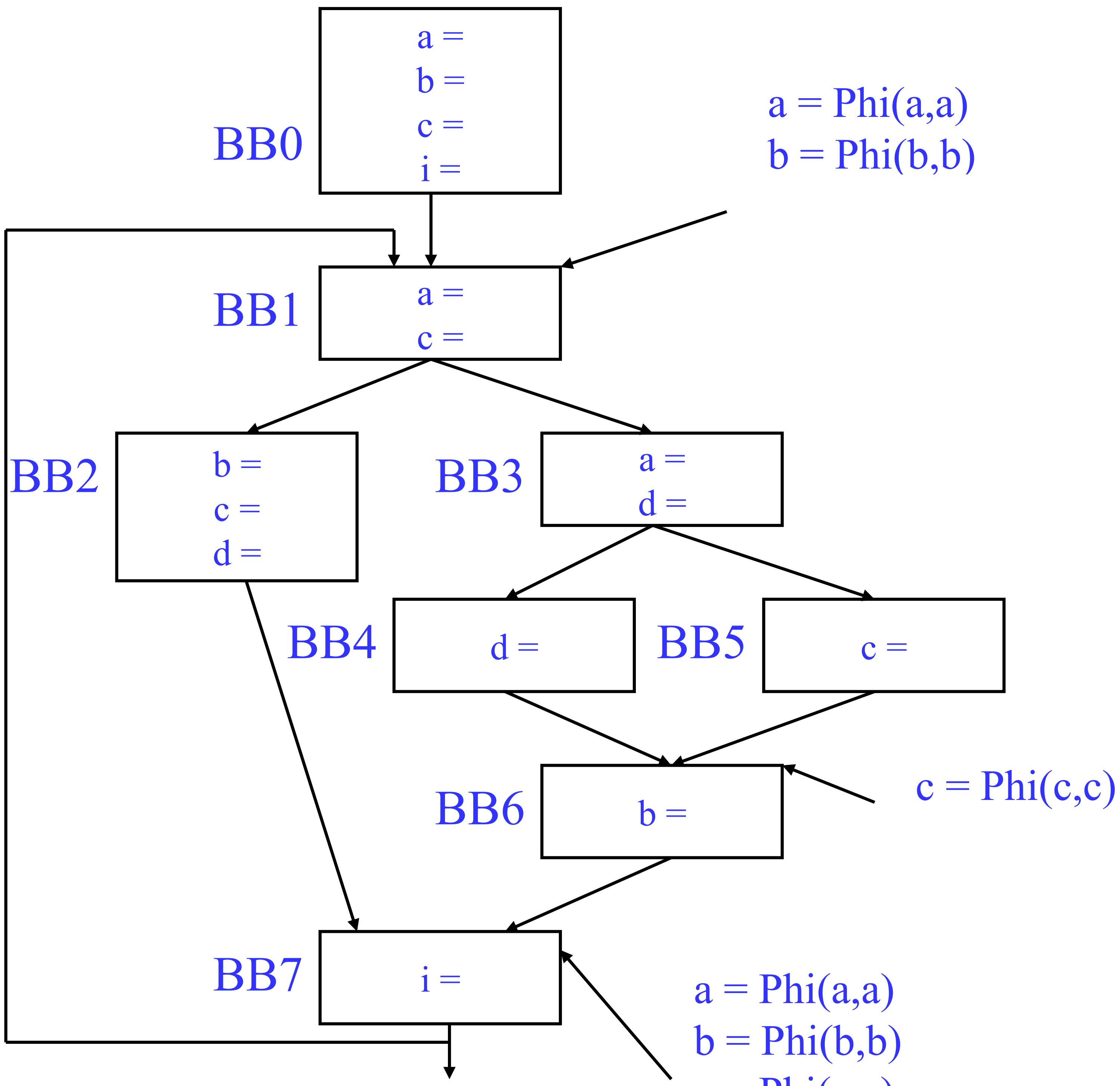
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6, 7, 1
c	0, 1, 2, 5
d	
i	

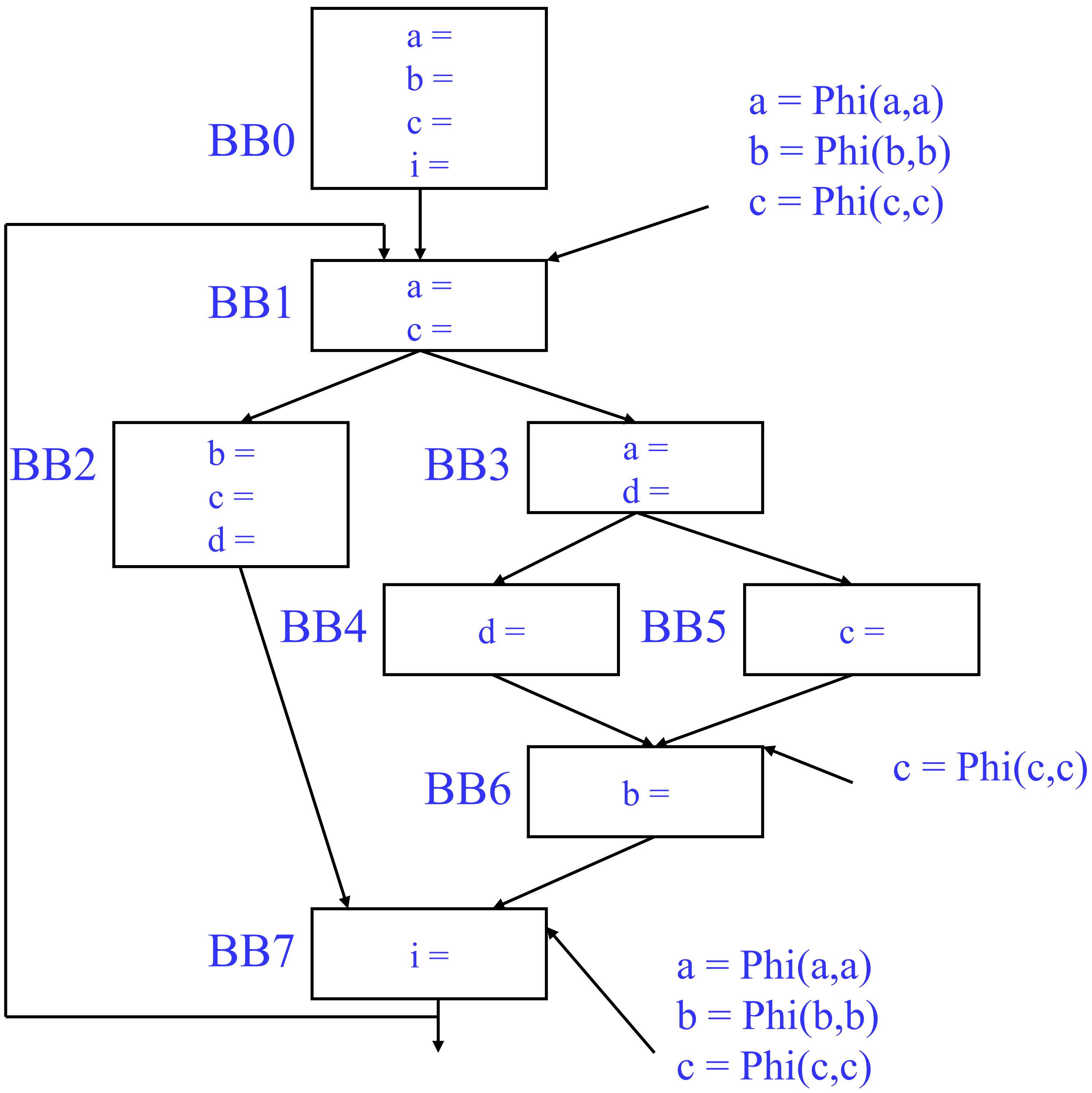
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6, 7, 1
c	0, 1, 2, 5, 7, 6
d	
i	

Phi Node Insertion: Example



BB0
a =
b =
c =
i =

a = Phi(a,a)
b = Phi(b,b)
c = Phi(c,c)

BB1
a =
c =

BB2
b =
c =
d =

BB3
a =
d =

BB4
d =

BB5
c =

BB6
b =

c = Phi(c,c)

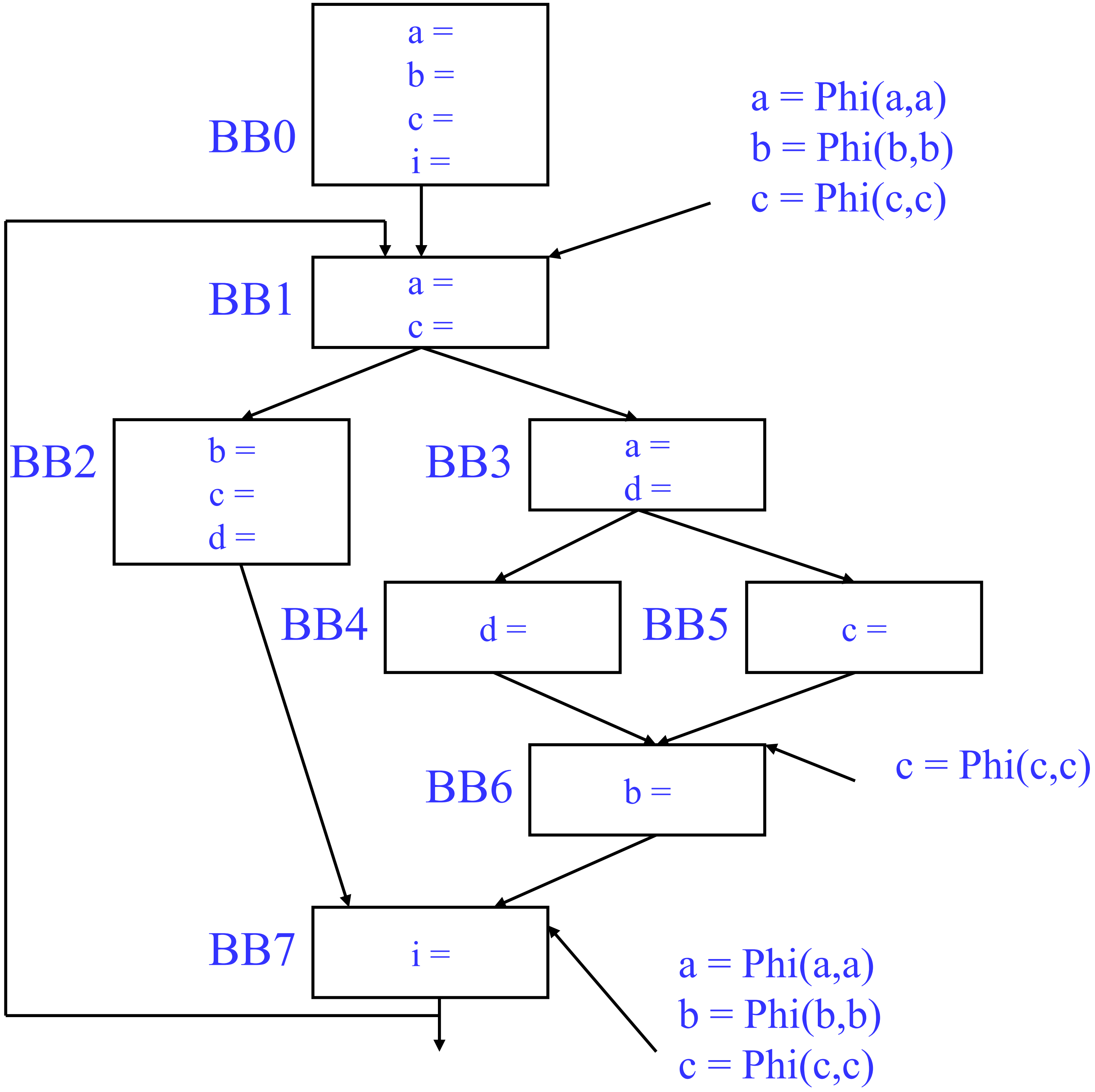
BB7
i =

a = Phi(a,a)
b = Phi(b,b)
c = Phi(c,c)

BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6, 7, 1
c	0, 1, 2, 5, 7, 6
d	
i	

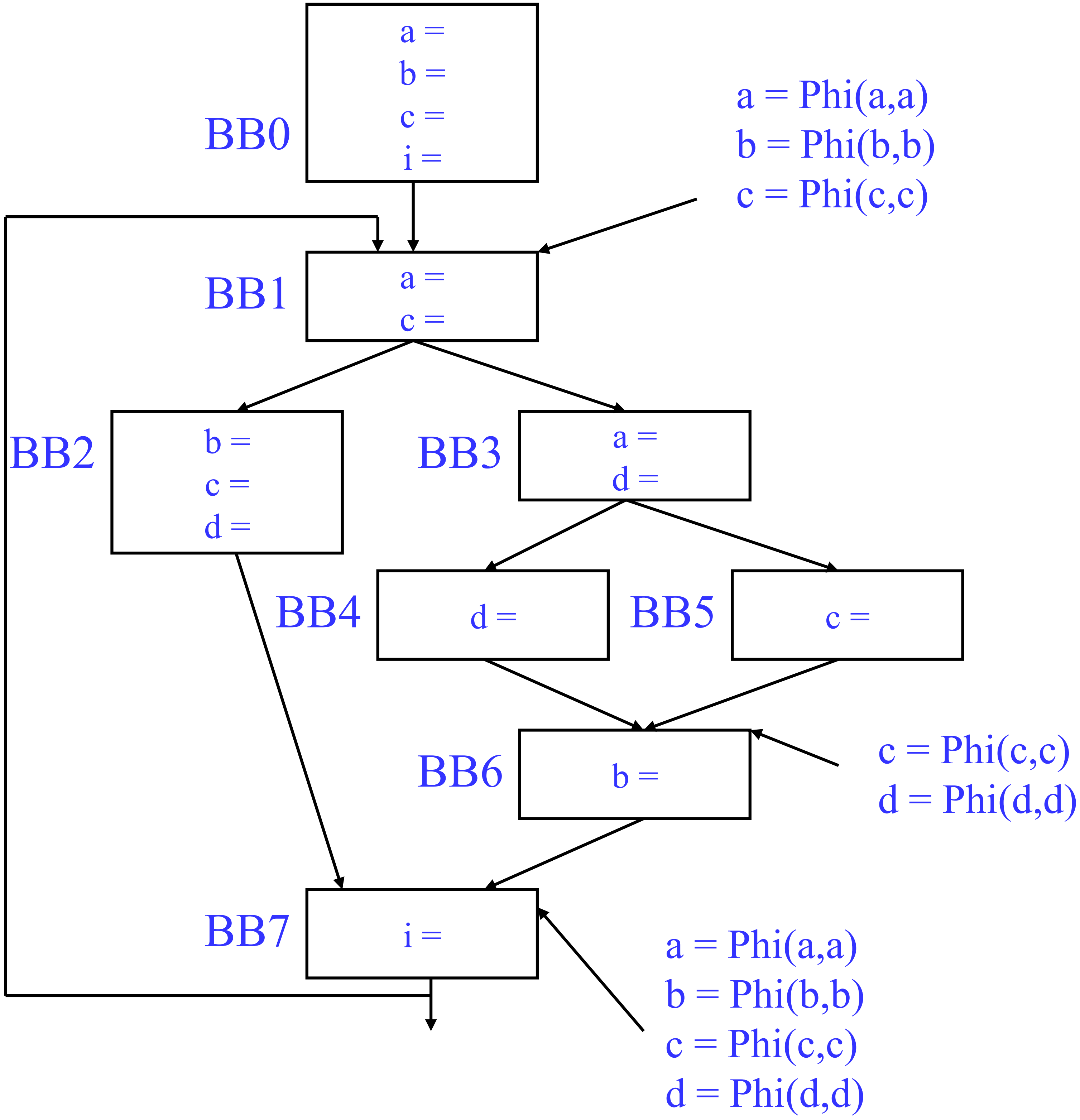
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6, 7, 1
c	0, 1, 2, 5, 7, 6
d	2, 3, 4
i	

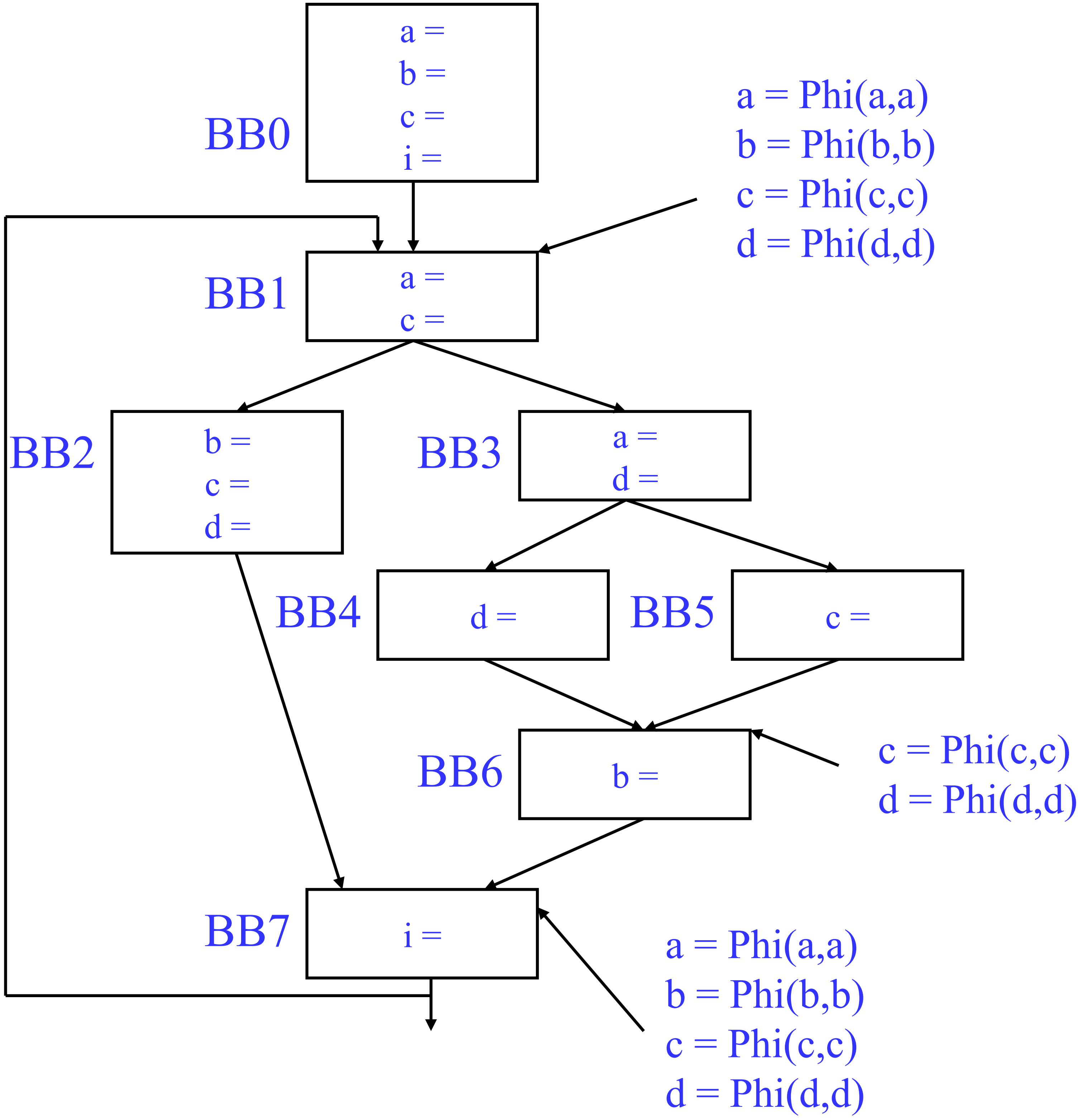
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6, 7, 1
c	0, 1, 2, 5, 7, 6
d	2, 3, 4, 7, 6
i	

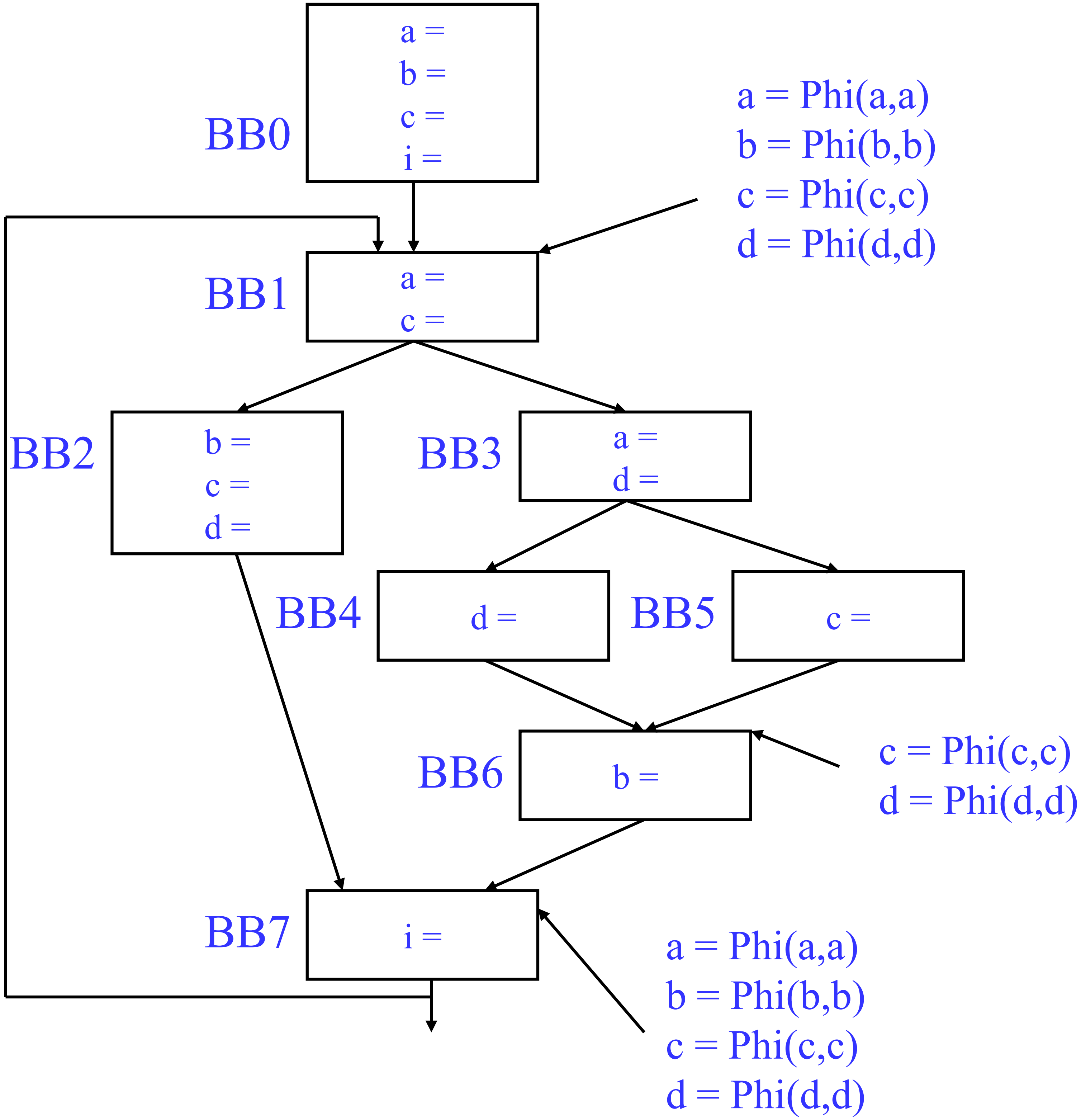
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6, 7, 1
c	0, 1, 2, 5, 7, 6
d	2, 3, 4, 7, 6, 1
i	

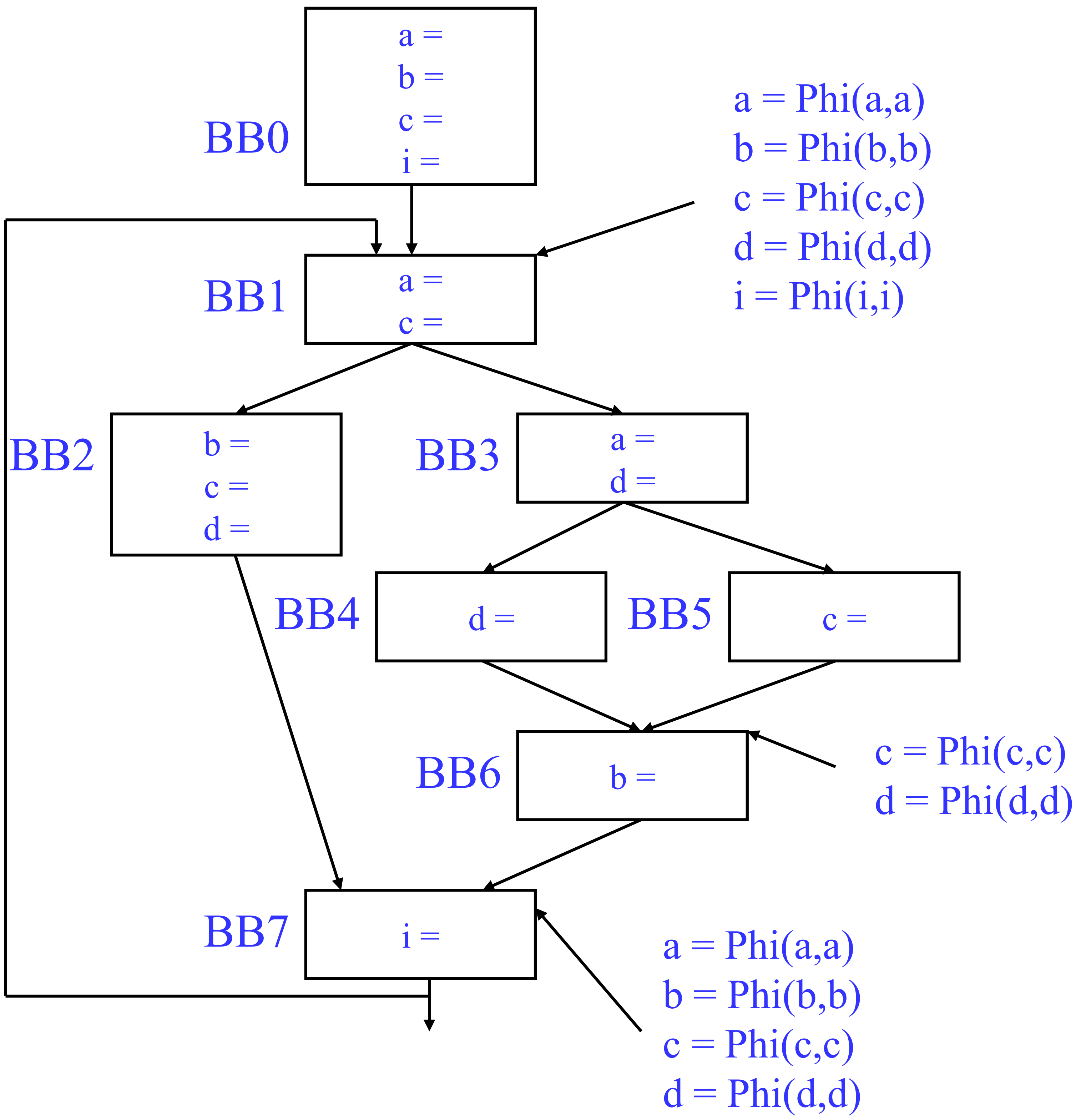
Phi Node Insertion: Example



BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6, 7, 1
c	0, 1, 2, 5, 7, 6
d	2, 3, 4, 7, 6, 1
i	7

Phi Node Insertion: Example

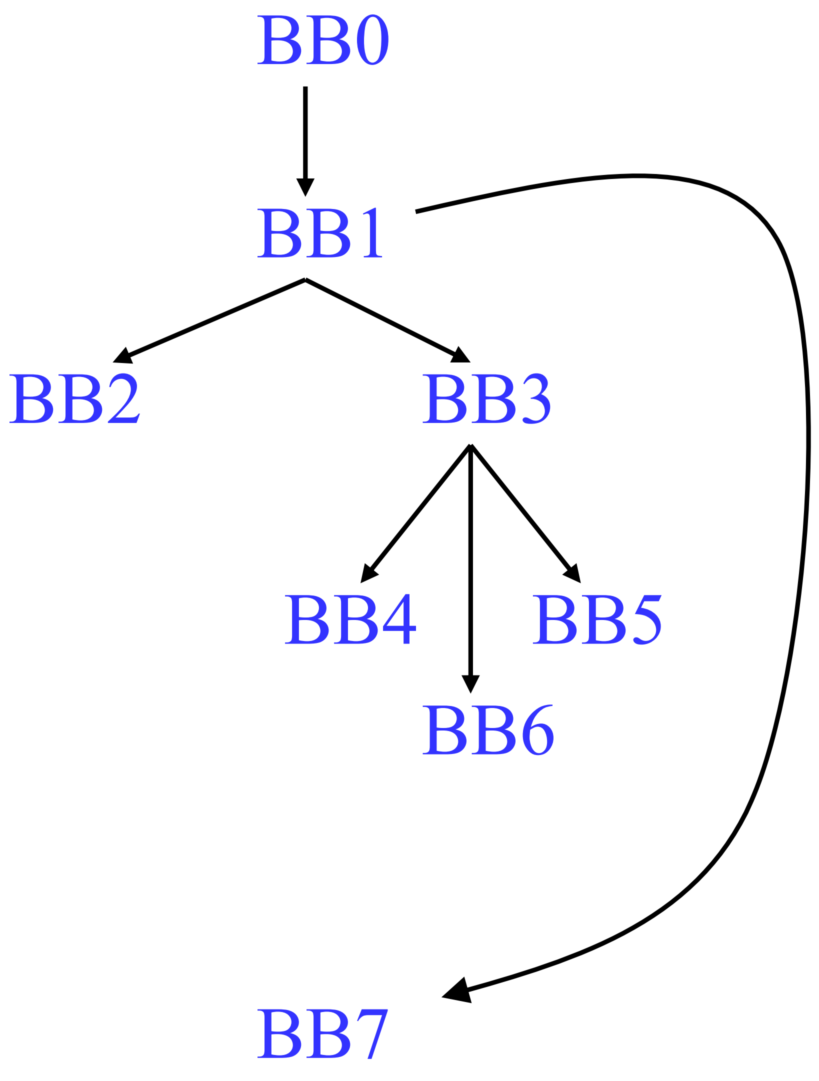


BB	Dom	DF
0	0	-
1	0, 1	-
2	0, 1, 2	7
3	0, 1, 3	7
4	0, 1, 3, 4	6
5	0, 1, 3, 5	6
6	0, 1, 3, 6	7
7	0, 1, 7	1

variable	Def
a	0, 1, 3, 7
b	0, 2, 6, 7, 1
c	0, 1, 2, 5, 7, 6
d	2, 3, 4, 7, 6, 1
i	7, 1

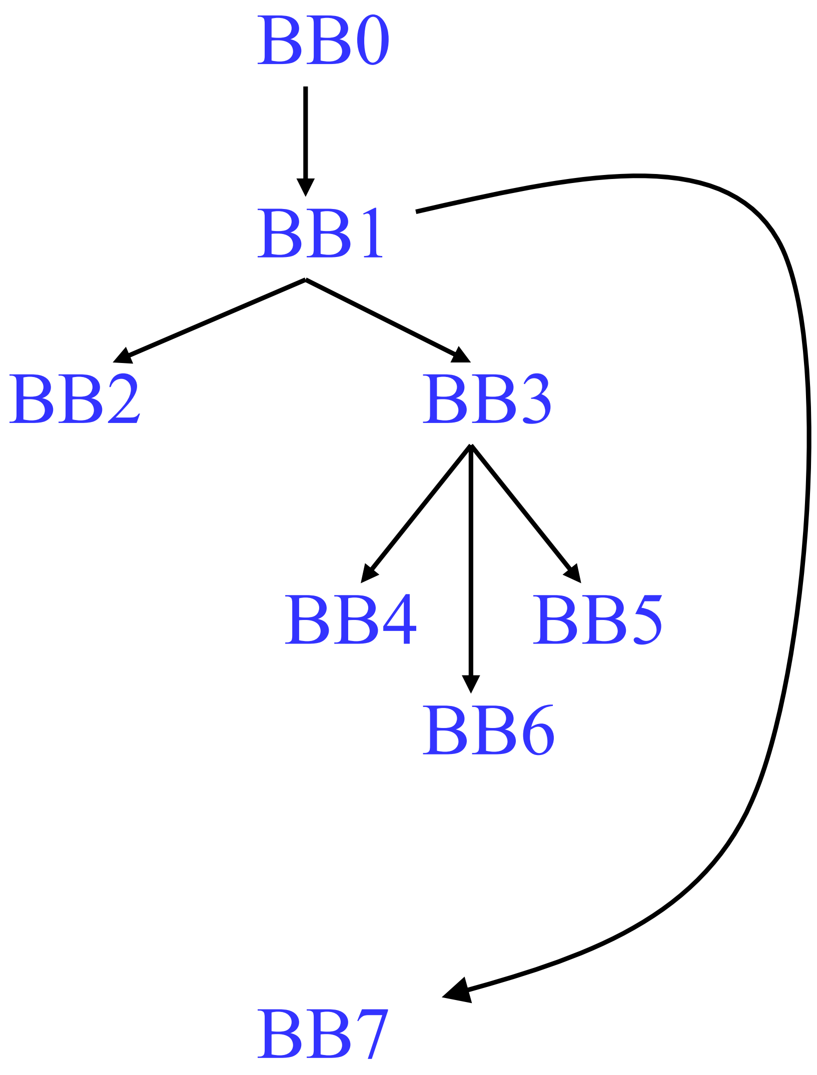
Variable Renaming (1/3)

- Constructing the dominator tree
  - The parent of a basic block is its immediate dominator
- For each variable, maintain the following data structures
  - A counter for creating new names
  - A stack to keep track of currently available names for this variable
    - The top of the stack is the name defined in its nearest dominators



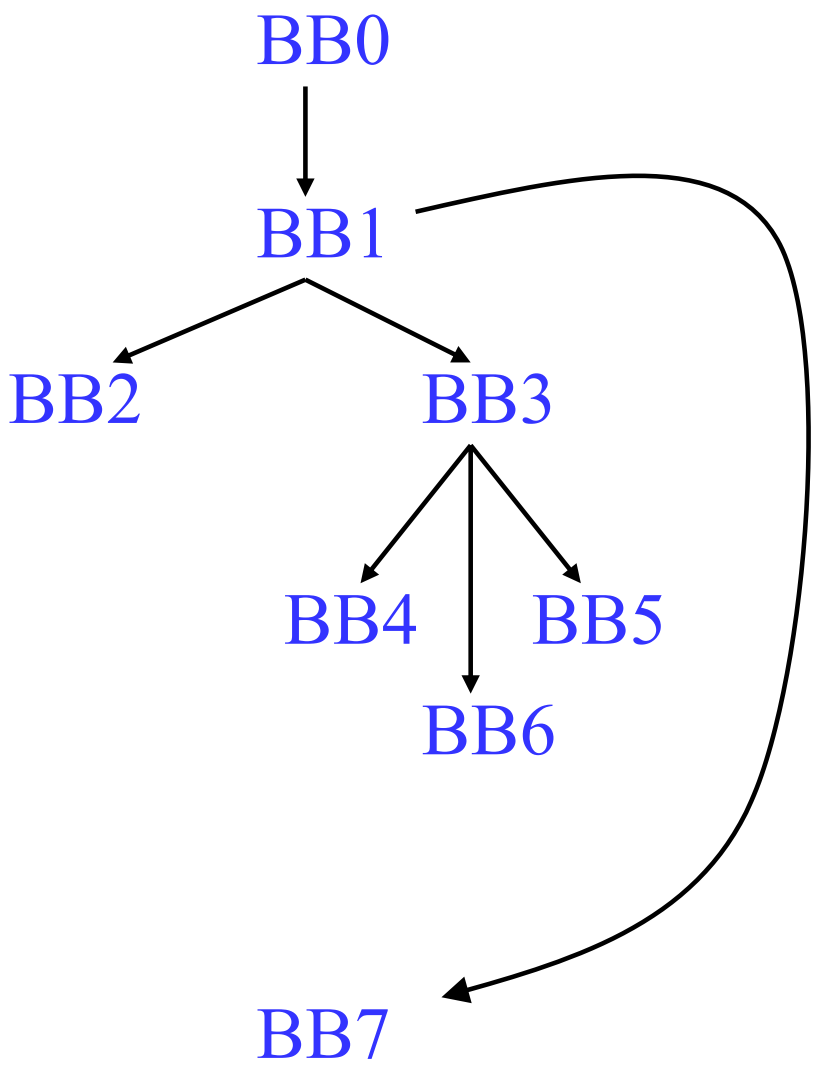
Variable Renaming (2/3)

- Process each basic block in preorder of the dominator tree
  - Rewrite each instruction (including the Phi nodes) in forward order
    - For each use, replace the name with the latest name at the top of the stack
    - For each def, generate a new name
      - New name = original name + counter
      - Increment the counter by 1
      - Push the new name into the stack
  - Propagate the new names to the Phi nodes of its successors
  - Recursively process its children
  - Pop names generated in this basic block from the stack

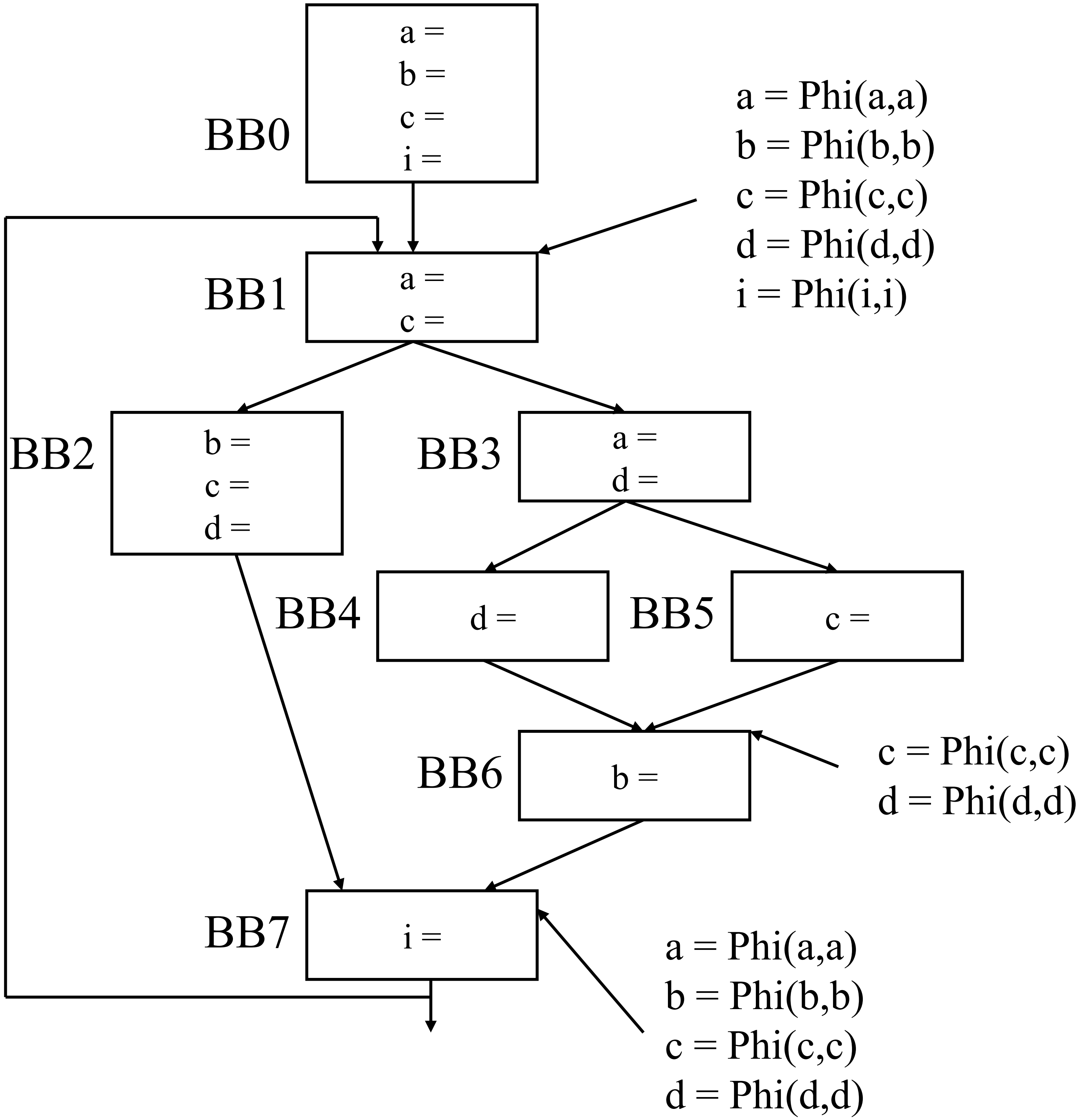


Variable Renaming (2/3)

- Why preorder traversal
  - If a variable has two definitions in different paths
    - A Phi node would be inserted
    - The two names for the definitions would be propagated from its predecessors
  - If a variable is defined only in the dominators
    - The top of the stack is the name of the latest definition

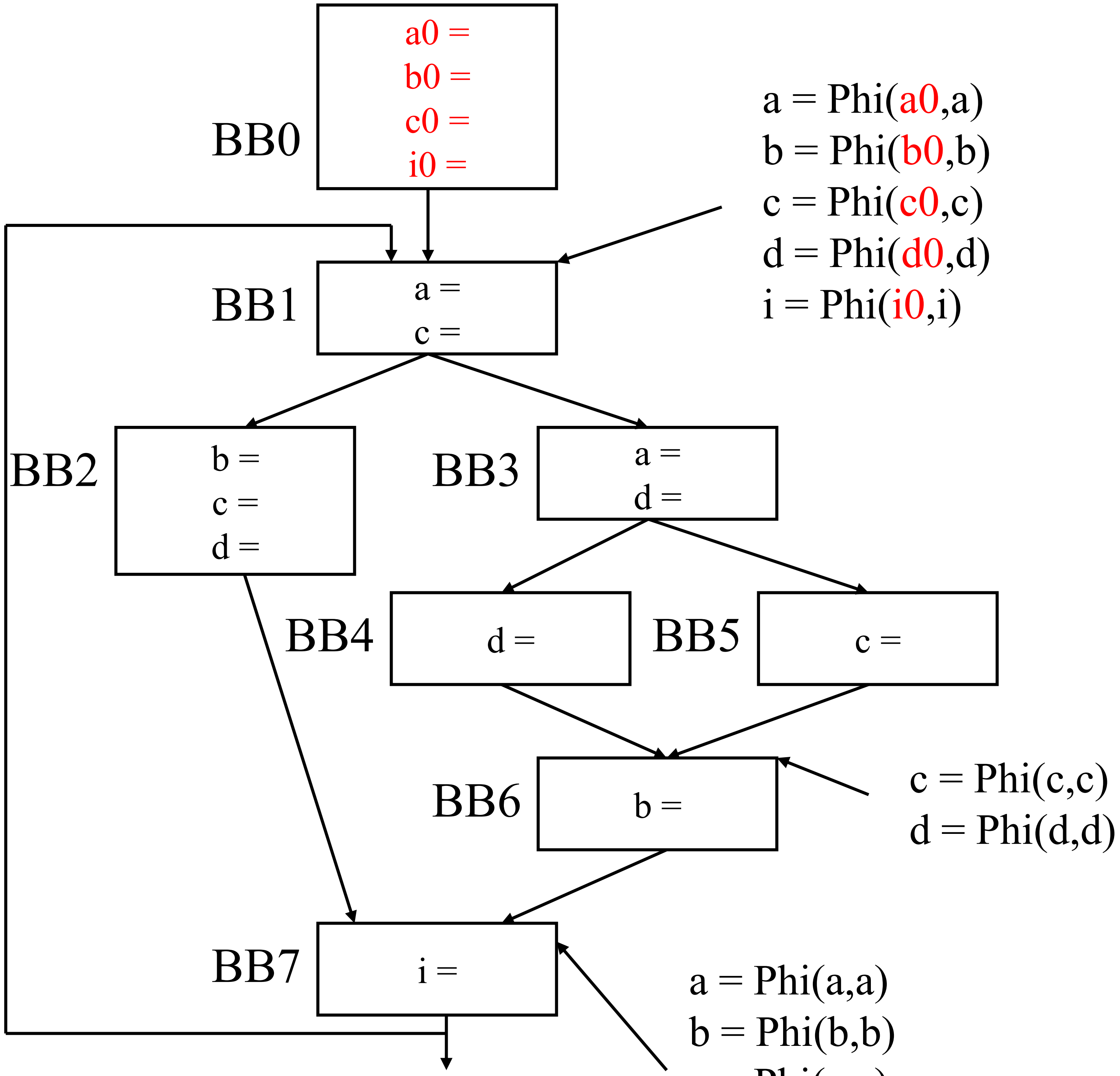


Variable Renaming: Example



var:	a	b	c	d	i
ctr:	0	0	0	0	0
stk:	a0	b0	c0	d0	i0

Variable Renaming: Example



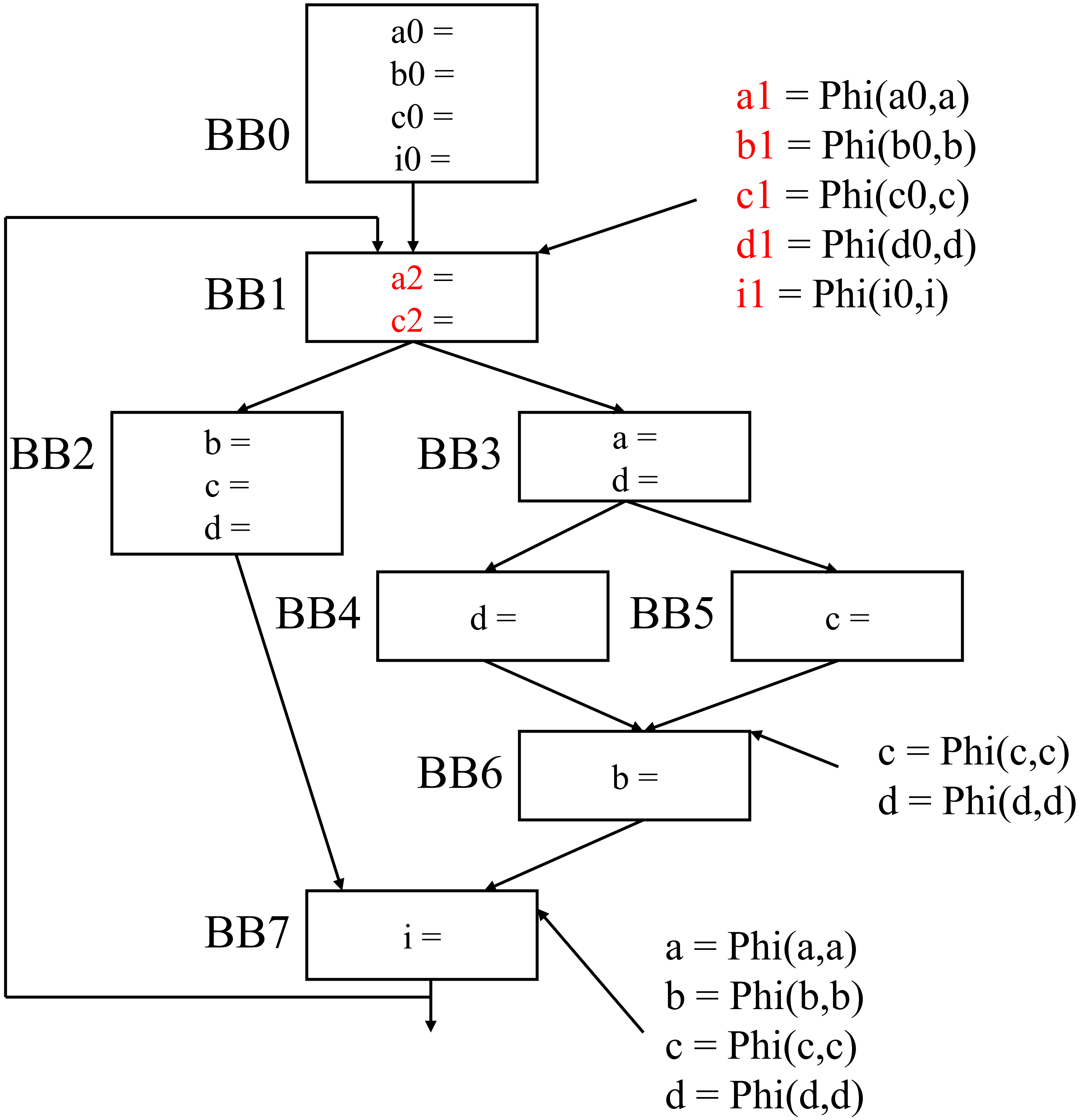
a = Phi(a0,a)
b = Phi(b0,b)
c = Phi(c0,c)
d = Phi(d0,d)
i = Phi(i0,i)

c = Phi(c,c)
d = Phi(d,d)

a = Phi(a,a)
b = Phi(b,b)
c = Phi(c,c)
d = Phi(d,d)

var:	a	b	c	d	i
ctr:	1	1	1	1	1
stk:	a0	b0	c0	d0	i0

Variable Renaming: Example



BB0
a0 =
b0 =
c0 =
i0 =

a1 = Phi(a0,a)
b1 = Phi(b0,b)
c1 = Phi(c0,c)
d1 = Phi(d0,d)
i1 = Phi(i0,i)

BB1
a2 =
c2 =

BB2
b =
c =
d =

BB3
a =
d =

BB4
d =

BB5
c =

BB6
b =

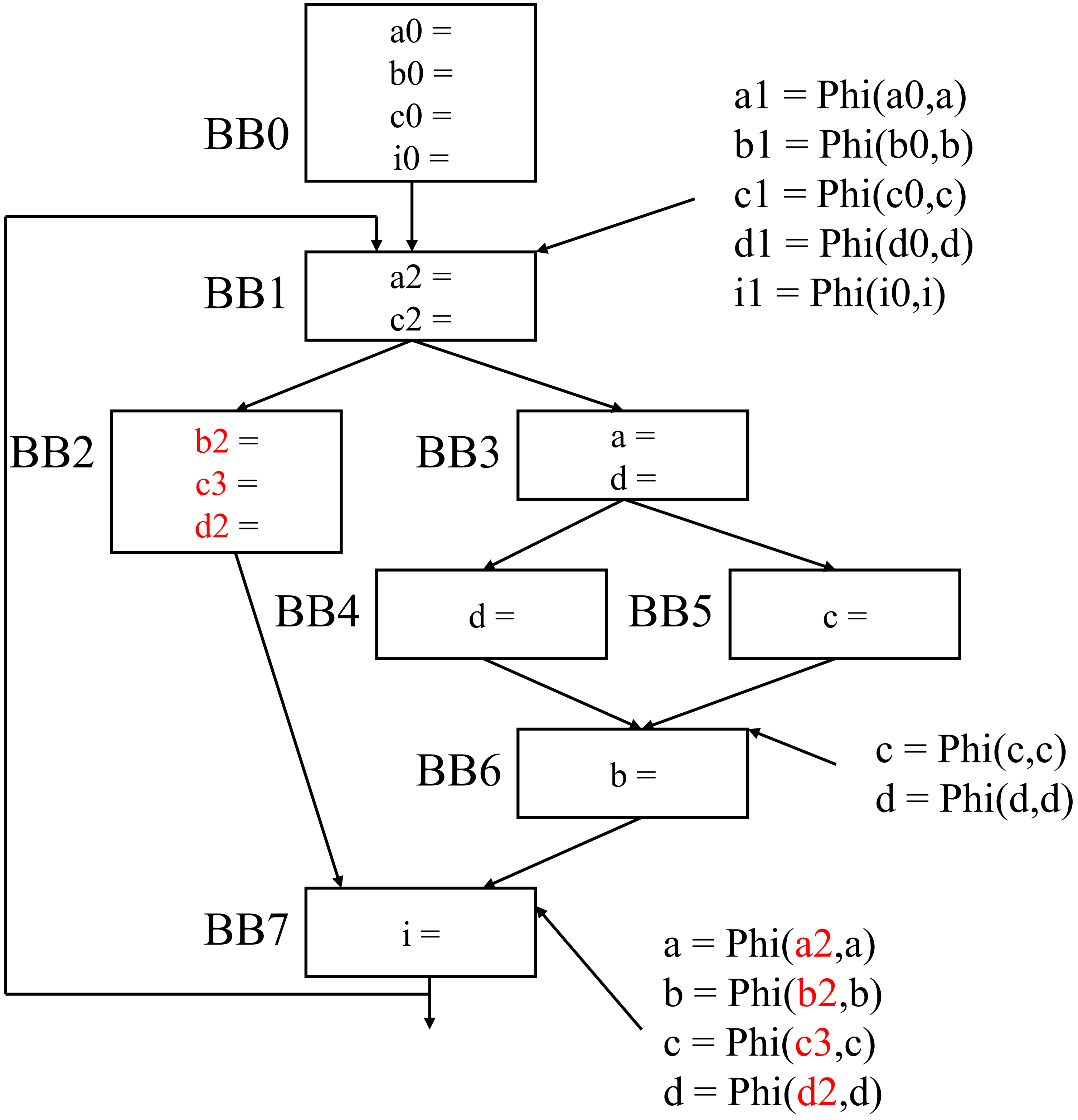
c = Phi(c,c)
d = Phi(d,d)

BB7
i =

a = Phi(a,a)
b = Phi(b,b)
c = Phi(c,c)
d = Phi(d,d)

var:	a	b	c	d	i
ctr:	3	2	3	2	2
stk:	a0	b0	c0	d0	i0
	a1	b1	c1	d1	i1
	a2		c2		

Variable Renaming: Example



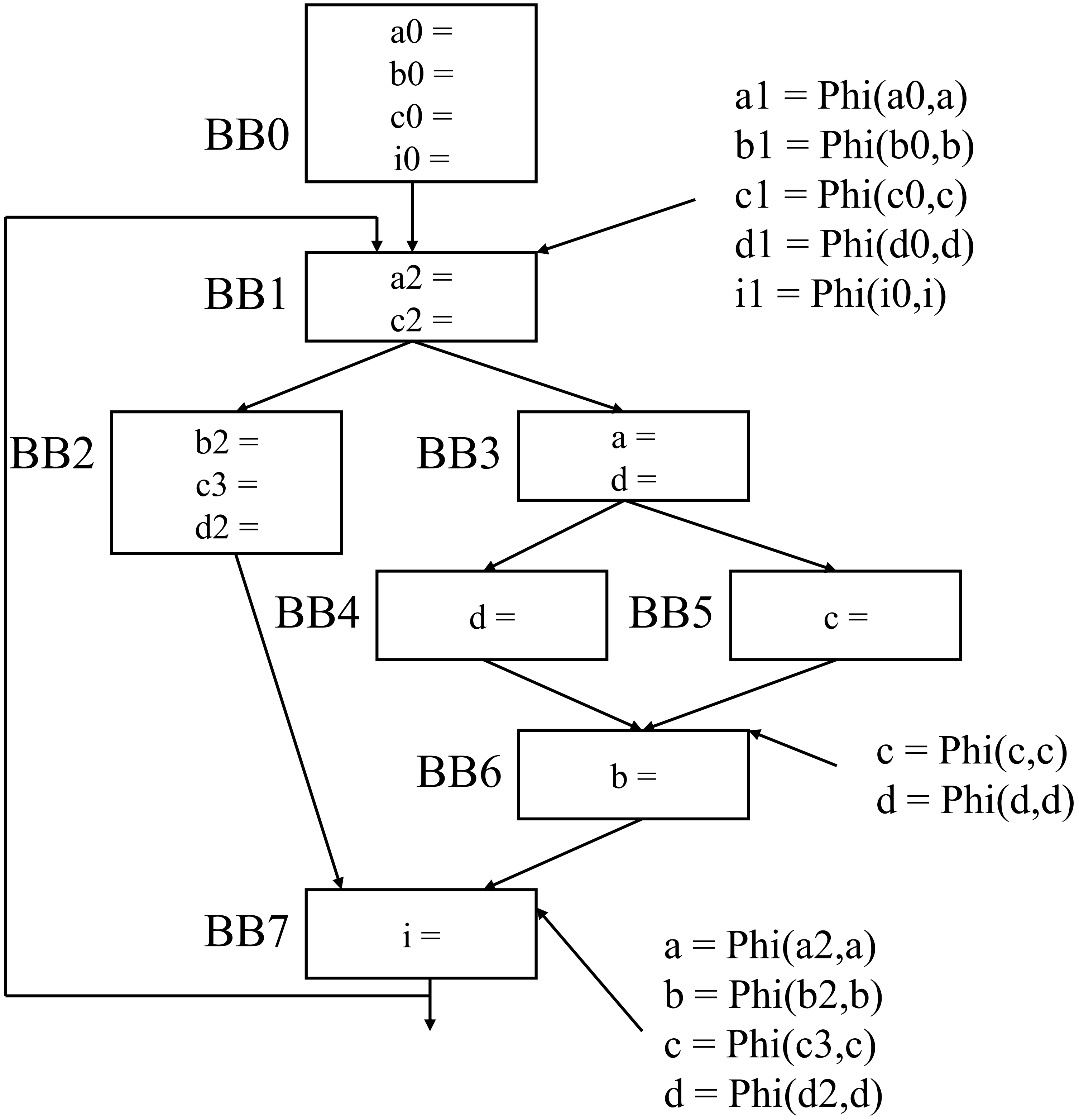
a1 = Phi(a0,a)
b1 = Phi(b0,b)
c1 = Phi(c0,c)
d1 = Phi(d0,d)
i1 = Phi(i0,i)

c = Phi(c,c)
d = Phi(d,d)

a = Phi(a2,a)
b = Phi(b2,b)
c = Phi(c3,c)
d = Phi(d2,d)

var:	a	b	c	d	i
ctr:	3	3	4	3	2
stk:	a0	b0	c0	d0	i0
	a1	b1	c1	d1	i1
	a2	b2	c2	d2	
			c3		

Variable Renaming: Example



BB0

a0 =
b0 =
c0 =
i0 =

a1 = Phi(a0,a)
b1 = Phi(b0,b)
c1 = Phi(c0,c)
d1 = Phi(d0,d)
i1 = Phi(i0,i)

BB1

a2 =
c2 =

BB2

b2 =
c3 =
d2 =

BB3

a =
d =

BB4

d =

BB5

c =

BB6

b =

c = Phi(c,c)
d = Phi(d,d)

BB7

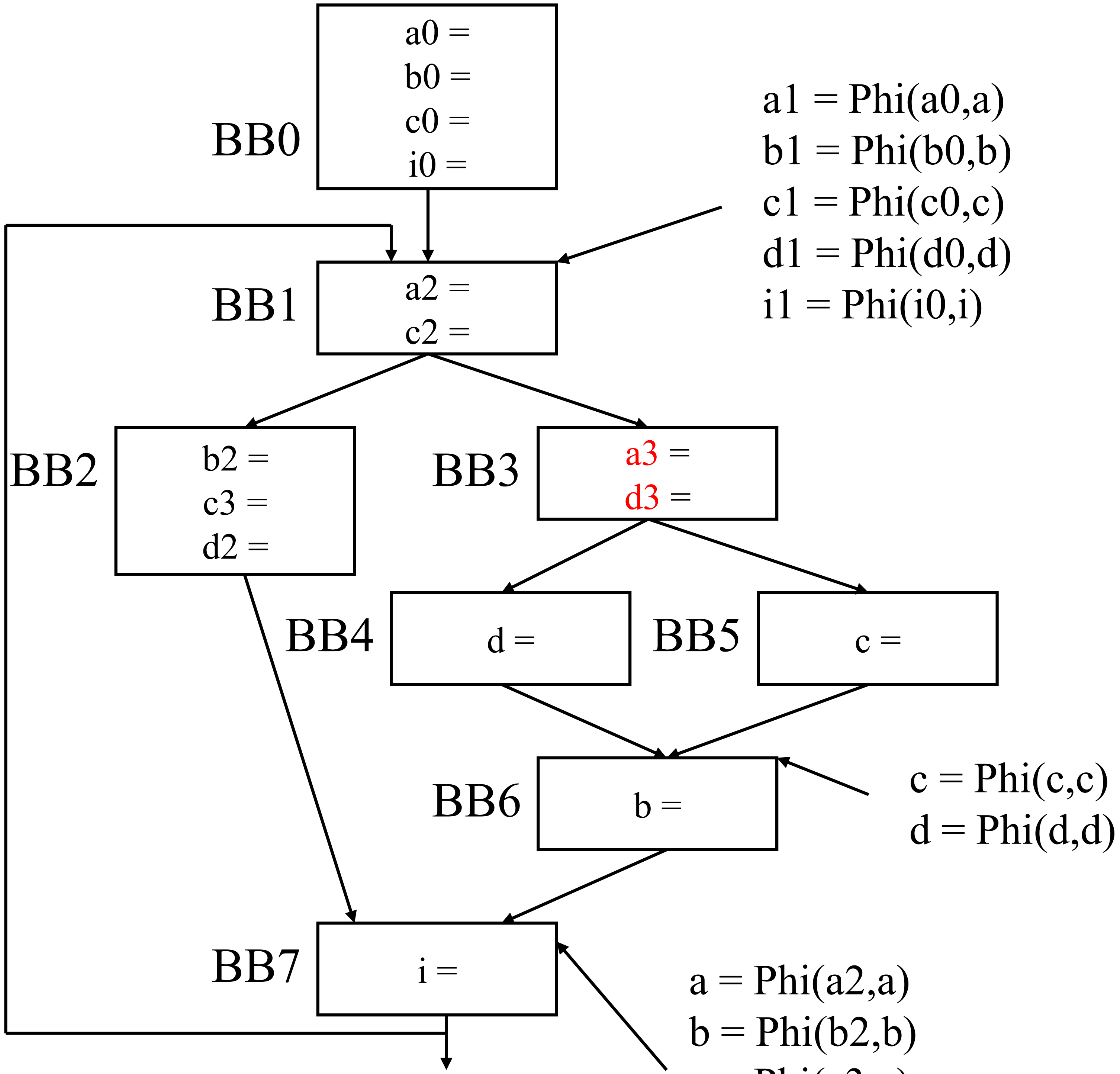
i =

a = Phi(a2,a)
b = Phi(b2,b)
c = Phi(c3,c)
d = Phi(d2,d)

var:	a	b	c	d	i
ctr:	3	3	4	3	2
stk:	a0	b0	c0	d0	i0
	a1	b1	c1	d1	i1
	a2		c2		

Pop names after BB2

Variable Renaming: Example



BB0
a0 =
b0 =
c0 =
i0 =

BB1
a2 =
c2 =

a1 = Phi(a0,a)
b1 = Phi(b0,b)
c1 = Phi(c0,c)
d1 = Phi(d0,d)
i1 = Phi(i0,i)

BB2
b2 =
c3 =
d2 =

BB3
a3 =
d3 =

BB4
d =

BB5
c =

BB6
b =

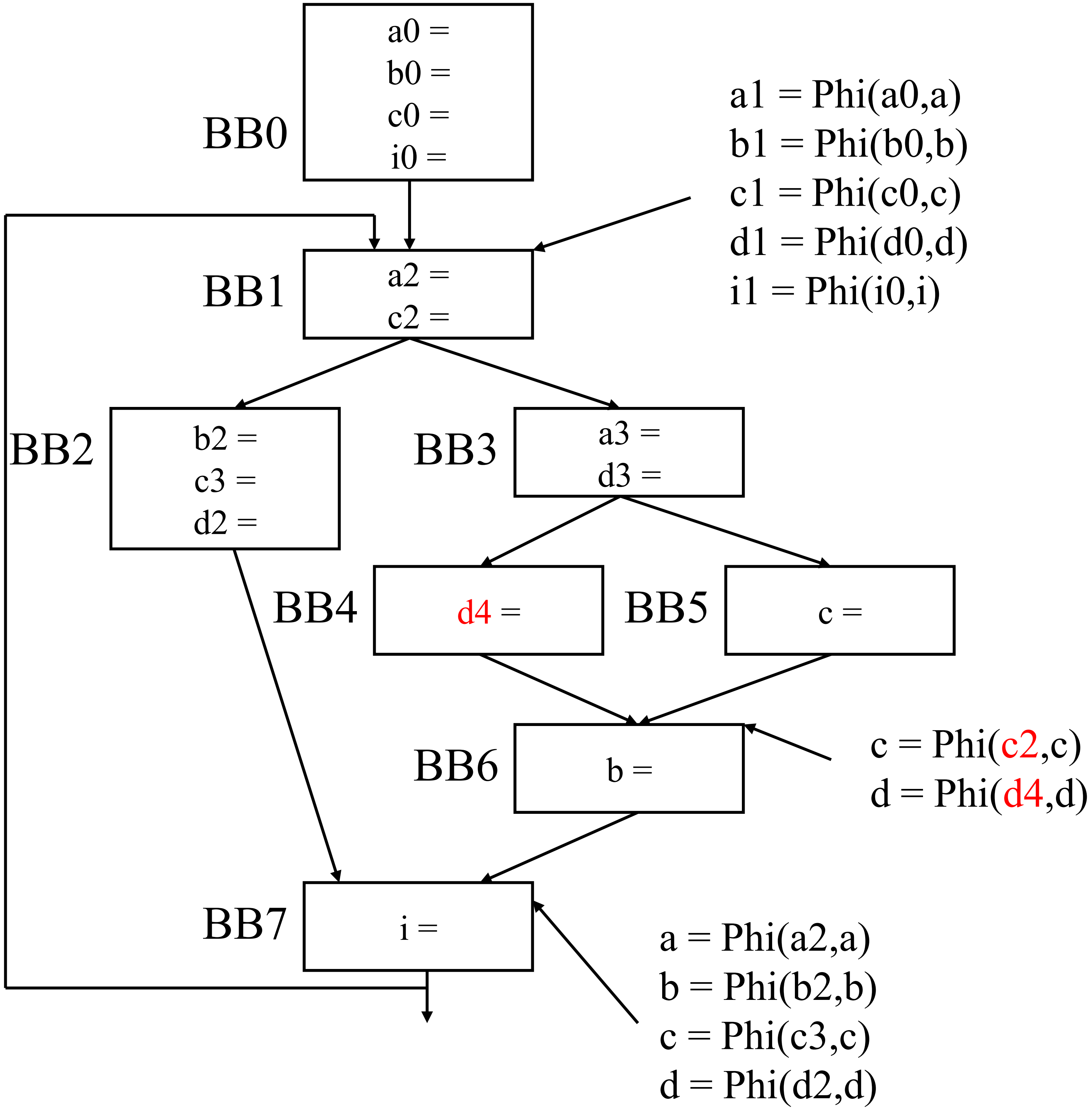
c = Phi(c,c)
d = Phi(d,d)

BB7
i =

a = Phi(a2,a)
b = Phi(b2,b)
c = Phi(c3,c)
d = Phi(d2,d)

var:	a	b	c	d	i
ctr:	4	3	4	4	2
stk:	a0	b0	c0	d0	i0
	a1	b1	c1	d1	i1
	a2		c2	d3	
	a3				

Variable Renaming: Example



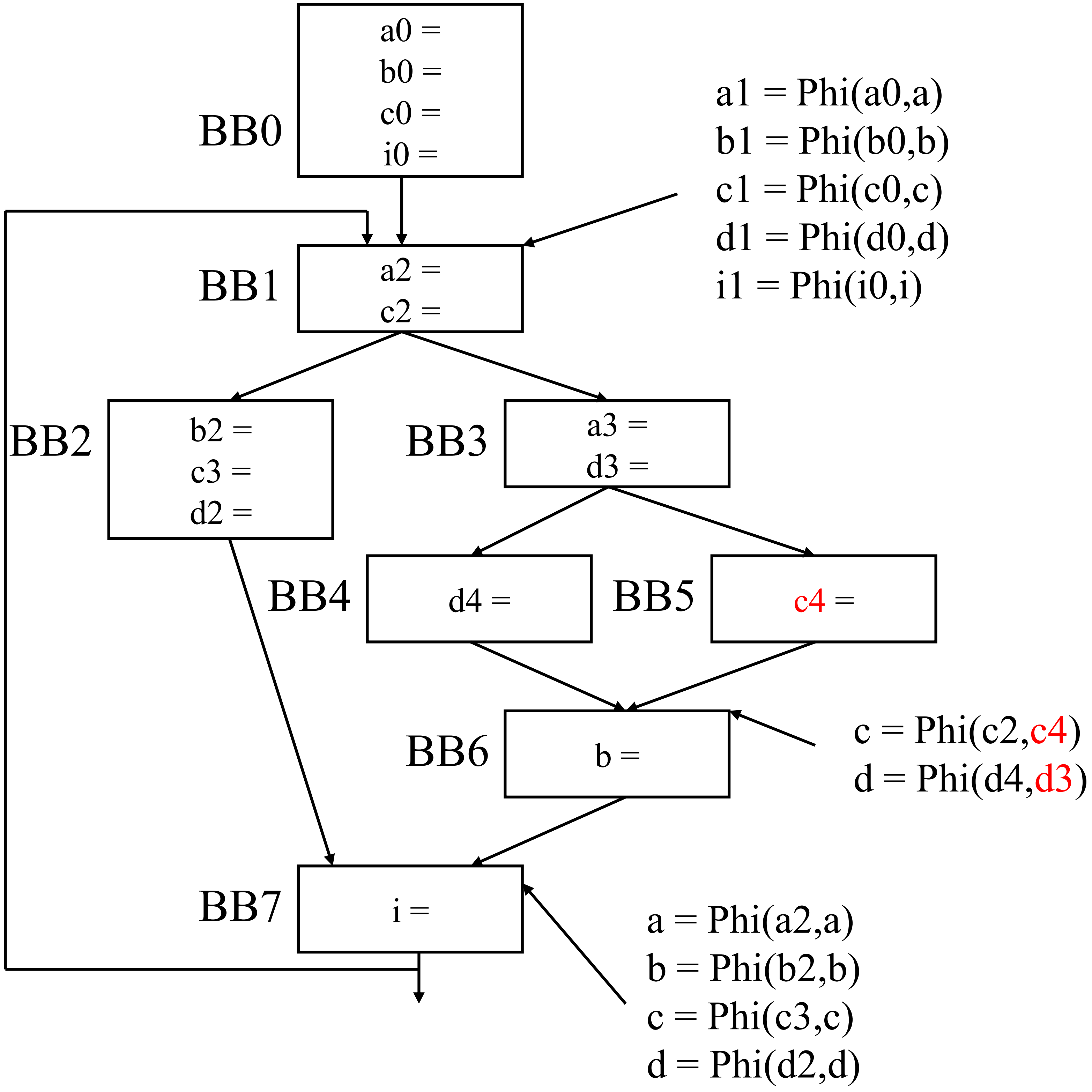
a1 = Phi(a0,a)
b1 = Phi(b0,b)
c1 = Phi(c0,c)
d1 = Phi(d0,d)
i1 = Phi(i0,i)

c = Phi(c2,c)
d = Phi(d4,d)

a = Phi(a2,a)
b = Phi(b2,b)
c = Phi(c3,c)
d = Phi(d2,d)

var:	a	b	c	d	i
ctr:	4	3	4	5	2
stk:	a0	b0	c0	d0	i0
	a1	b1	c1	d1	i1
	a2		c2	d3	
	a3			d4	

Variable Renaming: Example



BB0
a0 =
b0 =
c0 =
i0 =

a1 = Phi(a0,a)
b1 = Phi(b0,b)
c1 = Phi(c0,c)
d1 = Phi(d0,d)
i1 = Phi(i0,i)

BB1
a2 =
c2 =

BB2
b2 =
c3 =
d2 =

BB3
a3 =
d3 =

BB4
d4 =

BB5
c4 =

BB6
b =

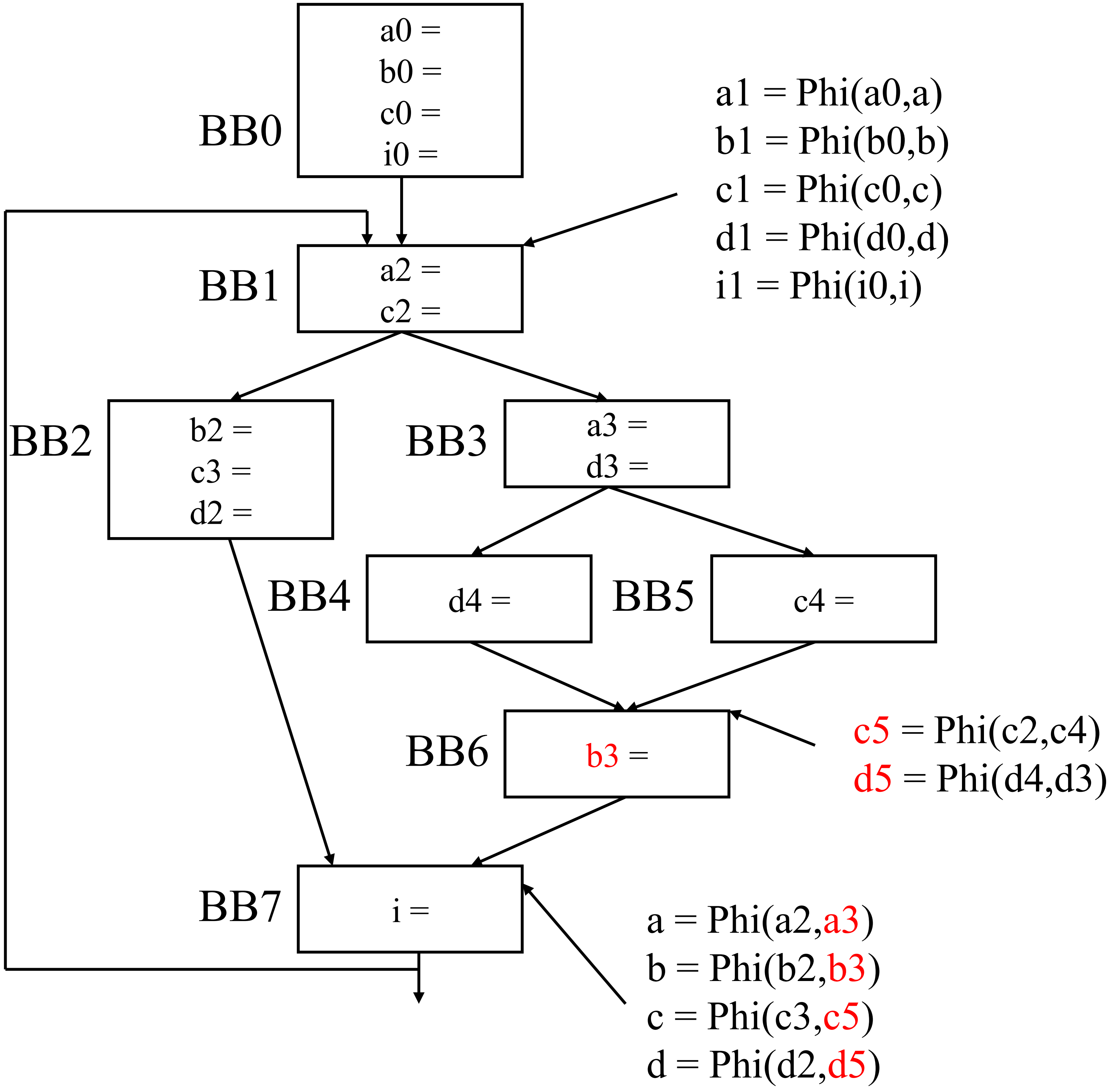
c = Phi(c2,c4)
d = Phi(d4,d3)

BB7
i =

a = Phi(a2,a)
b = Phi(b2,b)
c = Phi(c3,c)
d = Phi(d2,d)

var:	a	b	c	d	i
ctr:	4	3	5	5	2
stk:	a0	b0	c0	d0	i0
	a1	b1	c1	d1	i1
	a2		c2	d3	
	a3		c4		

Variable Renaming: Example



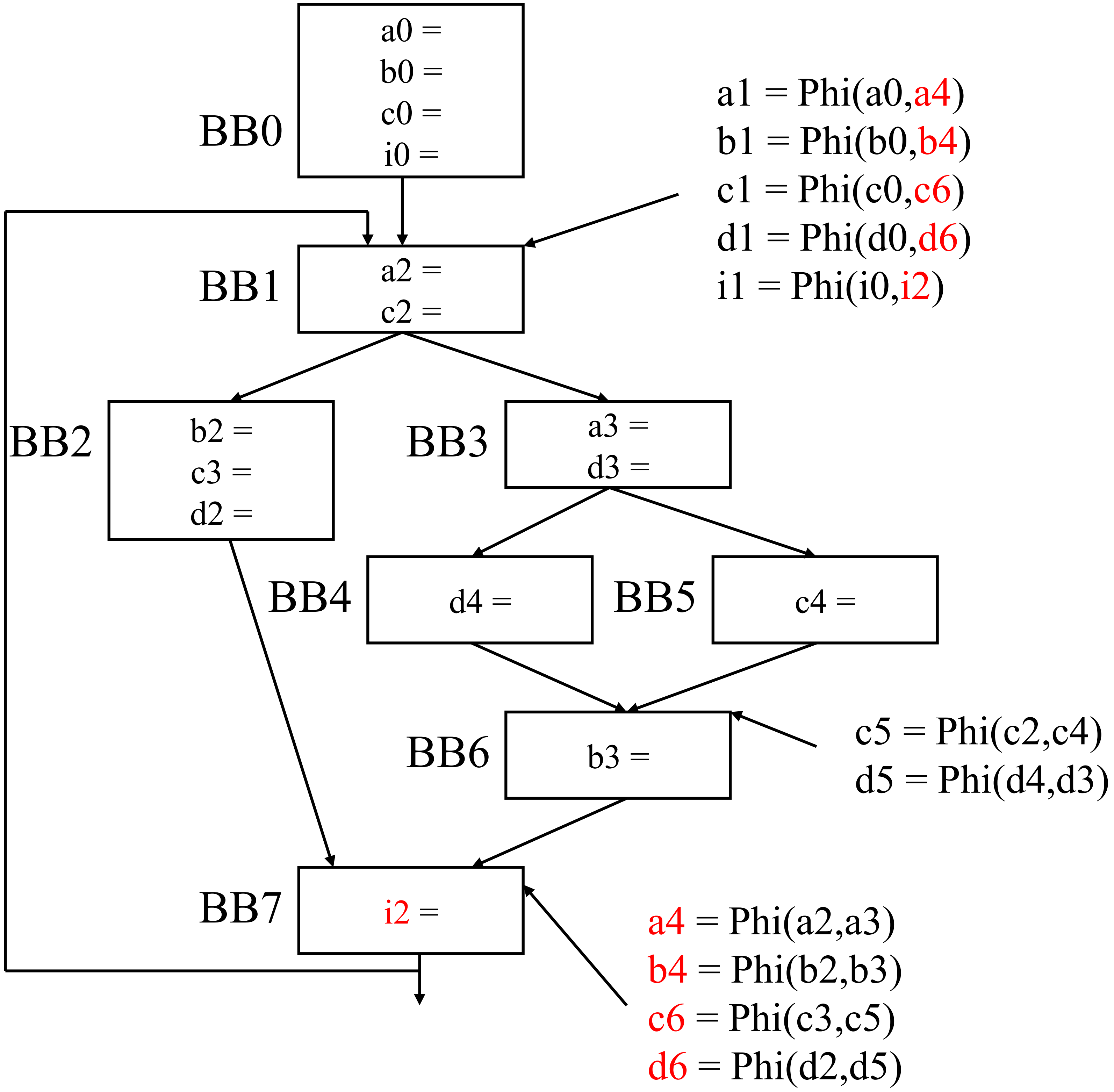
a1 = Phi(a0,a)
b1 = Phi(b0,b)
c1 = Phi(c0,c)
d1 = Phi(d0,d)
i1 = Phi(i0,i)

c5 = Phi(c2,c4)
d5 = Phi(d4,d3)

a = Phi(a2,a3)
b = Phi(b2,b3)
c = Phi(c3,c5)
d = Phi(d2,d5)

var:	a	b	c	d	i
ctr:	4	4	6	6	2
stk:	a0	b0	c0	d0	i0
	a1	b1	c1	d1	i1
	a2	b3	c2	d3	
	a3		c5	d5	

Variable Renaming: Example



BB0
a0 =
b0 =
c0 =
i0 =

BB1
a2 =
c2 =

a1 = Phi(a0,a4)
b1 = Phi(b0,b4)
c1 = Phi(c0,c6)
d1 = Phi(d0,d6)
i1 = Phi(i0,i2)

BB2
b2 =
c3 =
d2 =

BB3
a3 =
d3 =

BB4
d4 =

BB5
c4 =

BB6
b3 =

c5 = Phi(c2,c4)
d5 = Phi(d4,d3)

BB7
i2 =

a4 = Phi(a2,a3)
b4 = Phi(b2,b3)
c6 = Phi(c3,c5)
d6 = Phi(d2,d5)

var:	a	b	c	d	i
ctr:	5	5	7	7	3
stk:	a0	b0	c0	d0	i0
	a1	b1	c1	d1	i1
	a2	b4	c2	d6	i2
	a4		c6		

Thanks & all the best!